Cells For Sustainable Generation Fuel and Storage of Hydrogen – A Review

B. Ananth Krishna

Introduction:

As the global demand for energy increases, there is a need to shift towards clean energy sources. In 2022, fossil fuels accounted for over 82% of the global energy consumption, which resulted in over 34.74 billion tonnes of CO_2 being emitted.[1] Moreover, the world's energy demand is set to increase 30% over the next two decades, and with costs of fossil fuels such as coal and petrol increasing, there is a growing need for sustainable and clean energy.[2,3]

Fuel cells, which are devices that convert fuels directly into electrical energy more efficiently, quietly and in a more environmentally friendly way, are a major improvement over fuel cells in terms of usability, sustainability, environmental compatibility and efficiency.[4,5] Fuel cells are also suitable for a large variety of applications, including power generation, vehicles, electronics and military uses.[6]

Fuel cells can be classified based on their electrolyte, since the electrolyte influences the electro-chemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors.[7,8] Based on the state of the electrolyte, fuel cells can be classified into solid and liquid state fuel cells, and further into Polymer Electrolyte Membrane Fuel Cells (PEMFCs), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs), Direct Methanol Fuel Cells (DMFCs), Molten Carbonate Fuel Cells (MCFCs) and Solid Oxide Fuel Cells (SOFCs).[9] The differences between solid and liquid fuel cells are given in Table 1, and the details about the different types of fuel cells, including their catalysts, electrolytes, fuel sources, efficiencies and their advantages and disadvantages are given in Table 2.[5]

Of the following types of fuel cells, SOFCs possess multiple advantages, such as high efficiency, easy to handle solid electrolyte, wide range of operating temperatures, and fuel flexibility, as it does not require pure H_2 as fuel and can use CO, methanol and biogas as a fuel source.[5,9,10] It is for this reason that SOFCs are being considered vital to the future development of fuel cells. Currently, SOFCs find applications in large scale power generation and distribution, Co-generation, transportation and portable applications with power outputs ranging from 5kW to 3MW.[5,11](Why a review of SOFC is very important, environmental implications, profitability, importance of LCA, all in a broad tone)

In this review, the various types of fuel cells will be discussed, along with a review of the Solid oxide fuel cell (SOFC), and its components, including their purpose, material of construction, limitations faced by them and solutions to mitigate them. The SOFC holds a lot of promise, specifically for its high efficiency and flexible fuel choices.[5] Also, there will be a summary of the limitations of fuel cells, along with an elaboration of its commercial aspects and future prospects, which will include a LCA of the SOFC to analyse it and suggest improvements to improve performance and cost effectiveness. There will also be a mini-review of Microbial Fuel Cells (MFCs), a new and promising technology that utilizes microorganisms to generate electricity from organics substrates, regarding its components, limitations, strategies to improve and profit analysis.

<u>Types and Design of fuel cells:</u>

As discussed earlier, a fuel cell is a device that converts chemical energy into electrical energy through chemical reactions that do not involve the formation of any intermediate byproducts.[755,5,7,10]. The fuel cell consists of three basic components: the anode, the cathode and the electrolyte [12]. Other parts of the cell include the steel interconnects, which enable the electrical connections between adjacent fuel cells and allow fuel and air to be supplied to the anode and cathode respectively, as well as a solid-ceramic separator, which isolates the fuel and the oxidant [1314]. The choice of materials is vital in ensuring the components function properly over a long period of time, and new materials must be developed such that critical issues of degradation and corrosion are either mitigated or eliminated, without compromising on longevity and reliability [13]. In this regard, given below is an overview of each of the main 3 components, along with their materials, flaws associated with such materials and recent advancements in their fields:

Table 1: Comparison between solid state and liquid state fuel cells. [5]

Solid-state fuel cells	**Liquid-state Fuel cells**
• Solid-state fuel cells use a solid electrolyte, which can be either a ceramic material or polymeric material • Examples of solid electrolytes: 1. Yttria stabilised zirconia (YSZ) 2. Lanthanum Gadolinium oxide	• Liquid state fuel cells use a liquid electrolyte, that can be either acidic or basic solutions. • Examples: 1. Phosphoric acid (acidic) 2. Sodium Hydroxide (basic)
• Examples: SOFC (solid oxide fuel cell), Molten Carbonate Fuel Cell	• Examples: PEMFC (proton exchange membrane fuel cell), AFCs (Alkaline Fuel Cells)
Advantages: • Less risk of electrolyte leak • Better durability and less prone to impurities	**Advantages:** • Lower operating temperature • Fast start up and shut down • Wide range of available electrolytes
Disadvantages: • Requires thermal management and specialized materials due to high temperatures • Long start-up and shut-down time	**Disadvantages:** • Lower durability than solid state fuel cells • Risk of electrolyte leakage
Applications: Large scale power applications	**Applications:** Portable applications, vehicles

2.1 Cathode:

The cathode is the electrode to which the negative terminal is connected, and is where the reduction process occurs. In the SOFC, oxygen gas enters through a vent near the cathode, and is reduced to form O^{2-} as follows[5]:

$$O_2 + 2e^- \rightarrow 2O^{2-}$$

The resulting oxide ion diffuses through the electrolyte. The cathode is

The material chosen for the cathode must possess certain characteristics, such as high electrical conductivity (more than 100 $Ohm^{-1}cm^{-1}$ in an oxidising atmosphere), thermal compatibility with other components, high thermal and chemical stability, high catalytic activity in the oxygen reduction reaction (ORR), porosity to allow oxygen gas to permeate easily, and low cost.[1515,16]

Traditionally, Co-based materials, such as cobalt doped PBSCFO materials, have been used as cathodes in SOFCs, owing to their high activity in ORR, due to the cobalt content increasing the porosity thus increasing the oxygen diffusion rate.[51715] However, their high costs and incompatibility with the electrolyte material limit the usability to the SOFC.[18] In this regard, Cobalt free cathode systems, such as Gadolinium Barium Ferrite (GBF) and Strontium Barium Ferrite (SBF) are receiving considerable attention owing to their low operating temperatures and low cost of operations.[15] Zhang et al. synthesized a cobalt-free cathode material from $SrFe_{0.9}Nb_{0.1}O_{3-\delta}$ (Nb is the alloying element) and constructed a single cell with a peak power density of 1403 mW cm^{-2} at operating temperature of 800 °C.[18] Zhang et al. studied Mo-doped PBFO ($PrBaFe_2O_{5+\delta}$) as a cobalt-free cathode material, and achieved a peak power density of 0.8 W cm^{-2} at 800 °C.[19] It was noted that Mo-doping significantly improved the performance of the PBFO cathode, by increasing the oxygen vacancy content and decreasing the polarization resistance.

2.2 Anode:

The anode is connected to the negative terminal, and is where the oxidation process occurs. In the SOFC, the fuel (H_2/CH_4) is oxidised by the O^{2-} ion after it passes through the electrolyte as follows: [5]

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-$$

$$CH_4 + O^{2-} \rightarrow CH_3OH + 2e^-$$

Conventionally, cermet (a combination of a ceramic material and a metal) such as Ni-YSZ, Ni-GDC are used as anode materials, owing to their high electrocatalytic activity, low cost of manufacture and good thermal compatibility with the other electrolyte materials.[20] However, these materials have some drawbacks, such as carbon deposition when using hydrocarbon fuels, as the Ni reacts with CO present in the fuel and methane forms carbon at the anode. The carbon formed settles on the active sites of the anode, which can decrease efficiency. Additionally, any H_2S

present in the gas can severely affect the performance of the fuel cell, owing to sulphur deposition on the anode. [2020,21]

Perovskite oxides appear as promising materials for the anode, owing to their good redox stability, high activity as a catalyst, good electrical conductivity and resistance to impurities.[20] The perovskite materials can be classified into three subcategories: single perovskite materials, double perovskite materials and Ruddlesden-Popper (RP) materials. Single perovskites have a general formula XYO_3, where X refers to an alkaline or rare earth metal, and Y refers to a transition metal. Variations in the structure of the same gives rise to the other forms, double perovskites ($X_2YY'O_6$) and RP perovskites (X_2YO_4). In spite of their advantages, perovskite oxides have a lower performance than the conventional anode materials, due to inadequate electronic conductivity and poor catalytic activity.

2.3 Electrolyte:

The electrolyte is a conducting material present between the cathode and anode, which allows for the transportation of ions from cathode to anode, or vice versa.[8] In the case of the SOFC, the oxygen ions are transported via defects in the structure of the electrolyte, from the anode to the cathode, thereby creating a potential gradient between them, allowing electrons to flow through the circuit connected to the cell.[22] The material selected for the electrolyte must have high ionic conductivity, high density, and high thermo-mechanical and chemical stability.[4]

Traditionally, electrolytes such as stabilized zirconia, (ZrO_2), doped ceria (CeO_2), $LaGaO_3$ and Bi_2O_3–based are used.[22] Zirconia is primarily doped with yttria to form YSZ, owing to Yttrium's good mechanical properties and chemical stability over a wide range of temperatures, while also having a high ionic conductivity due to an increased number of oxygen vacancies.[12,22] However, these electrolytes can face issues such as lowered ionic conductivity due to excessive doping or formation of insulating phases within the electrolyte. They can also react with the cathode material at higher temperatures, thereby affecting the cell's performance.[8] A strategy to mitigate the lowered ionic conductivity is co-doping with metals such as aluminium, calcium and niobium to improve conductivity, reduce defect association and remove harmful pollutants such as silica from the electrolyte.[23–25]

Doped ceria is a promising alternative to zirconia, as it can show a much higher ionic conductivity and mobility than YSZ when doped with either gadolinium or samarium, especially at lower temperatures.[26] The most extensively used ceria-based electrolyte $Ce_{1-x}Gd_xO_2$ (CGO) shows a higher conductivity than YSZ at temperatures below 600 °C, with conductivity also increasing with increase in dopant concentration until a maximum value (0.2-0.25 Gd).[8,27] Other promising dopants for ceria include lanthanum, yttrium, ytterbium and neodymium, with similar conductivities to CGO.[28–31] Doped ceria also shows a greater chemical stability than zirconia, allowing it to be used with a large variety of different electrode materials.[8] Combining bismuth oxides (Bi_2O_3) with the ceria based electrolyte is an effective strategy to increase conductivity, as the bismuth oxides have high ionic conductivity and the ceria electrolyte prevents the bismuth oxides from decomposing due to low oxygen partial pressures.[32]

Another promising electrolyte is $LaGaO_3$, a perovskite oxide that is doped with either strontium or magnesium.[33] For example, $La_{1-x}Sr_xGa_{1-y}Mg_yO_3$ (LSGM) shows high conductivities at lower temperatures, which is higher than that of Zirconia and comparable to ceria.[8] A strategy to improve the conductivity of the electrolyte is by doping with a transition metal, such as Fe or Co.[34,35] However, both can decrease hole conductivity, which affects the cell's performance. Additionally, LSGM interacts with the nickel present in the electrolyte, forming an insulating phase, thereby reducing cell performance.[36] This issue can be sorted by reducing the sintering time and temperature.[37] LSGM and doped ceria both show great promise for use in low-temperature SOFCs.

Other promising electrolytes include proton conducting electrolytes and dual ion conducting electrolytes, as their ions are not diluted in water vapour during transport. $BaCeO_3$ is an example of a proton-conducting electrolyte, and shows promise when co-doped with neodymium and ytterbium.(cite 35)

Table 2: Materials used for Cathode, Anode and Electrolyte of SOFC

Cathode	Anode	Electrolyte
Cobalt doped PBSCFO system: • Example: $PrBa0.5Sr0.5Co2-xFexO5+\delta$ 11 • Co increases greatly the number of pores and thus enhances the diffusion of	Ni ceramic mixtures: • Ni-GDC • Ni-SDC • Ni-YSZ	Oxygen-ion conducting electrolyte: 1. Stabilised ZrO_2 2. Doped CeO_2 3. Bi_2O_3 based electrolytes

oxygen ions during operation of SOFCs12 • [PrO] and [CoO] ensured rapid transfer of oxygen, which has a pronounced effect in exchange with the surface oxygen.		4. $LaGaO_3$ based perovskite type electrolyte
Cobalt free cathode system: • Their advantage is the low operating temperature and the cost of operation, and increases the ionic conductivity of the cathode • Eg: Gadolinium Barium Ferrite (GBF)	Perovskite-based materials: • LaCrO3 • LaCoO3	Proton Conducting Electrolyte: • Doped $BaCeO_3$ • Doped $BaZrO_3$ • BaCexZr1-xO3-based electrolytes
Molybdenum doped perovskites: • PBFMO (PrBaFe1.9Mo0.1O5+δ) (Zhang et al., 2023)	Double perovskite-based materials: • Sr2xFexMo2O6	Dual ion Conducting Electrolyte: • Perovskite Fuel cells • Doped CeO_2-carbonate composites
Bismuth doped Perovskites: Eg: NdBaCo2−xBixO5+$\boldsymbol{\delta}$ (NBCBO)	Copper-CeO2 cermets: • Doped cerium dioxide, has_been considered as an alternative to YSZ because it presents conductivity that is four to five times higher than t of YSZ.	

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3. Limitations and Commercial Aspects:

Although fuel cells show promise as an alternative to fossil fuels, thanks to their high efficiency, flexible fuel choices and easy operations, they face a set of drawbacks, as discussed below:[39]

Firstly, solid oxide fuel cells suffer from hardware corrosion issues, as the pollutants such as silica, moisture in the air and CO_2 react with the cathode material and reduce the effective area for the reaction to occur.[5,11] The CO_2 interacts with the perovskite oxides, and gets adsorbed. These CO_2 molecules compete with oxygen at the active binding sites, and reduce the rate of oxygen reduction reaction. Inhibition is likely to take place at lower temperatures, and metals such as strontium, lanthanum and Barium. Silicon from the glass seals can react with the cathode material and from a salicaceous layer, which can reduce the conductivity of the cathode.[11] The effect of silicon on the cathode is dependent on the presence of moisture in the system.

One strategy to reduce CO_2 poisoning in the cathode is by doping the active sites with bismuth. [21] The Bi-doped perovskite showed enhanced catalytic activity, improved reaction stability and greater CO_2 tolerance. Also, engineering the cathode to include silicon in the composition can be done to reduce cathode poisoning. Also, doping the cathode with metals such as Fe/Nb shows promise as a way of mitigating cathode poisoning.[11]

Another problem concerning SOFCs is the long start-up time, and the poor longevity of its parts due to the high operating temperatures.[39] The SOFC is also highly temperature sensitive, and so even a 10% drop in temperature can result in a 12% drop in efficiency. A well-known strategy for mitigating these issues is lowering the operating temperatures.[5,39] By lowering temperatures, more materials can be selected, parts become cheaper to fabricate, start-up times get lowered and there is greater longevity and durability of the fuel cell.[40] However, there is often a drop in performance in the cell when using lower temperatures, as the internal resistance of the cathode increases, so designing new materials, including PBFMO as discussed earlier, for use in these cells.[19] Ralph et al. studied various cathode materials for use with a YSZ electrolyte in an SOFC operating at 700-800 °C. [41] They noted that both $La(Sr)FeO_3$ and $Pr(Sr)FeO_3$ could be used as effective cathode materials with YSZ at an operating temperature of 800°C.

SOFCs have a very good market potential, primarily due to their very wide range of power outputs (5kW to 3MW) and their high efficiency.[5] They are also very flexible when it comes to fuel choices, and they do not use any noble metals in their construction, making them cheaper.[42]

When constructing a fuel cell, it is important to analyse the cost of each of its components, and thereby conducting a profit analysis of the fuel cell and determining the pay-back time on the investment. Colantoni et al. conducted an economic analysis on SOFC systems used for power generation.[43] They noted that the primary influencers of the system's overall cost were the peripheral systems (including the piping, desulfurizer, and heating) and control systems (valves and sensors, nsafety equipment and computer hardware). Furthermore, they noted that the costs of fuel processing components and the fuel cell stack would have to be reduced to be competitive with ICE technologies, and that material selection would play a large role in lowering costs. SOFCs already possess the advantage of not using noble metals in its construction, and by coupling with lowered operation temperature, the selection of durable, cheap and efficient materials to construct the SOFC becomes easier.[4042] Lastly, they noted that maintenance costs would play a key role in the profitability of the fuel cell, and that there would be a 7-year payback period when investing 5% of the initial cost of the SOFC to maintenance. Therefore, to be profitable, the maintenance costs of the SOFC should be lowered.

A popular approach to SOFCs is to couple them with other applications such as gas turbines and waste generation.[44] In this setup, the SOFC uses gases generated by the application, to generate electricity, thereby mitigating emissions and improving the system's efficiency. Omosun et al. studied system efficiencies when coupling an SOFC with a biomass gasification system.[44]The study analysed gas recovery under both hot and cold temperatures, and modelled system efficiency and energy cost per kWh based on both. The primary costs were attributed to the SOFC, precipitators and gasifiers and fuel handling and preparation. Although the high temperature system had a higher efficiency than the cold system, the cold system had a lower system cost and a cheaper energy cost.

Another advantage of using a combined SOFC system is profitability. Marocco et al. conducted a cost-analysis on a combined heat and power SOFC system for supermarket use.[45] They noted that both capital expenditure (Cap-ex) and spark spread (difference between the cost of electricity of the device and cost of electricity of natural gas; a negative value implies a loss) would drive the profitability of the system. The authors noted that the system would be profitable if the Cap-ex was set to 0.1 €/kWh, with a cap-ex of 6 €/kWh and a fuel cell lifetime of 5 years. Furthermore, they noted that the fuel cell could achieve a 46% drop in the LCOE (levelized cost of electricity) and be profitable, with a spark spread of 0.1 €/kWh and a fuel cell cost of 1.2 €/kWh. Despite the high current cost of SOFC (12 €/kWh), this target is achievable given higher SOFC production, which will become possible in the near future; With cheap electricity, subsidies and incentives from the government, and strategies designed to minimize the cost of the SOFC, the technology can become profitable and cost-effective.[5,45]

In summary, SOFCs can be profitable and produce electricity cheaply and effectively, provided its limitations are mitigated or corrected, cost saving measures and strategies are implemented to reduce the SOFC's cost, and by coupling it with other applications to improve efficiency.

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4. <u>LCA and Future Perspectives:</u>

An LCA can be used to measure the rate of resource consumption and environmental degradation, by analysing the life cycle of the fuel cell.[46] It takes into account various factors: Fuel cell inputs, outputs, manufacture, use, maintenance, and disposal, and allows for researchers to make calculations and decisions on environmental compatibility, and comparisons with other sources of energy. SOFCs should, in theory, emit zero greenhouse gases, thereby necessitating an LCA to verify the claim, measure efficiency and durability and also draw comparisons to other energy sources.[47]

A typical LCA analysis consists of four procedures: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation.[46] These procedures cover the purpose and scope of the fuel cell, collecting data from the SOFCs and other energy sources and comparing them, and weighing environmental aspects of the fuel cell.[47,48] This is essential as this determines the most relevant source of energy to choose.

Figure 3 demonstrates the life cycle of an SOFC, and it is evident that SOFCs follow a cradle-to-grave approach, where the raw materials are extracted, fuel cell components are manufactured, fuel cell is used and then disposed.[47] However, various studies have ignored factors such as manufacturing, maintenance and disposal, thereby attributing all the environmental impacts on both raw material extraction and cell operation. Additionally, information regarding the SOFCs is limited, due to both competition and the technology's early stage of development.[49] Therefore, it is impossible to obtain a clear overview of the whole system, and how it interacts with the environment. Recent studies have focussed on the aspects of the SOFC's disposal, and they noted that the metallic components made of nickel and steel would be recycled, while the ceramic components would be disposed.

The Life Cycle Impact Assessment is essential when determining the environmental impact of the fuel cell. The SOFC is noted for its heavy reliance of stainless steel in its construction for the interconnects, which can increase the overall environment impact of the SOFC stack.[47]

When it comes to greenhouse gas emissions, studies reported that SOFCs generate 2,415,755 Kg CO2 eq., assuming a life span of 10 years or 80,000 h when using a 1 MW SOFC. Of this, 71% is emitted during the operation phase due to the usage of natural gas as fuel, and the remaining during the manufacturing stage, owing to heavy electricity usage. Despite the high emissions, the development of clean electricity and further improvements in the production process will help SOFCs become more environmentally sustainable.

SOFCs hold a lot of promise as a future energy source. However, their widespread use is limited by two factors: the high operating temperatures and heavy reliance on rare-earth metals. These factors contribute to the high costs and maintenance associated with SOFCs. However, recent research has focussed heavily on finding alternative materials that are more efficient and cheaper than conventionally used materials. The choice of new materials must also focus heavily on chemical compatibility with the other SOFC materials, and also having high thermal stability. The electrolyte material, in particular, will be a crucial factor in the SOFC's design, as it affects the cell's performance considerably. The electrodes are also important components to consider, as they face major limitations due to external pollutants: Ni based anodes suffer from coke deposition and H_2S poisoning, LSM materials are affected by chromium and silicon from the interconnects, and cathode materials LSFM and PBFO are highly sensitive to CO_2 in the atmosphere. However, strategies such as adding particles such as BaO to engineer tolerance to impurities in the electrolytes, lowering operating temperatures and using new chromium and silicon-free interconnects are being applied to address and tackle these flaws. There has also been progress in engineering materials for use at lower temperatures (below 600 C), which should improve costs and durability. Researchers have also begun using modern tools, such as computer modelling, LCAs to identify key areas of improvements. Overall, future research should focus extensively on identifying cost-effective, durable and highly efficient materials, to make SOFCs a technological and commercial success.

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Another option is to explore other potential fuel cell candidates. In this regard, Microbial Fuel Cells (MFCs) stand out for possessing multiple advantages such as running at ambient temperatures and using organic wastes, including wastewaters, as substrates.[50] They consist of a cathode and anode, with a proton exchange membrane (PEM) between them. Microorganisms are used as bio-catalysts here, as they actively break down glucose to produce electrons, which are sent to the anode, and the hydrogen ions produced pass through the PEM and react with oxygen gas at the cathode to produce water as follows:[51]

$$C_2H_4O_2 + 2H_2O \rightarrow 2CO_2 + 8e^- + 8H^+$$

$$2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$$

MFCs can come in either a two-chamber (anode and cathode in separate chambers) or single-chamber setup (anode and cathode in the same chamber). The microorganisms break down glucose and transfer it to the anode, which is typically made of graphite fibre brush, carbon brush, carbon paper, and graphite rods owing to their high stability in microbial cultures, good electrical conductivity and high surface area.[52] Further research into MFC anodes includes the usage of modified carbon, organic polymers and metal-based anodes to boost fuel cell performance.[53,54] The cathode reduces the incoming protons from the PEM to form water, and shares the same materials as the anode.[50] Some recent strategies to modify the cathode include Pt-doping; using of oxidising agents; and also biocatalysts, in which microorganisms catalyse the reaction at the cathode, thereby saving costs and improving utility.[53,55] The use of mediators, which are electron transporters from the cathode to the final donor, such as ferrocyanide ($[Fe(CN)_6]^{4-}$) can also be used to boost fuel cell performance.[56]

Although MFCs appear to be highly promising, they face a few limitations. Firstly, they suffer from low power density and high internal resistance, which can affect cell performance.[57] Additionally, there are problems during practical applications and scaling up, such as turbulence within the fuel cell compartments, resistance in the PEM, and high energy wastage.[58,59]

A major advantage of MFC systems is their applications outside of electricity generation: they can be used for biohydrogen production, biosensors and wastewater treatment.[50] Therefore, there is a high scope for MFCs to be profitable. Zheng and Zhen (2016) conducted a feasibility analysis on an MFC of 200 litre capacity, coupled with wastewater treatment.[60] The system was of a modular type, which is advantageous, owing to its higher power density (>500 W m^3). The total cost of each of the 96 modules was $23.18, with the main cost being the PEM (60% of the cost). The total capital cost of the system was $6064, with a capital cost per gpd (gallons per day) of wastewater treated at $58, which is comparable to other small scale wastewater treatment plants, with a possible reduction in price through cheaper materials for the PEM. The authors noted that the process is best suited for small scale operations in niche locations, such as hotels, remote communities and military bases. This proves that MFCs can be profitable and energy efficient, and are best suited to be coupled with other applications. In summary, MFCs are a highly promising and eco-friendly alternative to fossil fuels, with easy operation and the capability of recycling organic wastes. Future research should focus on improving efficiency of the reactor, and finding cost-effective materials to construct the fuel cell without compromising on efficiency, to make MFCs successful.

	Proton Exchange Membrane Fuel Cell	Alkaline Fuel Cell (AFCs)	Phosphoric Acid Fuel Cell (PAFCs)	Direct Alcohol Fuel Cell (DAFCs)	Metal Carbonate Fuel Cells (MCFCs)	Solid Oxide Fuel Cells (SOFCs)
Catalyst	Pt	Pt or Ni	Pt	Pt/Ru	Ni or Ni based alloys	
Electrolyte	Nafion	Alkaline	Phosphoric Acid	Nafion	Molten Carbonate	Yttria stabilised Zirconia (YSZ)
Fuel	H_2			Methanol / Ethanol	H_2/CO/CO_2	
Advantages	• Vast power range • Easy scale-up • Short start-up time • High power density	•Possibility of replacing Pt • Cheaper • High activity • short start-up time • Simple heat management • Can tolerate a very small amount of CO • fast kinetics	• Can tolerate 1–2%CO • Cheaper due to lower of Pt usage • Ability to be used in CHP systems • High stability • Low vapor pressure • Higher tolerance to CO2	• No CO2 emissions • Low start-up time • High energy density • Methanol is easy to obtain and store • Resistant to CO poisoning • Methanol is cheap	High Efficiency • Variety of Fuel • Usable with gas turbines (?) • Cheap – look into it • High activity • Supports internal reforming (?)	
Drawbacks	• Slow oxygen kinetics – (?) • Heat and water management • CO poisoning • Requires high purity H2 – (?)	• Intolerance to CO2 • Requires pure O2	• Long start-up time • Limitation in material selection • Low membrane ionic conductivity • Low power density • Intolerant to CO	• Fuel Crossover • Expensive (using Ru and Pt) • Cathode Poisoning • Methanol is highly flammable • Methanol is toxic	• Hardware corrosion • Low power density – Search for higher power density materials. • Cathode dissolution – Better choice of cathode/ using a new alloy material to tackle the problem • Long start-up time	
Efficiency	50-70%	60-70%	40-55%	20-30%	45-55%	55-65%

2**Conclusions:**

Fuel Cells appear to be an environmentally friendly and cost-effective solution to provide energy whilst mitigating emissions. Furthermore, Solid Oxide Fuel Cells are a highly promising type of fuel cell, owing to its high efficiency (up to 60%), easy usage and flexible fuel choices (can use a larger variety of gases than other fuel cells). This paper summarises the materials used in the construction of the SOFC, and identifies the most suitable materials for each of its three main components: the cathode, the anode and the electrolyte. SOFCs are, however, hampered by drawbacks such as high operating temperatures, long startup time, poor longevity and poisoning. The paper investigates potential solutions to mitigate or eliminate these drawbacks. The paper analyses the costs of the SOFC to analyse the technology's profitability, to secure the SOFCs position as a clean, efficient and cost-effective energy source. Also, a LCA is performed to highlight the environmental impacts and efficiency of the technology, along with areas for improvement.

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