Performance Evaluation of Cogeneration Systems: an Approach Based on Incremental Indicators

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Abstract: - Cogeneration systems are becoming more and more important thanks to their enhanced efficiency and the possibility of exploiting distributed cogeneration technologies for small-scale applications. There are several techniques to perform cogeneration plant evaluation, from an energy saving, environmental and economic standpoint. In this paper, an approach based on incremental indicators, for both electrical and thermal production, is presented and exemplified with numerical applications, focusing in particular on the most widespread cogenerative prime movers on a small-scale basis, namely, microturbines and internal combustion engines.

Key-Words: - Cogeneration, Distributed energy resources, Distributed generation, Incremental indicators, Internal combustion engine, Microturbine, Performance evaluation, Production efficiency.

A. Acronym list

CHP	Combined Heat and Power
DER	Distributed Energy Resources
DG	Distributed Generation
EIHR	Electrical Incremental Heat Rate
EUF	Energy Utilization Factor
FESR	Fuel Energy Saving Ratio
ICE	Internal Combustion Engine
IHR	Incremental Heat Rate
ITHR	Incremental Trigeneration Heat Rate
MT	Microturbine
SP	Separate Production
TIHR	Thermal Incremental Heat Rate

B. Symbols

A positional coding is used for symbols. Subscripts represent energy sources or end use (*e*=electricity, *t*=thermal, *y*=cogeneration) and specify the measuring units. η denotes efficiencies. For electricity, W is energy [kWh$_e$] or average power [kW$_e$]. For heat, Q is energy [kWh$_t$] or average power [kW$_t$]. For fuel, F is thermal energy [kWh$_t$] or average thermal power [kW$_t$].

1 Introduction

The issues and debates related to energy production optimization have been fast augmenting in the last years, due to a host of reasons ranging from environmental constraints to political aspects. From this standpoint, the new energy production paradigm set up by the spread of Distributed Generation (DG) systems [1] has an impact going further than the sheer production of electricity. Indeed, the potential exploitation of small-scale prime movers that also produce *in situ* thermal power leads towards a development of a Distributed Energy Resource (DER) framework aimed at satisfactorily meeting the overall user's needs in terms of both electrical and thermal energy.

Following this reasoning, Combined Heat and Power (CHP) plants [1,2] may represent one of the solutions to the energy issues and problems recently raised. Cogeneration technologies, in fact, have been long known for the highly efficient fuel primary energy exploitation with respect to the Separate Production (SP) of electricity and heat (which, in addition, allows also for improved plant economics). However, the widespread profitable utilization of CHP systems also on a small-scale basis (namely, below 1 MW$_e$) has not been feasible until the introduction on the market of thermal prime movers such as Internal Combustion Engines (ICEs) or Microturbines (MTs) [1,3]. In this way, it has been possible to adopt cogeneration for several different small-scale applications (for instance, office buildings, hospitals, residential blocks, malls and schools [4]), whereas in the past the utilization of cogenerated heat was mostly limited to higher size applications (typically, district heating and industrial processes [2]).

The classical performance evaluation of cogeneration prime movers is based on the adoption of different indicators [2], among which the Fuel Energy Saving Ratio (*FESR*) [2] and the Incremental Heat Rate

(*IHR*) [2,3] (although in literature they may be known with different names) are widely used. In addition, these indicators are also often adopted from a Regulatory point of view in several Countries [5].

However, whereas the *FESR* has been extensively studied [2,5], fewer works refer to the *IHR*. Furthermore, the *IHR* can also be used for economic evaluation purposes, especially when there is no direct way to price the heat produced, or anyway there is no need to do it.

Since, as it is well known, the electricity has higher thermodynamic value than the heat [2], in general smaller importance is given to the evaluation of the heat production. In spite of this, from several standpoints it is actually interesting to properly evaluate also the heat production performance of a multi-generation energy system (including also, in case, trigeneration plants [6]). For instance, when willing to assess the environmental impact of distributed CHP systems with respect to the separate production of the same energy vectors, it would be more correct to refer to the heat production rather than to the electricity production, since the energy sources to be potentially substituted are represented by the industrial boilers spread on the territory [7]. Similarly, in some applications one could be interested in evaluating, from an economical point of view, the actual plant performance in producing heat (for instance when selling heat to a district heating network). In general, in these cases a possible approach to evaluate the plant performance could be to evaluate the heat production, taking into account that *also* electricity is produced, in a fashion exactly dual with respect to the *IHR* definition.

On these premises, in this work the performance characteristics of CHP systems are analysed by resorting to an approach based on incremental indicators for both electricity and heat production. In particular, an incremental indicator for heat production in cogeneration is introduced and utilized, along with the classical *IHR* for cogeneration systems, and in analogy with the *ITHR* indicator introduced and used by the authors in [8] for trigeneration systems. The equipment considered in the analysis is modelled by means of black boxes characterized by the efficiency characteristics of the single plant components. The analysis entails considering different cogeneration characteristics, according to different prime mover technologies that it is possible to find on the market. From this point of view, parametric analyses are presented, and, in particular, the focus is set on some numerical aspects related to the MTs and ICEs, in order to highlight the characteristics of nowadays' most spread small-scale DG cogeneration prime mover technologies.

2 Characteristics, planning and evaluation of cogeneration systems

2.1 General aspects of CHP planning

A CHP system in its most general form can be composed of several components and according to several schemes [1,2,6]; in particular, the cogeneration systems of interest in this work are characterized by the following equipment:

- A cogenerative prime mover, that produces both electrical energy and cogenerated heat and represents the core of the plant. For small-scale applications usually gas MT(s) or gas ICE(s) are adopted [1,3], and fuel cells could assume to some extent an increasingly important role in the future [1,3].
- A CHG group, normally composed of industrial boilers [9]. The group is aimed at both back-up and thermal peak shaving use, in all those cases when the heat produced by the CHP unit should not satisfy the end-user requirement [6].

The energy flow interactions within the plant and with the outside may depend on both load levels and *regulation strategies*, such as thermal/electrical base-load or load-following applications for the CHP prime movers and the CHG [6].

2.2 CHP components and models

As the energy flow interactions among the different equipment within the plant and with the outside (electricity and fuel distribution networks) are very tied, the equipment involved in the DER design needs to be properly modelled in order to correctly assess the overall performance of the plant and thus its economy [1,6].

The fundamental characteristics of the CHP prime movers can be described by means of the electrical efficiency η_W, electrical output to fuel thermal input ratio, and the thermal efficiency η_Q, thermal output to fuel thermal input ratio:

$$\eta_W = \frac{W_y}{F_y} \tag{1}$$

$$\eta_Q = \frac{Q_y}{F_y} \tag{2}$$

which depend on the technology, the heat recovery system, and the enthalpic level at which the heat is provided to the user [1-3]. In (1) and (2), the subscript y points out cogeneration production. The sum of the electrical and thermal efficiencies (1) and (2) represents the cogeneration overall efficiency, or Energy Utilization Factor (*EUF*) [2], that is,

$$EUF = \eta_W + \eta_Q \tag{3}$$

which is often used to give a first hint on the overall exploitation of the fuel primary energy input.

In general, partial-load efficiency curves are provided by points by the manufacturers; mathematical models of these curves, suitable for computer implementation and plant simulation, are thus usually derived by means of linear or quadratic interpolation. In addition, often expressions or charts describing the dependence of the cogenerator performance on the outdoor characteristics (temperature, height, and humidity, for instance) may be provided, especially for turbines and microturbines [1,3,10].

Similarly, the performance of the CHG, normally composed of industrial boilers, is described by means of the thermal efficiency η_t, thermal output to fuel thermal input ratio:

$$\eta_t = \frac{Q}{F} \tag{4}$$

Likewise for the prime movers, the partial load behaviour is usually described by means of models that can be implemented in simulation codes, for instance, as a function of the fuel input with respect to the thermal load [9].

2.3 CHP system classical performance evaluation

As mentioned in the introduction, one of the classical performance evaluation techniques for CHP systems is based on an indicator (the *FESR* [2]) aimed at assessing the primary energy saving with respect to the separate production of heat and electricity. The success of this approach, also from a Regulatory point of view, is basically due to the match with the most recent energy saving and environmental (GHG emission) issues. In alternative, in some Countries [5] the indicator used to evaluate the plant performance is the *IHR* (also considered in some technical documents such as [3]), which assess the *actual* efficiency for electricity production, taking into account that heat is produced at the same time from the same source of energy. In the next section, the *IHR* will be presented in detail and its generalization will be provided to include the evaluation of the thermal production in cogeneration.

3 CHP system performance incremental indicators

3.1 The reference indicators

In order to evaluate the efficiency in producing different energy vectors through different equipment and technologies, a common ground needs to be set, being namely represented by the primary energy necessary to produce a given amount of a certain type of energy [6]. From this outlook, it is possible to simply define for the electricity and heat production respectively an Electrical Heat Rate (*EHR*, coincident with the classical heat rate [1,3] for power plant evaluation) and a Thermal Heat Rate (*THR*), defined as

$$EHR = \frac{F}{W} = \frac{1}{\eta_e} \tag{5}$$

$$THR = \frac{F}{Q} = \frac{1}{\eta_t} \tag{6}$$

where η_e and η_t are in general the electrical and thermal efficiency of given components.

The *EHR* and *THR*, properly assessed, represent the energy consumption references to which to compare any other generation system.

3.2 The CHP incremental indicators

The rationale behind the definition of the *IHR* [2,6] lies in the fact that it is not possible to distinguish between *two* separate amounts of fuel needed for producing electricity W_y and heat Q_y in cogeneration; therefore, a conventional efficiency is defined, considering that the energy F_y in the fuel supplied to the CHP plant is supposed to be reduced by the amount that would have been however required to produce the heat Q_y. This amount of fuel is conventionally calculated supposing that the thermal energy would have been generated in a boiler for heat-only production, of efficiency η_t^{SP}, so that what we call in this work *EIHR* (for nomenclature conformity with the thermal indicator we will define in the sequel), coincident with the classical *IHR*, is given by [2,6]

$$EIHR = \frac{F_y}{W_y} - \frac{Q_y}{\eta_t^{SP} \cdot W_y} \tag{7}$$

Thus, from (7) it is straightforward to evaluate the “actual effectiveness” in producing electricity while cogenerating also heat, or, which is the same, to evaluate the “actual” amount of fuel needed for electricity-only production. Of course, the definition and interpretation of the *EIHR* is conventional, and other alternative approaches can be considered for the electricity evaluation, for instance based on the exergy theory [2].

Following the same logic considered for the *EIHR* (7), it is also possible to define, in a dual fashion, a Thermal Incremental Heat Rate (*TIHR*) as

$$TIHR = \frac{F_y}{Q_y} - \frac{W_y}{\eta_e^{SP} \cdot Q_y} \tag{8}$$

through which it is somehow possible to compare the "actual" production of heat in a cogeneration plant, excluding that part of fuel that would have been anyway needed in order to produce the same amount of electricity in separate generation. Again, the definition (8) is completely conventional, but it can be sometimes useful in those cases in which the focus of the analysis is on the thermal production (for economic and environmental issues, for instance).

It is easy to show that when, for the sake of simplicity, all the heat and electricity are produced in cogeneration (no production from the auxiliary boilers and no electricity drawn from the grid), considering the prime mover electrical and thermal efficiencies (1) and (2), the expressions (7) and (8) can also be rewritten as

$$EIHR = \frac{1}{\eta_W} - \frac{\eta_Q}{\eta_W \eta_t^{SP}} \tag{9}$$

$$TIHR = \frac{1}{\eta_Q} - \frac{\eta_W}{\eta_Q \eta_e^{SP}} \tag{10}$$

The relationships (9) and (10) allow for a fast evaluation of the cogenerator performance on the basis of its efficiency characteristics (which can be evaluated in every operation point, accounting for partial-load evolution and outdoor-dependence characteristics).

3.3 The separate production reference efficiency values

The evaluation of the incremental indicators (7) and (8) can give useful information on the comparative assessment of the production efficiency from different prime movers. However, as a general and common reference, it is interesting to compare them also with the reference (non-incremental) indicators (5) and (6), so as to have first hints on the cogeneration production effectiveness with respect to the separate production, which is as better as more true are the expressions

$$EIHR < EHR^{SP} \tag{11}$$

$$TIHR < THR^{SP} \tag{12}$$

It is apparent that the values to assign to the reference electrical and thermal efficiency (from the separate production, for instance) play a major role in evaluating the relationships (11) and (12).

In general, today average values for heat generator efficiencies are about 0-8-0.85 for residential equipment (< 50 kW_t) and 0.9 for bigger (industrial) boilers [5,9,11]. Consequently, THR^{SP} may typically be about 1.2 (residential) or 1.1 (industrial).

Differently, as far as the separate production reference electrical efficiency is concerned, it is possible, generally speaking, to undertake two different approaches, in line with what suggested in different Regulatory frameworks in several Countries [5] for the evaluation of the primary energy saving with respect to the separate production (through the *FESR*).

One approach is to assign to η_e^{SP} a value corresponding to the average bulk production efficiency from the power system (in this case, a value equal to about 0.4 could be, for instance, representative of the Italian power system, including transmission losses); this case would yield EHR^{SP}=2.5.

A second approach, instead, would be to consider, as comparative reference, the best available technology, at the time, for electricity production (in which case a value equal to about 0.55 seems to be a reasonable value corresponding to most of commercial combined-cycle plants). In this case there would be EHR^{SP}=1.8.

Again, when differently suggested or obliged by the Regulation, it is up to the designer to consider the best reference efficiency values (also other than the two "boundary" cases exemplified here).

4 Numerical applications of the incremental indicators

4.1 Electricity production evaluation from different CHP prime movers

An interesting and effective way to evaluate different cogenerators and/or cogeneration technologies on the basis of their electricity production is to plot the *EIHR* (9) against the electrical efficiency (1), given the thermal efficiency (2) as the curve parameter (Fig. 1). In the picture, an upper limit of 0.9 as *EUF* has been considered (boundary limit for basically all today's technologies). Also a comparison with the prime mover *EHR* (of course function of the electrical efficiency as well, according to (5)), that would be the actual fuel consumption rate without considering the cogenerated heat, is shown. In addition, the EHR^{SP} for the separate production of electricity, useful to evaluate the relationship (11), is also shown, with two values equal to 1.8 (η_e^{SP}=0.55) and 2.5 (η_e^{SP}=0.4), according to what discussed in the previous section.

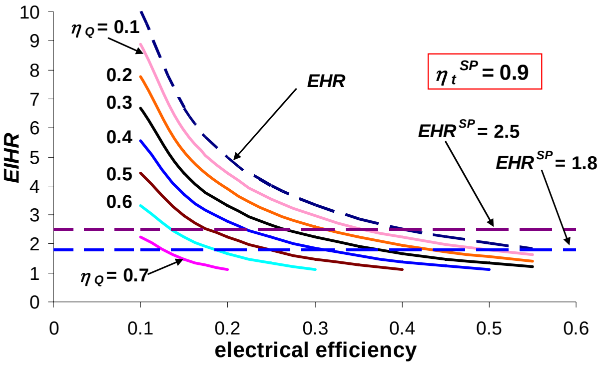

Fig. 1. CHP plant *EIHR* for different values of electrical and thermal efficiency (η_t^{SP} =0.9)

Commenting the results, in general it is apparent that, especially for lower electrical efficiencies and higher thermal ones, the *EIHR* can be quite lower than the corresponding *EHR* (that would occur if no heat were cogenerated, and thus if only electricity were produced with the same amount of fuel, i.e., with $\eta_Q = 0$); this highlights the potential of the cogeneration, whereas the almost *obligation* to cogenerate in order not to waste primary energy from the fuel is pointed out in presence of lower electrical efficiency, when only for relatively high thermal efficiencies the relationship (11) holds true. Furthermore, it can be seen how the cogeneration of heat can bring an "actual" fuel consumption for electricity production even less than the one corresponding to today's best technology (EHR^{SP}=1.8 for η_e^{SP}=0.55), even with the lowest electrical efficiency, as long as a good thermal efficiency is achieved. In general, considering small-scale applications, both ICEs (with characteristic efficiency values close to, averagely, η_w=0.4 and η_Q=0.4) and MTs (with characteristic efficiency values close to, averagely, η_w=0.3 and η_Q=0.5) can achieve quite good performance in terms of "actual" fuel consumption for producing electricity.

4.2 Heat production evaluation from different CHP prime movers

A reasoning dual to the one from the previous paragraph can be carried out for the thermal production in cogeneration. Fig. 2 and Fig. 3 show the *TIHR* as a function of the prime mover electrical efficiency (as the horizontal axis variable) and thermal efficiency (as the curve parameter), for two different values of η_e^{SP}, respectively η_e^{SP} =0.55 and η_e^{SP} =0.4, in line with what discussed above. In this case, the results are compared with those ones when heat is produced separately through boilers (considering only the THR^{SP}=1.1 corresponding to η_t^{SP} =0.9).

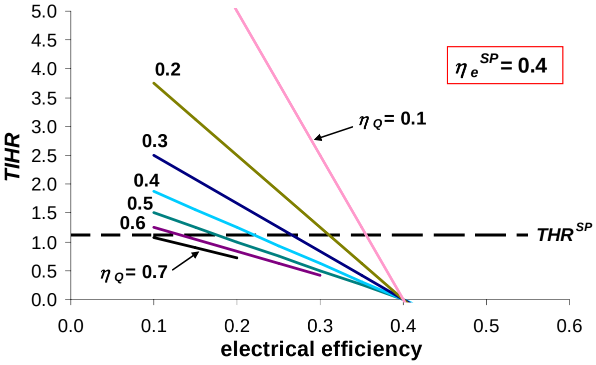

Fig. 2. CHP plant *TIHR* for different values of electrical and thermal efficiency (η_e^{SP} =0.4)

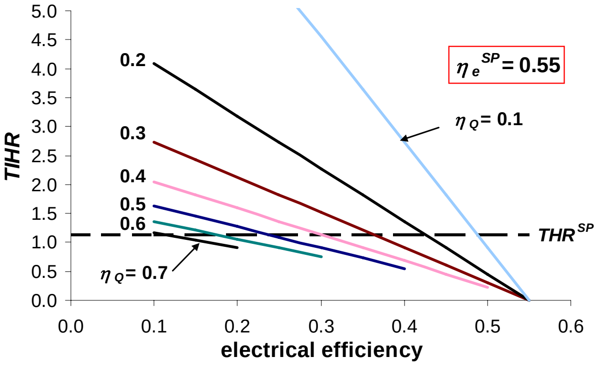

Fig. 3. CHP plant *TIHR* for different values of electrical and thermal efficiency (η_e^{SP} =0.55)

As general considerations on the results, with η_e^{SP}=0.4 (which seems definitely a more correct reference value when willing to evaluate small-scale technologies), with a minimum amount of heat cogenerated (η_Q =0.1, for instance) the *TIHR* is less than the THR^{SP} if the prime mover electrical efficiency is higher than about 0.36 (values easily feasible for small-scale ICEs under rated conditions); with electrical efficiencies of about 0.3 (a reference rated value for MTs, for instance), the thermal recovery should be at least about 25 % of the fuel primary input, in order to have $TIHR<THR^{SP}$.

If considering η_e^{SP}=0.55, for electrical efficiencies about 0.3, the thermal recovery should be at least about 45 % in order to have *TIHR* less than the THR^{SP} (an upper limit with today's MT technology). Again, an easier condition would occur for ICEs (considering η_w=0.4), for which the relationship (12) would be verified with thermal efficiencies higher than about 0.25. However, as said, a value of 0.55, as also indicated by the Regulatory position in many Countries (Italy, for instance [11]), seems too high when evaluating the performance of DG prime movers (that, with respect to the "bigger" relatives, are penalised because of the well know scale factors).

5 Concluding remarks

Cogeneration plants, especially on a small-scale, represent an important energy source to exploit in order to improve the performance of modern energy systems, complying with the more and more stringent requests in terms of energy saving, environmental and economic issues.

In this work, an approach based on incremental indicators aimed at assessing the CHP performance in the *single* production of electricity and heat (taking into account that the other respective energy vector is also cogenerated) has been presented. This approach reflects the fact that incremental indicators are used or may be used for certain types of evaluation. In particular, the *IHR* (here called *EIHR*) is adopted in several Regulatory frameworks in order to assess the cogeneration performance of the plant [5]; the *TIHR*, instead, defined and illustrated in this work, could be adopted for economic evaluation (in analogy with the electricity production evaluation, which may be carried out through the *IHR* for cogeneration plants [2] and the *ITHR* introduced by the authors for trigeneration plants [8]); in addition, it could also be adopted for environmental assessment purposes, backing up other approaches based for instance on emission balances [7].

Numerical analyses have been performed, also comparing in particular the cogeneration characteristics of MTs and ICEs, nowadays the most widespread technologies. In general, ICEs have resulted performing better than MTs in terms of both *EIHR* and *TIHR*; however, these results are only partial and cannot be generalized, since of course also other considerations play an important role when planning a new DER system, such as the electricity and heat load patterns, the quality of the heat to provide, the environmental constraints, and, above all, the economic analysis outcomes.

Finally, the approach illustrated is completely general, and could be used in order to carry out comparative analyses with any other type of cogeneration technology, for instance fuel cells, which are recently gaining some market shares and are one of the most promising technologies for the future development of energy systems.

References:

[1] A.M. Borbely and J.F.Kreider (ed.), *Distributed generation – The power paradigm of the new millennium*, CRC Press, Boca Raton, FL, 2001.
[2] J. H. Horlock, *Cogeneration-Combined Heat and Power (CHP)*, Krieger, Malabar, FL, 1997.
[3] US EPA, *Catalogue of CHP Technologies*, available at www.epa.gov.
[4] Cogeneration website www.cogeneration.com.
[5] E.Cardona and A.Piacentino, Cogeneration: a regulatory framework toward growth, *Energy Policy* **33** (2005) 2100-2111.
[6] P.Mancarella, *From cogeneration to trigeneration: energy planning and evaluation in a competitive market framework*, PhD Dissertation, Politecnico di Torino, Torino, Italy, April 2006.
[7] A.Canova, G.Chicco, G.Genon and P.Mancarella, Environmental impact of small-scale distributed cogeneration systems, *Proc. VI World Energy System Conference*, Torino, Italy, July 10-12, 2006, 689-696.
[8] G.Chicco and P.Mancarella, Planning Evaluation and Economic Assessment of the Electricity Production from Small-scale Trigeneration Plants, *WSEAS Transactions on Power Systems*, **1**, 2, 393-400, Feb. 2006.
[9] J. F. Kreider (ed.), *Handbook of Heating, Ventilation and Air Conditioning*, CRC Press, Boca Raton, FL, 2001.
[10] P.Gomatom and W.Jewell, Fuel parameter and quality constraints for microturbine distributed generators, *Proceedings of Power Systems 03: Distributed Generation and Advanced metering*, 2003.
[11] Autorità per l'energia elettrica e il gas, (Authority for electrical energy and gas), website www.autorita.energia.it.