Proc. of the 5th WSEAS/IASME Int. Conf. on Electric Power Systems, High Voltages, Electric Machines, Tenerife, Spain, December 16-18, 2005 (pp320-325)

Electricity Production from a Small-scale Trigeneration Plant: a Planning Tool based on Economic Assessment

GIANFRANCO CHICCO and PIERLUIGI MANCARELLA
Dipartimento di Ingegneria Elettrica
Politecnico di Torino
Corso Duca degli Abruzzi 24, I-10129, Torino
ITALY

Abstract: - The recent development of efficient technologies for small-scale energy production has increased the possibilities of adopting local generation sources and exploiting them in the energy market. Trigeneration is emerging as a viable and powerful solution for various applications requiring the simultaneous production of electricity, heat and cooling. This paper proposes a new planning tool based on economic assessment for comparing different trigeneration alternatives. Results based on time-domain simulations are shown for a case study.

Key-Words: - Cogeneration, Trigeneration, Distributed generation, Performance indicators, Economic assessment, Planning tool.

A. Acronym list

CERG Compression Electric Refrigerator Group
CHCP Combined Heat Cool and Power
CHP Combined Heat and Power
CITHR Cooling-side Incremental Trigeneration Heat Rate
COP Coefficient Of Performance
EDS Electricity Distribution System
EHP Electric Heat Pump
EITHR Electrical-side Incremental Trigen. Heat Rate
FESR Fuel Energy Saving Ratio
GARG Gas Absorption Refrigerator Group
GDS Gas Distribution System
ICE Internal Combustion Engine
IHR Incremental Heat Rate
ITHR Incremental Trigeneration Heat Rate
MT Microturbine
PES Primary Energy Saving
TITHR Thermal-side Incremental Trigeneration Heat Rate
TPES Trigeneration Primary Energy Saving
WARG Water Absorption Refrigerator Group

B. Symbols

Subscripts represent energy sources or end use (*y*=cogeneration/trigeneration, *e*=electricity, *t*=thermal, *c*=cooling, *F*=fuel, *g*=gas, *d*=demand) and specify the measuring units. They are also used in economic study entries (*I*=investment, *M*=operation/maintenance). For the energy vectors, the same symbols are used for energy [kWh] or average power [kW]: W denotes electricity, Q denotes heat, R denotes cooling (refrigeration), F denotes fuel. η denotes efficiencies. χ and ρ are energy unitary cost and price [euro/kWh]. C represents cost in general [euro].

1 Introduction

The adoption of high-efficiency/renewable energy systems within the distributed generation paradigm represents a key aspect of present and future power system development [1]. The cogeneration systems (CHP plants) have been extensively adopted in the past decades for getting significant primary energy efficiency and economic performance where the simultaneous provision of electricity and heat was requested [2], especially for large industrial users. Nowadays, the availability of consolidated distributed generation technologies, such as ICEs and MTs, allows for the design of small-scale (below 1 MW_e) *thermal* plants, widening the horizon of cogeneration utilisation. Moreover, for several new potential small-cogeneration users (hospitals, office buildings, hotels, department stores, commercial buildings, etc.) the energy needs include also cooling. This threefold energy need can be satisfied by designing a so-called *trigeneration* or CHCP plant [3-5], representing the extension of a cogeneration plant where electricity, heat and cooling are produced on-site. The literature in this field refers to trigeneration with special focus on the combination of a traditional CHP group with a WARG, fed by hot water or steam produced in cogeneration [3-5]. The global efficiency of such a CHCP plant can be even better than for a CHP system, due to a larger exploitation of the cogenerated heat, which leads to shorter Pay Back Times [1,2].

In the conventional energy systems, consumers are supplied from electricity and gas utilities. Nowadays, they can also buy gas and electricity within the energy markets. In addition, they can also combine supply from energy networks with their own energy equipment to satisfy their final demand. Since in a competitive energy market scenario gas and electricity prices are subject to high variability and volatility, it is interesting to consider the adoption of various combined generation alternatives, aimed at allowing the market players to satisfy their final energy demand (i.e., electricity, heat and cooling) in a more profitable and effective way. Following this reasoning, the authors have, in previous works, introduced [6] and developed [7,8] a broader approach to trigeneration. This newer point of view consists of studying the effectiveness of considering and comparing other chilling equipment (e.g., GARG, reversible EHP, CERG with/without heat recovery condenser, to mention the most commercially available [9]), leading to an extended plant design problem, i.e. choice and rating of prime mover and cooling equipment, also including different regulation strategies and the interactions with the energy markets. Indeed, the decisions on when, whether and how running the cogenerator, buying/selling electricity, and feeding the cooling equipment with differentiated energy vectors (e.g., gas, electricity, as well as steam or hot water produced by the CHP module) can assume a strategic role. As a result, the profitability of the trigeneration solutions [6] depends on the choice of the technologies, management and performance of the equipment, as well as various and complex factors in continuous evolution, such as market, tariffs, legislation framework and so forth.

While evaluating the feasibility of a trigeneration system, it is important to have effective tools for assessing the characteristics and performance of a CHCP plant as opposed to another one. The utilisation of the same tools used in the CHP system evaluation represents a good starting point, although special care has to be taken to avoid some pitfalls the designer could run into. In particular, it is insufficient to consider only rated-condition values [10] and in general a time-domain approach, comprehensive of the out-of-design models of all the equipment forming the energy system [6-8], is needed. The time horizon and the time step of the plant simulation depend on the specific case and on the purpose of the study. The economic assessment of the trigeneration alternatives can be carried out according to several techniques [1,2]. A comprehensive example is shown in [6].

In this paper, we first present the general aspects of CHCP plants for small-scale applications along with some techniques to characterize the trigeneration system at a planning stage. Afterwards, we introduce some performance indicators to assist the CHCP design and a technique (based on one of these indicators) to price the produced electricity. A case study, based on time-domain simulations, is shown to highlight the practical aspects.

2 Planning and evaluation of trigeneration systems

2.1 General aspects of CHCP plants

A trigeneration plant in its most general structure is made up of a “cogeneration side” and a “cooling side”. For small-scale (below 1 MW_e) distributed generation, the “cogeneration side” is usually formed by gas-fed groups, typically ICEs or MTs [11], with back-up and/or peak-shaving boilers and grid connection to satisfy the energy needs in any condition. The fuel, typically gas, is drawn from the GDS. The “cooling side” can be made up of different equipment, ranging from a WARG (the classical trigeneration reference, with absorption machine fed by cogenerated heat) to a traditional CERG, a direct-fired GARG or an EHP, usually reversible and hence usable for both heating and cooling purposes [9]. Different cooling machines lead to different plant layouts and significantly different interactions of the energy flows. Fig. 1 shows a simplified diagram.

As for cogeneration plants, at a preliminary stage of the trigeneration system design it is important to set up the *energy inputs* (typically gas drawn from the GDS and electricity exchanged with the EDS), the desired *energy outputs* (electricity, heat and cooling load profiles), the technical and economic *interface characteristics* of the plant with the supply networks (gas and electricity spot prices, contract prices, utility tariffs, market conditions), the *regulatory* and *environmental* constraints and finally the *economic/financial* analysis parameters.

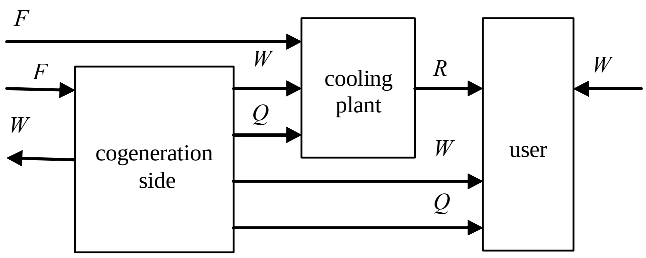

Fig. 1. General CHCP Plant Layout and Energy Flows

Once established all the above information, the system design can be seen as the comparative analysis of possible alternatives for the cogeneration and cooling sides. Also the *regulation strategies* play an important role in the evaluation. For instance, the cogenerator can be run under (heat) electricity base-load/load-following, electrical peak-shaving and always on/off mode, just to mention the most used ones [7,8]. Moreover, it is normal practice to turn the cogenerative groups off, because of efficiency drop, under 50% of the rated load [11]. Also the cooling equipment can be subject to regulation strategies [9].

The general trigeneration system *operational planning* problem can be formulated as the comparative evaluation and selection of the "most convenient" option among a set of alternative equipment for the cogeneration and cooling sides, taking into account regulation and market interaction strategies and *out-of-design* models of all the equipment, within a time-domain simulation approach.

2.2 Characterization of CHCP plants

At the planning stage, it is important to adopt indicators able to synthetically characterize the plant needs and help the designer to approach the prime mover choice and sizing. Simple tools are needed as a starting point before stepping further (running time-domain simulations) in the design. In the classical cogeneration approach, the analysis includes the introduction of the *demand-related* cogeneration ratio λ_d, thermal to electrical power demand ratio, and the *production-related* cogeneration ratio λ_y, ratio of thermal to electrical power developed by the prime mover, namely:

$$\lambda_d = \frac{Q_d}{W_d}; \qquad \lambda_y = \frac{Q_y}{W_y} \tag{1}$$

Although ideally it should be $\lambda_d = \lambda_y$, (*"matched"* plant) this almost never happens, and in general it is quite tough even to define a rated cogeneration ratio for the user, because of the continuous variability of the loads, whereas a rated ratio is naturally defined for the prime mover by using the rated outputs. In a CHCP plant design, the choice of the prime mover looking at the λ_d is even tougher. In fact, the cooling power introduces a new load, which may impact on either or both the thermal and electrical load, by "coupling" the cooling need to the other two user's needs: different types of cooling equipment can change the electricity or heat demand and subsequently the demand cogeneration ratio, besides the absolute thermal/electrical load. For instance, a WARG would result in additional heat demand; a GARG, directly fed from the GDS, would decouple the cogeneration from the cooling production, whereas the adoption of a CERG or EHP would result in additional electricity demand [7,8].

2.3 Evaluation of CHCP plants

The classical approach to assessing CHP plant performance is based on the analysis of some indices [2] aimed at evaluating the effectiveness of the heat and electricity production. Although most of them are of straightforward use, the designer should pay a lot of attention while using them. In particular, one of the main and frequent pitfalls to avoid is to evaluate them only on the basis of rated-condition entries [10], without considering out-of-design and more realistic performance of the plant. At the planning stage, while evaluating different alternatives, neglecting this kind of analysis could in general lead to biased results of the feasibility study [1,2,12]. To overcome such inaccuracies in the design, these indices should be evaluated after running time domain simulations including adequate out-of-design models of the equipment [6].

The most used and easy-to-use performance indicator [2] is the *FESR* for assessing the fuel savings compared to the separate generation of heat and electricity, which is generalized, as *PES*, to CHCP cases with absorption machines in [13] and [14]. In [8], the authors extend its application to every kind of trigeneration plant and call it *TPES.* The *TPES* allows for evaluating the effective fuel saving of alternative trigeneration solutions with respect to the separate production of the three energy vectors. However, although very effective to assess the overall energy performance, the *TPES* is not very useful to point out the efficiency of the single energy vector production (i.e., how well the system performs in individually producing electricity, heat and cooling). Under this point of view, for CHP plants, if the electricity production is somehow considered "weighing" more than the heat production (e.g., for economic reasons), it is possible to use other indicators, such as the *IHR* [2] (generalization of the classical heat rate used for power plant performance). Following this approach, the authors have introduced in [8], in analogy to the *IHR*, a *ITHR array* of new indices able to assess, for a CHCP plant, the "equivalent" production efficiency of the single trigenerated vector. The array contains the *EITHR* for the electricity-only production efficiency, putting aside (conventionally) the part of fuel that would be needed to produce heat and cooling. With the same principle, the *TITHR* and the *CITHR* are defined, so yielding:

Proc. of the 5th WSEAS/IASME Int. Conf. on Electric Power Systems, High Voltages, Electric Machines, Tenerife, Spain, December 16-18, 2005 (pp320-325)

$$EITHR = \frac{F_y - \dfrac{Q_y}{\eta_t} - \dfrac{R_y}{COP^* \cdot \eta_e}}{W_y} \quad (2)$$

$$TITHR = \frac{F_y - \dfrac{W_y}{\eta_e} - \dfrac{R_y}{COP^* \cdot \eta_e}}{Q_y} \quad (3)$$

$$CITHR = \frac{F_y - \dfrac{W_y}{\eta_e} - \dfrac{Q_y}{\eta_t}}{R_y} \quad (4)$$

where F_y [kWh$_t$] is the overall fuel thermal input to the trigeneration system, W_y [kWh$_e$] is the trigenerated electricity (for user's need and sold to the grid), Q_y [kWh$_t$] the trigenerated heat for user's need (including boiler production), R_y [kWh$_c$] the cooling production; η_t, η_e and $COP*$ are the reference average efficiencies for separate production. The *ITHR* array can be applied to a CHCP system to evaluate, for each design alternative and operating condition, the overall system efficiency in generating each energy vector.

3 Economic assessment of the electricity production from trigeneration systems

Among the several possible approaches to evaluate the economics of a distributed generation plant [1,2,9], we use in the sequel the one based on referring the electricity production *annual* cost [1,2]:

$$C_e = C_I + C_F + C_M \quad (5)$$

where C_e is the annual cost of the electricity produced [euro/year], C_I is the annualized capital cost of plant [euro/year], C_F is the annual fuel cost [euro/year] and C_M is the annual cost of operation and maintenance [euro/year]. The annual production cost C_e, once referred to the energy unit, becomes the *average production cost of electricity* (*"unitised" production cost*) χ_e [euro/kWh$_e$] and has to be compared to the average available electricity price ρ_e, in order to assess the convenience of building the power plant. However, a CHCP plant is doing more than just producing electricity, that is, it produces simultaneously also thermal and cooling energy, with a net fuel saving. Under this point of view, equation (5) holds in general true also for the trigenerated electricity, but now C_I and C_M become "additional" costs ΔC_I and ΔC_M for setting up the energy system as compared to the conventional production systems for the three energy vectors (electricity bought from the grid, heat produced in boilers, cooling power produced through CERG); likewise, C_F has to take into account the fuel savings due to the other trigenerated vectors. Therefore, for electrically "matched" plants (where the production equals the need), the economic fuel cost balance over one year can be expressed through:

$$\chi_F \cdot W_y = \rho_g \left(F_y - \frac{Q_y}{\eta_t} - \frac{R_y}{COP^* \ \eta_e} \right) \quad (6)$$

that is

$$\chi_F = \rho_g \cdot EITHR \quad (7)$$

where *EITHR* is calculated on the basis of annual entries, χ_F is the *average fuel cost for electricity production* [euro/kWh$_e$], W_y [kWh$_e$/year] the annual trigenerated electricity and ρ_g [euro/kWh$_t$] the average gas price (with, as planning approximation, the same price for gas for boilers and prime movers).
Using (5) and (7) together yields

$$\chi_e = \frac{\Delta C_I}{W_y} + \rho_g \cdot EITHR + \frac{\Delta C_M}{W_y} \quad (8)$$

When the plant is not "matched" and the annual electricity produced W_y exceeds or fails the annual user's need W_d, the annual electricity balance (with all the entries in [kWh$_e$/year]) in general yields:

$$W_y = W_d + W_o - W_i \quad (9)$$

where W_i is the annual electricity purchased from the grid (*in*) and W_o the annual electricity sold to the grid (*out*). In the economic balance also the cost of the in-electricity and the profit from the out-electricity has to be considered. In this case, the actual reference to evaluate the various alternatives is the cost for producing the given electrical output W_d, while producing also Q_d and R_d. Accordingly, the *unitised "equivalent" electricity cost* χ_e^* [euro/kWh$_e$] to satisfy the annual electrical demand W_d is

$$\chi_e^* = \frac{\chi_e \cdot W_y + \rho_e (W_i - W_o)}{W_d} \quad (10)$$

where ρ_e [euro/kWh$_e$] is the grid electricity average price, assumed, in a first planning approximation, equal for both selling and purchasing. Combining (8), (9) and (10) with the plant *feasibility condition*

$$\chi_e^* < \rho_e \quad (11)$$

yields the alternative feasibility condition:

$$\rho_g \le \rho_g^* \quad (12)$$

Proc. of the 5th WSEAS/IASME Int. Conf. on Electric Power Systems, High Voltages, Electric Machines, Tenerife, Spain, December 16-18, 2005 (pp320-325)

Table 1. Comparisons among different solutions and regulation strategies for the trigeneration equipment.

case	Regulation strategy	Prime mover	Refrigerator	Rated lambda	*EITHR* [(1)]	W_y [kWh$_e$/year]	ΔC_I [euro/year]
1	A	ICE330	CERG	1.1	2.08	1,134,300	16,800
1	B	ICE330	CERG	1.1	1.28	202,130	16,800
1	C	ICE330	CERG	1.1	2.14	2,533,000	16,800
1	A	ICE525	CERG	1.2	2.75	787,670	27,300
1	B	ICE525	CERG	1.2	---	0	27,300
1	C	ICE525	CERG	1.2	2.30	4,198,200	27,300
2	A	ICE330	WARG	1.1	2.33	1,212,165	19,950
2	B	ICE330	WARG	1.1	2.07	1,216,900	19,950
2	C	ICE330	WARG	1.1	2.16	2,805,000	19,950
2	A	ICE525	WARG	1.2	3.28	503,340	30,450
2	B	ICE525	WARG	1.2	2.16	860,290	30,450
2	C	ICE525	WARG	1.2	2.17	4,470,200	30,450
3	A	ICE330	GARG	1.1	2.29	1,212,165	19,950
3	B	ICE330	GARG	1.1	2.11	474,130	19,950
3	C	ICE330	GARG	1.1	2.19	2,805,000	19,950

(1) η_t=0.9, η_e=0.4, and *COP**=4

where ρ_g^* can be seen as *"equivalent" gas price*.

$$\rho_g^* = \frac{\rho_e}{EITHR} - \frac{\Delta C_I + \Delta C_M}{EITHR \cdot W_y} \tag{13}$$

After running the suited plant operating simulations over a one-year time span (which give W_y and *EITHR*), (12) allows for a straightforward comparative economic evaluation of the CHCP alternatives, as practically shown in the next section.

4 Case study application

In order to apply the above concepts to a case study, let us consider for instance a hospital site. Fig. 2 shows the load duration curves of the electrical, thermal and cooling load (details in [8]).

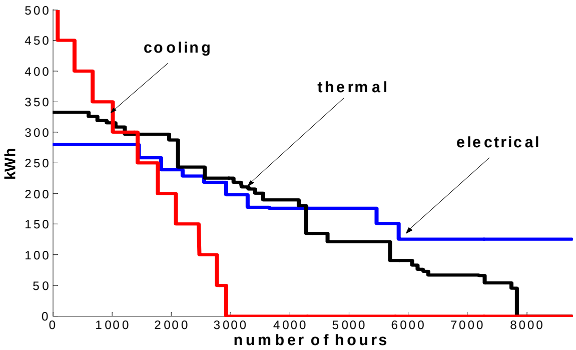

Fig. 2. Load duration curves.

Let us now consider three cases for the cooling side, with also different prime movers:

- *case 1*: *CERG* (two 250 kW$_c$ electric chillers), fed by the CHP system and/or EDS); as a prime mover a gas-fed 330 kW$_e$ ICE or a gas-fed 525 kW$_e$ ICE;
- *case 2: WARG* (one 515 kW$_c$ unit), fed by cogenerated hot water when the CHP system is ON, otherwise by boilers); as a prime mover a gas-fed 330 kW$_e$ ICE or a gas-fed 525 kW$_e$ ICE;
- *case 3: GARG* (two 281 kW$_c$ units), directly fed by the GDS); as a prime mover, a gas-fed 330 kW$_e$ ICE.

In all the cases, complete energy back-up is ensured through grid connection and a heat production group (e.g. an adequate number of 200 kW$_t$ boilers). All the equipment is available from commercial catalogues.

For each case, hourly time-domain simulations over a one-year span have been run, also considering three regulation strategies (*A*: *electrical load-following*; *B*: *thermal load-following*; *C*: *engine always-on*). Out-of-design models of all the equipment as in [6,7] have been used in the simulations. Some results are summarized in Table 1.

Applying the formulation of the previous section (without present worth analysis [1,2], for sake of simplicity), with expected plant useful life of 15 years, from the simulations we obtain the results shown in Fig. 3. The *equivalent gas prices* (13) are plotted against the average grid electricity prices, for the simulated plants resulted convenient the most. An average gas price (aligned with European ones) is also shown as a reference.

The results of Fig. 3 can be interpreted as follows: for every average electricity price, viable solutions are represented by all the ones for which the equivalent gas prices exceed the given average gas price. In this way, considerations (*a posteriori* of the simulations) on the possible gas and electricity average prices the system could face can help choose the best solution. In the case studied, the CERG with the 330-kW$_e$ ICE can be identified as the most effective solution, slightly better than other ones adopting the WARG. Moreover, the benefits from suitably exploiting the trigeneration systems strongly depend on the regulation strategies. As a general indication, the strategy C can be seen as the most effective one.

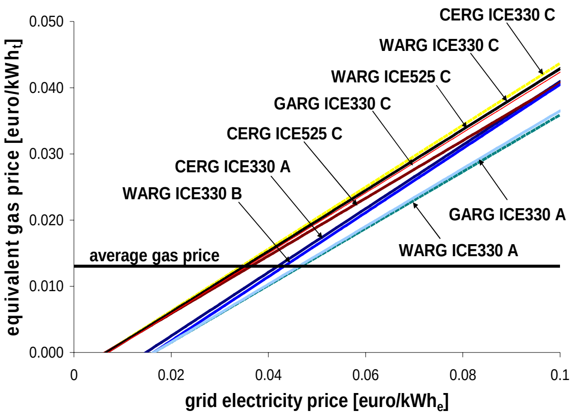

Fig. 3. Equivalent gas price map.

5 Concluding remarks

Trigeneration system planning represents a challenging problem. A useful planning tool, based on the definition and evaluation of the *equivalent gas price*, has been introduced for assessing the feasibility of a CHCP plant and comparing different trigeneration solutions according to given values of the average electricity and gas prices. An example referred to a hospital site has been presented. The results of the comparisons among the different solutions arising from this numerical application cannot be generalised, since they depend on many specific parameters and evolutions of generation and load. However, the concepts used to develop the approach presented can be applied to any kind of trigeneration planning. Moreover, the approach used could be extended to the other trigenerated vectors, with possible inclusion of further scenarios with the presence of district heating or cooling networks.

Future developments are in progress to perform a comparative assessment of the trigeneration solutions within a time-domain simulation-based operational planning framework, in order to study the effects of possible hourly interactions between the regulation strategies and the hourly prices in the energy markets.

References:

[1] H.L.Willis and W.G.Scott, *Distributed power generation: planning and evaluation*, Dekker, New York, 2000.

[2] J.H.Horlock, *Cogeneration-Combined Heat and Power (CHP)*, Krieger, Malabar, FL, 1997.

[3] Resource Dynamics Corporation, *Cooling, Heating, and Power for Industry: A Market Assessment*, Final Report prepared for U.S. Department of Energy and Oak Ridge National Laboratory, Vienna, VA, August 2003, Available: www.cogeneration.net.

[4] E.Cardona and A.Piacentino, A method for sizing a trigeneration plant in Mediterranean areas, *Appl. Therm. Eng.* **23** (2003) 1665-1680.

[5] J.Bassols, B.Kuckelkorn, J.Langreck, R.Schneider and H.Veelken, Trigeneration in food industry, *Appl. Therm. Eng.* **22** (2002) 595-602.

[6] G.Chicco and P.Mancarella, From cogeneration to trigeneration: profitable alternatives in a competitive market, *IEEE Trans. on Energy Conversion*, in press.

[7] G.Chicco and P.Mancarella, Characterization, modeling and operational options for the adoption of a trigeneration plant, *ISEE 2005*, Targoviste, Romania (Oct.17-19, 2005) paper B_5.

[8] G.Chicco and P.Mancarella, Planning Aspects and Performance Indicators for Small-scale Trigeneration Plants, *FPS 2005*, Amsterdam, The Netherlands, November 16-18, 2005.

[9] J.F.Kreider (ed.), *Handbook of Heating, Ventilation and Air Conditioning*, CRC Press, Boca Raton, FL, 2001.

[10] K.R.Voorspools and W.D.D'haeseleer, The impact of the implementation of cogeneration in a given energetic context, *IEEE Trans. on Energy Conversion* **18**, 1 (March 2003) 135-141.

[11] S.Barsali, M.Ceraolo, R.Giglioli and P.Pelacchi, Microturbines for dispersed generation, *CIRED 1999*, Nice, France (June 1-4, 1999).

[12] M.Denton, A.Palmer, R.Masiello and P.Skantze, Managing Market Risk in Energy, *IEEE Trans. on Power Systems* **18**, 2 (May 2003) 494-502.

[13] V.Havelsky, Energetic efficiency of cogeneration systems for combined heat, cold and power production, *International Journal of Refrigeration* **22** (1999) 479-485.

[14] P.M.T.Heteu and L.Bolle, Economie d'énergie en trigenération, *Internat. Journal of Thermal Sciences* **41** (2002) 1151-1159.