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METHODOLOGY TO REACH OPTIMAL DESIGN OF CHP PLANTS

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ABSTRACT

A methodology to reach the best CHP plant design is proposed. The standard method to choose the best fit in the process design of a CHP plant is improved considering off-design simulation of the pre-selected schemes. The off-design simulation deals specifically with economic dispatch optimization applied on each pre-selected plant to calculate the operation performance under well-known heat and power loads. The economic dispatch include fuel, uniform series payments related with investment and operation & maintenance costs and evaluates the variable behavior for power and heat along time with a scenario that takes into account transactions with the utility grid as well as auxiliary or back up boilers. It is shown the different result reached in each approach and the new point of view gotten with the use of the methodology proposed.

Keywords—Combined Heat and Power, optimal design, economic dispatch, modeling process.

NOMENCLATURE

C = Total cost function
FC = Fixed charge
f = Coefficient that gives the equilibrium in a characteristic inequality linear constraint for a CHP unit
h = Heat
hrs = Hours
i = Annual rate
m = Coefficient related with heat production in a characteristic inequality linear constraint for a CHP unit
n = Project life in years
p = Power
UC = Unitary charge
u = Coefficient related with power production in a characteristic inequality linear constraint for a CHP unit
$\alpha, \beta, \gamma, \delta, \varepsilon, \zeta$ = Coefficients used in the fitted fuel cost functions
ϑ = Coefficient used in the fitted operation & maintenance cost function
cap = Capacity
chp = Combined Heat and Power
inv = Investment
L,l = Characteristic inequality linear restrictions in CHP units
nom = Nominal
o&m = Operation & Maintenance

INTRODUCTION

Industries with heat and power demands usually supply these demands with Combined Heat and Power (CHP) systems. Sometimes these industries remain interconnected to the electric utility grid to purchase electricity or even to sell it, if required. These transactions of power ensure the supply of power at any given time, especially for industries with variable energy demands, but at higher cost. CHP plants designers must consider this variable behavior to get more flexibility.

The increasing use of CHP plants in industry, commercial and residential buildings, schools, etc. has been a good practice all over the world to optimize the use of fossil fuels and to minimize the greenhouse effect caused by contaminant gas emissions to the atmosphere.

Meanwhile the fossil fuels may be available in spite of their prices, optimal designs for these plants will be necessary for whoever involved as a project developer, constructor, engineering firm, etc.

The design process can be as sophisticated as we wish depending on investment level, operation flexibility, number of motors and others variables desired to find the CHP plant that best fit the load requirements.

The standard method to design involves the use of peak, average and minimum loads to arrive to the final design that may not be accurate or proved to be the best fit. In this paper we will refer the standard process to design as the classical method. The designer may be happy comparing several options generating a lot of possible CHP schemes and calculating the levelized tariff or the annual cost or whatever economical indicator along the time life of the plant and choosing the best choice. But this is a particular case that not takes into account the effect of variable loads going from minimum to peak during the day, the month, the year or the total life of the plant.

This paper presents a new method that improves the design process for cogeneration plants with variable electric and thermal demands. The variable behavior for power and heat is evaluated by solving Economic Dispatch (ED) problems for the CHP system with different generating units taken from the classical method. The objective function in these dispatching problems considers expenses of fuel, operation & maintenance and those related with the investment. Indeed the dispatching problems take into account the transactions with the electric utility grid at any given time with the opportunity to supply the power demand and even to increase profit with the power sales. The traditional design process is used to get the best feasible cases while the ED leads to the best result. The kindness of the proposed method lies on an accurate performance of the plant selected to operate with the greatest savings.

The modeling process to get the off-design performance for the generating units required to solve the ED problem is achieved by computational means with the THERMOFLOW's Company software. The ED algorithm used is an author's optimization method that takes the basis of Sequential Quadratic Programming (SQP) algorithms used to solve nonlinear optimization problems and the logic of the Lagrangian relaxation technique used on optimal schedule of CHP systems [1].

We assume that thermal and electric loads are known *a priori* if we are designing a new CHP plant or they are known using historical records if we are searching a CHP plant for an existing user.

The following sections are included in this paper: Description of the classical method to design CHP plants, explanation of the methodology proposed, case study and conclusions.

CLASSICAL METHOD TO DESIGN CHP PLANTS

In the classical method to design CHP plants the main goal is to cover peak thermal and electric loads required by the industrial user. The National Council of Energy Saving in Mexico [2] gives an example of this method. The goal is achieved testing several technologies as gas turbines, steam turbines, reciprocating motors, boilers, grid connection and combination among them.

This procedure requires applying heuristic logic combined with experience to arrive to the final design. That is, to build a set of several possible CHP schemes that can satisfy the peak and minimum demands.

Normally the classical method begins testing the thermal driven schemes that may satisfy the design requirements as shown in Fig. 1. This sort of design may lead to lack or excess of power according to the searched design point (H [MW_{th}], P [MW]). In case of lack of power this can be solved interacting with the electric grid and purchasing the rest of the needed electricity. Otherwise the excess power can be sold to the grid or to operate the CHP plant in partial load, which is not a good recommended practice because of the increment on heat rate.

Figure 2 shows the other alternative followed by the classical method. This is called the electrical driven design. In this case the CHP schemes selected may lead to the lack of thermal energy that may be supplied using auxiliary boilers. Other typical situation in this procedure depending on the technology selected is to have excess of thermal energy, which can be condensed or sent to other user out of the fences.

Once we selected and evaluated the thermal balance of each possible final design it's necessary to know the economical behavior of each candidate. This economical assessment usually takes average values in thermal and electric demands to avoid low or over calculation in the use of fuel.

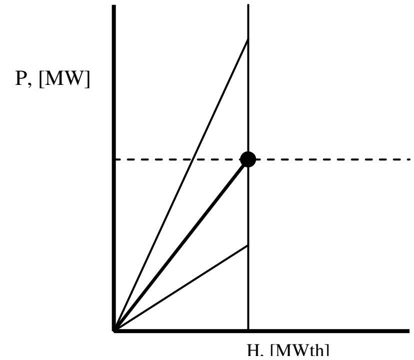

Figure 1. Thermal Driven Design.

One typical reference that explains the economical assessment is [3].

The final decision of the best fit with this method comes when comparing the levelized tariff or the Return on Investment or the Net Present Value generated by each possible plant and selecting the lowest tariff or the maximum Return on Investment or the maximum Net Present Value, in summary the CHP plant that shows the best economical behavior.

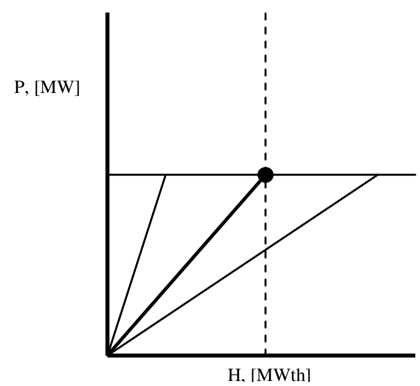

Figure 2. Electrical Driven.

DESIGN METHODOLOGY PROPOSAL

Considering average values on power and heat from historical data doesn't assure the real operation from the fossil fuel. Take into account the variable behavior over the time for power and heat would fulfill the users' operation requirements.

In this section a proposal to the design process for cogeneration plants is presented. It includes fuel, uniform series payments related with investment and operation & maintenance costs; the algorithm evaluate the variable behavior for power and heat along time with a scenario that takes into account transactions between the electric utility and the plant as well as auxiliary or back up boilers. The traditional design process is used to pre-select the best feasibility cases, then an authors' optimization algorithm solves ED problems for every pre-selected plant taking into account their demands profile. The cost functions used in these dispatching problems involve the proper operation & maintenance cost as well as a cost related with investment and the cost associated with fuel for every pre-selected plant. At the end, the lowest arithmetic sum of ED problems for each alternative along the project life gives the best result.

A. Starting with the classical design.

The classical design gives us the guideline with the set of possible alternatives that fit the users' requirements. These alternatives can be chosen to fulfill electricity applying the electrical driven design or to fulfill heat applying the thermal driven design or by the other hand we can chose a plant that doesn't match electricity or heat by introducing to the algorithm the model of such a plant that can condense or blow out to the atmosphere the excess heat or by using a back up boiler; that is the case of most industries that require heat to their process and supply it with boilers before the installation of the CHP plant.

B. Generating units modeling.

The algorithm proposed here requires accurate models describing the operation for every pre-selected CHP plant. The modeling process to get the performance for all generating units used on this paper is achieved by computational means with THERMOFLOW's Company software. Convex quadratic cost functions like [4], [5], and [1] are used here. For CHP units these cost functions are expressed as:

$$C_{fuel_{chp}}(p_{chp}, h_{chp}) = \alpha_{chp} + \beta_{chp}\cdot p_{chp} + \gamma_{chp}\cdot p_{chp}^{2} + \delta_{chp}\cdot h_{chp} + \varepsilon_{chp}\cdot h_{chp}^{2} + \zeta_{chp}\cdot p_{chp}\cdot h_{chp} \qquad (1)$$

These units work inside a power vs. heat plane [1] as shown in Fig. 5 to Fig. 8; where each side of the plane is represented as:

$$u_{chp,l}\cdot p_{chp} + m_{chp,l}\cdot h_{chp} \geq f_{chp,l} \qquad l = 1...L \qquad (2)$$

C. Power and Heat demands profile.

Depending on each type of industry we must consider the characteristic heat and power profile and relate it to the production with a characteristic index. If we are considering a new user plant we must use historical data from similar industries and their characteristic indexes. The power and heat profile could be hourly, weekly, monthly, etc. Frequency histograms can help us to get significant information to be used in the ED problems and can replace the use of the time dependence load profile. The ED problems that lead the design will have a better approach as accurate the profile is.

D. Operation scenario.

The CHP operation scenario considered here insures that the customer electric and thermal demands are always going to be satisfied as shown in Fig. 3. In the case of lack or surplus of thermal power, it is assumed that any excess is going to be condensed or blow out to the atmosphere, and if lack exists then the back up boiler will supply it. In the case of electric power it is assumed that the industry is connected to the electric utility grid and transaction of purchase and sale exists.

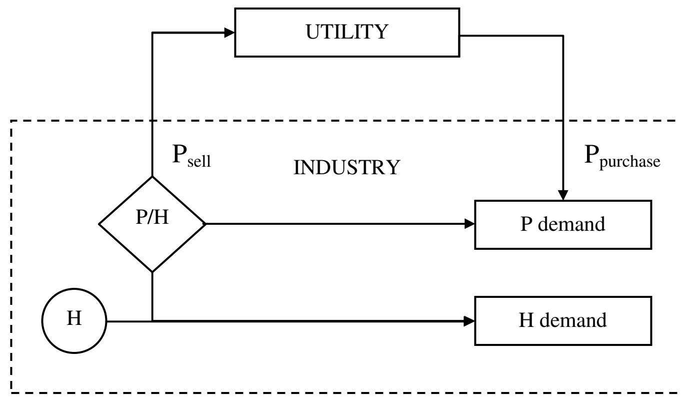

Figure 3. Operation Scenario.

E. Cost structure.

Several costs appear in CHP systems, the big ones are those related with fuel, investment, and operation & maintenance. The cost from the fuel (1), the cost from operation & maintenance (3) and a cost related with investment are used to solve the ED problems and must be expressed in USD/h; the cost of the investment can be fitted to such units on two simple steps; first with economic techniques such as find uniform series given a present value (4) we find the fixed capacity charge [6] then with (5) we find the cost function of investment in similar units to (1) and (2). It is important to mention that the cost function of investment is a fixed payment.

$$C_{o\,\&\,m_{chp}}(p_{chp}) = \vartheta_{chp}\cdot p_{chp} \qquad (3)$$

$$FC_{cap_{chp}} = UC_{cap_{chp}} \frac{\frac{i}{12}\left(1+\frac{i}{12}\right)^{12\cdot n}}{\left(1+\frac{i}{12}\right)^{12\cdot n} - 1} \qquad (4)$$

$$C_{inv_{chp}} = \frac{FC_{cap_{chp}}\cdot P_{nom_{chp}}}{hrs_{month}} \qquad (5)$$

F. ED mechanism to design.

The Objective Function to solve each ED problem will be the sum of the cost functions of all units appearing in the operation scenario. For every CHP alternative the total cost function will be the sum of (1), (3), (5), the back up boiler cost function and the cost functions for p_{sell} and $p_{purchase}$. The transactions between the plant and the utility as well as that of the back up boiler will be assumed to be linear functions [1].

The objective is to solve a nonlinear optimization problem subject to linear equality, linear inequality and simple bounds restrictions as is expressed with:

$$\min_{x} F(x)$$

s.t.

$$A_{eq} \cdot x = B_{eq}$$

$$A_{in} \cdot x \le B_{in}$$

$$LB \le x \le UB \tag{6}$$

Detailed information of the procedure to find the minimum and the restrictions is found in [1].

G. Result.

The best result is obtained when comparing values of the objective functions from the ED problems of each alternative along the period under study.

CASE STUDY

The demands profile for the industry under consideration is given in Fig. 4.

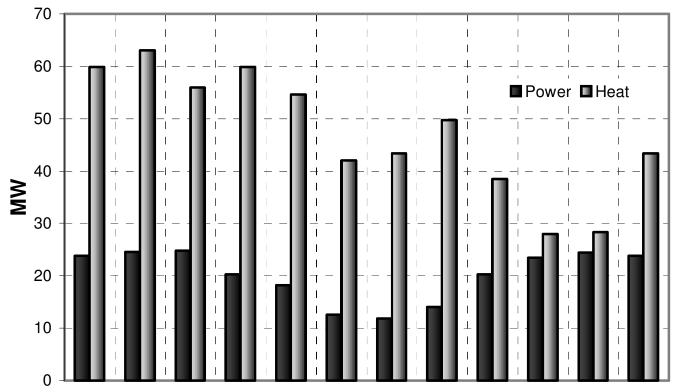

Figure 4. Demands profile.

Four alternatives, two electrical driven and two thermal driven, are chosen with the classical design procedure, the alternatives consist of one or two gas turbines plus a Heat Recovery Steam Generator (HRSG) with duct burner. See Table 1.

Alternative	Description of units	P_{nom} (MW)
1	1 GT + HRSG + DB	38.347
2	1 GT + HRSG + DB	20.219
3	2 GT + HRSG + DB	83.424
4	2 GT + HRSG + DB	18.668

Table 1. Pre-selected alternatives.

The modeling processes to get the fuel cost functions considered here take into account a fixed fuel cost of 5 USD/MBTU for all four alternatives. The fuel cost functions for these alternatives expressed in USD/h are:

$$C_{fuel_1}(p_1, h_1) = 537.226 + 0.0023 \cdot p_1 + 0.389 \cdot p_1^2 + 15.492 \cdot h_1 + 0.0162 \cdot h_1^2$$

$$C_{fuel_2}(p_2, h_2) = 289.336 + 2.911 \cdot p_2 + 0.736 \cdot p_2^2 + 15.934 \cdot h_2 + 0.019 \cdot h_2^2 + 0.0083 \cdot p_2 \cdot h_2$$

$$C_{fuel_3}(p_3, h_3) = 836.835 + 0.0025 \cdot p_3 + 0.239 \cdot p_3^2 + 17.841 \cdot h_3 + 0.0007 \cdot h_3^2 + 0.0012 \cdot p_3 \cdot h_3$$

$$C_{fuel_4}(p_4, h_4) = 289.336 + 2.911 \cdot p_4 + 0.736 \cdot p_4^2 + 15.934 \cdot h_4 + 0.019 \cdot h_4^2 + 0.0083 \cdot p_4 \cdot h_4$$

These units operate inside the power vs. heat planes represented in Fig. 5 to Fig. 8.

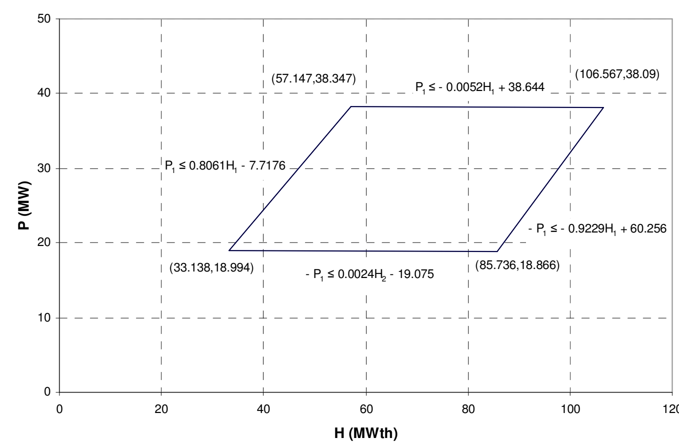

Figure 5. Feasible operating region for alternative 1.

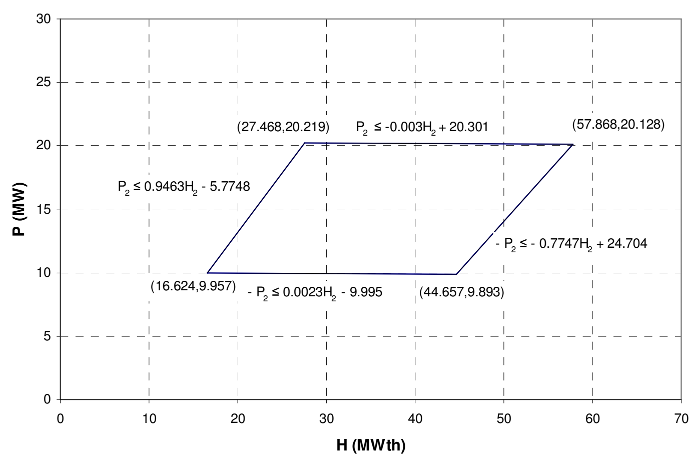

Figure 6. Feasible operating region for alternative 2.

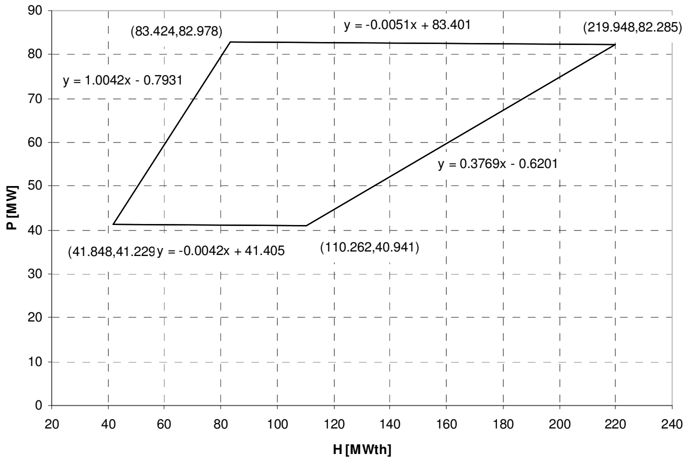

Figure 7. Feasible operating region for alternative 3.

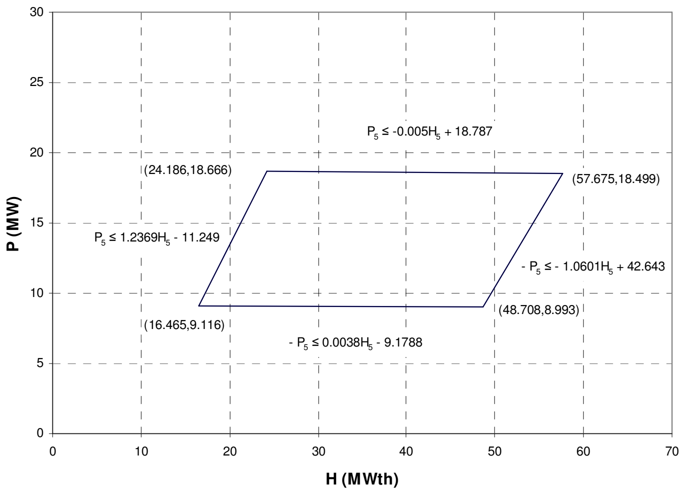

Figure 8. Feasible operating region for alternative 4.

The cost functions of investment as well as the cost functions of operation & maintenance for every alternative are expressed in USD/h as follows:

$$C_{inv_1} = 461.053 \quad ; \quad C_{o\&m_1} = 7.8 \cdot P_1$$

$$C_{inv_2} = 358.205 \quad ; \quad C_{o\&m_2} = 8.5 \cdot P_2$$

$$C_{inv_3} = 826.473 \quad ; \quad C_{o\&m_3} = 8.0 \cdot P_3$$

$$C_{inv_4} = 332.866 \quad ; \quad C_{o\&m_4} = 8.8 \cdot P_4$$

Joining all cost functions of each alternative CHP plant we get the respective total CHP cost function for that plant. This is expressed in Fig. 9 to Fig. 12.

The cost functions to sell and purchase power to and from the utility are assumed to be constant and are expressed with:

$$P_{sell} = 35 \cdot P \quad ; \quad P_{purchase} = 70 \cdot P$$

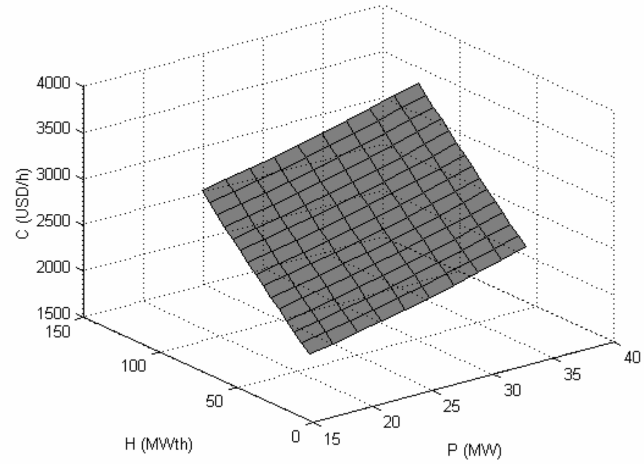

Figure 9. Total CHP cost function for the alternative plant 1.

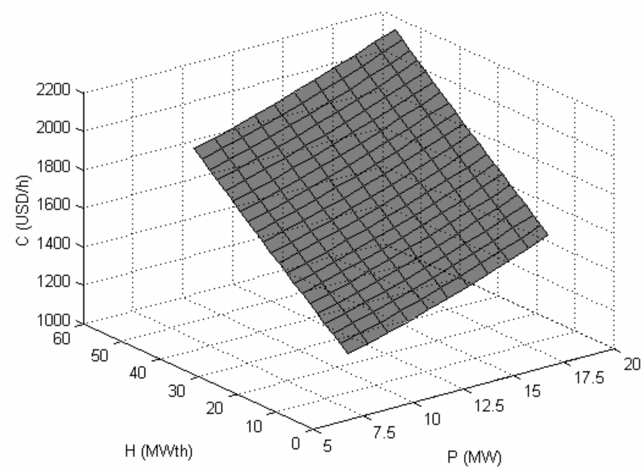

Figure 10. Total CHP cost function for the alternative plant 2.

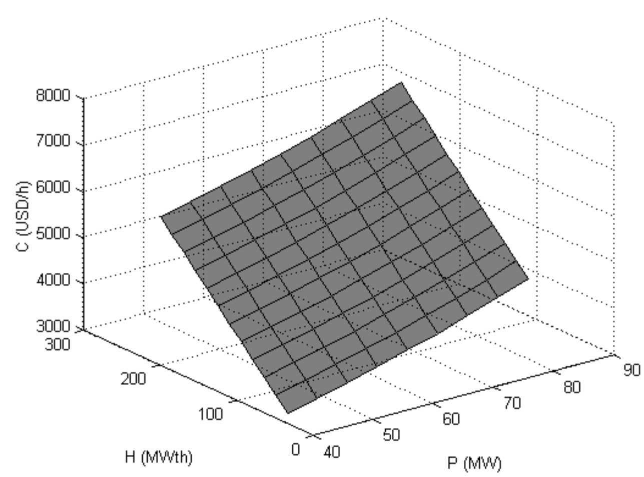

Figure 11. Total CHP cost function for the alternative plant 3.

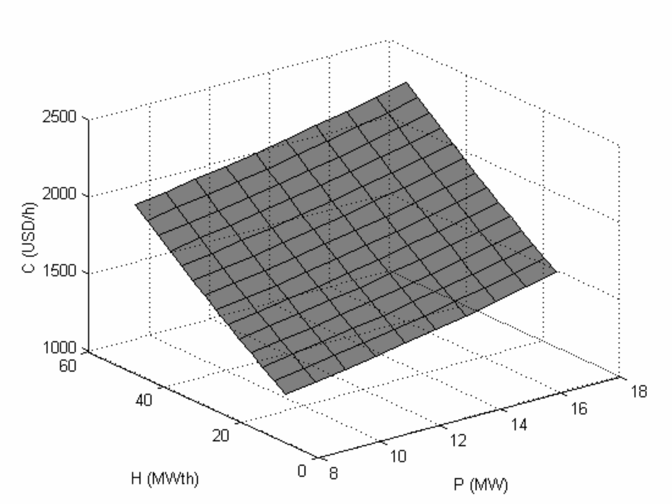

Figure 12. Total CHP cost function for the alternative plant 4.

The classical method give us as best fit the option number 4 while the proposed methodology gives the option number 2 as best fit as seen in Fig. 13. The best fit for the classical method is true for flat demand profile, but the load variations take us to another solution. This different solution is the result of operational choices introduced by the proposed methodology and therefore an aid to improve the election of the best fit.

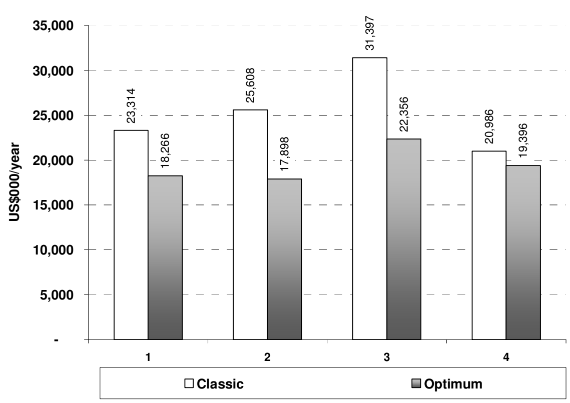

Figure 13. Total yearly cost (US$) for each plant studied.

The huge yearly cost for option 3 using the classic method is caused by the stronger assumption introduced in this method. That is, the cogeneration system and its loads are operating in average level. The extra cost is mainly fuel that the optimization algorithm considers non-necessary to spent as a result of its adjustment to minimize overall cost. However, the capital cost is its worst enemy resulting also as the worst option to be implemented. In summary the optimization is moving the strategy for each plant as seen in Table 2.

Plant	Strategy
1	Sometimes sells power to the utility
2	Transactions for both sides of the utility occur (not simultaneously) The boiler is working frequently
3	Always sells power to the utility. The boiler is working frequently
4	Sometimes purchases power from the utility The boiler is working frequently

Table 2. General optimization strategy for each plant.

CONCLUSIONS

The classical method to design CHP plants is improved by adding the electric and thermal load profiles and by using Economic Dispatch procedures. Considering average values for power and heat do not reflect the operation that the user would have. By using and evaluating variable loads for both heat and power the design will be moved to get the greatest economical assessment along the plant life. As it was shown in the case study, if the best fit using classical method is operated optimally, the annual cost is not necessarily the minimum (see case 4). The case number 2 is the best fit using the proposed methodology; however it would be the third choice using the classical method. Then, these results indicate the no co-relation among different pre-selected plants and therefore the necessity to evaluate one by one to choose the best. For the particular case study described before one can conclude that the best options are the three cases nearer to the maximal load point, see Fig. 14.

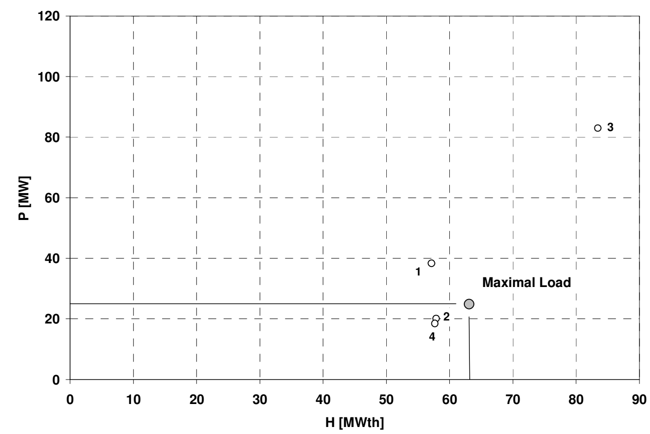

Figure 14. P – H diagram for each pre-selected plant. The points represent the output with the classical method.

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