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Design and techno-economic analysis of high efficiency reversible solid oxide cell systems for distributed energy storage

Christopher H. Wendel, Robert J. Braun *

Department of Mechanical Engineering, College of Engineering and Computational Sciences, Colorado School of Mines, 1610 Illinois Street, Golden, CO 80401, USA

HIGHLIGHTS

- Reversible SOC systems for distributed electricity storage are conceptualized.
- Computational modeling is used to assess system energetic and economic performance.
- Impact of water management strategy via different configurations is assessed.
- Roundtrip efficiency of nearly 74% and storage density of 90 kWh/m^3 are achieved.
- Capital cost is used to assess tradeoffs between efficiency and energy density.

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ABSTRACT

Reversible solid oxide cell (ReSOC) systems are conceptualized and analyzed to assess technical performance in distributed energy storage applications (100 kW/800 kWh). The ReSOC systems operate sequentially between fuel-producing electrolysis and power-producing fuel-cell modes with intermediate tanking of reactants and products. Maintaining the high conversion efficiencies seen in laboratory-scale cell tests at the system-level requires careful system design to integrate storage and electrochemical conversion functions. By leveraging C–O–H reaction chemistry and operating at intermediate temperature, the ReSOC is mildly exothermic in both operating modes, which simplifies balance-of-plant integration and thermal management. System configurations explored herein range from a simple system with minimal balance-of-plant components to more complex systems including turbine expansion for increased electrical efficiency, and separating water for higher energy density storage. The efficiency, energy density, and capital cost tradeoffs of these configurations are quantified through computational modeling. Results indicate that a roundtrip efficiency of nearly 74% is achieved with relatively low tanked energy density (~20 kWh/m^3) for systems configured to store water-vapor containing gases. Separately storing condensed water increases energy density of storage, but limits efficiency to 68% based on the energetic cost of evaporating reactant water during electrolysis operation. Further increases in energy density (to 90 kWh/m^3) require higher storage pressures (e.g., 50-bar nominal) which lower roundtrip efficiency to about 65%. Cost of energy storage is strongly influenced by stack power and system energy densities because the storage tanks and stack comprise a majority of the system capital cost.

1. Introduction

Electrolysis with solid oxide cells to generate fuel and other products from electricity is an attractive option for utilizing excess renewable energy generation [1–4]. This technology can also be used in a more traditional energy storage capacity by operating sequentially in both electrolysis and fuel cell modes to compete with advanced batteries, compressed air, and pumped hydro energy management methods [5–9]. Achieving competitive performance with reversible solid oxide cells (ReSOC) requires advancement in both materials and system design to enable efficient and inexpensive operation. The unique characteristics of solid oxide cells (i.e. high temperature, carbonaceous reactants) allow them to exceed the roundtrip energy storage efficiency of typical low-temperature reversible fuel cells [10]. This study explores different system configurations and operating conditions in order to evaluate the potential of ReSOCs to compete with present and future energy storage technologies. It presents the first system

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* Corresponding author.
E-mail addresses: christopherhwendel@gmail.com (C.H. Wendel), rbraun@mines.edu (R.J. Braun).

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configuration and economic trade study assessing high-temperature reversible solid oxide cells serving as a distributed energy storage system.

The considered system operates in either fuel cell (SOFC) or electrolysis (SOEC) modes with intermediate tanked storage of reactants and products. Fig. 1 shows a simplified schematic of the envisioned process. The energy storage system charges by operating the ReSOC stack as an electrolyser, in which exhaust species – primarily H_2O and CO_2 – are discharged from a storage tank, heated, delivered to the stack, and co-electrolyzed with an input of electricity to produce a fuel mixture. The generated fuel is cooled and compressed to a separate storage tank for later use. The system discharges by operating in SOFC mode, in which the tanked fuel mixture is preheated, delivered to the stack and electrochemically oxidized, producing electricity and exhaust species to re-fill the exhaust tank.

An oxidant flow is required in the SOFC mode to provide oxygen for the electrochemical reactions and regulate stack temperature. In SOEC mode, the airflow acts as a sweep gas to increase electrical efficiency by diluting generated oxygen in the oxygen channel and serves as a heat sink for exothermic operation.

Some unique challenges arise in designing ReSOC systems, including: (i) overcoming the thermal disparity between fuel cell (typically exothermic) and electrolysis (typically endothermic or near thermoneutral) operation using a unitized cell-stack and common hardware, (ii) selecting configurations and operating conditions (T, p, utilization, composition) that promote high efficiency in both operating modes, and (iii) thermal integration between high temperature stack operation and lower temperature, pressurized storage. Furthermore, because reaction products are tanked for use in the opposite mode of operation, they must be processed to enable compression to storage pressure with minimal energetic cost.

The systems under consideration simplify system thermal management by combining co-electrolysis with in-situ fuel synthesis (i.e., methanation) and electrochemical oxidation with internal fuel reforming such that the stack is slightly exothermic in both SOFC and SOEC modes. By using this strategy, the cell can operate exothermically at electrolysis voltages that would otherwise be endothermic, enabling increased electrical efficiency without utilizing an external heat source. This approach enables high efficiency and thermally self-sustaining operation, but requires operating the ReSOC stack under conditions that promote methane formation in electrolysis mode. Methanation is catalysed on nickel present in the ReSOC fuel electrode and is promoted by low temperature and high pressure stack operation.

Promoting in-situ methanation in ReSOCs has been considered previously for energy storage applications. Bierschenk et al. [6] showed thermodynamic analysis indicating that operating the stack at 600°C and/or 10 atm promotes sufficient methane formation for system thermal management. Wendel et al. [11] presented modeling analyses of large-scale (>10 MW) ReSOC systems showing roundtrip efficiency >70% at stack operating conditions of 680°C and 20 bar. Wendel et al. [12] also employed cell-stack models using parameters fitted from experimental button cell data to explore the effects of reactant composition, flow configuration, and current density on roundtrip efficiency and stack thermal behavior. Jensen et al. [5] considered large-scale ReSOC systems (250 MW) coupled with underground cavern storage of methane and carbon dioxide. The system achieved roundtrip efficiency of 70% and cost of 3 ¢/kWh performing load-levelling services with high penetration of wind energy. For comparison, low temperature reversible fuel cell systems typically achieve roundtrip efficiencies of 20–55% [13–15].

1.1. Objectives

The objective of this work is to determine favorable system configurations and operating conditions for stand-alone ReSOC systems by evaluating the technical and economic performance for distributed scale energy storage applications (~100 kW/800 kWh). This objective is achieved by simulating roundtrip operation of a ReSOC system through steady-state computational modeling with a physically based ReSOC model and thermodynamic system component models. The ReSOC model was previously calibrated to high performance intermediate temperature magnesium- and strontium-doped lanthanum gallate (LSGM)-electrolyte cells operated at 600°C [12]. Various system configurations are evaluated based on roundtrip efficiency, tanked energy density, and capital cost. The conclusions from this study inform major design decisions that have not been considered in prior publications including storage conditions, system operating conditions, BOP configuration, and system hardware. These conclusions – along with the methods described herein – provide an important foundation for continued analysis and eventual deployment of ReSOC energy storage systems.

First, the thermodynamics of ReSOC operation are considered by comparing steam–hydrogen, methane-CO_2/H_2O red-ox, and

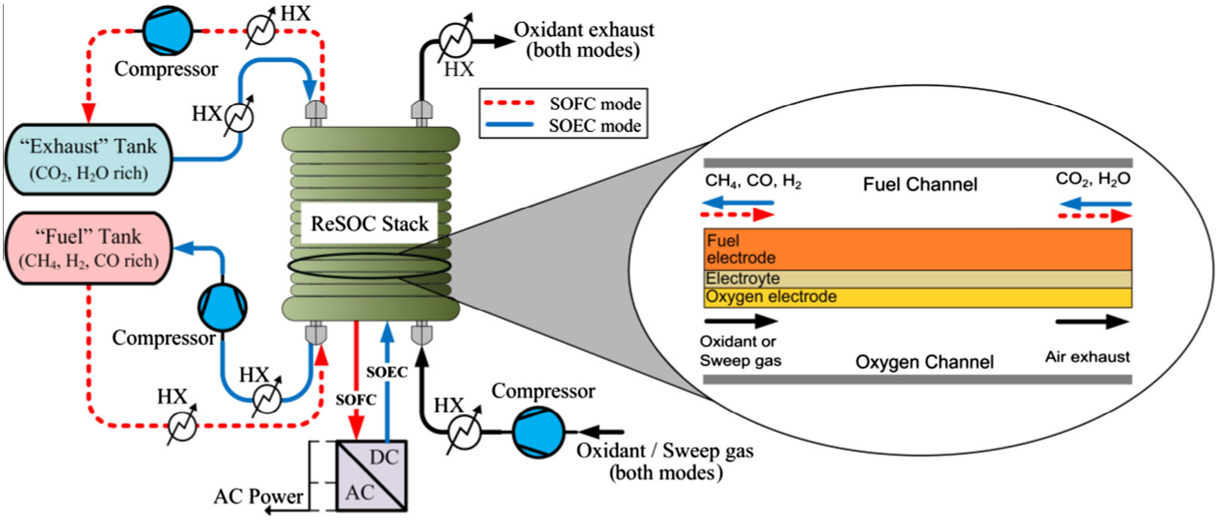

Fig. 1. Simplified schematic of a reversible solid oxide cell system and cell schematic showing fuel channel, oxidant channel, and membrane electrode assembly.