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Direct ammonia fueled solid oxide fuel cells: A comprehensive review on challenges, opportunities and future outlooks

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Abstract

Nowadays, the most decisive challenges we are fronting are perfectly clean energy making for equitable and sustainable modern energy access, and battling the emerging alteration of the climate. This is because, carbon-rich fuels are the fundamental supply of utilized energy for strengthening human society, and it will be sustained in the near future. In connection with this, electrochemical technologies are an emerging and domineering tool for efficiently transforming the existing scarce fossil fuels and renewable energy sources into electric power with a trivial environmental impact. Compared with conventional power generation technologies, SOFC that operate at high temperature is emerging as a frontrunner to convert the fuels chemical energy into electric power and permits the deployment of varieties of fuels with negligible ecological destructions.

According to this critical review, direct ammonia is obtained as a primary possible choice and price-effective green fuel for T-SOFCs. This is because T-SOFCs have higher volumetric power density, mechanically stable, and high thermal shocking resistance. Also, there is no sealing issue problem which is the chronic issues of the planar one. As a result, the toxicity of ammonia to use as a fuel is minimized if there may be a leakage during operation. It is portable and manageable that can be work everywhere when there is energy demand. Besides, manufacturing, onboard hydrogen deposition, and transportation infrastructure connected snags of hydrogen will be solved using ammonia. Ammonia is a low-priced carbon-neutral source of energy and has more stored volumetric energy compared with hydrogen. Yet, to utilize direct NH_3 as a means of hydrogen carrier and an alternative green fuel in T-SOFCs practically determining the optimum operating temperatures, reactant flow

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rates, electrode porosities, pressure, the position of the anode, thickness and diameters of the tube are still requiring further improvement. Therefore, mathematical modeling ought to be developed to determine these parameters before planning for experimental work. Also, a performance comparison of AS, ES, and CS- T-SOFC powered with direct NH_3 will be investigated and best-performed support will be carefully chosen for practical implementation and an experimental study will be conducted for verification based on optimum parameter values obtained from numerical modeling.

Keywords: Tubular SOFC; Direct Ammonia; Challenges; Opportunities; Future Outlooks

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Abbreviations

SOFC:	Solid Oxide Fuel Cell
SOFCs:	Solid Oxide Fuel Cells
YSZ:	Yttria-stabilized Zirconia
LSM:	Lanthanum Strontium Manganite
T-SOFC:	Tubular Solid Oxide Fuel Cell
AST-SOFC:	Anode Supported Tubular Solid Oxide Fuel Cell
EST-SOFC:	Electrolyte Supported Tubular Solid Oxide Fuel Cell
CST-SOFC:	Cathode Supported Tubular Solid Oxide Fuel Cell
IT-SOFCs:	Intermediate Temperature Solid Oxide Fuel Cells
TECs:	Thermal Expansion Coefficients
ES:	Electrolyte support
AS:	Anode support
CS:	Cathode Support
PEMFCs:	Polymer Electrolyte Membrane Fuel cells
APU:	Auxiliary Power Units
Ni:	Nickel
NH_3:	Ammonia

1. Introduction

Energy is one of the ultimate prerequisite tools to bring sustainable economic development and improve citizen's quality of life for any country. A few decades ago, speedy industrializations, growing of inhabitants, and urbanizations have huge pressure on crude oil, coal, and other fossil fuels. These fuels are limited and finite resources hence they may be suspended or finished in the near future. Consequently, fossil fuel consumption is snowballing and the upsurge in carbon-rich fuel demand is leading to rapid fossil fuel reserve depletion. Moreover, carbons rich fuels are the principal source of greenhouse gases which resulting in a destructive influence on the environment. For these reasons, finding an alternative green and clean renewable source of energy and efficient technologies is unquestionable responsibilities for a researcher to modify the current energy system, advance their efficiency, and minimizing the devastation of the environment.

Today, the furthermost resounding challenges we are pebbledash are clean and environmentally friendly energy making and overcoming the encountered climate changes. The hydrogen economy has abundant significance for stationary, mobile, and vehicles application. Yet, the most decisive challenges that were faced to realizing the implementation of the hydrogen economy are the production, onboard storage, and distribution systems. On the contrary, hydrogen can be deployed as a possible choice carbon-free energy vector when it stored in different hydrogen contained chemical bonds like ammonia[1]. Ammonia is carbon neutral like hydrogen at the final consumer's even if the discharge of CO_2 is depending on the kinds of energy sources utilized for both productions. Thus, to tackle such energy challenges, ammonia is an encouraging green fuel for miscellaneous applications that offers an easy way to synthesize and transport via existing infrastructures and reimburses the deviation of renewable energies.

Fuel cells are an efficient dirt-free electrochemical energy conversion technology that transforms the fuel's chemical energy directly into electricity without intermediate products and combustion by bringing together the fuel and an oxidant through electrochemical reactions. It is also characterized as a highly efficient energy transformation technology that operates as far as reactants are delivered continuously to its electrodes. This is a unique characteristic of fuel cell that distinguishes its working condition from a battery which is a storage form of energy and becomes discarded after a finite period of working time. The main components of a single cell are interconnector for current collection, a non-porous electrolyte sandwiched between a porous anode and cathode electrodes, channels for fuel and air supply.

In 1893, Sir William Grove was the pioneer of a fuel cell thought [2]. After this, several kinds of electrochemical technologies were innovated and classified based on the working temperatures, types of electrolytes, and fuel use. These are the Polymer Electrolyte Membrane Fuel Cell (PEMFC)[80°C, H^+], Alkaline Fuel Cells (AFC) [150°C, OH^-], Direct-Methanol Fuel Cells (DMFC) [80°C, H^+], Phosphoric Acid Fuel Cells (PAFC) [220°C, H^+], Molten Carbonate Fuel Cell (MCFC) [700°C, CO_3^{-2}], Oxygen and Proton ion-conducting Solid Oxide Fuel Cells (SOFC-H, 650°C, H^+], [SOFC-O, 900°C,O^{-2}][3]. Among them, AFC, PEMFC, and PAFC have lower electrical efficiency since they function at low and medium temperature compared to MCFC and SOFCs that runs at high temperatures. Nevertheless, fuel cells functioning at low and medium temperatures are well-matched for automotive and portable electrical systems [4], [5]. This is often as a result of they can be started quickly and has less thermomechanical stresses while cells that run with high temperatures have comparatively higher electrical efficiency. Hence, they are appropriate for continuous electricity production for stationary application and has high-quality waste heat available for the co-generation purpose [5], [6]. Yet, they need long start-up times and periodical maintenance. Compared to high temperature operating cells, the cost of low and medium temperature cells is higher. This is because they require precious noble metal catalysts such as Rubin and Platinum to boost the activation due to intolerance for low-quality fuels. However, high-temperature fuel cells are accommodating less expensive catalysts such as Nickel and are much diversified in the consumption of fuels. In line with this, the popularity of SOFCs is rapidly snowballing due to having many benefits (high efficiency, low emission, compactness, modularity, and fuel diversity). SOFCs are very important for power generation using alternative green fuels without environmental burdens. Therefore, the central objective of this review is concentrated on the state-of-

the-art of SOFC technologies to pinpoint the existing gaps, challenges, opportunities, and future outlooks to utilize ammonia as a promising choice green fuel for tubular configuration of SOFCs.

2. Solid Oxide Fuel Cells

Solid oxide fuel cells (SOFCs) are the most efficient electrochemical devices yet invented and developed for power generation without combustion by changing the fuel's chemical energy directly into electricity without intermediate products via the combination of numerous fuels (gaseous, gasified, liquid) with an oxidant mainly air[7]. Additionally, SOFCs can be used all-ceramic devices for sustainable stationary and moveable generation of electric power that runs at a temperatures range of 500 to 1000^{o}C [8], [9]. They are easily scalable, flexible in fuel use, has no movable parts, eradicates the utilization of costly catalysts, and are built in different sizes. Besides, they are quite solid-state devices that have vibration-free operation hence noise commonly allied with customary power production systems are eliminated and built-in different sizes with zero contaminants and greenhouse gas emission when carbon-free fuels are applied. Also, different studies confirmed that SOFCs combined with heat engines result in higher efficiency from any power making system built-up till now[10], [11]. This is because they have high-quality recoverable waste heats from exhausted gases. They have also negligible carbon emissions compared with conventional power making systems even using fossil fuels. For these reasons, they are receiving more attention and they will be a prospective candidate for inclusive power generation systems.

They are developed as non-combustible electric power generation systems. Because of their raised maneuver temperature, some hydrocarbon fuels like natural gas can be reformed within the cell stacks which eliminate the requirement of an expensive external reformer [10], [12]. Besides, conventional heat engines like gas turbines can be integrated with SOFCs to recover the waste heat from exhausted gases [12], [13]. In line with this, different studies confirmed that SOFCs combined with gas turbines and heat engines result in higher efficiency from any power generation system built-up nowadays [10]–[12]. According to Singhal [5], the efficiencies of hybrid SOFC-gas turbine power systems are estimated to 70%. Besides, when integrated with heat recovery systems, the efficiencies of hybrid SOFC-gas turbine power systems are more than 90% with zero pollution [6]. This is because the exhaust product is only water when cells run with carbon-free fuels. Nevertheless, the practical endurance of the cell is limited by its degradation during operation.

They are potentially feasible and applied in many application areas such as residential, commercial, industrial, and military services [10], [14]. Presently, they are being chosen for automotive and APUs compared with PEMFCs. This is because, despite the slow start-up time, they have cogeneration and internal reforming opportunities, no need for water management, simple reformer technology, high electrical efficiency, no noble catalyst, low sound, and fuel diversity [15], [16]. Yet, the cell costs have to be reduced remarkably to realize the commercialization of SOFC technology.

Generally, there are four kinds of SOFCs configurations in literature. These are tubular (micro-tubular, high-density power, flatted), planar, monolithic, or coplanar designs that are distinguished as an anode, electrolyte, cathode- or metal supported cells [15]. They are fabricated by numerous techniques from wet ceramic processing such as slip casting[17], extrusion[18] electrophoretic deposition (EPD)[19], physical vapor deposition (PVD) and electrochemical vapor deposition (EVD) [20]. The planar

configurations are commonly manufactured by tape-casting practice from which a thin layer can be simply attained and assembled to form the cell. As well, it can be also manufactured by spray coating in which a thin electrolyte and cathode sheets are coating on anode substrate prepared by slip-casting[21]. Screen-printing and brush painting are also alternatives and economical techniques for producing thin electrolyte and cathode layers for anode-supported planar cells [22]. On the opposite hand, tubular SOFCs are principally manufactured by the extrusion process up to diameters as low as 0.4 mm [4], [23], [24]. Alternatively, spray deposition or dips coating techniques are used to coat the subsequent layer which is often used for functional layered ceramic fabrication with a simple device and easy processing [25], [26].

Today, tubular and planar type configurations are the most advanced designs of SOFCs [16]. In line with this, the tubular SOFCs(T-SOFCs) have been built as anode supported (AS)[19], [27]–[33], cathode supported (CS) [16], [21], [34]–[40], and electrolyte supported (ES)[17], [26], [41], [42]. In ES-SOFCs, the thickness of fuel and air electrodes should be as thin as 50μm and integrated with more than 100μm electrolyte thickness whereas in electrode supported SOFC, it should be thick enough habitually between 0.3 and 1.5 mm to function as a support for the entire cells while the electrolyte thickness as thin as 10μm [7]. T-SOFCs are commonly ES whereas the planar one is mostly AS. Yet, currently, AS-T-SOFCs are the most frequently preferred cell design because of difficulty in preparing a dense electrolyte coating on a porous cathode support surface and comparatively high-temperature requirement in ES. Besides, as the thickness of the ionic conductor upsurges, ohmic loss also upsurges hence the electrolyte should be thin as good as possible. In a monolithic configuration, a layer of fuel and air electrodes are grooved on either side of three layers to create fuel and air conduits [7]. Furthermore, Milad et al.[43] have been made a techno-economic comparison of AS, ES and CS-SOFCs. Their finding confirmed that the CS has a maximum power density and the ES is obtained to be the optimal choice when considering the power and materials cost as an objective function respectively. Though, at once considering both functions, the AS outperforms over CS and ES one.

One of the primary challenges of SOFCs is the advancement of suitable sealant materials which is strictly obligatory for the planar design[44]. This is often as results of the sealants have functioned as both a separator of oxidant and fuel and as a structural component to assure the mechanical integrity at extraordinary temperatures. Conversely, in the tubular cell, the current paths through the electrodes are longer compared with the planar cell design. For this reason, the power density (1-2 W/cm^2) of a planar structure is more than the tubular (0.1-1 W/cm^2) one. However, the tubular cells are thermal stability over planar cells [45].

Furthermore, one of the unique rewards of SOFC over the other fuel cells is operating at a raised temperature which gives a high quality of waste heat used for combined heat and power, or combined cycle gas-turbine applications [6]and it also eradicates the utilization of costly catalysts. Besides, carbon monoxide is a contagion for low-temperature fuel cells due to large carbon deposition whereas it acknowledges as fuel for SOFCs[9]. Hence, SOFCs have negligible emissions compared with customary power production systems even using hydrocarbon fuels. Therefore, SOFCs are prospective candidates for comprehensive electrical power applications [14].

Many types of research are focusing on SOFC that operates at high-temperature varied between 800^oC and 1000^oC whereas SOFCs operating at intermediate temperature (IT-SOFCs) that functions between

550^{o}C and 800^{o}C has more advantages [7], [46]. This is because, in IT-SOFCs, metal ceramics are used instead of ceramics that can be functioned in all SOFCs running at raised temperatures. Besides, in IT-SOFCs, stainless steel interconnects are employed as a substitute for more expensive high-chrome alloys or oxides. Yet, to use ammonia as a direct fuel in SOFCs, a slight bite higher temperature mainly 750^{0}c is compulsory to decompose ammonia in to constitute elements.

2.1. Working principles of Solid Oxide Fuel Cells

Solid oxide fuel cells consist of three major components. These are a porous fuel electrode (anode), a porous air electrode (cathode), and a non-porous solid ceramic electrolyte sandwiched in the middle of these electrodes as presented in figure 2. They have also channeled for fuel and air supply. The electrolyte is a conductor of negatively ionized oxygen or proton ions working at a comparatively high temperature. As well, the fuel and air electrodes are coupled by interconnectors for current collection where electrons are attracted by the positive voltage of cathode. The electrons are combined with oxygen or air to produce oxygen ions by means of the electrochemical reduction reaction. This is often as a result of the existence of a perovskite catalyst that may empower the ionization of oxygen under electrical load at the air electrode surfaces. Electrical power is generated when electrons are discharged from anode passed to the cathode via an external wire.

In SOFC-O, the ionized oxygen formed at the cathode directly moves in the direction of the anode across the porous ion-conducting ceramic electrolyte. At the anode-electrolyte interface, it combines with fuel and generates electron that flows via an external circuit that supplies electrical power then enters into the cathode. Besides, in the anode, once the fuel combines with oxygen ion, water is produced and oxygen chemical potential gradient is developed across the electrolyte. At a similar time, the overflowing of atmospheric oxygen in the direction of the cathode is motivated. Oxygen flow is possible once there's a pressure distinction between the fuel and air conductor that could be a driving power for an electric current generation across the external circuit. Hence, the partial pressure of oxygen in the anode sideways should be very low compared to the air electrode compartment to develop practical cell voltage by enhancing the movement of oxygen ions towards the anode compartment. While in proton-conducting SOFC, the working principles are opposite. The proton ions migrate from fuel to air electrode thence water is formed at the air electrode sideways as presented in figure 2[12].

Fuel cells can be built as AS-, ES-, CS- and metal supports. Currently, anode layer support is the most rampant solution because of having lower electrical losses compared with other support cells. However, the electrolyte-supported design was the first cell, which resulted in reasonably high ohmic resistance. For this reason, in ES- cells, high temperatures application is compulsory to overcome such resistance. Planar cell structures are more compact thus they are well-known by smaller losses. Yet, they have substantial temperature drops compared with tubular cell construction during hydrocarbon internal reforming. Besides, the tubular structure momentously simplifies the sealing issues over the planar cell structure.

Furthermore, regardless of the geometric features, in SOFCs, yttria-stabilized zirconia (YSZ) is the most recurrently deployed oxide ion conductor electrolyte running at raised temperatures. Nickel/zirconia cermet is applied as anode materials [8]. This is often as a result of it has high electrochemical performance, acceptable chemical stability, and low cost. As well, perovskite ceramics like a composite

of lanthanum strontium manganite (LSM) and YSZ is utilized as a cathode electrode [47]. Since the thermal expansion coefficients (TECs) of the materials are not the same, mechanical failure of SOFCs may be happed due to thermal stress and misalliance of TEC [48]. Therefore, as good as possible materials that have virtually the same thermal expansion coefficients must be installed to diminish the failures. Today, lanthanum chromite ($LaCrO_3$) is the most recognized candidate for interconnector material because it has a comparatively high electronic conductivity, reasonable stability in the fuel cell environment, and has superior compatibility with other constituents of cells with regard to phases, microstructure and thermal expansion.

3. Ammonia as a Possible Choice Green Fuel for SOFCs

Nowadays, different fuels (hydrocarbons, hydrogen, natural gas, biogas, methanol, ethanol) have been all investigated as a possible energy source for fuel cells. Among them, hydrogen is a perfect fuel choice from environmental outlooks and energy density. Yet production, deposition, and distribution associated problems are still critical issues[1], [3], [49]–[54]. Connecting with this, different numerical modelings and experimental investigations with pre-decomposed and direct NH_3 powered SOFCs have been studied but most of them were concentrated on planar design[4], [25], [41], [49], [55]–[59].

Globally, ammonia is the most essential and widely manufactured industrially chemicals next to sulfuric acid. As a result, annually greater than 150 million tons of NH_3 is produced and transported [1]. In line with this, greater than 50% of the produced hydrogen in the chemical industry is used for ammonia production [1], [60]. This is because the transportation or distribution infrastructure of NH_3 is soundly established. On the contrary, for hydrogen still, it is not available especially pipe distribution systems which is one of the distinguished challenges for hydrogen technologies. Hydrogen is manufactured from NH_3 via electrolysis, electro-oxidation, or thermal catalytic cracking process. As well, it may be directly oxidized without a detached reactor in SOFCs. NH_3 can be manufactured with similar procedures applied for hydrogen from biomass, fossil fuels, nuclear, biosynthesis, and photosynthesis. Therefore, the ammonia economy can accomplish similar reimbursements and solve the current challenges we are encountered in the hydrogen economy.

Nowadays, the thought of an ammonia economy has acquired more attention [1], [61], [62]. This is often as a result of ammonia is free from carbon like hydrogen that can be synthesized from different energy resources. Compared to hydrogen, NH_3 has also some noteworthy advantages along with storing and transporting. These are easily liquefaction processes between 8-10 bars at room temperature, no need off costly cryogenic storage like hydrogen and deposited in a similar way resembling propane[1], [52], [62]. Hence, NH_3 can be deposited and distributed safely over hydrogen. The unique drawbacks of ammonia compared with traditional fuels is its smell and thence it is well-thought-out as a toxic [63] yet it can be utilized as appositive opportunities to distinguish the gas leakage even at safe levels of concentration (<1ppm) [52]. As well, it is acknowledged as nonflammable thence it is appropriate for transportation. This is often thanks to having a narrower flammable range compared with hydrogen that burns vigorously with an undetectable flame [61].

Conforming with the per unit mass, the energy density of H_2 is above any typical fuels. On the opposite hand, the volumetrical energy density of the gas is a terribly low owing to having low density compared with hydrocarbon and ammonia as given in table 1 [1], [61], [62]. However, the pressurized ammonia energy density is virtually greater than pressurized natural gas (CNG) and hydrogen gas whereas lower

than liquefied propane gas (LPG) and gasoline. The ammonia energy cost is a little bit above hydrogen energy cost per unit volume. Yet, ammonia has more stored energy than hydrogen per volume. Hence, according to per unit energy, ammonia is that the most cost-effective and economical energy supply as indicated in table 1 [1], [61], [62]. Therefore, NH_3 is found as an awfully possible and price-effective fuel for electrochemical technologies.

Table 1 The Energy Storage Abilities of selected Fuels

storage method of fuel	Pressure (bar)	Energy Density (GJ/m³)	Specific Volumetric cost (US$/m³)	Specific Energy Cost (US$/GJ)
Ammonia gas / pressurized tank	10	13.6	181	13.3
Hydrogen / metal hydride	14	3.6	125	35.2
Gasoline (C_8H_{18}) / liquid tank	1	34.4	1000	29.1
LPG (C_3H_8) / pressurized tank	14	19.0	542	28.5
CNG (CH_4) / integrated storage	250	10.4	400	38.3
Methanol (CH_3OH) / liquid	1	1	11.4	693

As can be depicted in table 2, Lipman and Shah [64]have been revealed that natural gas reforming is the supreme cost-competitive approach of hydrogen extraction at a large scale above 1000 m³/hour. Yet, productions of hydrogen using the ammonia cracking method have remarkable economic benefits over other technics of hydrogen manufacturing principally from natural gas reforming for small scale below 10m³/hour. Table 2 displays the manufacturing of hydrogen by electrolysis, natural gas reforming, methanol-reforming, and ammonia cracking from water, natural gas, methanol, and ammonia, correspondingly.

Table 2 Economic comparison of hydrogen extraction through different systems

The scale of H_2 making [m³/hour]	Cost of H_2 production, US$ / (m³/hour)			
	Water	Natural Gas	Methanol	Ammonia
10	0.943	0.390	0.380	0.343
100	0.814	0.261	0.285	0.279
1000	0.739	0.186	0.226	0.241

3.1. Ammonia Powered Polymer Electrolyte Membrane Fuel Cells

The central goal of introducing the hydrogen economy is fighting global climate change by diminishing greenhouse gasses emissions. According to different studies, more than 23% of the global CO_2 emissions are released from vehicles running with fossil fuels [60]. On the Contrary, utilizing fuel cells powered with hydrogen to power electric vehicles is carbon-free and zero pollutant emissions at the final consumer. This can be owing to the last exhaust of hydrogen fuel is merely water. Yet, onboard hydrogen deposition and distribution infrastructures are remains as a serious challenge. Along with this, the critical challenges for the commercialization of PEMFC powered with H_2 fuel and air as oxidant are cost and durability issues[65]. Besides, problems like load change, reactant starvation, and low catalyst performance are happed as of cell reversal that creates a permanent deterioration of cell hence it

truncates its duration[66]. On the opposite hand, hydrogen also can be deposited tortuously in ammonia, methanol, ethanol, methane, etc. Among them, ammonia is a carbon-free energy carrier which is an alternative solution for the transport segment [7].

Halseid et al [67] have been described the effect of ammonia fuel in PEMFC performance in comparison with hydrogen. Their experimental finding confirmed that the ohmic overpotential is higher owing to the deterioration of the electrolyte membrane of the cell. In addition, both the fuel oxidation and the oxygen reduction reaction have been significantly influenced by ammonia. In line with this, NH_3 as a hydrogen source has been advised to employ in PEMFCs. Yet, it is thermodynamically antagonistic at low temperature for internal ammonia decomposition. Accordingly, NH_3 must be decomposed externally into its component elements at raised temperatures to supply pure hydrogen for PEMFCs. This is because the Nafion membrane characteristically deployed in PEMFCs is strongly affected by trace amounts of ammonia. Since ammonia is primarily fueled to the fuel electrode, it affects the anode coating catalyst sooner than the air electrode coating catalyst. In addition, the durability and performance of PEMFC working with PT/C electrodes are largely affected by carbon accumulation and a small amount of ammonia[60]. Therefore, SOFCs directly fed with not only ammonia but also other fuels are the most promising ways for power generation.

Furthermore, to supply hydrogen produced from NH_3 for PEMFCs, the unconverted trace ammonia should be cleansed before subjected to the cells. This is because the Nafion membrane that is acidic is incompatible with ammonia even in trace quantity (0.1 ppm). This can be as a result of acidic Nafion reacts with basic ammonia to make salts that may increase the resistance of the cell quickly. Hence, an external ammonia decomposition reactor and onboard hydrogen storage system is needed. Besides, since ammonia decomposition is an endothermic reaction a significant energy input is required. Thence, it needs additional prices that make it less applicable for onboard applications. For that reason, the manufacturing of hydrogen from ammonia and related chemicals for PEMFCs is inappropriate and infeasible in economic outlooks.

3.2. Direct Ammonia Powered Alkaline and Alkaline Membrane Fuel Cells

In 1960, Cairns et al [3]have been identified KOH solution supported electrolyte cells powered with NH_3 as fuel and realized that it can be employed as a direct fuel for alkaline (KOH) electrolytes fuel cells. In agreement with this, later, Hejze et al [68]have been conducted an experimental investigation on NH_3 as a hydrogen vector for alkaline fuel cells. Their results disclosed that alkaline fuel cells are ammonia tolerant and have no negative effects on cell performance in comparison with PMEFCs when the supplied gas contained low concentrations of NH_3. This is for the reason that the conversation of NH_3 to hydrogen is simple and free from CO_X emissions. However, the sturdiness of KOH-based electrolyte NH_3-fuel cells is a serious issue like normal alkaline fuel cells. This is due to the reaction between KOH and CO_2 that comes from atmospheric air used as an oxidant [3].

Further, Ganley et al [69] have been examined a direct NH_3 supplied molten hydroxide electrolyte alkaline fuel cell at a working temperature range of 200 – 450^{o}C. The outcome of the work realized that NH_3 can be utilized as a fuel supply for this cell and it yields 40mW/cm^2 at 450°C using Ni in both electrodes yet the cell performance is dominated by ohmic polarization.

Besides, Yang et al[70] have been examined molten hydroxide fuel cell fuelled with straight ammonia using Pt conductor in a molten NaOH–KOH ionic conductor function at 200–220°C. The mass

spectrometry and cyclic voltammetry investigation were revealed that Pt electrode plays a prodigious role for the oxidation of NH_3 in the molten hydroxide ionic conductor via electrochemical reaction and obtained an uppermost power density of 16 mW/ cm^2 at 220 °C. Yet, the achievement of the cell is very low compared with the other mature cells. This is because the cell performance is dominated by polarization resistance. Hence, to enhance the results either increasing the temperatures, using more active materials, or replacing with ceramics. This is much lower than the value achieved using direct carbon fuel employing the same electrodes and electrolyte operating at 550^oC [71].

3.3. Mathematical Modelling for Direct Ammonia Powered Solid Oxide Fuel Cells

Mathematical modeling is a modern and effective scientific tool to get clear information about the fuel cells that may not be able to directly measure in places. Besides, modeling of the cells has frolicked imperative roles in electrochemical technology development. Because of micro-scale geometries and high side ratios, it is impracticable to measure the potentials, spatial differences in species concentrations, temperatures, and current densities through an experiment. Therefore, mathematical or computational modeling has played an indispensable role in sympathetic the phenomena happening within the cells before planning to experimental work. However, several models explained in literature so far have been thermo-electrical models with very few CFD modeling using the parameters reported in experimental work which may lead to an inappropriate conclusion due to different geometrical dimensions and analysis techniques.

Nowadays, a different model of direct and pre-decomposed ammonia driven SOFCs have been developed while more of them were focused on planar arrangements. Ni [49] has been developed a 2D ammonia powered thermo-electrochemical model of planar SOFC to investigate the electrochemical reactions, thermal disintegration of NH_3 into the constituent elements, fuel flow rate, mass and heat transfer. The conclusion of the study revealed that higher electrical output is realized when the ammonia fuelled SOFC inlet temperature is hovering on the other hand the gradient close to the entrance of SOFC is implicitly higher. As well, their effort comprehended that the NH_3 driven SOFCs performance is slightly diminishing when the inlet gas velocity upsurges from 1m/s to 10m/s yet the temperature field is not considerably affected. On the other hand, the gradient temperature is powerfully reduced once the speed of the inlet gas is slashed to 0.2m/s. Therefore, one in all the solutions to diminish the gradient is decreasing the inlet gas speed suitably. This is because ammonia decomposition is an endothermic reaction thereof decreases the temperature sharply as it split into hydrogen and nitrogen. These temperature differences can upshoot in high thermal stresses. Consequently, the materials may be physically damaged. Different simulations demonstrate that diminishing the inflow rates can support to decline of this temperature drop. Yet, the best outcomes still indicate at 67 °C temperature drop over a 5 mm distance from the inlet temperature of 700°C, and a fuel utilization factor of only 15% [72]. Therefore, reusing the anode outlet will minimize the temperature drop considerably and additionally enhances the fuel utilization.

Kishimoto et al [55] have been developed a 2D numerical model of ammonia-fueled planar SOFC to investigate the distribution of temperature, flow, species, and electrochemical natures within the cell. Their findings discovered that direct and pre-decomposed NH_3 driven SOFCs have comparable performance. They also recommend further work to validate the anticipated current-voltage features and dissemination of the temperature with experiments. Furthermore, Tan [73] has been developed a 3D

numerical simulation for planar SOFCs and investigate its performance using ammonia as a fuel that cracked internally. The conclusion of their confirmed that deprived current density distribution has mainly resulted in a poor distribution of gas concentration in the cathode conduit. Similarly, they have also studied the aspect ratio effect on planar SOFC powered with disintegrated ammonia. The aspect ratios were between 0.130 and 7.68 with a steady reactant flow rate. The simulation outcome discloses that the cell that has the highest aspect ratio accomplishes the highest cell performance during operation. On the opposite hand, at 0.67 maximum voltage efficiency and 0.80 fuel utility, the cell that has an aspect ratio of 0.750 has a capacity in thermally satisfying for NH_3 cracker from sidewalls thermal radiation[74].

Additionally, Ni et al [75] have been performed a thermodynamic analysis of NH_3 supplied SOFCs for planar configuration to relate the hypothetical performance of SOFC-H and SOFC-O. The study disclosed that the efficiency of SOFC-H is higher by 11% compared with SOFC-O operating at 800°C and 1atm. Besides, the study has been assumed 100% ammonia conversion, no generation of NOx, 80% fuel, and 20% oxygen utilization. This is for the reason that the partial pressure of hydrogen is higher whereas the steam partial pressure is lower compared with SOFC-O. As well, at the anode of SOFC-H water is not formed therefore hydrogen is not diluted and the likelihood of NO_X formation is negligible. Yet, it needs more expensive barium cerate electrolytes compared with SOFC-O[76]. Similarly, Meng Ni et al [28] have been developed a mathematical model to study the electrochemical performance of SOFC-H and SOFC-O powered with ammonia using different electrolytes. However, the outcomes of their work revealed that the particular performance of SOFC-H powered with ammonia is substantially below SOFC-O that is completely different from the previously thermodynamic analysis reports. This is often primarily related to the higher ohmic overpotential of the SOFC-H electrolyte. As well, the outcomes of this study specify that SOFC-O has greater anode concentration and lower cathode concentration polarization over SOFC-H. The study also discloses that the utilization of dissimilar electrolytes can cause dissimilar ion conduction features at the electrolyte and the concentration polarization at the electrodes is meaningfully influenced. Thus, currently, there is no clear-cut agreement between SOFC-O and SOFC-H which one is better.

Furthermore, Ishak et al[27] have been described the thermodynamic analysis of AS- SOFC-H and SOFC-O fuelled with direct ammonia. As well, the thermodynamic and electrochemical performances were compared at open and closed-circuit circumstances. According to the finding, complete ammonia conversion is achieved at 1atm and a temperature of 427^{o}C which is lowered than the temperature reported by Ni et al [75]. As well, it is obtained that the cell performance is strongly dependent on the functioning temperature, the ionic, and electronic conductor layers properties. The average maximum power density of NH_3 supplied SOFC-H is higher by 20-30% over SOFC-O which is exceeding the value reported by Ni et al [75].

According to different studies, maximum power densities have been accomplished both in SOFC-H and SOFC-O with thin electrolytes. Comparing to SOFC-H, SOFC-O needs comparatively high working temperatures mainly in the range of 800-1000°C to augment YSZ electrolyte conductivity. This is due to the conductivity of the SOFC-O electrolyte is meaningfully reduced when an intermediate temperature mainly from 400-600°C is deployed. As a result, SOFC-H with a thinner electrolyte is deployed to solve this problem. This is often thanks to the $BaCeO_3$ and $SrCeO_3$ electrolytes which are commonly used in SOFC-H have better ionic conductivity at medium temperatures than YSZ. Thus,

SOFC-H is a good-looking alternative for cells running at medium temperatures. Besides, in SOFC-H, since oxygen ions are not transported to the fuel electrode, the likelihood of NOx formation is almost zero. Yet, the performance comparison of SOFC-O and SOFC-H fuelled with ammonia and hydrogen fuel has not been shown a meaningfully powers densities difference. Though, some studies have informed that there is a formation of NOx at the anode of SOFC-O yet practically it has not been detected. The possibility of NO_X formation in SOFC-O running with NH_3 as the fuel is expected at raised current densities and temperature when there is high ammonia breakdown and O^{2-} flow rate. Though, according to [25] studies, the release of NO was not identified up to 800°C.

Parallel to this, Zhang et al [77] have been examined gas chromatography studies on anode supported SOFC-O powered with ammonia using a thin YSZ electrolyte. The experimental outcome confirmed that ammonia is entirely decomposed into chemical elements of H_2 and N_2 using Ni catalyst before it arrives at the TPB. Hence, the likelihood of NO_X formation is negligible. Furthermore, the conclusion of different studies realized that hydrogen extraction from NH_3 is not an ideal solution for fuel cells functioning at low temperatures. Yet, SOFCs powered with direct NH_3 and correlated chemicals are more competent and economical solution compared with other fuel cells [60].

Furthermore, Leung et al [78] have been reviewed different kinds of literature on ammonia powered SOFC-H and SOFC-O for power generation. Their review proves that ammonia is technically feasible and promising candidate fuel for straight supply in SOFCs. Besides, their work disclosed that the performance of NH_3 supplied SOFC is comparable with that of the H_2 supplied one with negligible NOx formation. In agreement with this, ammonia is an appropriate fuel for stationary and small scale SOFCs [10], [14]. This is often owing to the start-up time would be too long to use SOFCs powered with direct NH_3 to power an electric vehicle. This is also interlinking with the high working temperature requirement of SOFCs. However, they may be useful in APU for a coach, lorry, ship, or plane. According to Farhad and Hamdullahpur[4], studies on ammonia supplied portable anode supported 3D planar SOFC, 0.8 liters of NH_3 can offer nearly ten hours of continuous power using a 100 W SOFC assembly at the operating voltage of 0.73V and 800^{o}C. This is for the reason that ammonia is easily cracked at raised temperatures thence it is not acting as a contagion to the ceramic electrolytes employed in it. Besides, the lowest cell voltage at 80%, 70%, and 60% fuel employment was recorded as 0.566V, 0.573V, and 0.575V, correspondingly.

In 1980 Vayenas and Co-workers have investigated the direct use of NH_3 in SOFC for nitric oxide and electricity production. NO is formed in platinum rhodium-based catalysts during ammonia decomposition due to the partial oxidation reaction. Connecting with this, Wojcik et al [63] have been performed an experimental study on direct ammonia fueled tubular SOFCS with or without a packed bed iron catalyst at 800°C. In this study, YSZ electrolyte, Ag, and Pt electrodes were used. The outcomes of the study showed that the performance of NH_3 driven tubular SOFCs using the Pt electrode without any catalyst is almost identical to hydrogen-powered SOFCs. This is often as a result of Pt has a very surprising surface area and high porosity within the anode microstructure which adds a power to decompose ammonia completely into chemical elements of nitrogen and hydrogen. Nevertheless, Pt is extremely overpriced thence it is impracticable for commercialization. The results additionally indicate that because of temperature surges, the enactment of tubular SOFC powered with straight ammonia is virtually approached that of the H_2 fed. This is often as a result of nearly 100% ammonia conversion is occurred at a higher temperature. They also recommended that Ni can be utilized both as fuel electrode

materials and catalysts for complete ammonia conversion even if they did not include in their studies. Furthermore, their work proposed that there may be a possibility of NO formation at the fuel electrode if a suitable catalyst is not applied as shown in equation [1]. This is because selective catalysts are very essential to decompose the NH_3 into H_2 faster than NO formation.

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O \quad [1]$$

Also, SOFCs fuelled with ammonia as a primary green fuel that has Ni-YSZ anode, YSZ ionic conductor and Ag air electrode has better performance over hydrogen fed operating at a temperature of 700^{o}C. As well, the observed supreme power density for tubular and planar configuration of SOFC is 10 mW/cm² and 75mW/cm² with 1mm and 0.4 mm thick electrolyte, correspondingly at 800 °C. This indicates that as the thickness of the electrolyte decreases the enactment of the cell augments. In line with this, a maximum power density of 60 mW/cm^2 at a current density of 200 mA/cm^2 and more than 90% of ammonia conversion using nickel cermet fuel electrode, and Ag air electrode with 400 μm thickness of 8 mol% YSZ ionic conductor was attained by Fournier et al[79]. As well, direct ammonia supplied cell has better performance over hydrogen at 800 °C.

Furthermore, Ma et al [25] have been fabricated Ni-BaCe0.8Gd0.2O2.9 (BCGO)/BCGO/ La0.5Sr0.5CoO3-δ (LSCO)-BCGO SOFC supplied with direct commercial liquefied NH_3 as the fuel. The cell performance was investigated at a temperature of 600^{o}C at 1.102 $V_{OC,}$ and 750°C at 0.985 V_{OC}. The results of the study revealed that the maximum power density of the cell supplied with ammonia was recorded as 355 mW/cm^2 at 700°C and for hydrogen, it was 371 and 324 mW/ cm^2 with pure oxygen and air, correspondingly at that temperature. Therefore, liquefied ammonia has good performance over hydrogen.

Furthermore, Dekker and Rietveld [41] have been developed anode- and electrolyte supported highly efficient ammonia conversion using NiO-YSZ/YSZ/LSM to examine the cell voltage as a function of current, temperature and NH_3 flow. The study found that the electrical efficiency of fuel cells working with ammonia is augmented by 13% compared to dry hydrogen. Besides, the outcome of the study disclosed that up to 70% and 60% of electrical cell efficiencies can be accomplished at 0.35 A/cm^2 and 0.6 A/cm^2, correspondingly using LHV at 800^{o}C for anode supported whereas 60% and 53% electrical cell efficiencies can be accomplished at 0.35 A/cm^2 and 0.6 A/cm^2, correspondingly using LHV at 950^{o}C for electrolyte supported. As well, cell deterioration was not observed due to the ammonia existence. Since the electrochemical cell reaction consumes the hydrogen, 100% of ammonia conversion was observed at temperatures greater than 800^{o}C. According to this study, as the temperature upsurges, the likelihood of NOx discharge in the outlet also increases and reaches 4ppm at 1000^{o}C. They also recommended that a minimum of 700°C temperature is needed for applicable ammonia conversion.

Ammonia fueled SOFCs are relatively suitable compared to carbon-containing fuels. As a result, fuel humidification is generally not mandatory to maintain carbon accumulation and less cathode gas flow is possible owing to the endothermic nature of ammonia disintegration into hydrogen and nitrogen. Therefore, ammonia powered SOFCs have comparatively small heat exchangers with minor parasitic power losses. Connecting with this, S.S. Shy et al [58] have been studied the enactment of electrochemical impedance and power of anode-supported SOFCs(530-μm-Ni-YSZ/3-μm-YSZ/15-μm-LSC-GDC) driven with pressurized NH_3 at varying temperatures and pressures. Their results proved that ammonia driven SOFCs power densities are linearly improving and becomes approximately equal to

hydrogen when the temperatures and pressures of fueled ammonia are snowballing. Besides, 100% of ammonia disintegration into free hydrogen and nitrogen were perceived greater than 750 °C.

Different studies disclosed that Ni has very good performance with above 90% of ammonia conversion at 800°C compared with Ag and Pt. Corresponding to this, Goodman and Choudhary [80] have been realized that electrodes prepared from Ni can produce greater power densities compared with Ag or Pt. The power density of NH_3 fueled SOFC-O systems with skinny electrolytes has been terrifically improved. This is for the reason that the ammonia transformation into hydrogen using Ni anode or as a catalyst is augmenting at higher temperatures. Consequently, NH_3 powered cell performance is enhanced and approaches with that of hydrogen supplied one. This shows that Ni is an inexpensive energetic catalyst for ammonia cracking in the first step and hydrogen oxidation in the last stage. However, the anode reaction is the rate-limiting factors [81] due to sluggish oxygen ions diffusion via the electrolyte. This may be permitted NOx production at the electrode although utilizing Fe based catalysts can support in dropping the likelihood of NOx generation. Yet, practically it has not been detected.

Recently, most of the efforts have been devoted to ionic conductor supported cells nevertheless the ohmic polarization is high. In line with this, the uppermost power densities are low which is less than10 mW/cm². Zhang et al [77] made AS (NiO-YSZ) tube by extrusion method with 15μm thickness thin YSZ electrolytes by coating onto the anode substrate by a vacuum-assisted dip-coating method. The results confirmed that the highest power density of direct ammonia fed cells was 200mW/cm² at 800°C with nil NOx emissions which are nearly the same as hydrogen fed cells (202mW/cm²). Ma et al[59] have been carried out an experimental investigation of liquid ammonia supplied AS-SOFCs using 30μm thin-film YSZ electrolyte made by dry pressing. The inference of the study is confirming that the power densities were 299 at 750°C which is lowered than the value informed by [25] and 526 mW/cm² at 850 °C which is sensitive to high temperature. The electrolyte resistances of hydrogen and ammonia powered cells are very similar yet the SOFCs running with ammonia shows a greater interfacial overpotential opposition below 750 °C.

Liu et al [82]have been examined the performance of direct liquid methanol powered SOFC compared with ammonia and hydrogen fuels employing NiO-SDC anode, a 24μm SDC electrolyte, and Sm0.5Sr0.5CoO3 (SSC)-SDC cathode. The result of this study confirmed that the peak power densities were found as 870mW/cm², 698mW/cm², and 467mW/cm² for hydrogen, methanol, and ammonia, respectively at 650°C. It also found that the performance of methanol is higher than ammonia without remarkable deterioration and carbon deposition at the node. On the opposite hand, Meng et al [57]have been conducted a comparative study on the performance of 10μm thick SDC electrolyte SOFC powered with ammonia and hydrogen. They were fabricated a nickel-based anode-supported (Ni-SDC) with Ba0.5Sr0.5Co0.8Fe0.2O3-δ (BSCF) as the cathode component using a glycine-nitrate process. As publicized in table 2.11, the uppermost power density of SOFC powered with hydrogen and ammonia as direct fuel was found as 1190mW/cm² and 1872 mW/cm², correspondingly at 650°C. Even though the cathode component and the thickness of electrolyte are different, the performance of ammonia supplied SOFC is superior convenient liquid fuel than the methanol powered one which is opposite to the reports of Liu et al [83]. As well, contrary to the previous works, this study revealed that hydrogen has better performance with a significant difference over ammonia at the respective temperatures. Besides, compared to hydrogen supplied cells, the power density variation of ammonia is considerably large at lowered working temperatures. This is often because ammonia cracking is an endothermic reaction that

makes the actual cell temperature is dropped than the thermocouple reading. However, up to nowadays, the power densities were the maximum among the reported in the literature. This is maybe interconnected with the thickness and the ionic conductive of the electrolytes.

Hajimolana et al [84] have developed a dynamic model of ammonia supplied tubular SOFCs to investigate the ammonia decomposition reaction, electrochemical reactions, diffusion, transport (heat and mass transfer), inherent impedance, activation and concentration overpotential of electrodes. They also considered the design parameter's effects on the performance of the cell by considering the fuel-cell-tube temperature, dynamic output voltage, and efficiency connected with the inlet fuel flow pressure with different values. The finding of their study disclosed that the inside cell tube diameter has the sturdiest impacts on the efficiency of the cell among the considered parameters in the study. On the opposite hand, cathodic porosity has a higher influence on the performance of the cell compared with anodic porosity. Besides, changing the length of a fuel cell has higher effects on the sizes of micro and macro-structures. Additionally, it is found that the performance of ammonia powered SOFC is virtually the same as that of hydrogen supplied one. Thence, ammonia is an appropriate fuel candidate to utilize in place of hydrogen.

Mechanical damage is that the fundamental factor that restraining the SOFCs stability in the long-term [48]. The mechanical reliability of planar SOFCs made of Ni-YSZ, YSZ, and LSM-YSZ as an anode, electrolyte, and cathode materials, respectively was analyzed using the structural mechanics model with composition-dependent mechanical properties. The result disclosed that the mechanical steadiness is mainly influenced by the number of fractions and thickness of anode, electrolyte and cathode materials, and its supported types. Besides, the likelihood of anode failure is connected with the content of Ni hence the quantity of Ni fraction is underneath 65%. Moreover, to augment the electrochemical achievement and maintain the mechanical steadiness of the LSM-YSZ cathode, the recommended LSM volume fraction is within 45–55. And also, to be mechanically stable, the anode-supported cell should have above 0.5 mm thickness with 20 μm thick electrolyte [48]. Further, the anode-supported planar configuration SOFCs is found to be mechanically gentle and high electrochemical performance than that of the electrolyte and cathode-supported cell. The failure probabilities for the anode-, cathode-, and electrolyte-supported cells are the lowest, medium, and highest, respectively[48]. Yet, when comparing in terms of efficiency, the CS is superior to anode and electrolyte supports. Similar to the planar structure, the AS-T-SOFCs are preferable both in mechanical steadiness and electrochemical performances. Yet in contrary to planar, the AS-T-SOFC has greater efficiency over the other two supports when considering the power density and material cost as an objective function simultaneously. Additionally, Kim et al. [42] were performed a numerical model and their results confirmed that the mechanical strength increases as the thickness of anode increase yet the performance of the cell is lowered.

Milad et al.[43] have been made a techno-economic comparison of AS, ES, and CS-SOFCs and obtained a maximum power density of CS when power is taken as the only objective function whereas when considering the materials cost as an objective function, the ES-SOFC is obtained to be the optimal choice. Though, at once considering both objective functions, the AS has the best performance than CS and ES one. This study is also supported by kakaç et al. [7] who have been performed a theoretical comparison analysis on supporting layer thickness and obtained as the performance of AS is superior over an ES. Also, ES has underprivileged performance compared with the AS cells as confirmed by

Chan et al.[39]. The Zhao has been performed an experimental investigation and confirmed that the power outcomes of AS- SOFC is diminished as the thickness of supporting layer upsurges[85]. Moreover, the effects of different supporting element thickness on AS cell performance have been studied by Moon et al.[86]. Their results revealed that the electrolyte thickness is more sensitive in cell performance than the thickness of the electrode. Shichuan et al.[11] has been developed a numerical model and confirmed that CS stack outperforms over the AS stack one.

4. Challenges in Straight Ammonia Fueled Solid Oxide Fuel Cells

Today, SOFCs are receiving more thoughtfulness as alternative energy conversion electrochemical technologies owing to their high overall efficiencies and have better fuel diversity. Yet, connected with high working temperature, many challenges are fronting that must be overcome through different researches. These are a mechanical strain as a result of having different TECs, interfacial diffusion between cell components, poisoning and sintering can be resulting in electronic conductor deactivation during fabrication and operation. Moreover, steam is added to humidify the hydrocarbon fuels including hydrogen to prevent the fuel electrode surfaces from carbon deposition and to maintain the operating temperature of SOFCs. As a result, water control systems are becoming complex. Therefore, utilizing tubular SOFCs fuelled with straight ammonia are playing a key role in addressing the problem. In addition to the aforementioned, the primary challenges we are encountered in SOFCs progress are reducing the working temperatures on one side and enhancing the conductivity of ionic conductors and efficiency in other sides. This is because SOFCs working at low temperature requires solid electrolytes with high conductivities and also ammonia conversion is very low at a lower temperature. Besides, the unwanted reaction may accelerate because of high functioning temperature which may create materials challenges. Different electrode materials are applied to a single cell because it has a different partial pressure which can cause the voltage loss between the porous electrodes. Besides, unable to attain a gas-tight seal among compartments is a very serious challenge. This is because it results in gas escape and ultimately the stacked cells may be damaged especially in a planar configuration. Therefore, sealant requirement is the other critical challenges in planar structures but this may be solved with tubular configurations.

The other challenges of the fuel cell, in general, are the accumulation of large amounts of produced water molecules which hinders the mass transport in turn influence the overall electrochemical performances. In many types of fuel cells, due to having an exothermic electrochemical reaction, the generated heat should be removed continuously to avert components of cell damage. Yet, this doubt is solved using SOFC.

Today, despite their promise, the challenges that are deterring SOFCs commercialization are its cost and system faithfulness. Because of the high functioning temperature, SOFCs have immeasurable opportunities. These are utilizing almost all types of fuels using reforming and oxidation processes and, they can deliver extraordinary quality waste heat for cogeneration power generation systems. Yet, they require materials with exceptional properties to withstand high operational temperatures. Connecting with this, thermal, electrical, and chemical mismatches among metals and ceramics components used in the cells are also the critical issues that need to be achieved in SOFC technology development. Therefore, dropping the working temperature of SOFC ranging from 800 to 1000^{o}C to 500 to 800^{o}C has more advantages for practical implementation and to create acceptable commercialization for SOFC

devices. As well, dropping the working temperature can also provide long-term operation, materials stability, minimize thermal stress, cost, and safety benefits. Also, they are best suited for combined heat and power application systems. Yet, to utilize ammonia as a direct fuel in IT-SOFCs, its conversion efficiency is below 17%. Therefore, SOFCs running with straight ammonia needs a temperature of more than 700^{o}C for effective conversion of ammonia into free hydrogen and nitrogen using a non-expensive Ni as fuel electrode and catalysts.

5. Opportunities and Future Outlooks of Solid Oxide Fuel Cell

The driving power of realizing more efficient clean energy production and consumption is the rising of fuel prices and environmental destruction interlinking with the augmented consumption of electricity. Fuel cells are clean and efficient electrochemical energy converter that transforms the chemical energy of fuels into electricity directly without combustion. In contrast to a heat engine, a fuel cell has an advantage in single-step chemical to electrical energy conversion device contrasting heat engine Accordingly, they are not governed by Carnot thermal efficiency.

SOFCs are the supreme encouraging electrochemical devices in costs among different fuel cells. Besides, since they have a solid ceramic electrolyte, they eliminate the electrolyte administration difficulties connected with PAFC and MCFC. They are allowing the use of non-valuable materials as electrolytes, electrodes, or catalyst components due to high operating temperatures. The second most opportunity for SOFCs is fuel tolerance due to having high working temperatures. Besides, the hybrids of SOFCs with Rankine or Brayton for extra power generation using cogeneration or trigeneration are providing additional opportunities to recover the exhaust waste heat from the cells. Agreeing with this, the different analyses revealed that the peak efficiency of the SOFC integrated CHP system can be reached up to 90% depending on the operational circumstance and the types of arrangement. They are the most efficient devices yet invented and developed for electric power generation without combustion. Besides, they are quite solid-state devices that have vibration-free operation hence noise commonly allied with customary power production systems are eliminated.

Also, compared to other supply of hydrogen, the deployment of ammonia as a secondary energy vector for SOFCs have noteworthy benefit. These are low prices, easy storage, well-established transportation infrastructures, and carbon-free emission. Conforming with the per unit mass, the energy density of H_2 is above any typical fuels. On the opposite hand, the volumetrical energy density of the gas is a terribly low owing to having low density compared with hydrocarbon and ammonia. However, the pressurized ammonia energy density is virtually greater than CNG and hydrogen gas whereas lower than LPG and gasoline. The ammonia energy cost is a little bit above hydrogen energy cost per unit volume. Yet, ammonia has more stored energy than hydrogen per volume. Hence, according to per unit of energy, ammonia is the most cost-effective and economical energy supply. As a result, NH_3 is found as a promising and price-effective alternative green fuel for electrochemical technologies. Besides, Nickel is the most economical and effective candidate as either a fuel electrode or catalyst for SOFC. This is because Ni has the power to breakdown ammonia into its chemical constituent elements and oxidizes the hydrogen through a consecutive electrochemical process that plays a critical role in cost reduction. To sum up, SOFCs offer a unique combination of advantages in terms of energy efficiency, Environment, and Energy security. Therefore, SOFCs constructing from nickel/zirconia cermet anodes are effective due to having higher surface areas and compatibility nature with other components.

6. Conclusions

Diminishing the release of carbon and its related to fight global climate alteration is one of the predominant challenges we are fronting at this time. However, hydrogen, ammonia, and associated chemicals that are carbon-free can be deployed as an alternative energy carrier for both the transport sector and power generation systems. Yet, during hydrogen and ammonia production, carbon-rich fuels have to be circumvented as sources of energy to minimize the release of carbon-related emissions

Hydrogen is a perfect fuel choice from environmental outlook and energy density nonetheless production, handling, and transportation interconnected problems are the foremost challenges for hydrogen technologies. On the opposite hand, hydrogen also can be deposited tortuously within the variety of ammonia, methanol, ethanol, methane, etc. Among them, ammonia is a carbon-free energy carrier like hydrogen which is an alternative solution for the transportation sector. As well, the transportation or distribution infrastructure of ammonia is well established. Further, compared with hydrocarbon fuels, ammonia can be directly oxidized without a separate reactor or reformer in SOFCs. Thus, the ammonia economy can accomplish similar reimbursements and can overwhelm the challenges we are faced in the hydrogen economy.

SOFC is an ideal and extraordinary electrochemical energy converter to change the chemical energy of ammonia into electrical energy without intermediate products at high temperatures. Yet, to realize Direct ammonia powered T-SOFCs for stationary and mobile electric power generation, determining the optimum operating temperatures, pressure, reactant flow rates, electrode porosities, location of the anode, thickness, and tube diameters are still requiring further improvement. Thus, mathematical modeling should be developed to determine these parameters before planning for experimental work.

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Conflicts of interest

The author has no conflict of interest.

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