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Comprehensive review of methane conversion in solid oxide fuel cells: Prospects for efficient electricity generation from natural gas

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ABSTRACT

Natural gas is an important energy resource for electric power generation and other energy needs. Recent discoveries of vast reserves of shale gas greatly increased its abundance while lowering its cost. Combined with its significantly smaller carbon-footprint than coal, natural gas has increasingly become the preferred choice to generate electrical power even at the expense of converting existing coal fired power plants to run on natural gas. However, most natural gas combustion-based power plants currently operate at efficiencies in the low 30%. Conversion of natural gas in solid oxide fuel cells (SOFC) promises to increase system level conversion efficiencies to above 60%, doubling the current efficiencies and significantly reducing the CO_2 emissions by a factor of 2. Such dramatic improvements in conversion efficiency and ease of CO_2 capture are currently out of reach for the combustion-based power generation technologies. Equally importantly, the CO_2 produced from methane conversion leaves the fuel cell in a highly concentrated form. As nitrogen is blocked off by the impervious ceramic electrolyte of the SOFC from entering the process stream, methane oxidation produces a flue stream that is primarily made of the oxidation products CO_2 and steam. The latter can easily be condensed out to capture CO_2, thus eliminating the need for expensive and energy intensive post separation operations otherwise required to separate CO_2 from N_2 for storage purposes. So if successfully developed and deployed widely, natural gas conversion in SOFCs will greatly reduce CO_2 emissions, help mitigate climate change, and minimize the environmental impact of power generation.

This article organizes and critically reviews the current state of understanding in methane catalysis and oxidation with particular emphasis for electrochemical conversion in SOFCs. It presents a comprehensive review of a vast volume of published work (>600 references) extending from fundamental studies in C—H bond activation and methane catalysis to basic concepts of electrochemical conversion in fuel cells, to strategies for effective utilization of methane in SOFCs, and associated technical difficulties such as deactivation due to sulfur and carbon yet to be overcome for realizing natural gas conversion, to impactful opportunities provided by recent theoretical advances in computational catalysis and materials screening studies, and innovative concepts such as strain effects and nanostructuring toward enhancing catalytic rates. It provides tutorial-type information at the appropriate level for the uninitiated but interested reader as well as critical discussions of fundamental phenomena and assessment of recent advances for active researchers in the field. The article is weighted around materials and surface properties and provides an in-depth review with emphasis on electronic structure, charge transport and catalysis. It presents an impartial evaluation of the opportunities as well as the challenges to natural gas utilization in SOFCs. Finally, it concludes that natural gas conversion in SOFCs promises very attractive opportunities for efficient and environmentally friendly power generation, while recognizing and offering in-depth discussions of the challenges facing this technology before it can be considered for large-scale power generation applications.

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1. Background

Natural gas makes up a significant segment of the global energy portfolio and is rapidly becoming the preferred fuel for thermoelectric power generation partly because of its relatively lower carbon intensity compared to other fossil fuels such as coal and oil. In the U.S., natural gas makes up more than 27% of our energy consumption (see Fig. 1). As the least carbon-intensive fossil fuel with abundant reserves, especially after the recent finds of shale gas reservoirs in the U.S. and around the world, natural gas may serve as the "bridge fuel" during the next several decades to transition into a low-carbon energy economy. Indeed, its share in global electric power generation is expected to increase from 22% in 2010 to 24% in 2040 [1]. It is also expected that the installed capacity for natural gas-based power generation will increase more than 50% during this period.

By all accounts, fossil fuels are expected to dominate both energy consumption and electricity production at the global scale. Table 1 compares the global installed and actual production statistics for electric power generation [3]. Electricity generation relies heavily on fossil fuels, which provide more than 2/3rd of the global electricity that was generated and consumed in 2012, while the renewable energies such as wind and solar provide only a small fraction. Also note the expected discrepancy between the installed capacity and actual production for wind and solar due to the intermittency of these sources, while electricity production from fossil fuel and nuclear plants are significantly higher than installed capacity share, demonstrating their availability and reliability.

A complementary cut with growth projections by the U.S. Energy Information Administration is presented in Table 2, which summarizes the 2008 global installed capacities for six prominent power generation technologies and their expected capacities in 2035 [4]. It shows that the total electricity production is expected to increase 1.7% annually from 4623 GW in 2008 to 7272 GW in 2035. The table also highlights the large investments expected for non-OECD countries in all forms of power generation technologies to meet the demand for electricity to catch up rapidly with OECD (i.e., Organization for Economic Cooperation and Development) countries. Table 2 also clearly indicates that fossil-based power generation will likely dominate global electricity production for decades to come, where wind and solar electricity, albeit their rapid growth rates, are

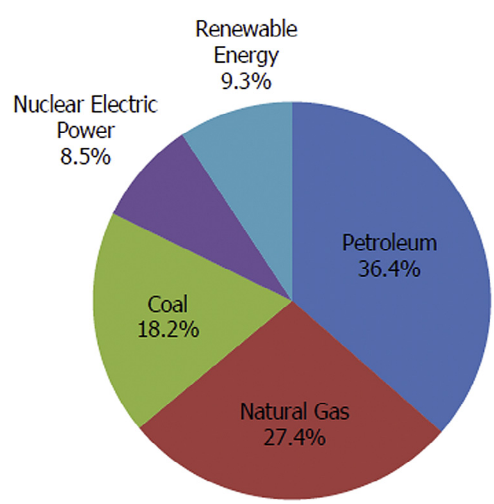

Fig. 1. U.S. energy consumption in 2012 by energy source (from Ref. 2).