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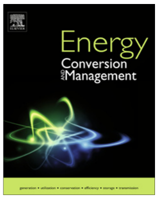

Optimal operating strategies of combined cooling, heating and power systems: A case study for an engine manufacturing facility

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ABSTRACT

In this paper, a detailed numerical analysis of a Combined Cooling, Heating and Power system is presented, aiming at determining its optimal operating strategy in a real industrial application. The system layout includes a reciprocating engine, fuelled by natural gas, heat exchangers for waste-heat recovery, pumps, storage tanks, a single-effect water lithium bromide absorption chiller, a cooling tower, a back-up vapour-compression electric chiller, mixers and valves. A dynamic simulation model of the whole system was developed in TRNSYS. A case study was analysed, referred to a real industrial application, where the system under evaluation should be installed in the near future, providing electricity, mainly used for the production process, and space cooling. Real measured data were used to estimate the electric energy demand of the factory. A detailed building simulation model was used to calculate heating and cooling demands. A detailed economic analysis was carried out, aiming at evaluating: (i) the optimal size of the Combined Cooling, Heating and Power system; (ii) the optimum control strategy, from a thermo-economic point of view, comparing three different cases: Base-Load operation, electric load tracking and a new hybrid strategy based on the simultaneous tracking of electric and thermal-loads. The results showed that the optimal capacity of the system was lower than that selected by the designers of the real unit to be installed. The hybrid control strategy obtained the best profitability, achieving a simple pay-back period equal to 3.8 years, compared to 4.1 years achieved in case of electric-load tracking.

1. Introduction: cogeneration and trigeneration systems

Cogeneration and trigeneration represent a well-known and mature technology able to ensure significant economic and energy savings, due to the simultaneous production of electric, cooling and thermal energy, using a single primary energy input [1]. In a trigeneration system (Combined Cooling, Heat and Power, CCHP), all these three energy outputs can be produced [2]. Conversely, cogeneration systems (Combined Heat and Power, CHP) only produce heat and electricity [3]. Finally, a polygeneration system is a special case of CCHP, where useful by-products (e.g. alcohols, hydrogen, glycerine, etc.) are also provided [2]. The basic principle of CHP and CCHP systems lies in the possibility of recovering the exhaust heat rejected by a Prime Mover (PM) in order to provide thermal energy for heating or cooling (by means of a thermally-driven chiller [4]). Obviously, such thermal and cooling energy does not require any additional amount of fuel with respect to the one used to produce electricity [5], leading to a potential reduction of fuel consumption and greenhouse gas emissions with respect to the conventional separate production, where electricity is provided by a public grid, heat by boilers and cooling energy by electric vapour-compression chillers [3]. Further potential advantages are reduction of fuel and operating costs, increased energy reliability, easier energy capacity expansion, higher flexibility in distribution [3]. CHP and CCHP systems showed good energy, environmental and economic performance for large number of applications, such as: chemical industries [6], other large-sized industries (steel and iron factories, pharmaceutical, textile, glass and plastic, etc. [7]), hospitals [8], paper mills [9] and food industries [10]. In addition, in some rare cases, cogeneration is also exploited for other specific applications, such as: sludge treatment [11], minutes reserve markets [12], heat source for natural gas expansion systems [13], residential applications [14], salt production [15].

As mentioned before, CCHP and CHP systems are based on the recovery of thermal energy normally rejected by a prime mover used to convert a fuel into electric energy [2]. The most common technologies are the following:

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Nomenclature

a	discount rate
ANN	artificial neural network
AF	annuity factor (years)
ACH	absorption chiller
c	unit cost (€/kW h or €/S m^3)
C	cost (€)
CCHP	combined cooling, heating and power
CHP	combined heat and power
COP	coefficient of performance
c_p	constant pressure specific heat (kJ/kg K)
CT	cooling tower
CTK	cold tank
D	diverter
DHW	domestic hot water
E	Energy (kW h/year)
EED	energy efficiency directive
ESC	energy savings certificates (€/toe)
ExJw	heat exchanger exhaust gases – jacket water
f	dimensionless design factor
F	thermal energy recovered fraction
FC	fan coils
G	gains (€/year)
GSHP	ground source heat pump
H	operating hours (h)
HEC	high efficiency cogeneration unit
HEW	heat exchanger winter
HTK	hot tank
HwDHW	heat exchanger heating water – domestic hot water
I	intercooler
ICE	internal combustion reciprocating engines
IGCC	integrated gasification combined cycle
IPC	individually prioritized control
IRR	internal rate of return
J	component capital cost (€)
JwHw	heat exchanger jacket water – heating water
LHV	natural gas low heating value (kW h/S m^3)
$\dot{m}$	mass flow rate (kg/h)
M	mixer
Ma	maintenance
MILP	mixed-integer linear programming
NPV	net present value (€)
OC	heat exchanger oil cooler
ORC	organic rankine cycles
P	mechanical power (kW)
P(1, 2, 3...)	Pump
PCM	phase change materials
PE	primary energy (kW h/year)
PES	primary energy saving (kW h/year)
PI	profit index
PLR	part-load ratio
PM	prime mover
PMD	prime mover dissipator
PV	photovoltaic
$\dot{Q}$	heat flow (kW)
S	economic saving (€/year)
SEN	smart energy networks
SNG	synthetic natural gas
SP	selling price
SPB	simple pay back (years)
T	temperature (°C)
TES	thermal energy storage
U	transmittance (kW/m^2 K)
UA	Thermal transmittance [kJ/hK]
V	volume (m^3/year)
η	efficiency
Δt_n	nominal temperature difference (°C)
ΔC	operating costs savings (€/year)

Subscripts

amb	ambient
aux	auxiliary
cool	cooling
ch	chilled
chw	chilled water
cw	cooling water
dem	demand
DL	design load
eff	effective
el	electrical
exh	exhaust
eq	equivalent
fl	*fluid*
glob	global
h	heating
H	from the heat source
hot	hot source
HP	heating pump
hw	hot water
in	inlet
Jw	jacket water
L	to the load
m	mechanical
min	minimum
N	nominal
OFF	office zone
op	operating
out	outlet
PROD	production zone
rated	at nominal conditions
ref	of reference
req	required
RS	reference system
set	set by the controller
NG	natural gas
taxfree	without taxes
th	thermal
thd	thermodynamic
tot	total

- Steam Turbines (Rankine cycle), typically used in the range from 50 kW up to 500 MW, can provide low-temperature heat by back-pressure condensation or medium/high temperature heat by steam extraction [3]. Both heat recovery techniques negatively affect the electrical efficiency of the system [16].
- Gas Turbines (Brayton cycle), typically used in the range from 1 MW up to 200 MW. In case of microturbines [17], the electrical capacity ranges from 30 kW to 350 kW. In case of gas turbines, high-temperature heat can be recovered by the exhaust gases [3]; so, these prime movers are also suitable for coupling with double-effect absorption chillers in trigeneration systems [18].
- Combined cycles, coupling a topping cycle (Brayton) and a bottoming one (Rankine), which are typically used in large power plants (>100 MW), featuring ultra-high electric efficiency [3]. However, in these plants the amount of thermal energy available for recovery is low, with respect to the power capacity, and heat recovery determines a reduction of the electrical efficiency [19].

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