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Novel electrical energy storage system based on reversible solid oxide cells: System design and operating conditions

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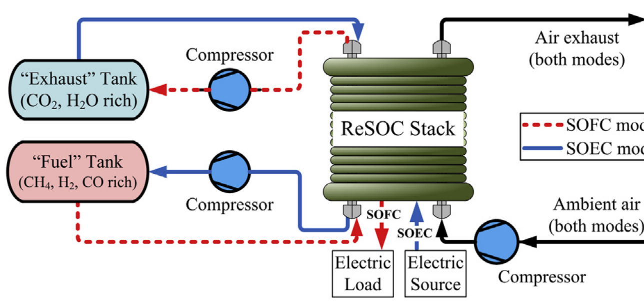
HIGHLIGHTS

- An electrical energy storage system using reversible solid oxide cells is modeled.
- Thermal management with carbonaceous reactant species increases system efficiency.
- System modeling reveals tradeoffs between roundtrip efficiency and energy density.
- Roundtrip efficiency >70% is achieved by operating the stack at 20 bar and 680 °C.

GRAPHICAL ABSTRACT



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ABSTRACT

Electrical energy storage (EES) is an important component of the future electric grid. Given that no other widely available technology meets all the EES requirements, reversible (or regenerative) solid oxide cells (ReSOCs) working in both fuel cell (power producing) and electrolysis (fuel producing) modes are envisioned as a technology capable of providing highly efficient and cost-effective EES. However, there are still many challenges and questions from cell materials development to system level operation of ReSOCs that should be addressed before widespread application. This paper presents a novel system based on ReSOCs that employ a thermal management strategy of promoting exothermic methanation within the ReSOC cell-stack to provide thermal energy for the endothermic steam/CO_2 electrolysis reactions during charging mode (fuel producing). This approach also serves to enhance the energy density of the stored gases. Modeling and parametric analysis of an energy storage concept is performed using a physically based ReSOC stack model coupled with thermodynamic system component models. Results indicate that roundtrip efficiencies greater than 70% can be achieved at intermediate stack temperature (680 °C) and elevated stack pressure (20 bar). The optimal operating condition arises from a tradeoff between stack efficiency and auxiliary power requirements from balance of plant hardware.

1. Introduction

Electrical energy storage (EES) allows for temporal decoupling of electric power generation and consumption and has been projected as a key component of the future electric grid to increase efficiency and allow large-scale penetration of intermittent renewable resources, such as wind and solar [1–4]. The U.S. DOE

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recently published long-term targets for grid energy storage of 80% roundtrip efficiency, 150 $/kWh capital cost and 10 ¢/kWh-cycle levelized cost to fulfill energy management applications like energy time-shifting, transmission and distribution upgrade deferral, and customer energy management services [1]. Many technology solutions are being considered to meet the above energy storage targets, although each faces unique implementation challenges.

Pumped hydro storage presently accounts for 95% of worldwide electrical energy storage [1], but requires a geographically suitable site to be implemented effectively (i.e., adjacent reservoirs separated by a height difference). Other EES technologies including compressed air energy storage, conventional batteries (e.g., lead-acid, nickel–cadmium), advanced batteries (e.g., sodium–sulfur, lithium-ion, redox flow, etc.), and energy flywheels are at various stages of development and commercialization, though none are currently able to provide a comprehensive energy storage solution [5,6]. Furthermore, because of the variety of energy storage applications, a range of operating requirements are needed, including operating durations, dynamic requirements, and energy-to-power ratios, such that a portfolio of energy storage technologies is beneficial.

Recent studies suggest that a reversible solid oxide cell (ReSOC) is a technology capable of working as a highly efficient (>70% roundtrip) and potentially cost-effective energy storage device at large-scales (<4 US¢/kWh/cycle) [7]. The ReSOC is a solid-state, electrochemical energy conversion device that operates at high temperature (600–1000 °C). Physically, the ReSOC is constructed of a membrane electrode assembly (MEA) comprising a laminated fuel electrode, solid electrolyte, and oxygen electrode. State-of-the-art ReSOCs typically leverage solid oxide fuel cell (SOFC) material sets made from nickel–impregnated yttria-stabilized zirconia (Ni–YSZ) cermets for the fuel electrode, a dense YSZ electrolyte layer, and lanthanum strontium-doped manganite (LSM) for the oxygen electrode [8]. These state-of-the-art cells are mechanically supported by the fuel electrode (e.g., anode-supported) to allow thin solid electrolytes with low resistance and high catalyst surface area for heterogeneous fuel reforming on the nickel present in the fuel electrode. Intermediate temperature ReSOCs employing $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (LSGM) as the electrolyte are also promising candidates under development, particularly for operating temperatures <700 °C [9,10]. Although fuel cells are currently the primary application, ReSOCs can operate either as a fuel cell to generate electrical power and consume fuel, or as an electrolyzer to produce fuel from reactant species such as H_2O and CO_2 with an input of electrical power [11].

A stand-alone energy storage system is realized from this technology by coupling the two modes of operation with intermediate storage of gaseous “fuel” and “exhaust” species. Thus, this system has the advantage of independently sizing power and energy capacity by the ReSOC stack and storage tank sizes, respectively. Fig. 1 shows a simplified schematic of an energy storage system concept based on ReSOC technology. The ReSOC stack is comprised of many single cells configured in electrical series. The energy storage device is charged by operating the stack as an electrolyzer or in solid oxide electrolysis cell (SOEC) mode. In this mode, reactant species are delivered to the stack from the “exhaust” storage tank where they are electrochemically reduced to form fuel species (i.e., H_2, CO, CH_4) with a supply of electricity from a renewable resource, for example. The produced fuel is compressed and stored in a “fuel” tank for later use. In SOFC mode, the device is discharged as fuel species are delivered to the stack from the “fuel” tank where they are electrochemically oxidized to generate electrical power. The exhaust species, which are primarily H_2O and CO_2 with some unspent fuel, are compressed and stored in the pressurized “exhaust” tank.

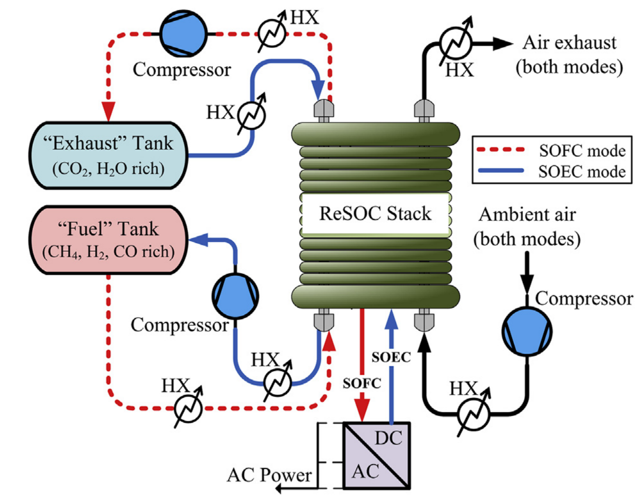

Fig. 1. Simplified schematic of a stand-alone energy storage system utilizing reversible solid oxide cells (ReSOCs).

Airflow is delivered to the ReSOC stack in both modes of operation. In SOFC mode, air provides oxygen for the global electrochemical oxidation reactions; while in SOEC mode, air acts as a sweep gas to reduce the partial pressure of generated oxygen from the electrochemical reduction of steam/CO_2, thereby increasing the efficiency of fuel production.

ReSOCs themselves are capable of achieving highly efficient (>80%) roundtrip performance for energy storage applications [12,13]; however, the roundtrip system efficiency must also be assessed, including considerations for thermal integration and parasitic energy from system components, such as compressors. The EES system concept presented in Fig. 1 motivates lines of investigation towards determining desirable storage tank gas compositions and pressures, and establishing ReSOC stack temperature, pressure, and reactant utilizations to achieve roundtrip efficiencies that are competitive with other EES technologies.

Here we present a viable system configuration based on the ReSOC concept suitable for intermediate- (~MWh) and large-scale (GWh) EES applications. Roundtrip system efficiency estimates are generated from computational modeling using performance on par with state-of-the-art H_2/steam fueled ReSOCs in conjunction with a thermal management strategy during electrolysis mode that relies on exothermic methanation within the ReSOC. Parametric studies of important ReSOC operating conditions, including stack temperature, pressure, and fuel utilization are conducted with the objective of determining suitable operating points that retain the theoretically high energy conversion efficiency of the ReSOC stack itself.

1.1. System integration challenges

One significant challenge of designing the proposed system is its thermal management. The hydrogen oxidation and steam reduction reactions are highly exothermic and endothermic, respectively, such that under typical operation the SOFC mode requires excess heat rejection while SOEC mode requires heat supply to maintain the desired ReSOC operating temperature. Another thermal management challenge is integrating ambient temperature gas storage and high temperature electrochemical energy conversion in the ReSOC stack. Because the system includes storage of vapors, specifically H_2O, there is an added complication of storing and compressing both gaseous and liquid reactants and products.

Among the above system design issues, overcoming the endothermic electrolysis process such that the system is thermally self-