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Thermo-economic analysis of air bottoming cycle hybridization using heliostat field collector: A comparative analysis

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ABSTRACT

Nowadays, climate change has become a vital issue prompting investigations for increasing the share of renewable energy employment in power generation industry. Solar energy is arguably the most favorable solution for a greener power generation technology. With the current level of maturity, solar energy contribution is limited due to intermittency and storage issues. A possible solution to the aforementioned difficulties is power plant hybridization. In this paper, thermo-economic optimization of a hybrid air bottoming cycle (ABC) power plant is accomplished with the objective of minimizing the levelized cost of electricity. The aforementioned hybrid ABC optimization results are compared with a hybrid conventional combined cycle power plant to identify the most cost effective combined cycle configuration for a 50 MWe hybrid power plant. Finally, an already existing ABC power plant hybridization is investigated utilizing payback period, life cycle saving, and levelized cost of electricity approaches.

1. Introduction

Electricity has become an inseparable element in our daily life. However, multiple reports point to the exceptional rate of increase in world's energy demand. A 35% growth in energy demand from 2010 to 2035 is predicted [1]. Another important factor in fossil fuel power generations is their considerable contribution in greenhouse gases emission. It is reported that fossil fuel and natural gases power plants are responsible for 80% of electricity generation worldwide [2]. Nowadays, climate change has become a vital issue prompting investigation to increase the share of power generation implementing renewable sources of energy [3]. Solar energy is arguably one of the most favorable solutions for a greener power generation. Concentrated solar power (CSP) technology can be integrated with different types of power generation cycles including but not limited to steam turbine, gas turbine, and combined cycles. Based on a study by Jacobson and Delucchi [4], CSP technology has the second highest potential to be employed for power generation. With the current level of solar technology's maturity, solar energy cannot provide a significant contribution to the world's energy demand due to intermittency and storage issues [5]. A possible solution to the aforementioned difficulties is power plant hybridization.

There are three recommended approaches for power plant hybridization including the solarized gas turbine, the hybrid combined cycle, and the solar reforming system [6]. In the first two categories, solar energy is utilized along with a supplementary heat source to operate the plant. In other words, a portion of the necessary thermal input for power generation is provided by a renewable energy source. In solar reforming, solar energy is employed to convert the fuel, mostly natural gases, into syngas. Afterward, the produced syngas is employed for power generation, bearing in mind that syngas has higher heating value. Hybridization can be considered as a temporary solution for increasing the renewable energy share of contribution in power generation. Hybrid power plants are capable of generating electricity with higher efficiency compared to solar only power plants and they are more economically justified. Additionally, storage difficulties associated with solar only power plants are alleviated by the auxiliary combustion chamber utilization during nights and low insolation periods.

Power plant hybridization is subjected to rigorous investigation in recent years. A model was developed by Yan et al. [7] to evaluate the economics of CSP integration with different plant size. Conventional Combined cycle (CCC) hybridization was investigated by

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Nomenclature

Symbols

A	Surface area [m^2]
$a_1 \ldots a_n$	Dimensionless NASA polynomial curve fit coefficients
C_p	Specific heat capacity [kJ/kg.K]
f	Factor
i	Loan interest rate
LHV	Lower heating value [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
N	Number, number of years
$\dot{Q}$	Rate of thermal energy [kWth]
R	Gas constant [kJ/kg.K]
r_{ins}	Insurance rate
S	Life cycle saving [US$]
s^0	Temperature dependent specific entropy [kJ/kg.K]
T	Temperature [K]
V	Volume [m^3]
W	Generated electricity [MWh]
$\dot{W}$	Power [kWe]
w	specific work [kJ/kg]
Z	Capital investment cost [US$]

Abbreviation

BCPR	Bottoming cycle pressure ratio
CCC	Conventional combined cycle
CEPCI	Chemical engineering plant cost index
CRF	Capital recovery factor
CSP	Concentrated solar power
DNI	Direct normal irradiation
DOSH	Degree of superheating
GTIT	Gas turbine inlet temperature
HRSG	Heat recovery steam generator
LCOE	Levelized cost of electricity
MFRR	Mass flow rate ratio
TCPR	Topping cycle pressure ratio
UAE	United Arab Emirates

Greek symbols

$\alpha; \beta$	Thermo-economic coefficients
ΔT	Temperature difference [K]
η	Efficiency
ρ	Mirror reflectivity

Subscript

$1y$	First year
a	Air
ad	Additional
ann	annual
at	Attenuation
B	Bottoming
c	Compressor
$civil$	Civil Engineering
con	Construction
cos	Cosine
cw	Compressor washing
dec	Decommissioning
ele	Electrical
ex	Exhaust
f	Fuel, field
G	Generator
g	Gas
hel	heliostat
inv	Investment
lab	Labor
M	Mechanical
mai	Maintenance
mw	Mirror washing
$m\&o$	Maintenance and operating
net	Net
opt	Operation, optical
pb	Payback
$pinch$	Pinch
ref	Reference
s	Steam
sat	Saturated
sav	Save
sh	Superheater
sol	Solar
sp	Spillage
$s\&b$	Shading and blocking
T	Topping
t	Turbine
w	Water, weighted

Barigozzi et al. [8]. Two different concentrated solar collectors, heliostat field collector and line focusing parabolic trough, were considered. Spelling et al. [9] conducted a thermo-economic optimization of a hybrid CCC with heliostat field collectors. Dry solar reforming for a CCC with a triple pressure heat recovery steam generator (HRSG) was studied by Sheu et al. [5]. In another study by Sheu and Ghoniem [10], steam solar reforming was investigated for a CCC power plant.

In a simple gas turbine cycle, substantial waste heat is available in the exhaust gases which can be recovered and further exploited. One alternative is to employ the available waste heat in the gas turbine exhaust gases as a source of process heat [11]. Another option is to devise a bottoming cycle with significantly lower operating temperature to generate additional power and enhance the plant overall efficiency. The most popular and widely used bottoming cycle is steam (Rankine) turbine cycle. It is a well-known fact that CCC, i.e. topping gas turbine and bottoming steam turbine cycles, is one of the most thermodynamically efficient combined plant configurations [12]. Nonetheless, CCC power plants are not the most economically justified configuration for small-scale power plants [13]. For capacities less than 50 MWe, the complication and high expenses due to the HRSG and steam turbine argue in favor of seeking alternatives [12].

An alternative to CCC configurations is to employ another gas turbine cycle for heat recovery purposes. This combined cycle configuration, which is referred to as air bottoming cycle (ABC), was patented by W. Farrell in 1988 [14]. ABC has several advantages over CCC power plants such as shorter installation time, shorter start up time, lower capital investment, lower operating and maintenance cost, more compact size, and simpler operation [15–17].