The Direct Ammonia Fuel Cell: Revolutionary Applications in the Field of Renewable Energy

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Abstract

Ammonia, being a prospective ancillary hydrogen energy carrier, with traditional storage and distribution associations, discloses as a convenient energy source. The incipient concept of 'green ammonia, produced *via* greener routes, could unfold futuristics markets and assist decarbonize various fossil fuel-dependent applications. This review outlines a contrastive analysis of direct ammonia fuel cells, operational principles, advantages as well as shortcomings. It emphasizes the contemporary developments and technology's readiness for future implementations. Current complications regarding the NO_x species formation, selection of materials, constrained power densities, carbon dioxide endurance and long-lasted durability, are also deliberated.

1. Introduction

Over the past few years, the excessive use of carbon-based non-renewable fuels has wreaked havoc both on the wellbeing of the mankind and the environment, prompting the long-lasting search for cleaner alternatives, recognizing the potential of green hydrogen as a superlative renewable energy fuel [1]. However, transitioning to the greener hydrogen fuel requires the advancement of viable production, supply and particularly suitable ambient conditions assisted storage engineering, which are not adequately suitable in the contemporary times, due to its low energy density and safety concerns[2,3]. Ammonia, with its high hydrogen content and existing substructure for distribution, has been utilized periodically in the earlier times as a potential fuel for fuel cells and internal combustion engines (ICEs), as depicted in **Figure 1** [3,4].The ammonia has significantly notable advantages as a transportation fuel, which can be relatively compared with liquid hydrogen. Also, it showcases higher density to tackle the infrastructural and storage problems as compared to hydrogen fuel. Despite its toxicity, ammonia claims various advantages like high-

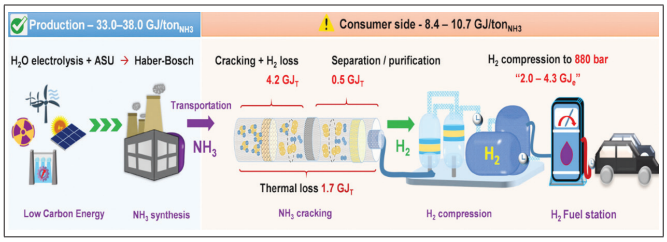


Figure 1: Pictorial depiction of production, supply and utiliztion pathway of NH_3 as a potential green energy vector. Reproduced with permission from *ref*. 3. Copyright 2021 American Chemical Society

octane rating along with facile thermal cracking to produce hydrogen. [5,6] The worldwide distribution system of ammonia is already well-established, and it's also safer than other fuels, due to its unique properties, like rapid degeneracy, low flammability and facile detection process. Furthermore, synthesis of ammonia can be carried out from various sources, such as all kinds of fossil fuels (*e.g.*, natural gas, coal, naphtha, petroleum *etc.*), from other green energy resources (*e.g.*, wind, solar, geothermal, hydro, heat waste, ocean and nuclear *etc.*), *via* employing biomass, water, organic waste (including metropolitan wastes) and air as major power supplies, making it an environmentally friendly alternative[7] . As ammonia decomposes into water and nitrogen, which are abundantly available in the Earth's atmosphere, it can be considered as fully recyclable material. As it is mentioned above, the very technologies for extracting hydrogen from ammonia, like thermal cracking and electrolysis, are already in development, though it remains a challenge to make compact, operational and efficient designs. Since the year 1966, several studies have been developed by the scientific and industrial communities on the latent utilizations of ammonia in fuel cells. Ammonia has already been employed to power the regular fuel cells. Recent advances have led to the development of proton conducting solid oxide membranes that can also function at elevated temperatures[8,10]. These membranes are beneficial in several ways:

i. Facilitation of ammonia molecules to break down into useful components at one part of the fuel cell.

ii. Facile transference of the protons through the membrane from one side of the cell to the other, which eventually generates water releasing energy.

iii. The process exhausts the overall fuel supply, thereby mitigating the necessity for additional procedures.

iv. Upon the completion of the process, the enduring nitrogen can be employed in various operations or safely discharged into the atmosphere.

When the hydrogen gas is being obligated to be extracted from ammonia, there are two main methods: thermochemical processes and electrochemical processes. Alternatively, in fuel cell ammonia can directly be used, without requiring prior decomposition or cracking. The fuel cell technology mainly generates electricity from chemical sources through electrochemical reactions. Generally, depending upon the materials subjected as electrolytes, their future applications, and the conditions under which they operate, fuel cells can be classified in different types. These classes include solid oxide fuel cell (SOFC), proton exchange membrane fuel cell (PEMFC), alkaline membrane fuel cell (AMFC), alkaline fuel cell (AFC) *etc* [11,12].

The extensive utilization of fuel cells in various domains of renewable and sustainable energy production consequently presents distinctive challenges that requires deliberate scientific attentions. One of the major hurdles impeding the development of ammonia fed fuel cells is the lack of efficient and cost-effective technologies associated with production, assembly and distribution[14] . Contemporary methods of ammonia synthesis for fuel cells predominantly encompass the energy-intensive Haber-Bosch process, which profoundly relies on carbon-based fossil fuels which emits significant amounts of greenhouse gases[15]. Furthermore, the marginal infrastructure which is obligatory for the widespread supply of ammonia as a fuel source is still underdeveloped. Without any inclusive clarification to these challenges, the potential advantages of ammonia fuel cells may not be fully comprehended. Therefore, the articulation of the problem resides in the development of innovative and sustainable techniques for ammonia production and storage [15], while simultaneously establishing a robust circulation network to support the incorporation of ammonia fuel cells into the vast domain of renewable energy. As we thoroughly investigate the potentials of ammonia fed fuel cells as a novel sustainable energy source, it is exceedingly crucial to develop distinct research questions that will steer our investigation and analysis. The major questions may concentrate upon the efficiency and

effectiveness of ammonia fuel cells in comparison to the pristine fuel sources, the global environmental and economic consequences of ammonia production and utilization, and the scalability of ammonia fed fuel cell technologies for pervasive utilization in numerous sectors. By considering these research questions, we can improve the comprehensive understanding of the viability and real-time practicality of incorporating ammonia fuel cells into the worldwide renewable energy framework. Additionally, estimating the financial inferences and the regulatory infrastructures encompassing the ammonia fuel cells can deliver valuable perceptions into their long-term implacability as novel green energy solution. Through meticulous research and analysis, we can facilitate the ammonia revolution to emerge as a feasible and operative substitution to the conventional energy sources[16].

2. Fundamentals of Ammonia Fuel Cell

The alteration regarding the Renewable Energy Sources (RES) and the imperative necessity to address the prevailing energy crisis have driven the exploration of alternative energy generation methods. Within this landscape, fuel cells have been developed as a fruitful technology for sustainable energy production. Particularly, the development of high-gain DC–DC boost converters has facilitated the integration of fuel cells, such as hydrogen fuel cells, into various applications, including electric vehicles (EVs) and utility grids[17]. Furthermore, as countries worldwide strive to meet their energy demands while adhering to sustainable goals, the focus on H_2-based energy storage infrastructure has intensified, with water electrolysis playing a crucial role in large-scale hydrogen production for fuel cells and other electrochemical applications[18]. This intensive initiative not only establishes the foundation for a greener energy economy but also emphasizes the potential of fuel cells, especially ammonia-fed fuel cells, as a real-time implacable and effective green energy substitution technology with noteworthy economic reimbursements and environmental advantages.

Meticulous investigations associated with various classes of fuel cells are indispensable in advancing the development of renewable energy technologies. The proton exchange membrane fuel cells (PEMFCs) are among the most frequently employed fuel cell technologies, owing to their relatively reduced operating temperatures, high-power density, and rapid starting periods. Meanwhile, solid oxide fuel cells (SOFCs) function at comparatively elevated temperatures and are extremely efficient in fuel-to-electricity conversion, making them apposite for stationary power generation applications. Meanwhile, the alkaline fuel cells (AFCs) represent an established and efficient technology in the operative domain of fuel cell systems, harnessing an alkaline electrolyte to accomplish effective reduction of oxygen and oxidation of hydrogen reactions. Recognizing their abilities to function at diminished temperature conditions and their epoch-making implementation in space exploration, AFCs endure to be a crucial domain of investigation for sustainable and high-efficiency energy solutions. Whereas, the alkaline membrane-based fuel cells (AMFCs) unfold a novel method associated to the fuel cell technology by incorporating a polymer-based membrane enable of conducting hydroxide ions. This advancement augments the holistic performance and endurability of the fuel cell, making AMFCs a promising futuristic substitution for a broad spectrum of applications, from mobile power devices to large industrial-scale energy systems.

The above discussed esteemed classes of direct ammonia fuel cells (DAFCs) have been acquiring considerations for their aptitude to utilize ammonia as a green and renewable fuel source. These various classes of fuel cells provide distinct advantages as well as challenges, providing an assorted landscape of options for the amalgamation of sustainable green energy sources into the contemporary energy systems. By venturing the assets and limitations of each class of fuel cell technology, the scientific community can conclude facile evaluations for the most suitable options with diversified applications in the evolution towards a greener energy future.[16]

Commercially available precious metal based electrocatalysts, such as PtIr/C, Pt/C, and PtRu/C[19], along with ruthenium-based catalysts like Ru/Al_2O_3, Ru/MgO, Ru/CNT, as well as metal alloy based catalysts have been extensively employed as anode materials. However, the high cost and limited availability of Pt, Ru and Ir metals significantly constrain the large-scale application in fuel cells. This limitation underscores the development of non-precious metal catalysts for cost-effective, efficient, and durable alternatives.

Recently, Ni-based catalysts exhibit as a promising alternative due to its affordability and higher intrinsic ammonia oxidation reactivity. Some metal alloy catalysts such as Ni-Fe, Ni-Cu[20], Ni-Mo[21], Co-Ni-P have shown considerable potential. Additionally, transition metal nitrides and carbides *e.g.*, Fe–N–C[22], metal oxide such as TiO nanofibers[23] and Metal-Organic-Frameworks (MOF) derived materials have been extensively explored. Notably, Zhang *et al*. have synthesized a ternary NiCuFe alloy that exhibited remarkable catalytic activity and durability as an electrode in commercial anion exchange membrane (AEM) electrolytes[24]. Jiang *et al*. have deposited $NiCo_2N$ composite on Ni foam, which has demonstrated significant efficacy as an electrode material for electrocatalytic decomposition of ammonia[25].

2.1. Solid Oxide Fuel Cell (SOFC)

SOFCs are often contemplated as the most effective device to generate power by the chemical energy translation into electrical energy and are amongst the frequently investigated category of ammonia-based fuel cells[26]. SOFCs has excellent efficiency regarding energy conversion operations and offers tremendous flexibility in the overall fuel utilization. Ammonia cracking, occurring in these systems, particularly takes place at high temperatures ranging from 500°C and 1000°C. One significant benefit of the applied high temperature conditions is that the breakdown of ammonia and power generating processes can be efficiently merged. Therefore, without the need of pre-processing, ammonia can be employed directly in SOFCs[27,28]. The elevated temperature conditions also[16]. Reduce the requirement and cost of a discrete separate unit to decompose ammonia, and also improves the electrolyte's capability to transfer ions, thus dropping the electrical losses[26]. In 1980, the initial direct ammonia SOFC was pioneered by Vayenas and Farr [29]. Their major objective was to operate nitric oxide as a viable feed material, while electricity being generated concurrently. The fuel cell contained of Pt electrodes along with a ZrO_2 zirconia (YSZ) electrolyte stabilized *via* Y_2O_3[30,31]. Meanwhile, YSZ is the one of the most extensively utilized electrolyte, which is due to the augmented ion mobility, which facilitates the operative movement of oxygen ions throughout the electrolyte, thereby lowering internal resistance. Moreover, similar solid electrolytes exhibit an augmented thermal and chemical stability, which is also critical for high temperature applications[32]. Another conventional anode, Ni/YSZ (Nickel/yttria-stabilized zirconia) for SOFCs efficiently decomposes ammonia at elevated temperatures above 700˚C. However, Ba-modified Ni/YSZ (Ba-Ni/YSZ) anode catalyst decomposes at significantly lower temperature[33]. Ceria-based electrolytes, like samarium-doped ceria (SDC), secured potential scientific attentions, owing to their remarkable ionic conductivity even at low temperature conditions[31].

Owing to the sluggish diffusions of oxygen ions across the employed electrolyte, equation (1) becomes the step that limits the rate of reaction. Meanwhile, the most pertinent question can be "what causes the NO level to approach 60%?". Initially, the prior purpose of the technology was to generate sufficient power to produce nitric oxide, although, the nitric oxide formation is not preferable, when the fuel cell is completely employed to generate electricity[29]. Consequently, the advancement of SOFC has relocated towards producing N_2 as the only nitrogenous compound.

Solid oxide fuel cells are categorized into two types: oxygen-ion-conducting (SOFC-O) and proton-conducting (SOFC-H). For SOFC-O, the anode side reactions resemble with reactions (1) and (2), while the cathode side reaction corresponds to the reaction

(3), which is depicted in **Figure 2**.

Anode reaction : $5O^{2-} + 2NH_3 \rightarrow 2NO + 3H_2O + 10e^-$ (1)

$3NO + 2NH_3 \rightarrow 5/2N_2 + 3H_2O$ (2)

Cathode reaction : $O_2 + 2\ e^- \rightarrow 2\ O^{2-}$ (3)

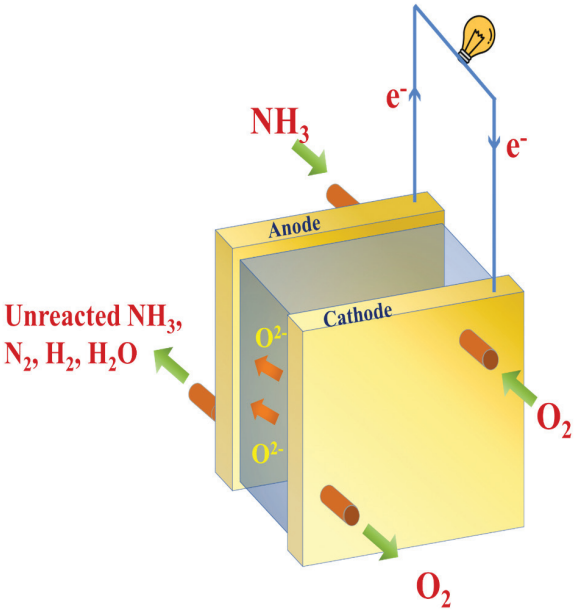


Figure 2: Schematic of the ammonia-fed SOFC-O.

Meanwhile, the working principle is not much different for SOFC-H. The anode side reaction can be represented with reaction (4), where the cathode side reaction resembles with reaction (5), which is depicted in **Figure 3.**

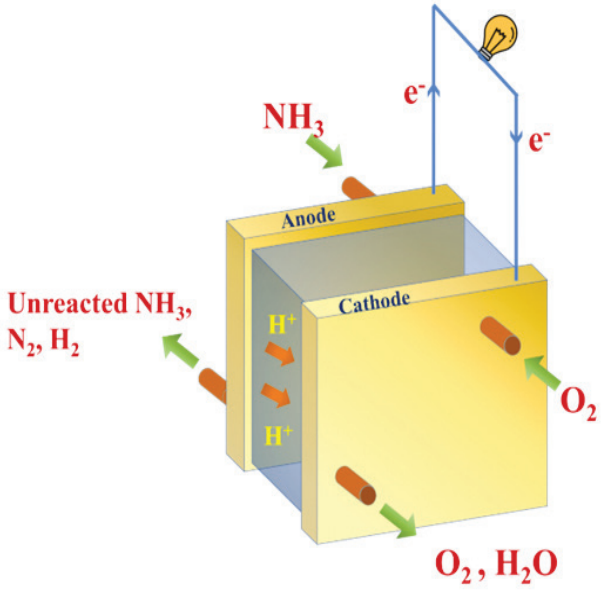


Figure 3: Graphitic design of the ammonia-fed SOFC-H

Anode reaction : H2 → 2H+ + 2e- (4)

Cathode reaction : 2H+ + O2 + 2e- → H2O (5)

Proton mediating electrolytes encompasses a reduced energy barrier for H^+ conduction, which allow SOFC-H to operate potentially at lower temperatures than SOFC-O. Hence, the proton-conducting SOFC inclines to possess advanced energy efficiency[34]. In recent times, several promising electrolytes have been developed which aimed at enhancing the conductivity as well as boosting the power density. Additionally, to reduce nitric oxide formation, doping materials like $BaCeO_3$ and $BaZrO_3$ have been under development, where the employed materials consist of $BaCe_{0.9}Nd_{0.1}O_{3-\delta}$ and $Ce_{0.8}Sm_{0.2}O_{1.9}$ [35,36]. Novel lab-scaled ammonia-fed SOFC systems, incorporated with internal combustion engines which are integrated with a stack in a hybrid configuration, were also developed, which achieved a potential efficiency of up to 67.5%[37].

2.2. Alkaline & Alkaline Membrane-Based Fuel Cell

From the initial phases of fuel cell development, alkaline fuel cells (AFCs) are being extensively researched and implemented in real-time feasible systems like transportation vehicles, space applications and energy storage systems *etc*[38-42]. The first generation of ammonia AFC was designed *via* Cairns *et al*[43], in 1960, using a KOH-based electrolyte functioning at temperature ranging from 50 to 200°C[43]. Such systems generate electricity though utilizing an aqueous KOH solution as electrolyte, allowing OH^- species to move throughout the electrolyte for executing the complete circuit and acquiring electrical energy. Subsequent efforts have focused on advancing molten hydroxide electrolytes. According to Hejze *et al*[43]., they reached a power density of order 40 $mW \cdot cm^{-2}$ at 450°C using ammonia fuel and a molten NaOH/KOH electrolyte [44]. A similar system that was capable of achieving a optimum power density of 16 $mW \cdot cm^{-2}$ at 220°C was first investigated by Yang *et al* [45]. In another approach, a direct ammonia-based fuel cell with a molten NaOH/KOH electrolyte established an open circuit voltage of 0.4 V and a highest power density of 0.225 $mW \cdot cm^{-2}$ at 220°C[46]. Although, the main challenge of such fuel

cells is the durability performances, as the carbon dioxide present in atmosphere reacts with the OH^- electrolyte to generate carbonate species, like K_2CO_3. These carbonates can form precipitation and potentially impair the cell's performance over time.

Alkaline membrane-based fuel cells (AMFCs) function on parallel principles to that of alkaline fuel cells, where OH^- ions transfer through the electrolyte, as depicted in **Figure 4**. They operate at relatively lower temperatures, typically around 50–120°C[41]. At the cathodic

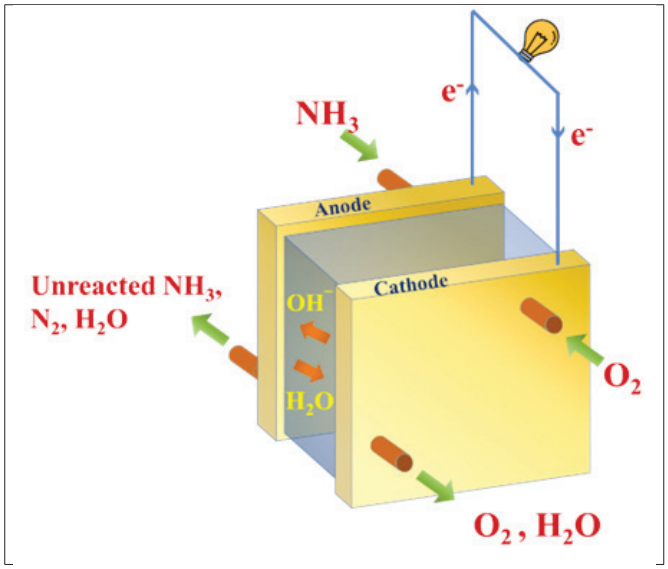


Figure 4: Graphic design of the ammonia-fed AMFC

component, significant reaction occurs between oxygen & water to produce hydroxide ions. These hydroxide species then transport through an alkaline-based membrane to the anode producing nitrogen and water, after reacting with ammonia. Upon the utilization of alkaline membrane as the electrolyte, the cathodic and anodic and reactions are given below:

Anode reaction : 6OH- + 2NH3 → N2 + 6H2O + 6e- (6)
Cathode reaction : 3/2 O_2 + 3H_2O + 6e- → 6OH^- (7)
Overall reaction : 2NH3 + 3/2 O2 → N2 + 3H2O (7)

Since the only products of the ammonia-fed alkaline membrane-based fuel cells are water and nitrogen, this technology is highly recognized for its environmental cleanliness. In contrast to solid oxide fuel cells (SOFCs), where the degradation of ammonia takes place breaking down to the corresponding elements, AMFCs utilize ammonia directly as fuel. This eliminates the requirement for elevated temperatures & ensures that the reaction advances without the need for a decomposition step. [47,48].

To boost the fuel cell power density, hydroxide ions are commonly implemented into the anode to accelerate the reaction described in equation (6). This approach diminishes the dependency of ammonia oxidation on the hydroxide- mass transfer throughout the electrolyte. Therefore, numerous scientific personals examine the impact of both ammonia concentration and OH^- ion concentration on improving performance.

Electrolyte selection for ammonia-fed AMFCs prioritizes augmented ion conductance, elongated chemical durability, and strong mechanical durability. As these particular technologies are also reviewed with the carriage of hydroxide ions, that are generated at the cathodic end and gets utilized at the anodic end, the swelling of electrolyte from water assimilation must also be prevent, which can be considered as a critical consideration for membrane performance[42,49-51]. Unlike conventional AFCs, the susceptibility of the alkaline membranes to reaction with the atmospheric carbon dioxide is high, therefore they do not form precipitates like K_2CO_3 and Na_2CO_3. Instead, the OH^- reacts with the atmospheric carbon dioxide to generate CO_3^{2-} ion.

$$CO_2 + 2OH^- \rightarrow CO_3^{2-} + H_2O \quad (12)$$

As, such ions possess comparatively reduced specific conductivity, the presence of CO_3^{2-} ions poses challenges like reducing overall membrane conductivity, increasing electrolyte resistance, and resulting in decreased performance. Additionally, carbonate ions reduce the obtainability of hydroxide ions for reacting with ammonia, eventually lowering the regional pH[52]. Therefore, sound chemical durability of a OH^--conducting electrolyte is vital to attain viable endurance of AMFC.

Resembling the SOFCs, the width of the electrolyte in AMFCs is critically important. Thinner membranes decrease ohmic losses by shortening diffusion paths for OH^- ions which improves reactant

delivery to the anode. However, maintaining mechanical strength is vital while pursuing thinner membranes. Excessive membrane thinning can lead to fuel permeation, causing fuel crossover and potentially inundating the cathodic end[52]. Recent developments have improved the performance and longevity of membranes in AMFCs by developing anion exchange membranes (AEMs) with boosted mobility and robust mechanical as well as chemical endurance[53]. Significant efforts have been focused towards the development of AEMs that remain stable in alkaline conditions at temperatures of 80°C and above[49,50,54,55]. These membranes are usually integrated with a polymer backbone along with a reinforced ion-conductive component. For example, a poly(aryl piperidinium) membrane that exhibited improved OH^- conductivity with increasing temperature was demonstrated by Wang and team[55]. Similarly, Lee *et al*. observed that OH^- conductivity in a PAP membrane amplified from 54 to 112 $mS \cdot cm^{-1}$ as the temperature rises from 25 to 80°C[49]. At these higher temperature conditions, an enhanced assimilation of water was also observed. These polymer-based membranes show ability for overcoming temperature-related boundaries, which can be observed in conventional AEMs when used in AMFCs.

3. Technological Advancements and Applications of Ammonia Fuel Cell in Renewable Energy

Most of the investigational studies on ammonia-based SOFC anodes have mainly investigated materials based upon nickel. The major issues regarding the utilization of Ni include generation of nitride and particle coarsening throughout the cell operation. Research has mainly emphasized on stabilizing the nickel derived anodes, enhancing the rate of ammonia degradation, and elucidating the impact of supporting materials in the process. Yang *et al*[56]. demonstrated that, although the anodes derived from Ni-YSZ and Ni-SDC revealed similar catalytic activity for ammonia decomposition, the electrochemical activity of the Ni-SDC anode was notably better than the Ni-YSZ anode, in the 500 to 700 °C temperature window. This superior performance is attributed to the superior electrochemical properties of Ni-SDC, which are eminently favourable for the efficient operation of fuel cells. The study emphasizes the importance of material choice in maximizing fuel cell performance and underlines the potential of Ni-SDC as a more efficient anode material in ammonia-fuelled solid oxide fuel cells (SOFCs). The gadolinium-doped ceria (GDC) supports demonstrated better catalytic activity and minimizing activation polarization than yttria-stabilized zirconia (YSZ) supports in Ni-based anode materials, especially at high temperatures up to 800 °C[57]. The improved performance of Ni-GDC can be ascribed to two primary factors: the synergistic interaction prevailing between GDC and Ni, which improves the ammonia degradation characterises, and the improved performance of the Ni-GDC- based anode with H_2 fuel, which further enhances its efficiency with NH_3. The authors reformed the Ni-GDC anode through enlarging the active surface of the GDC, thereby cumulative both the ammonia degradation performance and the electrochemically active three-phase boundary (TPB) region of the anode catalyst. Additionally, bimetallic catalysts show significant potential in assisting NH_3 decomposition. A *d*-block metal with a augmented M-N bond energy, like Mo, Cr or Fe, can be integrated with another metal with a lower bond energy, like Ni. Nickel transmits boosted catalytic characteristic for ammonia degradation, while encouraging the N_2-desorption of from the surface of bimetallic compound[58–62].

The advancements in fuel cell technology, primarily in the naval sector, are transforming the renewable energy sector focusing on sustainability and emissions reduction. Hydrogen, ammonia, and renewable methane assist as clean fuels, with ammonia exhibiting significant potential in Solid Oxide Fuel Cells (SOFCs). Studies reveal impressive electrical efficiency and competitive normalized energy costs, focusing on ammonia's role as a carbon-free energy source. Integrating ammonia fuel cells into existing infrastructure is a significant step towards a financially feasible and environmentally sustainable energy transformation. The transition to sustainable energy is vital for

extenuating the environmental influences of fossil fuels. Advanced technologies like high-gain DC-DC boost converters and microbial fuel cells demonstrate potential in enhancing alternative energy sources.[17,63]. By leveraging converter topologies and bioelectric potential from electroactive bacteria, one can augment power generation, mainly with ammonia as a green energy vector. Understanding extremophiles and maximizing microbial fuel cells' bioelectricity conversion capabilities can development the ammonia revolution, auxiliary future energy demands and sustainable practices[63].

To address the challenges of sustainability and environmental impact in the transportation sector, the incorporation of ammonia fuel cells has received substantial focus in the contemporary times. Ammonia has the potential to be a promising energy carrier for marine fuel and renewable energy transport, but its use in road and rail transport is limited due to safety concerns and low energy content.[64]. Ammonia fuel cells offer a sustainable solution in the transportation sector by providing a carbon-free substitute to fossil fuels, remarkably minimizing greenhouse gas emissions. Ammonia produced from renewable sources like solar, wind and hydropower increase its appeal as a clean energy option. By using ammonia fuel cells, vehicles can play a crucial role in achieving eco-friendly transportation systems.[65]. Furthermore, the ammonia based fuel cells are also utilized in the wastewater treatment which is cost effective and energy demanding. Furthermore, microbial fuel cells (MFCs) provide a cost-effective process for converting wastewater into electricity, taking advantage of the energy within the waste[66]. Directly fed ammonia microbial fuel cells (AMFCs) take advantage of high ammonia content without the need for extraction, increasing cost efficiency. Almomani *et al*. demonstrated that electro-oxidation effectively removes more than 96% of the ammonia, making it a viable treatment method[67]. Recent studies show that AMFCs using landfill leachate achieve 96.5% ammonia reduction and produce prominent energy density, showcasing their potential for wastewater applications[68]. The graphical representation of recent and potential progress demonstration of ammonia fuel cell applications as depicted in **Figure 5**.

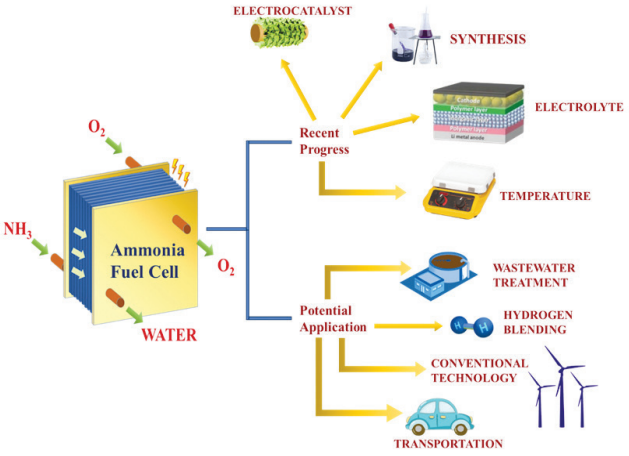


Figure 5: Ammonia fuel cell applications demonstrate sustainable energy solutions in action.

Ammonia fuel cells demonstrate remarkable potential in environmentally friendly energy applications, particularly in SOFCs for marine fuels and wastewater treatment. The advances in stabilizing Ni-based anodes and integrating ammonia fuel cells into current infrastructure show greater potential for efficiency and reduced emissions. Mankind can notably advance renewable energy solutions and address environmental challenges by leveraging ammonia's carbon-free properties and optimizing microbial fuel cells.

4. Environmental and Economic Impacts of Ammonia Fuel Cells

Ammonia fuel cell integration with renewable energy sources has the potential to revolutionize the environment and the economy. Ammonia-based Solid Oxide Fuel Cells (SOFCs) have plenty to offer in terms of environmental benefits. When measured against conventional diesel systems, they reduce greenhouse gas emissions by 92% and NO_x emissions by an incredible 93.4%. The International Maritime Organization's (IMO) progressive goals of lowering greenhouse gas emissions by 50% and CO_2 emissions by 70% by 2050 are ideally aligned with this significant reduction. Adoption of SOFCs operating on ammonia is crucial to the global maritime industry's decarbonization. Diesel and other conventional marine fuels are

significant causes of air pollution and greenhouse gas emissions[69,70]. The shipping sector may reduce its environmental effect significantly by switching to ammonia, a fuel that emits no carbon. Particularly interesting are feeder container ships powered by ammonia. These ships mark a revolutionary advancement in the field of zero-carbon maritime transportation. In the maritime industry, feeder ships play a vital role in moving goods from minor ports to larger hubs. These ships can considerably lower the industry's carbon footprint by using ammonia as fuel, improving the environment and the quality of the air. Additionally, SOFCs based on ammonia offer a dependable and effective energy supply. They can use a range of fuels, including renewable ammonia made from green hydrogen, and they run at very high efficiency. This adaptability promotes the incorporation of renewable energy sources into the maritime industry and improves energy security. Ammonia-based SOFCs offer advantages beyond their positive effects on the environment. They provide financial benefits as well. Because ammonia is widely available and has a relatively low cost of manufacture, using it may result in decreased operating expenses. Furthermore, by complying with strict environmental standards, shipping businesses can avoid potential fines and penalties thanks to the lowered emissions[71].

5. Economic Impacts of Ammonia Fuel Cells

Ammonia fuel cells make a strong case for sustainability and cost effectiveness from a financial point of view. Ammonia is a more cost-effective solution for storage and transportation than hydrogen, requiring up to 75% less space in storage. Reductions in production costs to 70% make the ammonia-based SOFC power train, which has a maximum efficiency of 56%, economically feasible. Blue ammonia SOFC systems have an annual levelized cost of energy of only $0.19/kWh and a noteworthy 5.71% reduction in total expenditures. Green ammonia SOFC systems in marine applications support the IMO 2030 target for emission reductions with an amazing cost-effectiveness of $172.92 per tonne of decreased emissions[69]. Transporting ammonia from India to Japan involves a range of expenses. Using a very large gas carrier (VLGC) with a capacity of 55,000 metric tons, which costs US$88 million, the study estimates port charges of $50,000 at Kandla and $60,000 at Tokyo. The round trip of 13,652 nm takes 36 days at 16.5 knots. Fuel consumption is 48 metric tonnes per day at sea and 10 metric tonnes at port, with heavy oil priced at $530 per metric tonne. Total transportation expenses are US$43 per metric ton from Kandla and $36 from Chennai[72]. Table 1 delivers a clear picture of the economic metrics for different types of fuelling systems.

Table 1: Illustration economic feasibility in comparison of price and efficiency parameters of ammonia fuel and other fuels[73–75].

Fuel Type	Physical State	Energy Density	Current International Costing	Fuel Efficiency
Petrol	Liquid	44-46 MJ/kg	$3.59/gallon	22.41 Km/litre (For 1197 cc Engine)
Diesel	Liquid	42-46 MJ/kg	$3.88/gallon	28.4 Km/ litre (For 1197 cc Engine)
Compressed Natural Gas (CNG)	Compressed gas (lighter than air)	42-55 MJ/kg	$2.86/GGE (Gallon of Gasoline Equivalent)	31.12 Km/gm (For 1197 cc Engine)
Hydrogen	Compressed gas (lighter than air) or liquid	120-142 MJ/kg	$1.80/GGE (Using Compressed Electrolyses)	148 Km/ Litre (Approx.) (For Four Stroke Engine)
Ammonia	Liquid	12.7–15.6 MJ/L	$1.92/GGE	26.67-36.67/Kg NH_3

While large-scale systems have been examined, small-scale systems for distributed power are still less studied. The three proposed systems include: a simple SOFC-engine hybrid, a SOFC with water removal to increase hydrogen concentration, and a SOFC engine with recirculation. Modelling showed that the efficiency of the SOFC-engine hybrid increased by 6.2%, while the efficiency of the recirculation system reached 67.4%. The hybrid recirculation system attained a peak efficiency of

67.5%, showing the unique potential of ammonia-based SOFCs for further development [37]. Wang *et al*. introduced the Ammonia Fuel Cell-Internal Combustion Engine Hybrid Vehicle (AFC-ICE HV), depicted in Figure 6, as a solution to global warming and carbon emissions. This hybrid vehicle presents energy savings, lower grid impact and lower emissions than conventional vehicles. The AFC-ICE HV addresses the limitations of current hybrids by offering lower carbon emissions, higher mileage (1600-2200 km), quick refuelling (3-5 minutes), low operating cost ($0.81-1.12 per 100 km), high energy conversion efficiency (over 80%), and advanced safety features [75].

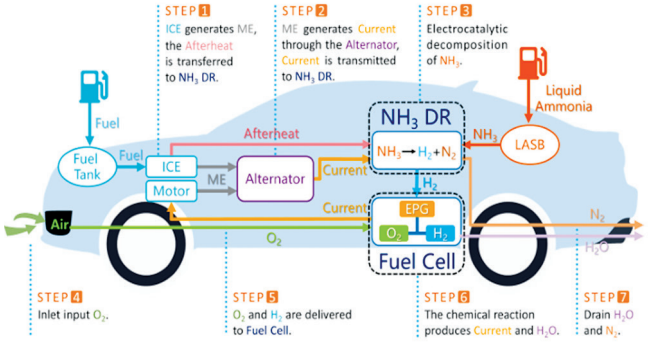


Figure 6: Working Principle of ammonia fuel cell-internal combustion engine hybrid vehicle. Reproduced with permission from ref. 75. Copyright 2023 Elsevier.

The production of green ammonia in India proposes a substantial economic advantage. By expanding its production capacities, India can substantially reduce its import dependence, improve the trade balance and reduce foreign exchange expenditure. [76] Photovoltaic (PV)-based green ammonia production is considered economically viable, with costs expected to be less than 800 €/tonne in many regions, which is competitive compared to conventional methods, especially when integrated with battery storage and other renewable energy sources. India's substantial renewable energy potential, particularly onshore wind and solar power, can meet global ammonia needs, and foster employment growth in the renewable energy sector and related industries.[77] Moving towards green ammonia production also supports India's climate goals by reducing greenhouse gas emissions. A carbon tax of 224 to 335 €/tonne of CO_2 could increase the competitiveness of green ammonia compared to conventional methods, and promote sustainable practices within the industry. Furthermore, committing in NH_3 can diversify India's economy by generating new markets and industries concentrated on sustainable energy solutions, thereby growing economic resilience and motivating technological innovation. The development of green ammonia production facilities and related renewable energy infrastructure will generate a large number of jobs, contribute to the local economy and reduce unemployment. Collectively, these factors ensure a more sustainable and adaptable economy for India[77].

The incorporation of ammonia fuel cells into power plants and transportation vehicles represents an encouraging path toward cost-effectiveness and sustainability, minimizing both operating costs and emissions. As research explores deeper into the economic and environmental impacts of using ammonia fuel cells in energy systems, the potential of these innovative technologies to move forward the ammonia revolution as a green energy alternative becomes more evident.

6. Future Scope & Conclusions

The direct comparison of fuel cell types has become challenging these days due to different testing conditions, which require explicit evaluation to determine the best technology for specific applications based on performance criteria. Ammonia-based solid oxide fuel cells (SOFCs) and ammonia microbial fuel cells (AMFCs) demonstrate encouraging outcomes in hybrid systems, transportation, and wastewater treatment.

Hybrid systems show a viable path towards incorporating ammonia as an energy carrier in the near future, which will aid its acceptance and utilization. By combining SOFCs with gas turbines (GTs) in pressurized environments, achieved remarkable efficiencies of up to 70%, far exceeding conventional SOFC performance. Studies demonstrated that ammonia-fuelled SOFCs exhibit increased power density with atmospheric pressure, highlighting their potential in hybrid

SOFC-GT systems. The integration into combined cooling, heating and power cycles further increases efficiency and takes advantage of the refrigeration properties of ammonia in a cost-effective manner. [78,79].

In transportation, ammonia-fuelled SOFCs are incipient for cleaner applications. Integrated with gas turbines and ammonia-organic Rankine cycles, these systems efficiently recover and utilize waste heat, achieving elevated energy efficiency of up to 79.88%. Such systems are particularly suitable for powering fuel cell vehicles (FCVs) and providing hydrogen for small-scale refuelling stations, ensuring that energy demand can be met sustainably without CO_2 emissions[80–82].

Ammonia-rich wastewater presents undeveloped energy resources for SOFC applications. Technologies such as microbial fuel cells (MFCs) and direct ammonia-based AMFCs provide efficient means for converting sewage directly into electricity, reducing operating costs and environmental impacts. Processes such as struvite decomposition extract ammonia for SOFC fuel, demonstrating noteworthy energy recuperation potential and reduced CO_2 emissions compared to conventional wastewater treatment[83,84]. Studies comparing different feedstocks for SOFCs, including ammonia derived from renewable sources such as wind electrolysis, highlight their potential to significantly reduce the impacts of climate change. Ammonia-based SOFCs generate approximately 0.16 kg CO_2 per kWh of electricity, demonstrating their environmental superiority over natural gas-based alternatives[12].

Ammonia-based fuel cells, particularly SOFCs and AMFCs, represent a prospective improvement in energy technology, poised to meet diverse application needs ranging from hybrid power generation to sustainable transportation and wastewater management. Their integration into hybrid systems enhances efficiency and reliability, supporting a transition towards cleaner energy solutions. Moving forward, continued research and development are essential to optimize performance, expand application possibilities, and ensure the environmental and economic viability of ammonia as a key component in future energy systems.

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