

Thermodynamic and Economic Analysis for Simple Cogeneration Systems

Miguel A. Lozano and José Ramos

ABSTRACT

Many countries in Europe promote cogeneration as a way to meet energy needs in residential and commercial buildings. They do this to save primary energy and reduce CO₂ emissions. This article presents an energy and economic analysis approach for cogeneration plants hosted by such buildings. The plants use gas-fired internal combustion engines as prime movers. Technical criteria to characterize annual operation for cogeneration systems with seasonally and daily variable heat demand are defined. The focus is on determining the total engine size or output by considering different operational strategies. The methodology is illustrated by applying it to a cogeneration plant that meets domestic hot water and heating demand in a residential complex in Spain. The resulting graphical analysis allows one to compare various operational strategies.

Keywords: *cogeneration, CHP, energy efficiency, energy savings, thermodynamics, system size, operational strategy, legal restrictions*

INTRODUCTION

Cogeneration is defined as the concurrent production, in a sequential energy conversion process, of mechanical and electrical energy (power) and useful thermal energy (heat). Such combined-heat-and-power or CHP systems can use one or more sources of primary energy or fuel. For commercial and residential buildings in Spain, it is customary to design such systems so they fulfill the site's heat demand; since it's not viable to exchange heat in the form of hot water or steam with an external supplier. On the other hand, one can buy electricity and also sell it back to the grid, under certain conditions. When the cogeneration system is

designed to meet the site's power need, without the support or back up of electric utilities, it's called a *Total Energy System*. The references (e.g. Petchers, 2003) show further descriptions of such concepts and systems.

There is an increasing evidence of a world future which may not be sustainable energy wise. Despite several initiatives by both governments and business, CO₂ emissions have increased by 20% during the last decade. A recent International Energy Agency study (IEA, 2006) estimates that the emissions by year 2050 will double the current (2006) ones. This alarming scenario can be avoided, in part, by using cogeneration to increase the efficiency of energy supply in the form of useful heat and power. In addition, with on-site cogeneration or distributed generation, it's possible to save in electrical transmission and distribution losses. In fact, the installed electrical power generating capacity from industrial cogeneration systems has increased in the last decades realizing great energy and economic savings. However, in Europe, much of the cogeneration potential in industry has been realized and now, the efforts are directed to the commercial and residential buildings. For instance, in Spain less than 5% of the installed cogeneration electrical power corresponds to the residential-commercial sector. Considering the large consumption of domestic heat water (DHW), as well as space heating and cooling energy in this sector, there is an enormous savings potential. There are three reasons often cited for this *status quo*: i) many users think that the traditional energy services from separate heat and power suppliers are more dependable, ii) the low technical expertise or lack of qualified personal to operate and maintain integrated energy systems, and iii) the difficulty in defining a adequate configuration for a on-site energy plant due to large seasonal and daily fluctuations in heat and power consumption.

To realize such potential, some countries have promulgated regulations and taken actions to promote the use of cogeneration and District Heating and Cooling (DHC). In the European Union (EU), *Directive 2002/91/CE* about *building energy efficiency* states: "The housing and services sector, made up mainly of buildings, demands over 40% of the energy consumed in the *Community* and is expanding, which will increase the overall energy consumption, and therefore, CO₂ emissions." Article 5 of this directive states: "In new buildings, with a useful area of more than 1000 m², the member States will ascertain technical, environmental and economic viability of alternative systems such as cogeneration and central heating and cooling... be taken into account before construction

begins." From a different view point, *Directive 2004/8/CE* relative to promotion of cogeneration recognizes: "Now the Community is underutilizing the cogeneration potential as a means to save energy." This directive considers cogeneration to be of high efficiency whenever the energy savings are higher than 10% of the base-case or present consumption.

The cogeneration systems which supply buildings (commercial centers, hospitals, hotels, etc) and housing subdivisions are designed to meet the electrical, DHW and heating demands. The economic feasibility of these systems is assured when the concurrent production of power and heat, particularly heat, is supported by an effective demand during many hours in the year (Cardona y Piacentino, 2003).

If the utilization factor (UF) of the cogeneration modules is high, greater savings and shorter payback periods are attainable. This occurs in facilities located in colder climates which demand heat most of the year for heating and DHW. On the other hand, in location with more temperate climates, the heat demand is smaller, lasts a few months and the savings are smaller. Thus, there are two poor options: (i) there is a short period in a year when the engine is running and is limited by smaller heat recovered and savings, which makes it hard to timely recover the investment; (ii) there is a high rate of wasted heat, which is limited by the self-generator's legal condition, which can only result economically attractive under extraordinary conditions of fuel and electricity prices. A potential alternative is to use trigeneration (TriGeMed, 2003; Lozano et al., 2004b). In trigeneration, the utilization factor is improved by using cogenerated heat during the summer to cover the air-conditioning demand through absorption chillers integrated to the cogeneration plant.

To obtain greater energy savings in conjunction with a higher economic profitability in building hosted cogeneration systems, a greater attention should be paid to the plant sizing as well as to the plant's operating strategies. One way to address this problem is to use complex numerical optimization programs (Yokohama et al., 1994; Lozano, 2001). Another useful approach is an analytical approximation (Lucas, 2000; Tchouate y Bolle, 2002; Cardona y Piacentino, 2003), as suggested herein. Thus, this work presents an energy and economic evaluation method, for cogeneration facilities tasked to supply energy to larger buildings and urban complexes. The underlying methodology comprehends the following stages: i) characterization of cogeneration module energy outputs, ii) on-site heat demand graphical depiction and modeling, and

iii) determination of the cogeneration plant size to be installed and the operating strategy to be followed by the plant. The methodology is applied in the pre-design phase for a mid-size (0.5 – 2 mW) cogeneration plant and is based on gas fired IC engines, tasked to meet the host building DHW and heating demands.

EFFICIENCY CRITERIA

To characterize cogeneration systems we need to define a set of parameters that allow us: (i) evaluate investment opportunities, (ii) select the best match system, y (iii) optimize its operation, once installed. Let's suppose, to simplify, the cogeneration system is a black box, as in Figure 1. The system consumes F units of fuel energy (lower heating value) and at the same time it produces W units of work and Q units of heat. For energy analysis, it is convenient to express F , W y Q as energy flows in the same Unit System. Let's define the following parameters

$$\text{Electrical Efficiency} \quad \alpha_W \equiv W/F \quad (1)$$

$$\text{Thermal Efficiency} \quad \alpha_Q \equiv Q/F \quad (2)$$

$$\text{Global Efficiency} \quad \eta \equiv (W + Q)/F \quad (3)$$

$$\text{Heat/Work Ratio} \quad \beta \equiv Q/W \quad (4)$$

Note, however, to characterize the whole system it's enough to know only *three* independent variables of the seven above. For example, we could use W , α_W y β . Other interesting parameters, depicted in Figure 2, show the comparative advantage of cogeneration over the conventional systems, both with the same heat and work outputs.

Suppose we need to supply the demands W and Q . This means deciding between (a) a cogeneration system or (b) a conventional plant which implies purchasing electricity from a utility (Generator) with efficiency η_W and installing on-site a boiler with efficiency η_Q . The decision to favor cogeneration will result in fuel savings of

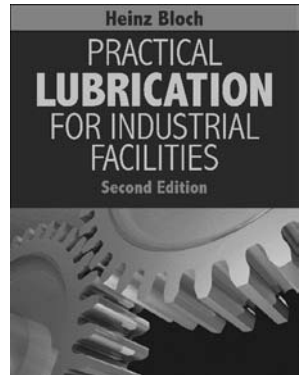
$$\Delta F \equiv F^* - F = \frac{W}{\eta_w} + \frac{Q}{\eta_Q} - F \quad (5)$$

Related to the concept in equation (5), there is the primary energy savings index or *Fuel Energy Saving Ratio (FESR)*, which expresses fuel savings per unit of energy used in the conventional plant:

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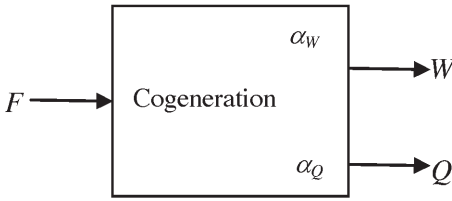


Figure 1. Cogeneration System

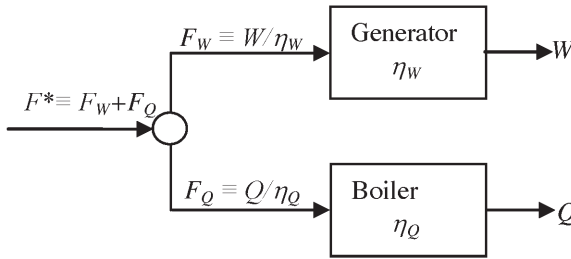


Figure 2. Conventional Plant

$$FESR \equiv \frac{\Delta F}{F^*} = 1 - \frac{F}{\frac{W}{\eta_W} + \frac{Q}{\eta_Q}} = 1 - \frac{1}{\frac{\alpha_W}{\eta_W} + \frac{\alpha_Q}{\eta_Q}} \quad (6)$$

The last parameter to be defined here is the *equivalent electrical efficiency*, which comes from a criterion used to allocate the fuel consumption between the two products of cogeneration: heat and power. Hence, if a conventional boiler with efficiency η_Q consumes the fuel $F_Q = Q/\eta_Q$ to produce the required useful heat Q (without cogeneration), the decision (based on profitability) to invest in a cogeneration system, assumes an additional fuel consumption of $F_{eqW} = F - F_Q$ to generate electrical power W . F_{eqW} is also known as the *fuel chargeable to power*. Therefore, the *equivalent electrical efficiency* is

$$\eta_{eq} \equiv \frac{W}{F_{eqW}} = \frac{W}{F - Q/\eta_Q} = \frac{\alpha_W}{1 - \alpha_Q/\eta_Q} \quad (7)$$

Note the criteria given by $FESR$ and η_{eq} emphasize finding out whether a cogeneration system is more efficient in obtaining the required energy products (heat and power) than a conventional plant.

The reduction in CO₂ emissions is an environmental criterion which is estimated directly from the fuel savings, whenever the fuel is the same for both cogeneration and conventional plant (e.g. natural gas). If the fuels are different, the reduction in CO₂ is

$$\Delta CO_2 \equiv cF_w \frac{W}{\eta_w} + cF_Q \frac{Q}{\eta_Q} - c_F F \quad (8)$$

where cF_i is the CO₂ per unit of energy in fuel i .

COGENERATION SYSTEMS

The majority of cogeneration facilities in buildings use gas engines and sometimes gas turbines. Martens (1998) and Li et al. (2006) have conducted a statistical analysis for the outputs of such plants. On the other hand, steam turbines, micro turbines, fuel cells and other cogeneration plants have a much smaller representation. In this work we only consider cogeneration with gas engines. The maximum cogeneration-module energy efficiency is limited by the amount or recoverable heat from the engine, but also by the required temperature (heat quality) for building or process heating. The heat recovery system is configured taking into account the heat demand characteristics and the convenience of using one or more temperature levels. A greater efficiency (or heat exchanger effectiveness) is obtained by recovering heat at a lower temperature level (Ramos, 2003).

To illustrate the parameters given in the above equations (5 through 7), Figure 3 shows the energy balance of a cogeneration module based on reciprocating internal combustion engine (RICE) with a nominal size larger than 100 kW (Lozano et al., 2004a). An "average" RICE with an efficiency $\alpha_W = 0.42$ consumes 100 kW of fuel to generate 42 kW of power. It's possible to recover the following heat streams at the stated temperatures: (i) 4 kW (Q_o) as hot water at $t \approx 55^\circ\text{C}$ from the lube oil cooling circuit; (ii) 16 kW (Q_w) as hot water at $t > 90^\circ\text{C}$ from the jacket coolant circuit; and (iii) from the exhaust gases (Q_g), 24 kW as hot water at $t > 90^\circ\text{C}$.

Suppose all the heat streams from the RICE are recovered as $Q = Q_g + Q_w + Q_o = 44$ kW. This results in a cogeneration system with $\alpha_Q = 0.44$, $\eta = 0.86$ y $\beta \approx 1.05$. Next, assume the system avoids conventional

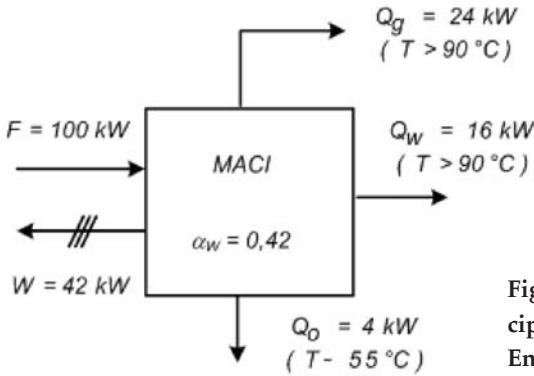
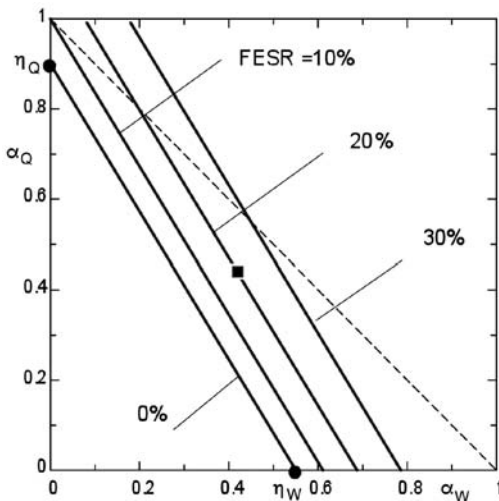


Figure 3. Cogeneration with Reciprocating Internal Combustion Engine (MACI in Spanish)

electrical power W , from combined cycle plants with overall efficiency $\eta_W = 0.55$, and the production of heat Q , in a gas-fired boiler with efficiency $\eta_Q = 0.90$. Then, the saving in natural gas is equivalent to 20% ($FESR \approx 0.20$) and the equivalent electrical efficiency is 82% ($\eta_{eq} = 0.82$). Figures 4 y 5 show the outputs and efficiencies of this case example. The square point (\blacksquare) in these figures represent the given cogeneration system performance and operating point.

Figure 6 depicts a simple cogeneration system showing the most important energy flows. The building demands heat Q_D and power E_D which must be supplied by the cogenerated heat and power W_C and Q_C or conventionally (buy electricity E_C and produce heat Q_A in a boiler). In general, when the cogeneration system outputs surplus energy, it's assumed the system can sell power E_V and will reject heat Q_L to the environment.



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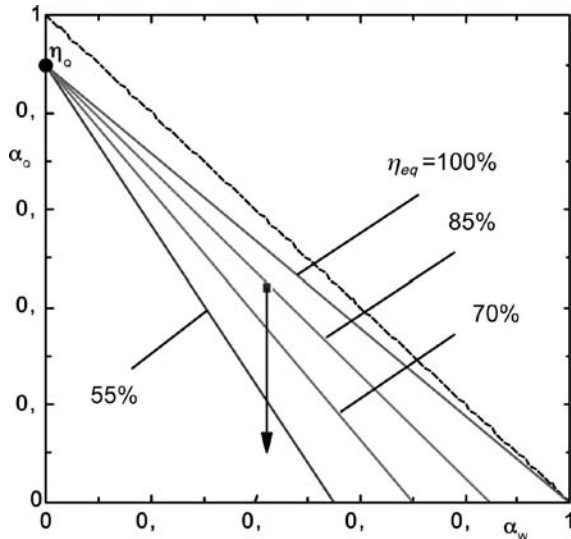
ENERGY DEMAND

Building energy demand has the following characteristics: (i) various energy needs (electricity,

Figure 4. Fuel Energy Savings Ratio, FESR

Figure 5. Equivalent Electric Efficiency, η_{ea}

heat, DHW, etc.); (ii) concentration of certain space conditioning services depending of the season or month of the year; and (iii) significant daily variation of energy demand based on occupancy patterns and environmental factors. Thus, it's important to know the most complete data about energy demands to be able to get the best design possible for building service equipment and also for a cogeneration system.



There are different ways to organize and present demand data: (i) using estimates of the for the maximum demand and specific annual consumption (e.g. 0,2 kW/m² y 50 kWh/(m² year)); (ii) through load-duration curves (see Figure 7); y (iii) "hour-by-hour" demand measurements (for existing building) or simulation estimates (for new buildings), throughout the year. The first way gives too little information and is only useful for simple buildings where well documented past experience supports the estimates. The second way, which is used herein, is used to make decisions about what kind of equipment will meet the demand and to evaluate various modes of operation. The third way supplies detail information, but it's often difficult to get and doesn't allow a generalized analysis. Note that often hourly data from the third way are graphically summarized using the second way, as load-duration curves.

LOAD DURATION CURVE

This article uses the annual load duration curves shown in Figure 7 to estimate the equipment size for a residential complex of 5000 dwellings located in Zaragoza, Spain. The load duration curve represents the number of hours a year (abscissa axis) with a heat demand equal to or

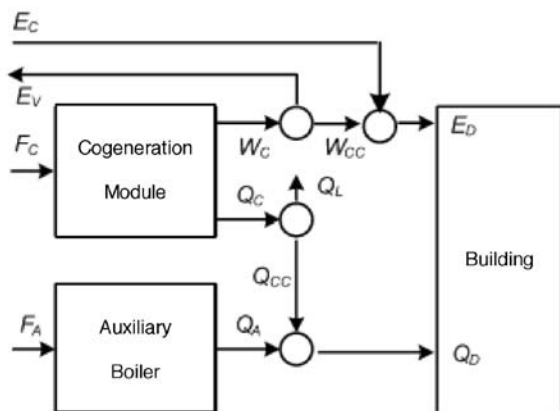


Figure 6. Simple cogeneration system

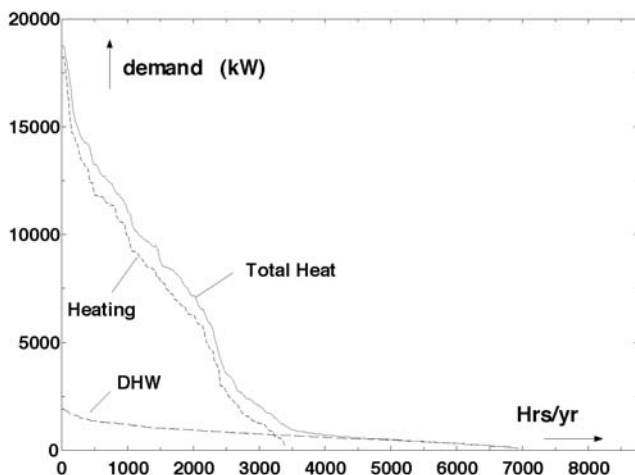


Figure 7. Heat demand load duration curves

larger than the heat demand shown in the ordinate axis. Thus, the *total heat demand* curve in Figure 7 indicates the building complex: (i) has a peak heat demand of ~ 18 MW; (ii) demands space heating during ~ 3500 hours a year, (iii) the demand exceeds ~ 5 MW about 2200 hours a year, and so on.

To develop a load duration curve which graphically models the combined effect of several heat demand streams we proceed as follows:

Step 1: Present the load duration curves of all heat demand streams on the same graph;

Step 2: If the demands are concurrent, the total load duration curve is obtained by adding (vertically) the demands corresponding to each time increment or hour.

Step 3: If the heat demands are not concurrent, the total load duration curve is obtained by adding (horizontally) the hours corresponding to the same demand.

As shown in Figure 7, the Total Head demand results from adding the concurrent Heating and DHW demands for each hour.

MODELING THE LOAD DURATION

Using the annual heat demand EQD_{year} [kWh/year], its duration H_{max} [hrs/year] and maximum or annual peak power QD_{max} [kW], then the total Heat load duration curve can be approximated by the simple exponential model $Q_D = a \cdot \exp(-b \cdot H)$, where a and b are model fitting coefficients. One way to determine such coefficients is to impose the condition that the maximum heat demand $a = QD_{max}$ and to compute b so the annual thermal energy or heat balances as $EQD_{year} = \int_0 \rightarrow H_{max} Q_D(H) dH$. For the total building heat demand shown in Figure 7, $EQD_{year} = 29,054 \cdot 10^3$, $H_{max} = 6,935$, $QD_{max} = a = 18,762$ y $b = 0.000638$. A plot of the resulting model equation is shown in Figure 8.

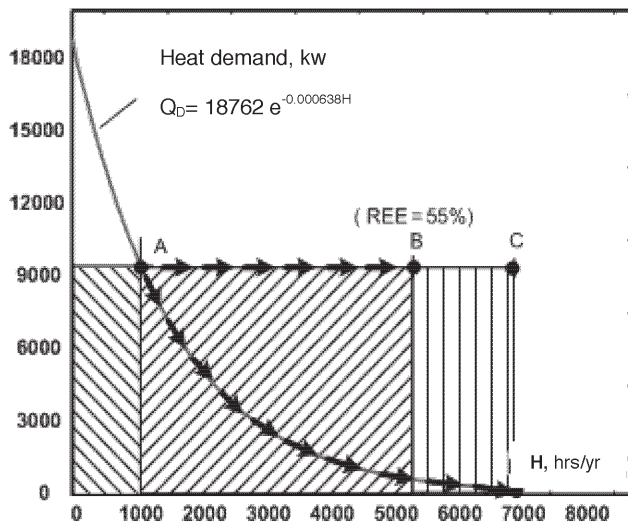


Figure 8. Strategies of operation

ECONOMIC EVALUATION

Two important decisions in cogeneration system design are: (1) to determine the system capacity to be installed W_{ins} [kW], which is made up of a number of modules or engines and (2) the strategy to be used to operate the system. Both decisions are intertwined. The following analysis explains the link between these two decisions and is based on the previously discussed efficiency criteria and in operational criteria which we shall discuss as follows.

Operational Criteria

The *utilization factor* for the installed capacity is given by

$$FUW = \left(\int_0^{Hope} W_c(H) dH \right) / (8760 W_{ins}) \quad (9)$$

where W_c [kW] $\leq W_{ins}$ is power cogenerated throughout the annual hours of operation *Hope* [hours/year].

Then, the *coverage ratio* is the heat consumption fraction served by cogeneration, or

$$TCQ = \left(\int_0^{Hope} Q_{cc}(H) dH \right) / EQD_{año} \quad (10)$$

where Q_{cc} [kW] is the heat recovered and later utilized to heat the building (there is no wasted heat here, see Figure 6). Next, the *degree of cogenerated heat utilization* GAC can be stated as a function of previously defined parameters and the heat-to-power ratio or characteristic β of the selected cogeneration modules:

$$GAC = \frac{\int_0^{Hope} Q_{cc}(H) dH}{\int_0^{Hope} Q_c(H) dH} \approx \frac{TCQ}{FUW} \frac{EQD_{year}}{8760 W_{ins} \beta} \quad (11)$$

Note the waste heat $WH = 1 - GAC$ is the amount of heat that is not utilized by the building and is rejected to the environment.

Ideally, the best cogeneration system design implies a larger GAC . So, the best cogeneration system design will operate at a high rate of coverage (a greater contribution of cogeneration to serve the building

heating needs), a high degree of utilization resulting in a better energy efficiency and an elevated utilization factor, thus resulting in a quicker return on investment. The load duration curve is quite useful in assessing how close a given system approaches such desirable operating conditions. Thus, if we know the heat and power outputs for the cogeneration modules, and the ways to modulate such outputs to match the building varying heat load, we can easily estimate the parameters given above and conduct a quick estimation of the cogeneration investment feasibility.

Economic savings and legal restrictions

The estimated net annual savings [\$/year] from cogeneration are

$$A = W_{ins} 8760 \cdot FUW \left(p_e + \beta \cdot GAC \frac{p_{fa}}{\eta_c} - \frac{p_{fm}}{\alpha_W} \right) \quad (12)$$

where p_e , p_{fa} y p_{fm} [\$/kWh] are the electricity, auxiliary boiler and cogeneration fuel prices, respectively. To maximize the annual savings, it's advisable to install a high enough cogeneration capacity ($W_{ins} \uparrow$) and to maximize its utilization ($FUW \uparrow$). But we also need to maximize the utilization of cogenerated heat ($GAC \uparrow$). In most buildings in this study, there is a conflict between heat and power utilizations, particularly when the power demand is not well correlated to heat demand. In addition, we need to consider the legal limitation for electricity sold to the grid (Cardona y Piacentino, 2005). The legislation in Spain, requires there is a minimum equivalent efficiency (rendimiento eléctrico equivalente, REE) of 55% in cogeneration with gas-fired engines, assuming a fixed boiler efficiency $\eta_{Q^*} = 0.9$. Next, we have

$$REE = \frac{\int_0^{Hope} W_c(H) dH}{\int_0^{Hope} (F_c(H) - Q_{cc}(H) / \eta_{Q^*}) dH} \geq 0,55 \quad (13)$$

Operational Strategies

In general, there are two sensible ways to operate a building cogeneration system: (1) run the cogeneration modules at full load or (2) adjust the output or load impose on the cogeneration modules according to the heat demand. In the first case, the utilization factor (hours a year) will

be the highest, but the cogenerated heat will be less utilized. The second approach assures the highest engine heat utilization, but the engine utilization factor will be limited. Taking advantage of one or the other way depends on economic factors as well as in norms to assure ease of operation and maintenance, system reliability and durability. Note that to keep things manageable in modeling we make the assumption that the buying and selling electricity prices are the same and constant over time, which is not always true.

According to Equation 12, when $p_e \geq p_{fm}/\alpha_w$ the price of electricity avoided by cogeneration compensates the fuel cost needed to produce it, even when some waste heat occurs. Note the fully loaded engine operation running most hours per year is preferred. For this type of operation the economic savings can be rewritten as

$$A = W_{ins} \cdot Hope \left(p_e - \frac{p_{fm}}{\alpha_w} \right) + TCQ \cdot EQD_{año} \frac{p_{fa}}{\eta_c} \quad (14)$$

The second term in this equation states the savings from fuel that is avoided in the auxiliary boiler. As see in Figure 8, once $Hope > HA$ a portion of the cogenerated heat at full load has to be rejected because of not enough demand. Next, when $Hope$ increases, TCQ also goes up while GAC drops (see Figure 9). Therefore, the second term will continue to increase with TCQ until the limit $HC = Hmax$. When $Hope > Hmax$ the second term no longer grows but the first term increases, so it still makes economic sense to run the engine as many hours as possible. But there is a limit to this when the plant is required to sell electricity to the grid. For instance, the equivalent electrical efficiency is required to exceed the limit $\eta_{w*} = 55\%$ to achieve the *autogenerator* qualification in Spain. This condition can be expressed as

$$GAC(H) \geq \frac{\eta_{Q^*}}{\beta} \left(\frac{1}{\alpha_w} - \frac{1}{\eta_{w*}} \right) \quad (15)$$

The condition of a equivalent electrical efficiency of 55% is achieved when the number of operating hours HB , for fully loaded engines, is between two bounds: $HA < HB < HC$ (See Figures 8 y 9). In our case, this is achieved when $GAC(HB) = 0.4835$, which means that the maximum allowed wasted heat from the cogeneration system (not utilized in the building) is $WH_{max} = 1 - GAC(B) = 51.6 \%$.

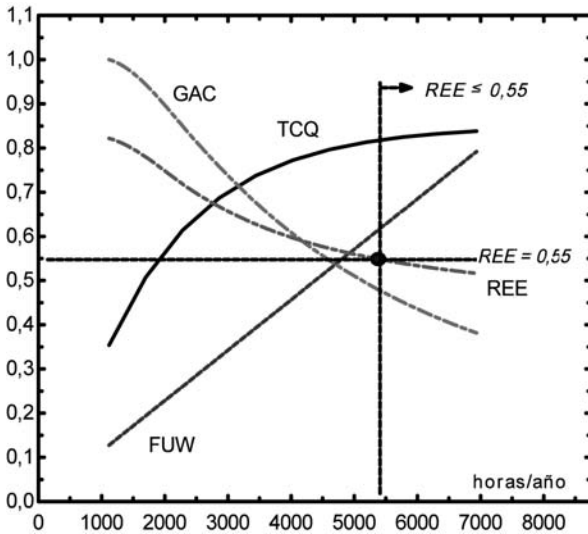


Figure 9. Engine operation at full load

As depicted in Figure 10, with the strategy of modulating the engine load and not wasting heat, we get a higher equivalent electrical efficiency REE , but with incur in a lower utilization factor FUW , which causes a slower investment recovery.

Figures 11, 12 and 13, respectively show the heat demand coverage TCQ , the engine utilization factor FUW and the degree of heat utilization GAC for three operating strategies at full load:

- A) longest operating hours HA that supports total heat utilization,
- B) longest operating hours HB that meets the equivalent electrical efficiency limit,
- C) longest operating hours with a heat demand H_{max} ;

In addition, a fourth strategy is evaluated as

- D) modulate the electrical power output so the cogenerated heat just matches the heat demand.

In the Figures 11, 12 and 13, the abscissa represents the ratio Q_{ins}/QD_{max} between the available heat from cogeneration $Q_{ins} = \beta W_{ins}$ and the maximum instantaneous head demand QD_{max} . Operating strategies B y D are represented by points in the plots. Then we evaluate the results of installing 2, 3 or 4 engines with a nominal electrical power of de 2928 kW each. Note installing 2 engines and operating with the B

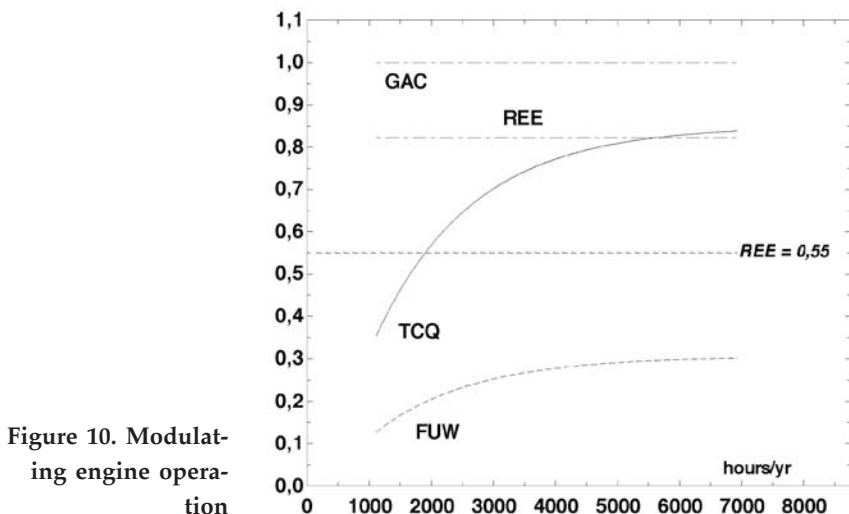


Figure 10. Modulating engine operation

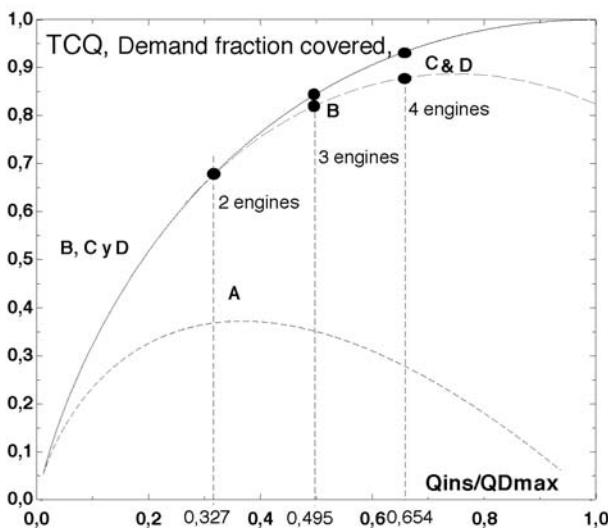


Figure 11. Fraction of Demand Covered by Engines

strategy allow a high heat demand coverage TCQ (~70%) and also a high utilization factor FUW (~75%). With 3 and 4 engines the heat demand coverage increases but at the detriment of FUW . Then, load modulating strategy D results in a low engine utilization.

A detailed analysis (Lozano et al., 2004b) yields an optimal solution when installing 3 engines running under strategy B: longest operating hours while meeting the limit $\eta_{W^*} = 55\%$. This solution results in a high

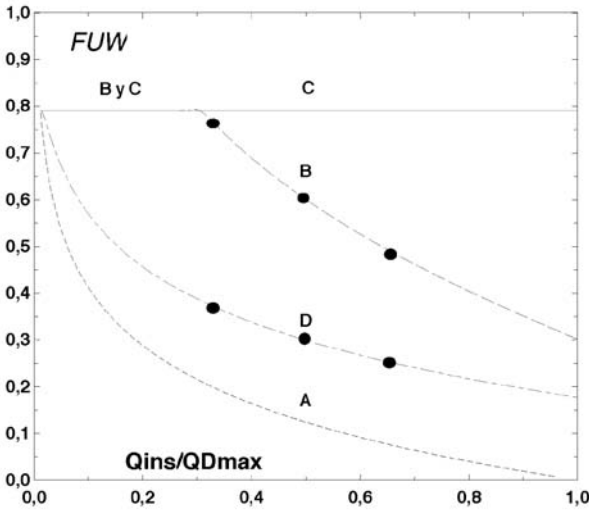


Figure 12. Engine Utilization Factor, *FUW*

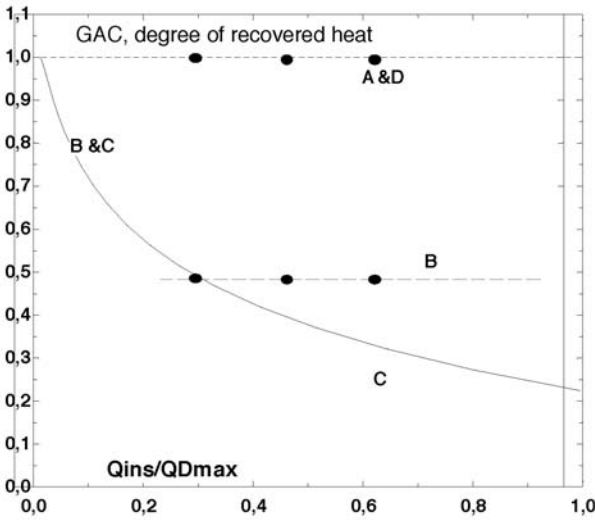


Figure 13. Recovered heat

coverage of demand ($TCQ \sim 80\%$, Figure 11, Point B) and a reasonable utilization factor ($FUW \sim 60\%$, Figure 12, Point B).

CONCLUSIONS

The traditional criteria of energy savings, equivalent energy efficiency, and economic savings which are easily computed for industrial

cogeneration systems running at fully loaded or nominal conditions, can also be estimated without difficulties (even graphically) for building cogeneration systems with variable heat demand. This is accomplished by building upon the technical and economic characteristics of the underlying cogeneration modules and on the heat demand load duration curves. The development of three operational parameters (utilization factor, demand coverage and degree of heat utilization) provided sufficient and effective criteria to select the most economical system size and operating strategy.

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ABOUT THE AUTHORS

Miguel A. Lozano and José Ramos

GITSE-I3A, Dpto. de Ingeniería Mecánica, Universidad de Zaragoza; C/Maria de Luna s/n, 50018 Zaragoza, Spain; (e-mail: miguel.lozano@unizar.es, jose.ramos@unizar.es)