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An energy and exergy analysis of a high-efficiency engine trigeneration system for a hospital: A case study methodology based on annual energy demand profiles

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A B S T R A C T

The efficient use of natural resources is an important contribution to the creation of a more sustainable world. Decentralized electricity production through trigeneration systems can save primary energy if these systems operate with a high energy utilization factor (EUF). A high EUF is obtained when the system produces electricity and a substantial amount of the energy rejected by the prime mover is used to meet on-site thermal demands. Energy consumption in buildings varies as the activity, climate and occupancy change at different hours of the day, days of the week, weather conditions and seasons. In this study an annual analysis of an engine trigeneration system is developed as an integrated thermal system (ITS) through a computational simulation program. The ITS simulation uses the characteristics of the system, characteristics of the individual pieces of equipment, design assumptions and parameters, off-design operating conditions, energy demands profiles of the site and climatic data to evaluate the system performance. The obtained results revealed an EUF between 58 and 77% and an exergy efficiency between 35 and 41% for the system. The primary energy savings (PES) analysis showed that the proposed trigeneration system is better than the best available technology used in centralized thermal plants.

1. Introduction

Sustainably using natural resources is an important contribution to reducing the environmental impact of human activities. Climate change is expected to be extended by increasing concentrations of greenhouse gases produced by human activities, such as burning fossil fuels and deforestation. Water vapor, carbon dioxide (CO_2), methane and ozone are the main greenhouse gases. Electricity production is a major cause of the current high levels of CO_2 emissions, given that fossil fuels represented 67.4% of the global electricity produced in 2010 [1]. CO_2 annual emission rose more than 93% between 1973 and 2010, annual emissions were 15,637 Mt (million tons) in 1973 and 30,326 Mt in 2010 [1]. High-efficiency electricity production systems that use fossil fuels can reduce the rise in CO_2 emissions, assist in expanding electrical systems (due to increasing electricity demands in the world) and substitute for existing low-efficiency thermal plants. Thermal plant efficiencies are being raised by advances in engineering fields, such as materials, manufacturing process, fluid flow, heat transfer, combustion, instrumentation, electronics and others. A trigeneration system takes advantage of these engineering advances and incorporates them into the equipment, however, high-efficiency trigeneration systems need a good match between the site energy load and the trigeneration system energy.

A previous study [2] that simulated a gas engine trigeneration system, and summer energy demands, which utilized the primary energy savings (PES) analysis, concluded that the trigeneration system can compete with the best available technology in centralized thermal plants (thermal efficiency close to 60%) if a substantial amount of the prime mover rejected energy is recovered to meet site energy demands. PES analysis can be utilized to compare the performance of trigeneration system and centralized thermal plant using system components efficiencies, site to source energy conversion factors, and different energy demand scenarios [3,4].

Trigeneration systems, or combined heat, cooling and power systems, can be applied in industrial processes and buildings. Industrial processes and administrative buildings can be located at the same site and their associated energy demands can be met by a trigeneration system. Trigeneration is proposed to participate in an integrated multi-energy systems (MES) framework, whereby electricity, heat, cooling, fuels, transport, and so on optimally interact with each other [5].

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Nomenclature

$\dot{E}_{steam}$	energy rate of produced steam (kW)
$\dot{E}_{ht}$	energy rate of produced hot water (kW)
$\dot{E}_{cw}$	energy rate of produced chilled water (kW)
EUF	energy utilization factor
$\dot{E}x_{flow}$	exergy rate of trigeneration flow products (kW)
$\dot{E}x_{steam}$	exergy rate of produced steam flow (kW)
$\dot{E}x_{ht}$	exergy rate of produced hot water flow (kW)
$\dot{E}x_{cw}$	exergy rate of produced chilled water flow (kW)
h	specific enthalpy (kJ/kg)
LHV_{fuel}	fuel lower heating value (kJ/kg)
ech_{fuel}	fuel chemical exergy (kJ/kg)
$\dot{m}_{cog}$	mass flow rate of trigeneration products (kg/s)
$\dot{m}_{fuel}$	fuel mass flow rate (kg/s)
s	specific entropy (kJ/kg.K)
T_0	ambient reference temperature (K)
$\dot{W}_{net}$	net electrical power (kW)
ε	exergy efficiency of the trigeneration system

The prime mover (power production unit) is the main equipment of trigeneration systems. Different prime movers can be utilized, including (i) internal combustion engines [6–8], (ii) gas turbines [9] and micro gas turbines [10–12], (iii) fuel cells [13,14], (iv) steam turbines and (v) stirling engines [15]. A combination of different prime movers in the same system can also be utilized [16].

Energy and exergy analysis are used to compare the performance of different systems. Design parameters can be modified to raise the efficiency. The global and local environmental impact of natural gas trigeneration systems is a concern when evaluating decentralized electricity production. CO_2 emissions are associated with the system efficiency, while NO_x and CO depend on the prime mover type. Studies evaluating the exhaust gas emissions of cogeneration and trigeneration systems [17–20] can contribute to the decision. Biofuels can also be applied, Huang et al. [21] presented a study evaluating the performance of a building engine trigeneration system fueled by biogas. A biogas fueled micro gas turbine cogeneration system for a sewage treatment plant was investigated by Basrawi at al. [12].

Computer-based decision support tools are being developed for the evaluation of thermal plant performance [22,23], as this analysis requires several types of operational data, flows and thermodynamic properties. Computational simulations can contribute to predicting performance and finding high-efficiency solutions.

The objective of this study is to demonstrate a methodology, applied as a case study, to predict the performance of an engine trigeneration system. This methodology is proposed as a tool to develop high-efficiency solutions. The software COGMCI [24] is utilized to develop the simulation analysis. The flexibility of this software in computational simulation enables system performance prediction for different configurations, capacities (sizes) and operation modes, e.g., designs for matching base-loads or for exporting surplus. The computational program simulates the system as an integrated thermal system (ITS), and provides an analysis of the hourly profile of a given trigeneration system producing electricity and thermal flows (steam, hot water, chilled water). Simulation outside the design condition (i.e., partial engine load) has shown that engine load affects the energy delivered to the heat exchangers for hot water production, the energy delivered to the absorption chiller for chilled water production, and the energy delivered to the heat recovery steam generator (HRSG) for steam production. Annual site energy demand profiles are compared with the trigeneration system energy by means of equipment simulation methods. Three criteria are used to evaluate the system performance: (i) EUF, (ii) exergy efficiency and (iii) PES.

2. Case study: hospital

The energy demand of a Brazilian university hospital is assessed. The hospital, classified as a medium hospital [25], is located in the southeastern region of Brazil and has a constructed area of 65,000 m^2 (403 beds, an intensive care unit for 50 persons and 25 surgery rooms). The hospital buys electricity from the grid; the hospital also produces steam in a combustible oil-fueled steam generator, hot water in oil-fueled boilers and chilled water in a water-cooled screw compressor chiller.

Energy consumption in buildings varies as the activity, climate and occupancy changes at the different hours of the day, days of the week, weather conditions and seasons. Several authors have studied energy consumption in buildings. Ortiga et al. [26] presented a method for the selection of typical days for the characterization of energy demand in buildings. EnergyPlus [27] benchmark models were proposed to estimate energy consumption in buildings by Fumo et al. [28]. In accordance with Cardona and Piacentino [6] "a suitable examination period can be considered equal to one year, the minimum time after which consumption should theoretically, repeat themselves approximately equal".

In this study, the energy demand profiles were obtained through a data acquisition system installed to register the hospital energy demands (Fig. 1). The system monitored the total electricity demand, sanitary hot water demand, steam demand and electricity demand from the electrical chillers at a one-hour time interval. The daily weather profiles were obtained at a climatic monitoring station located at the university campus. The data were obtained in 2006.

The mean daily energy demand profiles were grouped for eight different groups with similar behavior: (i) summer weekdays (60 days), (ii) summer weekends/holidays (29 days), (iii) autumn weekdays (65 days), (iv) autumn weekends/holidays (28 days), (v) winter weekdays (67 days), (vi) winter weekends/holidays (27 days), (vii) spring weekdays (60 days) and (viii) spring weekends/holidays (29 days). The climatic data were grouped in mean daily profiles for each weather season.

Fig. 2a and b shows the mean electricity demand profiles. Fig. 3a and b show the mean sanitary hot water demand profile. Fig. 4a and b show the steam demand profile. Fig. 5 shows the electrical chillers demand profile (cooling load) in refrigeration tons (RT, 1 RT = 3.52 kW); the electricity demand of the chiller is included in the electricity demand profiles (Fig. 2a and b). Fig. 6 shows the mean dry bulb temperature and relative humidity season profiles.

In Table 1, the daily electricity, hot water, steam and chilled water consumptions of the hospital were calculated taking into account the mean demand profiles. Table 2 reveals the daily and

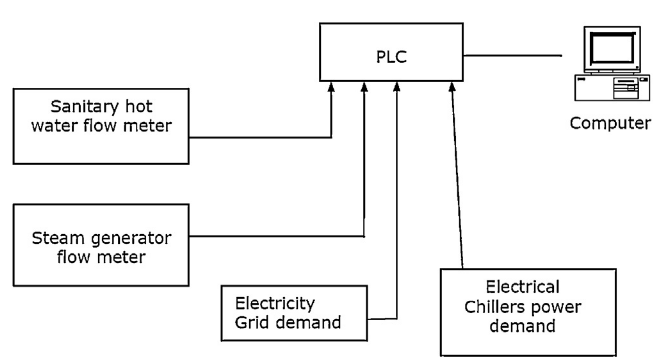

Fig. 1. Data acquisition system.