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Cogeneration Potential in the Industrial Sector and Gas Emission Reduction: A Case Study

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ABSTRACT

The aim of the current paper is to discuss the replacement of diesel oil (DO) consumption by natural gas (NG) in a cogeneration system. A specific industrial consumption case study was chosen to be the method used to accomplish a robust analysis. The results have shown the advantages in reducing CO₂, CH₄, N₂O and particulate matter emissions, as well as the need to keep the NOx emission rates. After proceeding with theoretical studies concerning our case, we concluded that the diesel oil replacement by natural gas is beneficial for gas emission reduction. Public policies should consider local development based on the use of different fuels, such natural gas, to achieve the integration between decentralized energy generation and energy-efficient initiatives.

Keywords: Air pollution Fuel replacement Cogeneration system Decentralized generation Industrial sector

1. Introduction

The use of different fuels has become an important concern when it comes to Climate Change debate, to pollution impacts from local to global levels, as well as to lifestyle changes within modern society. Therefore, the use of low carbon alternative fuels began to gain more space in politics and public planning. Thus, many researches have been focused on diesel replacement to lesser pollutant fossil fuels, such natural gas [1, 2].

Society is now living a time when its demands regarding amenities provided by different forms of fuels are clear. Thus, it is mandatory to think, create and build practices that meet community demands in order to help solving the emerging environmental problems.

The aim of the current paper is to discuss local development based on replacement of fuels (natural gas instead of diesel) in order to achieve the integration between decentralized energy generation and energy-efficient initiatives. Our study is based on a specific industrial consumption case study to accomplish a robust analysis, specifically the cogeneration potential in the industrial sector of Novo Hamburgo City.

Thus, in order to achieve our goal, section 2 exposes the literature review. Section 3 includes our methods. Section 4 shows our results. Finally, section 6 presents our conclusions.

2. Literature Review

2.1 Combined Heat and Power (CHP)

CHP or cogeneration consists of a way to produce heat
and power within the same system. Such technology provides two ways of using energy from the same fuel, minimizing wastes. There is a vast literature on CHP. It demands lower costs and causes lesser GHG emissions than other electricity and heat production mechanisms [3].

Conventional electricity generation systems are usually centralized, and in Brazil it is mainly based on thermal and hydroelectric powerplants. Within such concept, it is necessary to invest in long electricity transmission and distribution lines in order to connect the centralized generation to the customers, in other words, to a distributed demand [4].

On the other hand, it is possible to produce energy in a decentralized pattern way. This method is called distributed generation and its main feature is that electricity generation is close to the consumer point [5, 6, 7].

The benefits of adopting CHP as a distributed generation source are: elimination of technical losses in transmission and distribution [8]; diversification of the energy matrix [9, 10]; decreased energy intensity [9]; improved energy efficiency [11]; fulfillment of GHG reduction targets [12]; and CO₂ emission reduction [11].

Ouellette et al. [12] found that the implementation of a CHP system in Alberta may result in the approximately 15–24% CO₂ reduction expected by the 2008 Alberta Climate Strategy. Thus, CHP implementation could bring up significant contributions to the achievement of the Kyoto Protocol’s emission reduction targets [11].

Cogeneration also presents negative points such as the need to invest in CHP equipment, a more complex and demanding operation and the lack of technical training, as it was already stressed by Andreos [5] and Baer et al. [13]. Also, Baer et al. [13] have pointed out that CHP installations have high upfront costs and long payback periods, when they are compared to traditional equipment.

CHP has been mainly used by industries and for district heating worldwide [14, 15, 16]. It has been analyzed as part of a system involving the eco-industrial park concept (EIP) [17]. According to some authors, local heating systems distribute the centralized-generated heat in a residential and sometimes commercial location, managed at low costs [18, 19].

Chung et al. [20] analyzed a CHP plant case study applied to a set of buildings such as residential buildings, offices, hospitals, stores, and schools in Korea. They found that the payback period might be of approximately two years in buildings investing in a generator with the capacity to hold 50% of their electricity peak demand.

Nowadays, several countries are developing their own policies to promote small-scale cogeneration in the residential sector. Small-scale residential cogeneration systems are widely recognized as efficient systems and they have an important potential for energy and economic saving [21, 22]. They are often used in industries that use their on waste as a fuel such as the sugarcane, chemical, petrochemical and pulp and paper industries.

Brazil had only 550 working cogeneration units up to 2000. However, this scenario began to change in 2010 when this indicator went up to 851 units. Today, the country has approximately 943 working cogeneration units [23]. In addition to such fact, the recent discovery of the pre-salt layer in the Santos basin doubled the Brazilian oil and gas reserves, leading the country’s gas market to a favorable scenario [5].

The installed cogeneration capacity in Brazil will reach its peak (14,056.0 MW) in 2015, time when it is going to have the same production as Itaipu hydroelectric powerplant, which has an installed capacity of 14,000 MW [5].

Hwang [24] pointed out many studies that evaluate the efficiency of this process in industries. Hwang [24] looked for ways to improve existing technologies or even for possible innovative cogeneration uses in different industrial processes.

The present research aims to determine the cogeneration potential in the industrial sector of Novo Hamburgo City, by considering the importance of implementing integrated decentralized energy generation and energy-efficient initiatives. The analysis was made through the replacement of diesel oil (DO) consumption by natural gas (NG) in a CHP system in the industrial sector of the abovementioned city.

Natural gas has been pointed out as a transition fuel that will facilitate the insertion of renewable fuels [4, 1, 2]. There is a lot of research studying the use of renewables such as biogas in the cogeneration process [25, 26]. Additionally, Celma et al. [27] and Andersen and Lund [28] have pointed out that CHP systems, along with the renewable energies (solar, wind, biomass etc.), are key elements for future cleaner energy policies.

Usually, the heat and power production in a cogeneration system releases considerable amounts of GHG into the atmosphere. Accordingly, the study by Aldrich et al. [29], is an attempt to expose and evaluate different allocation methods, to apply them to a combined heat and power plant integrated to a paper mill, and to propose an alternative method to better calculate the efficiency of the process.

Finally, the present research is an attempt to show that there are alternative fuels ready to be consumed in the study area, such natural gas (a fossil fuel lesser pollutant than diesel). However, investors lack information on the feasibility of the project [30]. Therefore, we also show the
possibility of reducing local environmental impacts, and the feasibility of using already established technology in the electricity production market at lower costs.

It is worth minimizing the emission of pollutants resulting from the decentralized CHP conversion process, since it is often located close to urban perimeters. Thus, it is important to present the results by Fahlén and Ahlgren [31], who account for the social and environmental costs of the local heating process when the option for using CHP technologies is made. Fahlén and Ahlgren [31] pointed out that the use of district heating processes is just justified when natural gas is used as fuel.

3. Material and Methods

The methods used in the current study consist of a case study, considering quantitative and qualitative approaches.

The case study concerns a Decentralized Energy Plan (DEP) in Novo Hamburgo City, which is located in the metropolitan region of Porto Alegre, Rio Grande do Sul State, Brazil. This case study focuses on the Novo Hamburgo industrial sector and is divided in 4 parts:

a. Industrial sector evaluation;

b. Fuel replacement evaluation, from DO to NG;

c. CO₂ emissions reduction evaluation.

The DEP of Novo Hamburgo is part of a data acquisition system initiated in 2011 during the research project: “The data survey, the analysis of energy diagnosis, and the evaluation of potential renewable sources in Novo Hamburgo County” [32]. The study was conducted in State University of Rio Grande do Sul under the supervision of Professor Elton Gimenez Rossini.

However, in 2015, the study faced changes and updates in order to evaluate the replacement of DO by NG in a cogeneration system.

Thus, the present research aim to contribute to integrate an environmental analysis towards an eco-industrial park (EIP) program in Novo Hamburgo’s industrial park when it comes to the industrial ecology (IE) field. As Korhonen [33] (p. 509) have stated, the IE concept draws “from the metaphor that a natural ecosystem is a vision for industrial environmental management and environment policy.”

3.1 Assumptions

The following assumptions were made in order to compare the use of DO and its replacement by NG in a cogeneration system at the municipal industrial sector:

A. The DO generator specific fuel consumption considered was 0.26 l/kWh. Based on an efficiency of the generator of 35%, a typical calorific value of 8,560 Kcal/m³, and a capacity factor rated 80% of nominal capacity;

B. The NG generator specific fuel consumption considered was 0.3m³/kWh. Based on an efficiency of the generator of 35%, a typical calorific value of 8,560 Kcal/m³, and a capacity factor rated 80% of nominal capacity;

C. The cogeneration system considered the same temperature in all systems presenting 85% efficiency, and 80% of capacity factor; so, the total system efficiency is 68%;

D. An ICE (Internal Combustion Energy) fueled by NG and with power capacity of 100kW per consumer, operated for 12 hours a day, 22 days a month, which is equivalent to 3168 hours a year;

E. Only the following industries were considered likely to substitute DO generation by NG in a cogeneration system: the metallurgical, mechanical, chemical, textile, food and beverage industries.

3.2 Calculation

3.2.1 NG Evaluation for DO Replacement

Equations 1, 2 and 3 summarize the calculations to evaluate the amount of necessary NG in a CHP system to replace the DO consumed in the industrial sector in one year.

\[ EE_j = \sum_{j=1}^{n} DO_t \times SFC_{do} \]  
\[ NG_j = \sum_{j=1}^{n} \frac{EE_j}{SFC_{ng}} \]  
\[ NG_{coj} = \sum_{j=1}^{n} NG_j \times Efng \]

Where: \( DO_t = \) total diesel oil consumption by the industrial sector, in liters, l; \( SFC_{do} = \) specific fuel consumption of diesel generator, l/kWh; \( NG = \) natural gas consumption to generate the same amount of energy generated by diesel oil, m³; \( EE = \) electric energy generated by diesel oil, kWh; \( SFC_{ng} = \) specific fuel consumption of natural gas generator, m³/kWh; \( NG_{co} = \) natural gas necessary to substitute diesel oil in a cogeneration process, m³; \( Efng = \) efficiency of natural gas generator; \( j = \) time considered, one year, 2013.

3.2.2 CO₂ Emission Estimation

We estimated the CO₂ emissions of the DO electric generation using a top-down approach designated by IPCC [34] against the emissions of the cogeneration system fueled by NG. Six (6) steps were used to evaluate CO₂ emissions the flowchart shows in summary all the steps.
Step 1: Energy Consumption Estimations

It is necessary to multiply the fuel consumption by the following factors, namely: conversion factor (toe/fuel unit), correction factor (dimensionless) from Higher Heating Value (HHV) to Lower Heating Value (LHV), and $45.2 \times 10^{-3}$ TJ (equivalent to one Brazilian toe, in order to convert the energetic content from toe to TJ) in order to find the energy consumption in joules, as shown in Eq. (4).

$$EC = FC \times ConvF \times CorrF \times 45.2 \times 10^{-3} \tag{4}$$

Where: EC = Energy Consumption (TJ); FC = Fuel Consumption (fuel unit); ConvF = Conversion Factor (toe/fuel unit); CorrF = Correction Factor (dimensionless) of Higher Heating Value (HHV) to Lower Heating Value (LHV); $45.2 \times 10^{-3}$ TJ = 1 Brazilian toe (to convert the energetic content from toe to TJ).

Step 2: Carbon Amount Estimation (GgC)

It applies the following equation, Eq. (5):

$$CA = EC \times EmissF \times 10^{-3} \tag{5}$$

Where: CA = Carbon Amount (GgC); EC = Energy Consumption (TJ); EmissF = Emission Factor (tC/TJ).

Step 3: Calculation of Carbon Fixed Value (GgC)

In this case, the carbon fixed value (CFV) equals zero, because there is no carbon energy consumption, since all the fuel is burned to generate electricity [35]. Thus, Eq. (6) equals zero.

$$FCA = 0 \tag{6}$$

Step 4: Calculation of Net Carbon Emissions (GgC)

Since the CFV is equal to zero, net carbon emissions (NCE) is equal to CA, as exemplified in Eq. (7).

$$NCE = CA - FCA \tag{7}$$

Step 5: Calculation of Real Carbon Emissions (GgC)

The RCE (GgC), Eq. (8), is the multiplication of the NCE (GgC) found in Eq. (7) by the OCF (dimensionless). The factors used for each type of fuel are shown in Table 3.

$$RCE = NCE \times OCF \tag{8}$$

Where: RCE = Real Carbon Emissions (GgC); NCE = Net Carbon Emissions; OCF = Oxidized carbon fraction (dimensionless).

Step 6: Real CO2 (GgCO2) Emissions

The real CO2 emissions are obtained by Eq. (9).

$$RCO2 = RCE \times \frac{44}{12} \tag{9}$$

Where: RCO2 = Real Carbon Dioxide Emissions (Gg CO2); RCE = Real Carbon Emissions (Gg C); $\frac{44}{12}$ = Ratio between CO2 and C molecular weights.

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1 The used correction factor (Fcorr) to turn HHV into LHV are 0.95, for solid and liquid fuels, and 0.90, for the gaseous fuels [35, 36].

2 The correction factor (Fcorr) to transform the HHV in LHV, used are 0.95 for solid and liquid fuels and 0.90 for the gaseous fuels [35, 36].

3 GgC is a unit used to measure the mass of emitted CO2 and it means Giga grams of CO2, it is also common to be used tons of CO2, tCO2.
4. Results and Discussions

Results are presented as follows.

4.1 Industrial sector evaluation

According to the Commerce, Industry and Services Association of Novo Hamburgo, Campo Bom and Estância Velha [37] the main industrial activities in Novo Hamburgo are: footwear, metallurgical, textile, and chemical industries. The city also stands out as a hub of trade and services [38]. Fig. 2 shows the number of industrial business registered at ACI-NH/CB/EV [37], in 2014, a total of 3,202 industrial companies are registered. The footwear sector accounts for 30% of this total, and it is followed by the metal sector, which represents 17% of the companies in this sector. It is worth noticing that only 1,293 of these companies have their industrial activities located in Novo Hamburgo County.

Figure 2. Industrial business types in Novo Hamburgo

The industrial sector aggregates energy consumption data from all industrial plants, in this case: 1,293 industrial plants. Energy consumption in this sector was characterized in 2013, and shown in Fig. 3. It is important to notice, that this sector is the only one presenting energy consumption reduction of approximately 12% between 2005 and 2013, probably because of the reduction in exports of footwear industry [32].

Figure 3. Total energy consumption in Novo Hamburgo’s industrial sector (2005 – 2013)

Next, Fig. 4 shows the percentage of energy sources consumed by Novo Hamburgo’s industrial sector; Diesel oil is the most consumed energy, thus accounting for 55% of all the energy consumed by the sector in 2013.

Figure 4. Energy consumption by source in the industrial sector of Novo Hamburgo in 2013

Energy consumption behavior can be analyzed through the final energy consumption related to the number of consumers within the main economic sectors. The final electricity consumption per consumer in Novo Hamburgo’s industrial sector was similar to that of Rio Grande do Sul State up to 2010, approximately 147.6 MWh/end user, as shown in Fig. 5. In 2013, the electricity consumption per end user in Novo Hamburgo was 149.3 MWh/end user, growing at low rates.

Figure 5. Final electricity consumption according to the number of consumers in the industrial sector of Novo Hamburgo County and in Rio Grande do Sul State from 2005 to 2012 - MWh/end user

4.2 Fuel replacement evaluation, from DO to NG

According to Sulgás [40], companies subject to cogeneration use, in other words, those simultaneously demand electricity production and heat, i.e: engineering, food, beverage, chemical, automotive, textile, paper, non-ferrous and white ceramic industries, among others.

Therefore, considering such industries at Novo Hamburgo and also their energy consumption it was possible to estimate the cogeneration potential. The estimated total
number of industries able to use cogeneration systems in industrial production system was 213. The estimated mean consumption, according to the proposed methods, was 149.3 MWh/year, and 19,450 liters of DO per year. Values of NG use in a CHP system to replace DO are shown in Table 4, and they were based on the aforementioned data and on the assumptions originated from the herein proposed methods.

**Table 4.** Results on the necessary amount of NG in a CHP process to replace the DO consumed in Novo Hamburgo’s industrial sector

<table>
<thead>
<tr>
<th>DO consumed</th>
<th>2013</th>
<th>Base unit</th>
</tr>
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<tbody>
<tr>
<td>4,142,637 l (liters)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.077,086 kWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.590,285 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.333,686 m³</td>
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4.3 CO₂ emissions reduction evaluation

According to the method used it was possible to measure DO emission in 2013: 11,061 GgCO₂. So, if we replaced the fuel used in the industrial sector for NG, the total annual NG emission would be: 4,541 GgCO₂. Fig. 6 shows the total emission of each fuel type by considering the time estimated for the project (10 years).

**Figure 6.** Total CO₂ emission by fuel type

We found that at the end of the project (considering a 10 year period) we estimate 65,196 GgCO₂ or 6,520 GgCO₂/year (6.52 MtCO₂/year) on emissions savings. So, the difference of using a NG CHP system presents approximately 60% lesser GHG emission than that using DO.

5. Conclusion

Diesel replacement to natural gas can be a powerful instrument to achieve integration between decentralized energy generation and energy-efficient initiatives. Thus, CHP is a potential technical solution to be explored in the integration of energy generation initiatives in the industrial sector of Brazilian cities.

A comparative analysis of the DO use and replacement by NG in a CHP system at the municipal industrial sector was performed due to such opportunity. It was estimated that the mechanical, chemical, textile, metallurgical, food and beverage industries in Novo Hamburgo consume a lot of power and heat in their industrial processes; therefore, they are suitable for the use of cogeneration systems.

In addition, it was estimated that if NG replaces the current electricity generation by DO in cogeneration systems in Novo Hamburgo’s industrial sector, NG consumption in 2013 would have been almost half of the DO consumption.

An evaluation of CO₂ emissions and the difference in using a NG cogeneration system on GHG emissions is approximately 60% lower than the emissions of CO₂ from DO, representing a reduction of 6.52 MtCO₂/year.

Such difference in the industrial activities will benefit the environment as a whole and the people who live in Novo Hamburgo since it will be good to their health, due to the decrease in the emission of hazardous gases.

Therefore, the results showed that the replacement by cogeneration plants fueled by NG in the studied industries, it is a suitable solution from an energetic, economic and environmental point of view. Public policies should play an important role in promoting investments in order to increase NG consumption in Novo Hamburgo’s the industrial sector. In addition, we recommend studies that compare those systems combined with renewable resources (solar, wind, biomass, hydro-electric power) in order to improve the cleaner energy practices in this city.

**Acronyms**

- C Carbono
- CA carbon amount
- CH₄ Methane
- CHP combined heat and power
- CO₂ Carbon dioxide
- ConvF conversion factor
- CorrF correction factor
- DO diesel oil
- DOt total diesel oil consumption
- EC energy consumption
- EE electric energy generated per year
- EmissF emission factor
- FCA fixed carbon amount
- GHG greenhouse gases
- HHV higher heating value
- ICE internal combustion engine
- IP installed power
- J Joule
- LHV lower heating value
- N2O Nitrous oxide
- NCE net carbon emissions
- NG natural gas
- NGc natural gas consumption
- NGco natural gas in a cogeneration system necessary to substitute diesel oil
- NGe natural gas emissions
- NOr natural gas emissions
- OFC oxidized carbon fraction
- PM particulate matter
- RCE real carbon emissions
- RECO2 real carbon dioxide emissions
- T Tonne
- TOE tonne of oil equivalent
- toe tonne of oil equivalent

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