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Advances and Perspectives on Solid Oxide Fuel Cells: From Nanotechnology to Power Electronics Devices

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Solid oxide fuel cells (SOFCs) hold an important place in energy conversion and storage systems due to their fuel flexibility, high efficiency, and environmental sustainability. The scorching temperature (≥800 °C) to operate SOFCs results in shorter life span due to rapid deterioration of accompanying components. Nanomaterials have attained considerable attention in recent years due to their great technological importance in fuel cell technology. Nanoengineering of the architectures of known materials and adopting composite approach can effectively enhance the active sites for electrode reactions. The use of nanotechnology will make SOFCs environment friendly and sustainable through green manufacturing processes of nanotechnology. Overviews of the contributions of nanotechnology and power electronics technologies to SOFCs, the transition of SOFCs from macro- to nanotechnology, the significance of nanomaterials in SOFCs, dynamic modeling, the function of optimization techniques, and the requirement for power electronics converters in SOFCs are all provided in this piece of work. The applications of SOFCs in different sectors, prominent institutes/labs and companies involved in SOFCs' research, future challenges, and perspectives are also highlighted.

1. Introduction

Owing to the adversarial environmental effects, ever-increasing energy crisis, fuel flexibility, modularity, and continuous fast depletion of petroleum reserves have exposed fuel cells (FC) as a source of clean and reliable energy across the globe. The widespread applications, (i.e., industrial cogeneration, automotive and transportation, renewable energy systems, etc.) of FCs have overwhelmed the energy market opportunities. FCs are highly efficient energy conversion devices that produce electrical energy from hydrogen through electrolysis. The superior reliability with zero mechanical loss and independence of Carnot cycle efficiency are additional benefits of FC systems compared to diesel generators.[1] FCs are classified into several types. Among all, solid oxide FCs (SOFC) have been recognized as the likely FC that will catch the most substantial place in the future energy industry.[2] Some unique features such as high tolerance to impurities, high current density, high efficiency in reverse mode, high cost-effectiveness due to high operating temperature (ranging from 400 to 1000 °C), reusability of heat in the bottoming cycle, very fast reaction kinetics, and internal reforming provide a better performance of SOFC among other.[3]

Despite their high efficiency, there are quite a few concerns in the commercialization of SOFCs. Factors such as high material cost, Ohmic and concentration losses, high operating temperatures, stack fabrication, thermal instability, issues of safety,

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routine maintenance, and insufficient life span are some of the concerns regarding SOFCs. Although, high-temperature operation boosts the reaction kinetics and charge transportation yet it causes many hindrances to practical deployments of SOFCs such as cell complexity and material degradation including electrode sintering and interfacial diffusion between electrolyte and electrode materials. In addition, on the system level, one of the crucial problems with SOFCs is the slow dynamic behavior and load tracking capabilities during transient operation in demand power.[4] This is because power transients result in fluctuations in fuel utilization. Technically, high fuel utilization is desirable for better efficiency. The desired utilization is around 80%–90%.[5] When an SOFC is operated under large power fluctuations, it experiences an instant drop off of the voltage in the current–voltage (I–V) curve. In addition, a swift variation in load demand also becomes the reason for the hydrogen starvation in SOFCs.[6]

Over the last few years, substantial studies, research, development, and demonstrations have been performed by different researchers to improve the performance of SOFCs. To date, various approaches and designs of SOFCs have been adopted based on novel materials selection,[7,8] including choice of interconnect materials,[9] novel system modeling,[10–12] fuel considerations,[13] novel infiltration method for nanostructured electrode fabrication,[14] system integration,[15,16] optimization,[17,18] and advanced power control.[1] Special contributions have been made at the nanoscale level including the synthesis of new nanostructured electrolytic, electrode materials, and new coating for metallic interconnects, which can lead to SOFC durability and performance enhancement at low temperatures in a variety of applications.

Similarly, the slow load-tracking problem of SOFC and power control have been addressed by many researchers through system integration with fast dynamics and power electronics control strategies.[2,19] Ultra-capacitors have a high output response to rapid load demand, and therefore, SOFC is normally integrated with ultracapacitor in a hybrid system for distributed generation applications and/or in electric vehicles.[20,21] Likewise, different power converters based on proportional–integral–derivative (PID) controller,[22,23] feedforward–feedback control,[24] fuzzy control,[25] artificial neural network (ANN),[26,27] fuzzy-neural controller,[28] adaptive neuro-fuzzy,[29,30] predictive control,[31,32] sliding mode control,[33] genetic algorithm,[34] genetic fuzzy,[35] particle swarm optimization (PSO),[36,37] whales optimization algorithm,[38] Kalman filter,[39] Luenberger observer,[40] and graphical method[41] have been introduced by many authors for the better performance of SOFCs.

Although many excellent reviews on SOFC have already been reported in the literature, the topic of SOFC is very broad and different authors have discussed it in different ways. For example, few focused on material selection,[42,43] while some have discussed SOFCs in terms of optimization techniques,[44] integration strategies,[45] nanoelectrode fabrication and characterization,[14,46] model-based diagnosis,[47] electrospinning,[48] nanoionics,[49,50] macroscopic models,[51] and mathematical modeling with respect to the planar and tubular configurations.[52] Similarly, some authors have reviewed SOFCs in terms of applications in different sectors such as in power generation,[53] stationary, mobile, transport, and military.[54,55] However, so far, no paper has discussed the role of nanotechnology and power electronics technologies concerning SOFCs in one place.

This article aims to provide the broadest possible overview of the contribution of nanotechnology and power electronics technology to SOFCs. The role of nanomaterials effects and the evolution of SOFC are described. The dynamic modeling and power control of SOFCs and the contribution of optimization paradigms in SOFCs have been discussed. We also focused on SOFC cost analysis and applications, as well as currently active research on SOFCs around the world. This review is structured in different sections, i.e., the basic working principle of SOFCs; the classification of SOFCs based on different parameters; the technical barriers hindering the SOFCs commercialization; the role of nanometric size; the transition of SOFCs from the macro-technology level to the nanotechnology; the importance of nanomaterials in SOFCs; the dynamic modeling and power electronics control of SOFCs; the optimization methods in SOFCs; the cost analysis of SOFCs; the applications of SOFCs in different sectors; active research; state-of-the-art facilities; companies related to SOFCs; and finally the conclusion.

2. Working Principle and Classification of SOFCs

SOFCs have two porous electrodes, i.e., the anode as well as the cathode with a sandwiched electrolyte. The porosity of electrodes is a prerequisite as it is vital for the passage of oxidants and fuel during FC operation. Fundamentally, based on the electrolyte used, an SOFC can be distinguished into two categories viz., proton-conducting (PC) SOFC (H-SOFC) and oxide ion–conducting SOFC (O-SOFC). A chemically stable electrolyte with negligible electronic conduction is necessary for better performance.[56] **Figure 1**a,b depicts the working principle of O-SOFC and H-SOFC, respectively.

SOFCs can be grouped into different classes based on their operating temperature, type of support, cell and stack design, fuel reforming type, and flow configuration, and presented in **Table 1** with a schematic representation in **Figure 2**.

3. Current Technical Barriers and Challenges in SOFCs

Some major barriers which limit the commercial use of SOFCs are a) the deposition of sulfur and coke causing poisoning, surface poisoning, and charge-transfer distortion in the anode; b) O^{2-} migration restrain leading the electrochemical reactions occur in the solid electrolyte; c) coefficient thermal expansion (CTE) mismatch of cell components; d) cathode rate determining factors such as the existence of over potential in addition to active surface geometry; e) chemically unstable and incompatible cellular components under oxidizing and reducing conditions; f) poor thermal resistance; g) complexity in reforming hydrocarbon fuels; h) SOFC stacks giving insufficient and undesirable overall energy efficiency; i) partial fuel utilization in the anode; j) rapid degradation of SOFCs components due to high-temperature operation resulting in high cost; and k) less production of electrical power in low-temperature regime (300–600 °C).[43]

The scorching temperature to operate SOFCs (800–1000 °C) results in inadequate thermomechanical stability and difficult sealing. It results in a short life span and ultimately leads to high cost. Another main disadvantage of high-temperature operation is the corrosion at the anode, the cathode, current collector, and the separator plates.[57] The low ionic conducting materials and

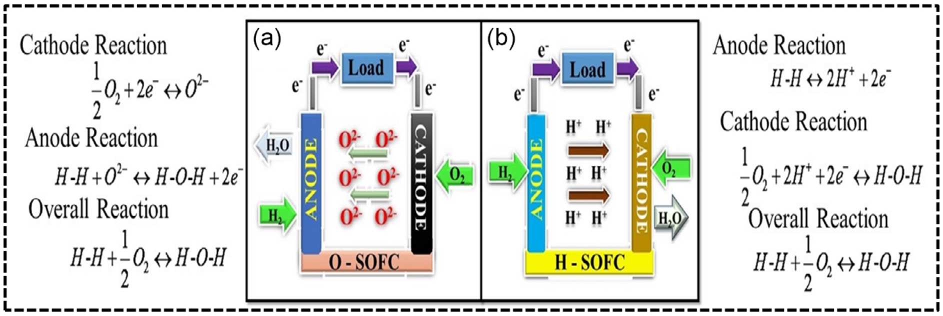

Figure 1. Schematic of solid oxide fuel cells (SOFC) for a) O^{2-} movement and b) H^+ movement. Reproduced with permission.[7] Copyright 2020, Elsevier.

Table 1. Classification of SOFCs based on different parameters.

Classification	Subclass & Salient Features	Refs.
Operating temperature	HT–SOFCs (≥800 °C)	[56]
	IT–SOFC (600–800 °C)	
	LT–SOFC (≤600 °C)	
Cell and stack design	Planar	[56,67]
	Tubular	
	Segmented in series	
Support type	Electrolyte supported	[56,67]
	Anode supported	
	Cathode supported	
Fuel reforming type	External reforming	[56,67,176]
	Internal reforming	
	Indirect internal reforming	
	Direct internal reforming	
Flow configuration	Co-flow	[56,67,176]
	Cross-flow or counterflow	

reduced cathodic reaction rates at low temperature govern the high operating temperature of SOFCs for which nanostructured materials have been shown to have higher ionic and electronic conductivities.[58] This is because nanostructured materials furnish large reactive regions and decreased energy loss.[59]

Nanoengineering of the architectures of known materials and adopting composite approach can effectively enhance the active sites for electrode reactions. Nanocomposites may provide additional synergistic effects like regenerative properties, chemical as well as thermal steadiness, and resistance to impurity poisoning.[60]

Key developmental challenges to be achieved include a) improving SOFC efficiency to 60% without compromising on carbon capture and sequestration; b) a proven lifetime of 40 000 h or more; c) degradation rate <0.2%/1000 h; d) SOFC stack cost <\$225 kW^{-1}; and e) SOFC system cost < \$900 kW^{-1}.[61] The current technical barriers and challenges in SOFC commercialization are shown in **Figure 3**.

4. Nanomaterials and Size Effects

Nanomaterials have attained considerable attention in recent years due to their great technological importance in FC technology. For FC materials, the nanometric size effects have been categorized into two classes: 1) trivial size effects, relying on the surface-to-volume ratio increment and 2) true size effects, involving the surface properties influencing overall behavior with the possibility to tailor electrochemical and other properties when FC systems' dimensions are confined. Due to the very small particle size, the surface and spatial confinement have a significant effect on the physicochemical properties. Fundamental advances may be allowed by new nanomaterials leading to FC performance improvement. Nanostructured FC electrodes enhance the catalytic surface area to increase fuel-catalyst contact resulting in improved efficiency of the system.[62]

Generally, compared to bulk or macroscale, nanomaterials exhibit varying properties at the nanoscale. At the nanolevel, some materials are stronger and lighter having the potential to conduct heat and electricity better and reflect light more efficiently. While others may exhibit magnetic properties differently or, under special circumstances, become chemically active.[63] The logic behind this behavior is that if the material has one or more nanoscale dimensions, the usual physical science rules do not apply. Resultantly, materials start exhibiting surprising characteristics. Their strength, electrical conductivity and reactivity rate increase surprisingly. For instance, nanoscale silver exhibits better antimicrobial properties, materials like gold and platinum, which are normally inert in bulk form, act as catalysts and some stable materials become combustible, e.g., aluminum.

Compared to the bulk, nanocrystalline materials also exhibit some new properties like the increased conduction, shifting and broadening of Raman-allowed modes, lattice relaxation (size-induced), phase transformation due to pressure, and the shift in ultraviolet absorption spectra.[64] Low-dimensional nanoelectrodes are attractive for SOFCs as they ensure the provision of long-range charge-transport pathways, inimitable porous structure which are dimensionally confined with unique anisotropy for the diffusion of gaseous fuels and extended triple phase boundary (TPB).[60] The electrocatalytic activity of nanofiber electrodes is greatly enhanced due to their unique microstructure resulting in improved electrochemical performance of cell.[65] These stimulating properties of nanoscale materials have allowed scientists to use them in areas such as energy and health for the benefit of mankind.[66]

5. Transition of SOFCs from Macrotechnology to Nanotechnology

Increased fossil fuel consumption is causing global energy problems, both industrially and environmentally. As the demand for

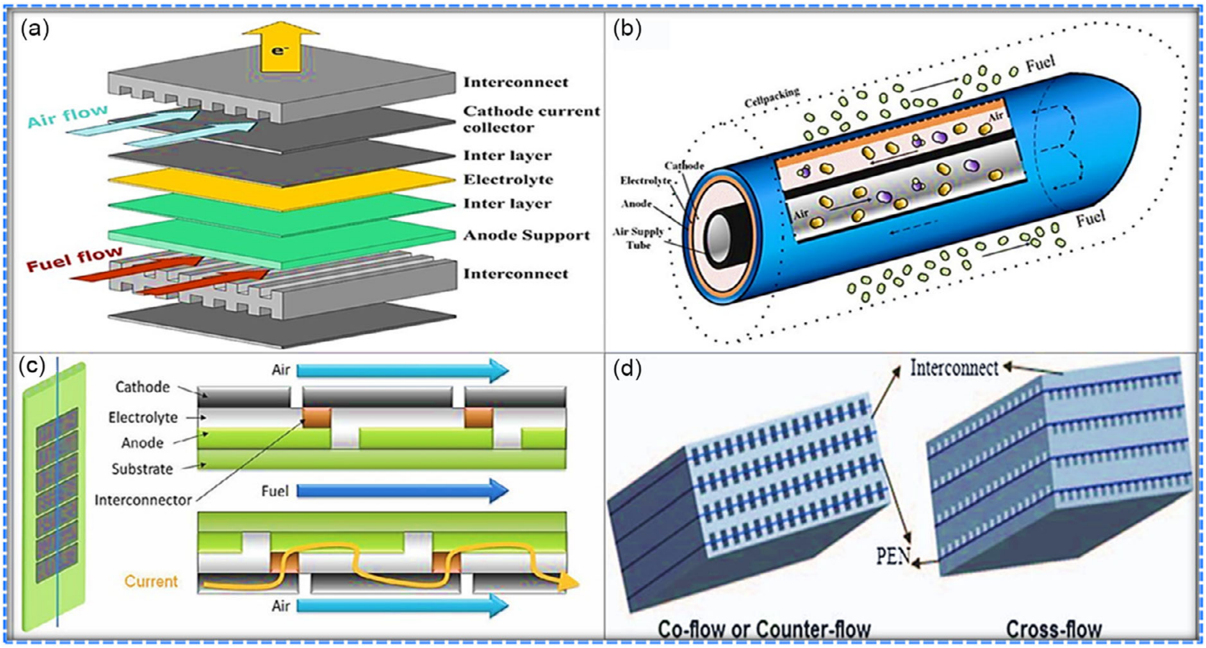

Figure 2. Schematic representation of a) planar SOFC and b) tubular SOFC. Reproduced with permission. c) Segmented-in-series SOFC and d) co-flow or counter flow and cross-flow configurations. a) Reproduced with permission under the terms of the Creative Commons CC BY license.[174] Copyright 2013, the Authors. Published by MDPI. b) Reproduced with permission under the terms of the Creative Commons CC BY license.[175] Copyright 2018, the Authors. Published by MDPI. c) Reproduced with permission.[176] Copyright 2012, Elsevier. d) Reproduced with permission.[56] Copyright 2013, The Royal Society of Chemistry.

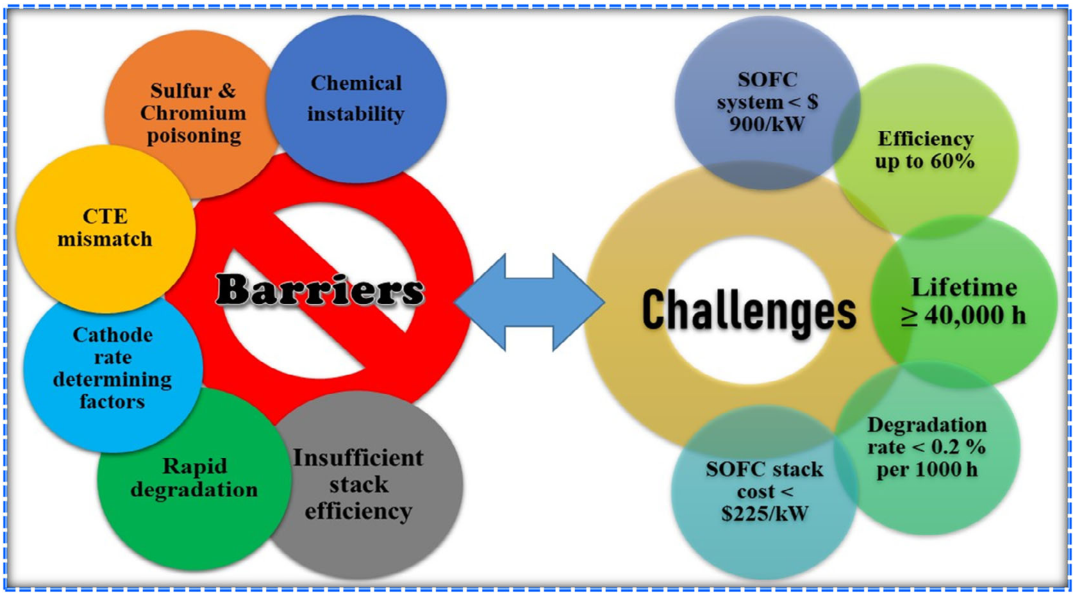

Figure 3. Current technical barriers and challenges in SOFC commercialization.

energy grows, scientists are striving to find alternatives to address and overcome energy challenges. In consequence, SOFCs have emerged as an efficient and clean power-generating technology. Over the last century, significant advancement in SOFCs technology has been witnessed, from conventional to nanoscale, to meet the energy requirements of varying capacities, from distant villages to small portable devices.[55,62,67] **Figure 4** depicts the FCs/SOFCs transition from micro- to nanolevel.[68] SOFC durability is important in developing SOFC trends for a particular application through 1) characterization of cells,

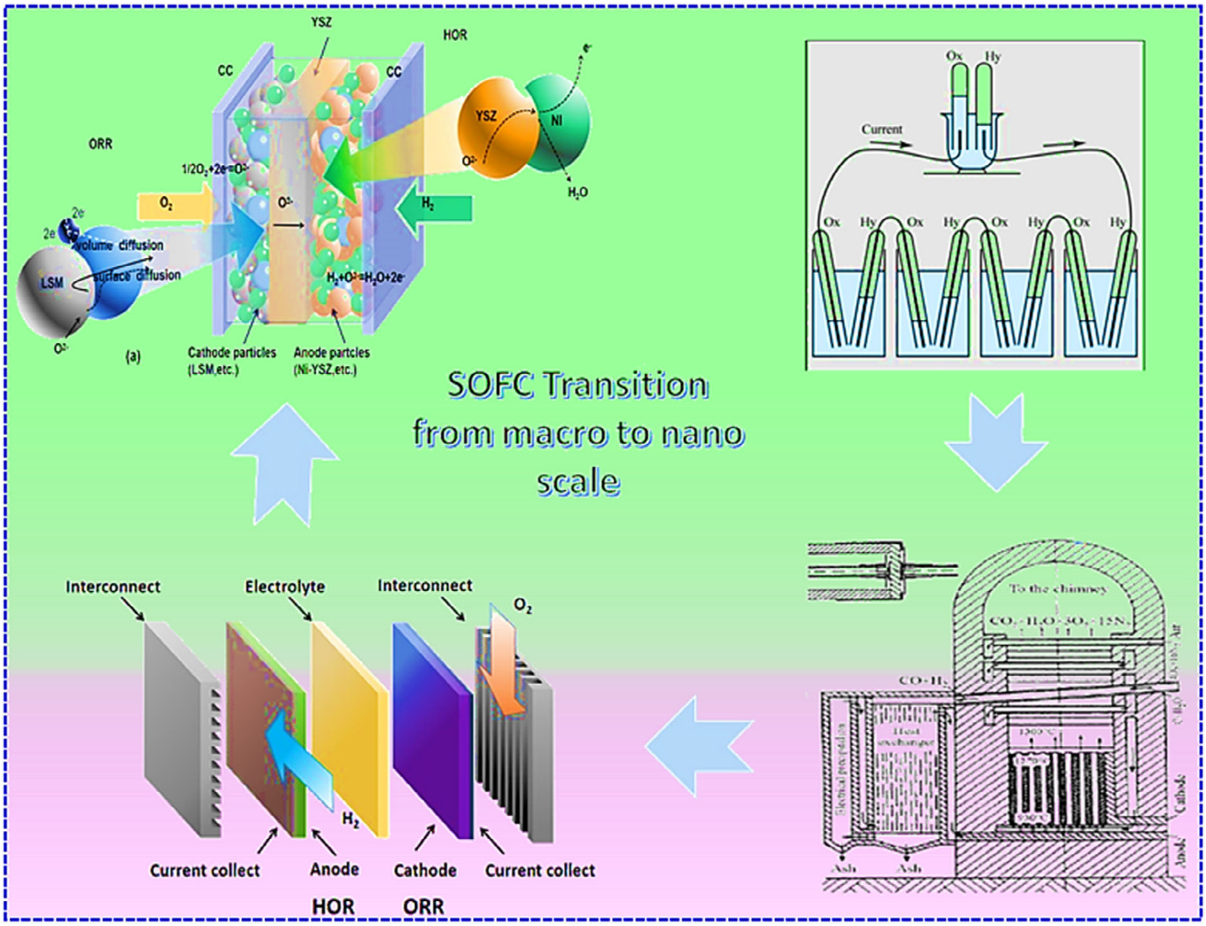

Figure 4. Fuel cell/SOFCs transition from conventional to nanoscale. Reproduced with permission.[43] Copyright 2018, Elsevier. Reproduced with permission under the terms of the Creative Commons CC BY license.[72] Copyright 2021, the Authors. Published by OAE Publishing Inc.

2) degradation studies, and 3) optimization of working conditions.[69] Nanotechnology has played a vital role in improving the electrocatalytic properties of redox reactions, impacting the cost of FC devices. The application of nanostructured materials to FC devices has increased efficiency and reduced catalyst load,[62,63] while bringing down the operating temperature from 1000 to 300 to 400 °C.[70] In addition, nanostructured materials provide good thermal stability with acceptable conductivity values. Furthermore, they show good tolerance toward sulfur and no carbon deposits on the anode side when hydrocarbons are used as fuel.[62,71] The use of nanomaterials for SOFCs makes the attainment of desired performance easy and with little effort.

The transition of SOFCs from macro- to nanoscale can exceed the current SOFC technology with regard to reliability, robustness, and cost.[72] However, a thorough investigation necessitates a deep clarification of the key concepts of this technology. Therefore, new architectures or material sets can be used to control the electrical, chemical, mechanical, and manufacturing requirements of SOFCs.[73] In principle, the conversion system should be able to offer fuel flexibility, the highest efficiency, the lowest SO_x and NO_x emissions, and modularity. The fundamental concepts from the macro- to nanolevel are similar. The production of nanostructured materials requires the selection of appropriate synthetic pathways. The method for characterizing nanomaterials is the same as the conventional SOFC method.

6. Role of Nanomaterials in SOFC

Over the last few decades, considerable efforts have been made in nanoresearch around the world to develop new FC materials and systems. For instance, research to lower the SOFCs operating temperature has unlocked new possibilities for the application of nanomaterials. One way to decrease the operating temperature below 500 °C is to use nanoscale electrolytes.[62,70] Decreasing the SOFC operating temperature improves performance in terms of thermal stability, durability, and dynamic response, and has expanded its use as an auxiliary battery for automobiles.[74,75] Similarly, nanostructured electro ceramic materials are highly used in intermediate-temperature SOFCs.[62,76] For instance, the fabrication of SOFC microstructure elements is performed with nanosized particles having different electrocatalytic and ion-conduction characteristics from polycrystalline materials.[77] Similarly, the reduction in the size of the electro-catalysts has highly improved the performance of SOFC due to growth at the three-phase interface and enhanced catalytic activities of nanoparticles.[78] Interest in nanostructured materials stems from their distinctive variable properties of increased thermal and electrical conductivity. This happens because a nanostructured material undergoes a transition process from an infinitely extended solid to a particle containing a definable number of atoms.[79] It has been reported that SOFC performance has a close correlation with electrode microstructure.[80]

6.1. Electrolytes

Electrolytes play a very vital role in SOFCs. In a broad sense, electrolytes can be of two types: a) oxide ion–conductive electrolytes, and b) proton-conductive electrolytes.

6.1.1. Oxide-Ion-Conducting Electrolytes

Electrolytes that exhibit oxide ion conduction are composed of perovskite or fluorite oxides with oxygen deficiency, creating oxygen vacancies that allow the movement of oxide ions through them. Yttria-stabilized zirconia (YSZ) has been widely used due to its superior ionic conduction at higher temperatures (≈1000 °C) and good stability under oxidizing and reducing conditions, however, its conductivity decreases significantly below 800 °C. Scandium-doped zirconium is also known to exhibit better ionic conductivity than YSZ, but its questionable stability over long-term use and high cost make it less attractive for real-world applications.[81]

In general, zirconia-based electrolytes show the best conductivity values when dopant and host cation sizes are comparable and the charge present on dopant is approximate to that of the host cation. Apparently, the lattice strain is absent in such cases. The presence of local strain causes uneven bonding of metal–oxygen throughout the lattice. The greater the dissimilarity between the dopant and host charge, the greater the charge defects formed having stronger coulomb interaction with the oxide vacancies, thus resulting in lower mobility.[82,83] Bismuth oxides having a fluorite structure have shown the highest value of oxide conduction among the SOFC electrolytes reported so far. The superior ionic conduction of δ-Bi_2O_3 gets affected due to high oxygen vacancies concentration and high mobility of anion.[84] However, when cooled down below 730 °C, a transformation of pure δ-Bi_2O_3 to monoclinic α-phase occurs, resulting in a discontinuous conductivity drop. However, high-temperature δ-Bi_2O_3 can be stabilized to room temperature using different dopants.[85]

Ceria-based solid electrolytes have emerged as potential alternatives to zirconia electrolytes due to their excellent conductivity in the lower temperature range.[7] However, cerium ions have lower redox stability causing a change from $Ce^{4+} \rightarrow Ce^{3+}$ in anodic circumstances, eventually increasing electronic conduction and chemical expansion. Resultantly, the desired open-circuit voltage is never achieved which decreases the efficiency of fuel conversion. The mechanical integrity of the cell is compromised by chemical expansion. This leads to mechanical failure due to the expansion of the anode region as the dimensions of the cathode region remain the same. These two effects are less relevant at lower temperature ranges, rendering ceria materials potential electrolytes for practical applications in SOFCs.[86] Improved conductivities and FC performance have been noted for composite electrolytes (e.g., ceria with an amorphous carbonate), presented in **Figure 5**. The latest trend includes the introduction of a semiconductor membrane with electrolyte to get superior performance at low temperature (<500 °C). A breakthrough was recently achieved with the introduction of semiconductor heterojunction membrane, which may serve as an alternate electrolyte and performs better. The acronym SIMFC (or semiconductor–ionic membrane FC) was used to describe this new architecture.[87]

6.1.2. PC Electrolytes

PC electrolytes have been known to scientists since the 1960s and have been investigated in detail. The first report on proton conductors is presented by Kreuer.[88] ABO_3-type perovskite is the most investigated PC electrolyte where X^{3+} dopant is partially replaced with B^{4+} impurity to create oxygen vacancies, represented later.[89]

$$X_2O_3 \overset{BO_2}{\rightarrow} 2X'_B + 3O_o^x + V_o^{\cdot\cdot} \tag{1}$$

The hydroxide defects formed in the presence of wet atmosphere result in protons according to the following equation.

$$H_2O + 3O_o^x + V_o^{\cdot\cdot} \Leftrightarrow 2OH^{\cdot} \tag{2}$$

H_2O dissociates to form a hydroxide ion, which fills the oxygen vacancy, and a proton forming a covalent bond with the lattice oxygen. The migration of proton from one oxygen to another takes place through hopping and rotating and moves easily due to its small volume and lighter weight compared to oxygen ion, thus making it attractive for electrolytic applications in SOFCs.

Certain oxides have been shown to have the ability to conduct protons in the presence of water vapors or hydrogen environments.[88,90] Excellent prospects exist for proton conductors in low-temperature (LT)–SOFCs. This is because the hydrogen ion mobility is high due to the small size of the hydrogen ion, and the activation energy is low. Notable values of conductivity have been recorded in the perovskite systems with composition $A^{+2}B^{+4}O_3$, e.g., $SrCeO_3$, $BaCeO_3$, $BaZrO_3$, etc., in the low to intermediate range. Many researchers studied the host cation substitution (B-site) with different dopants in the ABO_3 perovskite system reviewed in refs. [88,90]. Oxygen vacancies are formed due to the incorporation of dopants. Lattice oxygen and holes are formed when oxygen combines with vacancies, and protons form when water combines with holes or oxygen vacancies. Proton concentration is also increased when hydrogen combines with holes. The proton thus created can move freely, improving conductivity.[88,90] Norman et al.[91] noted that co-doping of cerate-based electrolyte with transition-metal (In) enhances the chemical stability, sinterability, and ionic conductivity. A perovskite-type $BaCe_{0.5}Zr_{0.3}Y_{0.1}Yb_{0.05}Zn_{0.05}O_{3-\delta}$ electrolyte was prepared by Afif et al.[92] which showed high density, good protonic conductivity, as well as peak power density in the intermediate temperature range (700 °C).

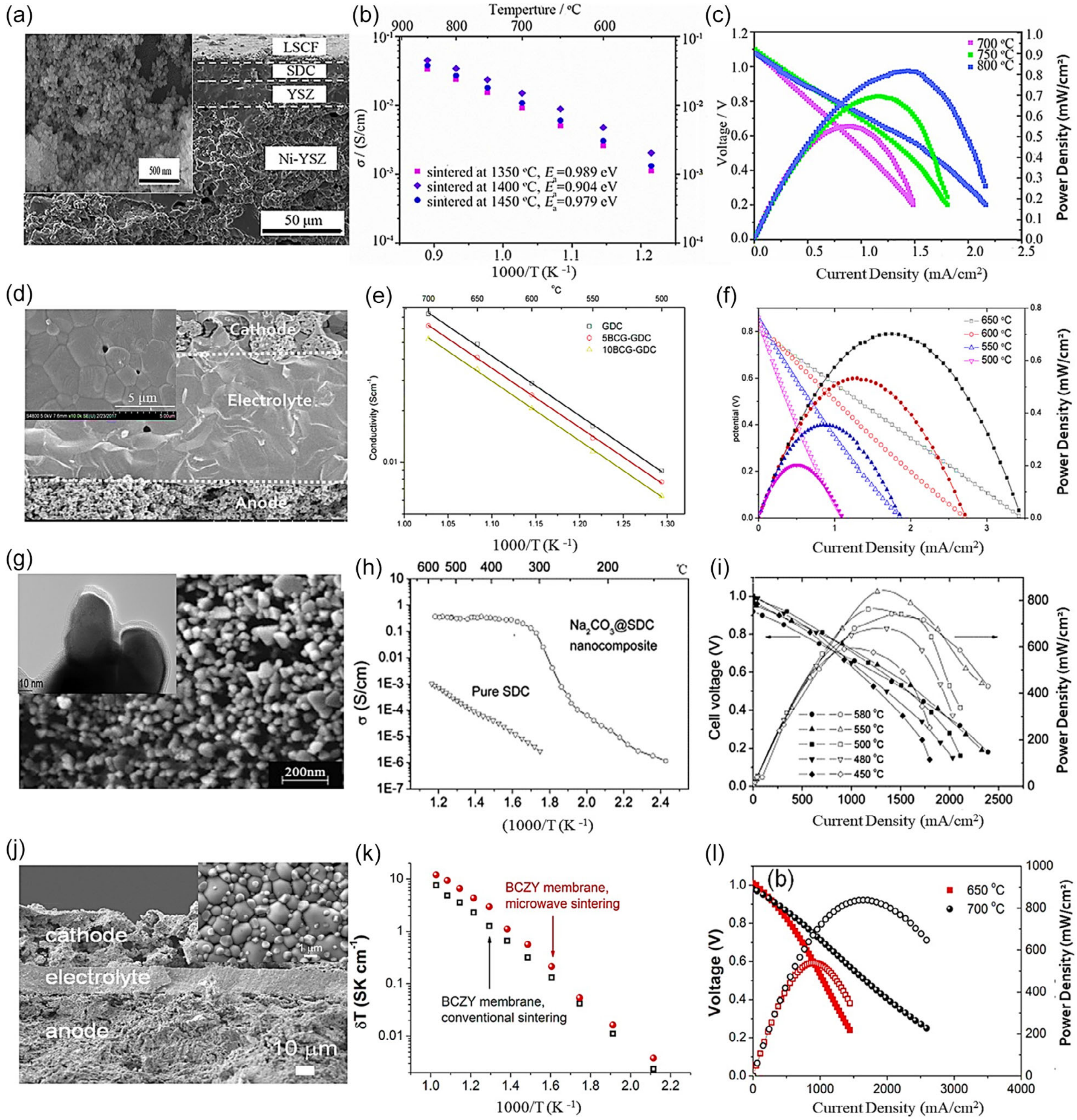

Figure 5. Comparative analysis of SOFCs with different configurations: a) scanning electron microscope (SEM) cross section of a single cell with composition Ni–yttria-stabilized zirconia (Ni–YSZ)/YSZ/$Sm_{0.2}Ce_{0.8}O_{1.9}$/$La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$ (LSCF), b) total conductivity values of YSZ powders sintered at different temperatures, c) current–voltage (*I*–*V*) and current–power density (*I*–*P*) curves of Ni–YSZ/YSZ/SDC/LSCF cell, d) cross section of cell, e) total conductivities of gadolinium-doped ceria (GDC) electrolyte with and without carbonate, f) *I*–*V* and *I*–*P* of cell Ni-GDC/5BCG-GDC/LSCF, g) microstructure of SDC–Na_2CO_3 (transmission electron microscope [TEM] image), h) comparison of total conductivities of SDC electrolyte with and without carbonate coating, i) *I*–*V* and *I*–*P* curves of cell prepared using SDC–Na_2CO_3, j) cross section of cell prepared using $BaCe_{0.7}Zr_{0.1}Y_{0.2}O_{3-\delta}$ (BCZY) electrolyte (inset), k) total conductivities, and l) *I*–*V* and *I*–*P* characteristics of single cell. a–c) Reproduced with permission.[177] Copyright 2023, Elsevier. d–f) Reproduced with permission.[178] Copyright 2022, American Chemical Society. g–i) Reproduced with permission.[180] Copyright 2008, Elsevier. Inset in (g) Reproduced with permission.[179] Copyright 2020, Elsevier. j–l) Reproduced with permission.[181] Copyright 2018, Elsevier.

The stability of PC electrolytes can be enhanced using more electronegative elements for doping.[93] Highly conductive and stable PC electrolytes have been developed using a bilayer approach taking advantage of the stability of the doped barium zirconates and the conductivity of the doped barium cerates, rendering them effective for LT–SOFCs.[94]

6.2. Anode

The anode is an important part of the SOFC that catalyzes the fuel reaction with O^{2-} from the electrolyte by providing reaction sites and conducting electrons to the external reactions generated in an electrochemical reaction.[83]

$$H - H + O^{2-} = H - O - H + 2e^{-} \tag{3}$$

Desirable properties for the anode include high electron conductivity, resistance to coke formation, thermal expansion coefficient (TEC) matching, nanostructured particle size, electrolyte compatibility, high porosity with large three-phase boundaries, and well-mixed conductor.[95] Despite the poor performance, traditional anode materials have long been practiced. However, research on new anode materials to improve properties has also been conducted. Although intensively studied, iron-based anodes are not attractive in practical use due to corrosion problems and the reduced activity of iron. Cobalt has also been exploited as an anode material due to its stable nature, but its high cost and the ability to promote carbon formation inhibit its use.[96]

Since its introduction in 1995, Ni–zirconia has been widely used as anode material. However, at high temperatures, Ni thermal expansion mismatches with stabilized zirconia.[97] Also, the aggregation of Ni particles reduces the anode porosity due to the TPB elimination resulting in decreased cell performance. To enhance TEC compatibility between YSZ electrolytes and anodes, Westinghouse Electric Corporation (WEC) developed Ni–YSZ cermet as an anode for SOFCs. Due to the electron insulation of YSZ, the conductive path through the anode requires the presence of a sufficient concentration of Ni phase in the anode cermet. Numerous studies have shown that an anode material with a Ni concentration of 40–60 vol% is required to achieve both sufficient conductivity and balanced TEC.[98]

SOFC anode materials are typically limited to Ni–YSZ cermets and provide adequate stability and electrical performance in prototype demonstration units under H_2/O_2 fuel conditions. The growing interest in the direct oxidation of hydrocarbon fuels at the anode has changed the specifications of the anode materials, rendering traditional Ni-based cermets undesirable due to the deposition of carbon, which is enhanced due to the presence of Ni.[8] Ceramic materials exhibit well-mixed conductivity under reducing conditions and can therefore be used as anodes. In addition, these materials exhibit good catalytic activity for hydrocarbon fuels.[8]

Titanate-based anode materials ($SrTiO_3$) have also been developed; however, instead of showing p-type conduction, these materials exhibited n-type conductivity with size changes in reducing atmospheres.[98] The direct electrochemical oxidation of fuels, e.g., ethane, methane, toluene 1-butene, etc., is possible due to the use of these materials proposed in refs. [98,99]. Perovskite-based materials are resistant to carbon deposition and sulfur poisoning and have attracted much attention due to their high redox stability, suitable ionic/electronic conductivity, and high activity toward fuel decomposition.[100] Perovskite materials based on $SrTiO_3$ and $LaCrO_3$ have been proposed as potential anodes for SOFCs, which exhibit a wide range of physical properties when partially substituted with alkaline earth and transition metals (Ti, Cr, Co, Fe, etc.).[98,99]

According to the literature, composite cermet anodes like Cu–Ni/YSZ, (Ni,Fe)–YSZ, (Ni,Co)–YSZ, (Cu,Co)–YSZ, (Ni, Cu)–YSZ, and (Cu,Co,Fe)Ni–YSZ are also not feasible due to low power density of YSZ in comparison to some metal elements. Consequently, composite anodes like Cu–Ni–CGO and Cu–CGO have been introduced for better performance, chemical compatibility and stability than the existing anodes for SOFCs.[8] Mixed electronic, as well as ionic conductivity, is shown by Cu–Ni–CGO and Cu–CGO, and cheap and fast techniques, e.g., glycine–nitrate can be used for their synthesis.[101] The $Ce^{+4} \rightarrow Ce^{+3}$ conversion governs very good catalytic activity and better electronic conduction of CeO_2-based anode materials. Furthermore, for Cu-ceria-based anode materials, the hydrocarbon fuels can be directly supplied to the anode.[102]

Due to their ability to resist carbon deposition and sulfur poisoning, together with good electrical conduction, cermet anode materials including Cu–CeO_2, Ni–CGO, Cu–Ni–CGO, and Cu–CGO, reviewed in ref. [8], have also been investigated. Gan et al. used a dual-modification strategy to fabricate Sn-doped $Ce_{0.8}Sm_{0.2}O_{2-\delta}$ anode (**Figure 6**).[103] The Sn–Ni-alloy-anode-based cell showed high peak power densities for H_2 (1.99 W cm^{-2}) and CH_3OH (2.11 W cm^{-2}) fuels at 700 °C with extraordinarily high coking resistance of the anode. Advancement in protonic ceramic FCs has triggered research on Ni–zirconate–cerate-based anode materials.[104] Spinel-type metal aluminates MAl_2O_4 (M = Ni, Co, Zn, Mg, Ca, Sr) have also been investigated as potential anodes for SOFCs due to their porous and thermally stable structures.[105]

Despite extensive research on material development, SOFCs have failed to deliver reasonable stability coupled with a suitable performance at a low-temperature regime. The focus is now to engineer the structural architectures of SOFCs using thin-film and microfabrication techniques. This includes reducing the electrolyte thickness and enhancing the reaction surface.[106] Nanomaterials have been used to enhance the mechanical strength and long-term stability of commonly used anode support (Ni–YSZ) for SOFCs.[107] The development of LT–SOFCs using 3D multiscale architectures via micro-patterning and thin-film deposition techniques has been found effective. Using this, Shin et al. reported an exceptionally high performance of 13 W at 500 °C for a multiscale structured SOFC with excellent stability (**Figure 7**).[106]

Thin-film SOFCs operate more effectively in low-temperature regimes (below 600 °C) than the usual SOFCs, however, suffer from fuel flexibility issues especially when hydrocarbon fuels are used, thus requiring expensive noble-metal catalysts. Thieu et al.[108] used a multiscale-architecture approach to insert the inexpensive catalysts (Cu and CeO_2) at the anode (**Figure 8**) which not only improved the durability and performance but also enhanced the steam reforming reaction for a hydrocarbon-fueled SOFC, that too at low temperature.

The effect of anode thickness on the electrochemical properties of thin-film SOFCs has also been investigated. Lee et al.[109] deposited Ni–gadolinium-doped ceria (Ni–GDC) anode of varying thicknesses (1–5 μm) on nanoporous anodic aluminum oxide and showed that proper balancing of ionic as well as electronic properties results in 40.1% performance increment compared to cells of similar architectures reported in the literature (refer to **Figure 9**).

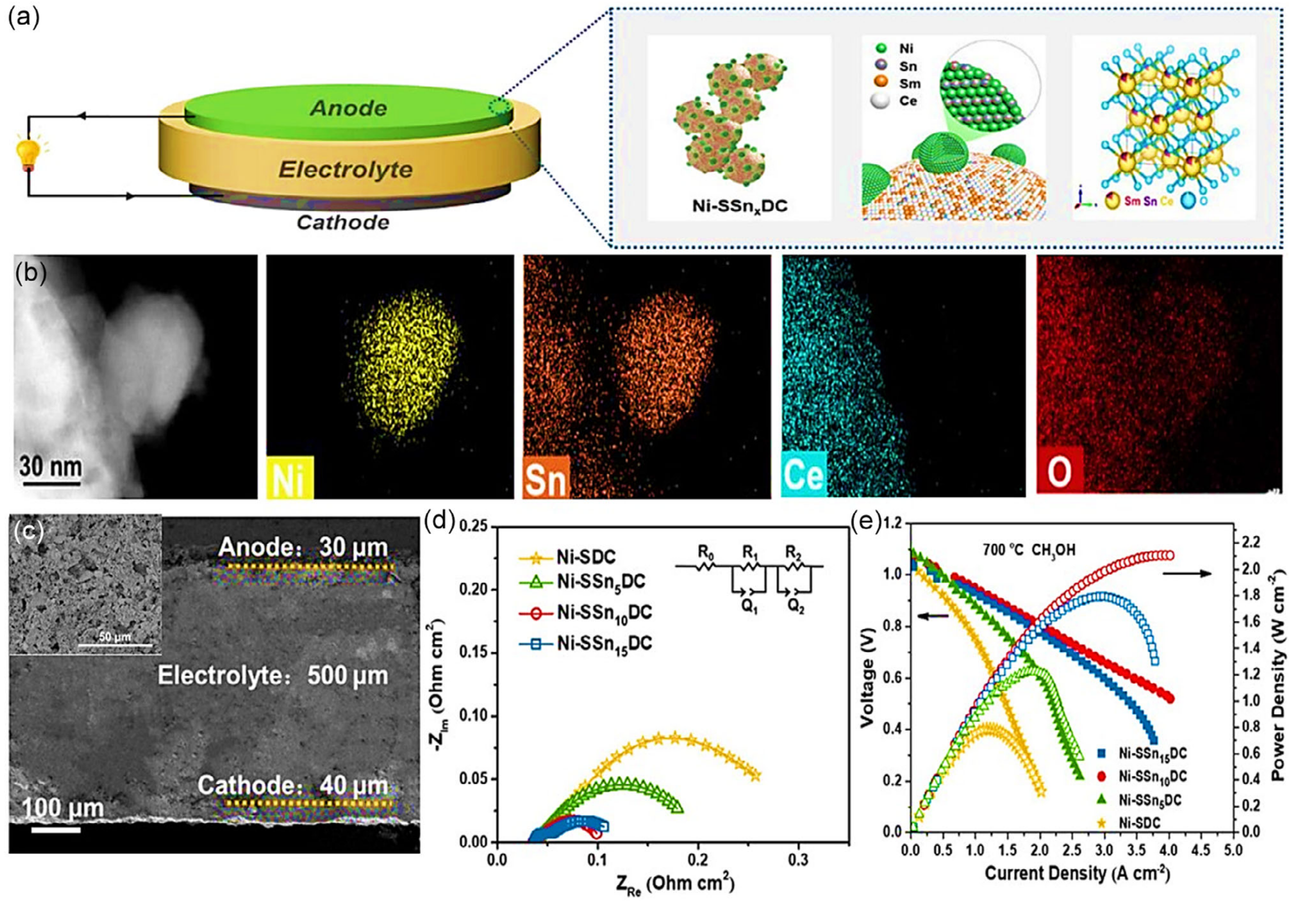

Figure 6. a) Schematic representation of structure of Ni-SSnxDC anode, b) high angle annular dark field-scanning transmission electron microscope (HAADF-STEM) image of reduced Ni-SSn10SC, c) SEM image of cross section of cell with inset showing surface of NiO-SSn10DC anode, d) Nyquist plots of symmetric cells recorded at 700 °C using H_2 fuel, and e) *I–V* and *I–P* curves of Ni-SSnxDC-based single cells fed with methanol at 700 °C. Reproduced with permission.[103] Copyright 2022, Elsevier.

6.3. Cathodes

The cathode is important for SOFC technology due to its catalytic role in the following reaction.

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \tag{4}$$

The cathode helps improve SOFC performance by minimizing power loss and offering a good electrical connection between the electrodes and interconnected components.[110] The desirable properties of a cathode include excellent porosity and stability, excellent electrical conductivity, inactivity to electrolyte materials, and excellent catalytic activity.[110,111] Currently, the most common cathode for high-temperature (HT)–SOFCs with YSZ electrolyte is $La_{1-x}Sr_xMnO_3$ (LSM) perovskite. However, under low-temperature conditions, the activation energy and polarization resistance of LSM increase, and SOFC performance deteriorates.[112] Additionally, LSM may react with the electrolyte material at a temperature above 1100 °C.[113] $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$ (LSCF) in combination with GDC was investigated with a focus on operational performance increment.[114]

Materials with structures like $A_2BO_{4+\delta}$ (A = rare-earth element; B = Fe, Cu, and Ni) have been studied for application to SOFCs as cathodes. Lanthanum nickelates exhibit very high oxygen surface exchange coefficients, high porosity and lower activation energy,[115] suitable electrical conductivity coupled with good chemical stability,[116] and improved tolerance to chromium poisoning.[117]

$LnBaCo_2O_{5+\delta}$ (Ln = La, Nd, Pr, Gd, Sm, and Y) exhibits stimulating properties and includes high electron conductivity and high oxygen surface exchange coefficient. Compared to commonly employed electrode materials, cobalt-based materials demonstrate higher coefficients of thermal expansion.[118,119] This property can be attenuated by adding elements to their structures which enhance the cathode performance. For example, the synergistic effect of co-doping in double perovskite $LnBaCo_2O_{5+\delta}$ (Sr on A-site and Fe on B-site) in creating pore channels for fast oxygen ion diffusion and surface oxygen exchange was investigated.[120] Density-functional theory (DFT) calculations were used to elucidate the most probable pathway for oxygen reduction reaction (ORR) shown in **Figure 10**.

Due to some disadvantages of cobalt-based materials like high cost as well as high TEC, cobalt-free compounds giving greater

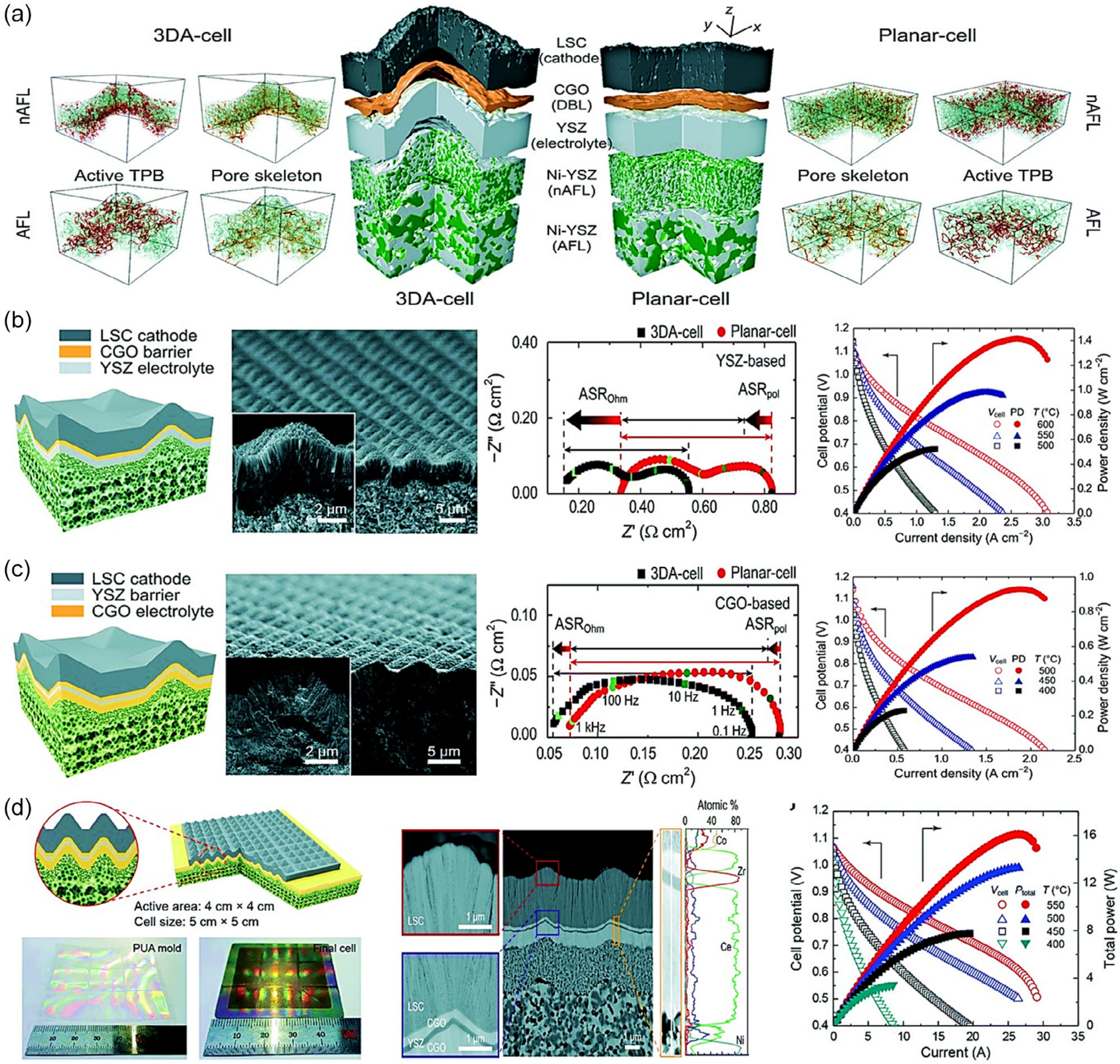

Figure 7. a) YSZ-based three dimensional architectured cell (3DA)-cell (left) and planar cell (right), b) SEM image of a YSZ-based 3DA cell, c) SEM images of impedance spectra of CGO-based 3DA cell, and d) images of a large-sized (active area = 4 × 4 cm) CGO-based 3DA cell. Reproduced with permission.[106] Copyright 2020, The Royal Society of Chemistry.

performance are highly desired.[121] A novel cobalt-free $NdBaFe_{2-x}Mn_xO_{5+\delta}$ with enhanced electrical conductivity (114 S cm^{-1} at 550 °C) was reported in ref. [122]. Cobalt-free $SrFeO_3$-based perovskite systems are also low-cost and highly active in redox reactions (ORRs). And, 4–8 times higher ORR activity was recorded for $Sr_4Fe_6O_{13-\delta}$ in ref. [121]. Song et al.[123] prepared a cobalt-free multiphase nanocomposite ($Sr_{0.9}Ce_{0.1}Fe_{0.8}Ni_{0.2}O_{3-\delta}$: SCFN2) by smart self-assembly (**Figure 11**). A synergistic effect created due to interaction between different phases leads to superior ORR activity, and ultimately to enhanced FC performance for SFCN2 based cell.[123]

Although the addition of alkaline earth metals to the perovskites generates oxygen vacancies and improves their performance, there are some drawbacks to using alkaline earth elements. For instance, the long-term performance of these materials can be affected by chromium poisoning and surface segregates upon interaction with other elements.[124,125] Perovskites that do not contain alkaline earth metals have also been investigated. In ref. [126], $PrNi_{0.4}Fe_{0.6}O_{3-\delta}$ was prepared through solid-state reaction and examined with respect to thermal stability, oxygen nonstoichiometry and diffusion characteristics, showing an increase in electrical conductivity for intermediate ranged 600–800 °C SOFCs. Martínez–Coronado et al.[127] reported a double-perovskite

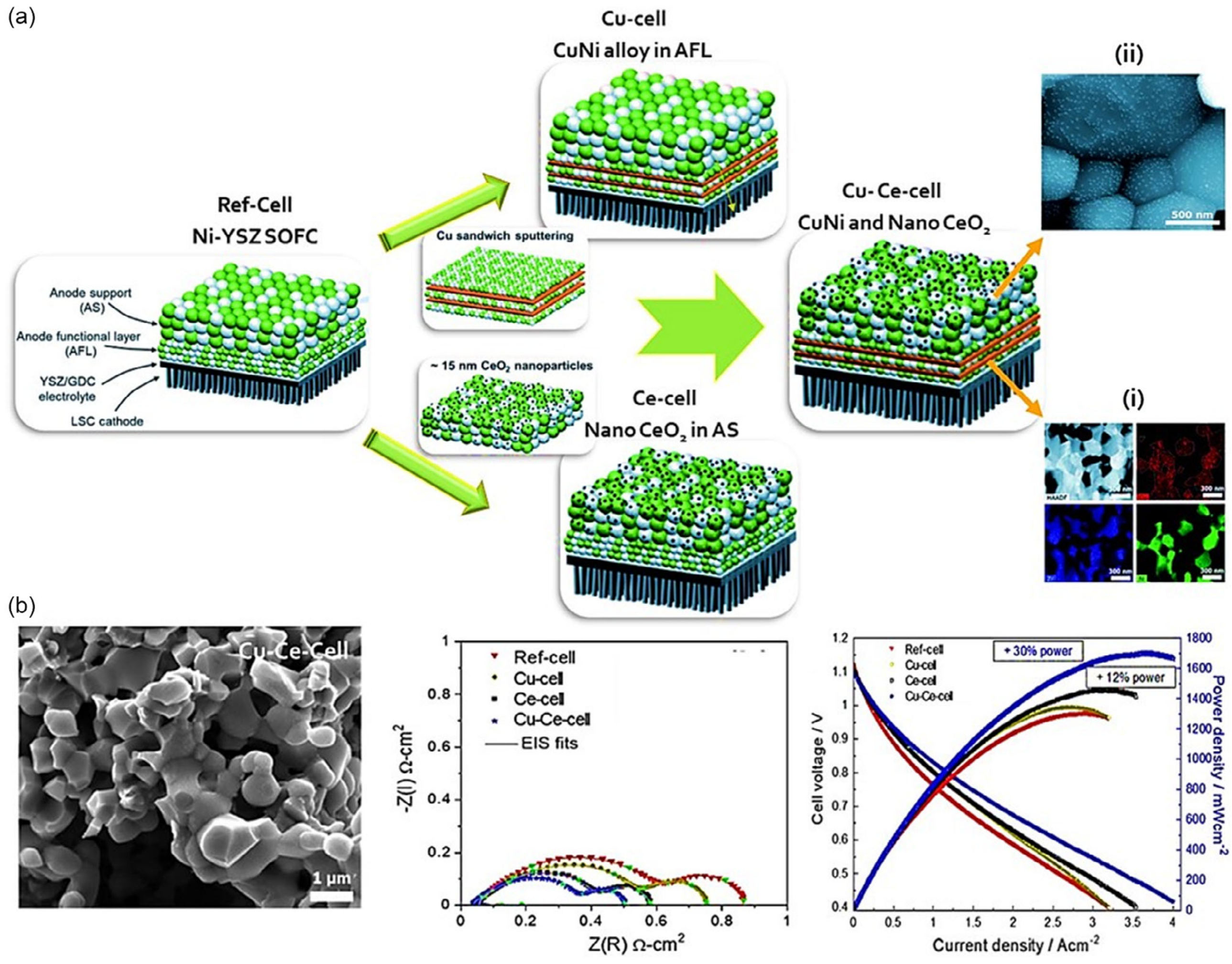

Figure 8. a) Schematic representation of incorporation strategies of different catalysts and the resultant thin film SOFCs. Arrows show i) HAADF–STEM image energy-dispersive X-ray spectroscopy (EDS) analysis, ii) SEM micrograph of anode support. b) Surface morphology of Cu–Ce cell, Nyquist plots and *I–V* and *I–P* curves of different cells measured at 600 °C. Reproduced with permission.[108] Copyright 2022, The Royal Society of Chemistry.

La_2ZnMnO_6 for application as SOFC cathode while improved conductivities in lower temperature range were obtained by partial substitution of Ni for Mo in $LaNi_{1-x}Mo_xO_3$.[128]

Nanostructure engineering to fabricate 3D core–shell architecture has proven successful in enhancing the ORR activity of cathodes. Bai et al. used coaxial electrospinning to prepare 3D core–shell heterostructures of $PrO_{2-\delta}$-decorated LSCF (LSCF@$PrO_{2-\delta}$).[129] Compared to simple LSCF nanostructures, LSCF@$PrO_{2-\delta}$ nanofibers (**Figure 12**) showed improved stability, ensured the provision of a continuous charge-transfer path and extended the three-phase interphase to improve the ORR activity, suggesting a potential strategy to develop high-performance cathodes.

Optimizing the interfacial activity and extending the TPB of composite cathodes could boost FC performance. For example, Yin et al.[130] prepared Co-doped $La_{0.5}Sr_{0.5}MnO_{3-\delta}$ ($La_{0.5}Sr_{0.5}Mn_{0.9}Co_{0.1}O_{3-\delta}$: LSMCo) and coupled with $BaZr_{0.8}Y_{0.2}O_{3-\delta}$ (BZY) to prepare composite cathode which showed dramatic improvement in FC performance for H-SOFCs (**Figure 13**). DFT results validated that Co addition triggered the interfacial activity while BZY coupling caused a more active TPB.

7. Latest Developments and Future Recommendations

SOFCs have the potential to play an important role in replacing lithium-ion batteries for portable applications due to their high energy density. For low-temperature applications, although there is a constant search for new electrolytes, ceria-based electrolytes have so far been recognized as potential replacements for high-temperature ZrO_2-based electrolytes due to the aforementioned advantages.[7,84] PC–SOFCs have also gained renewed interest as the H^+ conductivity may exceed the O^{2-} conductivity in the temperature range of 400–600 °C. In a project funded by the US DoE Office of Energy Efficiency and Renewable (EERE), Philip 66 has achieved ≈70% round trip efficiency at 1 A cm^{-2} for proton conductors–based reversible solid oxide cells.[131] Similarly, a report by Duan et al.[132] indicating excellent performance between 500

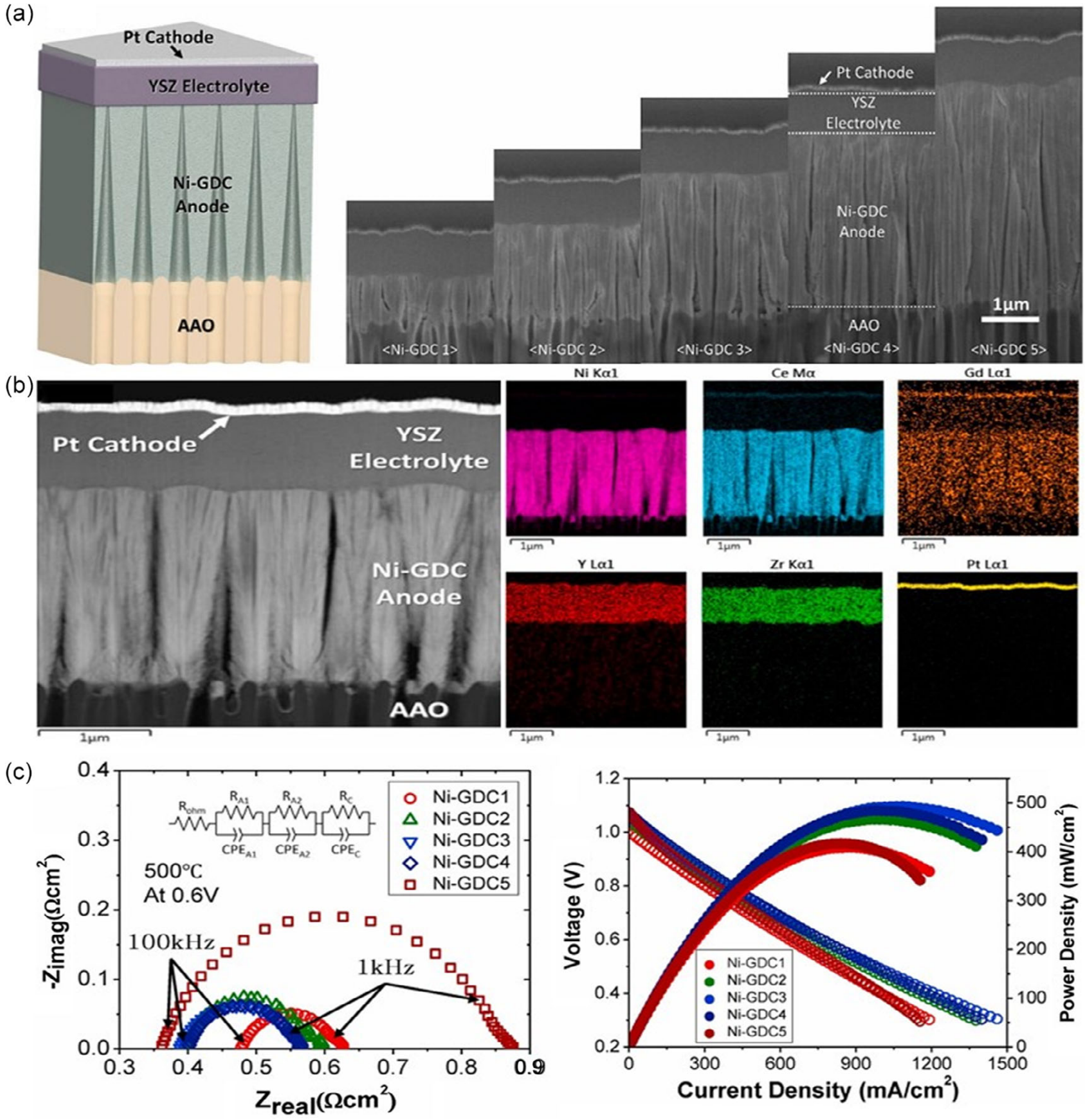

Figure 9. a) Schematic diagram of Ni–GDC anode, b) TEM cross section of 3 μm thick Ni–GDC cell with EDS mapping, and c) electrochemical impedance spectroscopy (EIS) results and *I–V* and *I–P* curves of Ni–GDC-based thin-film SOFCs. Reproduced with permission.[109] Copyright 2022, The Royal Society of Chemistry.

and 600 °C with impressive durability (degradation rate <1.5%/1000 h under multi-fuel conditions) for PCFCs has triggered the research in this field.

Ni-based cermets are the most widely used anodes for SOFCs. However, Ni is less tolerant to sulfur contamination and deactivates due to carbon deposition from the direct oxidation of hydrocarbon fuels.[133] Hence, there is a growing interest in using the least quantity of Ni or improving its redox stability through microstructure optimization along with continuously searching for alternate Ni-free anode materials.[134] Reports of new cathode materials continue to be published, but LSM and LSCF have proven to be the most successful and reliable ones. The focus is now on mitigating Cr and sulfur poisoning when operating in stack form, as well as reducing material costs within SOFC development.[61] It also includes the preparation of nanostructured cathodes using synthetic routes that are simple, less time-consuming and do not require prolonged high-temperature treatments with sophisticated environments. For example, spray pyrolysis has been reviewed in ref. [133], which allows the growth of layered cathode materials directly on the electrolyte overcoming the compatibility issues and offering pros like the attainment of a variety of morphologies by small variations in deposition conditions. In addition, improved performance at low temperatures is also sought through microstructural strategies. Recent efforts focused on the development of composite cathodes to enlarge the TPB i.e., mixing a mixed ionic and electronic conductor (MIEC) with a high ionic conducting phase, e.g., doped ceria and Bi_2O_3.[135,136] Triple conducting (O^{2-}/e^-/H^+) cathode materials have also been focused on in literature.[137]

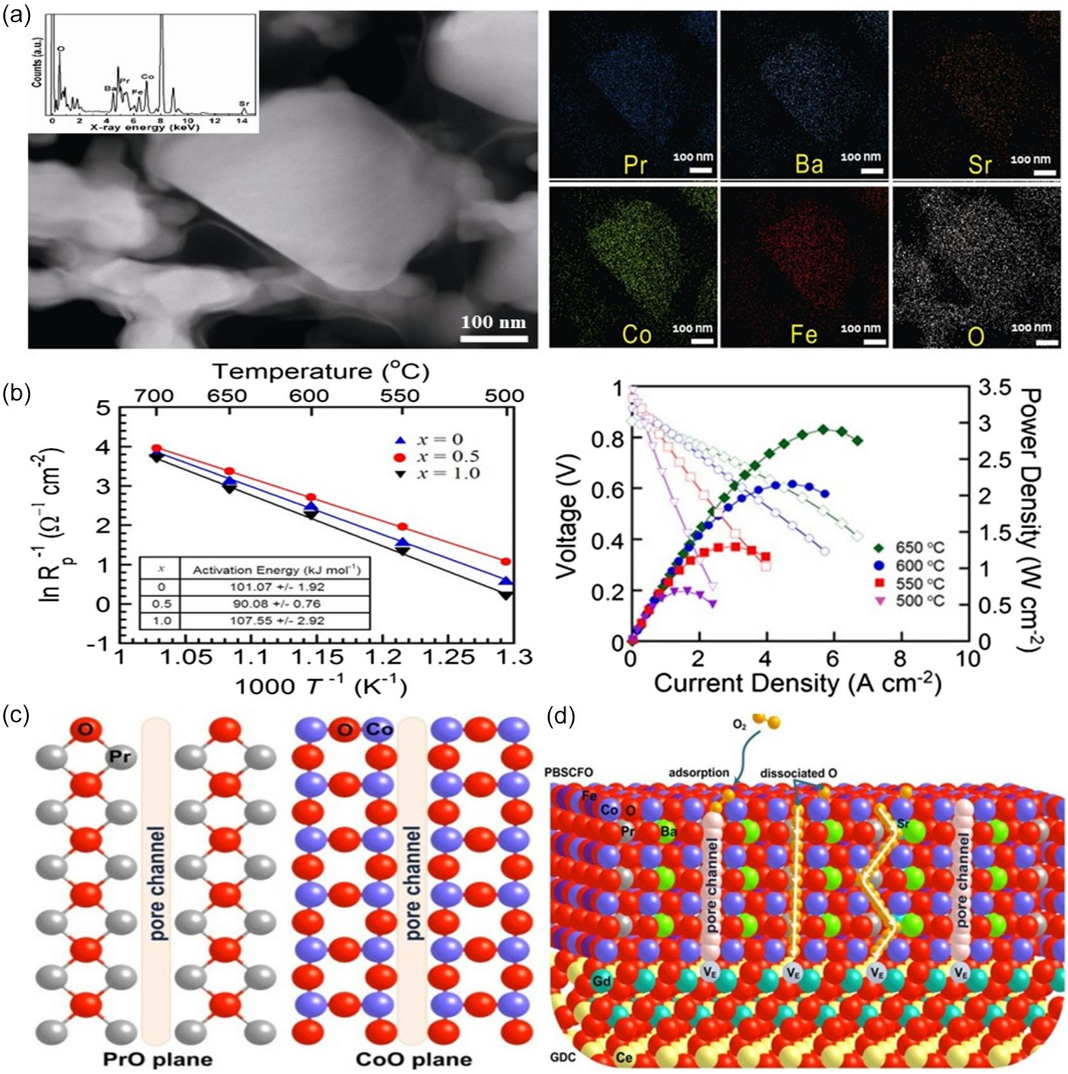

Figure 10. a) HAADF–STEM image of $PrBa_{0.5}Sr_{0.5}Co_{1.5}Fe_{0.5}O_{5+\delta}$ particle with EDS, b) Arrhenius plots of $PrBa_{0.5}Sr_{0.5}Co_{2-x}Fe_xO_{5+\delta}$, c) DFT calculations, and d) suggested mechanism of surface oxygen reduction reaction (ORR) and bulk diffusion across. Reproduced with permission.[120] Copyright 2013, the Authors. Published by Springer Nature.

In recent years, single-component SOFC has also drawn a lot of attention. It differs from the conventional SOFC in the sense that it features dual-ion (O^{2-}/H^+) conduction based on the semiconductor-ion heterostructure materials. The Schottky-junction-integrated electric field provides proof that the FC operates at low temperature, introducing a new, imposing framework for FC study and development[138] (**Figure 14**).

Machine learning is also gaining importance to comprehend the mechanistic chemistry of SOFCs. Since experimental studies on SOFC are costly, labor intensive, and time consuming, quantitative mechanistic models are helpful for SOFC scientists and developers, as they can assist to comprehend the chemistry involved within the cell and allow optimization of materials, cells, stacks, and systems. Modeling SOFCs using artificial intelligence has the potential to pinpoint the conditions that could lead to optimal results. When preparing nanoelectrodes, the models based on ANNs can forecast the surface area and conditions to achieve desired performance.[139]

8. Dynamic Modeling of SOFC System

SOFCs use an electrochemical reaction to convert chemical energy stored in hydrogen molecules into electricity, generating heat and water (steam) as a by-product. The SOFC dynamic model has been discussed in refs. [140,141]. This present model is derived using the output voltage produced by an FC stack ($V_{F.C}$) and the Nernst's potential (E).[142,143]

$$V_{F.C} = \underline{N}s - V_L \tag{5}$$

where $\underline{N}$s indicates the number of cells linked in series, V_L exhibits irreversible voltage losses. E can be determined as

$$E = E_o + \frac{RT}{2F} \ln \frac{p_{H_2} p_{O_2}}{p_{H_2O}} \tag{6}$$

where Eo is reaction-free energy, T is the FC temperature, R and F provide the general gas constant and Faraday's constant,

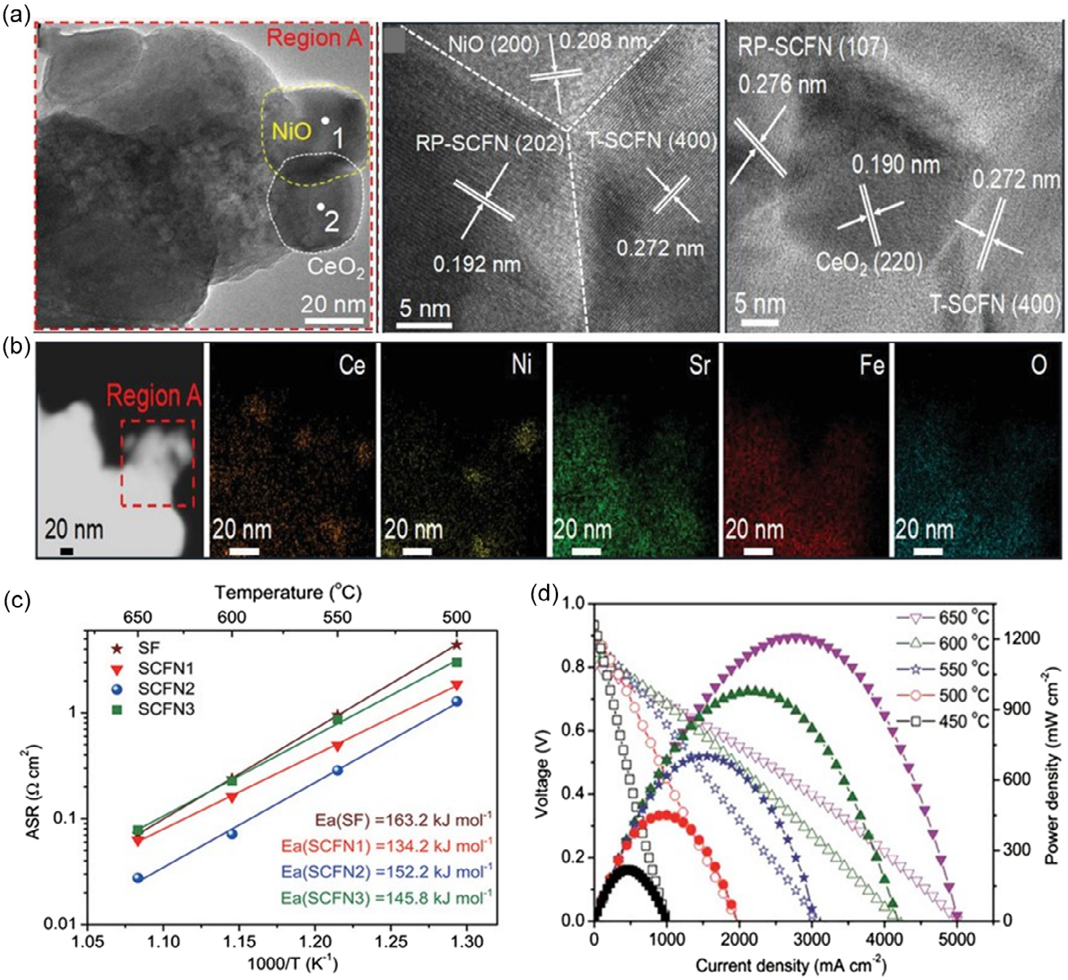

Figure 11. a) STEM image, high-resolution TEM (HR-TEM) images of SCFN2 sample, b) STEM–EDS mapping, c) Arrhenius plots of the area specific resistance (ASR) values of different samples, and d) *I*–*V* and *I*–*P* curves recorded from 450 to 650 °C. Reproduced with permission.[123] Copyright 2020, Wiley-VCH.

respectively. p_{H_2O}, p_{H_2}, and p_{O_2}indicate the partial pressures of water, hydrogen, and oxygen, respectively.[142] The values for p_{H_2O}, p_{H_2}, and p_{O_2} can be determined as

$$\begin{aligned} p_{H_2} &= -\frac{1}{X_{H_2}}\left(p_{H_2} + \frac{1}{K_{H_2}}\left(M_{H_2.FC} - 2K_r I_{FC}\right)\right) \\ p_{H_2O} &= -\frac{1}{X_{H_2O}}\left(p_{H_2O} + \frac{2}{K_{H_2O}}K_r I_{FC}\right) \\ p_{O_2} &= -\frac{1}{X_{O_2}}\left(p_{O_2} + \frac{1}{K_{O_2}}\left(M_{O_2.FC} - K_r I_{FC}\right)\right) \end{aligned} \tag{7}$$

where $M_{H_2.FC}$ and $M_{O_2.FC}$ represent the molar flow for hydrogen as well as oxygen, respectively.K_{H_2O}, K_{H_2}, and K_{O_2} are constants; K_r is also a constant and can be expressed with the help of a relation between FC current (I_{FC}) and rate of reactant hydrogen d'_{H_2}as follows

$$d'_{H_2} = 2K_r I_{FC} \tag{8}$$

8.1. Electrolyzer Model

Electrolyzer (ELZ) uses electric power to generate hydrogen. The famous ELZ model can be used for different applications. The voltage drop can be calculated through each ELZ cell.[140,144]

$$\begin{aligned} E_{cell} = E_0 &+ \frac{I_{ele}(r1 + r2T_{ele})}{A_{ele}} \\ &+ E_1 \log\left\{\left(\tau_i + \frac{\tau_2}{T_{ele}} + \tau_3/T_{ele}^2\right)\Big/ A_{ele} + 1\right\} \end{aligned} \tag{9}$$

where T_{ele} and E_0 are ELZ temperature and thermodynamic cell voltage, respectively; τ_i and E_1 are ELZ over voltage parameters; *r_i.* represents Ohmic resistance parameter and A_{ele} denotes electrode area. V_{ele} denotes the total voltage drop across ELZ and can be defined as

$$V_{ele} = N_{ele} E_{cell} \tag{10}$$

where E_{cell} indicates the number of cells. The ELZ net power consumption is calculated as

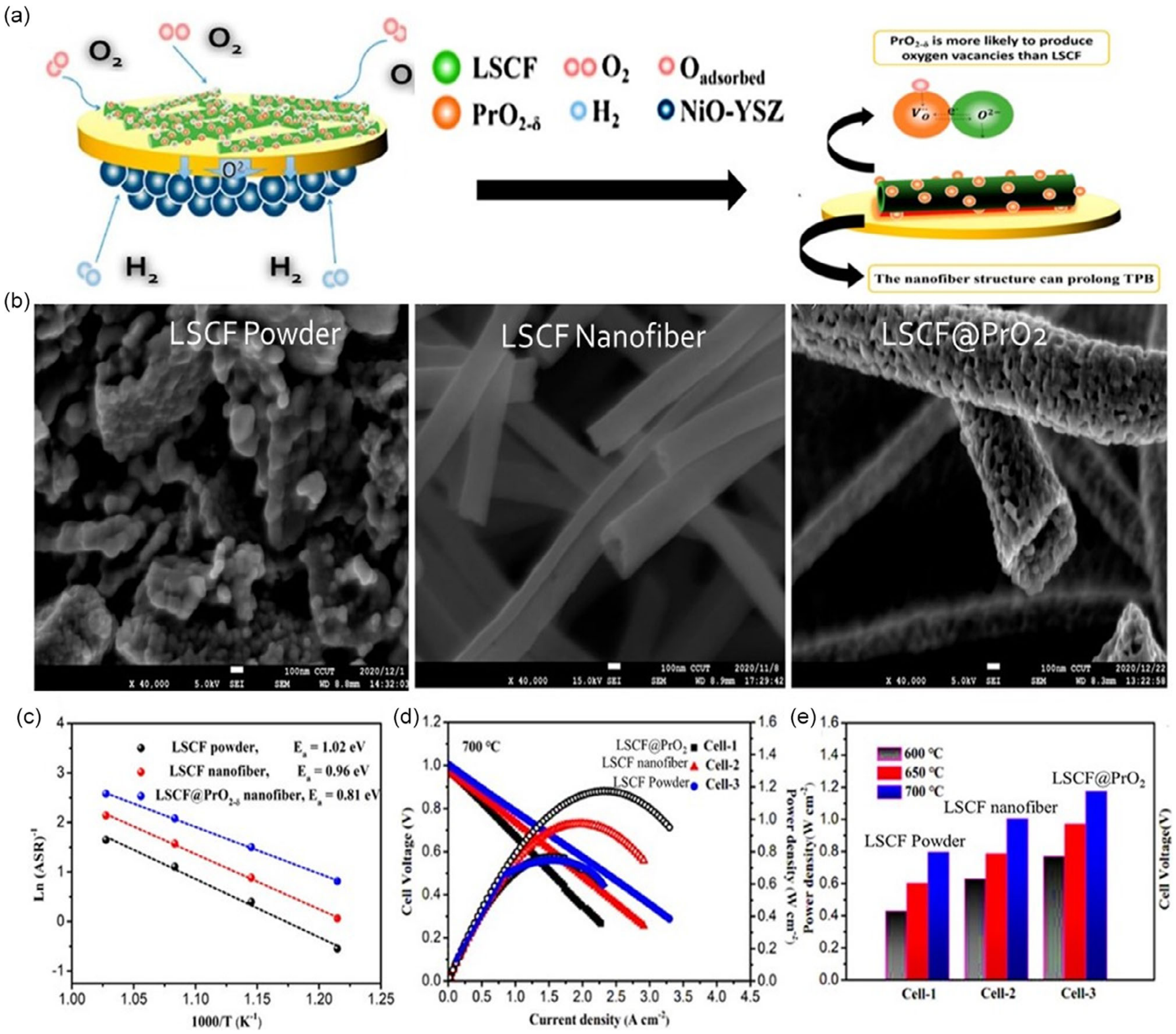

Figure 12. a) Schematic illustration of operation of a cell with LSCF@PrO$_{2-\delta}$ cathode, b) SEM micrographs of different cathodes, c) Arrhenius plots plotted by the reciprocal of ASR for different cathodes, d) *I–V* and *I–P* curves of cells measured at 700 °C, and e) comparison of power densities of different cells with different cathodes. Reproduced with permission.[129] Copyright 2022, American Chemical Society.

$$P_{\text{ele}} = V_{\text{ele}} I_{\text{ele}} \tag{11}$$

The rate for hydrogen production R_{H_2} can be written in terms of applied current as

$$R_{H_2} = \lambda(T, D)\frac{N_{\text{ele}}}{2F} I_{\text{ele}} \tag{12}$$

where D is the current density and λ represents temperature as well as the current density function. To maintain constant hydrogen pressure, Equation (13) must be obeyed, i.e., the rate for hydrogen production must equal to outlet rate of hydrogen.

$$\frac{C_{\text{ele}}}{RT_{\text{ele}}}\frac{d}{dt} p_{H_{2,\text{ele}}} = R_{H_2} - R_{H_2,\text{ele}} \tag{13}$$

where C_{ele} is the cathode volume and $R_{H_2,\text{ele}}$ is the molar hydrogen outflow rate to the hydrogen tank.

8.2. Compressor and Hydrogen Tank Model

A relationship between $R_{H_2,\text{ele}}$ and compressor power (P_c) can be developed as

$$R_{H_2,\text{ele}} = \frac{\beta_c}{\Upsilon} P_c \tag{14}$$

where

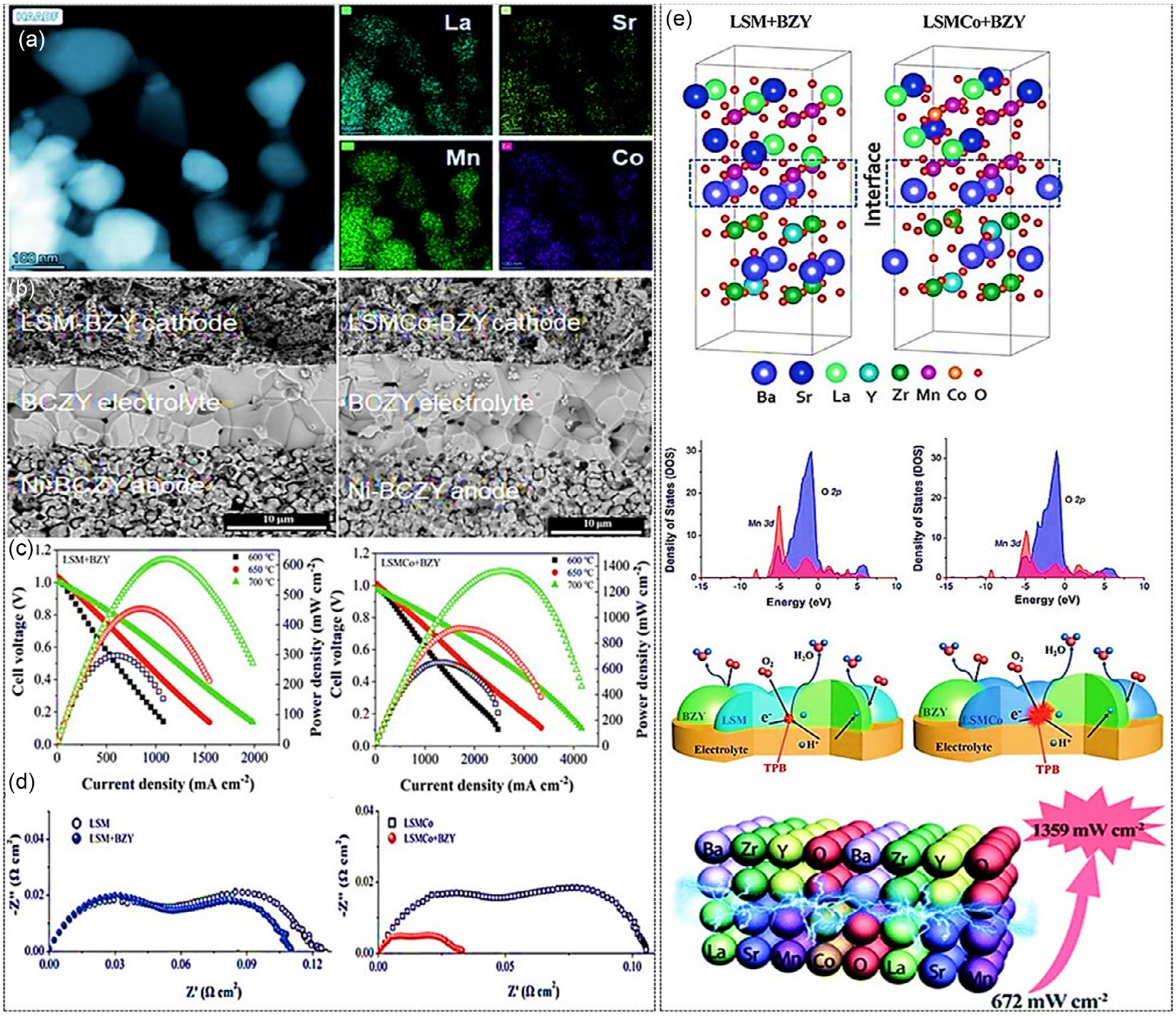

Figure 13. a) HAADF-EDS of $La_{0.5}Sr_{0.5}Mn_{0.9}Co_{0.1}O_3$ (LSMCo) with elemental mappings, b) SEM cross sections of cells with LSM–$BaZr_{0.8}Y_{0.2}O_{3-\delta}$ (BZY) and LSMCo–BZY cathodes, c) *I–V–P* curves of LSM–BZY and LSMCo–BZY cathodes–based cells, d) comparison of impedance spectra of different cathodes, and e) DFT calculations configurations of LSM–BZY and LSMCo–BZY interfaces. Reproduced with permission.[130] Copyright 2022, The Royal Society of Chemistry.

$$\Upsilon = \frac{kRT_{\mathrm{ele}}}{k-1}\left\{\left(\frac{t_{\mathrm{p}}}{p_{\mathrm{ele}}}\right)^{\frac{k-1}{k}} - 1\right\} \tag{15}$$

The required amount of hydrogen is sent by ELZ to FC ($R_{\mathrm{H_2,ele}}$) and the remaining amount of hydrogen denoted by ($R_{\mathrm{H_2,NET}}$) is transported to tank is indicated by the relation as follows

$$R_{\mathrm{H_2,NET}} = R_{\mathrm{H_2,ele}} - R_{\mathrm{H_2,SOFC}} \tag{16}$$

The stored hydrogen pressure ($P_{\mathrm{H_2}}$) can be used as

$$\frac{d}{dt}P_{\mathrm{H_2}} = \frac{RT_{\mathrm{t}}}{\tilde{V}_{\mathrm{t}}}R_{\mathrm{H_2,NET}} \tag{17}$$

where T_{t} and $\tilde{V}$ indicate the storage tank temperature and storage tank volume, respectively.[145]

9. Power Electronics in SOFCs

Power electronics are important in the control of SOFCs. The power electronics architecture of SOFCs is the same as renewable energy systems, including electrical vehicles. The polarization–current (*P–I*) and (*V–I*) curves of an SOFC are nonlinear which are depicted in **Figure 15**. The SOFC output power can be determined as

$$P_{\mathrm{FC}} = V_{\mathrm{FC}}I_{\mathrm{FC}} \tag{18}$$

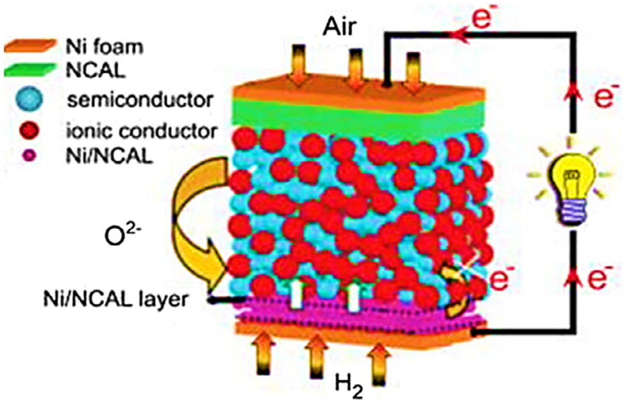

Figure 14. Schematic of a single component SOFC. Reproduced with permission.[138] Copyright 2022, Elsevier B.V.

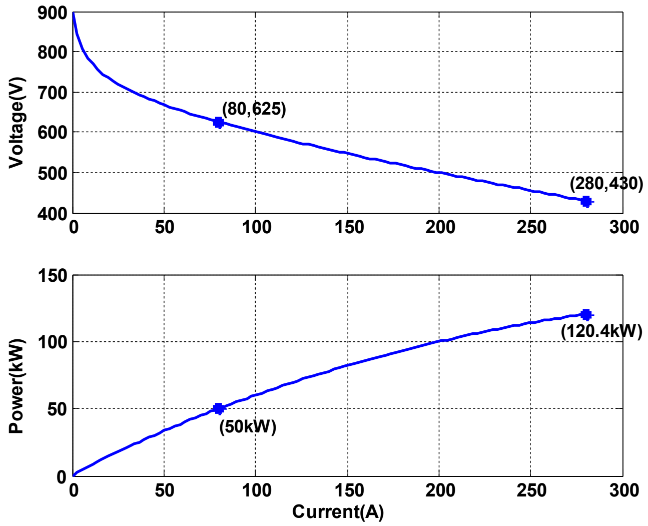

Figure 15. *P–I* and *V–I* curves of an SOFC. Reproduced with permission.[145] Copyright 2023, AIP Publishing.

To effectively utilize the SOFC output power, a control system is necessary for the regulation of hydrogen flow.[146] Different power control methods such as proportional–integral (PI)/PID-based boost/buck converter, sliding mode controller, predictive controller, etc., have been proposed by researchers for the control of SOFCs.[3,5,22–36,142,143]

9.1. DC–DC Converter for SOFCs

There are three basic types of DC–DC power converters that are used in the control of SOFCs, i.e., a buck, a boost, and a buck–boost. Generally, SOFC stacks operate at relatively low voltage, and therefore, a boost converter based on PI or PID controller is used as the fluctuation of voltage takes place in accordance with the dynamic operating point. The boost converter provides an output voltage that is based on the duty cycle using pulse width modulation (PWM) generator as shown in **Figure 16**a and given in the following equation

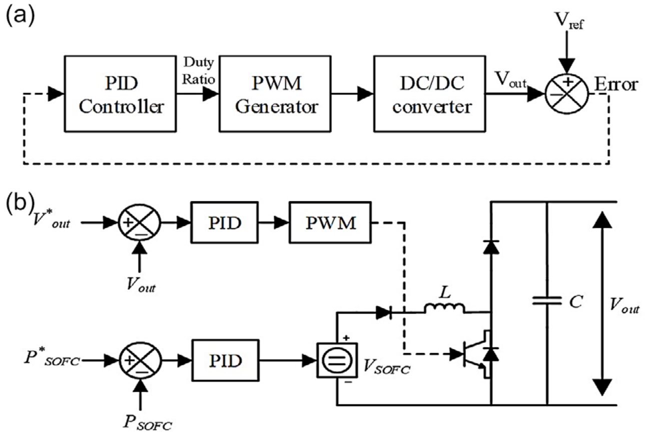

Figure 16. a) Control strategy of SOFC/electrolyzer (ELZ) system and b) proportional–integral–derivative (PID)-based SOFC controller. a) Reproduced with permission under the terms of the Creative Commons CC BY license.[182] Copyright 2016, the Authors. Published by Advances in Science, Technology and Engineering Systems Journal. b) Reproduced with permission.[145] Copyright 2023, AIP Publishing.

$$V_{\text{out}} = \frac{1}{1-d} V_{\text{t}} \tag{19}$$

As d ε (1, 0), the output voltage generated by the boost converter is always higher than its input. Figure 16b depicts the control of the FC.

9.2. Electrolyzer Control of SOFCs

In the SOFC system, ELZ is crucial which utilizes an electric current to split water into hydrogen and oxygen. By controlling the input current, the ELZ can be controlled. For the regulation of power flow, a buck converter can be applied in ELZ[143] and is illustrated in **Figure 17**.

9.3. DC–AC Inverter for SOFCs

For grid-connected or distributed generation applications, the regulated DC output voltage of SOFCs is converted to AC via an inverter. The inverter is controlled through different control strategies depending on the application. For example, in ref. [2], two PI controllers embedded in hysteresis current control are used to control the inverter for the SOFC power plant. This is the simplest

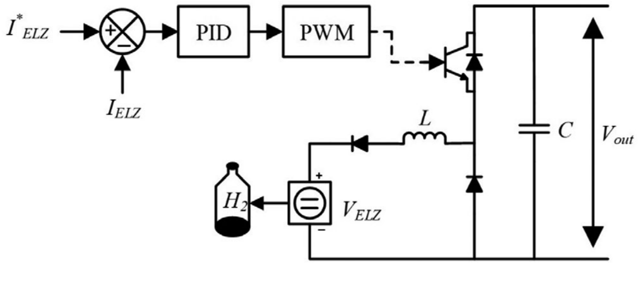

Figure 17. PID-based controller for ELZ. Reproduced with permission.[145] Copyright 2023, AIP Publishing.

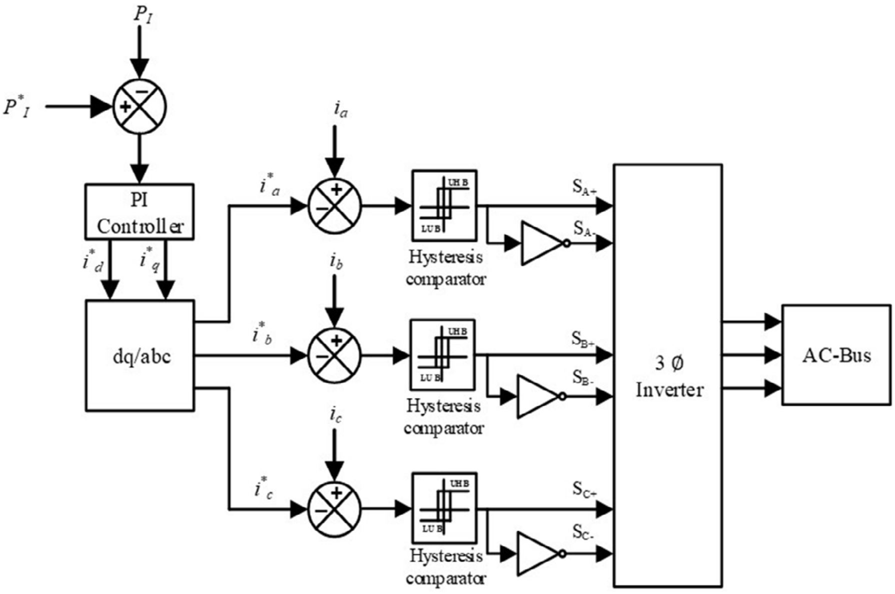

Figure 18. Control of inverter system. Reproduced with permission.[183] Copyright 2016, IEEE.

method to design and shows a better performance against load.[146] In this technique, the actual and reference powers are compared and the abc reference currents are generated via dq/abc transformation. Then, the reference currents and the actual currents are compared. Further, the error signal (current) is processed through the PI controllers embedded hysteresis current controller, which sends a set of proper signals to the PWM signal generator.

In grid-connected applications, grid voltage and injected inverter current must be synchronized. In this context, the frequency and instantaneous phase angle of a grid voltage is very important to synchronize the grid with the rest of the system.[147] Phase locked loop is used to measure the phase angle. The control strategy is shown in **Figure 18**.

Likewise, similar power electronics control schemes are also found in refs. [145,148,149]. In ref. [145], an SOFC is integrated with a hybrid system to supply power to the grid and grid-integrated load. The SOFC was controlled via a PID-based boost converter. A small-scale power plant consisting of SOFC, an ultra-capacitor, and a micro-turbine for distributed generation is the purpose of ref. [148]. SOFC-based three-level neutral points clamped grid integrated inverter is developed in ref. [149]. The overall system is controlled through PI/sliding mode controllers.

10. Optimization Methods in SOFCs

Different methods can be used for the optimization of SOFCs and can be grouped into three different categories, i.e., stochastic, deterministic, and meta-heuristic methods.

10.1. Deterministic Methods

In the deterministic method, calculus-based iterations with mathematical calculations are used for optimizing parameters. For parameters of simple and single SOFC, simplex algorithm, linear programming, and numerical computation can be used to conduct the deterministic optimization. Numerical simulation for optimizing and controlling a tubular SOFC stack is studied in ref. [150]. Numerical simulations at the microstructure level to maximize electrical power are developed in ref. [151]. Linear programming and evolutionary algorithm (EA) integrated operating strategy optimization and sizing optimization.[152] Linear programming was implemented using the a mathematical programming language (AMPL) in the system's daily operation having independent decision variables like heat exchanger (HEX) size, absorption chiller size, and storage size.

SOFC design and operating conditions can be optimized using different deterministic approaches which use dynamic methods and computer programs, including sequential quadratic programming, nonlinear programming (NLP), and mixed-integer-linear programming (MILP). In ref. [153], the authors have optimized the number of cells and operating parameters of an SOFC stack for control applications by implementing constrained NLP. An SOFC–proton exchange membrane (PEM) fuel cell combination for power generation uses NLP considering the PEM pressure, fuel utilization of SOFC, and equivalence ratio for SOFC.[154] In comparison to separate applications, the SOFC–PEM combination raised ≈12% current density. Similarly, MILP was proposed in refs. [155,156] to optimize the operating strategy and size of the SOFC stack system.

10.2. Stochastic Methods

For complex problems having unclear constraints and decision variables, stochastic approaches come into practice which generate very precise and good solutions to individual goals but can also be stuck in local optima depending upon the constraints when applied to complicated systems. A computational time issue is faced when complex problems are solved to have an exact solution. To optimize SOFC, various methods have been reported in the literature, which include Pareto set, the Lagrange method, Newton's iteration, and real-time optimization.[152–158]

Lagrange multiplier method was used to conduct thermoeconomic optimization.[157] The optimized variables used were operating and sizing conditions. These variables were used to determine the minimal cost of lifecycle per generated plant energy. In addition, the authors, in ref. [158], have proposed Pareto frontier–based multi-objective optimizer. Sensitivity analysis was performed for global electrical efficiency, area-specific resistance, and system's net present value. To optimize SOFC power generation and electrical efficiency, real-time optimization was proposed via modifier adaptation.[159] The method could deal with disturbances and uncertainties during the operation. A similar study was conducted by Bunin to maximize the system's efficiency. To optimize the steady state voltage of SOFC cells and plants, the iterative algorithm was used during this study.[160]

10.3. Meta-Heuristic Methods

The meta-heuristic comes into use when randomized approximate solutions are obtained using a stochastic approach. More accurate solutions are obtained using meta-heuristic which improves the search method and offers faster computational time. It is also given the name as intelligent optimization and runs with evaluated and controllable random solutions. The nature-inspired algorithm is used in its evaluation and the best solutions are used to avoid local optima stuck. However, because of the simple computing process, the computational time issue may be faced. These methods have received considerable attention in the last few years for implementation in power systems. Different methods, including PSO, simulate annealing, genetic algorithm (GA), and EA are under development. Intensive studies have been done on these systems to investigate their applications in SOFCs. GA has been expanded and improved into various modified methods like nondominated sorting GA as well as improved GA (IGA).

GA was implemented by Moller with tournament selection and different operating parameters were optimized in the integrated SOFC–gas turbine (SOFC–GT) system.[161] It was proved that stack temperature plays the most important role in enhancing power efficiency. Using GA, microstructure optimization was conducted to acquire the optimum distribution of electrode pore size and porosity.[34] To maximize cell output, optimization was performed in several cases based on the concentration ratio of H_2 and H_2O. In ref. [162], modified several steps on GA optimization and a proposed IGA was developed. An improvement in error reduction between optimum voltage and sample voltage was obtained by the proposed method. In ref. [39], the authors have used PSO to optimize supply area location and its net present value. It involved a comparison between PSO and GA to find the best integrated SOFC–GT system optimization method.

11. General Cost Analysis of SOFCs

In general, the cost model of SOFC can be described as consisting of three parts: fuel cost, capital cost, and maintenance cost, that is

$$X = X_{\text{fuel}} + X_{\text{capital}} + X_{\text{maintenance}} \tag{20}$$

The cost of electricity, obtained from the SOFC stacks, is the output acquired from this model. The SOFC cost model proposed in ref.[163] can be used for the capital cost. The capital cost of SOFC can be divided into two parts. The first part represents the pressurized enclosure cost (insulation), given as

$$X_{\text{VP}} = 10^{\text{K1+K2log(thermal load)}} \tag{21}$$

$$X_{\text{VBM}} = X_{\text{VP}} \times F_{\text{BM}} \times F_{\text{pressure}} \tag{22}$$

The other part involves FC cost as well as the stack housing cost, written as follows

$$X_{\text{cell}} = A_{\text{cell}} X_{\text{spec}} \tag{23}$$

$$X_{\text{FCstack}} = F_{\text{BM}} \left(X_{\text{cell}} \dot{N}_{\text{cells}} + 2 \dot{N}_{\text{stack}} \times A_{\text{cell}} \times F_{\text{hs}} \times C_{\text{h,spec}} \right) \tag{24}$$

where $\dot{N}_{\text{stack}} = \dot{N}_{\text{cells}} / \dot{N}_{\text{cells,max}}$

The present cost value can be expressed as

$$X_{\text{capital}} = F_{\text{a}} (X_{\text{VBM}} + X_{\text{FCstack}}) \tag{25}$$

To bring the cost to a present value, F_{a} (the annual recovery factor) is defined as

$$F_{\text{a}} = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{26}$$

The electricity cost in $\$\,\text{kWh}^{-1}$ can be determined using the capital cost as well as the annual cost

$$X_{\text{capital,annual}} = X_{\text{capital}} \frac{r(1+r)^n}{(1+r)^n - 1} \tag{27}$$

The consumption of methane during the life cycle of the system and the hydrogen heating value (kJ kg^{-1}) can be used to calculate the fuel cost. The cost analysis assumes that hydrogen is sourced from natural gas, has a duration of 10 years, and has an interest rate of 9%. In addition, the system annual maintenance cost is supposed to be 3% of its capital cost. Alternatively, the following expression can be used to show the fuel cost

$$X_{\text{fuel}} = X_{\text{H}_2} \times LHV_{\text{H}_2} \times n_{\text{H}_2} \times M_{\text{H}_2} \times PF \tag{28}$$

where PF indicates the power factor equivalent to $6000\ \text{h year}^{-1}$. The total cost in Equation (22) can be divided by stack output electrical power and gives the electricity cost in $\$\,\text{kWh}^{-1}$.

The cost of SOFCs is gradually reducing due to research and development in this field. Plug, a US-based company, developed the Plug Power 7000 with a presale price of USD $1500\ \text{kW}^{-1}$; however, due to mass production, the price dropped over the course of 5 years from USD 300 to USD $700\ \text{kW}^{-1}$.[164] Siemens Xiwu company stated in its economic report that the cost of SOFCs could be reduced to USD $1000\ \text{kW}^{-1}$, making them competitive with current power generating technology, if the production scale of SOFCs reached 3 MW.[164,165] It is believed that SOFC technology has the potential to replace conventional power-generation systems. According to the International Thermoelectric Alliance (IGA), the goal is to promote decentralized, clean, and effective power production technology globally, as this is also the direction of the 21st century.[164]

12. Applications of SOFCs

Due to high efficiency, fuel flexibility, negligible pollution, and noise-free operation, SOFCs find applications in different sectors. In the military sector, SOFCs are used in ship propulsion and ship power service, mobile power generators, as well as auxiliary power units (APUs) to provide power to army ground vehicles.[54,55] For residential buildings, SOFCs can be used to generate combined heat and power on a small scale (1–5 kW), using natural gas as fuel. Large SOFC systems are potential candidates for distributed power generation.[53] Due to their ability to use CO as a fuel and internal reforming of the hydrocarbon fuels due to higher temperature operation, SOFCs can be used for on-board APUs. SOFCs can be used to supply power to heavy-duty trucks, recreational vehicles, and luxury automobiles. The power demand of different comfort items like computers, televisions, and microwaves may be fulfilled using APUs.[54,55] A hybrid system consisting of SOFC, and GTs can be used to enhance energy conversion efficiency and is considered as new power-generation technology. The waste heat produced during SOFC operation can also be utilized for heating homes or air conditioning.[53] **Table 2** briefly lists the applications of SOFCs in various sectors.

13. Labs, and Active Research in SOFC Technology

To advance SOFC technology, 16 projects were selected by the US Department of Energy's (DOE's) Office of Fossil Energy (FE) and provided $10.2 million in funding. Technical issues related to SOFC cost and reliability will be addressed in these applied research projects. The projects have been divided into two subject areas: 1) SOFC prototype system testing and 2) core technology development.[166]

Table 2. Applications of SOFCs in different sectors.

Targeted sector/market	Applications	Refs.
Military	Ship propulsion and ship power service	[54,55]
	Mobile power generators	
	APUs for power supply to army ground vehicles	
Residential & industrial	Stationary power generation for homes and businesses	[53,139]
	Combined heat and power on a small scale (1–5 kW)	
	Combined distributed power generation (power grid)	
	Remote area power supply	
Transportation	Heavy-duty trucks	[54,55,184]
	Recreational vehicles	
	Luxury automobiles	
	On-board APUs	
Portable appliances	Laptops/computer	[53–55]
	Televisions	
	Microwave ovens	

A prototype FC will be installed and tested by the National Energy Technology Laboratory in Pittsburg to meet energy needs and help Pittsburg become a clean energy city of the future. At the U.S. DOE's Pacific Northwest National Laboratory, researchers have developed small-scale SOFCs capable of achieving efficiency up to 57%, significantly higher than previously reported SOFCs of similar size.[167] The list of universities/institutes with active research on SOFCs is given in **Table 3**.

A triple combined-cycle power-generation system is being developed by Mitsubishi heavy industries in Japan. This project involves integrating SOFCs into a GT combined-cycle power-generation system and is expected to furnish the highest commercial-scale power generation using SOFCs.[168] To develop low-cost SOFC technology capable of producing power from coal resources, research funding of $500 000 has been announced by the US DOE.[169] UK-based SOFC developer Ceres Power has made great strides in improving the reliability of CHP products and the derating performance of core technology. The latest results show that Ceres is heading for the mass market.[170] Table 1 lists some of the major universities/institutions conducting SOFC-focused research.[171–173]

14. Some Active Companies in SOFCs

There are some notable companies working on the production of SOFC for different applications. **Table 4** lists some of them.

15. Future Challenges and Perspective

Of course, SOFCs are being used for a long time but the use of technology may be a boon for these devices to offer excellent services. But there are many challenges to tackle in making the perfect SOFCs. The most important challenges that need to be addressed are the need for high performance, durability, inexpensiveness, and sustainability. These challenges may be addressed by using a nanotechnology approach in SOFCs; involving the nanomaterials, design, and fabrication of SOFCs. By using these approaches, the challenge of high-temperature operation may be tackled by using nanomaterial and coating nanomaterials that can withstand high temperatures and resist degradation. The durability of SOFCs may be enhanced by designing nanomaterials of high durability that may resist stresses. The problem of compatibility with certain fuels may be tackled by developing nanocatalysts and membranes that can increase fuel flexibility and decrease the need for fuel processing. The challenges of power density may be overcome by developing new electrode materials that can augment the power density of SOFCs. Finally, the inexpensiveness of SOFCs may be achieved by developing new manufacturing methods that are more inexpensive, i.e., nanostructured materials or advanced deposition techniques.

The most important applications and contributions of nanotechnology in SOFCs are the amalgamation of SOFCs and applications of nanotechnology. For example, smart nanomaterials

Table 3. List of universities/institutes with active research on SOFCs.

Country	University	Country	University
US	The University of South Carolina	UK	University of St Andrews
	University of California San Diego		University of Birmingham
	The University of Texas at Austin		Imperial College London University of Warwick
	University of Maryland		University of Southampton
	University of Connecticut		Queen Mary University London
	Montana State University		University of Loughborough
	Michigan State University		
	Georgia Institute of Technology		
	University of Pennsylvania		University of Nottingham
	Tennessee Technological University		
	Northwestern University		
	Massachusetts Institute of Technology	Canada	University of Victoria
	University of Missouri		University of Calgary
	Rensselaer Polytechnic Institute		University of Waterloo
	South Carolina University		
	Ohio University		
	Kent State University		
Germany	Max Planck Institute for Solid State Research		University of Toronto
	University of Stuttgart		University of Alberta
	Heidelberg University		
	University of Bonn		Queen’s University
	University of Karlsruhe		
	Technical University of Darmstadt		
	Technical University of Munich	France	École Nationale Supérieure d’Électrochimie et d’Électrométallurgie de Grenoble
	Institute of Energy and Climate Research (IEK) in Forschungszentrum Jülich		
	University of Ulm		École nationale supérieure de chimie de Paris
Italy	University of Genova	Sweden	Lund University
	University of Messina		
	Sapienza University of Rome		Chalmers University of Technology
	University of Perugia	Switzerland	École polytechnique fédérale de Lausanne
	Polytechnic University of Milan		ETH- Swiss Federal Institute of Technology
Norway	Norwegian University of Science and Technology	Denmark	Technical University of Denmark
	University of Oslo		
Austria	University of Leobon		Aalborg University
	Graz University of Technology		
Finland	Aalto University		Aarhus University
Spain	Catalonia Institute for Energy Research		Copenhagen University
Estonia	University of Tartu		
Netherlands	Delft University of Technology	Poland	Institute of Power Engineering
			AGH University of Science and Technology
			Warsaw University of Technology
Japan	National Institute of Advanced industrial Science and Technology	South Korea	Korea Institute of Energy Research
	Kyushu University		Pohang University of Science and Technology
	Kyoto university		Gwangju Institute of Science and Technology
	The University of Tokyo		Seoul National University
	Tohoku University		Sungkyunkwan University
	Mie University		Yonsei University
	University of Yamanashi		Nanyang Technological University
	Yokohama National University	China	Ningbo Institute of Materials Technology & Engineering
Taiwan	Taiwan Institute of Nuclear Energy Research		Shanghai Institute of Ceramics
	National Taipei University of Technology		Tsinghua University
Turkey	Niğde Ömer Alasdair University		Southeast University
Brunei Darussalam	Universiti Brunei Darussalam		
India	Indian Institute of Technology-Bombay		Hubei University
	Pondicherry University		Harbin Institute of Technology
	Banaras Hindu University		
Iran	Niroo Research Institute		University of Science and Technology China
Pakistan	COMSATS University Islamabad, Lahore Campus, Lahore		Huazhong University of Science and Technology
			Chongqing University

may be prepared that withstand high temperatures, resist degradation, and increase performance; especially nanostructured ceramics may be used to increase electrode surface area thereby augmenting their catalytic activities. The other application of nanotechnology in SOFCs may be nanoimprint lithography to fabricate SOFCs components with excellent accuracy and

Table 4. List of companies/manufacturers producing solid oxide fuel cells (SOFCs).

Companies/manufacturers	Product features
Aisin Corporation, Japan	SOFC stacks for residential cogeneration
Automotive Industry Company, Austria	SOFC stacks (5–10 kW) for mobile power generator and maritime applications
Bloom Energy, US	SOFC stacks (100–250 kW) for grid connected and/or configured independently applications
Catator AB, Sweden	SOFC stacks (from 100 W to 50 kW) for reformation of jet fuel, like JP8, or other similar fuels
Ceres Power, UK	SOFC systems for residential and energy security applications
Convion Oy, Finland	SOFC systems (50–300 kW) for distributed power generation and industrial self-generation purposes
Delphi Corporation, US	SOFC systems military applications, vehicle propulsion and stationary power
Eberspächer, Germany	SOFC technology (from 50 W to 3 kW) for portable power generation and automotive applications
Elcogen AS, Finland/Estonia	Elcogen specializes in the commercialization of anode-supported SOFCs (sub-kW–multi-MW) and use cases in multiple applications
FuelCell Energy, US	SOFCs (sub-kW–multi-MW) for transportation and industrial applications
Materials & Systems Research, Inc., US	Planar anode supported SOFCs (1–3 kW class) for military applications
Mitsubishi Power, Ltd., Japan	SOFC with micro gas turbines (250 kW) for high power generation
Nexceris, US	SOFC (from 2 to 5 kW) for military applications
POSCO, South Korea	SOFC technology (from 100 kW to 2.5 MW) for building
Protonex, US	SOFC (20–200 W) for portable, mobile, and remote applications
Robert Bosch	SOFC (10 kW) for households/building applications
SOFCMAN, China	SOFC (from 1 to 200 kW) for grid-connected applications
SOLIDpower Group, Germany	SOFC (from 1.5 to 2.5 kW) for family homes and commercial and public buildings applications
SunFire GmbH, China	SOFC system (from 750 W to 2.6 MW) for different applications
Suzhou Huatsing Jingkun New Energy Technology Co., Ltd., China	SOFC stack (from 1 to 5 kW) for distributed power-generation applications

precision. In addition, novel electrode designs may be achieved by nanotechnology that may augment the power density of SOFCs by improving the electrochemical interface between the electrolyte and the electrode. Miniaturization is one of the most important assets of nanotechnology that can be used to miniaturize SOFC components; compact and portable. This approach may be beneficial for developing small, inexpensive SOFCs; required in portable electronics, remote power generation, and military operations.

The future perspective of SOFCs is quite bright by adopting nanotechnology applications. This could lead to high durability, low operating temperatures, good power densities, and enhanced fuel flexibility; making SOFCs more modest with classical power-generation technologies. The reduced cost of SOFCs will make them commercially available for a wider range of uses. The use of nanotechnology will make SOFCs environment friendly and sustainable through green manufacturing processes of nanotechnology. Overall, the future perspectives of nanotechnology in SOFCs are auspicious, with the possibility to enhance durability, augment performance, and inexpensiveness; leading to new applications and encouraging sustainability. As nanotechnology remains to advance, and consequently, it is hoped that further innovations and breakthroughs are on the way in SOFCs.

16. Conclusions

This article provides an overview of the application of nanotechnology and power electronics technology in SOFCs. The biggest obstacles to the commercialization of SOFCs are high operating temperature, which hastens the degradation of SOFC components, sulfur poisoning, low electricity yields in low-temperature operating conditions, CTE mismatch, overpotential and subpar energy efficiency of SOFC stacks, slow dynamic response, and system integration. The SOFC operating temperature can be lowered and the endurance increased by using nanomaterials. Particularly nanostructured materials, which increase surface area and boost electrocatalytic activity, have shown the greatest potential for low-temperature operation. The problem of compatibility with certain fuels may be tackled by developing nanocatalysts and membranes that can increase fuel flexibility and decrease the need for fuel processing.

The current emphasis is on using thin-film and microfabrication techniques to engineer the structural topologies of SOFCs. This involves increasing the reaction surface and decreasing the thickness of the electrolyte. The use of nanomaterials can enhance the mechanical strength and long-term thermal stability of SOFCs. Nanotechnology can enable low-temperature operation and help the SOFC last longer. The use of nanomaterials could result in SOFCs for commercial use. Identifying the conditions that might produce the best results might be made easier by computer modeling. These aspects have been covered in this study. It also reports on a wide range of SOFC applications, from APUs in vehicles to stationary power generation. Finally, this article described some prominent research institutes and companies engaged in SOFC research around the world. This study will be of interest to a wide audience, including those interested in SOFC research, from material selection to system modeling.

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Conflict of Interest

The authors declare no conflict of interest.

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