ARTICLE INFO:
Received : March 03, 2017
Revised : February 15, 2018
Accepted : March 08, 2018
CT&F - Ciencia, Tecnologia y Futuro Vol 8, Num 1 June 2018. pages 101 - 112
DOI : https://doi.org/10.29047/01225383.97

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TECHNO-ENVIRONMENTAL ASSESSMENT OF A MICRO-COGENERATION SYSTEM BASED ON NATURAL GAS FOR RESIDENTIAL APPLICATION

EVALUACIÓN TÉCNICA-AMBIENTAL DE UN SISTEMA DE MICRO-COGENERACIÓN BASADO EN GAS NATURAL PARA APLICACIÓN RESIDENCIAL

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ABSTRACT

The study carried out here aims to determine the advantage of using in-situ electricity generation facilities versus conventional generators, being evaluated from the environmental point of view. For this, an environmental analysis on the production of CO_2 has been applied to two scenarios of electricity generation for a residential building in Medellin city (Colombia). The first one refers to La Sierra thermo-electric plant located in La Sierra, municipality of Puerto Nare, in the Antioquiashire, which is the most efficient plant in Colombian thermal generation. The second comparison scenario refers to the annual operation of a micro-cogeneration facility, which satisfies the building's hot water and electrical energy needs. Using the capabilities of the TRNSYS v17® energy simulation software and the emission equations available in the public domain, the comparative environmental analysis is carried out between one and the other for the same load. The losses in electric transmission are assumed to be 10%. This analysis has shown a difference of more than 50% in emissions generation, with the main cause being the amount of fuel used, which for both cases is natural gas. On the other hand, this study shows the environmental advantages in the use of in-situ generators, decreasing transmission losses.

RESUMEN

El estudio realizado aquí busca determinar la ventaja que tiene el uso de instalaciones de generación eléctrica in-situ frente a generadoras convencionales, siendo evaluadas desde el punto de vista tecno-ambiental. Se ha aplicado un análisis de desempeño técnico y ambiental con respecto al consumo específico de combustible y de producción de CO_2, respectivamente, aplicados a dos escenarios de generación eléctrica para un edificio residencial en la ciudad de Medellín (Colombia). El primero hace referencia a la termoeléctrica la Sierra la cual es la de mayor eficiencia en generación térmica de Colombia. El otro escenario de comparación hace referencia al funcionamiento anual de una instalación de micro-cogeneración, la cual satisface las necesidades de agua caliente y energía eléctrica del edificio. Con el uso de las capacidades del software de simulación energética TRNSYS v17® y de las ecuaciones de cálculo de emisiones disponibles en el dominio público, se lleva a cabo el análisis tecno-ambiental comparativo entre uno y otro para una misma carga. Las pérdidas de transmisión eléctrica son asumidas en un 10%. Este análisis ha mostrado una diferencia de más del 50% en generación de emisiones teniendo como condicionante principal la cantidad de combustible usado (gas natural), el cual se reduce en una misma proporción. Por otro lado, este estudio permite evidenciar las ventajas técnico- ambientales en el uso de generadores in-situ, haciendo menores las pérdidas por transmisión.

KEYWORDS / PALABRAS CLAVE

Simulation | TRNSYS | Greenhouse effect | CO_2|
Electricity generation | Fossil fuel.
Simulación dinámica | TRNSYS | efecto invernadero |
CO_2 | generación de electricidad | combustible fósil.

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1. INTRODUCTION

Humanity has a natural tendency to develop and grow in every way, and as part of this growth it has developed energy generation alternatives to meet increasing demand. These alternatives that have been developed include thermoelectric and micro-cogeneration units. The former generally works based on the ignition of a fossil fuel; this process is carried out in a turbine that, when connected to a generator, produces electrical energy. Thermoelectric plants are low-cost generating plants, their construction is straightforward and the savings per megawatt generated make them attractive in comparison to other forms of generation, providing extra efficiency compared to other generating systems. In addition, the residual energy from this type of generation can be used to meet other demand. The latter are micro-cogeneration units; these also work based on the ignition of fossil fuels, generally in a piston engine. Micro-cogeneration units can be summarized as the simultaneous production of useful heat and electric power, in the same process. The principle is comparable to a car, when the electric generator is activated, the engine produces heat that is trapped by the cooling system and implies the heating and/or hot water production system. The installation of these systems is simple and low cost, provides reliability in energy supply and, what's more, reduces losses from electricity transmission since it is an on-site installation. When working with fossil fuels, these two energy generation systems produce emissions such as sulphur dioxide (SO_2), oxides of nitrogen (NO_x), carbon monoxide (CO), particulate matter (which may contain minor metals) and carbon dioxide (CO_2). Each of these elements directly influences global warming, altering how the planet naturally functions; so it is important to analyse, characterise and act on each of these elements' emission sources. The amount of emissions for each of these generators depends on the size and type of the generating facility, and also depends on the quantity and type of fuel used. A techno-environmental analysis makes it possible to have an idea of how efficient an energy-generating system can become and how its usage affects the planet's health, through understanding that critical points in the operation of these types of generators, as these are decisive in terms of the quantity of gases produced. Previous examination of these subjects only consider techno-economic issues and life cycle analyses, leaving big gaps regard of knowledge of environmental effects resulting from the use of energy generation alternatives, despite the fact that this issue is an important part of the Colombian National Inventory for Greenhouse Gases, see **Figure 1**. Furthermore, the study in this paper could be a good reference for the Colombian context.

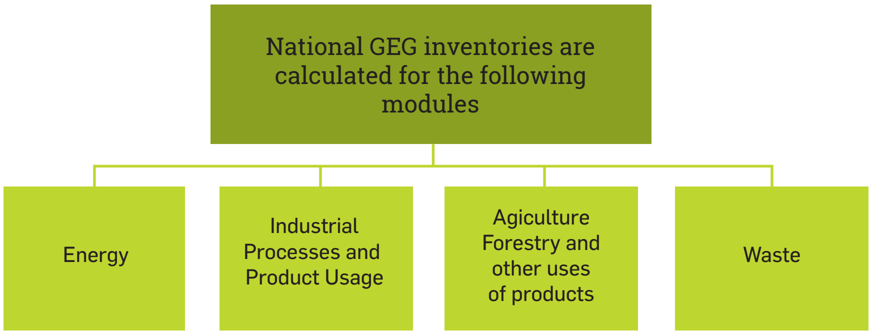

Figure 1. National inventory modules for greenhouse gasses

2. STATE OF THE ART

Romero, Salmerón, Sánchez, Rodríguez and Domínguez [1] assessed the economic and emissions performance of different hybrid system designs comprising solar thermal collectors, photovoltaic panels and natural gas internal combustion engines installed in a building using TRNSYS 17®, coupled with the GenOpt optimization tool. Five locations in Spain with several climatic characteristics were used as the case scenarios. The Life Cycle Cost for the conventional scenario is the best among all the scenarios, while energy consumption and emissions are decreased for the hybrid systems.

A modelling framework combining HOMER® and RETScreen® software tools was used for assessing renewable energy systems focusing on power systems providing electricity, developed by Salehin *et al.* [2]. As a case study, a Solar PV-diesel energy system and a wind-diesel energy system in Kutubdia Island (Bangladesh) were simulated. The main outcome of this study is as follows: the solar PV-diesel energy system has a lower payback period as compared to the wind-diesel energy system, while net annual GHG emissions are lower for the former.

Yang and Zhai [3] modelled a solar hybrid conventional combined heat and power (CCHP) system based on a hotel building and utilized a particle swarm optimisation (PSO) algorithm to identify the optimum design parameters. Five operation strategies were applied for the solar hybrid CCHP system. The results show that the hybrid CCHP system under the FEL-ECR mode is the best choice.

Huang *et al.* [4] performed comparative techno-economic evaluations of two small-scale biomass fueled Combined Heat and Power (CHP) systems to highlight the potential for their uses in the UK and Europe. The energy and mass balance function of the simulation software ECLIPSE® was used, see **Figure 2**. ECLIPSE® is a computational tool that makes it possible to estimate capital investment along with the fixed and variable operating and maintenance costs (O&M). The following two engine configurations were assessed: Organic Rankine Cycle (ORC) and Internal Combustion Engine (ICE) integrated with biomass gasification systems for generating heat and electricity. The proposed biomass CHP system consists of a biomass preparation and feeding unit, downdraft gasifier, wet gas scrubbing system, gas engine-generator (this is the system's basic prime mover), ash removal and water treatment systems to meet environmental regulations, along with the heat recovery equipment and heat storage.

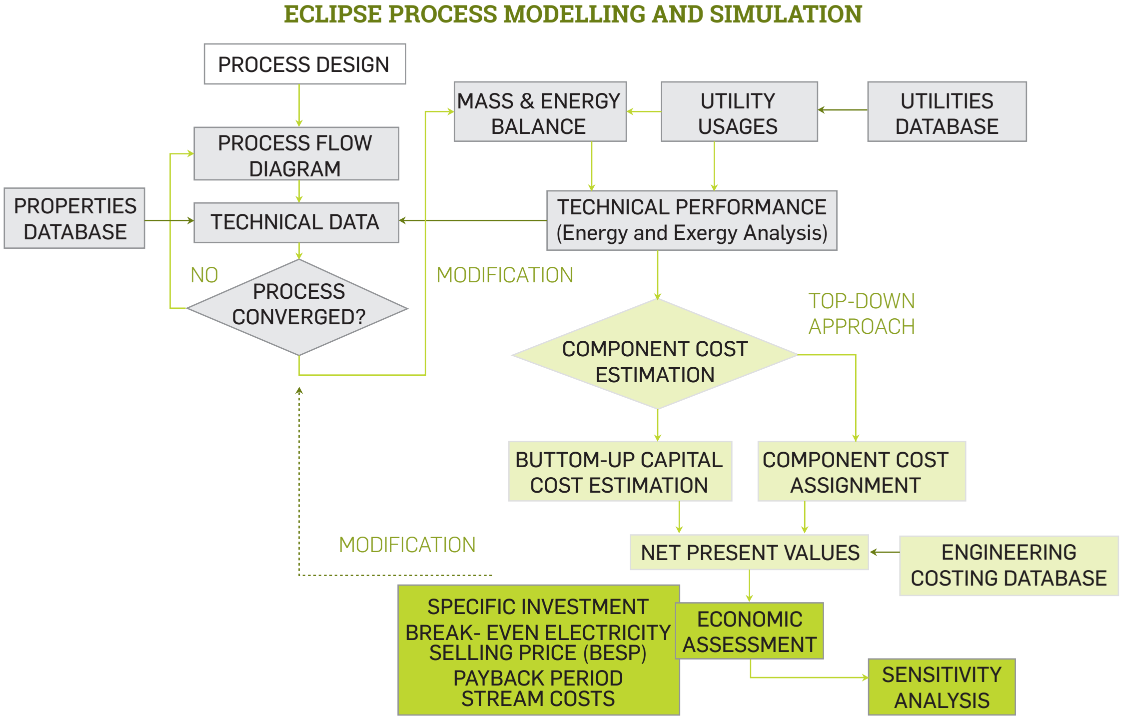

Figure 2. Modelling and simulation in ECLIPSE [4]

As a basis for the analysis, the assumptions related to the capacity and efficiency of the plant, the biomass delivery characteristics (location, transportation), the capital and deterioration costs, and emission data were used. A model was developed considering the basic heat and mass balance of a power plant and technical performance variation relationships, as well as cost parameters included from available information from the pilot plant test data. To establish operating costs, the cost of biomass purchase and transport was estimated; for capital investment, the capital recovery factor (CRF) was calculated using the equal annuity to be paid over a number of years (economic life of the plant); for the additional expenditure (per year) for the operating life of the plant, both the operating cost and annuity for the loan capital was calculated; for emissions, the reduction in CO_2 (ΔCO_2, in ton year^{-1}) was assessed on the basis of the reduction in coal fired in the boiler and considering biomass as a CO_2 neutral fuel. Then, an engineering-economic analysis was carried out to assess the effect of different operating, logistical and economic parameters on the additional costs for power generation as a result of biomass cofiring.

Osman and Ries [5] present a model developed to optimise the selection and operation of energy systems in commercial buildings based on their potential life cycle environmental impacts using the Energy 10® software. The approach comprised energy simulation, life cycle assessment (LCA), and an optimisation model to optimise the selection and operation of cogeneration systems, average electric grid, gas boilers, and absorption and electric chillers (please refer to **Figure 3**).

The first phase, energy simulation, was used to define the building's characteristics and determine the building energy use profile (i.e. hourly heating, cooling, and electrical loads of a building). The second phase, life cycle assessment, was used to develop energy system models that were used in meeting the building's energy demand using a functional unit (i.e. 1-kWh) and system boundaries (i.e. elementary flow at system boundaries and the defined technology specifications).

The environmental impact indicators chosen to quantify the potential contribution of the products' inventory flow were: Primary Energy Consumption, Global Warming Potential (GWP), Tropospheric Ozone Precursor Potential (TOPP) and Acidification Potential (AP). Life cycle (LC) emission factors were expressed as the weight of the pollutant in terms of the environmental impact indicators divided by a unit (kWh) consumed. These emission factors were then used as coefficients of the decision variables in the objective function of the optimisation model. The third phase, optimisation, is aimed at determining the optimum energy systems and operational strategies used to meet building's energy demand. The optimisation model resulted in a mixed integer linear programming (MILP) problem.

The objective function of the optimisation problem was formulated by using continuous decision variables for energy supply and the emission factors as coefficients of the variables for the energy systems considered. The performance criteria used were primary energy consumption (PEC) and tropospheric ozone precursor potential (TOPP).

Campos, Pérez, Sala, and del Portillo [6] carried out a thermo-economic analysis of a micro-CHP installation using the TRNSYS® v.16 thermal simulation software, taking into account both the thermal and electric load, see **Figure 4**. This model was developed using a grey-box approach for the modelling of combustion-based micro-CHP units, considering all the main transient effects taking place in it. In order to better define the specific performance of the

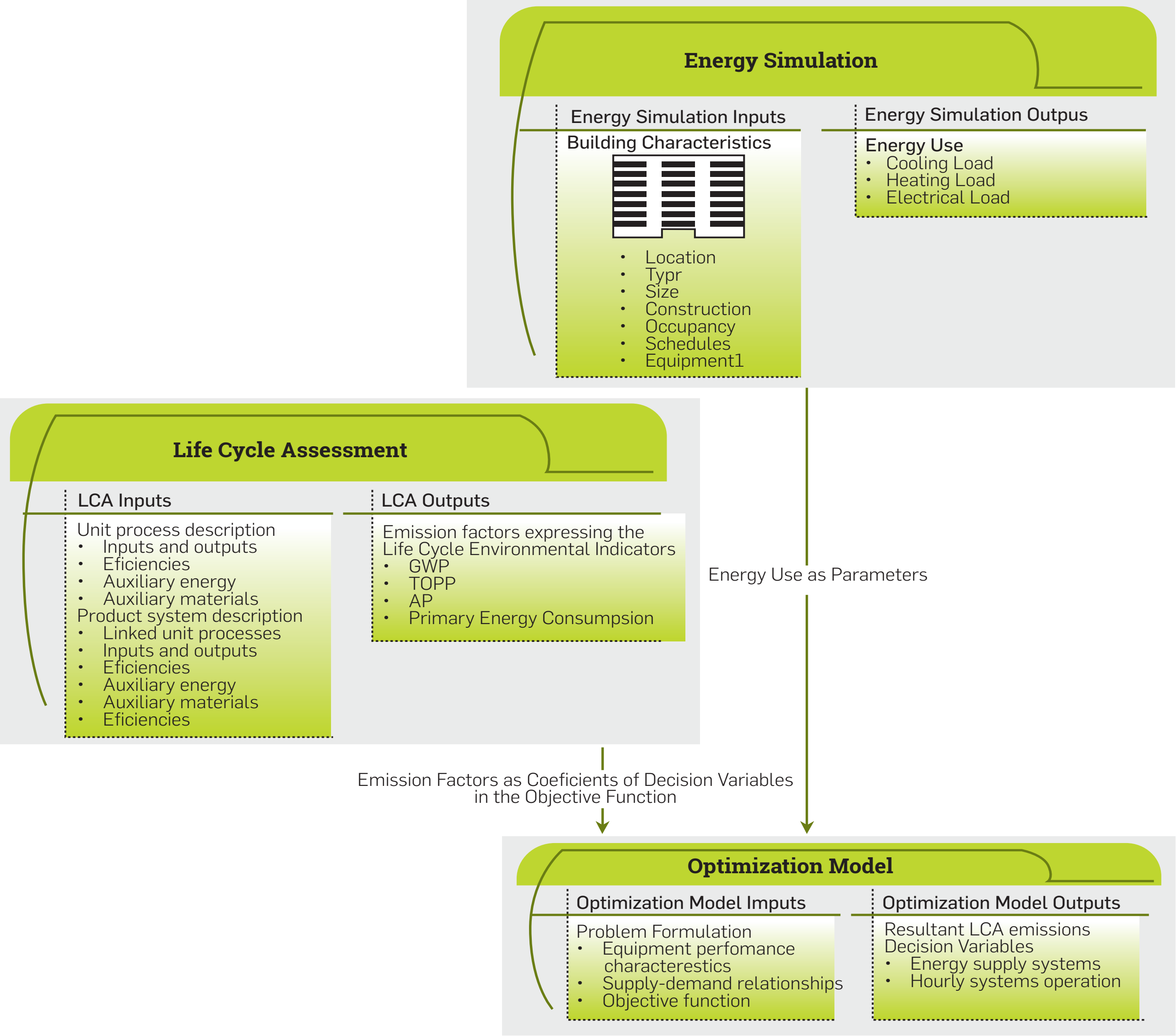

Figure 3. Life cycle energy optimisation model schematic [5]

micro-CHP unit within the plant, the authors used the Primary Energy Saving (PES) concept calculated using the useful heat production, the electricity from cogeneration, the natural gas consumption of cogeneration and the harmonised efficiency reference values published by the European Commission. The exergy content of the components (CExD) was directly obtained from the Cumulative Exergy Demand method used by the Simapro LCA® tool designed to collect, analyse and monitor the sustainability performance of products and services. In the exergy analysis, the exergy content of the different components and flows of the system was determined for each 6-min time step. The exergy flows were calculated as the sum of the physical and chemical exergy, neglecting the kinetic and potential exergy. The authors included the transient response of the equipment to the dynamic nature of the loads in the annual analysis of the plant, which is a novel approach to this kind of study.

In 2011, the Sustainable Energy Authority of Ireland wrote a report on a field trial commissioned to assess the operation, performance and benefits of micro-CHP in commercial scenarios [7]. Data was collected from 13 sites across Ireland including residential apartments, care and nursing homes, a hotel, a crèche, offices and a fire station. The micro-CHP engines analysed were integrated with supplementary heating appliances; they were designed to provide heating and hot water for use on site. The electricity generated was mainly used locally; as most of the sites had significant load, very few of them exported to the national grid. All energy flows in and out of the micro-CHP appliance were monitored; this means metering the gas and electricity use of the appliance and the heat and electricity generated and used on site. The majority of sites also had a heat meter on the buffer tank, which made it possible to assess the performance and losses of the buffer tank. The data was collected initially on a weekly basis and, after validation, reduced to monthly basis. The data collected was analysed and assessed in terms of overall engine efficiency, thermal efficiency, electrical efficiency, primary energy consumption and savings, engine operating hours and cycling patterns, carbon benefit ratio and absolute CO_2 savings,

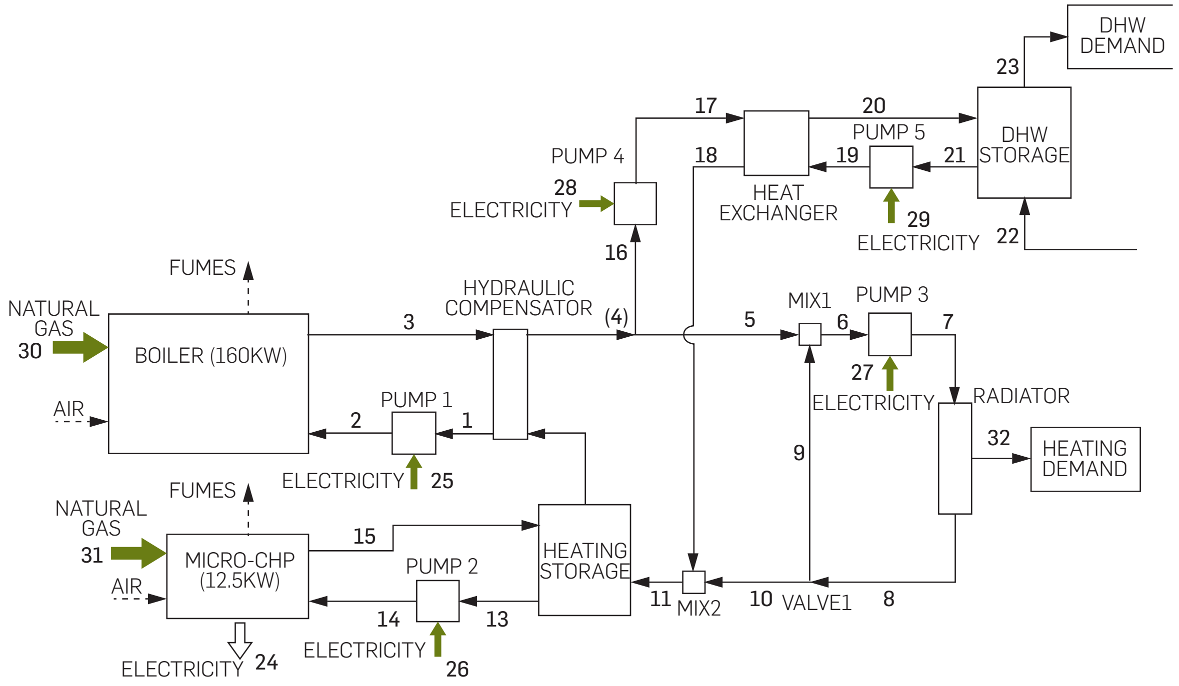

Figure 4. Schematic representation of the micro-CHP system [6]

see **Figure 5**. Maintenance and system integration were also considered, as these are very important determinants of the success of an installation. The data then served as input for the financial assessment, considering the fuel, capital, operating and maintenance costs for commercial-scale micro-CHP and calculating the simple payback period for the field trial installations against their utilisation factors.

Di Pietra [8] evaluated the applicability and the potential of an internal combustion engine in a micro cogeneration application in terms of energy savings, emissions and cost reduction, and then compared it to conventional systems from Italian residential building stock, see **Figure 6**. The TRNSYS® tool was used for the building and cogeneration plant simulation. The internal combustion engine was modelled using the IEA Annex 42 model, adapted as Type 154 to TRNSYS®. Buildings were modelled using the multi-zone building model Type 56, in order to estimate winter thermal loads and temperature trend inside the building. Three types of energy consumption were considered for the assessment: 1. Net energy demand: energy demanded from the cogeneration, gas boiler systems and electric grid to cover the demands for space heating, domestic hot water and electricity; 2. Delivered energy: energy delivered to the building as natural gas, heat or electricity; 3. Primary energy: fossil energy. The performance assessment analysis was based on the energy analysis, the CO_2 emission analysis (environmental impact analysis), the economic analysis (specific costs for electricity and for natural gas) and a simplified approach.

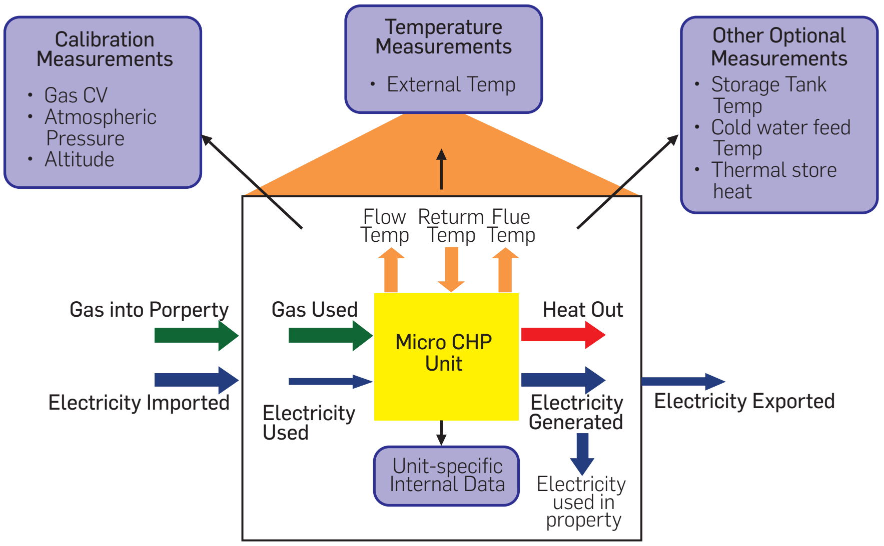

Figure 5. Schematic representation of the key parameters measured [7]

Cullen and Macgovern [9] addressed the need for efficiency gains in the modern industrial engine as utilised in combined heat and power (CHP) generation and other distributed generation conditions. Power generation is discussed in terms of reciprocating-engine-based plant operating on Otto type thermodynamic cycles. Internal combustion engine performance improvement, in the industrial engine sector, focuses on its combustion characteristics with emphasis on areas such as piston design, valve timing, and supercharging. A life cycle cost model was presented to illustrate the importance of different parameters in the modelling of CHP systems. The techno-economic modelling equations were derived in terms of the operational parameters of the chosen plant, such as: fuel consumption, brake

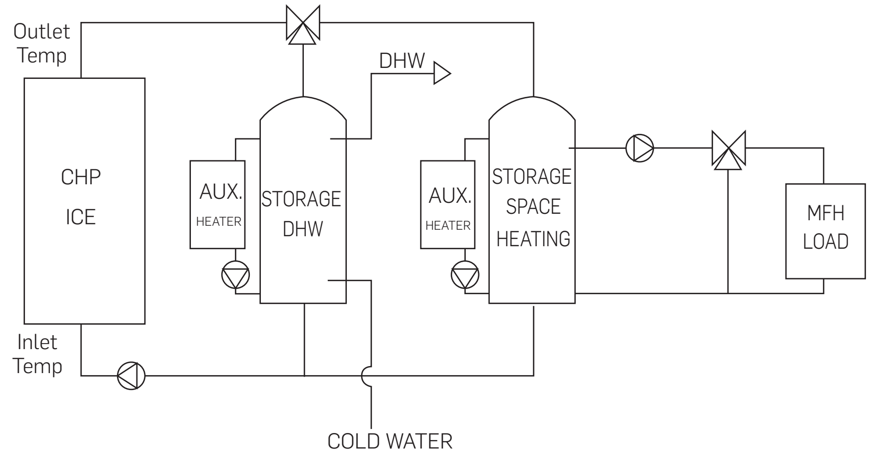

Figure 6. Schematic representation of the CHP system [8]

power, electrical power, and thermal power outputs. Unit costs for both electrical and thermal power purchases from a local utility were accounted for, as were maintenance costs, transmission charges associated with grid distribution of fuel and electrical power, and unit charges for electrical power export to the utility.

Mago, Chamra and Hueffed [10] analysed a natural gas engine CHP system together with a vapour compression system for different American climate zones. Performance was measured in terms of operational costs, primary energy consumption (PEC), and carbon dioxide emissions as a percent of a reference building to compare the performance of a CHP system operating 24 hours a day with a system that only operates during typical office hours. The system was optimised based on reducing PEC, minimising costs and reducing emissions. The benefits of CHP systems based on the Energy Star program, a program that offers energy management strategies and tools to help improve and track energy performance for commercial buildings and the Leadership in Energy and Environmental Design (LEED) certification were also presented.

Other techno-economic, environmental and optimization approaches have been used to assess energy consumption, demands, environmental and economic performance for aircraft applications which can be interesting as a methodology starting point for the studies carried out in this paper [11]-[14].

3. THEORETICAL FRAME

Human beings are a great cause of global warming, and we have the task of solving or mitigating the consequences of this lack of environmental control. That is why many solutions have been implemented, and one of these is the use of on-site micro-cogeneration units; given their characteristics, they can support energy demands, harnessing each flow in their operation, and they produce lower emissions compared to a conventional generation system (i.e. thermoelectric plants).

As mentioned above, with the increase in energy demand comes high costs and increased emissions, making this type of unit become a possible alternative in the mitigation of these problems. These systems are composed of engines that commonly work with natural gas and, when in operation, they generate instantaneous electricity and useful heat in the same process. The heat produced is used to meet needs for Domestic Hot Water (DHW) and the electric energy is used for common demands, as can be seen in the Figure 7. The general summary of its characteristics or advantages is as follows:

- Contribution to the environment, with the reduction of CO_2 emissions of up to 70%.
- Local energy generation.
- Lower electricity costs.
- Independence from the conventional electrical grid.
- Easily coupled to energy systems previously established in buildings.
- Its working capacity is generally high, which ensures a great degree of coverage regarding energy requirements.

From an environmental point of view, Colombia has regulations such as those contained in Decree 02 of 1982, Articles 73 and 74, which determine the State's obligation to maintain the atmospheric quality of air, so as not to cause discomfort or damage that interferes with the normal development of species and affect natural resources, as well as prohibitions and restrictions on the discharge of particulate matter, gases and vapors into the atmosphere. Therefore, solutions of this type would help greatly in terms of compliance with these laws, and in principle, their implementation would not conflict with the country's policies, as their implementation is attractive both in environmental and economic terms.

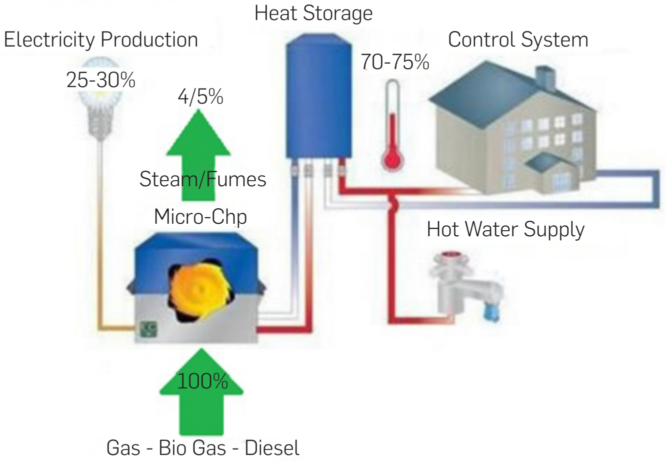

Figure 7. Schematic representation of the key parameters measured [7]

On the other side of the coin are thermoelectric plants that have become very important in Colombia. These types of generators, as already mentioned, are used to support the main energy supply that is based on hydroelectric plants, since year after year energy demand increases, see Figure 8. However, it is important to take into account that thermoelectric power stations are a major source of air pollution. In Colombia these are ranked third among polluters according to CONPES 3344, and their contribution to the country's electricity generation totals only 33%.

In their most efficient configuration, thermoelectric plant's turbines include a retriever or regenerator, which can be abbreviated as a heat exchanger that recovers the energy dissipated by the hot exhaust gases, and in this way preheat the air entering the combustion chamber. This method is commonly used in low-pressure turbines, **Figure 9.**

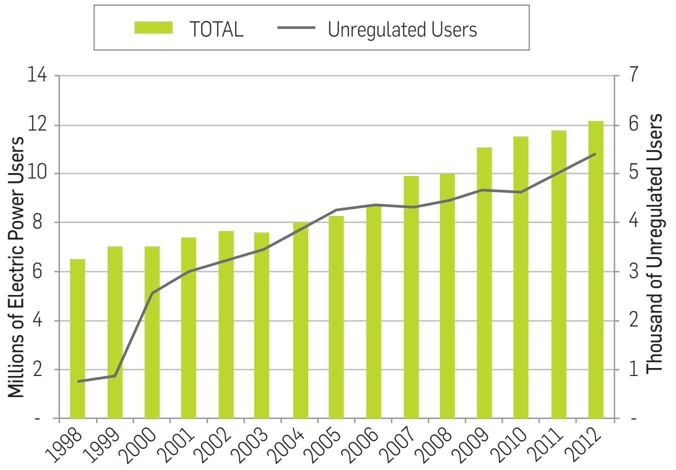

Figure 8. Increase of energy demand, Fuente: [15]

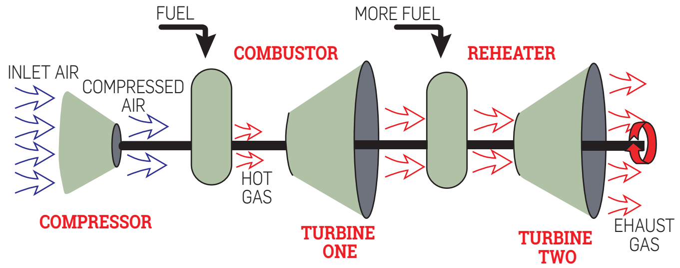

Figure 9. Gas turbine with a heat retriever

This is in contrast to turbines with high pressures where an intercooler is used to reduce the temperature of the air in the compression stages, which burns more fuel and thus is able to generate higher power, **Figure 10**.

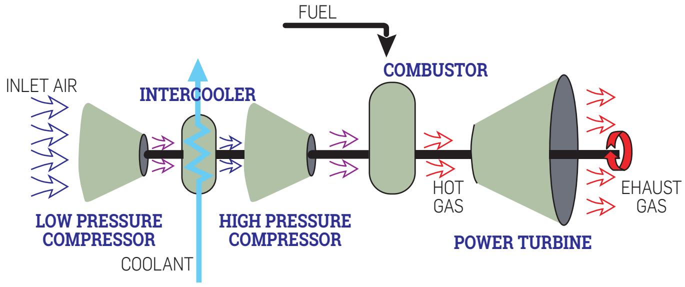

Figure 10. Gas turbine with an intercooler

An important factor limiting the amount of fuel used is precisely the temperature of the gases that are generated in combustion. The materials must withstand these temperatures without damage, making this a design restriction for the temperature and pressure relations in each stage of the turbine. It is possible to determine that its efficiency depends on the pressure and coefficient relation of the function. Please refer to Equations 1 and 2.

$$nterm=1-\frac{t1(\frac{t4}{t1}-1)}{t2(\frac{t3}{t2}-1)} \tag{1}$$

$$nterm=1-\frac{1}{(\frac{p2}{p1})(k-1)/k} \tag{2}$$

where

nterm: thermal efficiency (-).

t1, p1: compressor entry temperature (K) and pressure (Pa).

t2, p2: compressor exit temperature (K) and pressure (Pa).

t3: turbine entry temperature (K).

t4: turbine exit temperature (K).

k: heat capacity ratio (-).

For engines used in micro-cogeneration units, fuel efficiency is a result of the net power of the engine and the amount of fuel consumed, and this dependence is associated with the type of fuel and its characteristics. Please refer to equations 3 and 4.

$$\eta_{fuel}=\frac{Nominal\ Power}{Fuel\ Consumption} \tag{3}$$

$$\eta_{electric}=\frac{Nominal\ Power}{\rho fuel.\ \ Fuel\ consumption\ \ caloric\ fue\ power} \tag{4}$$

Where:

η_{fuel}: fuel efficiency (-).

$\eta_{electric}$: electric efficiency (-).

ρ_{fuel}: fuel density (kg/m3).

In each of these systems, directly or indirectly, power is closely related to fuel consumption and this in turn is directly proportional to the generation of CO_2 emissions. Refer to equation 5 [15].

$$EF_{EL.m.y}=\frac{\Sigma FCi.y\ .\ NCVi.y\ .\ EFCO2.i.y}{EG_{m.y}} \tag{5}$$

Where:

$EF_{EL.m.y}$: CO_2 emission factor of generation units m in year y (t CO_2 / MWh)

$FC_{i,y}$: quantity of fossil fuel type i consumed in the year and of generation units m (MWh).

$NCV_{i,y}$: net calorific power of the fossil fuel type i in year y (TJ / unit of mass or volume)

$EF_{CO2.i.y}$: CO_2 emission factor by type of fuel i in year y (t CO_2/tJ)

$EG_{m.y}$: net energy generated in year y (MWh)

m : all generation units connected to the grid in the year y

i : all fuels used by generating units m in the year y

y : year corresponding to the data used for the analysis.

4. EXPERIMENTAL DEVELOPMENT

In order to carry out this analysis, a 5-floor residential unit or apartment building in the city of Medellín (Antioquiashire - Colombia) was used as the basis of study. The distribution is 3 apartments per floor, except for the first as it is a reception, giving a total of 15 apartments. In each of these, there are families consisting of 3 members and a pet.

With a record of electricity consumption, hot water and monthly air conditioning for the apartments, annual energy loads were obtained for each residential unit. This record comprises only electricity-related loads, while the hot water and air conditioning are set out in electrical behavior.

The energy system in the building is made up of a micro-CHP (micro-combined heat and power) unit with a maximum power of 5.5 kW (manufactured by Senertec Dachs); this unit will deliver the energy produced and if the system requires more, the conventional power grid will supply it. The system also consists of a 160 kW boiler or gas heater, and an air conditioning or heating system. The total annual electrical energy load in the building is 1.8 MWh, and 51.26 MWh distributed between air conditioning and hot water.

Through the micro-cogeneration unit, water is circulated to maintain it at a suitable working temperature, acting as a thermal buffer. As the unit operates below 83 °C, if this point is exceeded then the engine will shut down. The water that is circulated by the micro-cogeneration unit is used to meet the hot water demand in the building. If at any point it does not have the right temperature for the minimum requirements (i.e. > 60 ° C) the heater or boiler will bring it to the required temperature. A schematic of the system configuration is depicted in **Figure 11.**

Table 1. Sources and components used on TRNSYS®

Method	Lineal range	Lineal range
Low-temperature boiler	Type 751	TESS
Micro-CHP units (DEGS)	Type 120	TESS
Hydraulic compensator	Type 38	Standard
Constant flow pumps	Type 114	Standard
Hot water storage tank	Type 4a	Standard
Flow diverter	Type 11f	Standard
Proportional controller	Type 669	Tess
Heat exchanger	Type 91	Standard
Radiator	Type 682	Tess

TRNSYS® SIMULATION

In order to carry out the simulation of the energy system in TRNSYS® v17, the Types that would enter into operation and its location or source within the software as defined in **Table 1** were defined.

The whole system is governed by controllers with temperature signals that turn each device on and off, according to the system's needs. It should be noted that the micro-cogeneration unit evaluated is composed of a diesel engine modified to natural gas. This whole set of units and their operation was simulated and verified using the Trnsys software, delivering fuel consumption results and efficiencies in each unit.

Table 2. System model verification

Method	Article	Trnsys System	error
Micro-CHP operation time (hours)	4322	4321	0.02
Micro-CHP fuel consumption (MWh)	102.31	105.68	3.29
Micro-CHP Electric production (MWh)	23.77	23.72	0.21
Micro-CHP thermal production (MWh)	66.54	65.28	1.89
Boiler fuel consumption (MWh)	83.68	83.66	0.02
Boiler thermal production (MWh)	71.96	74.96	4.17
Overall plant fuel consumption (MWh)	185.99	189.34	1.8
Heat storage thermal losses (MWh)	1.57	1.54	1.91
DHW Tank thermal losses (MWh)	0.21	0.2086	0.67

VERIFICATION

For the verification, the same system architecture was used as for the system evaluated in the article by A. Campos-Celador *et al.*, whose energy loads were taken from the Annex37: Low Exergy Systems for Heating and Cooling [16]. Located in the International Energy Agency (IEA) of the European Union and conditioned to the city of Bilbao in Spain. The verification gave a difference of less than 5%, which means a reliable system model is obtained in Trnsys® (see **Table 2**).

The controllers were integrated with the following subsystem, in each subsystem or set of Types associated in the simulation. In this way, errors related to the handling or passage of flows from one to another can be avoided, with a general rule being the determination of its functions through calculation controls offered by the software. The entire set was conditioned for use or control of a year, making adjustments in the software to avoid errors in each of the components and their relation to each other.

Both electrical, DHW and Ventilation, Heating and Air Conditioning (HVAC) demands were taken at 6-minute intervals, giving a total of 87,600 energy demand records for each of the 6 minutes. In these records or demands, inductive loads are taken into account due to the fact that demands from electrical appliances and energy in general required by the user at that time are included in a single 6-minute record, as is heating or air conditioning and the supply of domestic hot water. In order to achieve each of these energy demands, an average base load was taken from European Electrical Standard Profiles for 2008, and was adjusted to the requirements of the city of Medellin, **Figure 12**. The TRNSYS® program calculates the fuel consumption and power output, leading to the specific fuel consumption for each demand at the different times recorded for one year (see Appendix B). The system simulated in TRNSYS® can be seen in **Figure 13**.

Once the software calculates the parameters for the technical performance of the system for each of the scenarios to be compared, they are taken for the calculation of CO_2 emissions.

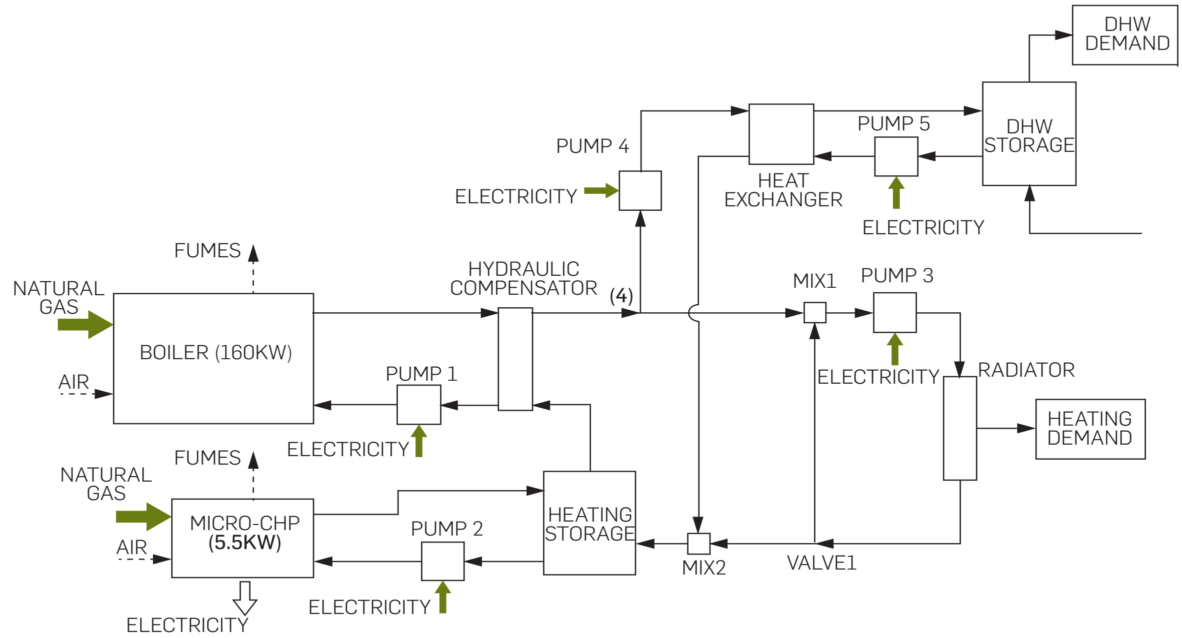

Figure 11. General system scheme

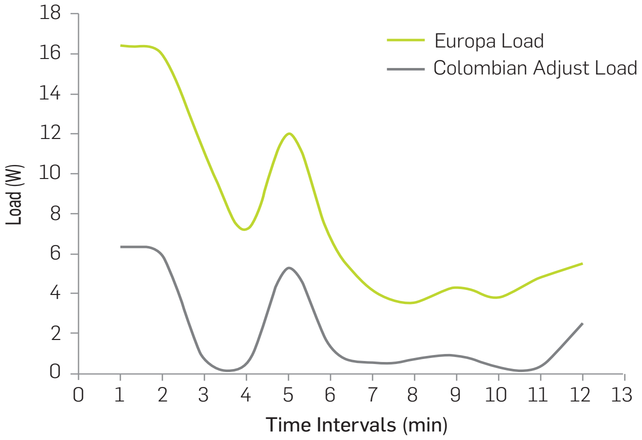

Figure 12. Load adjustment based on European Electrical Standard Profiles in 2008

5. RESULTS

Below is a summary of the technical performance parameters for an entire year obtained in TRNSYS® with the load for the building established in the previous section:

Table 3. System technical performance parameters in TRNSYS

Element	Article
Micro-CHP operation time (hours)	385.45
Micro-CHP fuel consumption (MWh)	28.91
Micro-CHP Electric production (MWh)	2.12
Micro-CHP thermal production (MWh)	24.15

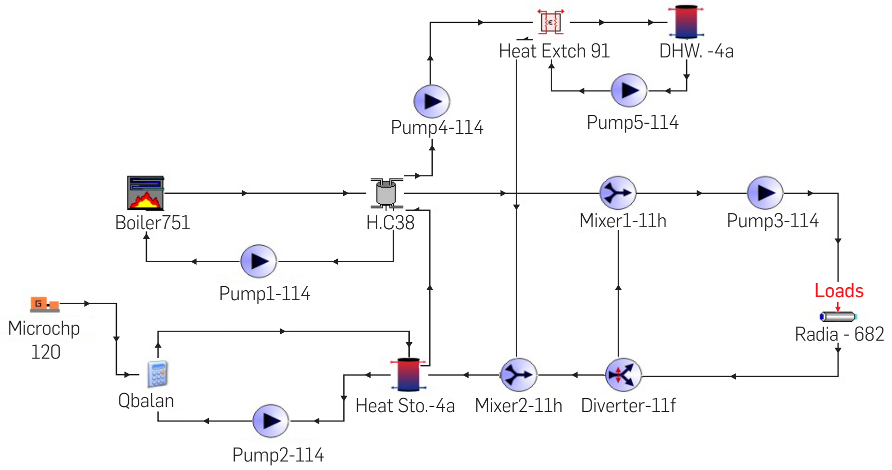

Figure 13. TRNSYS® system diagram

As mentioned above, the calculations for consumption and energy production were made by evaluating energy requirements during every 6 minutes of the consumption profile coupled to the system, including inductive loads and the result in fuel consumption and electric production for the same time (refer to Appendix B).

We now proceed to analyse the CO_2 generation factor of this unit, taking into account that the type of fuel used was natural gas. There are several equations to determine this factor, and their use depends on the information available. For generation units in which fuel consumption and net energy information relates to the grid, Equation 5 is used.

The CO_2 emission factor and the net calorific value of the fuel are taken from the tables contained in the CO_2 Emission Factor of the Environmental Energy Information System – SIAME for 2009.

With the data obtained via TRNSYS® simulation for the micro-cogeneration unit running on natural gas, the emission factor is as follows:

$$EF_{EL.1.1} = \frac{(28,91)\,.\,(46,5)\,.\,(54,30)}{2,12} \quad (6)$$

$$EF_{EL.1.1} = 34,43\ \frac{tCO2}{MWh} \quad (7)$$

Table 4. Micro-cogeneration unit emissions factor calculation

Outputs	Micro-CHP
$EF_{EL.m.y}$ (tCO2/MWh)	34.43
$FC_{i.y}$ (MWh)	28.91
$NCV_{i.y}$ (TJ/ unit of mass or volume)	46.5
$EF_{CO2.i.y}$ (Tco2/TJ)	54.3
$EG_{m.y}$(MWh)	2.12
m	1
i	1
y	1

For the evaluation of the generation scenario in "La Sierra" thermoelectric power plant, its consumption is characterised taking into account the government records recorded by the Colombian Mining Planning Unit (UPME) [18], bearing in mind the last year registered, then this consumption is adjusted to the energy demand in the building. Therefore, we proceed to calculate its emission factor based on Equation (5), the results obtained are summarised in Table 5.

Table 5. Emissions factor calculation for "La Sierra" thermo-electric power plant

Outputs	Thermo- La Sierra
$EF_{EL.m.y}$ (tCO2/MWh)	78.89
$FC_{i.y}$ (MWh)	76.17
$NCV_{i.y}$ (TJ/ unit of mass or volume)	46.5
$EF_{CO2.i.y}$ (Tco2/TJ)	54.3
$EG_{m.y}$(MWh)	2.12
m	1
i	1
y	1

6. RESULTS ANALYSIS

Table 6 shows a comparison of the environmental and technical performance of the two power generation system scenarios. As shown in Table 6, the use of micro-cogeneration units not only decreases the production of CO_2, but they also reduce this type of gas to less than half when compared to the amount generated by "La Sierra" thermoelectric power plant. The reason for that is due to the amount of fuel consumed by the micro-cogeneration system to produce the same amount of energy is much lower, and this also leads to lower costs.

Table 6. Results comparison

Element	Micro-CHP	La Sierra	Deviation
$EF_{EL.m.y}$ (tCO2/MWh)	34.43	78.89	56.35
$FC_{i.y}$ (MWh)	28.91	76.17	62.05
Energy Demand (MWh)	1.8	1.8	N.A

When analysing the results it can also be determined that there is a high impact from specific fuel consumption, and therefore on the efficiency of the engines of both the micro-cogeneration unit and the thermoelectric power plant. To provide a more explicit analysis, the specific fuel consumption is defined as the amount of fuel in grams (gr) that the plant must consume in order to generate a certain power that is given in units of kilowatts (kW), all this in a measurement time of one hour (g / kWh).

By taking data on the fuel consumption results obtained from TRNSYS® for the micro-cogeneration unit and publically available information on thermoelectric power plants in Colombia, the specific fuel consumption and efficiency for these systems can be determined, see Figure 14.

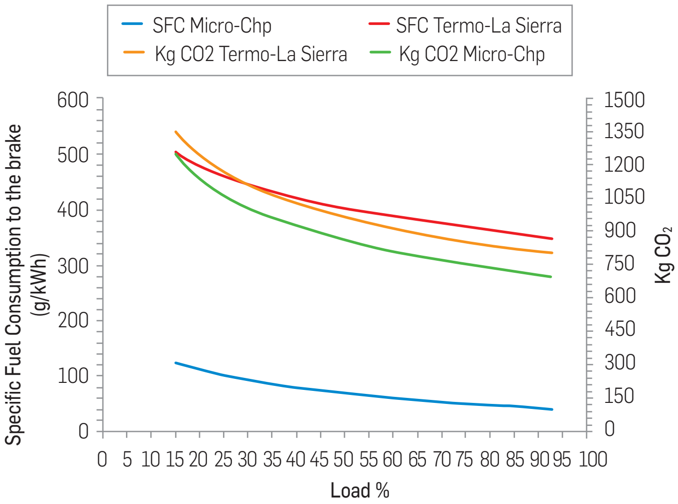

Figure 14. Specific fuel consumption to the brake vs Load (own source)

The specific fuel consumption in the micro-cogeneration unit is much lower than the fuel consumption of the thermoelectric power plant at each system load point, thus demonstrating greater efficiency in the in-situ unit. Likewise, it is possible to show each system's tendency to generate emissions, showing that the thermoelectric power plant - due to its higher fuel consumption for the case scenario in this paper - also generates a higher amount of emissions in lower power percentages compared to the generation reflected by the micro-cogeneration unit. One cause of this difference in fuel consumption is transmission loss, as this requires replacement of the energy loss to maintain energy demand and this is only achieved with higher fuel consumption, and therefore a greater generation of CO_2 emissions.

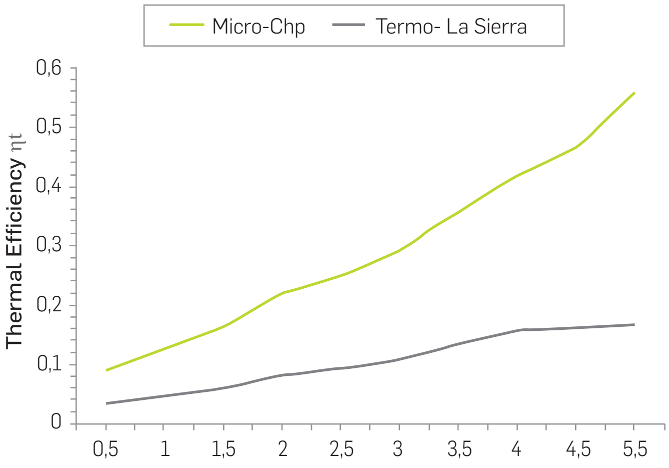

Figure 15. Thermal efficiency vs Power (own source)

Transmission losses are not taken into account for on-site generators since the distance that the energy must travel from the generator to its consumer is small.

In analysing the thermal performance of the micro-cogeneration unit and the thermoelectric power plant, see Figure 15, it can be determined that the former has a good advantage in terms of the engine performance reaching its maximum power limit, while the thermoelectric power plant exhibits relatively low performance for the case scenario under study. The whole micro-cogeneration system has a higher efficiency because the heat generated in the engine is used for heating water and heating systems, thus increasing its efficiency. This analysis determines the advantages of having individual systems for electricity generation that produce a small amount of energy in comparison to the large generators that distribute their large production, which exhibit losses in this process, while big generators also suffer an increase in the amount of heat that is wasted, thus decreasing their efficiency.

CONCLUSIONS

The generation of CO_2 is directly proportional to the amount of fossil fuel used and inversely proportional to the amount of energy generated, which defines the thermoelectric power plant as an inefficient generator for smaller and very efficient loads compared to micro-cogeneration units. Due to the amount of fuel burnt in micro-CHP units and its in-situ installation for the case study (for a residential building), these units produce less CO_2 than a centralized thermoelectric power plant. From this point of view, it is a technology that is worth starting to implement and adapt to the country's context, taking into account also that it can be used with different fuels to establish what advantages or what maximum value it could offer with the resources available in Colombia.

The use of micro-cogeneration units is shown as an economic solution to the generation of emissions in the residential sector, because its fuel consumption is lower, as is its production of pollutants. Countries such as Colombia, which have an extensive range of biomass, can explore their implementation with biofuels, thus making their implementation even more attractive from an environmental point of view, and would lead to an increase in the value of this biomass diversity, and decreased dependence on fossil fuels.

The use of these units also helps to make households independent of the generation of energy that's vulnerable to climate change, proving to be a very good option in times of climate phenomena. Colombia, being a country whose energy base is hydroelectric, is vulnerable to climate change or environmental phenomena that alter the water supply in dams. In addition, it would become a good option to support current generators that have to deal with the rapid increase in energy demand that the country is experiencing. The use of computational models makes it possible have advance knowledge of the results with little investment and in a short period of time, achieving quite an accurate reflection of reality, together with the information supplied by governmental entities. It is important to keep in mind that the use of these tools can save on-site evaluation costs.

ACKNOWLEDGEMENTS

This work was sponsored by the Universidad Cooperativa de Colombia under the research project "Environmental and Techno-economic Assessment of Micro-cogeneration Systems from Biomass," providing all necessary tools and equipment, as well as providing the necessary funds to carry out this project. Our thanks also go out to the "Catalysis for Sustainable Energy Production and Environmental Protection" Group of the Institute of Physical Chemistry of the Polish Academy of Sciences and to the Norwegian Institute of Bioeconomics Research for their contributions and supervision during the development of this research. Support from Action FP1306 of the COST (European Cooperation in Science & Technology) scientific network sponsored by Horizon 2020 is also acknowledged.

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ANNEX

A1. Behavior of the micro-cogeneration unit in the first minutes (144) of demand under inductive loads

Electrical demand for the first 144 minutes of the year (W)	Fuel Consuption Mchp (Nm3/h)	Electric Production Micro-Chp (W)
1132.72	0.36	3065.70
1012.72	0.36	2752.40
1000.72	0.36	2731.22
1000.72	0.35	2858.56
1000.72	0.33	2998.34
988.72	0.33	2976.13
1000.72	0.33	3026.30
1144.72	0.32	3477.99
1132.72	0.32	3457.72
1132.72	0.32	3474.07
1132.72	0.32	3483.10
1072.72	0.32	3300.10
988.72	0.32	3043.07
1000.72	0.32	3081.40
1000.72	0.32	3082.80
1000.72	0.32	3084.21
988.72	0.32	3048.61
1060.72	0.32	3272.11
1144.72	0.32	3532.84
1132.72	0.32	3497.41
1132.72	0.32	3498.20
1132.72	0.32	3498.20
1024.72	0.32	3164.66
1000.72	0.32	3090.54

APPENDIX

B1. UPME CO$_2$ emission factor and net calorific power of fuels for 2017

Calorific power of fuels used in the electric sector		Emission factor of used fuels in the electric sector			
Fuel	Net Calorific Power (TJ/1000 ton) (1)	Fuel	FE (kg CO$_2$/TJ) (2)	Fuel	FE (t CO$_2$/TJ)
Fuel Oil 4	39,8	Fuel Oil 4	75,500	Fuel Oil 4	75,50
Diesel	41,8	Diesel	72,600	Diesel	72,60
Natural Gas	46,5	Natural Gas	54,300	Natural Gas	54,30
Nafta	41,8	Nafta	69,300	Nafta	69,30
Fuel Oil 6	39,7	Fuel Oil 6	73,300	Fuel Oil 6	73,30
Bunker	39,7	Bunker	73,300	Bunker	73,30