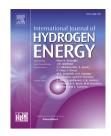
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Exergoeconomic and thermodynamic analyses of an externally fired combined cycle with hydrogen production and injection to the combustion chamber

Anahita Moharamian ^a, Saeed Soltani ^{a,*}, Marc A. Rosen ^b, S.M.S. Mahmoudi ^a

^a Faculty of Mechanical Engineering, University of Tabriz, 16471 Tabriz, Iran

^b Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada

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ABSTRACT

A hydrogen production unit is successfully integrated with an externally fired combined cycle using biomass fuel. The hydrogen produced in an electrolyzer can be used for other purposes, but when there is temporarily no market for it is injected into the combustion chamber of an externally fired combined cycle. Injecting hydrogen into the combustion chamber was found to reduce fuel consumption by almost 27%. Moreover, hydrogen injection decreased the energy efficiency and exergy efficiency by 45%, and decreased both the exergy loss and exergy destruction rates. Meanwhile, CO₂ emissions decreased by 32%. However, there are some disadvantages to hydrogen injection, especially from the viewpoint of exergoeconomics. The total unit product cost for the externally fired combined cycle with hydrogen injection is almost 27% more than the unit without hydrogen injection, although the exergy loss and destruction costs decreased with hydrogen injection. The value of the relative cost difference with hydrogen injection rises by 40%. Also the exergoeconomic assessment demonstrates that the cost of components (purchase and maintenance) are higher than cost of components' exergy destruction for both cycles, i.e., with and without hydrogen injection. As the compressor pressure ratio increases, optimal points are identified for biomass flow rate, energy and exergy efficiencies, exergy destruction and loss rates, exergy destruction and loss exergy cost rates, total unit product cost and relative cost difference.

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Introduction

Population growth and industrial development in many countries lead to environment impacts and ecosystem damage to (e.g., climate change due to greenhouse gas emissions). The use of renewable energy can help mitigate greenhouse gas emissions. Research on renewable energy technologies can improve their capabilities, and environmentally sensitive energy

* Corresponding author.

E-mail addresses: a.moharamian92@ms.tabrizu.ac.ir (A. Moharamian), soltani929@gmail.com (S. Soltani), marc.rosen@uoit.ca (M.A. Rosen), s_mahmousi@tabrizu.ac.ir (S.M.S. Mahmoudi). https://doi.org/10.1016/j.ijhydene.2017.11.136

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Nomenclature			Greek letter	
Ċ	Cost rate (\$/h)	η	Energy efficiency	
	Cost per unit exergy (\$/GJ)	$\eta_{\mathrm{is,C}}$	Isentropic efficiency of compressor	
C D	Membrane thickness (µm)	$\eta_{\mathrm{is,GT}}$	Isentropic efficiency of gas turbine	
D Ė		$\eta_{\mathrm{is,T}}$	Isentropic efficiency of steam turbine	
_	Exergy rate (kW)	$\eta_{\rm is,pump}$	Isentropic efficiency of pump	
E _{act,a}	Activation energy of anode (kJ/mol)	ε	Exergy efficiency	
E _{act,c}	Activation energy of cathode (kJ/mol)	σ (x)	Local ionic PEM conductivity (S/m)	
EFCCH	Externally fired combined cycle with PEM	σ_{PEM}	Proton conductivity in PEM (S/m)	
FECCIU	electrolyzer	λ_c	Water content at cathode-membrane interface	
EFCCHI	Externally fired combined cycle hydrogen	λα	Water content at anode-membrane interface	
P	injection	λ (x)	Water content in location x in membrane	
F	Faraday constant (C/mol)	β	Ratio of chemical exergy of organic reaction of	
G H	Gibbs free energy (J/mol) Specific enthalpy		biomass	
н ННV	Higher heating value (kJ/kg)	Subscripts		
J	Current density (A/m^2)	a	Anode	
Jo	Exchange current density (A/m ²)	act	Activation	
) Pre-exponential factor of anode (A/m ²)	AP	Air preheater	
	 Pre-exponential factor of cathode (A/m²) 	HRSG	Heat recovery steam generator	
m 'n	Mass flow rate (kg/s)	C	Cathode	
LHV	Lower heating value (kJ/kg)	Comp	Compressor	
Pi	Pressure at state i (bar)	CC	Combustion chamber	
r _p	Compressor pressure ratio	CI	Capital investment	
R _{PEM}	Proton exchange membrane resistance (Ω)	D	Destruction	
Т	Temperature (K)	Cond	Condenser	
TIT	Gas turbine inlet temperature (K)	G	Gasifier	
Ŵ	Work rate (kW)	GT	Gas turbine	
\dot{W}_{PEM}	Electrical power required to split water in the	in	Inlet condition	
	electrolyzer (kW)	i	Index for thermodynamic state point	
V ₀	Reversible potential (V)	is	Isentropic	
V _{act,a}	Anode activation over potential (V)	PEM	Proton exchange membrane	
V _{act,c}	Cathode activation over potential (V)	out	Outlet condition	
V _{Ohm}	Ohmic overpotential (V)	0	Reference	
Х	Steam quality	OM	Operation and maintenance	
Z	Investment expense of component (\$)	ohm	Ohmic	
Ż	Investment expense rate of component (\$/h)	ST	Steam turbine	
		-		

policies can support the utilization of renewable energy. In addition renewable energy mitigates many environmental consequences and enhances energy security for countries which are dependent on imported non-renewable fuels. Therefore non-fossil energy resources such as biomass can be appropriate alternatives to fossil fuels, in large part because biomass resources are scattered throughout the land. Also, biomass, a common material on Earth, has numerous advantages as an energy resource. It can be utilized directly or converted into various energy products such as biofuels [1]. The most common approach of utilizing biomass for energy is its direct combustion with coal [2]. Several technologies such as gasification and pyrolysis exist for converting biomass, but there remain challenges to its widespread use [3,4]. One approach to overcoming the weaknesses of biomass is to utilize it as a fuel in an externally fired gas turbine [5]; a diverse set of methods for doing so have been recommended [6,7]. Biomass

based cogeneration systems and power plants have been evaluated in several studies. Al-Sulaiman et al. [8] considered biomass trigeneration using an organic Rankine cycle (ORC), and found advantages to using biomass for trigeneration instead of electrical generation. Soltani et al. [9] demonstrated that biomass can be used without filtering in an externally fired combined cycle (EFCC) and that it has some advantages over internal fired units when utilized in this manner but also has some disadvantages such as low efficiency.

Hydrogen is the product of some cogeneration or multigeneration power plants. Hydrogen is not an energy source but rather is an energy carrier. Its use causes little pollution provided it is produced from clean energy sources. Hydrogen has been investigated extensively as an energy carrier that can help address numerous global energy issues, in large part by facilitating the use of renewable energy [10]. One device to produce hydrogen from water is an electrolyzer, which uses

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