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Benchmarking the expected stack manufacturing cost of next generation, intermediate-temperature protonic ceramic fuel cells with solid oxide fuel cell technology

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HIGHLIGHTS

- First production cost estimate of protonic ceramic fuel cell (PCFC) stacks.
- PCFC stack manufacturing cost estimates range up to 27–37% lower than SOFC.
- PCFC stack manufacturing cost estimates can be as much as 41% lower than MCFC.
- Solid-state reactive sintering (SSRS) cost estimate confirms promising cost saving.
- Greatest uncertainty in stack cost lie with seals, interconnects and assembly.

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ABSTRACT

Recent progress in the performance of intermediate temperature (500–600 °C) protonic ceramic fuel cells (PCFCs) has demonstrated both fuel flexibility and increasing power density that approach commercial application requirements. These developments may eventually position the technology as a viable alternative to solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs). The PCFCs investigated in this work are based on a $BaZr_{0.8}Y_{0.2}O_{3-\delta}$ (BZY20) thin electrolyte supported by BZY20/Ni porous anodes, and a triple conducting cathode material comprised of $BaCo_{0.4}Fe_{0.4}Zr_{0.1}Y_{0.1}O_{3-\delta}$ (BCFZY0.1). These cells are prepared using a low-cost solid-state reactive sintering (SSRS) process, and are capable of power densities of 0.156 W cm^{-2} at 500 °C operating directly from methane fuel. We develop a manufacturing cost model to estimate the N^{th} generation production costs of PCFC stack technology using high volume manufacturing processes and compare them to the state-of-the-art in SOFC technology. The low-cost cell manufacturing enabled by the SSRS technique compensates for the lower PCFC power density and the trade-off between operating temperature and efficiency enables the use of lower-cost stainless steel materials. PCFC stack production cost estimates are found to be as much as 27–37% lower at 550 °C than SOFCs operating at 800 °C.

1. Introduction

Fuel cells convert hydrogen, alcohol and hydrocarbon fuels into electricity with a higher efficiency and are less harmful for the environment than most conventional combustion-based distributed generation systems. Solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) have been used to demonstrate some of the highest electric conversion efficiencies for power generation equipment, particularly at distributed scales [1,2]. Their high operating temperature enhances fuel processing options and increases fuel flexibility. However, the high operating temperature also has drawbacks including large heat transfer loads for preheating the reactants, relatively slow dynamic response, faster degradation rates, lower durability, and high-cost materials [3]. Characteristics that include low activation barrier of protons in the electrolyte at lower temperature, novel cost-effective fabrication, and the development of a triple-conducting cathode specifically designed for protonic ceramic material sets rather than derived from SOFCs, have recently enabled high performance protonic ceramics fuel cells (PCFCs) [4–10]. The lower operating temperature

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PCFC has emerged as a potential solution to challenges encountered by SOFCs, such as durability and high-cost stack and balance-of-plant (BOP) hardware [8]. The combination of achieving high performance at low operating temperature and enabling low cost manufacturing techniques represents an opportune time to assess the economic outlook of PCFC stack technology compared to its higher temperature counterparts –namely SOFC and MCFC technologies. In particular, the overall analysis described in this work examines the trade-off between lower cell power densities (due to lower operating temperature) and lower-cost materials, manufacturing processes, and balance-of-stack components.

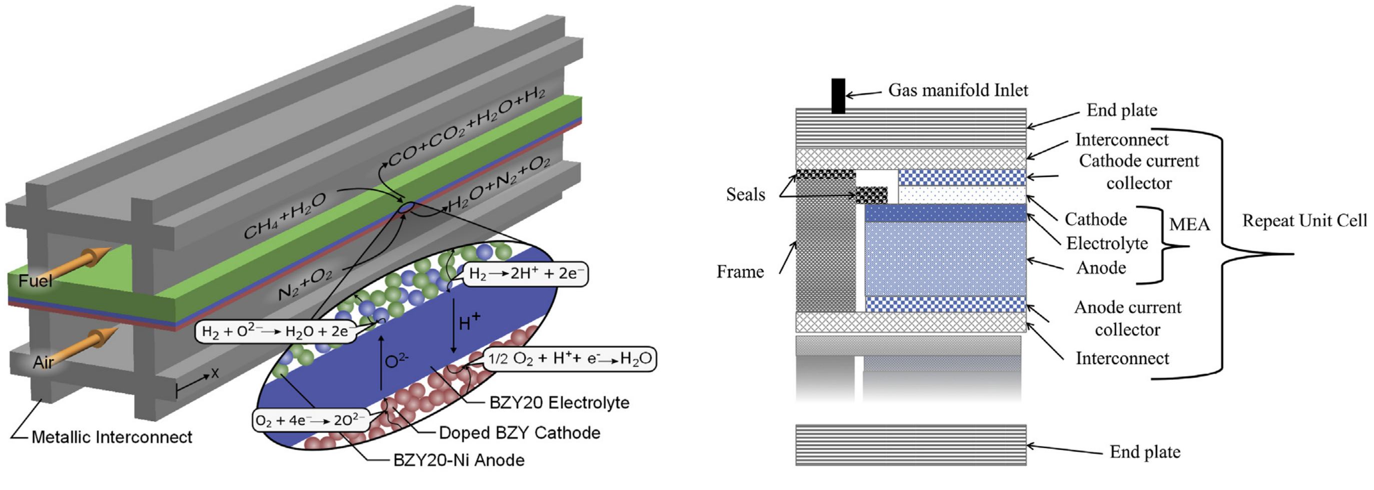
The main objective of this work is to provide a high volume, mature manufacturing cost estimation of PCFC stacks and compare them with SOFC and MCFC technology. The developed cost model accounts for the different cell manufacturing methods and the lower operating temperature of PCFCs. Stack power density is a parameter that relates to many techno-economic variables of importance, including performance, cost, and operating temperature. A primary motivation of this work is understanding the cost competitiveness of PCFC technology, its sensitivity to various stack design and economic parameters, and identification of power density requirements for cost parity with more mature, high temperature fuel cell technology. Thus, this paper aims to establish the techno-economic trade-off between lower cell operating temperatures (and the associated benefits of lower-cost materials and enhanced durability) and cell power density for the emerging planar PCFC stack technology described herein.

There are several important differences between MCFC, SOFC and PCFC operation and the material sets employed which strongly influence PCFC stack design and cost. In a PCFC, protons formed from hydrogen ionization reactions are transported from the fuel-side anode to the air-side electrode, where they react with oxygen to form water at the cathode, as illustrated in Fig. 1.(a). PCFC electrolytes, such as yttrium-doped barium zirconate (BZY), can conduct multiple charged defects (e.g., polarons, ions, electron holes) depending on temperature and gas environment and are, therefore, fundamentally different from oxygen-ion conducting SOFCs or carbonate conducting MCFCs. The BZY perovskite materials hydrate in the presence of water vapor pressure and are predominantly proton conductors. However, the presence of oxygen vacancies in these materials also enables oxygen transport (typically only 1–10% of the ionic conduction in PCFCs [11]). They also exhibit a small amount of electronic conductivity in oxidizing atmosphere, but without being detrimental for the operation of the fuel cell. The PCFC anode is made of a BZY-Ni ceramic metal composite (referred to as cermet) which promotes separate electronic and ionic conducting phases and charge transfer reactions at the three phase boundary (TPB) (see Fig. 1). The nickel-doped anode surface promotes heterogeneous steam methane reforming and water-gas shift reactions such that operation under humidified methane or other hydrocarbon fuel sources is possible. Breakthroughs in cathode materials for PCFCs have enabled 'triple conducting' characteristics which substantially lower cell polarization and higher power densities at practical voltage and current density conditions [10].

Table 1 summarizes the electrochemistry and the respective operating temperature of the fuel cell types studied here. In contrast to PCFCs, the oxygen conducting SOFC operates 200–300 °C higher and electrochemically oxidizes hydrogen and some carbon monoxide (the preferred pathway is water-gas shift for CO conversion), producing both water and CO_2 at the anode. The mixed ionic conduction in PCFCs produces water vapor at both the cathode and the anode. In hydrocarbon-steam fuel mixtures, the water vapor content in the anode decreases as internal fuel reformation consumes more water vapor than is formed via electrochemical oxidation [12]. Thus, both the cathode and anode sides of the PCFC can experience high moisture content, depending on how much excess air is required to maintain cell temperature.

Only button cells PCFCs have been tested up to now for several reasons: i) the BZY based materials require very high sintering temperature, and the preparation of larger cells can be problematic, even though this problem can be alleviated by using solid-state reactive sintering [13–19]; ii) the lack of appropriate interconnects, sealants and housing materials with matching thermal and chemical expansion coefficient. However, the performances reported on button cells are very promising and generates a lot of interest [4–10].

The economics of fuel cell systems are usually expressed in terms of capital and life cycle costs, and both of these economic metrics strongly influence the perception of the affordability of fuel cell systems, as well as their expected value proposition in various markets. The capital cost of fuel cell stacks is typically estimated to



(a.) PCFC channel (b.) PCFC stack

Fig. 1. PCFC channel and stack configurations.