A Complete Prefeasibility Evaluation of On-Site Energy Generation Systems

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ABSTRACT

The recent global concern to mitigate the ecological impact on energy production has promoted the search for alternatives that allow a better use of resources. In this panorama, the cogeneration process appears as a solution seen with good eyes thanks to its great efficiency, which is why many institutions and companies have opted for the transition from the traditional system of energy production to cogeneration. This article develops the selection of the best alternative among different suppliers to implement a cogeneration system in an energy production plant, taking into account economic factors, selecting the one that represents the greatest profitability in the shortest time.

Keywords: Cogeneration, Internal Rate of Return, Net Present Value

JEL Classification: Q42

1. INTRODUCTION

Cogeneration is an energy-efficient technology for generating energy and heat (Vukašinović et al., 2016), defined as concurrent production in a process of conversion of sequential energy, mechanical energy, electrical (power) and useful thermal energy (heat) (Lozano and Ramos, 2010). A cogeneration plant could have an efficiency of more than 90%, which is much higher compared to conventional systems (Onovwiona and Ugursal, 2006).

Choosing the best alternative among different distributors in order to achieve a better relationship between the cost of implementing the technology and its future efficiency is of vital importance in the design process (Frangopoulos, 2012), is for this reason that studies approach the issue from the perspective of methodological guidelines for the selection of cogeneration schemes in the process industry using Pinch technology for example (Tovar and Balbis, 2007).

Cogeneration systems must be designed and constructed in terms of primary energy efficiency and savings for the purpose of being eligible for economic and financial benefits, accompanied by the amount of electricity generated and useful heat. All these parameters are fundamental to the economic sustainability of the system (Lund and Andersen, 2005). In order to obtain greater energy savings along with greater profitability in the construction of cogeneration systems, attention must be paid to
plant dimensioning and operational strategies. These factors can be solved by complex numerical optimization programs (Lozano, 2001; Yokoyama et al., 1994; Manne, 1985), energy equilibrium models (Araújo and da Silva, 2010; Nagurney, 1987), economic models (Daniel and Goldberg, 1981; Wu and Fuller, 1995; Samuelson, 1983) or by analytical approximation (Heteu et al., 2002; Lucas, 2000). Despite the numerous criteria available, the most commonly used criteria for determining whether to reject or accept a project have been the net present value (NPV) and internal rate of return (IRR) that are used in this article, because they link and furthermore allow for the easy implementation of selection steps that are based on the technical and economic part as a whole, commonly known as thermo-economy (Frangopoulos, 1994; Tsatsaronis, 1993; da Gama Cerqueira and Nebra, 1999; Temir and Bilge 2004).

The projection over time of the implementation of a cogeneration system has a great influence on your choice, since these systems must have a large number of annual working hours to be profitable because a cogeneration system is normally measured in terms of its efficiency, availability, reliability, emissions and maintenance costs (Onovwiona and Ugursal, 2006; Cardona and Piacentino, 2003). If the utilization factor for cogeneration modules is high, greater savings and shorter payback times are achieved (Lozano and Ramos, 2010).

In this article, three alternatives were evaluated for the implementation of a cogeneration plant for energy supply and heat generation. These three alternatives were subjected to technical and economic study and the most viable option was chosen in a shorter time under the selected criteria.

2. METHODOLOGY

Based on the information collected on electricity consumption and demand (July and August) and comparing it with the growth plans for the next months and years of the cogeneration plant of electric and thermal energy in the form of steam, enabled to operate in synchronism with the public distribution network, the graph in Figure 1 was drawn up, which groups electricity demands by means of a histogram of frequencies.

The viability of a project of this type is based between the identified solution schemes and the electromechanical systems present. Factors such as fuel type, compatibility of heat/electricity ratio (Q/E) of demand and thermal engine, service availability, investment and operating costs.

Taking the data from Table 1 as a reference and taking into account that the maximum Q/E ratio (max thermal Dem/Dem max electrical) is approximately 1.6, it can be seen that according to this criterion the Internal Combustion Engine Technology (MCI) is the most suitable to supply the system needs.

To complement the reasons for selecting the ICE technology, additional factors such as equipment market supply, number of local suppliers, availability of equipment and delivery times and the possibility of using the open-loop system with

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**Table 1: Cogeneration technologies according to Q/E ratio**

| Item | Characteristics |
|------|----------------|
| <2   | Internal Combustion Engine |
| 2–4.5| Gas turbine |
| >4   | Steam turbine |

**Table 2: General comparison of alternatives**

| Alternative                      | Base case | Alt I  | Alt II | Alt II |
|----------------------------------|-----------|--------|--------|--------|
| Electricity generation           |           |        |        |        |
| Manufacturer                     | -         | Waukesha| Jenbacher| Cummins|
| Motor-generator model            | -         | APG1000| JMS 320| QSK-60G|
| Installed capacity (kWe)         | -         | 1.100  | 1.050  | 1.400  |
| Available capacity (kWe)        | -         | 1.080  | 1.030  | 1.380  |
| Generating production (kWh/month)| -         | 764.000| 691.000| 831.000|
| Purchase network or backup (kWh/month) | 903.000 | 139.000| 212.000| 72.000 |
| Gas consumption generation (m³/month) | -         | 223.000| 203.000| 270.000|
| Thermal energy generation (steam)|           |        |        |        |
| Boiler coal consumption (kg/month)| 180.000 | 121.831| 114.734| 101.571|
| Consumption of natural gas boiler (m³/month) | 105.801 | 76.610 | 67.439 | 59.702 |
| Production steam generated (lb/h) | 4.473   | 3.028  | 2.851  | 2.524  |
|Cogenerated steam production (lb/h) | -        | 1.446  | 1.622  | 1.949  |

Subtracted 20 kWe of self-consumption. Estimated natural gas consumption for steam generation. It is currently made with coal.
the highest possible electrical efficiency for a long time are analyzed.

A cogeneration process is chosen based on the analysis of the data collected during the first stage of the study. The cogeneration process satisfies electrical and thermal needs by producing steam using the exhaust gases of the motor generator using a recovery boiler.

Table 3: Economic evaluation components and characteristics

| Item                | Characteristics                                                                 |
|---------------------|---------------------------------------------------------------------------------|
| Investment          | • Basic and detailed engineering studies                                         |
|                     | • Main equipments (Motogenerator and Heat recovery system), auxiliary and the required connections |
|                     | • Assembly and start-up: civil, mechanical, electrical and instrumentation works |
|                     | • Nationalization, insurance and taxes                                           |
|                     | • Natural gas supply                                                             |
|                     | • Team tests. Commissioning and Start up                                         |
|                     | • Supervision of works                                                           |
|                     | • The system of administration, maneuvering, and control of sources (synchronism) |
|                     | • Equipment for sending information to the Network Operator                      |
|                     | • Application of tax benefits (law 1111 of 2006)                                 |
|                     | • Manpower of technicians and specialists with a permanent presence on site       |
|                     | • Project management                                                             |
| Operation           | • Natural gas for electricity generation                                           |
|                     | • Coal for steam generation in the base case                                     |
|                     | • The missing steam is analyzed under the coal and natural gas use schemes        |
|                     | • Preventive and corrective                                                      |
|                     | • Change and replacement of consumables (oils and refrigerant). Change of parts |
|                     | • Major repairs (overhaul)                                                       |
|                     | • Other activities required to guarantee the useful life of the equipment         |
| Maintenance         | • Coverage in the event of unforeseen events, service fees, applicable taxes, etc.|
| Others              | • 10 years                                                                       |
|                     | • Discount rate: 15.0% ac                                                        |
|                     | • Annual projections for CPI (3.7% annual average), IPP USA (1.33% annual average) along the project horizon, according to publications from financial institutions |
|                     | • TRM: $ 2,200/US$ fixed on the project horizon                                  |
|                     | • No financing                                                                   |
| Evaluation period   |                                                                                   |
| Financial & other   |                                                                                   |
|                     |                                                                                   |
|                     |                                                                                   |

Table 4: Annual cost equivalent for alternatives

| Concepts                        | Base case | Alt I Waukesha | Alt II Jenbacher | Alt II Cummins |
|---------------------------------|-----------|----------------|------------------|----------------|
| Gas consumption Moto generator (US$) | -         | 246.040        | 225.712          | 300.525        |
| Electricity Network (US$)       | 679.596   | 91.347         | 135.213          | 42.552         |
| Backup Contract Fee (US$)       | -         | 4.897          | 4.896            | 4.897          |
| Street Lighting (US$)           | -         | 5.516          | 7.952            | 2.896          |
| Environmental Impact Charge (US$) | -         | 5.560          | 5.076            | 6.099          |
| Operation and Maintenance (US$)  | -         | 85.840         | 100.540          | 113.655        |
| Other - Interruptions (US$)     | 2.612     | -              | -                | -              |
| Coal Steam Generation (US$)     | 76.154    | 50.676         | 48.542           | 42.973         |
| Operation and Maintenance Cogen System (US$) | -         | 6.474          | 6.474            | 6.474          |
| Total, ACE (US$)                | 758.362   | 496.350        | 534.406          | 520.071        |

Unsatisfied electrical energy will be covered with the purchase of energy from the grid. In case of thermal insufficiency, it will be covered using the existing generation system (coal boiler in operation or natural gas boiler).

Three alternatives of cogeneration systems with equipment from different manufacturers with similar capacities were evaluated. The differences between these alternatives are in efficiency, investment cost, maintenance periods and costs, fuel consumption, system availability and purchase of energy in the network.

Table 2 shows a general comparison of some characteristics of each alternative.

Table 3 shows the main aspects considered in the analysis of the economic proposals for the selected alternatives.

To calculate the economic feasibility of the proposed alternatives, the criteria of net present value (NPV) and internal rate of return (IRR) were used, the respective formulas are shown in (1) and (2).

\[
NPV = -I + \sum_{i=1}^{n} \frac{Q}{(1+IT)^{i}}
\]

(1)

Where \( I \) is the initial investment, \( Q \) the calculated cash flow or profit, \( n \) the number of years and \( IT \) the interest rate.

\[
NPV = -I + \frac{Q}{(1+IRR)^{n}}
\]

(2)

Where IRR is cleared by equating the NPV to zero.

3. RESULTS AND DISCUSSION

3.1. Missing Coal Steam Generation

Table 4 presents the summary of the results of the evaluation carried out taking into account the Annual Cost Equivalent (ACE) of the three pre-selected alternatives, comparing them with the current scheme of buying energy from the grid and generating missing steam with coal.
### Table 5: NPV & IRR values for alternatives

| Concepts                     | Alt I Waukesha | Alt II Jenbacher | Alt II Cummins |
|------------------------------|----------------|-----------------|----------------|
| NPV Analysis                 |                |                 |                |
| NPV @ 3 Years (US$)          | -172.397       | -210.377        | -232.913       |
| NPV @ 5 Years (US$)          | 278.038        | 87.710          | 150.466        |
| NPV @ 8 Years (US$)          | 758.830        | 463.778         | 615.511        |
| NPV @ 10 Years (US$)         | 1001.594       | 733.123         | 861.629        |
| IRR Analysis                 |                |                 |                |
| IRR @ 3 Years (US$)          | 5.96%          | 4.53%           | 2.92%          |
| IRR @ 5 Years (US$)          | 24.50%         | 18.15%          | 20.28%         |
| IRR @ 8 Years (US$)          | 32.62%         | 26.74%          | 29.44%         |
| IRR @ 10 Years (US$)         | 34.58%         | 29.75%          | 31.79%         |

### Table 6: Annual cost equivalent (ACE) for alternatives

| Concepts                                      | Base case | Alt I Waukesha | Alt II Jenbacher | Alt II Cummins |
|-----------------------------------------------|-----------|----------------|-----------------|----------------|
| Consumption Gas N. Equipment Generator (US$)  | -         | 246.040        | 225.712         | 300.525        |
| Electricity Network (US$)                     | 679.596   | 91.347         | 135.213         | 42.552         |
| Backup Contract Fee (US$)                     | -         | 4.897          | 4.896           | 4.897          |
| Street Lighting (US$)                         | -         | 5.516          | 7.952           | 2.896          |
| Environmental Impact Charge (US$)             | -         | 5.560          | 5.076           | 6.099          |
| Operation and Maintenance (US$)               | -         | 85.840         | 100.540         | 113.655        |
| Other - Interruptions (US$)                   | 2.612     | -              | -               | -              |
| Fuel Steam Generation (US$)\(^{(3)}\)         | 76.154    | 90.279         | 86.478          | 76.556         |
| Operation and Maintenance CHP (US$)           | -         | 6.474          | 6.474           | 6.474          |
| Total, ACE (US$)                              | 758.362   | 535.954        | 572.342         | 553.655        |

\(^{(3)}\) Steam generation in the base case is coal-fired. The new scheme proposes natural gas for missing steam.

### Table 7: NPV and IRR values for alternatives

| Concepts                     | Alt I Waukesha | Alt II Jenbacher | Alt II Cummins |
|------------------------------|----------------|-----------------|----------------|
| NPV Analysis                 |                |                 |                |
| NPV @ 3 Years (US$)          | -280.582       | -310.006        | -324.653       |
| NPV @ 5 Years (US$)          | 115.054        | -68.410         | 12.257         |
| NPV @ 8 Years (US$)          | 533.064        | 247.512         | 424.056        |
| NPV @ 10 Years (US$)         | 744.171        | 486.540         | 643.335        |
| IRR Analysis                 |                |                 |                |
| IRR @ 3 Years (US$)          | -0.15%         | -1.02%          | -2.23%         |
| IRR @ 5 Years (US$)          | 19.06%         | 12.45%          | 15.44%         |
| IRR @ 8 Years (US$)          | 27.77%         | 21.57%          | 25.23%         |
| IRR @ 10 Years (US$)         | 30.00%         | 25.13%          | 27.86%         |

The financial evaluation of the alternatives yielded the data shown in Table 5 according to the net present value (NPV) of savings and the internal rate of return (IRR) criteria.

A graphical representation of the behaviors obtained in the NPV and IRR analyses shown in Table 5 is shown in Figures 2 and 3.

Where the Waukesha brand’s alternative I show the most convenient results.

### 3.2. Missing Steam Generation with Natural Gas

The analysis of the cogeneration scheme with missing steam production using natural gas boilers presented the results indicated in Tables 6 and 7.

These results of missing steam production through the use of natural gas boilers were obtained using the evaluation criteria.
of annual cost equivalent (ACE), net present value (NPV) and internal rate of return (IRR).

4. CONCLUSIONS AND RECOMMENDATIONS

After carrying out the pre-feasibility study to implement a cogeneration system in a power generation plant, it is concluded that due to the operating conditions and energy costs of natural gas, it is technically and economically feasible to implement the cogeneration system.

According to the analysis carried out taking into account the NPV and IRR criteria, the implementation of a cogeneration system for electric energy and steam with an additional steam generation with coal is presented as the best scenario compared to the production of additional steam with natural gas.

The nominal capacity of the pre-selected internal combustion engines must be in the range of 1000–1400 kWe, although a control system must always be in place to ensure synchronism with the public distribution network and cover 100% of the requirements. In cogeneration, the need for steam fluctuates between 30 and 40% of the total average hourly hours, forcing to always have generation systems for missing steam.

The annual cost equivalent (ACE) analysis showed that this indicator is at least 25% lower for any of the three alternatives versus the current system. The same proportion shows the difference between the indicators per kWh calculated in each case. Taking into account the NPV and IRR criteria for different years on the project horizon, they indicate that any of the three alternatives are financially viable for periods longer than 4 years. The Waukesha brand alternative is the one that shows the best figures.

Based on the results of the feasibility analysis, it is recommended that basic and detailed engineering studies be carried out, as well as optimizing the purchase, transport, and installation of components, applying and complying with the current technical standards for electrical and thermal installations and for the operation of the systems. On the other hand, it is recommended the logical and safe structuring of the control architecture of the system and the coordination of electrical and thermal protections, as well as the optimal installation and supervision of the works and monitoring of the changes that have occurred during the assembly. Training and evaluation of the operators of the implemented system and finally the correct application of the procedures and administration of the system maintenance operation.

REFERENCES

Araújo, L., da Silva, E.T. (2010), Comparative Analysis of Cogeneration Power Plants Optimization Based on Stochastics Methods Using Superstructure and Process Simulator. Encon 2010: 13. Brazilian Congress of Thermal Sciences and Engineering. New Challenges in Thermal Sciences, Uberlândia, Mg (Brazil), 5-10 December, 2010.

Cardona, E., Picentino, A. (2003), A methodology for sizing a trigeneration plant in mediterranean areas. Applied Thermal Engineering, 23(13), 1665-1680.

Cerqueira, G., Da Araújo, S.A., Nebra, S.A. (1999), Cost attribution methodologies in cogeneration systems. Energy Conversion and Management, 40(15), 1587-1597.

Daniel, T.E., Goldberg, H.M. (1981), Dynamic equilibrium energy modeling: The canadian balance model. Operations Research, 29(5), 829-852.

Frangopolous, C.A. (1994), Application of the thermoeconomic functional approach to the cgam problem. Energy, 19(3), 323-342.

Frangopolous, C.A. (2012), A method to determine the power to heat ratio, the cogenerated electricity and the primary energy savings of cogeneration systems after the european directive. Energy, 45(1), 52-61.

Hernández-Santoyo, J., Sánchez-Cifuentes, A. (2003), Trigeneration: an alternative for energy savings. Applied Energy, 76(1), 219-227.

Heteu, T., Magloire, P., Bolle, L. (2002), Economie D’ énergie en trigénération. International Journal of Thermal Sciences, 41(12), 1151-1159.

Lozano, M. (2001), Diseño óptimo de sistemas simples de cogeneración. Informacion Tecnologica, 12, 53-58.

Lozano, M.A., Ramos, J. (2010), Thermodynamic and economic analysis for simple cogeneration systems. Cogeneration and Distributed Generation Journal, 25(3), 63-80.

Lucas, K. (2000), On the thermodynamics of cogeneration. International Journal of Thermal Sciences, 39(9), 1039-1046.

Lund, H., Andersen, A.N. (2005), Optimal designs of small chp plants in a market with fluctuating electricity prices. Energy Conversion and Management, 46(6), 893-904.

Manne, A.S., Ed. (1985), Economic Equilibrium: Model Formulation and Solution. Berlin, Heidelberg: Springer.

Nagurney, A. (1987), Computational comparisons of spatial price equilibrium methods. Journal of Regional Science, 27, 55-76.

Onowwiona, H.I., Ugursal, V.I. (2006), Residential cogeneration systems: review of the current technology. Renewable and Sustainable Energy Reviews, 10(5), 389-431.

Samuelson, P.A. (1983), Foundations of Economic Analysis. Enlarged Ed. Cambridge (Massachusetts): Harvard University Press.

Temir, G., Bilge, D. (2004), Thermoeconomic analysis of a trigeneration system. Applied Thermal Engineering, 24(17), 2689-2699.

Tovar, I., Balbis, M. (2007), Propuesta de guía metodológica para la
selección de esquemas de cogeneración en la industria de procesos mediante la tecnología pinch. Prospectiva, 5(2), 69-74.

Tsatsaronis, G. (1993), Thermoeconomic analysis and optimization of energy systems. Progress in Energy and Combustion Science, 19(3), 227-257.

Vukašinović, V., Gordić, D., Babić, M., Jelić, D., Končalović, D. (2016), Review of efficiencies of cogeneration units using internal combustion engines. International Journal of Green Energy, 13(5), 446-453.

Wu, Y.J., David Fuller, J. (1995), Introduction of geometric, distributed lag demand into energy-process models. Energy, 20(7), 647-656.

Yokoyama, R., Ito, K., Kamimura, K., Miyasaka, F. (1994), Development of a general-purpose optimal operational planning system for energy supply plants. Journal of Energy Resources Technology, 116(4), 290-296.