



Integration of an atmospheric solid oxide fuel cell - gas turbine system with reverse osmosis for distributed seawater desalination in a process facility



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ABSTRACT

The integration of a hybrid solid oxide fuel cell – gas turbine (SOFC-GT) system and reverse osmosis (RO) plant is evaluated thermodynamically and economically to enhance power generation and desalinate seawater on-site in a coastal energy-intensive industrial facility in the Persian (Arabian) Gulf. The power and fresh water co-generation scheme is based on the conversion of SOFC-GT exhaust thermal power into electrical work by a bottoming organic Rankine cycle (ORC) to drive the desalination high pressure pump. Seven ORC fluids are evaluated in terms of energetic and exergetic performance, as well as system size indicators. Depending upon the organic fluid selected, the net electrical power output generated from the exhaust of a 25 MWe hybrid SOFC-GT plant ranges from 1.2 to 2.4 MWe at an overall exhaust gas heat recovery efficiency of approximately 8–16% for R245fa and toluene, respectively. Compared with an existing standard GT cycle, the integrated SOFC-GT-toluene ORC-RO system enhances exergy efficiency by approximately 29%, while producing 494 m³/h of fresh water. The avoided purchase of fresh water, natural gas, and environmental emissions could generate net annual operating cost savings of 8–21 million USD based on subsidized and unsubsidized gas and water prices, respectively, and would become profitable within three to five years.

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1. Introduction

The projected increase in power and fresh water demands in the Gulf Cooperation Council (GCC) region, combined with elevated carbon footprints [1–3], requires new strategies for energy conservation and efficiency. Energy-intensive industries, such as the cement, iron and hydrocarbon sectors account for a substantial portion of energy use. Conventional gas power generation cycles used in such facilities offer limited efficiency, essentially due to high irreversibilities in the combustion process. The adoption of more efficient fossil fuel utilization technologies, such as solid oxide fuel cell (SOFC) systems, combined with waste heat recovery from either power generation or process equipment to drive seawater desalination, could aid in meeting the power and fresh water requirements of coastal facilities, as well as reduce emissions. SOFCs are fuel flexible, low noise and modular, with roadmaps projecting multi-hundred MW scale installations [4–7]. A number of SOFC integration strategies have been proposed for further efficiency improvement, including bottoming Brayton and Rankine cycles, co/tri-generation, energy storage and renewable energy

conversion devices [8–10]. The majority of proposed hybrid SOFC power generation systems have consisted of SOFC-Braytons, with emphasis on directly (i.e., chemically) coupled, pressurized SOFC stacks [10]. Although this type of integration promotes high efficiency (i.e., theoretically up to 75% on natural gas (LHV) [10]), technological difficulties remain in terms of reliability/stability issues induced by anodic-cathodic pressure differences, gas turbine (GT) pressure fluctuations, limited operating pressure and mass flow windows, and complex controls [9–12]. Although generally slightly less efficient than directly coupled systems, and despite the potential requirement for a high temperature/pressure recuperator between the atmospheric pressure SOFC exhaust gas and the compressed GT airflow, indirectly (i.e., thermally) coupled SOFC-GT hybrids can reduce design and operational complexity [10–12]. Thus in such systems, presented by e.g. [11,13,14], the normal operation of the base GT cycle compressor/turbine can be sustained, which enables retrofitting of an existing standard GT cycle. This is in contrast with the majority of SOFC-GT hybrids, which have been analyzed based on optimized SOFC and GT components that are not readily available, rather either existing gas turbines, or both existing SOFC stacks and gas turbines [15]. An indirect SOFC-GT coupling is thus selected in the present study for simplicity of integration and controls.

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Nomenclature

A	surface area (m ²)	ψ	exergy efficiency (%)
AER	avoided equivalent CO ₂ emission ratio (–)	σ	electrical conductivity (S/m)
C_p	specific heat capacity at constant pressure (J/kg K)	σ_0	pre-exponential coefficient for electrical conductivity (–)
E	potential (V)	v	specific volume (m ³ /kg)
E_{act}	activation energy (J/mol)		
$ExDF$	exergy destruction factor (–)	<i>Superscript</i>	
$\bar{e}x$	molar exergy (kJ/mol)	c	critical
$\dot{E}x$	exergy transfer rate (W)	ch	chemical
F	Faraday's constant (96,485 C/mol)	ph	physical
h	specific enthalpy (kJ/kg)	*	restricted dead state
H	enthalpy (kJ)		
$HXAI$	heat exchanger surface area index (kJ/kg K)	<i>Subscript</i>	
i	current density (A/m ²)	a	anode or air
I	current (A)	air	air
i_0	exchange current density (A/m ²)	act	activation
L	thickness (μm)	c	cathode
LHV	lower heating value (kJ/kg)	cd	condenser or condensation
\dot{m}	mass flow rate (kg/s)	$cell$	cell
\dot{n}	molar flow rate (mol/s)	$conc$	concentration
$NDExd$	non-dimensional exergy destruction (–)	$cons$	consumed
n_e	number of electrons produced per hydrogen mole reacted electrochemically (–)	$conv$	conventional
p	species partial pressure (bar)	d	destroyed
P	pressure (Pa)	e	electrical
P_0	environmental dead state pressure (Pa)	eq	equivalent
PEC	primary energy consumption (kW h)	el	electrolyte
$PESR$	primary energy saving ratio (–)	eva	evaporation
\dot{Q}	heat transfer rate (W)	f	feed or fuel
R	electrical resistance (ohm)	g	global
\bar{R}	universal gas constant (8.314 J/mol K)	G	generator
s	specific entropy (kJ/kg K)	i	component (i.e., species) index
VER	volumetric expansion ratio (–)	id	ideal
SP	turbine size parameter (m)	in	inlet
T	temperature (°C)	ign	self-ignition
T_0	environmental dead state temperature (Pa)	inv	inverter
U	fuel or oxidant utilization factor (%)	is	isentropic
V	voltage (V) or volume (m ³)	L	limiting
\dot{V}	volumetric flow rate (m ³ /s)	max	maximum
w	salt mass fraction (–)	min	minimum
\dot{W}	power (W)	mix	mixture
y	molar fraction (–)	net	net
		OCV	open circuit voltage
<i>Greek</i>		ohm	ohmic
β	charge transfer coefficient (–)	org	organic fluid
Δ	difference	out	outlet
ε	heat exchanger effectiveness (%)	P	pressure
γ	pre-exponential coefficient for exchange current density (–) or fuel exergy grade (kJ/kg)	req	required
μ	chemical potential (J/kg)	so	stand alone
η	energy efficiency (%)	suc	suction
ρ	density (kg/m ³)	T	temperature
		w	water
		0	environmental dead state

The use of industrial waste heat could significantly reduce the cost and environmental impact of water production and transportation on-site, particularly for remote process facilities. Waste heat utilization is implemented in certain centralized combined cycle (i.e., GT-ST) power generation plants that are integrated with either multi-stage flash (MSF) or multiple-effect distillation (MED) thermal desalination plants [16,17] in the Gulf region, but is typically not employed in industrial facilities. To facilitate the penetration of renewables in the power and buildings sectors in the region, initiatives are currently sought to decouple current centralized power and desalination plants. Unlike thermal desalination tech-

nologies (e.g., MSF, MED), that require both a heat (and electricity) input, reverse osmosis (RO) is a physical, membrane-based demineralization technique that separates dissolved solids (i.e., salt ions) from the seawater solution. This technique requires either electrical or mechanical power to pump, pressurize and permeate the saline water against a membrane, while the brine (i.e., concentrate) is discharged separately [18]. As RO offers lower specific energy consumption (SEC), environmental impact and footprint, and more flexible capacity than MSF [18], which is still predominant in the region [18,19], increasing the local share of RO could also help improve the sustainability of water production.

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