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Economic and environmental analysis of a trigeneration system for food-industry: A case study

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HIGHLIGHTS

- ▶ We measure and analyze energy request of a food-industry.
- ▶ Different sizes of possible to install tri-generation plant are considered.
- ▶ Economical and environmental benefits are evaluated by optimization procedure.
- ▶ Thermal energy storage is taken into account to improve the benefits.
- ▶ Contrast between economic and environmental benefits is remarked in the case study.

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ABSTRACT

The application of a trigeneration system to fruit conservation food-industry is studied. The economic and environmental benefits of the installation are analyzed by means of multi-objective optimization which takes into account operational costs of the system and greenhouse gas emissions. A contrast between the minimization of these two objectives is shown and thus different operative strategies are devised. Taken a practical case of the trigeneration load required by an industrial site in north-west of Italy where measurements of load profiles are available, different combined heat and power engines with and without a thermal energy storage system are studied and results are discussed. General considerations about the advantages of the proposed solutions are also presented.

1. Introduction

Over recent years, the growth of energy demand and concerns about climate changes have increased attention on high-efficiency polygeneration system. These systems are able to reduce fossil fuel consumption and greenhouse gases emissions. In fact, polygeneration produces different energy vectors (heat, cold and electricity) in a combined way, by using only one primary energy sources. Likewise, polygeneration systems can reduce the cost of the energy required from local users but economic gain are strictly related to the trend of load profiles [1,2] and to the incentive systems. Cogeneration and trigeneration systems are promising technologies for a decrease in energy request and in energy costs with respect to conventional separated productions. Trigeneration plants are widely used in different fields of applications like buildings, commercial and also food-industries, because of their high efficiency energy conversion [3–6]. However, the reduction of primary energy consumption as well as reduction of operational costs must be analyzed in detail. In cogenerative systems, where only electrical and heating power are involved, the use of a combined production nearly always reduces operational costs and saves primary energy. In trigeneration systems, where also cooling power is involved by using absorption chiller, the production performances of cooling power can be, in some cases, inferior. This fact is due to the high coefficient of performance (COP) values of compression chillers that outperform those of absorption chillers. This situation can be improved with the use of thermal storage systems [7]. The role of energy storage can, in this case, be crucial because it can shift energy production in time with respect to the local energy usage. For instance heating and cooling power can be produced when the costs of energy is low and supplied to thermal loads when the costs of energy is high.

Much research has focused on the economic gain of polygeneration systems. In some cases, the optimal lay-outs and operations are defined by using MILP and considering the partial load performances of polygeneration systems [8,9]. Other studies reveal that cogeneration and trigeneration plants are profitably managed by using the minimization of operational costs [10–12] also under

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Nomenclature

$B_c(t_i)$	input power of boiler (kW)
$B_t(t_i)$	thermal power produced by boiler (kW)
$P_c(t_i)$	input power of CHP (kW)
$P_t(t_i)$	thermal power produced by CHP (kW)
$P_e(t_i)$	electric power produced by boiler (kW)
$P_s(t_i)$	electric power sold to the grid (kW)
$P_p(t_i)$	electric power purchased from the grid (kW)
$E(t_i)$	cooling power produced by electric chillers (kW)
$A(t_i)$	cooling power produced by absorption chiller (kW)
$D(t_i)$	thermal power wasted in the environment produced by CHP (kW)
$S_t(t_i)$	thermal energy stored (kW h)
$U_e(t_i)$	electrical power demand (kW)
$U_t(t_i)$	thermal power demand (kW)
$U_c(t_i)$	cooling power demand (kW)
COP_E	coefficient of performance of electric chillers
COP_A	coefficient of performance of absorption chiller
Δt	time step for the optimization algorithm (h)
$\delta(t_i)$	binary variable that represent the for on/off status of CHP
$\delta_h(t_i)$	binary variable for partial load operation of CHP
$\delta_s(t_i)$	binary variable that shows if electricity is sold to the grid
$\delta_p(t_i)$	binary variable that shows if electricity is purchased from the grid
$y(t_i)$	binary variable that shows if CHP is on
$z(t_i)$	binary variable that shows if CHP is off
N_{on}	maximum number of CHP ignition
e	overall greenhouse gas emissions of the plant (kg)
e_{CHP}	greenhouse gas emissions of CHP (kg)
e_{conv}	greenhouse gas emissions without trigeneratiom (kg)
ϵ_{grid}	emission factor of grid (kg/kW h_e)
ϵ_{boiler}	emission factor of boiler (kg/kW h_t)
c	overall operational costs of the plant (kg)
c_{conv}	management costs without trigeneration (€)
c_d	average natural gas price with tax reduction (€/m^3)
c_{nd}	average natural gas price without tax reduction (€/m^3)
c_p	price of electricity purchased from the grid with tax reduction (€/kW h)
c_s	price of electricity sold to the grid with tax reduction (€/kW h)
H_i	lower heating value of natural gas (kW h/m^3)
η_{e_s}	electric efficiency of separated production
η_{e_s}	thermal efficiency of separated production
COP_s	coefficient of performance of separated production
η_b	thermal efficiency of the boiler
MILP	mixed integer linear programming
CHP	combined heat and power
PES	primary energy saving
TPES	trigeneration primary energy saving
TL	thermal limit
ΔCO_2	variation of CO_2 emissions
DPBP	discounted pay back period
TES	thermal energy storage
MOT	minimum on time
MST	minimum shutdown time

regulatory constraints [13,14]. In other contexts, optimal management is adopted, based on economic value of energy produced by the components of trigeneration plants [15,16].

However, it is equally important to consider the environmental impact of such systems. In fact, many studies have focused on the minimization of greenhouse gasses emissions of polygeneration systems. In some cases, optimal operations are achieved by the comparison of trigeneration plant emissions to conventional plant (separated production) emissions [17,18]. In other cases, the minimization of greenhouse gasses is based on LP [19] or MILP approach [13,20].

Possible contrast between the maximization of economic revenues and the minimization of emissions (no thermal power wasted in the atmosphere and modulation of equipment production) can be solved by optimal equipment management fulfilling the load requirements and seeking cost and greenhouse gases reduction [21–23].

This paper presents a case study in which the economic gains and environmental aspects are analyzed at the same time by means of a dynamic simulation tool. An energy management system is proposed based on mixed integer linear programming (MILP). It is evaluates the optimal configuration and operation of a trigeneration plant for food-industry facilities with relevant cooling demand, located in tshe north-west of Italy. Two different management strategies will be developed: the minimization of operational costs and the minimization of the CO_2 emissions. A thermal storage system is further proposed. The optimal size and operation of the trigeneration plant will be defined by taking into account partial operation points for different CHP sizes and evaluating economic, environmental and energy indicators. Binary variables will be introduced into the MILP formulation to evaluate the on/off status of the CHP, its partial load operation and to consider the operational duty cycle of CHP.

The paper is structured as follows: in Section 2 a description of the present and proposed new configuration for the food-industry plant, its energy costs and demands are presented; in Section 3 the economic, environmental and energy indicators, in order to compare the different management strategies are outlined; in Section 4 the possible management strategies for the plant using an optimization algorithm and a multi-objective approach are defined; in Section 5 the performance indicators obtained by the optimal configuration are highlighted and finally, in Section 6 results are discussed.

2. Problem description

The case study is a food-industry installation located in the north-west of Italy where fruit, which are cultivated in the area, are harvested and subsequently stored in 27 cells cooled by 9 conventional electric chillers. The cooling load profiles have been obtained by measurements of electricity consumption over one

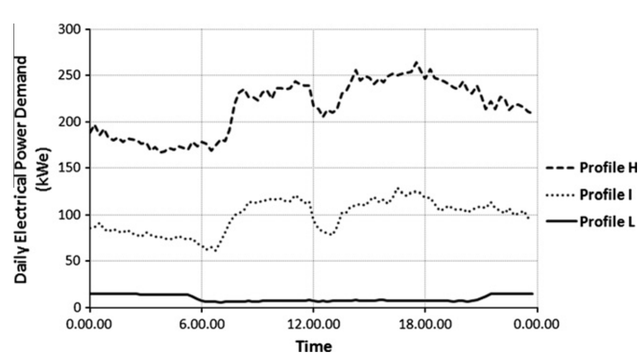

Fig. 1. Typical electrical load profiles used in the case study.