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Optimization criteria for cogeneration systems: Multi-objective approach and application in an hospital facility

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HIGHLIGHTS

- ▶ The analysis shows that a large PES (primary energy saving) percentage does not always lead to an economic advantage.
- ▶ For the test solutions, the global PES and the SPB (Simple Payback) even seem to be inversely proportional.
- ▶ The distribution of solutions in the objective function space shows a clear trade-off between PES and SPB.
- ▶ The introduction of tight constraints can result in a significant decrease in the available system configurations.
- ▶ The trade-off between PES and SPB confirms the need to do any predictive analysis using the Multi-objective optimization.

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ABSTRACT

Cogeneration is commonly recognized as one of the most effective solutions to achieve the increasingly stringent requirements in primary energy consumption reduction and greenhouse emissions reduction. The potential of cogeneration led to the adoption of specific directives promoting this technique. In addition, distributed generation plays a strategic role in power reliability. The study and prototyping of cogeneration plants has thus involved many research centers. Similar activities were carried out by DiME (University of Naples). These activities highlighted the need to study the cogeneration system-user interaction to estimate the real energetic and economic benefits.

The paper develops a specific methodology that is used to conduct an analysis on the loads of a specific hospital facility. The energetic and economic benefits generated by CHP plants depend on plant and user characteristics, plant layout, management strategies, and economic variables. Therefore, the potential benefits that have attracted the attention of the scientific community are not always granted. For this reason, a predictive analysis is needed to find the optimum configuration of the plant (i.e., engine size, plant configuration, management strategies, absorption chiller size, engine number) that approaches the best energetic solution while ensuring a reasonable profit. Therefore, this study attempts to determine the optimal configuration through a multi-objective approach.

1. Introduction

Energy supply is certainly one of the most critical elements in developed countries. Increasing welfare levels and the indiscriminate exploitation of global resources create a precarious balance between energy supply and demand. This fragility, which is often overlooked, is highlighted by geopolitical crises such as those that affected the countries of North Africa and the Persian Gulf in early 2011. The growing problems related to the pursuit of this balance are accompanied by the environmental impacts inherent in the use of traditional energy sources. Global human activity has required a Total Primary Energy Supply (TPES) of about 130,000 TW h in 2009, corresponding to an average hourly power of 15 TW [1].

Examining the individual sources of energy shows that oil contributes one-third to the TPES, coal contributes about one-fourth and natural gas contributes about one-fifth; the remaining 19% is achieved through a mix of different sources, both renewable and non-renewable, in which a significant role is played by nuclear and hydro power, whereas geothermal, solar and wind power make a more marginal contribution (Fig. 1).

Both the supply and demand of primary energy sources face critical problems. With regard to the extraction sector, for example, American oil fields reached peak production in the 1970s, and the maximum exploitation of the remaining world reserves has

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Nomenclature

Acronyms

AC	absorption chiller
ACU	Air Conditioning Unit
ASL	local healthcare company (according to Italian law: *Azienda Sanitaria Locale*)
CHP	combined heat and power
CHCP	Combined Heat Cooling and Power
CFU	coefficients of fuel utilization
DiME	Department of Mechanics and Energetics of the University of Naples Federico II
DHW	domestic hot water
IRE	Energy Saving Index (according to Italian law: *Indice di Risparmio Energetico*)
LT	Thermal Limit (according to Italian law: limite termico)
LPG	Liquefied Petroleum Gas
MOGA	Multi-Objective Genetic Algorithm
MPESM	Maximum Primary Energy Savings Management
MPM	Maximum Profitability Management
Mtoe	Million tons of oil equivalent
NPV	Net Present Value
PEC	primary energy consumption
PES	primary energy saving
PI	Profitability Index
PS	Proposed System (CHP/CHCP)
RS	Reference System (pre-existing)
SPB	Simple Payback
TPES	Total Primary Energy Supply

Latin

c_1	fluid specific heat of the engine side circuit (kJ/kg K)
P_t	average hourly thermal load in the hour "t" (kW)
h	hour of the year (h)
T_1	user-side fluid outlet temperature from the heat exchanger (°C)
C_1	fluid specific heat of the user side circuit (kJ/kg K)
t_{in1}	hot fluid temperature at heat exchanger inlet (°C)
t_{ex1}	hot fluid temperature at heat exchanger outlet (°C)
T_{in1}	maximum temperature of fluid delivery to user (°C)
T_{ex1}	fluid return temperature from the user (°C)
P_{tmax}	average hourly maximum thermal load (kW)
P_{enom}	CHP plant nominal electric power (kW)
P_{tnom}	CHP plant nominal thermal power (kW)
ΔEp	primary energy saving (kW h)
ΔCO_2	carbon dioxide emissions reduction (kg)
M	CHP plant maintenance costs for an electric energy production of 1 kW h (€/kW h)
ΔEp	percentage primary energy saving
CE_{uecog}	unit cost of cogenerated electricity (€/kW h)
C_{umcog}	unit cost of the natural gas for the cogeneration system (€/N m^3)
C_{ueFi}	unit cost of electricity in time band F_i (€/kW h)
C_{um}	unit cost of the natural gas for the boiler (€/N m^3)
p	factor representative of transmission and transformation losses on the electric grid
I_{um}	natural gas taxation (€/N m^3)
H_i	fuel lower heating value (kW h/N m^3)
m_c	fuel mass flow rate (N m^3/h)
P_{ueFi}	electricity selling price in time band F_i (€/kW h)
P_{tcog}	cogenerated thermal power (kW)
T	natural gas tariff (€/N m^3)
COP_f	electric chillers average coefficient of performance
$CE_{uerif,Fi}$	reference cost of electricity in the time band F_i (€/kw h)

Greek

η_e	nominal electrical efficiency of the CHP gas engine
η_{eref}	reference electrical efficiency
η_{tref}	reference thermal efficiency
η_{eREF}	average efficiency of thermoelectric power plants
ΔCE_{ue}	profitability of cogenerated electricity (€/kW h)
η_b	average boiler efficiency
η_t	actual thermal efficiency of the cogeneration plant ($P_{tcog}/m_c \cdot H_i$)
η_{tnom}	nominal thermal efficiency of the cogeneration plant
η_{tm}	average annual thermal efficiency of the cogeneration plant

recently been achieved [3]. At the current rates of extraction, humans may run out of oil sources in a few decades; the remaining old resources are estimated at 2.7×10^5 million m^3, and they began to form about three hundred million years ago [4]. One consequence of achieving "Hubbert's Peak" is an inevitable increase in the cost of extraction due to the exploitation of deeper deposits and the more sophisticated methods required for finding new sites. These economical and technological efforts will make this activity uneconomical in the coming decades. A century ago, for example, the energy equivalent of a barrel of oil was required to extract a hundred barrels, whereas now, the same amount of energy will allow the extraction of 20 barrels in Saudi Arabia or 5 barrels in Canada's oil sands.

The continuous increase in energy demand resulting from population growth and the extreme inequity in accessing global resources exacerbates the situation. The per capita energy consumption in the U.S. is equivalent to an hourly average absorption of power of 11,000 W compared to, respectively, 5500 W, 1800 W and 800 W for the European, Asian and African population. It is thus evident that the development of an energetic system that is stable, environmentally sustainable and capable of ensuring a more equitable distribution of resources cannot be separated from a more efficient use of energy and an increasing use of renewable energy sources.

Some studies indicate that a reduction in energy consumption of 20% is achievable simply by correcting certain habits and using new technologies. The climatic and environmental consequences of the use of fossil fuels can also be overcome through an immediate transition to the use of renewable sources, which will represent a significant portion of the energy supply in 2035. However, studies conducted as part of the Global Climate Energy Project at Stanford University clearly showed the enormous exergetic potential available and currently unexploited. It is estimated, for

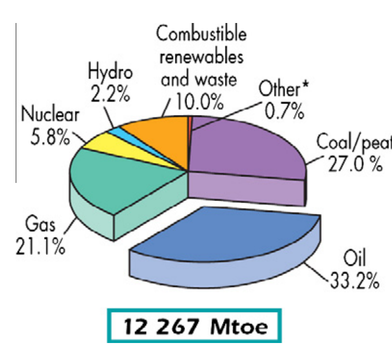

Fig. 1. Fuel shares of TPES in 2008 (142,665 TW h). *Other includes geothermal, solar, wind, heat, etc. [2].