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Liquids-to-Power Using Low-Temperature Solid Oxide Fuel Cells

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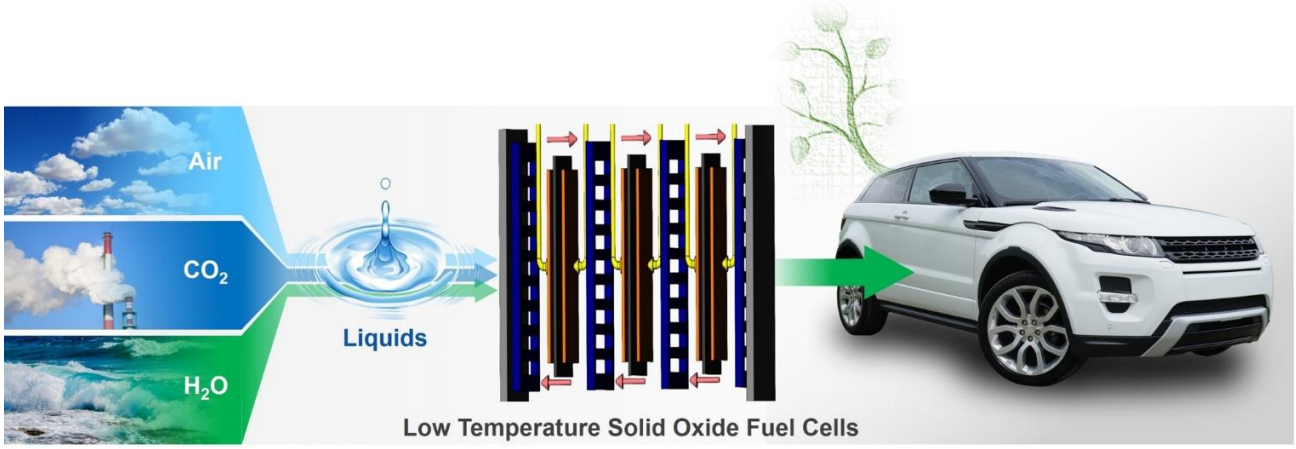

Keywords: LT-SOFC; liquid fuels; low temperatures; benefits; challenges; external reforming; automobile applications.

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Abstract

Solid oxide fuel cells (SOFCs) operating at high temperatures (>800°C) have been overlooked in the past for automotive applications, primarily due to their longer start-up times and inability to load follow (quickly respond to varying power demands). However, lower operating temperature SOFCs (LT-SOFCs) enable more rapid start-up and several other benefits. The rapid deployment of cost-effective LT-SOFC technology for automotive applications relies on the utilization of conventional ‘‘drop-in’’ fuels (e.g., gasoline, diesel, ethanol etc.), that adapts the existing fuel distribution infrastructure. In particular, the liquid-fed LT-SOFCs have the potential to deliver higher “well-to-wheels” fuel conversion efficiencies than H_2-fed fuel cells as well as take advantage of the higher fuel energy density. Therefore, this review focuses on the benefits/challenges of low-temperature SOFCs (350-650°C) running on liquid fuels. The critical role of anodes and requirements/status of advanced anode materials for the direct utilization of liquid fuels in LT-SOFCs are highlighted.

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Dr. Mohammed Hussain Abdul Jabbar is an Assistant Research Scientist (group leader for SOFC team) at the Maryland Energy Innovation Institute (University of Maryland). He is also currently serving as a Managing Editor for the International Journal of Ionics. He began his career as a Polymer Technologist (B.S. with *distinction* from Anna University, India). Later, he obtained Master of Science (M.S.) in Materials Science and Engg. from Gwangju Institute of Science and Technology (GIST), South Korea and a Doctor of Philosophy (Ph.D.) in Energy Conversion from the Technical University of Denmark, DTU. His research addresses the understanding of electrode materials for low-temperature solid oxide fuel cells. His research contributions resulted in 7 patent applications and several high-quality scientific publications.

Prof. Eric D Wachsman is Director of the Maryland Energy Innovation Institute, and Crentz Centennial Chair in Energy Research at the University of Maryland. He is a Fellow of The Electrochemical Society (ECS) and the American Ceramic Society, Vice President of ECS, Editor-in-Chief of *Ionics*, and on the Editorial Board of *Scientific Reports*, *Energy Systems*, and *Energy Technology*. His research is focused on solid ion-conducting materials, and the development of solid-state fuel cells, batteries, ion-transport membrane reactors, and gas sensors. He has more than 250 publications and 17 patents on ionic materials, and their electrocatalytic properties, and device performance.

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1. Introduction

The transportation sector alone consumes 28% of total energy produced in the United States[1]. The combustion of fossil fuels in vehicles are limited by Carnot efficiency and indeed contributes to a significant emission of greenhouse gases, with a typical passenger vehicle emitting about 4.7 metric tons of CO_2 per year, causing serious environmental consequences[2]. In contrast, energy conversion technologies such as fuel cells are cleaner than traditional technologies. In particular, solid oxide fuel cells (SOFCs) utilizing fossil fuels produce high power conversion efficiencies (~40-50%)[3], and the total system efficiency can increase even higher (~85%)[4] in combined heat and power cogeneration systems (as shown in Figure 1(a)). The cogeneration ability of SOFCs can be particularly important for direct load center applications e.g. remote data centers.

SOFCs are available in various designs/architectures, yet common to all is a dense solid electrolyte deposited with an anode and cathode on either side. SOFCs work by electrochemically converting the chemical energy stored in hydrogen (H_2), hydrocarbons (e.g., natural gas), complex liquid fuels (e.g., gasoline, diesel, kerosene-derived jet-fuel etc.) and alcohols into electrical energy, as schematically shown in Figure 1(b). The difference in oxygen partial pressure between the anode (varied depending on fuels, typically at p_{O2} = 10^{-20} to 10^{-31}atm) and the cathode (typically air, p_{O2} = 0.21 atm) generates an electromotive force across the electrodes, which drives oxygen-ion transport through the cell at an elevated temperature range, allowing electrical current to flow through the external circuit. Planar SOFC technology from a full format cell (e.g.,10×10cm), stack (a group of single cells), system (reformer, heat exchanger etc) to a plug-in-hybrid electric vehicle (PHEV) is shematically shown in Figure 1 (c-f)[5].

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State-of-the-art high-temperature SOFCs (HT-SOFCs) operate around ~800°C to ensure efficient diffusion of oxide-ion through the solid electrolyte and to accelerate electrode reaction kinetics[6]. HT-SOFCs can function independent of an H_2 economy, and can reliably operate on liquid fuels with unique advantages. Specifically, liquid fuels would enable the use of existing infrastructure to supply fuel to cars and commercial fleets. Moreover, liquid fuels possess higher theoretical energy density than H_2 and can deliver higher power output[7] and are more conveniently stored and easily transported[7b-d, 8]. Alternative liquid fuels e.g. alcohols are sulfur free and can be directly utilized in HT-SOFCs with enhanced safety and inorganic liquid fuels such as ammonia do not have a C-C bond and thus avoid deactivation of Ni-based anodes due to carbon formation[9]. However, operating SOFCs at high temperature imposes engineering challenges such as balance-of-plant, BOP (e.g., fuel processing, air management and power conditioning systems), rapid degradation caused by coarsening of electrode materials, inter-diffusion of elements between various SOFC components, higher maintenance requirements and inability to use inexpensive stainless steel as interconnects, which in turn elevates the cost of the SOFC technology[6, 10]. Especially, HT-SOFCs inability to rapidly start-up/shut-down and the limited load following capability restricts its deployment in mobile and transportation applications.

Therefore, our review article highlights the benefits and issues of low-temperature operating SOFCs (LT-SOFC, 350-650°C) running on liquid fuels. In particular, potential liquid fuels and their reforming strategies to develop robust LT-SOFC technology are described. This article further points out potential alternative anodes for LT-SOFCs that can efficiently utilize liquid fuels directly.

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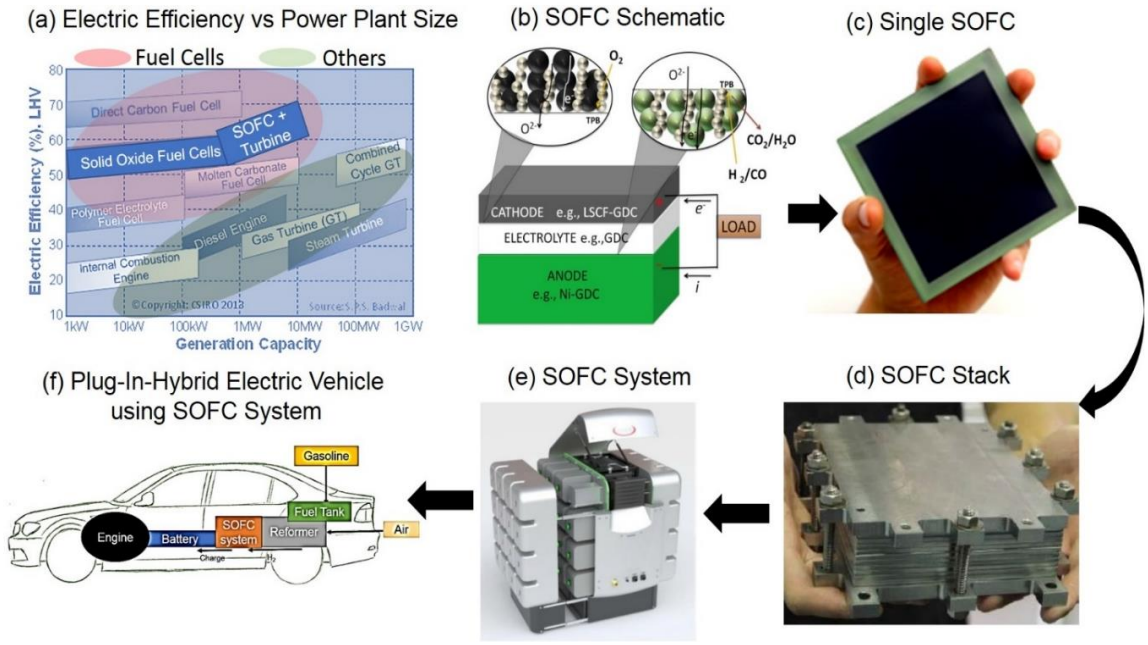

Figure 1. Illustration of SOFCs technology a) comparison of electric efficiency of fuel cells with other technologies (Figure 1a adapted from Badwal et al./CSIRO[4], b) schematic sketch of SOFC, c) actual SOFC single cell (10×10cm^2), d-e) SOFC stack assembly and system (Figure 1(c-e) adapted from Redox Power System, LLC[11]), and e) plug-in-hybrid electric vehicle (PHEV) with SOFC system as a range extender (Redrawn from Nissan e-bio fuel cell car [5]).

2. Benefits/Applications of Low-Temperature Operating SOFCs

LT-SOFC Benefits – Lowering the operating temperature of SOFCs results in decreased thermal stresses of LT-SOFC stacks allowing faster start-up and shut-down and greater load following capabilities. Further, LT-SOFCs make the power conversion technology more robust and reliable, all at a lower cost [12]. The material costs are reduced by using the less expensive stack and BOP components (e.g., stainless steel). In particular, the heat losses are minimized considerably (the heat radiation is proportional to the 4th power of temperature according to Stefan-Boltzmann's law), resulting in the requirement of less insulation leading to further cost benefits. Additionally, the electrical efficiency of SOFCs is higher at lower temperatures, especially when operated on liquid fuels. LT-SOFCs also offer improved materials stability by

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reducing inter-diffusion of elements, and vaporization of chromium (Cr) from stainless steel interconnects [13]. Importantly, high surface areas and lower particle sizes of the electrocatalysts are retained at low-temperature operation, enabling higher performance and stability[14]. Another inherent advantage of SOFC technology is reduced maintenance, due to limited moving parts in the system (e.g., blower).

LT-SOFC Applications - Figure 2 depicts various fuel options and potential application of LT-SOFCs for a wider power-hungry market. 0.01-1 kW of power production meets the requirements in the military and defense-related portable needs e.g. remote laptops, cell phones, and other electronic devices[12a, 12b, 12d]. Power production in the range of 1-10 kW for vehicular auxiliary power units (APUs), PHEVs, fuel flexible vehicles and other mobile applications. LT-SOFCs producing power in the range of 10-100 kW meet the power requirements for stationary applications e.g., residential and commercial buildings[15].

LT-SOFCs have greater power generation potential, both for centralized (e.g. stationary applications) and mobile power needs (e.g., transportation applications)[12b] due to greater load following and faster start-up/shut-down capability than HT-SOFCs[16]. For these reasons, LT-SOFCs have a unique ability to deliver relatively clean and reliable power for automotive applications. However, the issue of maintaining fuel flexibility at low temperatures remains a greater challenge for LT-SOFCs than HT-SOFCs. SOFC/battery hybrids for automotive applications are particularly attractive for the transportation industry e.g., PHEV running on liquid fuel (gasoline, ethanol etc.) with an SOFC as a range extender (*cf.* Figure 1(f)). Also, electrification of vehicle fleets using LT-SOFC based APU can significantly improve fuel economy and reduce emissions and noise for automobiles and heavy-duty trucks. Solving the issue of maintaining fuel flexibility at low temperatures with advanced anode materials would

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allow easier deployment of LT-SOFCs as APUs and range extenders for PHEVs across the automotive industries[17].

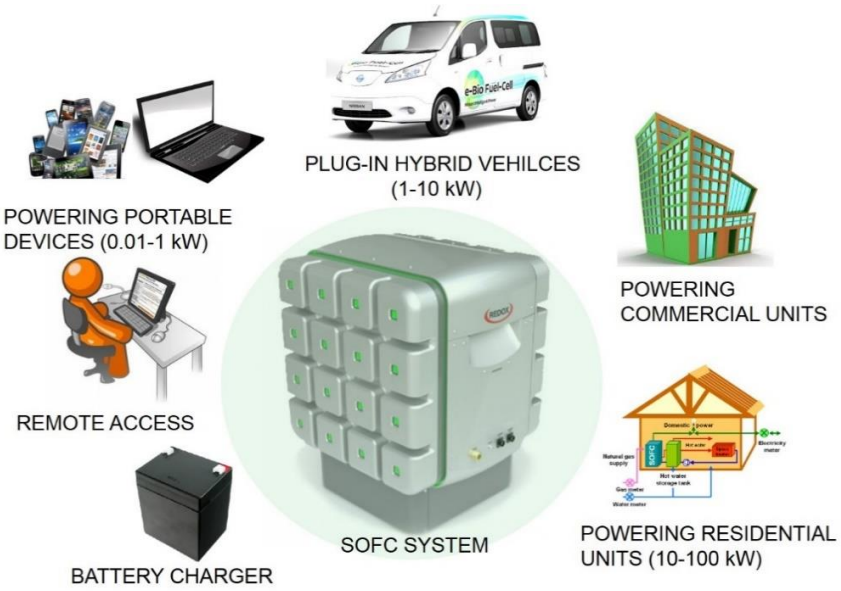

Figure 2. Fuel options and potential applications of lower temperature operating SOFC technology. Redox Cube (SOFC system) adapted from Redox Power System, LLC[11]. E-bio fuel cell car (plug-in-hybrid vehicle) adapted Nissan[5].

3. Brief Status of LT-SOFC Materials

Anodes - Anode-supported SOFCs enable reduced electrolyte thickness (~10μm) to minimize ohmic losses[18] and are the principal support for LT-SOFCs in an anode-supported SOFC configuration. Ni-GDC (Gd^{3+}-doped CeO_2) and Ni-YSZ (Y_2O_3-stabilized ZrO_2) are common cermet anodes for LT and HT-SOFCs, respectively. Ni-GDC anodes are more efficient and durable than Ni-YSZ anodes due to their higher coking resistance and sulfur tolerance capabilities. Such an ability of Ni-GDC originates from the $Ce^{3+/4+}$ redox couple and fast oxide ion conductivity in GDC[12c]. The Ni phase of Ni-GDC cermet offers both electrical conductivity and catalytic activity (e.g., H_2/CO oxidation reactions), while the GDC phase in cermet anodes

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assists in the enlargement of triple phase boundaries for effective electrode processes[19]. The microstructure of Ni-GDC cermet anodes prepared by the wet-chemical synthesis route is shown in Figure 3(a-d), the crystallinity of highly dispersed Ni and GDC was confirmed using an advanced TEM lattice imaging technique[20]. Moreover, the GDC and Ni phases occupy nearly half of the cermet composition, typically 1:1 by volume, to provide uninterrupted oxide ion and electronic conductivity. Although Ni-GDC cermet anodes are electrochemically more advantageous than Ni-YSZ certain inherent challenges still remain for both cermets e.g., redox instability, chemical stability in hydrocarbon fuels, etc.[13]. Progress has been made to increase the stability of SOFC anodes in hydrocarbon fuels either by modifying Ni-GDC anodes with additives ($H_xWO_{3-\delta}$, Sn, Cu etc.)[18, 21] or by identifying new ceramic oxide based anode materials (e.g., Nb-doped $SrTiO_3$) that can potentially replace Ni-based anodes[14a, 22].

Cathodes - Losses due to cathodes resulting from sluggish oxygen reduction reaction (ORR) kinetics is the major limitation in reducing the temperature for LT-SOFCs[23]. Popular choices of promising LT-SOFC cathodes include perovskites such as $La_{0.5}Sr_{0.5}FeO_{3-\delta}$ (LSF), $La_{0.6}Sr_{0.4}CoO_{3-\delta}$ (LSC) and $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ (LSCF)[23-24]. These perovskite oxides possess intrinsic characteristics to extend triple phase boundaries (TPB) for electrochemical reactions, due to their mixed ionic and electronic conducting (MIEC) nature. Conversely, commonly used $La_{0.8}Sr_{0.2}MnO_3$(LSM) cathodes have their TPB restricted to the cathode/electrolyte interface, unlike MIEC based materials. As shown in Figure 3(e), the area specific resistance (R_s) of LSC and LSCF are comparable and much lower than LSF[25]. Typically, cobalt-containing perovskites have high thermal expansion coefficients (TEC of ~ 20×10^{-6} K^{-1}), thus perovskite cathodes are used in combination with GDC (e.g., LSCF-GDC cathode). Such composite cathodes perform much better than single oxides. $Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ (SSC)[26] and $Ba_{1-x}Sr_xCo_{1-}$

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$_yFe_yO_{3-\delta}$ (BSCF)[27] have emerged as advanced LT-SOFC cathodes with much lower R_s (as shown in Figure 3(e)), specifically, BSCF has a relatively lower R_s of all cathodes investigated, however, it is unstable even in ambient levels of CO_2, making it unsuitable for air-fed SOFCs. We recently identified several other advanced cathode materials with lower R_s values, they include LSM-ESB($(Er_2O_3)_{0.20}(Bi_2O_3)_{0.80}$)[28] and bismuth ruthenate ($Bi_2Ru_2O_7$) pyrochlore, these cathodes are particularly suitable for LT-SOFCs with bismuth-based bi-layered electrolytes[29].

Electrolytes - SOFC electrolytes are dense, gas-tight, oxide ion conducting ceramic oxides sandwiched between the porous anode and porous cathode. Y_2O_3-stabilized ZrO_2 (YSZ) is one of the most well-developed, traditionally known electrolyte materials for SOFCs. However, it needs a high-temperature operation (800°C) for efficient oxide ion conduction. In contrast, Gd^{3+} doped CeO_2 (GDC) has fast oxide-ion conduction at lower temperatures (<700°C)[30]. Figure 3 (f) compares the various oxide-ion conductors with GDC. GDC has an oxide-ion conductivity of 0.01 Scm^{-1} at 550°C, much higher than YSZ (even at a higher temperature of ~700°C)[12a, 31]. Several other trivalent lanthanides and divalent alkaline earth cations have been (singly or doubly) doped with CeO_2 to achieve further enhancement in oxide-ion conductivity. Specifically, doubly doped Sm and Nd in CeO_2 (e.g., $Sm_{0.075}$ $Nd_{0.075}Ce_{0.85}O_{2-\delta}$, SNDC) showed 30% higher conductivity than singly doped GDC[32]. Fluorite oxide type bismuth oxide (δ-Bi_2O_3) is another fast-oxide ion conductor at low-temperatures. For example, $(Dy_2O_3)_x$-$(WO_3)_y$-$(Bi_2O_3)_{1-x-y}$ (DWSB) with 2:1 dopant ratio of Dy to W has an even higher oxide-ion conductivity of 0.1 Scm^{-1} at 500°C. This value is 3 times higher than $(BiO_{1.5})_{0.8}(ErO_{1.5})_{0.2}$(ESB), and 10 and 100 times higher than GDC and YSZ electrolytes, respectively[12a]. Other potential electrolyte materials for LT-SOFCs include $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$, LSGM, perovskite oxides, which have a higher conductivity than GDC[33] but are expensive due to the presence of Ga.

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Interconnects - Interconnects distribute fuel and air in the SOFC stack and also provide the necessary electrical and thermal connections between anode and cathode. Low-temperature operation of SOFC allows the replacement of expensive ceramic oxides e.g., doped-$LaCrO_3$ and high chromium alloys with inexpensive metal alloys (e.g., stainless steel)[34]. Utilizing metal-based interconnects has several advantages, such as high electronic and thermal conductivity at a lower cost[34b]. In particular, the high electronic and thermal conductivity of metal-based interconnect plates enable low ohmic resistance and enhanced heat conduction of fuel and air for efficient electrochemical reactions at the electrodes.

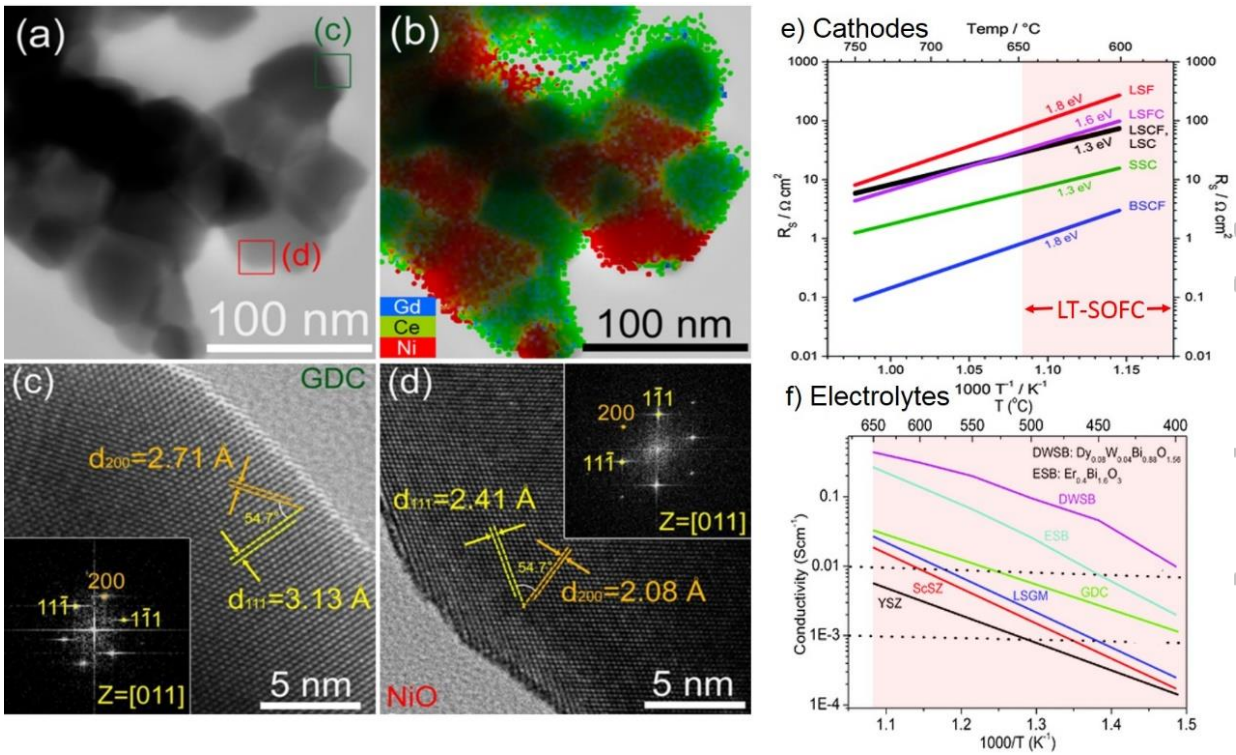

Figure 3. a-b) TEM morphology of Ni-GDC prepared by wet chemical method (reprinted from reference[20]), c-d) TEM lattice imaging of GDC and Ni using fast Fourier transform patterns (reprinted from reference[20]), e) area specific resistances of various cathodes suitable for LT-SOFCs (reprinted from reference[25]), and f) oxide ion conductivity of various LT-SOFC electrolytes (reprinted from references [12a, 35]).

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4. Specific Challenges Related to Liquid-Fed LT-SOFCs

Choosing an ideal SOFC operating temperature depends on several factors including desired lifespan, cost, fuel type, geometry, efficiency, start-up time, waste heat quality, etc[10]. Undoubtedly, lowering the operating temperature of SOFCs has several advantages, however, they are not free from challenges and have to be addressed for the rapid progress of the technology. Figure 4 (a) highlights specific challenges associated with the development of liquid-fed LT-SOFCs. SOFCs commonly operating at high temperatures permit direct utilization of hydrocarbon fuels by converting them into hydrogen on the anode by internal reforming, reducing the need for external fuel processors. In contrast, the lower operating temperature of LT-SOFCs may require an external reformer for efficient and robust long-term operation. The theoretical maximum efficiency of LT-SOFCs operating in H_2 as fuel is higher than HT-SOFCs (*cf.* Figure 4 (a)), however, the sluggish electrode kinetics of electrodes at low temperatures can diminish this thermodynamic advantage. It is thus important to develop highly efficient electrode materials for LT-SOFCs to increase the fuel reaction kinetics.

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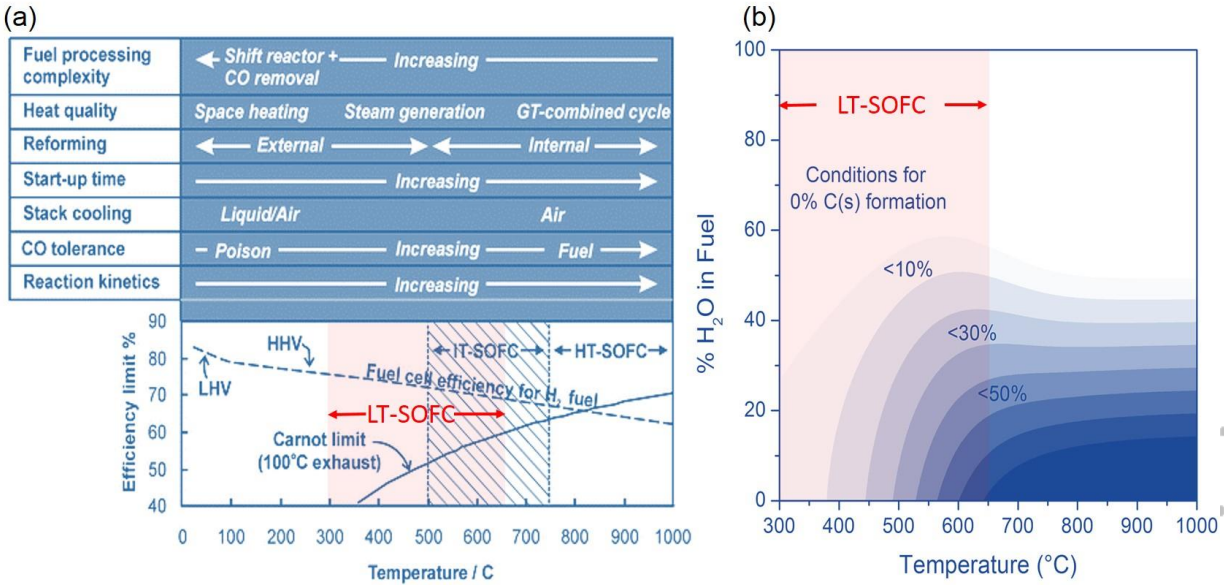

Figure 4. a) Critical considerations on operating temperature of SOFCs (reprinted from reference[10]), and b) thermodynamically predicted conditions for carbon formation in methane, as a function of temperature and H_2O content (reprinted from reference[36]).

The feasibility of direct utilization of liquid fuels in LT-SOFCs depends primarily on the nature of the anode materials and microstructure. Following are some of the major challenges of conventional Ni-based anodes that are traditionally employed in SOFCs.

Coking - A critical issue that needs significant attention with Ni-based anodes is the formation of solid carbon when operated on hydrocarbon containing fuels. Ni-based cermet anodes utilizing hydrocarbon liquid fuels may react homogeneously in the gas-phase and/or heterogeneously on the surface of the anode leading to carbon deposition[37]. In the heterogeneous reaction, hydrocarbon fuel is adsorbed onto the Ni surface and undergoes a dehydrogenation reaction resulting in the deposition of carbonaceous substances, such as adsorbed carbon, that form clusters and eventually coke, which can fill up the anode pores and even penetrate the grain boundaries causing mechanical damage to the anode[38]. Carbon deposition is problematic at all SOFC operating temperatures. At temperatures >650°C, methane cracking by pyrolysis ($CH_4 \rightarrow C + 2H_2$) is favored, while CO disproportionation ($2CO \rightarrow C + CO_2\ i.e.,$ Boudouard reaction)

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and CO reduction reaction ($CO + H_2 \rightarrow C + H_2O$) are favored at lower temperatures. Coking can be suppressed either by steam reforming ($CH_4 + H_2O \rightarrow CO + 3H_2$) or by water-gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$); however, both require large quantities of steam, affecting the cell voltage. As shown in Figure 4(b), carbon formation is thermodynamically less favored with an increase of H_2O content in the fuel. Specifically, at low temperatures (<500°C), the requirement of H_2O is >50% to completely eliminate carbon formation[36].

Sulfur Poisoning - A common issue with hydrocarbon containing liquid fuels is the presence of contaminants such as sulfur. Sulfur tends to poison the Ni-based SOFC anodes, resulting in performance decay and eventual disintegration of the entire cell [39]. Impurities such as sulfur have to be removed to very low levels (down to a 1 ppm) for Ni-based cermets as SOFC anodes[40]. Upon exposure to sulfur, an initial and rapid degradation in SOFC performance occurs due to the adsorption of sulfur species on active Ni-sites in the anode, which block the various processes for H_2 oxidation (absorption, dissociation, migration, and charge-transfer)[41]. On continuous exposure to sulfur, a slow and continuous degradation in performance occurs due to the surface reconstruction of Ni particles. The formation of the NiS phase eventually occurs, leading to the irreversible deactivation of the anode and microstructural changes, this stage could potentially lead to mechanical failure of SOFCs[42].

Coarsening – Depending on application SOFCs have to be operated for several tens of years. The microstructural anode changes caused by Ni coarsening/agglomeration correspond to performance decay[43]. The driving force for the agglomeration is bulk migration and surface diffusion of the Ni cation. The agglomeration of Ni results in lowering the active Ni surface area, which in turn decreases the electronic conductivity and catalytic activity for fuel oxidation. Various adsorbents on Ni react in different ways, for example, excess steam in the fuel can lead

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to the formation of nickel hydroxide complexes[44]. These adsorbed complexes then desorb and migrate from one Ni site (typically a small Ni particle) to a different Ni site (on a bigger Ni particle) causing agglomeration by Ostwald ripening mechanism.

Redox Instability - For automotive applications of SOFCs, transient/varying loads are inevitable, specifically, under high load/fuel utilization conditions, anodes have to undergo oxidation due to a local increase in the partial pressure of oxygen. Furthermore, the oxidation of Ni anodes can occur due to a gas leak in the stack compressive seals or due to accidental fuel supply interruptions[45]. The instability of Ni-based anodes under such conditions impacts the long-term operation and robustness of SOFC technology for mobile or portable applications. Figure 5 compares the SOFC half-cell microstructure that is pristine (0 redox cycle), after 10 redox cycles and after 20 redox cycles. Within 10 redox cycles, the SOFC electrolyte is cracked, followed by rupture of the half-cell. This is due to the oxidation of Ni-based anodes to NiO (a transition from Ni^0 to Ni^{2+}). Further reduction and oxidation lead to dimensional changes due to volumetric shrinkage and expansion, respectively. These reduction-oxidation processes result in irreversible dimensional changes affecting the structure and performance of SOFCs[46].

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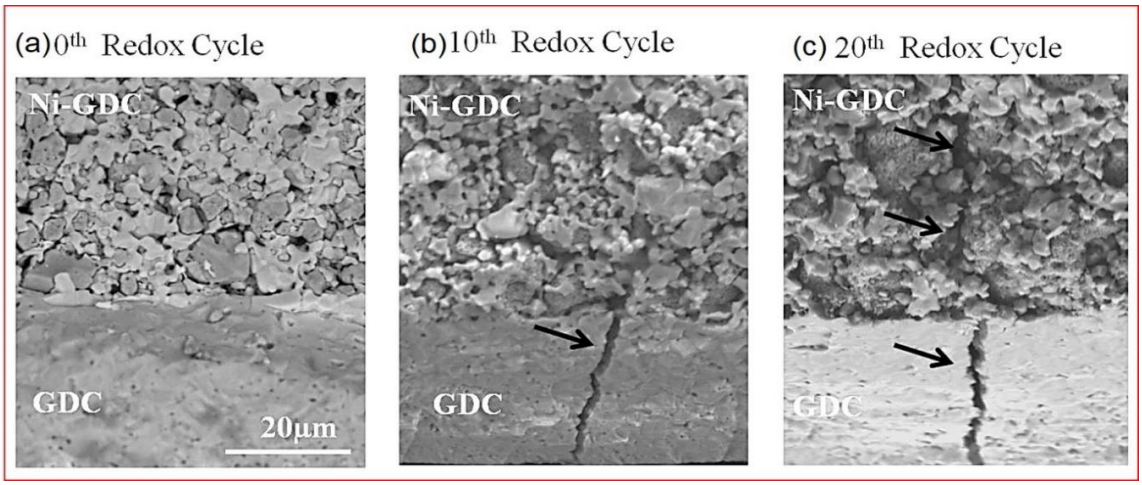

Figure 5. Redox (reduction/oxidation) stability of Ni-GDC anodes at 0th cycle, 10th cycle and 20th cycle. Cycled between reducing gas (10%H_2/N_2) and air at 650°C

5. Liquid Fuels, Fuel Utilization Strategies, and Status of Liquid-fed LT-SOFCs

5.1 Liquid Fuels

Liquid fuels are broadly classified as petroleum and non-petroleum fuels, based on their origin (shown in Figure 6(a)). Petroleum-based liquid fuels such as gasoline, kerosene, and diesel are derived from crude oil resources. Non-petroleum based fuels are derived from natural gas, biomass or the liquefication of coal, which includes biofuels (ethanol, methanol, biodiesel etc.), ammonia, hydrazine, and dimethyl ether (DME). A comparison of volumetric energy density and specific energy of various liquid fuels and H_2 is shown in Figure 6(b). The volumetric energy density (typically, joule per liter) of liquid fuels is much higher than H_2, however, the specific energy, energy content by mass (typically, joule per kilogram) for H_2 is much higher than liquid fuels. On a side note, 1 kg of H_2 has an energy content equivalent to that of 1 gallon of gasoline. The ideal standard potential (E_0) of various liquid fuels (in comparison to H_2/CO/CH_4) as a

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function of temperature is shown in Figure 6(c)[7a]. In the LT-SOFC region, E_0 of the liquid fuels such as methanol, ethanol, and ammonia is higher than H_2.

Kerosene-based liquid fuels or jet fuels contain special additives such as anti-icing, anti-static, corrosion inhibitors, lubricant improvers, metal deactivators, etc[47]. Jet fuels type Jet A, Jet A-1, and Jet B are applied in civilian aircraft, whereas, JP-1 to JP-9 are employed in military aircraft. The types of jet fuels are classified based on the concentration and type of additives influencing the required properties. The common surrogate for jet fuels is n-decane ($C_{10}H_{22}$) and n-dodecane ($C_{12}H_{26}$).

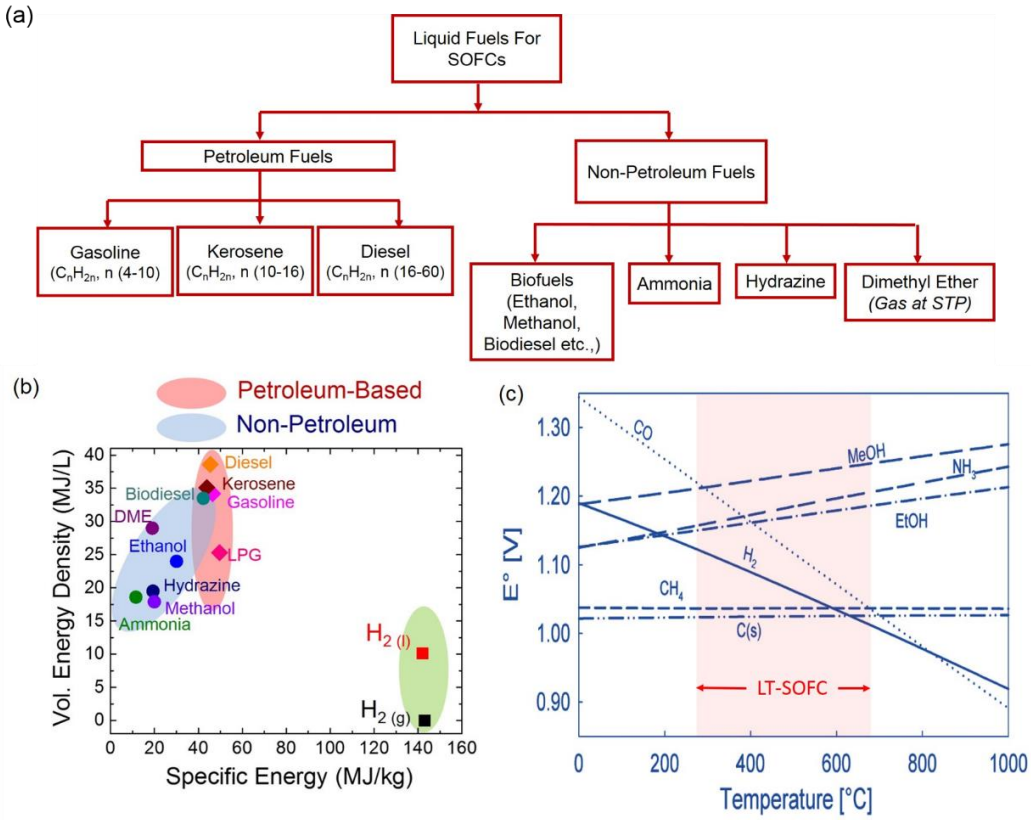

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Figure 6. a) Classification of liquid fuels based on petroleum and non-petroleum resources. b) Volumetric energy density vs. specific energy of various liquid fuels in comparison with H_2 and c) ideal standard potential as a function of temperatures for various liquid fuels in comparison with gaseous fuels (figure 6c reprinted from reference[7a]).

Gasoline (e.g., iso-octane (C_8H_{18})) based fuel is a complex mixture of hydrocarbons, having a high energy density of 46.4 MJ/kg[8a]. Gasoline typically consists of hydrocarbons (C_4-C_{12}), such as alkanes (4-8 %), alkenes (2-5%), isoalkanes (25-40%), cycloalkanes (3-7%), and cycloalkenes (l-4%). Gasoline includes additives such as aromatics (20-50%)[48] and other blending agents to enhance the stability and octane rating[49]. Gasoline-fed LT-SOFCs are well suited for mobile applications e.g., vehicle APUs and fuel-flex vehicles due to the widely available fuel supply infrastructure.

Alcohols such as methanol and ethanol are alternative promising fuels for LT-SOFCs[8a]. A majority of methanol (CH_3OH) is produced from natural gas as a source. Although the energy density of methanol (19.9 MJ/kg) is lower than petroleum-derived fuels (e.g., gasoline, 46.4 MJ/kg), it is free from sulfur contamination, heavy metals and other impurities[7a],[50]. Also, methanol is a polyol containing O-H group attached to each C atom, reducing carbon formation. A significant drawback of considering methanol as a fuel is its high degree of corrosiveness, as it even has the ability to corrode metals in the fuel-delivery system. Conversely, ethanol is essentially non-toxic and can be easily produced from biomass (e.g., corn, sugarcane etc.) and has an energy density similar to methanol. Fuels constituting up to 85 % ethanol (in gasoline) are directly used in fuel-flex vehicles, further, exhaust gases of ethanol-fed SOFCs are considered clean, and the emissions of greenhouse gases are greatly diminished[51].

Ammonia has been recently considered for automobile applications, as a fuel/hydrogen carrier, as it is carbon free and relatively inexpensive[52]. Furthermore, it is liquefiable at a moderate pressure and at room temperature, and 30 % of water is soluble in ammonia, making it easily

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stored and transported[9]. Challenges with ammonia occur because of its partial decomposition; any incomplete decomposition of ammonia creates mass transfer limitations and affects the SOFC performance, specifically, undecomposed ammonia remains inert and acts as fuel diluent, leading to the blockage of anode gas access pathways[53].

5.2 Fuel Utilization Strategies

The reforming process is the breaking down of complex fuel molecules into H_2 and/or CO by partial oxidation[7a]. Liquid fuels are indirect H_2 carriers and have to be reformed appropriately for LT-SOFC utilization (H_2 and/or CO-rich reformate gases *per se*). Hydrocarbon liquid fuels, specifically, gasoline and kerosene, can be utilized in SOFCs adopting four different modes: *1. external reforming, 2. internal reforming, 3. partial oxidation and 4. direct oxidation*. Modes 1-3 are reforming of fuels, wherein hydrocarbon fuels (e.g., C_nH_{2n+2}) are converted into syngas (H_2 and CO) and then electrochemically oxidized on the SOFC anode, whereas mode 4 is the direct oxidation of fuels on the anode.

Modes 1-3 produce syngas using one of the following strategies a) steam reforming b) dry/CO_2 reforming c) catalytic partial oxidation and d) oxidative steam reforming or auto-thermal reforming.

In steam reforming (SR), steam is used as the oxidant to reform the hydrocarbon fuels into syngas as shown in Eq. 1. It is highly likely the CO produced further reacts with H_2O forming CO_2 and H_2 *via* a water-gas shift reaction (Eq.2), depending on the temperature and steam-to-carbon ratio.

$$C_nH_{2n+2} + nH_2O \rightarrow nCO + (2n+1)H_2 \quad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

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In dry reforming (DR), CO_2 is used as the oxidant to reform the hydrocarbon fuels to syngas as shown in Eq. 3.

$$C_nH_{2n+2} + nCO_2 \rightarrow 2nCO + 0.5(2n+1)H_2 \quad (3)$$

In catalytic partial oxidation (CPOX), O_2 (or air) is used as the oxidant to catalytically reform the hydrocarbon fuels into syngas as shown in Eq. 4. CPOX is an exothermic reaction as the fuel enthalpy is converted into heat.

$$C_nH_{2n+2} + 0.5nO_2 \rightarrow nCO + (n+1)H_2 \quad (4)$$

In auto-thermal reforming (ATR), a combination of SR and CPOX is used. Both O_2 and H_2O are used as the oxidant to reform the hydrocarbon fuels into syngas as shown in Eq. 5.

$$C_nH_{2n+2} + aH_2O + bO_2 \rightarrow cCO + dH_2 \quad (5)$$

The type of reforming strategy is chosen based on its power producing capability, rapid start-up ability, geometry, weight, dynamic response, cost[54] and most importantly on the SOFC operating temperature[54b]. For high-temperature SOFCs, the hydrocarbon fuel is utilized through internal reforming and is directly reformed on the Ni anode (direct internal reforming, DIR) or by using a separate catalyst bed attached to the anode (indirect internal reforming, IIR). Moreover, endothermic reforming reactions on the anode can be useful in maintaining the temperature uniformity of the SOFC stack with regard to exothermic fuel oxidation. A uniform temperature distribution in the SOFC stack can avoid localized heating, resulting in reduced cell degradation and unwanted built-in thermal stresses within the cell components. However, the efficiency of internal reforming is hindered by sluggish electrode kinetics for LT-SOFCs. Externally reforming is thus an ideal strategy for LT-SOFCs, as the external reformer can convert the humidified hydrocarbon fuels into H_2-rich/CO-rich reformate gas before reaching the

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anode compartment, preventing carbon formation[55],[10]. In addition, external reformers are attached to desulphurization units and heat exchangers to prevent sulfur poisoning and to maintain uniform heat distribution throughout SOFC stacks.

5.3 Status of Liquid-Fed LT-SOFCs

Direct Oxidation and Direct Utilization - As opposed to reforming, hydrocarbon liquid fuels can potentially be utilized through direct oxidation, wherein liquid fuels are directly fed into the anode compartment in the absence of H_2O and CO_2. However, hydrocarbon-based liquid fuels (C_xH_y) are typically stable and are difficult to crack even at high temperatures, this leads to higher non-ohmic losses accompanied by severe carbon formation and the sulfur poisoning of Ni-based anodes[56]. For example, the direct oxidation of octane on Ni-YSZ based SOFC (Ni-YSZ anode|YSZ electrolyte|LSM-YSZ cathode) resulted in a low power density of 100mW/cm^2 at 650°C, primarily due thermal decomposition of octane into ethylene and methane [57]. However, an additional catalyst layer on Ni-ceria based anodes resulted in high performing and reliable LT-SOFCs *via* direct oxidation. For example, Murray et al. observed direct electrochemical oxidation on a ceria-based anode at low temperatures (550,-650°C), without evidence of carbon formation[58]. In addition, expensive noble metal catalysts e.g., Ru are required to efficiently oxidize hydrocarbons containing fuels by direct electrochemical oxidation[59]. Also, it must be noted that untreated hydrocarbon liquid fuels have a certain amount of sulfur as a contaminant, essentially diminishing the performance/stability of the anodes. [60]

The direct utilization of liquid fuels, on the other hand, by internal reforming would make the LT-SOFC system, simple and cost-effective [56]. Moreover, such reforming strategies for LT-SOFCs offer higher efficiencies and stable operation, preventing carbon formation when

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compared to direct oxidation. Several attempts were made to directly utilize liquid fuels for LT-SOFCs by internal reforming. A Ni-SDC based anode-supported SOFC (Ni-SDC anode|SDC electrolyte |LSCF-SDC/LSCF cathode) with Ru-CeO_2 based reforming catalyst layer produced a power density of 600 mW/cm^2 at 590°C by utilizing *iso*-octane (6% *iso*-octane–94% air) via an internal CPOX strategy[61]. Also, D. Ding et al reported that the Ni-SDC anode supported the SOFC (Ni-SDC anode |SDC electrolyte |SSC-SDC cathode) with SDC coating on the anode side, fed with iso-octane (3.9% *iso*-octane–96.1% air) utilizing CPOX strategy, producing a power density of 400mW/cm^2 at 600°C with good stability over a period of 260h and with no sign of carbon formation[62]. Furthermore, LT-SOFCs utilizing methanol *via* the SR strategy showed even higher performance at 600°C. Z. Gao et al. reported that SOFCs (Li-Ni-Cu-ZnO anode|SDC-Li_2CO_3-Na_2CO_3 electrolyte |Li-Ni-Cu-ZnO cathode) fed with methanol (at a steam-to-methanol ratio of 1:1), producing a power density of 603 and 431 mW/cm^2 at 600 and 500°C, respectively, using internal SR strategy[63]. Similarly, Y. Jiang et al reported a high power density of 600 mW/cm^2 at 650°C for an SOFC (Ni-YSZ anode|YSZ electrolyte|LSM-YSZ cathode) operating on methanol as fuel[64]. In addition, it was reported that a power density of 300 mW/cm^2 at 600°C is achieved in an SOFC (Ni-GDC anode|GDC-LiOH/NaOH electrolyte|LSCF-GDC cathode) by the direct utilization of ethanol *via* a thermal decomposition route[65]. M.D. Mat et al further reported that ethanol-fed SOFC (Cu-alloy anode|SDC- $LiNaCO_3$ electrolyte|BSCF cathode) operate even at a very low temperature of 500°C, producing a power density of 180 mW/cm^2 by the direct utilization *via* thermal decomposition route[66]. Similarly, several reports demonstrated the feasibility of the direct utilization of ammonia using LT-SOFCs, for example, an SOFC (Ni-SDC anode|SDC electrolyte|BSCF cathode) fed with ammonia efficiently operated at a low-temperature range (550-650°C), producing a high power

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density of 1190 mW/cm^2 at 650°C[67]. At temperatures ≥ 500°C, internal reforming is still a possibility, however, the extent of internal reforming depends on fuel electrodes/anodes and the nature of the fuel used. Examples of LT-SOFCs operating in liquid fuels are listed in Table 1. It is apparent from the comparison that performance of LT-SOFCs vary depending on the fuel, fuel utilization strategies and test conditions, however, LT-SOFC running on ammonia yielded the highest performance (1190 mW/cm^2 at 650°C).

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Table 1. LT-SOFCs, liquid fuels, fuel utilization strategies, and performance.

SOFC Configuration	Operating Temperature (°C)	Liquid Fuel	Peak Power Density (mW/cm^2)	Fuel Utilization Strategy
Ni-YSZ anode|YSZ electrolyte|LSM-YSZ cathode[57]	650	octane	100	Direct oxidation
Ni–SDC anode |SDC| LSCF–SDC, LSCF[61]	590	iso-octane/air	600	Partial oxidation
Ni-SDC anode |SDC electrolyte |SSC-SDC cathode[62]	600	iso-octane/air	400	Partial oxidation
Li-Ni-Cu-ZnO anode|SDC-Li_2CO_3-Na_2CO_3 electrolyte |Li-Ni-Cu-ZnO cathode[63]	600	methanol/H_2O	603	Steam reforming
Ni-YSZ anode|YSZ electrolyte|LSM-YSZ cathode[64]	650	methanol	600	Direct utilization
Ni-GDC anode|GDC-LiOH/NaOH electrolyte|LSCF-GDC cathode[65]	600	ethanol	300	Direct utilization

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Cu-alloy anode|SDC- $LiNaCO_3$ electrolyte|BSCF cathode[66]	500	ethanol	180	Direct utilization
Ni-SDC anode|SDC electrolyte|BSCF cathode[67]	650	ammonia	1190	Direct utilization
Ni-GDC anode |GDC electrolyte |LSCF-GDC cathode [12d]	550	JP-5 model	300	External reforming

External Reforming - As discussed, external reforming is one of the viable strategies to utilize liquid fuels in LT-SOFCs. As shown in Figure 7(a), JP-5 reformate model fuel (1.1% CH_4, 12.3% CO, 12.3% CO_2, 40.5% H_2, and 24.5% H_2O balanced with N_2) had been studied on Ni-GDC based anode-supported SOFCs (Ni-GDC anode |GDC electrolyte |LSCF-GDC cathode)[12d]. At 550°C, only ≤ 15% decrease in power densities compared to H_2 as fuel is observed, as shown in Figure 7(b), this difference is due to the slightly higher area specific resistance of the JP5 fueled SOFC in the temperature range of 550-650°C, in fact, OCV showed no change at all (*cf.* Figure 7(c)). Moreover, as shown in Figure 7(d), despite an initial degradation in the first 100h (~15%), a stable power density of 0.2 W/cm^2 over a period of 500 h was achieved without coking.

Ni-GDC based cermet anodes in hydrogen as fuel have shown a high power density of $2W/cm^2$ at 650°C[68], nevertheless, the energy density of liquid fuels is much higher than hydrogen, yet such high performances are not usually achieved, this is due to the sluggish reforming kinetics of such fuels at low temperatures. In addition, direct feeding of liquid fuels on Ni cermet resulted in coking, accompanied by sulfur poisoning (depending on the fuel in use), which has a deleterious effect on SOFC operation. High performance in LT-SOFCs are usually achieved by attaching an on-anode internal reformer, however, they tend to increase the anode over-potential, due to mass transfer limitations, especially in liquid fuels. Developing advanced ceramic oxide anodes is the only feasible approach to efficiently operate liquid fuel LT-SOFCs without

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compromising stability. Thus, a focus on new anode materials is essential to demonstrate the direct utilization of liquid fuels in LT-SOFC with improved performance and enhanced long-term stability.

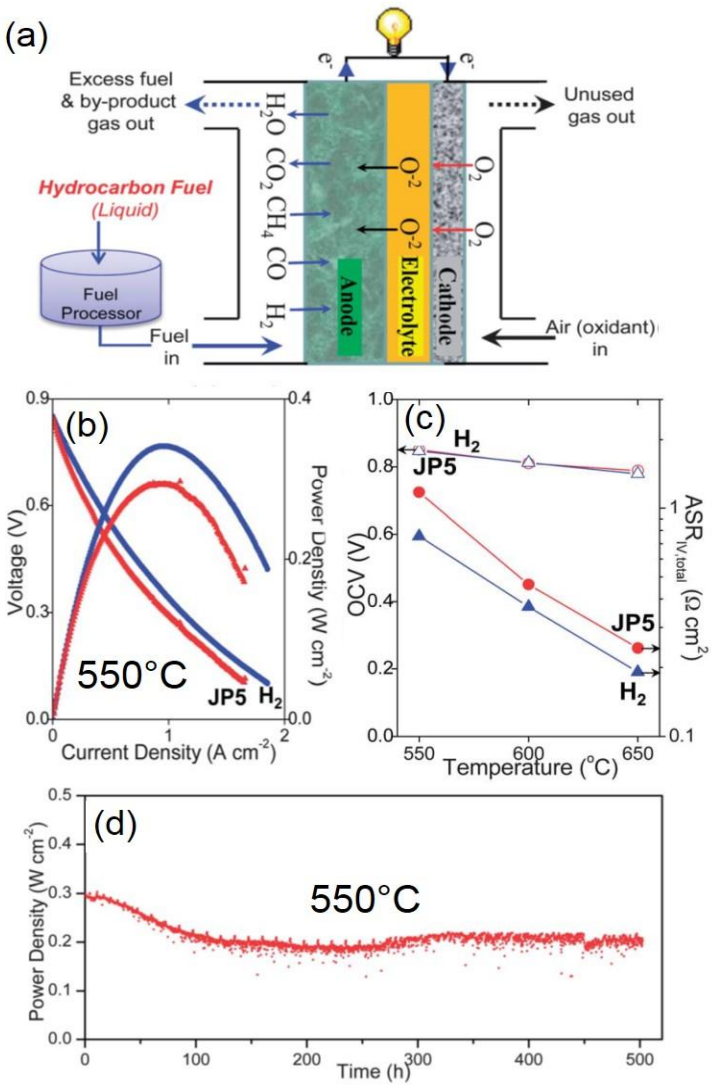

Figure 7. LT-SOFC on JP-5 liquid fuel a) Schematic sketch of SOFC with external fuel processor b) I-V and power density characterizations performed in H_2 and JP-5 model reformate fuel at 550°C and c) Temperature-dependent OCV and area specific resistance of the SOFC measured in H_2 and JP-5 model reformate fuel and d) long-term stability in JP-5 model reformate fuel at 550°C. Figure 7 reprinted from reference [12d].

6. Replacement of Ni-based Anodes with Conductive Oxides for LT-SOFCs

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The exploration of alternative oxide anode materials is essential because of the inherent challenges associated with Ni-based anodes (such as carbon formation, sulfur poisoning, coarsening, and especially redox instability).

Anode Requirements - For the direct utilization of liquid fuels, SOFC anodes should meet the following characteristics –a) electrical conductivity of the anode material must be >10 S/cm and the ionic conductivity must be >0.0095 S/cm to ensure low ohmic resistance[69] (the total area specific resistivity of the cell components should be less than 0.5 Ωcm^2 to ensure high gravimetric power density of ~1 kW/kg[13]); b) high electrocatalytic activity for oxidation/reformation of fuels[70]; c) thermal expansion coefficient (TEC) should match that of commonly used electrolytes (e.g., GDC-13.4×10^{-6}/K)[71]; d) high thermal conductivity (>5 W/mK) matching that of interconnects; e) structural stability e.g., no phase change which may lead to internal stress upon heating and cooling; f) redox cycle stability and chemical stability including sulfur tolerance and coking resistance[72]; g) anode-support (anode-supported planar design) must be sufficiently thick for internal reforming without limiting the diffusion of reactants and products; h) anode supports should also have high flexural strength between 25-100MPa depending on the porosity (30-50 vol. %) required for optimal gas transportation[73]; i) lastly, anodes should have >90,000 h of useful lifetime. Designing an anode material that satisfies all the above requirements is a sophisticated task and the design complexity depends on the type of fuel, which in turn depends on the targeted end-use and the subsequent power demand[54a].

Ceramic Anodes - Ceramic oxide anodes for LT-SOFCs are advantageous over traditional Ni-GDC cermet anode in several ways, especially for automotive applications where faster start-up times and transient loadings are prerequisites[74]. The oxygen non-stoichiometry in the mixed ionic and electronic-based ceramic anode has a much lower dimensional change in oxidizing and

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reducing conditions than Ni-based cermet anodes, therefore built-in internal stresses are reduced. Moreover, the ceramic oxides can have considerable mechanical strength both in oxidized and reduced states, and thermal expansion coefficients can be engineered appropriately to most commonly used electrolytes. The excellent chemical stability and sulfur tolerant properties of ceramic oxides make them attractive for direct utilization of liquid fuels in the low-temperature ranges.

However, there is no single ceramic oxide material meeting all the requirements of low-temperature (LT-SOFC) for direct utilization of hydrocarbons. Several ceramic anode materials that have been investigated mainly focused on high-temperature SOFCs[72]. The potential materials with required characteristics for LT-SOFCs can be broadly classified as titanates (e.g., $SrTi_{0.75}Nb_{0.25}O_3$)[22, 75], molybdates (e.g., Sr_2MgMoO_6)[76], chromates (e.g., $La_{0.2}Sr_{0.7}Cr_{0.5}Mn_{0.5}O_{3-\delta}$)[77] ferrites (e.g., $La_{0.6}Sr_{0.4}Fe_{0.9}Mn_{0.1}O_{3-\delta}$)[78] and vanadates ($La_{0.8}Sr_{0.2}VO_{3-\delta}$)[79]. Among the studied materials, substituted double perovskites e.g., Sr_2MgMoO_6 (SMMO) have shown desirable electrode properties for direct hydrocarbon utilization in high-temperature ranges of SOFC operation. Although SMMO can prevent carbon formation at 600°C[80], the major limitation preventing the application of LT-SOFCs is the requirement of higher temperature pre-treatment (under low pO_2 conditions, >900°C) to achieve the required electronic conductivity. This issue is also true for other ceramic materials, for example, the conductivity of $SrTi_{0.75}Nb_{0.25}O_3$ (SNT) pre-treated at 900°C is 8.2 S/cm at 400°C, however when pre-treated at 650°C, the value of conductivity reduced to 1.7 S/cm. This has limited the applicability of ceramic materials to HT-SOFCs and exclude the use of commonly used low-temperature electrolytes (e.g., GDC), as ceria-based MIEC electrolytes undergo fast Ce^{4+} to Ce^{3+} transition under low pO_2 conditions at temperature ≥700°C, leading to increased electronic leakage current

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in SOFCs and significant drop in open circuit voltage. Therefore, it is important to identify ceramic anode materials that can be reduced at low temperatures (≤ 650°C) to achieve desired electronic conductivity, facilitating the use of ceria-based fast oxide ion conducting electrolytes. In particular, ceramics oxides such as strontium molybdate and lanthanum vanadates have high electronic conductivities at low-temperature ranges; however, their structural changes create higher volumetric expansion similar to that of Ni-GDC cermet. Sr/Mn-substituted lanthanum ferrite ($La_{0.6}Sr_{0.4}Fe_{0.9}Mn_{0.1}O_{3-\delta}$) in combination with $Ce_{0.6}Mn_{0.3}Fe_{0.1}O_{2-\delta}$ has interesting catalytic properties for the oxidation of hydrocarbon fuels and has the ability to resist carbon formation. Nonetheless, they have low conductivity, especially at low temperatures (<1 S/m below 650°C)[78].

Chromates (e.g., $LaCrO_3$) are the most stable orthorhombic perovskite-type ceramic oxides materials. The electronic conductivity of $LaCrO_3$-based ceramic oxides is achieved by doping alkaline earth metals such as Sr or Ca[81]. Sr-doped $LaCrO_3$ ceramic has a conductivity two orders of magnitude higher than the undoped $LaCrO_3$ in air, as Sr-doped $LaCrO_3$ is electronic hole conductor in the oxidizing gas conditions (the hole carriers Cr^{4+} is generated by substitution of Sr^{2+} in the site of La^{3+})[82]. Both doped and undoped-$LaCrO_3$ have shown significantly lower conductivity in reducing gas conditions compared to oxygen-rich atmospheres, mainly because Cr^{4+} charger carriers will be reduced to Cr^{3+}, creating oxygen deficiency. S. Tao et al.[77b] replaced 50% of the B-site with Mn to obtain a new ceramic $La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$ (LSCM) exhibiting rhombohedral structure. The conductivity of this complex ceramic oxide decreased with Mn doping; however, investigations on LSCM revealed that at temperatures above 550°C, LSCM can directly oxidize methane. The key issues in utilizing LSCM for LT-SOFCs are a low catalytic activity for oxidation of hydrocarbon fuels, poor sinterability due to the high vapor

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pressure of chromium oxide, a thermal mismatch to that of electrolyte and low conductivity in anode working conditions.

Figure 8 compares the temperature dependent conductivity of various ceramic anodes. Our group revealed several promising new anode materials including V-substituted $SrTiO_3$, $SrTi_{0.65}V_{0.35}O_{3-\delta}$ (SVT)[83], La-substituted $BaSnO_3$, $Ba_{0.98}La_{0.02}SnO_3$(BSL)[75c], and Sr/V-substituted $NaNbO_3$, $Sr_{0.2}Na_{0.8}Nb_{0.7}V_{0.3}O_{3+\delta}$(SNNV)[84] with high electrical conductivities of 50, 230, and 300 S/cm, respectively. Also, $SrFe_xCo_yMo_{(1-x+y)}O_3$ (SFCM)[85] has sufficient electronic conductivity of ~30 S/cm, and these conductivity values are achieved at a low pre-reduction temperature of 650^{o}C. In particular, the conductivity values of SNNV and BSL are comparable to that of a standard Ni-GDC cermet anode. Although high conductivity has been achieved, several other processing challenges have to be addressed to fabricate anode-supported cells. One such predominant processing challenge is elemental interdiffusion between the electrode and electrolyte during the sintering process (1350-1450°C), which may affect the cell voltage during operation.

Another promising chromate based ceramic anode material (doped-$YCrO_3$) has been investigated by our group, showing conductivity in the order of ~2 S/cm at 650°C (under SOFC anode test conditions). Although this conductivity value is lower than other ceramic anodes compared in Figure 8 (a), chromate based perovskite oxides are typically compatible in hydrocarbon fuels and warrants further investigations[77]. Anode-supported SOFCs are advantageous as it allows using thin electrolytes, resulting in lower ohmic resistances. However, in the process of making anode-supported SOFCs high sintering temperature is required (≥1300°C), leading to elemental interdiffusion causing a drop in OCV (as discussed earlier). We prevented such issues utilizing fast oxide-ion conductor such as erbia-stabilized bismuth oxide (ESB) as bilayer electrolyte[68]. Figure 8(b-f) presents the preliminary data of ceramic anode supported SOFC using doped-

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$YCrO_3$ as anode support (infiltrated with Ni-GDC electrocatalyst), which is under further investigation for utilizing non-hydrogen fuels. The microstructure of the SOFC structure (doped-$YCrO_3$ anode|GDC-ESB bilayer electrolyte|LSM-ESB cathode) is shown in Figure 8 (b) along with the SEM-EDS (scanning electron microscopy-energy dispersive spectroscopy) elemental mapping of bismuth (Bi) in Figure 8(c). It is apparent that bi-based layer can be clearly distinguished from other SOFC components. For the preparation of anode-supported cells, GDC tape-casting slurry was prepared using an in-house recipe and by using the tape-casting method. To prepare SOFC half cells, the raw tapes were then laminated using a hot press with 20 µm GDC electrolyte, and heat-treated step-wise to 1350°C for 4h. The sintered half-cells were then co-deposited with ESB electrolyte and LSM-ESB cathode and fired at 775°C for 2h. The cube-shaped microstructure of ceramic anode with Ni-GDC nanoparticles are shown in Figure 8(d). The anode side of the cells was infiltrated with Ni-GDC (~2 wt. % loading) precursor to introducing catalytic activity for hydrogen oxidation. I-V characteristics in Figure 8(e) show a peak power density of 0.7 W/cm^2 at 650°C, measured in humidified H_2 as fuel. The OCV of the SOFC is 0.802V, demonstrating the suppression of elemental interdiffusion between the electrode and electrolyte. The active area of the fuel cells was 0.31cm^2, gold wires and silver paste was used as leads and the current collector, respectively. The I-V characteristics were determined using a Solartron 1470E. The electrochemical impedance spectroscopy (EIS) response of the fuel cells under investigation was obtained using Solartron 1425 frequency response analyzer.

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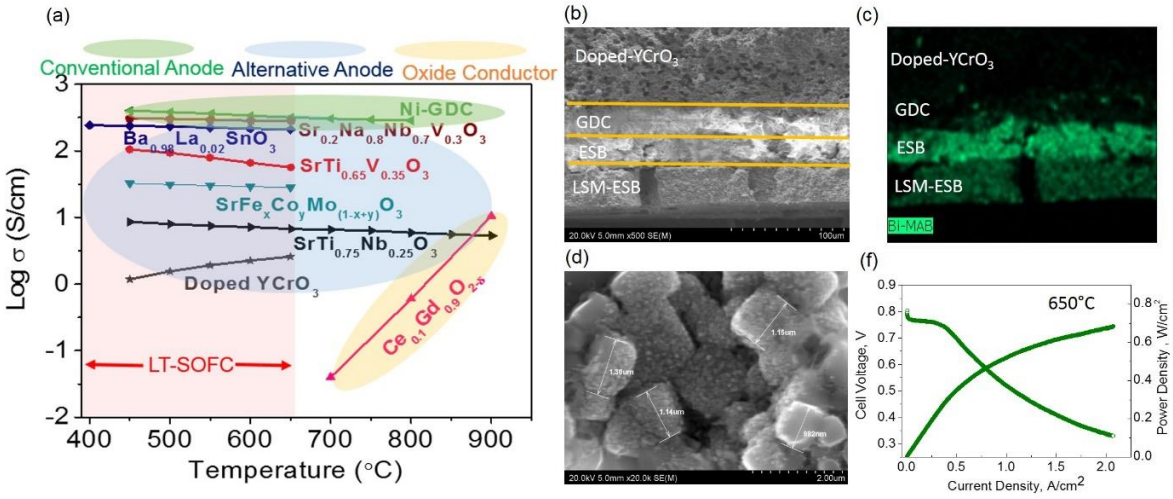

Figure 8. a) Conductivity of newly developed anode materials (compared with Ni-GDC cermet and GDC oxide conductor) for LT-SOFCs developed at the University of Maryland. The measurements are made in reducing gases (10%H_2/90%N_2) b-c) SEM micrograph and EDS mapping of ceramic anode supported SOFC using doped-$YCrO_3$ e) doped-YCrO3 support infiltrated with Ni-GDC electrocatalysts and f) I-V characteristics and power density curve of anode-supported SOFC using doped-$YCrO_3$ (measured in H_2/3%H_2O).

7. Summary and Future Outlook

HT- SOFCs are traditionally known for their large-scale stationary applications in the range of 1kW to 5 MW; however, they have been overlooked in the past for transportation applications requiring power in the smaller range of 1-5 kW. The main hindrance to HT-SOFC technology in transportation/portable mobile applications is longer start-up time and inability to quickly respond to changes in load. In contrast, LT-SOFCs enable rapid startup/cooling and load following capabilities with enhanced robustness appropriate for mobile applications.

From the review presented here, LT-SOFC technology has tremendous opportunities for various power-hungry markets, including automotive applications. For the unrestricted implementation of LT-SOFCs in the transportation sector, they have to be independent of an H_2 economy, and thus utilizing liquid fuels (e.g., gasoline, diesel etc.) with existing infrastructure is critical. Selecting appropriate reforming strategies mainly depends on operating temperature, and some

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degree of external reforming is appropriate for LT-SOFCs (≤600°C). However, it adds complexity and additional cost to the system. Conversely, the direct utilization of liquid fuels on LT-SOFCs is attractive for deployment in the transportation sector. Fuel electrodes for LT-SOFCs need significant attention, as liquid fuels are directly in contact with the anode and are severely impacted by the fuel composition. The requirements of anode materials are complex and depend on the fuel type and operating temperature, which in turn depends on the specific application and power demands. Direct utilization of liquid fuels (e.g., alcohols and ammonia) on Ni-GDC-based anode-supported LT-SOFCs have shown reasonable performance, nevertheless, they face critical challenges (redox instability, coking, sulfur poisoning etc.). To address these issues, alternative oxide anodes with conductivities similar to Ni-GDC have been developed, and new anode materials can solve specific challenges that are inherently associated with Ni-GDC anodes, leading to the deployment of LT-SOFCs in automotive applications, e.g., APUs or range extender in PHEVs.

Continued efforts should focus on the development of low-cost LT-SOFC technology, as it enables quicker adoption in various sectors including transportation. Particular attention should focus on the development of redox tolerant ceramic anodes that achieve high performance and stable LT-SOFCs operation via the direct utilization of 'drop-in' fuels from the existing infrastructure. This review focused on early-stage lab scale research work using button cell sized SOFCs; however, significant future efforts are needed at the stack and commercial scale before conclusions concerning the development of liquid-fed SOFCs can be conclusive. This, in turn, will profoundly take SOFC technology to a new level.

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