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Solar–thermal hybridization of advanced zero emissions power cycle

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A B S T R A C T

Four different integration schemes for the Advanced Zero Emissions Power (AZEP) cycle with a parabolic trough are proposed and analyzed: vaporization of high-pressure stream, preheating of high-pressure stream, heating of intermediate-pressure turbine inlet stream, and heating of low-pressure turbine inlet stream. The power outputs from these integration schemes are compared with each other and with the sum of the power outputs from corresponding stand-alone AZEP cycle and solar–thermal cycle. Vaporization of high-pressure stream has the highest power output among the proposed integration schemes. Both the vaporization and heating of intermediate-pressure turbine inlet stream integration schemes have higher power output than the sum of the power outputs from corresponding stand-alone AZEP cycle and solar–thermal cycle. A comparison of the proposed vaporization scheme with existing hybrid technologies without carbon capture and storage (CCS) shows that it has a higher annual incremental solar efficiency than most hybrid technologies. Moreover, it has a higher solar share compared to hybrid technologies with higher incremental efficiency. Hence, AZEP cycles are a promising option to be considered for solar–thermal hybridization.

1. Introduction

Global climate change and anthropogenic emissions of CO_2 have motivated the search for efficient and feasible environment-friendly technologies for power generation. Though fossil fuels continue to be a valuable source of energy because of reliability of fossil fuel power plants for continuous production, fossil fuels have drawbacks including being emissions-heavy and unsustainable [1]. Renewable sources of energy such as solar energy are gaining importance because of the worldwide large insolation, relatively low operating cost and CO_2 emissions.

Concentrated solar thermal (CST) is one of the most widely used methods for utilizing solar energy for power production. CST technologies use collectors (e.g., mirrors) that optically concentrate the sun's rays on to a receiver, which operates at a relatively high temperature. A concentrated solar receiver is either directly used to heat the power plant working fluid as in direct steam generation (DSG) or to heat the heat transfer fluid (HTF) which is then used to heat the power plant working fluid [2]. Different types of concentrated solar receivers include parabolic troughs, Fresnel reflectors [3,4], central receiver systems [5–8] and solar dish systems [4]. Parabolic trough is the most widely used form of CST technology [2]. Parabolic troughs use a single-axis tracking parabolic mirror to concentrate solar radiation on to a receiver pipe at the focal point, which contains the HTF or the power plant working fluid [2]. The receiver of the parabolic trough solar collector is called Heat Collector Element (HCE). The HCE consists of an absorber pipe through which the HTF flows. The absorber is typically made of stainless steel with a special selective coating on the outer surface to provide the required optical properties. A glass envelope protects the absorber pipe from material degradation and reduces heat losses. The operating temperatures of parabolic troughs can be as high as approximately 670 K [3,4]. The highest reported instantaneous solar to electrical energy efficiency of parabolic troughs is about 20% [3,4]. Solar to electrical energy efficiency is defined as

$$\eta_{\text{sol-elec}} = \frac{\dot{W}_{\text{solar}}}{\dot{Q}_{\text{solar}}} \tag{1}$$

where $\dot{W}_{\text{solar}}$ is the net power output of the solar only plant, and $\dot{Q}_{\text{solar}}$ is the solar energy rate input [9]. $\dot{Q}_{\text{solar}}$ is defined as $\dot{Q}_{\text{solar}} = \dot{q}_{\text{DNI}} \cdot A$, where $\dot{q}_{\text{DNI}}$ is the direct normal irradiance (DNI), and A is the projected normal reflective area of the collector. The projected normal reflective area has been used in the literature for calculating thermodynamic parameters such as efficiency [9]. But it

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Nomenclature

A	projected normal reflective surface area of the collector (m^2)
AZEP	advanced zero emissions plant (−)
c_p	specific heat capacity (J/(kg K))
CCGT	combined cycle gas turbine (−)
CCS	carbon capture and storage (−)
CFD	computational fluid dynamics (−)
CST	concentrated solar thermal (−)
d	day of the year (−)
$D_{glass,i}$	inner diameter of glass envelope (m)
$D_{glass,o}$	outer diameter of glass envelope (m)
$D_{pipe,i}$	inner diameter of receiver pipe (m)
$D_{pipe,o}$	outer diameter of receiver pipe (m)
DNI	direct normal irradiance (W/m^2)
DSG	direct stream generation (−)
EoT	equation of time (−)
f	friction factor (−)
h	heat transfer coefficient ($W/(m^2\ K)$)
HCE	heat collector element (−)
HRSG	heat recovery steam generator (−)
HTF	heat transfer fluid (−)
ITM	ion transport membrane (−)
K	incident angle modifier (−)
k	thermal conductivity (W/(m K))
L_{pipe}	length of the receiver pipe (m)
LHV	lower heating value of fuel (MJ/kmol)
LMTD	log mean temperature difference (−)
LST	local solar time (h)
LSTM	local standard time meridian (°)
LT	local time (h)
$\dot{m}$	mass flow rate (kg/s)
$\dot{n}_{fuel}$	mole flow rate of fuel (kmol/s)
N	number of discretization elements (−)
Nu	Nusselt number (−)
$\dot{q}_{DNI,nominal}$	nominal (taken at maximal) direct normal irradiance (MW/m^2)
$\dot{q}_{DNI}$	direct normal irradiance (MW/m^2)
$\dot{Q}_{abs}$	solar absorption in glass envelope (MW)
$\dot{Q}_{fuel}$	heating rate input from the fuel (MW)
$\dot{Q}_{solar}$	solar energy transfer rate (MW)
$\dot{Q}_{trough,nominal}$	nominal heat transfer rate from the receiver pipe to the heat transfer fluid (MW)
$\dot{Q}_{trough}$	heat transfer rate from the receiver pipe to the heat transfer fluid (MW)
$Q_{fuel,annual}$	total heat input of fuel in a year (MWh)
$Q_{trough,annual}$	total heat added to the heat transfer fluid by the parabolic trough in a year (MWh)
R_a	heat transfer resistance of air between outer surface of the absorber pipe and inner surface of glass envelope (K/W)
R_g	heat transfer resistance of air between outer surface of the glass envelope and surroundings (K/W)
R_p	heat transfer resistance of heat transfer fluid inside the absorber pipe (K/W)
Reflectivity	reflectivity of clean mirror (−)
T	temperature (K)
TC	time correction factor (−)
v	velocity (m/s)
w	aperture width (m)
$\dot{W}_{AZEP+solar,ref}$	power output of the reference combination of AZEP + solar plants (MW)
$\dot{W}_{ref}$	power output of the AZEP only reference plant (MW)
$\dot{W}_{solar}$	net power output of a generic solar only power plant (MW)
$W_{AZEP+solar,ref,annual}$	total work output of the reference combination of AZEP + Solar plants in a year (MWh)
$W_{hybrid,annual}$	total work output of the solar–thermal hybrid plant in a year (MWh)
$X_{s,i}$	solar share based on energy input (−)

Greek symbols

α	absorptance of glass envelope (−)
β	tilt angle (°)
δ	declination angle (°)
ε_1	HCE shadowing (bellows, shielding, supports) (−)
ε_2	tracking error (−)
ε_3	geometry error (mirror alignment) (−)
ε_4	dirt on mirrors (−)
ε_5	dirt on HCE (−)
ε_6	unaccounted losses (−)
ϕ	latitude (°)
$\eta_{inc\text{-}sol\text{-}annual}$	annual incremental solar efficiency (−)
η_{ref}	efficiency of AZEP only reference plant (−)
$\eta_{sol\text{-}elec,ref}$	solar to electrical energy efficiency of solar–thermal reference cycle (−)
$\eta_{sol\text{-}elec}$	solar to electrical energy efficiency of a generic solar –thermal cycle (−)
$\eta_{trough\text{-}elec,ref}$	concentrated solar energy to electrical energy efficiency of solar–thermal reference cycle (−)
η_{abs}	effective optical efficiency of glass envelope (−)
ω	hour angle (°)
θ	angle of incidence between the normal to the parabolic trough and the solar rays (°)
ρ_{HTF}	density of heat transfer fluid (kg/m^3)
ρ_{cl}	clean mirror reflectance (−)
τ	transmittance of glass envelope (−)

Subscripts

air	surrounding air
B	bulk
cond	conduction
conv	convection
fuel	fuel input
glass	glass envelope
HTF	heat transfer fluid
inf	environment
j	discretized element
pipe	receiver pipe
solar	solar field input
wind	wind

should also be noted that the actual area of the mirror is approximately 1.5 times larger than the projected area [10,11].

The major disadvantages in the use of solar energy are the requirement for large collector area, which leads to higher initial costs compared to conventional fossil fuel power plants [12], and the variability of supply throughout the day and year. This results in intermittent power production and requires some mode of energy storage in order to meet a given power demand profile. Hybrid