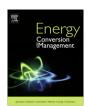
### **ARTICLE IN PRESS**

Energy Conversion and Management xxx (2017) xxx-xxx

Contents lists available at ScienceDirect



## **Energy Conversion and Management**



journal homepage: www.elsevier.com/locate/enconman

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

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#### ARTICLE INFO

Article history: Available online xxxx

Keywords: CCHP Dynamic simulation Optimum operation Absorption chiller

#### 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 backup 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 thermoeconomic 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.

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#### 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 thermallydriven chiller [4]). Obviously, such thermal and cooling energy does not require any additional amount of fuel with respect to

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http://dx.doi.org/10.1016/j.enconman.2017.06.028 0196-8904/© 2017 Elsevier Ltd. All rights reserved. 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:

Please cite this article in press as: Calise F et al. Optimal operating strategies of combined cooling, heating and power systems: A case study for an engine manufacturing facility. Energy Convers Manage (2017), http://dx.doi.org/10.1016/j.enconman.2017.06.028

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#### Nomenclature

а	discount rate	S	economic saving ( $\epsilon$ /year)
ANN	artificial neural network	SEN	smart energy networks
AF	annuity factor (years)	SNG	synthetic natural gas
ACH	absorption chiller	SP	selling price
С	unit cost ( $\epsilon/kW$ h or $\epsilon/S$ m <sup>3</sup> )	SPB	simple pay back (years)
С	cost (€)	Т	temperature (°C)
ССНР	combined cooling, heating and power	TES	thermal energy storage
CHP	combined heat and power	U	transmittance (kW/m <sup>2</sup> K)
СОР	coefficient of performance	UA	Thermal transmittance [kJ/hK]
$c_p$	constant pressure specific heat (kJ/kg K)	V	volume (m <sup>3</sup> /year)
СТ	cooling tower	η	efficiency
СТК	cold tank	$\Delta t_n$	nominal temperature difference (°C)
D	diverter	$\Delta C$	operating costs savings ( $\epsilon$ /year)
DHW	domestic hot water		
Ε	Energy (kW h/year)	Subscrip	ts
EED	energy efficiency directive	amb	ambient
ESC	energy savings certificates ( $\epsilon$ /toe)	аих	auxiliary
ExJw	heat exchanger exhaust gases – jacket water	cool	cooling
$f_{-}$	dimensionless design factor	ch	chilled
F	thermal energy recovered fraction	chw	chilled water
FC	fan coils	CW	cooling water
G	gains ( $\epsilon$ /year)	dem	demand
GSHP	ground source heat pump	DL	design load
Н	operating hours (h)	eff	effective
HEC	high efficiency cogeneration unit	el	electrical
HEW	heat exchanger winter	exh	exhaust
HTK	hot tank	eq	equivalent
	/ heat exchanger heating water – domestic hot water	fl	fluid
I ICE	intercooler	glob	global
IGCC	internal combustion reciprocating engines integrated gasification combined cycle	h	heating
IPC	individually prioritized control	H	from the heat source
IRR	internal rate of return	hot	hot source
I	component capital cost $(\in)$	HP	heating pump
J JwHw	heat exchanger jacket water – heating water	hw	hot water
LHV	natural gas low heating value (kW h/S m <sup>3</sup> )	in L	inlet indut water
т.	mass flow rate (kg/h)	Jw	jacket water
M	mixer	L	to the load mechanical
Ма	maintenance	m min	minimum
MILP	mixed-integer linear programming	min N	nominal
NPV	net present value (€)	OFF	office zone
OC	heat exchanger oil cooler	ор	operating
ORC	organic rankine cycles	out	outlet
P	mechanical power (kW)	PROD	production zone
P(1, 2, 3	) Pump	rated	at nominal conditions
PCM	phase change materials	ref	of reference
PE	primary energy (kW h/year)	req	required
PES	primary energy saving (kW h/year)	RS	reference system
PI	profit index	set	set by the controller
PLR	part-load ratio	NG	natural gas
PM	prime mover	taxfree	without taxes
PMD	prime mover dissipator	th	thermal
PV	photovoltaic	thd	thermodynamic
Ż	heat flow (kW)	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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