Energy Conversion and Management 170 (2018) 82–96

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Dynamic simulation and thermoeconomic analysis of a novel solar cooling system for a triple-pressure combined cycle power plant

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ARTICLE INFO

Keywords:
Dynamic simulation
Solar assisted triple-pressure combined cycle
Flat evacuated collector
Absorption chiller

ABSTRACT

This paper presents the design of a novel high-temperature solar assisted triple-pressure level combined cycle power plant. The system includes innovative high-temperature flat plate evacuated solar thermal collectors, a double stage lithium bromide/water absorption chiller, pumps, heat exchangers, storage tanks, mixers, diverters, controllers and a triple-pressure combined cycle power plant. This novel layout uses high-vacuum non-concentrating flat plate solar thermal collectors driving a double effect absorption chiller, leading to an overall high coefficient of performance for the solar cooling section. The provided cooling energy is used to cool gas turbine inlet air to enhance system efficiency and electrical capacity. This effect is mainly performed during central hours of the day when the conventional gas-fired combined cycles dramatically suffer for efficiency and capacity reduction, as a consequence of the corresponding increase of external air temperature. Such increase is related to the higher availability of solar radiation. This technology may be a viable solution, especially for hot and dry areas, in terms of primary energy savings and increased revenues. This prototypal system was numerically analysed for a combined cycle with a rated electrical power of 99 MWe and an electrical efficiency of 56%, developing a dynamic simulation model and detailed thermo-economic optimizations. Special attention is also paid to the design of novel control strategies aiming at maximizing the solar cooling effect. The results of the dynamic simulations show a very high average thermal efficiency of the solar collectors, equal to 34%. Implications of the performed work allowed an increase of the power output up to 5.5% and a satisfactory payback period equal to 10.7 years.

1. Introduction

Among power plants supplied by fossil fuels, such as fuel cells [1], cogeneration [2], reciprocating engines [3], combined cycles (CCs) [4] and organic Rankine cycles (ORCs) [5], the most efficient, reliable and mature technology is currently represented by CCs [6]. This technology consists of a Brayton cycle, bottomed by a Rankine cycle, able to reach very high electrical efficiencies (also higher than 60% [7]). In order to design efficient power, industrial and academic institutions are working on different strategies, such as developing very detailed control strategies [8], improving turbomachinery efficiency [9], optimizing the plant configuration [10], and coupling fossil power plants with renewable energy systems [11].

In particular, the possibility to achieve a power increase in CCs through renewable sources is very attractive, especially when using solar energy [12]. The majority of CCs coupled with the solar source use a high-temperature solar field (parabolic trough collectors (PTC) or linear Fresnel collectors, for example) to increase the steam production for the Rankine cycle [13]. In this kind of hybridization, the most adopted system layout integrates a CC and a solar steam generator driven by a PTC solar field [14]. This arrangement was firstly introduced by Luz Solar International in the 1990s and it is called integrated solar combined cycle (ISCC) power plant. ISCC power plants are especially attractive for regions where solar irradiation is high and an electrical demand is mainly affected by space cooling, especially during the sunny and hottest hours of the day.

In this framework, the power increase obtained through an ISCC layout can match the daily peaks of electricity demands [15] and, therefore, it was thoroughly analysed in several studies.

Behar et al. [16] reviewed the current status of ISCC technology, also listing the plants in operation and under construction around the world. In operation there are 140 MW, 150 MW and 470 MW power plants in Egypt, Algeria and Morocco, respectively. Several projects are under development in USA, Iran, Mexico, Italy, Kuwait and China [16]. Hence, the solar integration can easily balance the daily fluctuation of the electrical production [17] but hybrid solar CCs still need a

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https://doi.org/10.1016/j.enconman.2018.05.041

Nomenclature

a_0	zero loss efficiency at normal incidence, –
a_1	zero collector heat loss coefficient, W/m^2 K
a_2	temperature difference dependence of the heat loss coefficient, W/m^2 K^2
a_3	heat loss coefficient referred to wind dependency, J/m^3 K
a_4	long-wave radiation coefficient, –
a_5	effective thermal capacitance of the collector, J/m^2 K
a_6	wind speed dependence of the heat loss coefficient, s/m
A	area, m^2
c	unit cost, €/kW h or €/Sm^3
cp	specific heat, kJ/kg K
COS	cost, €
d	diameter, m
E	energy, kW h/year or MW h/year
E_L	long wavelength radiation (outside solar spectrum) onto the collector plane, W/m^2
FA	annuity factor, years
Fc	fuel cost, €/Sm^3
FO	objective function
Ga	economic gains, €/year
H	height, m
HEc	heat exchanger cost, €
HJ	Hooke-Jeeves
IAM	incidence angle modifier, –
ISO	international standards organization
IRR	solar irradiation, kW h/m^2 or MW h/year
I_T	total incident radiation, W/m^2
J	total capital cost, €
LCV	lower calorific value, J/kg
$\dot{m}$	flow rate, kg/s
Ma	maintenance, €
N	number, –
PSO	particle swarm optimization
PW	power, kW
Q	thermal power, kW
q	flow rate, kg/h
Sp	spacing, m
SPB	simple pay back, years
T	temperature, °C or K
Th	thickness, m
T_m	arithmetic mean inlet - outlet temperature of the collector, °C
u	wind speed in (parallel to) the collector plane, m/s
U	heat transfer coefficient, kW/(m^2 K)
UA	overall heat transfer coefficient, kW/K
V	volume, m^3
W	width, m

Greek symbols

β	collector slope
ΔCOS	yearly economic saving, €/year
ε	heat exchanger effectiveness, –
η	efficiency, –
λ	conductivity, W/mK
σ	Stefan-Boltzmann constant, W/m^2 K^4

Subscripts and superscripts

a	air
abs	absorber
ACH	absorption chiller
amb	ambient
ap	approach point
boil	boiling
b	beam
BOS	balance of system
ch	chilled
CC 1	objective function one
CC 2	objective function two
CCU	cooling coil unit
chw	chilled water
D	duct
dew	dew
diss	dissipated
d	diffuse
el	electric
F	fin
fl	fluid
HP	high pressure
i	number of heat exchanger
IP	intermediate pressure
Latent	latent
LP	low pressure
NG	natural gas
on	activation
pp	pinch point
R	row
ref	reference
RS	reference system
SACC	solar assisted combined cycle
SC	solar collector
SCool	solar cooling
sol	solar
T	tube
th	thermal

Components and loops

C	compressor
CC3LP	triple-pressure level combined cycle
CCh	combustion chamber
CCU	cooling coil unit
CH	chimney
CHA	chilled air
CHW	chilled water
CO	condenser
CSW	cooling sea water
D	diverter
DEA	deaerator
DSG	direct steam generation
ECO	economizer
G	generator
HESC	heat exchanger solar cooling
HRSG	heat recovery steam generator
HTF	heat transfer fluid
HW	hot water
ISCC	integrated solar combined cycle
M	mixer
ORC	organic Rankine cycle
P	pump
PrHe	pre-heater
PTC	parabolic trough collectors
RH	reheater
SACC3LP	solar assisted triple-pressure level combined cycle
SC	solar collectors
SCW	solar collectors water
SH	superheater