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Operational strategy and marginal costs in simple trigeneration systems

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ABSTRACT

As a direct result of economic pressures to cut expenses, as well as the legal obligation to reduce emissions, companies and businesses are seeking ways to use energy more efficiently. Trigeneration systems (CHCP: Combined Heating, Cooling and Power generation) allow greater operational flexibility at sites with a variable demand for energy in the form of heating and cooling. This is particularly relevant in buildings where the need for heating is restricted to a few winter months. In summer, the absorption chillers make use of the cogenerated heat to produce chilled water, avoiding waste heat discharge. The operation of a simple trigeneration system is analyzed in this paper. The system is interconnected to the electric utility grid, both to receive electricity and to deliver surplus electricity. For any given demand required by the users, a great number of operating conditions are possible. A linear programming model provides the operational mode with the lowest variable cost. A thermoeconomic analysis, based on marginal production costs, is used to obtain unit costs for internal energy flows and final products as well as to explain the best operational strategy as a function of the demand for energy services and the prices of the resources consumed.

1. Introduction

As life quality standards increase, the demand for comfort rises, together with a higher degree of conscience towards environmental issues. The satisfaction of such comfort demands generally leads to a greater consumption of energy services (for example, an increment in the use of air conditioning) while environmental conscience tries to compensate the greater consumption of fossil fuels and its consequences, by means of a more rational use of energy.

Polygeneration systems, which include appropriate energy process integration for the combined production of two or more energy services and/or manufactured products, significantly increase the efficient use of natural resources [1,2]. In the last decades cogeneration (Combined Heat and Power – CHP) has contributed considerably to the competitiveness, environmental protection and security of supply in the industrial sector [3,4]. Today, energy consumption of buildings in developed countries comprises 20–40% of total energy use and is above industry and transport figures in the European Union (EU) and USA [5]. The main lesson learned from some European research projects [6–8] is that there is a significant technical potential for the implementation of trigeneration in the residential and tertiary sector of countries in the Mediterranean area. In these countries the need for heating is restricted to few winter months, limiting the application of cogeneration systems. There is, however, a significant need for cooling during the summer period. In addition, the rapid increase of the air conditioning equipment penetration has added considerable loads to electricity networks, especially during peak demand periods [5,9]. It is essential to provide solutions and one of them is the use of absorption chillers for cooling. Lately, absorption chillers have provided an efficient way of recovering "waste" heat to cooling energy [10,11]. By combining CHP with heat-driven absorption chillers, the energy demand covered by cogeneration can be extended into the summer months to match cooling loads [12,13].

Fig. 1 shows a generic trigeneration system. Trigeneration systems may be constituted of a variety of technologies [14,15]. The efficiency of the consumed fuel (natural gas, for example) is one of the main benefits of the production of three types of energy services (heating, cooling and electricity) from the same energy source. This is important, since the better use of fuel assumes economic savings as well as a relief to the environment (less fuel consumed, less pollution generated). In summary, trigeneration presents as advantages: primary energy savings, reduction of pollutant emissions, and a lower cost of energy services [16]. To

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Nomenclature

AC	Absorption refrigerator,
AB	Auxiliary boiler,
CM	Cogeneration module,
EC	Electric driven chiller,
α_w	Cogeneration module work efficiency,
α_q	Cogeneration module heat efficiency,
η_q	Auxiliary boiler efficiency,
COP_q	Coefficient of performance of the absorption chiller,
COP_e	Coefficient of performance of the vapor compression chiller,
E_d	Electricity demand, kW,
E_p	Purchased electricity, kW,
E_r	Work to electric driven chiller, kW,
E_s	Sold electricity, kW,
F_a	Auxiliary boiler fuel, kW,
F_c	Cogeneration module fuel, kW,
Q_a	Heat from auxiliary boiler, kW,
Q_c	Cogenerated heat, kW,
Q_{cc}	Consumed cogenerated heat, kW,
Q_d	Heating demand, kW,
Q_l	Wasted cogenerated heat, kW,
Q_r	Heat to absorption refrigerator, kW,
R_d	Cooling demand, kW,
R_e	Cooling from compression refrigerator, kW,
R_q	Cooling from absorption refrigerator, kW,
W_c	Cogenerated electricity, kW,
W_{cc}	Consumed cogenerated electricity, kW,
p_{ep}	Price of purchased electricity, €/kWh,
p_{es}	Price of sold electricity, €/kWh,
p_{fa}	Price of auxiliary boiler fuel, €/kWh,
p_{fc}	Price of cogeneration module fuel, €/kWh,
r_{ql}	Unit cost of waste heat, €/kWh,
λ	Marginal cost, €/kWh,
HC	Operational variable cost, €/h,
fa	Amortization factor, yr^{-1}.

obtain these benefits by the optimal design of trigeneration plants for buildings, two fundamental issues should be addressed [17,18], i.e. the synthesis of the plant configuration (number and capacity of equipment for each type of technology employed) and the operational planning (strategy concerning operational state of the equipment, energy flow rates, purchase/selling of electricity, etc.). For new plants these issues are not separable, but for existing plants operational strategy is the only concern.

Synthesis of energy systems involves the search for a solution fulfilling an objective function (e.g. cost, environmental burden, thermodynamic efficiency), which is to be minimized or maximized. The variability of energy demands, as in buildings, requires a design methodology that builds flexible utility systems which operate efficiently (thermodynamic target), are capable to adjust to different conditions (combinatorial challenge), and are able to operate at a minimum economic cost [19]. The reviews of Chicco and Mancarella [20] and Hinojosa et al. [21] summarize the characteristics of the optimization methods for polygeneration systems presented in recent journal publications. Mixed-integer programming methods [22–25] fulfill the requirements and capture the complexities of an investment planning procedure for polygeneration energy systems by considering the superstructure of all alternatives.

To design an energy system, the following aspects must be considered simultaneously: (i) the technologies and equipment to install; (ii) the demands to be satisfied and the energy prices, and (iii) the optimal operation taking into account the possibility of operating the equipment at zero/partial/full load. This work describes a linear programming model capable of solving the optimal operation problem of simple trigeneration systems, based on the minimum variable cost HC, and also develops a thermoeconomic analysis of the operation.

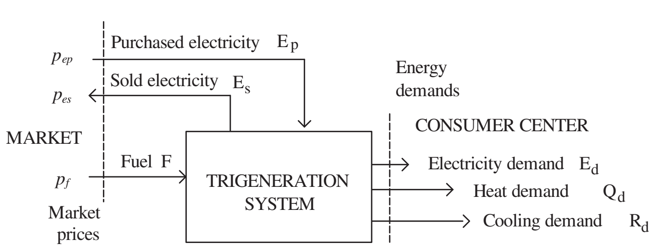

Fig. 1. Trigeneration system.

According to Gaggioli [26] the objective of thermoeconomics is to explain the cost formation process of internal flows and products of energy systems. The costs obtained with thermoeconomics can be used to diagnose the operation and to control the production of existing plants, and in addition, improve the processes and synthesis of new systems [27]. In Lozano et al. [28] three different approaches were used to determine the cost of internal flows and products: (i) analysis of marginal costs, (ii) valuation of products applying market prices, and (iii) internal costs calculation. Marginal costs, in particular, have important information for operational optimization of energy and process systems [29–31].

Both the optimization model and the analysis methodology applied in this paper can be extended to consider the total annual cost, including the amortization costs for the required investment of the new plant to be designed (depending on the power of each technology installed and on the annual amortization factor fa) as well as the turnover variable costs (depending on the demand to be satisfied in each operation period throughout the year and on the market prices of fuel and electricity for such period). The objective function will be

$$\mathrm{fa}\sum_{i}^{\mathrm{NTI}}\mathrm{Investment}_i(\mathrm{Power}_i) + \sum_{j}^{\mathrm{NOP}}\mathrm{HC}_j\left(\mathrm{Demand}_j,\ \mathrm{Market\ prices}_j\right) \quad (1)$$

where NTI is the number of technologies installed and NOP is the number of hourly periods of operation during the year. This paper only studies the second part of the objective function (the first part having been considered constant), minimizing the costs associated with the operation of a previously dimensioned system in order to analyze the operational strategy of simple trigeneration systems interconnected to the electric utility grid (both to receive electricity and to deliver surplus electricity). The minimization of costs should also be considered as an obligatory prior step/consideration of project and design methodologies for new trigeneration systems.

The profitability of operation depends on quantities demanded for energy services, and on fuel and electricity prices. A linear programming model was formulated, whose solution included the operational minimum variable cost, the magnitude of the energy flows involved in the productive process, and dual prices of the restrictions. The thermoeconomic analysis of the optimal solution