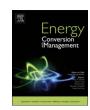
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# Designing and analyzing an electric energy storage system based on reversible solid oxide cells



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#### ABSTRACT

The Reversible Solid Oxide Cell (ReSOC), operating under electrolysis and fuel cell modes, is a promising technology that, thanks to high efficiency and fuel flexibility, can be applied in the development of Electric Energy Storage (EES) systems.

Several critical issues are required to be addressed, which are specific to ReSOC, such as oxidant electrode performance and reversibility, set of materials, cell/stack design and operating parameters suitable for reversible operation. Moreover, the optimal system design, to demonstrate the feasibility of the technology as well as the Balance of Plant (BoP) components at high operating temperatures, are also challenging factors.

Therefore, the objective of this work is to propose an HEES (Hydrogen-based Electric Energy Storage) system for distributed scale energy storage applications (100–200 kW) by taking into account some of these challenging issues. The proposed system consists of (i) the BoP section needed for the energy storage, (ii) the ReSOC module operating in reversible mode, (iii) the BoP section needed for the energy production.

In order to guarantee a competitive roundtrip efficiency, the design of the solid oxide cell unit and of the supporting auxiliary systems (BoP components) has been performed without external heat sources for the heating of feeding streams and for the thermal requirements of the ReSOC during its operation in the electrolysis mode.

The study has been carried out by developing a steady-state thermo-electrochemical model that has been built with a modular architecture. The model, validated by means of experimental data, has been used to assist the system designing and the thermal management optimization to ensure high performances from electric and thermal points of view.

Results highlight that the proposed system is able to store and use the renewable energy with a roundtrip efficiency of 60%. Moreover, thanks to the optimized thermal integration, additional heat is available for cogeneration purpose, with a cogeneration efficiency of 91%.

#### 1. Background and scope

In the last decade, the increasing environmental concerns have led the European Countries to energy and climate policies, aiming to a significant CO<sub>2</sub> emissions reduction by up to 95% by 2050. To achieve the target of reducing CO<sub>2</sub> emissions, the integration of renewable energy sources in the energy mix of the future is expected to grow. However, the output of many renewable energy sources, such as wind and solar, is highly variable, producing fluctuating and partly unpredictable amounts of electricity over time. Therefore, the constant mismatch between supply and demand can have a serious impact on grid reliability and security of supply. This represents a new challenge, in energy generation and load balance maintenance to ensure power

network stability and reliability. Among all the possible solutions, Electric Energy Storage (EES) has been recognized as one of the most promising approaches [1-10].

There are a number of benefits associated with the introduction of bulk energy storage systems into the electricity grid: (1) enabling time-shift of energy delivery to facilitate the balancing of electricity supply and load at reduced cost, (2) providing grid operational support to facilitate smooth, coordinated operation of the components of the electricity supply system, (3) maintaining power quality and reliability by providing energy to the system with very short response times, and (4) allowing integration of intermittent renewables generation by smoothing their energy output over time [5].

EES technologies can be separated into two categories [6]: high

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Nomenclature	Greec symbol				
$A_{cell}$ cell active area (cm <sup>2</sup> )	$\eta_{act}$ activation overpotential (V)				
ASR Area Specific Resistance ( $\Omega \text{ cm}^2$ )	$\eta_{conc}$ concentration overpotential (V)				
DH enthalpy change of the feeding streams (kW)	$\eta_{el,HEES-SOEC(SOFC)}$ HEES electric efficiency in SOEC or SOFC modes				
$E_{T,SOEC(SOFC)}$ overall cell power (kW) in SOEC or SOFC modes	(%)				
F Faraday constant (96,485 C/mol)	$\eta_{ohm}$ ohmic overpotential (V)				
$f_{stack}$ stack loss factor	$\eta_{RT,HEES}$ HEES roundtrip efficiency (%)				
$I_{cell}$ cell current intensity (A)	$\eta_{CHP,HEES}$ HEES cogeneration efficiency (%)				
j current density (A/cm²)	$\omega$ coefficient used in the ReSOC model equations: +1 for				
$j_0$ Exchange current density (A/cm <sup>2</sup> )	SOEC, $-1$ for SOFC				
OCV Open Circuit Voltage (V)					
$P_{BOP,SOEC(SOFC)}$ BoP Electric power consumption or generation (kW)	Subscript				
$p_{H2,SOEC(SOFC)}$ chemical power of hydrogen produced or used in the					
ReSOC module(kW)	DP Design Point				
$P_{SOEC(SOFC)}$ electric power supplied or generated by the ReSOC	EC Electrolysis Cell				
module	FC Fuel Cell				
$p_{cell}$ cell pressure (bar)	i index for denoting cell components (anode, cathode,				
$Q_{CHP,HEES}$ thermal power available from HEES system for cogenera-	electrolyte, interconnections)				
tion purpose (kW)	k index for chemical species				
$Q_{CR,SOEC(SOFC)}$ convective and radiative energy fluxes in SOEC or SOFC modes (kW)	Acronyms				
$Q_{LOSS,SOEC(SOFC)}$ heat production due to the overvoltage losses in	n n n l (n)				
SOEC or SOFC modes (kW)	BoP Balance of Plant				
$Q_{REACT,SOEC(SOFC)}$ thermal power due to the electrochemical reac-	BoP-EC Balance of Plant for the energy storage unit				
tions in SOEC or SOFC modes (kW)	BoP-FC Balance of Plant for the energy production unit				
$Q_{SOEC(SOFC)}$ net thermal power in SOEC or SOFC modes (kW)	CHP Combined Heat and Power				
R universal gas constant (8.314 J/mol K)	EES Electric Energy Storage				
$S_{cell}$ external cell surface (cm <sup>2</sup> )	FE Fuel Electrode				
$T_{cell}$ cell temperature (°C)	HEES hydrogen-based energy storage				
$V_{SOEC(SOFC)}$ cell voltage in SOEC or SOFC modes (V)	LHV/HHV Low/High Heating Value				
$V_{TN}$ thermo-neutral voltage (V)	OE Oxidant Electrode				
$W_{rev,SOEC(SOFC)}$ cell reversible electric power in SOEC or SOFC	ReSOC Reversible Solid Oxide Cell SOC Solid Oxide Cell				
modes (kW)					
W <sub>SOEC(SOFC)</sub> cell electrical power supplied/generated in SOEC or SOFC modes (kW)	TES Thermal Energy Storage				

power storage systems, that deliver energy at very high rates but typically for short times (less than 10 s) and high energy storage systems, that provide energy for hours. The electrochemical storage technologies can be employed both in high power systems and high energy systems.

Moreover, EES systems can be also classified referring to the mechanisms for storing electrical energy: electrical fields, mechanical energy and electrochemical/chemical energy. Table 1 summarizes the main technological features of EES systems [3,5,6].

Table 1
Features of main EES technologies [3,5,6].

		Energy Rating (kW h)	Power Rating (MW)	Power Density (kW/m³)	Energy Density (kWh/ m³)	Roundtrip Efficiency (%)	Discharge Time	Recharge Time	Response Time	Self discharg per day (%)
MECHAN	ICAL									
PHS		$2\cdot10^{5}$ - $5\cdot10^{6}$	$10^2 - 5.10^3$	0.1-0.2	0.2-2	70-80	1-24h+	min-h	min	0
CAES		$2\cdot10^5-10^6$	$10^2 - 3.10^2$	0.2-0.6	2-6	41-75	1-24h+	min-h	min	0
FES		> 10 <sup>5</sup>	< 20	$5.10^{3}$	20-80	80–90	s-min	< 15 min	< s	100
ELECTRO	CHEMICA	L/CHEMICAL								
BES	Ni-Cd	$10^{-2} - 10^{3}$	< 40	75-700	15-80	60-80	s-h	1h	< s	0.2 - 0.6
	LA	$10^2 - 10^5$	< 70	90-700	50-80	75-90	s-h	8-16h	< s	0.1-0.3
	Li-ion	$10^2 - 10^5$	10 <sup>-1</sup> -5	$1.3 \cdot 10^3 - 10^4$	200-400	65–75	min-h	min-h	< s	0.1-0.3
	Na-S	$6.10^3$ – $6.10^5$	0.5-50	120-60	15-300	70-85	s-h	9h	< s	20
FBES	VRFB	10-10 <sup>4</sup>	0.03-7	0.5-2	20-70	60-75	s-10h	min	< ms	0-10
	ZnBr	50-4·10 <sup>4</sup>	0.05-2	1-25	20-35	70–75	s-10h	3-4h	< ms	0-1
HEES		$> 10^5$	< 50	0.2-20	600 <sup>a</sup>	34–44	s-24h+	instant.	s-min	0.5–2
ELECTRIC	CAL									
SC		$10^{-3} - 10^{1}$	0.01-1	$4.10^4 - 1.2.10^5$	10-20	85–98	ms-1h	s-min	< s	20-40
SMES		$10^{-1}$ – $10^{2}$	0.01-10	$2.6 \cdot 10^3$	6	75-80	ms-8s	min	< s	10-15

Acronyms: PHS (Pumped Hydroelectric Storage), CAES (Compressed Air Energy Storage), FES (Flywheels Energy Storage), Batteries (Ni-Cd, Lead Acid, Li-ions, Na-S), FBES (Flow Battery Energy Storage: VFBR, Vanadium Redox Flow Batteries; ZnBr), HEES (Hydrogen-based energy storage), SC (Super Capacitors), SMES (Superconducting Magnetic Energy Storage).

<sup>&</sup>lt;sup>a</sup> For a storage pressure of 200 bar.

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