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Upgrading versus reforming: an energy and exergy analysis of two Solid Oxide Fuel Cell-based systems for a convenient biogas-to-electricity conversion

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ABSTRACT

Aiming at designing biogas-to-electricity advanced systems, Solid Oxide Fuel Cells are promising candidates. They benefit from scalability on plant sizes that suit anaerobic digesters potentialities. For biogas-Solid Oxide Fuel Cells applications, the implementation of an external pre-reformer is usually considered. However, the possibility to perform direct fuel feeding to the Solid Oxide Fuel Cell offers new opportunities towards the realization of lean systems, which are competitive especially on small-scale installations (i.e. on-farm biogas-to-electricity conversion). In this frame, scientific literature is rather poor and, to cover this gap, system simulations are called for two reasons: first, to demonstrate the potential efficiency gain of new concepts; second, to provide a meaningful support for long-term experimental investigation on Solid Oxide Fuel Cells operated upon direct feeding of unreformed biogas.

For that, the current study compares two system designs for biogas utilization into Solid Oxide Fuel Cells. The conventional one realizes biogas steam reforming prior the fuel cell, while the novel concept is based on direct feeding of partially upgraded biogas by means of carbon dioxide-separation membranes. As main outcome of the study, the system equipped with carbon dioxide-separation membranes achieves better performances than its conventional competitor does, scoring 51.1% energy efficiency and 52.3% exergy efficiency (compared to 37.2% and 38.6% respectively exhibited by the reformer-based system). Because of the lack a high endothermic process steps, the membrane-based system is also convenient whether heat recovery is required, producing a combined heat-and-power efficiency of 74.8% versus 47.0% obtained in the other system. Moreover, the results of a sensitivity analysis of the impact of membrane and reforming operating parameters on the overall system performances justify the convenience of adopting the solution of biogas direct feeding. Even in the hypothesis of a poorly performing membrane and an optimized reformer, the membrane-based system exhibits a gain in the system energy and combined heat-and-power efficiency of 25.2% and 34.9% respectively, with regard to the reforming-based concept. The forcefulness of this result is reinforced by a preliminary evaluation of capital expenditures, which represents a further economic advantage beside the economic revenue coming from a higher energy conversion efficiency.

1. Introduction

Global environmental and energy policies stress the need to increase the share of renewable resources and to enhance the efficiency of energy conversion plants, committing to retrofit existing plants and to develop advanced solutions for power production [1]. In the matter of fuels, going towards the so-called hydrogen society, low-carbon gases play an important role, since they contribute to lower greenhouse gases (GHG) emissions [2].

In this frame, biogas is an attractive fuel [3], both from the point of view of its supply-chain and exploitation. It is a valuable by-product of organic wastes processing (manure, agricultural scrap, waste-water), requiring well-known safety measures when it comes to its utilization. Normally, it meets the following major fates, as summarized by Wu et al. [4]: (I) on-farm energy conversion for electricity and combined heat and power (CHP) generation, (II) upgrading for substitute natural gas (SNG) production (see also the research of Scholz et al. [5]), for either gas distribution grid or chemical synthesis, (III) upgrading for substitute fuel for vehicle applications [6]. In addition to that, whether upgrading can be

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Nomenclature

Abbreviations and subscripts | **Descriptions**

AC	Alternating Current
AUX	Auxiliaries
BLW	Blower
BOP	Balance of Plant
BR	Burner
Capex	Capital Expenditures
CHP	Combine Heat and Power
DC	Direct current
ER	Energy recovery
GHG	Green House Gas
HRSG	heat recovery steam generator
HX	Heat Exchanger
INV	AC-DC converter (inverter)
KPI	Key performance indicator
KMP	Compressor
LV	Lamination valve
MX	Mixer
NiYSZ	Nickel Yttria-Stabilized-Zirconia
PM	Pump
REF	Reformer
SO	Solid Oxide
SOFC	Solid Oxide Fuel Cell
SV	Splitter valve
TRB	Turbine

Latin letters

A/F	combustion air-to-fuel ratio [–]
C	thermal capacity [kJ/K]
cp	constant pressure specific heat [kJ/(K mol)]
cv	constant volume specific heat [kJ/(K mol)]
db	dry basis [–]
dp%	Percentual Pressure Drop [–]
E	Stream total energy [kW]
Ex	Exergy flow [kW]
h	specific enthalpy [kJ/mol]
$\dot{n}_{i_j}$	i molar flow rate in stream j [mol/s]
O/C	Oxygen to Carbon ratio [–]
P	Power [kW]
Q	heat flow [kW]
S/C	Steam to Carbon ratio [–]
W	mechanical power [kW]
x_{i_j}	i molar fraction in stream j [–]

Greek letters

$\alpha_{A/B}$	A/B membrane selectivity [–]
γ	ratio of gas mixture specific heats (c_p/c_v) [–]
η_{blw}	Blower total efficiency [–]
$\eta_{e,is}$	Expansion isoentropic efficiency [–]
η_{HX}	heat exchanger efficiency [–]
$\eta_{DC/AC}$	inverter DC to AC efficiency [–]
$\eta_{k,is}$	Compression isoentropic efficiency [–]
η_{mec}	Turbomachinery mechanical efficiency [–]
η_{sep}	separation efficiency [–]
λ	Excess air [–]

Symbol subscripts

0	initial state of a thermodynamic transformation
act	actual
ds	dead state
el	electrical
f	final state of a thermodynamic transformation
is	iso-entropic
m	molar basis
ox	oxygen
perm	permeate
ret	retentate
shf	shaft
st	stoichiometric

fulfilled at low costs, on-farm energy utilization of upgraded gases ends up enhanced.

Aiming at designing biogas-to-electricity advanced systems, Solid Oxide Fuel Cells (SOFCs) are promising candidates: they benefit from the scalability of fuel cells even on a plant size that suits anaerobic digesters potentialities, as Trendewicz and Braun deepened in the paper at [7]. Furthermore, compared to other fuel cells technologies, SOFCs are carbon-tolerant and, thanks to their high operating temperature and the presence of a catalyst on the anode layer, light hydrocarbons (i.e. methane) decomposition occurs directly in the fuel cell.

In the recent years, SOFCs manufacturers and research institutions [8] working in the field have been publishing interesting results about long-term operation of SOFC stack, displaying and average degradation rate of 0.3% over 1000 h. This information is to be considered with regard to SOFC-based modules implementing a natural gas-fed steam reformer installed upstream the SOFC. In addition to that, similar system configurations [9] come across as good implementations also in the event of biogas utilization in SOFCs.

Beside external reforming, in the literature there is evidence of an increasing attention on the topic of SOFC direct feeding with both natural gas and biogas. In the literature, there are good works concerning the detailed modelling of SOFC chemistry when biogas is the anode feeding, such as the one published by Ni [10]. Promising modelling forecast find their validation in experimental works, such as the following listed hereinafter. In detail, Lanzini et al. [11] investigated how the addition of carbon dioxide to methane is beneficial for SOFC operation, since it mitigates the occurrence of carbon deposition. Similarly, Lin et al. [12] demonstrated that NiYSZ-anode SOFCs are suitable for carbon-free operation under direct feeding of methane, in a temperature range (T < 700 °C) which does not favour solid carbon formation via methane cracking.

In a research of Shiratori et al. [13], the feasibility of direct-biogas SOFC was proved experimentally. Tests were conducted on NiScSZ-anode SOFCs, revealing a good tolerance to carbon deposition, but still a marked sensitivity to sulphur compounds (H_2S), which are a crucial issue of the fuel considered. Further, in [14], Shiratori et al. went further on the experimental investigation of biogas direct-fed SOFC, providing results on a durability test. The latest experience revealed that the occurrence of small amounts of H_2S in biogas promotes coking over the fuel cell anodes, while simulated biogas fully desulphurized is suitable for a long and stable operation. The last point is in agreement with the findings in [11].

All of these results show good possibilities for methane-rich direct feeding to SOFCs, with a particular regard to biogas applications. This is gaining much interest, especially in the perspective of realizing on-farm biogas-to-electricity conversion. However, scientific literature concerning such innovative system concepts is rather poor.