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Thermodynamic evaluation of bi-directional solid oxide cell systems including year-round cumulative exergy analysis

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HIGHLIGHTS

- CE method can be used next to round trip efficiency to design Bi-SOC systems.
- Bi-SOC year-round cumulative exergy efficiency varies from 33% to 73%.
- Bi-SOC energy efficiencies range between 29% and 66%.
- Bi-SOC performance is higher for different operating condition of SOFC and SOEC.

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ABSTRACT

Bi-directional solid oxide cell systems (Bi-SOC) are being increasingly considered as an electrical energy storage method and consequently as a means to boost the penetration of renewable energy (RE) and to improve the grid flexibility by power-to-gas electrochemical conversion. A major advantage of these systems is that the same SOC stack operates as both energy storage device (SOEC) and energy producing device (SOFC), based on the energy demand and production. SOEC and SOFC systems are now well-optimised as individual systems; this work studies the effect of using the bi-directionality of the SOC at a system level.

Since the system performance is highly dependent on the cell-stack operating conditions, this study improves the stack parameters for both operation modes. Moreover, the year-round cumulative exergy method (CE) is introduced in the solid oxide cell (SOC) context for estimating the system exergy efficiencies. This method is an attempt to obtain more insightful exergy assessments since it takes into account the operational hours of the SOC system in both modes. The CE method therefore helps to predict more accurately the most efficient configuration and operating parameters based on the power production and consumption curves in a year.

Variation of operating conditions, configurations and SOC parameters show a variation of Bi-SOC system year-round cumulative exergy efficiency from **33%** to **73%**. The obtained thermodynamic performance shows that the Bi-SOC when feasible can prove to be a highly efficient flexible power plant, as well as an energy storage system.

1. Introduction

Efficient electrical energy storage and power-to-gas solutions could play a substantial role in increasing the penetration of fluctuating renewable energy resources, thus mitigating the worst impacts of climate change, and in integrating different energy grids and infrastructures [1–8]. Among the various technologies, solid oxide electrolyser cell (SOEC) is currently the focus of numerous research and development efforts because it converts electricity into chemical energy with a higher efficiency compared to alkaline electrolyser and proton exchange membrane electrolyser technologies [9]. Moreover, to the present knowledge, SOECs are the only electrolyser cells that have shown the possibility of operating in reversible mode without exhibiting severe degradation [10,11]. This allows them to compete with compressed air and pumped hydro energy storage methods, and advanced batteries [12–14].

Bi-directional solid oxide cell (Bi-SOC) systems store electricity by producing a synthetic fuel in the electrolysis mode and generating electricity by electrochemically oxidising fuel in fuel cell mode, based on the energy demand and production [12–14]. Fig. 1 sketches the working principle of a Bi-SOC system where power is produced from biomass-derived syngas or from H_2, and can then be used for a wide

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Nomenclature

Symbols

A	cell/stack area [m^2]
$\dot{E}$	molar energy flow rate of the fuel on the basis of LHV [kW]
Ex	exergy [kW]
F	Faraday constant [C/mol]
h	molar enthalpy of component [kJ/mol]
I	current [A]
J	current density [A/m^2]
$\dot{n}$	mole flow rate [kmol/s]
P	pressure [bar]
$\dot{Q}$	heat flow rate [kW]
T	operating temperature [°C]
t	operational hours [hours]
V	voltage [V]
$\dot{W}$	work flow rate [kW/MW]
z	number of electrons generated/required per electrochemical reaction [–]
η	efficiency [%]

Subscripts

D	destruction
ec	electrolyser cell
fc	fuel cell
in	inlet
k	component k
NST	nernst
out	outlet
sys	system

Abbreviations

ASR	area specific resistance
Bi-SOC	bi-directional SOC
CE	cumulative exergy
GT	gas turbine
LHV	lower heating value
REaccuracy	relative error
ReSOC	reversible SOC
SOC	solid oxide cell
SOFC	solid oxide fuel cell
SOEC	solid oxide electrolyser cell
UF	utilisation factor
TIT	turbine inlet temperature

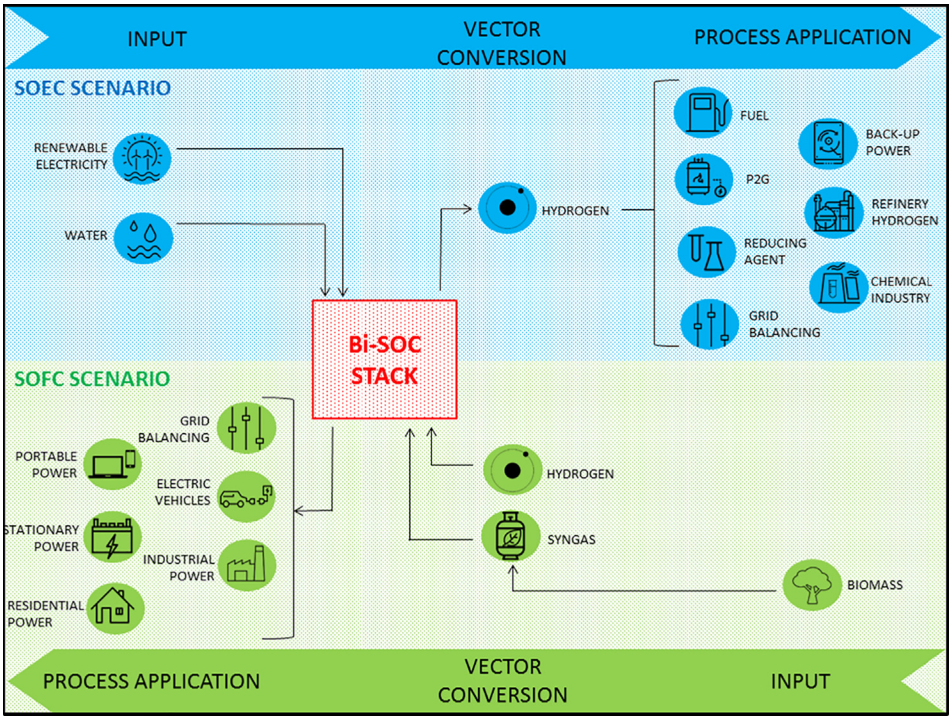

Fig. 1. Bi-SOC energy system.

array of applications. Analogously, H_2 is produced from H_2O in the electrolysis mode, using a renewable energy source (e.g., solar, wind, hydro). The H_2 produced can then be used in other processes, converted to others chemicals, or can be stored and converted again to power by the same Bi-SOC operating in the fuel cell mode when necessary.

Potentially, Bi-SOC systems are flexible regarding both the fuel and the energy sources fed to, compatible with reduced CO_2 emission targets in power generation mode, adaptable to local energy needs and to different applications [10]. However, this is not yet a sufficiently mature technology to set up efficient and cost-effective operation. Moreover, SOCs are now optimised for one mode only, while Bi-SOCs must operate efficiently in both SOFC and SOEC modes.

SOFC systems have been extensively investigated. Recent works focused on the optimization of SOFC and combined SOFC-Gas Turbine (SOFC-GT) systems. A techno-economic optimization of a SOFC micro-combined heat and power (CHP) systems (10–20 kW size range) is presented by Braun [15]. The system configurations and operating parameter selections could allow a minimum life-cycle cost while