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Allocation of economic costs in trigeneration systems at variable load conditions

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ABSTRACT

This paper presents a thermoeconomic analysis of a trigeneration system interacting with the economic environment. The aim is to determine the energy and total costs of internal flows and final energy services (electricity, cooling and heat). One of the main difficulties in calculating these costs in trigeneration plants within buildings is the continuous variation of energy supply services. Fuel prices and purchase/sale electricity tariffs can also vary. As a consequence there are different operation conditions that combine the possibilities of purchasing or selling electricity, consuming heat from auxiliary boilers, and wasting the excess of cogenerated heat. A novel cost allocation method valid for all possible operation conditions of the trigeneration system is proposed. The heat produced by cogeneration modules is disaggregated into three fractions: heat that meets the heat demand directly, heat utilized to drive absorption chillers (producing cooling), and heat dissipated to the environment. Cost allocation to all cogeneration co-products is determined by applying the principle of avoided expenditures. The cost allocation proposal is applied to a trigeneration system providing energy services to a hospital with 500 beds located in Zaragoza (Spain), encouraging rational and efficient energy services production and consumption.

1. Introduction

1.1. Energy supply systems for buildings

As the desire for high quality of life intensifies worldwide, the demand for comfort increases in parallel with a higher degree of environmental conscience. In general, meeting such comfort demands leads to greater consumption of energy services (for example, an increment in the use of air conditioning in buildings), which is offset by environmental concern regarding consumption of fossil fuels and more rational use of energy. Presently, energy consumption of buildings in developed countries comprises 20–40% of total energy use and is greater than industry and transport figures in the European Union (EU) and USA [1]. European research projects [2–4] agree on the significant technical potential of implementing trigeneration in the residential and tertiary sector of countries in the Mediterranean area. In these countries, the need for heating is restricted to a few winter months, limiting the application of cogeneration systems. However, there is a significant need for cooling during the summer period. By combining cogeneration and heat-driven absorption chillers, the energy demand covered by cogeneration could be extended into the summer months to match cooling loads [5,6].

Polygeneration is defined as the concurrent production of two or more energy services and/or manufactured products that, benefiting from the energy integration of the processes in its equipment, extracts the maximum thermodynamic potential of the resources consumed [7]. Polygeneration is a fully developed technology that has a long history in the industrial sector, particularly in chemical, food, petroleum refining, and pulp and paper industries. The primary motivation underlying the proposal of polygeneration systems in the commercial–residential sector is to increase the efficient use of natural resources by combining different technologies. This sector includes residential buildings, office buildings, hotels, restaurants, shopping centers, schools, universities and hospitals, among others. Energy demands in buildings depend on climatic conditions, architectonic features, and occupancy. The intricacies involved in developing energy systems for residential–commercial buildings are therefore obvious. In the case of residential buildings, the design of polygeneration systems can pose a significant technical challenge because of the potential non-coincidence of thermal and electrical loads and presence of multiple decision makers. Such unique challenge reinforces that ultimate penetration of polygeneration will depend on the type of building considered. Hospitals are good candidates for polygeneration systems because of their high energy requirements compared to other commercial buildings as well as their need for high power quality and reliability.

The enhanced fuel consumption efficiency is one of the main benefits of the production of three energy services (heat, cooling and electricity) from the same energy source in an optimized trigeneration system. This better use of fuel resources is impor-

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tant, as it is associated with economic savings and sparing of the environment with less fuel consumed and less pollution generated. In order to maximize these benefits, the optimal design of trigeneration plants for buildings needs to address two fundamental issues [8–12], including the synthesis of the plant configuration (e.g., number and capacity of equipment for each type of technology employed) and operational planning (e.g., strategy for operational state of the equipment, energy flow rates, purchase/selling of electricity, etc.). The variability of energy demands in buildings requires a design methodology that builds flexible utility systems which operate efficiently (thermodynamic target), capable of adjusting to different conditions (combinatorial challenge), and able to operate at a minimum economic cost. The reviews of Chicco and Mancarella [13] and Hinojosa et al. [14] summarize the characteristics of the optimization methods for polygeneration systems presented in recent journal publications, including the considered time scale, the objective function, and the solution method.

1.2. Allocation of economic costs to co-products

Widespread acceptance of polygeneration systems also depends on the rational allocation of costs to the products obtained. If consumers assess that cost allocation was fair, their buy-in is more likely to occur. Furthermore, an appropriate allocation of economic costs to the final products will provide the consumers with correct indications on the rational, efficient and environmentally friendly consumption of energy services.

This article presents a thermoeconomic analysis of trigeneration systems. According to Gaggioli [15], 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 control the production of existing plants, in addition to improving the processes and synthesis of new systems [16]. Several studies have been carried out on the thermodynamic aspects of cogeneration systems as well as on the allocation of costs based on different principles [17–22].

The growing significance of cost accounting in modern corporate economy has highlighted several problems that arise when joint costs are assigned, concerning managers, engineers, accountants, and economists [23]. Typically, there are common costs to the different products in polygeneration plants, and there is no way, based on pertinent facts, to determine the share of costs attributable to one or other product. Therefore the allocation of costs in polygeneration systems, as well as in any other multi-product system, is always arbitrary [22,24], requiring further rational analysis. In strict economic terms, there is a considerable leeway to distribute common costs between the products. However, the allocation of cost must allow all co-products to be profitable and remain competitive for consumers when market and/or demand conditions vary, sharing the benefits without cross-subsidization.

In contrast with the design of energy systems in industrial applications (characterized by steady energy demand profiles), in building applications the great number of components operating at unsteady conditions hinders the application of classical thermoeconomic cost accounting methodologies [25]. In Lozano et al. [26], three different approaches (with different applications) were used to determine the cost of internal flows and products in simple trigeneration systems, including (i) analysis of marginal costs, (ii) valuation of products applying market prices, and (iii) internal costs calculation. Thermoeconomic analysis based on marginal production costs can be used to explain the best operational strategy as a function of market environment, operational capacity limits of the productive units, and demand of different energy services [27].

This paper proposes a cost assessment method for complex trigeneration systems, implementing the consideration for cogenerated cooling; furthermore, capital and maintenance costs are also considered. It is proved that the same cost assessment rules applied for energy costs are valid for thermoeconomic cost assessment (including energy, maintenance, and capital costs). The proposal will obtain product costs that are reasonable and in accordance with the design objective of the system of providing product costs inferior to those of separate production. The allocation proposal assumes that the consumers will receive credits (in the form of a discount) for what was saved as a result of an efficient production. This proposal not only will shed light on the cost formation process but will also help inform the consumers of trigeneration systems on the costs associated with the consumption of each energy service.

The application of the new allocation method was demonstrated in a case study regarding a trigeneration system providing energy services (electricity, domestic hot water, heating, and cooling) to medium size hospital with 500 beds, located in Zaragoza (Spain).

2. Description of the trigeneration system

A previous paper [11] provided detailed information on demand for energy services for the hospital, explained the superstructure of the energy supply system considered for the synthesis of the trigeneration system (available technologies as well as technical and economic characteristics of equipment and operation modes), and presented energy purchase/sale tariffs and current legal requirements for operating a cogeneration system in Spain. A mixed integer linear programming (MILP) model was developed in that paper for the multiperiod synthesis and operational planning problem, including: (1) the determination of the type, number and capacity of the equipment installed in the energy supply system and (2) the establishment of the optimal operation for the different plant components on an hourly basis throughout a representative year. Regarding the economic objective function, it was observed that the installation of energy-efficient technologies (cogeneration modules and absorption chillers) was beneficial to achieve the minimum annual cost.

2.1. Energy demand

The energy demands considered for the hospital were heat, cooling, and electricity. The heat load included heat for sanitary hot water (SHW) and for space heating. In order to model the energy demands, a study period of one year was considered, distributed in 24 representative days (one working day and one holiday/weekend day for each month), each day being divided into 24 hourly periods. The annual electricity consumption of the hospital was 3250 MWh, the cooling demand was 1265 MWh, and the heat requirements (SHW + heating) were 8059 MWh. Energy demand fluctuations with respect to the time of day are shown in Figs. 1 and 2, respectively, for the days of maximum demands of heat (January, working day) and cooling (July, working day).

2.2. System configuration

The superstructure of the energy supply system for the hospital considered the possibility of installing energy production technologies such as gas turbine, steam boiler, gas engine, hot water boiler, heat exchangers (steam-hot water and hot water-cooling water), double and single effect absorption chillers, mechanical chiller, and cooling tower. All technology and equipment considered in the optimization were commercially available; therefore the size/configuration of the system was determined in terms of pieces of equipment. As the optimal solutions obtained in Lozano et al. [11] did not present the installation of all afore mentioned