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Application of a simulation tool based on a bio-inspired algorithm for optimisation of distributed power generation systems

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Abstract: The degradation of air quality, overheating and growing energy demand are closely related issues that indicate the impact of humankind on climate change. Consequently, governments and other multilateral agencies have shown interest in reducing air pollutant emissions from fossil fuel power generation sources. The most accepted options are related to clean energy sources, but, as we all know, we are far from meeting the world’s energy demand with clean generation sources. Other options are based on using fuels with a lower load of emissions and on the development of techniques to optimise power generation, reduce costs through efficient energy and reduce greenhouse gas emissions to the possible minimum. This study proposes a method to optimise the sensitivity factors as the operating point for a gas turbine power generator based on energy demands, electrical efficiency, fuel efficiency and the minimisation of

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PUBLIC INTEREST STATEMENT

The degradation of air quality, overheating and growing energy demand are closely related issues that indicate the impact of humankind on climate change. Consequently, governments and other multilateral agencies have shown interest in reducing air pollutant emissions from fossil fuel power generation sources. One way of emission mitigations is by the optimisation of the power generation operation using bio-inspired techniques leading to the best trade-off forenergy demands, electrical efficiency, fuel efficiency and greenhouse emissions.
greenhouse gas emissions. In order to address this, a multidisciplinary design/assessment framework was developed. The results obtained from the simulation of a one-year energy consumption model for an average family in Colombia produced the point of operation for a gas turbine based on energy demands, efficient energy and the reduction of CO₂ emissions to the atmosphere (i.e. the best trade-off). In this sense, the main contribution of this work is aimed at energy generation systems bio-inspired optimisation that reduce CO₂ emissions into the atmosphere, especially in non-interconnected (off-grid) zones, but they rely on fossil fuel plant-based-power distributed generation.

Subjects: Mechanical Engineering Design; Renewable Energy; Energy & Fuels; Bio Energy; Clean Technologies; Environmental; Renewable Energy

Keywords: micro-cogeneration; CO₂ emissions; particle cluster; electrical efficiency; fuel efficiency; sustainable development goals

1. Introduction

The scarcity of non-renewable resources, overpopulation and environmental degradation are the main topics in sustainable development. Moreover, the development of technologies for the continuity of sustainable and environmentally friendly development is a necessity for any future-minded society. In this sense, changes in both energy consumption and production habits will contribute to sustainable development as well as include populations that, owing to their geographical location, are not connected to a commercial power distribution grid. In this case, the energy supply is obtained from microgrids, which are small-scale power generation and transmission networks for small communities, such as islands or small towns. These systems are conventionally based on diesel generators that, with careful consumption monitoring, supply electricity to homes and small stores. Currently, low-environmental-impact power generation systems are being integrated into microgrids to reduce the carbon dioxide footprint caused by energy production. It should be noted that, since power generation is so variable in these systems, both main generation systems and backup systems must continue to depend on constant generation from hydrocarbons.

Power generation should be optimised in order to improve electrical efficiency, reduce both fuel consumption and greenhouse gas emissions depending on the power demands from microgrid users (Kanchev et al., 2011). In the case of small and remote populations, power generation solutions come from systems, four of which include wind power, photovoltaic panels, hydrokinetic turbines and combustion engines powered by hydrocarbon fuels. First, wind power systems depend on wind speed and current, which are difficult to predict; therefore, it is not possible to consider wind generators as the sole source of energy. Second, photovoltaic panels have become a low-cost solution for meeting energy needs. However, said low cost is associated with the lack of maturity of the technology. In other words, the efficiency of photovoltaic panels is low and depends on the radiation map of the sun, which in some cases is low because of excessive cloudiness during a large part of the day that prevents the power storage system from fully loading. The third identified solution concerns systems based on hydrokinetic turbines. Generators based on hydraulic energy are systems that leverage the kinetic and potential energy from water currents flowing through rivers, waterfalls and, in some cases, from submarine currents. In the case of remote populations, the implementations of these systems require the study of the capacity and flow of nearby rivers. In addition, they also require the study of the sediment level transported by the river since mechanical systems may easily become obstructed. Finally, fossil fuel engines are most commonly used power generators in remote and inaccessible populations. In this case, the combustion engine can be fed with diesel, gasoline or liquefied gas. However, this is the most polluting method and the one that generates the most greenhouse gas emissions.
The use of micro-cogeneration units is shown as an economic output to the generation of emissions in the residential sector; because its fuel consumption is lower as well as the production of pollutants. Countries such as Colombia that have a high range of biomass can explore their implementation with biofuels making their implementation even more attractive from an environmental point of view and would lead to the valorisation of this biomass diversity to become less dependent on fossil fuels. The use of these units also helps to make households independent of the generation of energy vulnerable to climate changes, proving to be a very good option in times of climate phenomena. Colombia being a country, whose energy base is hydroelectric, is vulnerable to climatic changes or environmental phenomena that alter the water supply in the dams. In addition, it would become a good option to support the current generators with the rapid increase in energy demand that the country has. The use of computational models allows knowing beforehand results with little investment and in short times, approaching to a great extent to the reality, together with the information supplied by the governmental entities. It is important to keep in mind that the uses of these tools can save on-site evaluation costs.

In this paper, we propose a method for optimising sensitivity factors as an operating point for a gas turbine generator in terms of energy demand, electrical efficiency and fuel efficiency, thus minimising the emission of greenhouse gases. The optimal operating point of a gas generator can be approached from two different perspectives; the first one is focused on finding the optimal operating point in terms of the thermodynamic efficiency of turbine generator, i.e. the operation variables of the turbine according to an optimal performance (Kong et al., 2005). A second topic is focused on determining operating parameters of the reactor according to power demand and electrical efficiency. In addition, this topic can be complemented with the reduction of gas emissions impacting on the atmosphere. In this context, it is important to consider the stages of grid design and management as they review the power modelling, planning and management of a microgrid in economic and environmental terms considering the installation and physical adaptation of the microgrid (Gu et al., 2014).

Further, this paper proposes a method for reducing greenhouse gas emissions to the atmosphere through the analysis of variables, such as energy demand, fuel properties, electrical efficiency and fuel efficiency. The proposed method is based on the implementation of an optimisation algorithm to assess the emissions model represented by the power generation system. The proposed optimisation method is geared towards bio-inspired Particle Swarm Optimisation (PSO), which assesses the function represented by the system and contains the thermodynamic model of the gas turbine. In this sense, there are some works found in the literature that use optimisation methods aimed at improving control techniques in order to increase the electrical efficiency in distributed generation systems (Wang et al., 2010). Mago & Chamra (Mago & Chamra, 2009) assessed the design of a system not only focused on reducing microgrid operation costs but

| Component            | Model   | Source |
|----------------------|---------|--------|
| 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 11 f | Standard |
| Proportional controller | Type 669 | TESS   |
| Heat exchanger       | Type 91  | Standard |
| Radiator             | Type 682 | TESS   |
also on other criteria as well. For these purposes, the authors use evaluation criteria such as primary energy consumption, microgrid operation costs, carbon dioxide emissions and the analysis of operational strategies by monitoring a hybrid electric charge during operation. The authors concluded that systems using any of the above optimisation criteria show a better performance than systems operating without any optimisation criteria. In this regard, bio-inspired algorithms are a good alternative to assess a wide solution design space and determine the operating point that minimises CO₂ emissions into the atmosphere.

There are different techniques and ways to apply optimisation methods, Tolba et al. (Tolba et al., 2018) propose a Renewable Distributed Generations (RGD) network managed by a hybrid method of PSO and the Gravitational Search Algorithm. The method proposed in this work is based on selecting the sensitivity factors of the RDG grid using PSOGSA (hybrid Particle Swarm Optimisation in addition to a Gravitational Search Algorithm) and refining the solution through Moth-Flame Optimisation in order to optimise the power generation capacity of the grid. Yang & Zhai (Yang & Zhai, 2018) propose a PSO-based optimisation model for adopting and selecting proper design parameters. In this sense, the authors conclude that these systems may assess different modes of operation in order to select the most appropriate mode. Recently, some papers have been released presenting models focused on specific industrial geographical affected by the climate change caused by high pollution levels. These models are based on alternative fuels (Román et al., 2018) or on integration models for distributed generation systems. Zeng et al. (Zeng et al., 2018) provide an interprovincial model of cooperative energy developed in China intended to become a development guide for other provinces also requiring the implementation of optimised distributed power generation models with low polluting emissions to the atmosphere. Generally, works that seek new methods for reducing greenhouse gas emissions are well accepted in the academic community. In this light, Kamdem & Shittu (Kamdem & Shittu, 2015) formulate a techno-economic and regulatory model focused on the adoption and operation of distributed energy grids in order to promote the decarbonisation of the atmosphere. As shown in this related literature, the PSO optimisation algorithm is a widely used technique in the selection of optimal design parameters. Therefore, it is a tool that allows to obtain the operating point that best compromises the electrical efficiency, fuel efficiency and minimises CO₂ emissions into the atmosphere.

2. Theory and calculations
The application of algorithms bio-inspired in the development and streamlining of distributed power generation systems consists of three parts: the first part involves determining the model of annual energy consumption sampled every six minutes in order to determine consumption habits and peak hours against demand. The second part consists of designing a target optimisation function based on the emission model for a gas turbine generator. The third part is the implementation of a bio-inspired optimisation algorithm that assesses the different configuration options that the model can adopt for obtaining the best possible levels of energy efficiency and low polluting emissions into the atmosphere. Figure 1 shows the block diagram of the proposed system.

2.1. Gas
The type of fuel used in this analysis is natural gas, with the characteristics granted by the Colombian government. In this analysis, for engines used in the micro-cogeneration units, fuel efficiency is given by the net power of the engine and the amount of fuel consumed. In addition, this dependence is associated to the type of fuel and its properties. In other words, fuel efficiency and electrical efficiency are directly or indirectly related to fuel consumption, which, in turn, is directly proportional to the generation of CO₂ emissions.

2.2. Electrical efficiency
Electrical efficiency means using less energy without decreasing output per unit of work. The benefits of electrical efficiency in micro-cogeneration grids are increasing the generation of KWh energy while reducing CO₂ and SO₂ emissions (Rafiei & Bakhshai, 2012). The technologies associated to micro-cogeneration systems that contribute gas emissions to the atmosphere are as follows:
- Diesel-powered generators.
- Natural gas turbine.
- Liquefied oil gas.
- Biomass.
- Coal.

2.3. Particle swarm optimisation (PSO) algorithm

PSO refers to a series of heuristic optimisation methods and algorithms that evoke the behaviour of swarms in nature, such as the movements of large groups of insects or flocks of fish. In these groups, the movements of each individual member in search of a common objective are studied, with the advantage that there is always some form of communication between the individuals, which denotes the social behaviour of the swarm to the entire population. In this way, each individual move driven by three variables: first, the experience of the best places they have been so far; second, the best place discovered by another member of the swarm and finally, an inertia component from the previous movement that buffers the speed of the individuals (Colmenares-Quintero et al., 2018; Colmenares-Quintero et al., 2019).

Equation (1) expresses the speed of the particle; the position of the i-nth particle is expressed in Equation (2) (Clerc, 2005; Leonard & Engelbrecht, 2013).

\[
\begin{align*}
    v_j^{(n)} &= \phi_1 v_j^{(n-1)} + \alpha_2 \phi_2 (\psi_j - x_j^{(n-1)}) + \alpha_2 \phi_2 (\psi_g - x_j^{(n-1)}) \\
    x_j^{(n)} &= x_j^{(n-1)} + v_j^{(n)}
\end{align*}
\]  

(1)

(2)

The PSO parameters are taken from the following.\textsuperscript{15}

\[
x_j^{(n)} = x_j^{(n-1)} + v_j^{(n)}, \quad \text{Adjusted speed;}
\]
\( v_j^{-(n-1)} \), Inertia of the movement itself;

\( \varphi_1 \), Particle speed coefficient \([0-1]\), herein \( \frac{1}{M_\text{max}} \);

\( \varphi_2 \), Coefficient of trust in own experience and experience of the swarm, \( \frac{1}{4} + \ln(2) \);

\( \psi_j \), Best previous position of the particle;

\( \psi_g \), Best previous position found by the group;

\( x_j^{(n)} \), Current position of the particle and

\( \alpha_2 N(0,1) \), a random variable extracted from a Gaussian distribution with zero mean and a variance of one.

To conduct this analysis, a residential unit or five-storey apartment building in the city of Medellín (Antioquia) is used as the basis for the study. The distribution is three apartments per floor, except for the first one, which is used as a reception apartment, for a total of 15 apartments. Each apartment is occupied by low-to-medium income families, with an average of three family members and a pet.

The annual energy loads for each residential unit were then obtained from their monthly electricity, hot water and air conditioning records.

The energy system in the building has a micro-cogeneration unit (micro-CHP, micro combined heat power) yielding a maximum power of 5.5 kW. This unit delivers the power it produces, and excess demands are covered by the conventional power grid. The system also consists of a boiler or gas heater of 160 kW and an air conditioning or heating system. The total annual electrical energy load for the building is 1.8 MWh, plus 51.26 MWh from air conditioning and hot water.

Water is circulated through the micro-cogeneration unit, acting as a thermal buffer to maintain it at a suitable working temperature of 83°C or below. If this temperature is ever exceeded, the engine shuts down. The water that is circulated through the micro-cogeneration unit is also used to supply the hot water demand in the building. If at any point, this water does not reach the adequate temperature for the minimum requirements (>60°C), the heater or boiler will heat it up to the required temperature. Figure 2 summarises the system configuration while Table 1 gives the details of the components used in TRNSYS simulation software, which was chosen due to its capabilities for energy system simulation coupled with the emission equations available in the public domain (Colmenares-Quintero, Latorre-Noguera et al., 2018).

Based on this assembly, the software determines the energy production characteristics of a gas turbine and the estimated emissions for different configurations based on electrical efficiency, fuel efficiency and \( \text{CO}_2 \) emissions to the atmosphere.

Figure 3 shows the optimisation model implemented to optimise electricity efficiency and reduce \( \text{CO}_2 \) emissions emitted to the environment.

The evaluation function is made of three objectives that contribute to the optimiser based on their assigned weight. The target function and each of its sub-objectives are described below:

### 2.4. Target function

The target function was obtained from the \( \text{CO}_2 \) emissions model, electrical efficiency and fuel efficiency. The function represented by the emissions model to be optimised is composed of three
separate objectives that contribute to the overall objective. Figure 4 shows the different sub-objectives of the function.

2.4.1. CO₂ emission factor component
Equation (3) shows the factor of CO₂ emissions over a period of one year.

\[ EF_{EL,my} = \sum FC_{iy} \times NCV_{iy} \times EFCO_{2, iy} \times EG_{my} \]  \hspace{1cm}(3)

In Equation (3), the variables are as follows:

- \( EF_{EL,my} \): CO₂ emission factor of the m generation units for the y year (t CO₂/MWh).
- \( FC_{iy} \): Quantity of fossil fuel type i consumed in the year and quantity of m generation units.
- \( NCV_{iy} \): Net calorific value of the fossil fuel type i for the y year (TJ/mass or volume unit).
- \( EFCO_{2, iy} \): CO₂ emission factor by fuel type i for the y year (t CO₂/TJ).
- \( EG_{my} \): Net energy generated for the y year (MWh).
- \( m \): All generation units connected to the grid in the year.
- \( i \): All fuels used by m generation units in the year.
- \( y \): Corresponding to the data used for the analysis.

2.4.2. Electrical efficiency component
Equation (4) shows the electrical efficiency factor of the micro-cogeneration system.

\[ e_{l} = \frac{Nominal\ Power}{Fuel\ Consumption \times Calorific\ fuel\ power} \] \hspace{1cm}(4)

2.4.3. Fuel efficiency component
For engines used in micro-cogeneration units, fuel efficiency is defined as the net power of the engine over the amount of fuel consumed in relation to the characteristics of the fuel type. Equation (5) shows the fuel efficiency factor of the micro-cogeneration system.
3. Results and discussions

Starting from the assembly of the system in the TRNSYS software, the electrical, DHW and Heating, Ventilation and Air Conditioning (HVAC) demands were taken at 6-minute intervals, totaling 87,600 energy demand records for each 6 minutes. These records or demands take into account inductive loads, because a single 6-minute record includes the demands from household appliances and energy in general required by the user at that time, as well as for heating or air conditioning and hot water supply. To satisfy each of these energy demands, an average base load of European Electrical Standard Profiles (2008) was used and adjusted to the requirements of the city of Medellin. The TRNSYS program calculates the fuel consumption and power output that leads to the specific fuel consumption for each demand in the different times recorded during one year. The TRNSYS simulation schematic can be seen in Figure 5.

Once the technical performance parameters of the system have been calculated by the software for each of the comparison scenarios, the equations for calculating CO₂ emissions are carried out, which are available to the public.

3.1. Optimisation of the emissions model

The optimisation of the emissions model consisted in evaluating the target function for a range of parameters defined from the weights assigned to each sub-objective. In this case, as there are three sub-objectives, the weights were assigned in the range of [0,1] to the algorithm randomly, where the weighted sum of these weights always gives 1. This made it possible to determine the relationship between the three sub-objectives, identifying the operating point that minimises CO₂ emissions. The weights were defined as WCO₂ for the CO₂ emission factor, Wnel to indicate the weight of electrical efficiency while Wfuel to indicate the weight of fuel efficiency. Figures 6 and 7 show the relationship obtained with the random assignment of weights. Finally, the analysis was carried out from the resulting Pareto front.

The optimisation process was based on the variation made by the PSO algorithm on the Nominal Generation Power (PDESG) in the range of [209.94 W to 3,514.74 W] which is the general input to the three sub-objectives. In this regard, since in PSO operation every particle is a possible solution, a very wide solution space could be assessed. Furthermore, considering the random weight assignment described above, the PSO optimiser explored relationships between the sub-objectives that could not be evidenced in any other way. The parameters of the PSO optimiser are described in Table 2 (Clerc, 2012).

The method to determine the best relationship between the sub-objectives is therefore to minimise the weighted sum of the contribution of each sub-objective, as shown in Figure 3 of
In this case, the optimiser was run 100 times with different weight settings for each one of the sub-objectives, which allowed obtaining the representative curve of the relationship between CO₂ emissions with respect to electrical efficiency and fuel efficiency. Finally, the optimiser was coded on the MATLAB 2017 tool and ran on a CORE i5 CPU with 8 GB of RAM.

Table 3 shows the optimiser results for 10 different weight variants as well as its run time.

The simulator values shown in Table 2 allow observing the results that support the analysis of the best configuration that relates CO₂ emissions along with fuel efficiency and energy efficiency. In this case, each row shows the weight Wₓ associated with the sub-objective and its final value found by the optimiser. Finally, the last column shows the execution time for each optimiser run, which has an average per execution of 20.3 ms

The relationship between CO₂ emissions and fuel efficiency is depicted in Figure 6.

Based on the relationship shown in Figure 6 from the weighted sum method, the ideal operating point between fuel efficiency and CO₂ emissions was found. In this case, the generator has an efficient operating point where the fuel efficiency is maximised without increasing the CO₂ emissions.
Figure 7 denotes the relationship between CO₂ emissions and electrical efficiency.

Analysis of CO₂ emissions with respect to electrical efficiency shown in Figure 7 identifies an optimal operating point between these two variables, in this case, the operating point is located at the inflection point in blue color. In this sense, a more efficient power generator operates at an “ideal” specific fuel consumption level, which decreases the generation of CO₂ because the systems waste less non-consumed fuel. In addition, regarding the other analyses, high greenhouse gas (GHG) generation is related to a low power generation with high fuel consumption where the electrical and fuel efficiencies are decreasing, i.e. the generation of CO₂ is directly proportional to the amount of fossil fuel used and inversely proportional to the amount of energy generated.

It is clear that, in this type of engine, the best environmental advantage (or lower GHG generation) is achieved when the engine is operating close to its nominal power or working power, due to its fuel consumption characteristics based on its size. This result is related to the fact that, depending on how close the power demand is to the nominal power of the engine, greater power generation...
performance is guaranteed based on the working condition according to its design. In addition, as power generation increases, the electrical efficiency of the engine also improves. The electrical efficiency also depends on the type of fuel and its quality, but when these qualities are constant, the ratio of growth of this feature depends largely on the power generated by the engine. Therefore, it can be inferred that, when approaching its maximum generation capacity, the engine will also reach its maximum electrical efficiency.

As evidenced by the results described above, there is a relationship between fuel efficiency, electrical efficiency and greenhouse gas emissions into the atmosphere, which were our optimisation objectives. In this sense, the PSO optimisation algorithm lists the best operating points for each objective for evaluating possible options within the solutions available and delivering the direct relationship between CO₂ emissions and the efficiency of the power plant.

4. Conclusions

The use of micro-cogeneration units is shown as an economic output to the generation of emissions in the residential sector; because its fuel consumption is lower as well as the production of pollutants. Countries such as Colombia that have a high range of biomass can explore their implementation with biofuels making their implementation even more attractive from an environmental point of view, and would lead to the valorisation of this biomass diversity to become less dependent on fossil fuels.

The use of these units also helps to make households independent of the generation of energy vulnerable to climate changes, proving to be a very good option in times of climate phenomena. Colombia being a country, whose energy base is hydroelectric, is vulnerable to climatic changes or
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This paper proposes a method to reduce greenhouse gas emissions into the atmosphere by assessing variables such as energy demand, fuel features, electrical efficiency and fuel efficiency, in search of the best operating point of the power plant. The proposed method consisted of designing a micro-cogeneration station using the TRNSYS software. The method was based on a residential unit or five-storey apartment building with an average load, i.e. the consumption of an average family. The simulation results could be integrated with an optimisation algorithm developed in previous works for analysis and optimisation of the power plant’s operating point.

The analysis of electrical efficiency, fuel efficiency, and CO₂ emissions was carried out by assigning random weights on each of the sub-objectives and performing the weighted sum of each one in the objective function. This concept made it possible to relate the operating points of the power generation plant system according to each of the objectives, without diminishing another objective of interest. In this sense, the results allow us to conclude that in order to improve energy performance and reduce fuel consumption by minimising CO₂ emissions into the atmosphere, the optimal work point that relates these three objectives must be determined. Therefore, the PSO optimisation algorithm shows to be an effective tool in the assessment of problems with multiple objectives, as is the case that was discussed in this work.

Finally, it can be concluded that analysing information such as energy demand and factors related to the type of fuel contribute to the reduction of CO₂ emissions. In addition, they allow establishing the optimum operating point of the power generation plant, with the goal of maximising power generation and reducing emissions of polluting gases into the atmosphere.

For future work, some comparisons between this PSO algorithm with other bio-inspired optimisation algorithms can be made to determine which techniques are better for this kind of optimisation problems.

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