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# Techno-economic and off-design analysis of stand-alone, distributed-scale reversible solid oxide cell energy storage systems

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## ABSTRACT

Reversible solid oxide cells may be a cost competitive energy storage technology at the distributed scale. Leveraging C–O–H chemistry and operating near 600 °C allows the cells to be exothermic in both modes, improving efficiency and operability. This study characterizes ReSOC balance-of-plant hardware off-design performance to investigate component mode compatibility, the effect of tank dynamics, and part-load performance for a 100 kW/800 kWh plant. We also introduce a variable volume floating piston tank concept to improve energy storage density and evaluate operability advantages. Results show that with proper system design, balance-of-plant components are compatible, and tank dynamics have minimal impact when tanks are uninsulated and designed for storage near ambient temperature. System AC roundtrip efficiency is between 53% and 54%, depending on the tank technology selected and the compressor operating approach. Energy density is 84.4 kWh/$m^3$ for rigid tanks, and 146.1 kWh/$m^3$ for the variable volume tank concept at 100 bar storage pressure. This study also shows that ReSOC systems can maintain high efficiency at part-loads as low as 15% of rated capacity. Economic analysis of the system estimates an installed capital cost of $422–452/kWh, and a levelized cost of storage of 18.8–19.6 ¢/kWh, values competitive with state-of-the-art battery technology.

## 1. Introduction

Electrical energy storage (EES) is expected to play a critical role in enabling greater penetration of renewables, but current technologies suffer from geological constraints, capacity limitations, and high cost [1–3]. Pumped-hydro storage is the most mature energy storage technology that accounts for the largest share of energy storage capacity worldwide, but has little opportunity for future growth due to its low energy density and the limited availability of suitable geological sites [2,4,5]. Compressed air energy storage (CAES) is another relatively mature technology, but also suffers from limited geological structures suitable for grid-scale storage plants, and conventional CAES also requires fossil fuel combustion resulting in some emissions [4]. Adiabatic CAES with thermal energy storage resolves the latter issue, but development of this technology has yet to proceed past the demonstration plant stage [5–9]. Redox flow batteries are an active area of energy storage research, but conventional electrolyte materials (e.g., vanadium) suffer from low energy density and high cost [4]. Several studies have reported that zinc-iron flow batteries may be able to achieve low energy storage costs, but this electrolyte combination requires a significant amount of additional research to understand cell behavior at higher states of charge, long-term durability and scale-up [10–12]. Lead acid, sodium-sulfur, and lithium-ion batteries are all mature technologies, but experience limitations in life, energy density, and/or cost [5].

A reversible solid oxide cell (ReSOC) is a ceramic electrochemical energy conversion device with similarities to both solid oxide fuel cells (SOFCs) and solid oxide electrolysis cells (SOECs) that can provide energy storage services. By operating sequentially between power-producing fuel cell mode and fuel-producing electrolysis mode, this device functions as a flow battery. Storage of fuel ($H_2$, CO, $CH_4$) and exhaust ($H_2O$, $CO_2$) in tanks at the distributed scale and large caverns at the grid scale allows ReSOC systems to provide stand-alone EES services [13–15].

Whereas the more common ReSOCs employ hydrogen and steam as the sole feedstocks and operate at 700–850 °C [16–18], this study considers intermediate temperature ReSOCs that employ carbonaceous reactants and promote internal methane reforming (fuel cell mode) and methanation (electrolysis mode). This strategy allows mildly exothermic operation in both modes, reducing or eliminating the need for external heat input or high over-potential (lower efficiency) operation during electrolysis [19,20]. Recent studies on intermediate-temperature cells using strontium- and magnesium-doped lanthanum gallate (LSGM) electrolytes have shown high performance at temperatures as low as 550–650 °C [21–28]. For example, one of these studies [22] identified

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area specific resistances as low as 0.18 Ω-cm$^2$ at 650 °C and a 50 mol% $H_2/H_2O$ mixture, and 0.40 Ω cm$^2$ at 594 °C with a syngas mixture (25%-$H_2$, 25%-$CH_4$, 38%-$H_2O$, 12%-$CO_2$).

While intermediate temperature carbonaceous ReSOCs have shown promise at the cell and short-stack scale, the technology has yet to progress to larger demonstration units or commercialization. Advances in system design, simulation, and economic analysis are critical to bridge the gap between experimental work and early commercialization, which would most likely serve the distributed energy storage scale below one MW in net power output and below 10 MWh of energy storage capacity [29]. Recent studies have developed viable system concepts, methodologies and approaches to design, and offered the potential economic outlook for energy storage based on emerging ReSOC technology [13–15,19,29]. Nevertheless, additional system research is necessary to move beyond the prior quasi-steady state design analysis towards understanding detailed system design requirements, higher fidelity off-design performance estimations, and optimal operating parameter selection that will minimize storage cost. More specifically, tanks are inherently dynamic, and balance-of-plant (BOP) component performance requirements vary between operating modes. Variations in tank properties could significantly affect system performance, and without considering BOP component off-design, it is difficult to say with certainty that those components can be used in both operating modes.

For these reasons, previous studies have recommended investigation of tank dynamics and BOP component off-design characteristics as a next step in the ReSOC technological development process [15].This study incorporates these design aspects to provide the most detailed performance and economic predictions for distributed-scale ReSOC systems to date. We assign design points and off-design characteristics to hardware to analyze mode compatibility and part-load performance. This paper also introduces a novel variable volume, “floating piston” tank concept to improve energy storage density, reduce tank transients, and compare dynamics to those of conventional rigid tanks. Finally, we calculate the levelized cost of storage for the system to compare to other energy storage technologies.

### 1.1. The case for co-electrolysis in intermediate temperature ReSOCs

Most ReSOC development has been for high-temperature hydrogen-steam systems and co-electrolysis systems that focus on production of a hydrogen and carbon monoxide syngas mixture from feedstocks of water and $CO_2$ [30–35]. This is in part because ReSOCs are typically constructed with materials limited to operating above 750 °C, such as nickel-impregnated yttria-stabalized zirconia (Ni-YSZ) cermets for the fuel electrode, a dense YSZ electrolyte, and lanthanum strontium-doped manganite (LSM) or LSCF for the oxygen electrode [16–18,21]. At these temperatures reaction thermodynamics favor production of carbon monoxide and hydrogen over methane [19]. Furthermore, hydrogen, carbon dioxide, and carbon monoxide are widely seen as the building blocks for synthetic fuel production [35–40]. Co-electrolyzing water and $CO_2$ with renewable electricity to produce syngas can serve as the initial step in production of methane via the Sabatier reaction [41,42], methanol [43], or liquid fuels via the Fischer-Tropsch process [44].

However, high temperature electrolysis systems have a few drawbacks. Startup time, hardware cost, durability, and balance-of-plant complexity generally increase with temperature [19]. Furthermore, many of these studies assume that the electrolysis cell stack is operated near the thermoneutral voltage to improve efficiency, and as a result, either additional electricity or external heat from concentrated solar, geothermal, or nuclear sources must be available to generate steam [36–39]. Requiring such an external heat source limits the flexibility and increases the complexity of an electrolysis system [20]. These systems may also be limited in turndown or part-load capacity, as operating the stack below the thermoneutral voltage could lead to large temperature gradients, causing excessive thermal stress [36,37]. Stable operation over a wide part-load range will be highly beneficial for any electrolysis system that must follow intermittent renewables.

Preliminary studies have shown that ReSOCs can achieve high efficiency and stable electrolytic operation by operating at intermediate temperatures, elevated pressure, and with carbonaceous reactants. Three primary reactions take place at the fuel electrode of a ReSOC: fuel oxidation (or exhaust reduction), steam-methane reforming (or methanation), and the water-gas shift (or reverse shift) process. In fuel cell mode, the endothermic steam-methane reforming reaction serves as a heat sink for the highly exothermic fuel oxidation reaction. In electrolysis mode, the exothermic methanation reaction provides heat for the endothermic exhaust reduction reaction. Promoting the methanation reaction by operating at intermediate temperature (600 °C) and elevated pressure with as low of a hydrogen-to-carbon ratio as can be tolerated without carbon deposition serves as the thermal management strategy for ReSOCs [19]. As will be shown, ReSOCs can be designed and operated in a manner that maintains cell voltage above the thermoneutral voltage, even at significant part-load. This approach is key to enabling ReSOC systems to operate efficiently across a wide range of loads without significant fluctuations in stack temperature. Furthermore, higher syngas methane content increases energy storage density, allowing smaller and less costly tanks.

### 1.2. Objectives

This paper aims to provide a detailed description of the design, performance, and cost of a distributed-scale reversible solid oxide cell energy storage system based on LSGM electrolytes. The 100 kWe/800 kWh system study performed by Wendel et al. [15] serves as a starting point. That study demonstrated that storing at 50 bar and separating water from the stack exhaust streams results in a lower storage cost than storing steam, due to significantly reduced tank temperature and volume. The ReSOC system described here is designed for nominal storage pressure of 100 bar, with an atmospheric pressure stack. Though previous studies have shown that pressurization of the stack can be beneficial for ReSOC energy storage [19], we present an atmospheric stack design here to better approximate realistic constraints on a first-of-a-kind, intermediate temperature ReSOC system with a carbonaceous feedstock.

The previous study by Wendel et al. calculated performance and cost based on a “snapshot” of the system in time, using average tank conditions rather than a simulation of operation throughout a charge/discharge cycle. It also assumed that BOP components such as compressors and heat exchangers would be compatible in both modes. Because fuel and exhaust feedstocks are stored in the vapor phase, their temperature and pressure may change as tanks are emptied or filled. These changes, along with different flow rates in different operating modes, could influence the performance and viability of the BOP machinery, which in turn effects system performance and cost.

Finally, the previous study did not consider operation away from rated power. Part-load and load-following are crucial features for any energy storage technology that must follow variable renewable energy resources, such as wind and solar. Although complete system transient analysis is beyond the scope of this work, some effort to characterize system performance at part-load is warranted. This work strives to answer the following questions:

1. Are balance-of-plant components compatible between operating modes and do they function sufficiently at part-load?
2. What effects do tank dynamics have on system performance? Could a variable volume tank reduce the levelized cost of storage relative to rigid tanks?
3. Can the ReSOC system be designed to accommodate a large part-load operating envelope, and if so, how?