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Environmental aspects of fuel cells: A review

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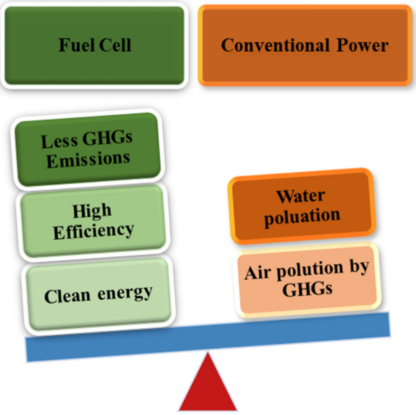
HIGHLIGHTS

- Environmental impacts of conventional energy conversion devices were discussed.
- Common fuel cells were summarized and compared to each other.
- Environmental aspects of different types of FCs were summarized.
- Fuel source has a substantial effect on the environmental impacts of FCs.

GRAPHICAL ABSTRACT



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ABSTRACT

Fossil fuels represent the primary energy supply utilized worldwide. Despite this, fossil fuels are both limited resources and have severe environmental impacts that result in climate change and several health issues. Fuel cells (FCs) are efficient energy conversion devices, which can be used for energy conversion and storage. Although different types of FCs exhibit promising features for future usage, they also have some environmental aspects that ought to be addressed. This review summarizes the different types of FCs, including the advantages and disadvantages of each. The different environmental aspects of the common types of FCs are then comprehensively discussed. This review also compares FCs to conventional power generation systems to illustrate their relative environmental benefits.

Although FCs are considered more environmental-friendly compared to conventional energy conversion systems, there are still evident operational and environmental setbacks among different FC types. These setbacks, however, must be compared in context of the intended application, fuel type, and all other involved factors in order to have a clear and fair comparison. FCs are considered environmentally friendly and more efficient. However, this is usually only when considering the operational phase or the operational perspective. The main challenge facing FCs still remains fuel sourcing, like, for example, in the case of obtaining hydrogen for hydrogen FCs, where hydrogen production causes environmental impacts. The same applies for electrode materials, where, in

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many cases, either a noble metal such as platinum, or other precious metals, or costly material. With this consideration, a life cycle assessment (LCA) is a useful tool that considers all of the manufacturing, fuel sourcing, and operational phases. Although using FCs shows evident environmental improvements compared to conventional energy sources, the LCA of FCs compared to that of conventional power sources shows a similar performance. This is mainly due to the EIs associated with fuel sourcing and material acquisition, either for precious metals used for low-temperature FCs, or thermally and chemically stable materials used for medium- and high-temperature FCs. Both of these also contribute largely to the cost of FCs. Developments in both areas will undoubtedly help to make FCs both more environmental-friendly and cost-efficient.

1. Introduction

Rapid population growth and advancements in civilization have resulted in a rapidly growing demand for energy sources that are mainly dependent on fossil fuels. Fossil fuels pose many disadvantages. Not only are their prices unstable and erratically fluctuating, but they are also a limited resource with severe environmental impacts (EIs), which result in global warming and other more severe health issues (Asongu et al., 2020; Ike et al., 2020). Renewable energy sources, such as: solar energy (Wilberforce et al., 2019a), wind energy (Nazir et al., 2019), geothermal energy (Wilberforce et al., 2019a), tidal and wave energy (Soudan, 2019) and biomass energy (Inayat et al., 2019; Nassef et al., 2019b) are considered the best potential candidates to replace fossil fuels for energy supply in the near future.

Conventional energy conversion devices, such as internal combustion engines and thermodynamic cycles, are commonly used for the extraction and conversion of chemical energy contained in different fuels (Ge et al., 2016). During this process, huge amounts of greenhouse gases (GHGs) are produced, resulting in a detrimental effect on the environment (Elsaid et al., 2020a; Turconi et al., 2013). To limit the detrimental effects of these fossil fuel-based devices, renewable energy-based fuels, such as biodiesel and bioethanol, have been proposed to decrease these major EIs (Mofijur et al., 2016). Though the potential of these strategies minimizing EIs is undeniable, there is still a considerable amount of GHGs produced. Full reliance on renewable energy sources requires the development of efficient energy conversion and storage devices, to further reduce or eliminate EIs.

Fuel cells (FCs) are energy conversion devices that convert the chemical energy of different fuels (including those from various renewable energy sources) directly into electrical energy at a much higher efficiency, both theoretically and practically, as compared to conventional power generation sources (Sayed et al., 2019). These FCs are not only efficient devices, but are also: small in size, silent, and have much lower EIs compared to other conventional devices or technologies specifically during the operational phase (Abdelkareem et al., 2019a). For example, a proton exchange membrane FC (PEMFC) fueled by hydrogen produces water as a byproduct, with a small release of waste heat. This is very promising compared to the huge gaseous emissions, waste heat, and cooling demand in conventional power generation systems (Sayed et al., 2020). FCs have several other advantages. For example, they cover a wide range of applications ranging from a few watts to several gigawatts (Wang et al., 2011). Microbial fuel cells are another class of FC that utilize microbes, hence, more environmental-friendly and eco-sound with a wide range of applications, ranging from power generation to desalination. (Olabi et al., 2020; Sayed et al., 2020; Sayed and Abdelkareem, 2013).

Several reviews have been carried out to evaluate the performance of different types of FCs, the catalysts used, and the operational conditions (Tiwari et al., 2013). However, to the best of the authors' knowledge, no previous reports have summarized or compiled the environmental impacts of the different types of FCs in one report. Although some works have partially addressed some of the operational and environmental aspects of specific FCs, they did not address the collective aspects of FCs, or compared them to conventional systems.

This review summarizes the different environmental aspects of FCs. The review starts with an explanation for conventional power generation and its environmental impacts. This explanation also serves as an aid in the comparison of the performance of FCs compared to conventional power systems. The review then provides some background information on the different types of FCs, and their operational aspects. This necessary introduction helps better understand the environmental aspects discussed in detail afterward. The review then thoroughly discusses and analyzes the environmental impacts of different FC types, followed by an inter-comparison among these FCs, to show the relative impacts of each FC type in comparison to both the other FC types and conventional systems. The discussion adopts the life cycle assessment (LCA) as much as possible, as it is an effective tool in assessing both operational and manufacturing phases. The review also discusses environmental aspects, which include both environmental benefits and negative impacts. Benefits include lower GHG emissions and fuel consumption due to higher efficiency, with other advantages mentioned when compared to conventional systems. Negative impacts, such as higher GHG emissions, more utilized resources, and other significant impacts, are discussed and compared when discussing different FC types.

2. Environmental impacts of conventional power generation systems

A wide variety of energy resources are readily available on the planet and can be classified broadly into energy stored in fuels and energy associated with renewable actions. The chemical energy stored in fuel has been the primary source of energy since the early era of the industrial revolution. Fig. 1 below shows the primary energy supply by the energy source in million-ton oil equivalent (Mtoe) over the last three decades. The figure shows that the energy supply is currently dominated by conventional energy sources, with fossil fuel accounting for about 81% (IEA International Energy Agency, 2020). The current power generation of about 25 PWh is sourced from different fuels; these include: 37.7% for coal, 22.5% for natural gas (NG), 16.1% for hydropower, 10.1% for nuclear power, 8.5% for renewables, 3.2% for oil, and 1.8% for biofuels (IEA International Energy Agency, 2020). Hydrogen fuel is a prime candidate to replace fossil fuels because of the many inherent advantages, such as zero carbon footprints. It can be obtained from a variety of renewable energy resources and waste materials (Ellabban et al., 2014). Biofuel is another leading alternative, which is a carbon-neutral fuel that is derived from biomass (Kamil et al., 2020). The relatively high energy content of biomass can be converted into other forms by a wide range of processes, such as: thermal, chemical, electrochemical, photochemical, and biochemical (Kamil et al., 2019).

The chemical energy stored in fuels can be released as thermal energy by an exothermic combustion reaction, and ultimately, altered into useful work by a heat engine (HE) or thermodynamic cycle (Sheykhi et al., 2019). At the onset, it is inevitable that any fuel conversion system has adverse side effects, particularly on the environment (Oetari et al., 2019). Internal combustion engines, which are the driver of the transportation means, are the most significant contributors, followed by industry and power plants (Lion et al., 2020). However, it

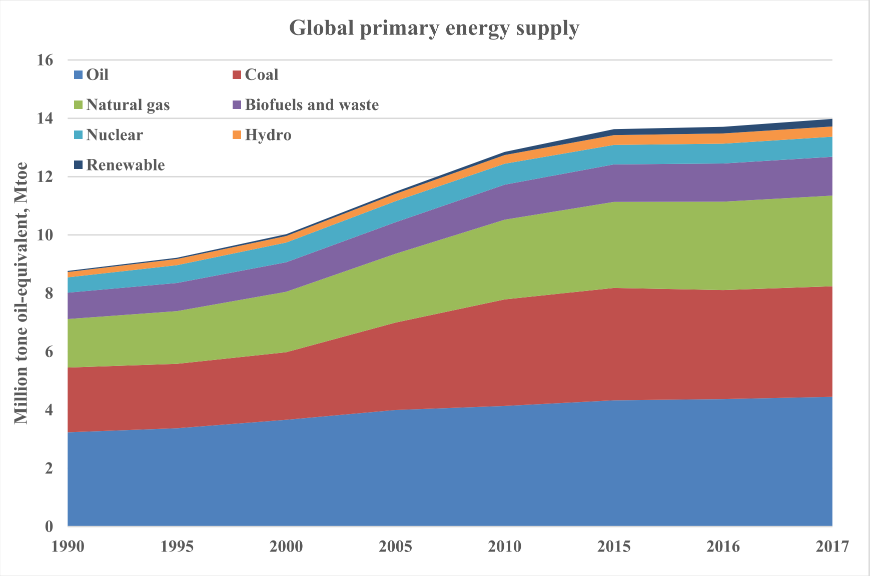

Fig. 1. Global primary energy supply by energy source [Source: International Energy Agency IEA, 2020] (IEA International Energy Agency, 2020).

has also been established that the benefits of these pivotal systems outweigh their adverse impacts (Sun and Cui, 2018). Therefore, conservation has been identified as the sole commendable way of addressing the adverse environmental effects of fuel conversion systems by means of more efficient utilization of energy resources (fuels) and using high-performance fuel conversion systems (Li and Xu, 2020).

2.1. Environmental impacts of conventional power generation

Power generation plants can cause a variety of detrimental impacts on the environment. These include greenhouse gas (GHGs) emissions, such as carbon dioxide CO_2, volatile organic compounds (VOCs), sulfur oxides SOx, nitrogen oxides NOx, and carbon monoxide CO. In addition, they

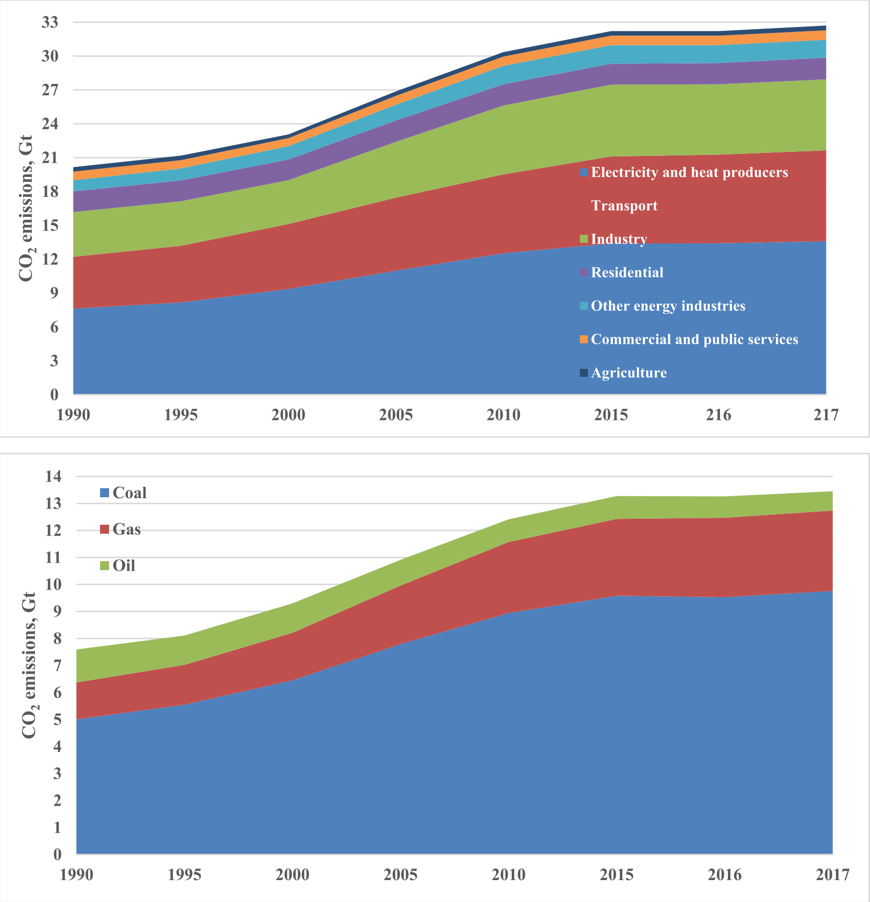

Fig. 2. Global CO_2 emissions per sector (top), and per fuel for electricity generation (bottom) [Source: International Energy Agency IEA, 2020](IEA International Energy Agency, 2020).

Table 1
Approximate greenhouse gases GHGs emissions for power generation according to fuel type.

Fuel	CO_2-eq, kg/MWh	NO_x, kg/MWh	SO_x, kg/MWh
Coal	660–1050	0.3–3.9	0.03–6.7
Oil	530–900	0.5–1.5	0.85–8
Natural Gas	380–1000	0.2–3.8	0.01–0.32

can expel particulate matters (PM) and other aerosols, thus can cause ecosystem degradation due to the contamination of air and water (Elsaid et al., 2020a, 2020c; Oetari et al., 2019). The power plant utilizes a huge amount of water for cooling purposes, treated specifically for this purpose by the addition of a wide range of chemicals. These chemicals can be toxic to both aquatic life and water bodies (Pan et al., 2018).

2.1.1. Gaseous emissions

The gaseous emissions ejected by power plants can be classified into two groups: GHGs and aerosols. GHGs are compounds generated in the mundane atmosphere by natural and anthropogenic activities, which cause the greenhouse effect (Dones and Heck, 2004). On the other hand, aerosols (such as VOC, PM, soot) are accumulated in the upper layers of the atmosphere, reflecting a portion from the incident solar radiation into space. This causes a decrease in the Earth's surface temperature, which is called the "Albedo effect" (Zhou et al., 2020). The equilibrium between the greenhouse and albedo effects plays an essential role in the Earth's climatic conditions.

Fig. 2 shows global GHGs emissions, which are of a very similar trends to those shown in Fig. 1 for primary energy supply, showing their interdependence (International Energy Agency, 2020). The figure shows that most of the global CO_2 emissions are due to: heat and power 41.6%, transportation 24.6%, and industry 19.2%. The figure also shows that 72.5% of the global CO_2 emissions for heat and power are due to coal, despite it is only accounting for 31.8% of the global power supply. Sulfur oxides (SO_x) are another primary pollutant, with coal being responsible for about 70% of total SO_2 emissions, which cause respiratory difficulties and harm to the environment, by the occurrence of acidic rains (Wang et al., 2018). Nitrogen oxides (NO_x) are other hazardous pollutants, which cause respiratory problems and also lead to acidic rains (Shcheklein and Dubinin, 2020). The more significant detrimental damage to the environment from SO_x and NO_x emissions is the acidification effect, which leads to an acid rain effect. The harmful effects of the acidic rain can be 1) deterioration in agronomic crops and forests, 2) corrosion to the exposed structures, 3) damage to the aquatic life and marine creatures, and 4) elevated acidity in rivers, lakes, and groundwater (US-EPA, 2020).

Table 1 below shows approximate values for gaseous emissions for different fuels (Turconi et al., 2013). The table shows a range for each fuel, as the emissions depend on the combustion technology used and their fuel efficiency, as well as the specific chemical composition of the fuel. It is clear that NG has the lowest emissions. Thus, its use for power generation has recently expanded from a share of about 14% in 1990 to 22.5% in 2017,- increasing from 1.75 PWh to 5.9 PWh, respectively (IEA International Energy Agency, 2020).

2.1.2. Cooling water

Water is an essential component to almost all industrial processes, including power generation. Process water is a necessary requirement for fuel extraction, i.e., coal, oil, and gas, as well as processing and purification (Elsaid et al., 2020b). Furthermore, a considerable amount is required as a heat transfer fluid for thermoelectric power generation. It has been estimated that almost 40% of the total water withdrawal in the US was for power generation, amounting to 200 billion cubic meters (BCM) (Kenny et al., 2009). The use of water for cooling purposes requires different treatments to make it suitable for the purpose it is needed for, such as filtration or chemical additions. The chemicals added are usually biocides and antiscalants to control biofouling and scaling on heat transfer surfaces, as well as corrosion inhibitors. The EIs of such treatment processes can be summarized as follows (Elsaid et al., 2020c; Peer and Sanders, 2018; Rahmani, 2017; Tidwell et al., 2014):

- ➢ Chemical impacts
  - o Formation of disinfection byproducts (DBPs), which are toxic to the aquatic environment.
  - o Introduces foreign materials to the marine environment.
  - o Discoloration of water due to the use of iron salts, which reduce light penetration depth.
  - o Increased concentration of heavy metals, which can be toxic to aquatic life.

- ➢ Physical impacts: Increased water turbidity due to discharge of suspended solids and metal oxides, which reduce light penetration depth.
- ➢ Biological impacts: Mortality and changes in the metabolic and growth rates of marine organisms.

3. Fuel cells

A fuel cell (FC) is simply a device that transforms fuels' chemical energy into power directly, without any intermediate energy forms, via a reaction between fuel and oxygen O_2 (Abdelkareem et al., 2020b). In FCs, the fuel and oxygen react via an electrochemical reaction, producing electrical energy, CO_2, H_2O, and some waste heat, which is much less than that in conventional combustion (Schäfer et al., 2006). An FC is made up of two electrodes, anode and cathode. A fuel passes through the anode bipolar plates into the FC while oxygen flows at the cathode (Abdelkareem et al., 2020c; Barakat et al., 2013). Fig. 3 shows a typical illustration of an FC.

3.1. Main features of fuel cells

FCs are differentiated according to the electrolyte used, the operating conditions, the required load, the available fuel, the starting time, and the application it used for. There are many types of FC electrolytes, in both solid or liquid states. These electrolytes function at either high or low temperatures. FCs that operate at low temperature conditions require a catalyst to speed up the chemical reaction (Abdelkareem et al., 2019a). The ideally used catalyst for low-temperature FCs is platinum Pt, which contributes significantly to the cost. High-temperature FCs do not require Pt to speed up the reaction. A wide range of fuels can be used for FCs, including gases such as hydrogen, and liquids such as methanol and ethanol (Abdelkareem et al., 2020b; Ghouri et al., 2020). The electrochemical reactivity of hydrogen is always higher compared to that of other fuels (Wilberforce et al., 2019b).

The fuel flows to the anode, while O_2 flows to the cathode. Electrons flow only when the anode, membrane, and cathode are connected. The movement of electrons via the electrodes lead to only heat energy being produced (Alami et al., 2020). This movement of electrons can only occur when the external circuit is connected, i.e., closed-circuit. The movement of ions via a membrane allows for the flow of charge, and has a different relationship to the conductivity of the membrane (Mohamed et al., 2017). The electrolyte is designed to allow only the flow of ions but not electrons, and is designed to serve as a barrier to prevent the reactant from mixing up while also mechanically supporting the electrodes (Tsujiguchi et al., 2010).

The membrane of an FC determines the operational characteristics of the cell, primarily temperature. FCs, whose operating temperature range exceeds 600 °C are considered as high-temperature FCs, which allow light hydrocarbon fuels to undergo reforming (Abdelkareem et al., 2019b). The rate of reaction in high-temperature FCs is readily high; meaning there is less need for a catalyst. Solid oxide fuel cells

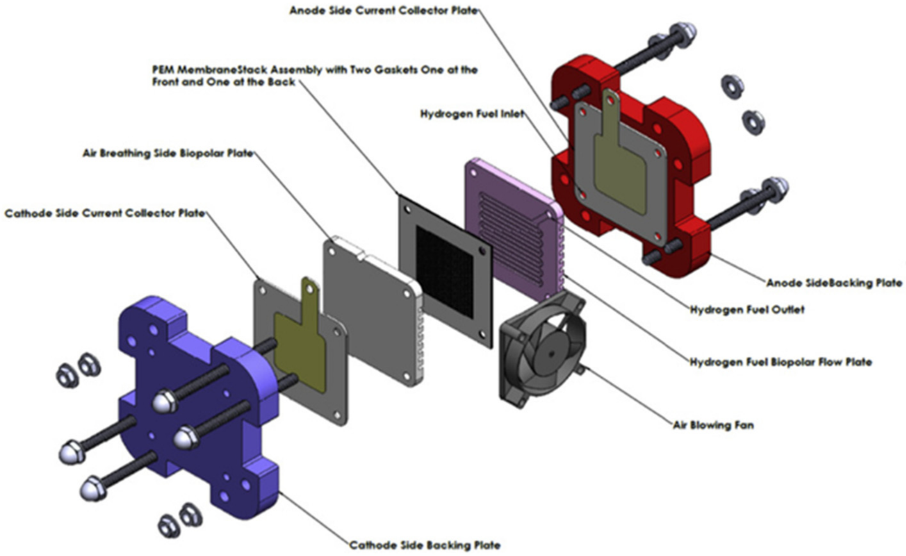

Fig. 3. Exploded view of proton exchange membrane fuel cell (PEMFC).

(SOFC) and molten carbonate fuel cells (MCFC) are common types of high-temperature FCs. FCs operating at temperatures below 250 °C are classed as low-temperature FCs (Baroutaji et al., 2019). These FCs cannot undergo fuel reforming, meaning the fuel has to be obtained externally. The different benefits associated with the use of FCs for power generation can be summarized as follows (Stambouli, 2011):

- ➢ Energy security: FC usually runs by utilizing locally available and abundant fuels as one of the criteria for FC selection, hence reducing oil importation and consumption.
- ➢ Reliability: As FC is characterized by high availability and operability, along with minimal degradation of <0.1%/1000 h, due to the lower operating temperature, and absence of moving parts.
- ➢ Low operating cost: Although of the relatively high capital cost of FC, this is compensated by the lower operating cost.
- ➢ Steady power supply: unlike diesel engines, backup generators, or uninterruptable power supply (UPS), FC is characterized by the steady current generation.
- ➢ The broad range of fuels: FC can be operated by many types of fuels (organic/inorganic, gas/liquid, …etc.) depending on its availability and local cost, in contrast to fossil fuels, which are usually imported.
- ➢ Eco-friendly: FC is environmentally friendly technology, the use of FC reduces or eliminates the emission of GHGs, especially in case of using H_2 as fuel or other bio-based fuels.
- ➢ Quit operations: FC operation is noiseless, enough to be installed indoors; with no need for sound-proofing or hearing-protection.
- ➢ High-efficiency: The energy conversion efficiency can reach up to 90% (with 30–40% heat recovery), which is much higher than that of diesel engines and gas turbines.
- ➢ Scalability and applicability: FCs are available in a wide range of power ratings from few watts, up to 2 MW. Also, it fits well for service in both stationary and portable applications.

3.2. Common types of fuel cells

3.2.1. Proton exchange membrane fuel cell

A proton exchange membrane fuel cell (PEMFC) is made up of an electrolyte that allows the flow of protons, i.e., H^+ from the anode to the cathode. This electrolyte or membrane comes as a solid polymer, with an operating temperature between 70 and 90 °C, and 1–2 bar pressure. The typical cell stack voltage for this type is 1.1 V for a single-cell stack, and increases proportionately with the number of cells in the cell stack (Ijaodola et al., 2018). Eqs. (1)–(3) summarize the electrochemical reactions in the hydrogen FC as a typical PEMFC.

$$\text{Anode}: H_{2(g)} \rightarrow 2H^+ + 2e^- \tag{1}$$

$$\text{Cathode}: \frac{1}{2}O_{2(g)} + 2H^+ + 2e^- \rightarrow H_2O \tag{2}$$

$$\text{Overall}: \frac{1}{2}O_{2(g)} + H_{2(g)} \rightarrow H_2O + electricity + heat \tag{3}$$

The anode and cathode are made up of bipolar plates (usually graphite), with flow channels that allow the flow of reactants into the FC. Therefore, the design of the bipolar plate geometry has a significant effect on the overall performance. It also determines the heat and water management in the cell. Some FCs have cooling plates positioned between the various cells in the stack to absorb excess heat generated in the FC (Mohammed et al., 2019). Optimization of the FC is crucial due to the cost of fuel. This can only be achieved via the optimization of various cell components. The designs of FCs vary depending on the required output voltage (Wang et al., 2011). The final design must be easy to manufacture, as well as cheap, to be able to compete with other energy storage or conversion devices (Ijaodola et al., 2018).

The electrocatalyst layer is critical as it contributes to the overall cost of the fuel cell. A PEMFC usually has Pt as a catalyst to speed up the chemical reaction. These catalysts are bound by a small amount of Nafion (Sulfonated Polytetrafluoroethylene) (Fathy et al., 2020). In the FC, electrons move from the anode via an externally connected circuit to reach the cathode. Simultaneously, the protons move via the electrolyte to reach the cathode. The electrons, protons, and oxygen eventually reach the cathode where reduction then occurs. Quick start-up, good mechanical structure, a wide range of power output from mW to kW scale, and easy scale-up are some of the advantages of these types of FC (Das et al., 2017). PEMFCs have some disadvantages, such as slow oxygen reduction kinetics, poor heat and water management, CO poisoning, and the need for high purity hydrogen as a fuel (Mohammed et al., 2019). Regardless, PEMFC is a promising candidate that can replace the gasoline engines in vehicle and aviation applications (Baroutaji et al., 2019).

3.2.2. Alkaline fuel cells (AFC)

The alkaline fuel cell (AFC) uses an alkaline-based solution such as NaOH or KOH as an electrolyte, and operates at low temperatures between 23–70 °C. An AFC is an anion exchange membrane fuel cell (AEMFC), unlike PEMFCs, and is the oldest type of FC (Alhassan and Umar Garba, 2006). KOH is the most commonly used electrolyte because of its high conductivity, as opposed to other alkaline solutions (Merle et al., 2011). The main benefits of AFCs are high efficiency, easier heat management, quick start-up, higher activity, lower cost, and fast kinetics of oxygen reduction (Ghouri et al., 2017). In AFCs, there is a possibility of replacing platinum Pt with nickel Ni or its alloys with other transition metals at the anode (Eisa et al., 2020). Due to having a higher activity than PEMFCs, AFCs can resist CO poisoning, but to a certain extent. A major disadvantage of AFCs is their intolerance to CO_2, which is a major reaction product with hydrocarbon fuels. This intolerance occurs as the CO_2 consumes the electrolyte, forming carbonate salt. The carbonate salt causes the ionic conductivity of the electrolyte to drop, and therefore, reduces the overall performance and efficiency. (Banjong et al., 2019). The electrochemical reactions of AFC can be simplified as follows, with an overall reaction similar to that of PEMFC:

$$\text{Anode}: H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \tag{4}$$

$$\text{Cathode}: H_2O + 2e^- + \frac{1}{2}O_2 \rightarrow 2OH^- \tag{5}$$

3.2.3. Direct alcohol fuel cell (DAFC)

Direct alcohol fuel cells (DAFCs) also operate at low-temperatures, usually <100 °C, and are mainly used for portable power applications below 250 W (Fadzillah et al., 2019; Feng et al., 2013). A wide range of alcohols are used as fuels, such as methanol and ethanol in direct methanol/ethanol fuel cells DMFC and DEFC (Abdelkareem et al., 2020a; Ghouri et al., 2020). The catalyst layer of DAFC is ideally made of Pt and ruthenium Ru, as the presence of Ru protects the Pt from CO poisoning (Ito et al., 2013). DAFCs have numerous advantages, such as: low start-up time, utilization of waste resources as a source of fuels (methanol or ethanol that could be obtained from wastes), high energy density, fuel is easy to use and to transport, and finally cost-effective (Abdelkareem et al., 2007). The main problem faced in DAFCs is the fuel crossover as fuel moves from the anode to the cathode due to concentration difference, causing mixed potential, which in turn decreases the overall performance and poisons the cathode (Abdelkareem and Nakagawa, 2006). Accordingly, a lower alcohol concentration is used, which lowers the energy density. In addition, alcohols are highly flammable and might pose some toxicity, like in the case of methanol. Furthermore, the catalysts used in DAFCs are based on Pt and Ru, which are precious and costly metals. The main electrochemical reactions that take place in DAFC are:

$$\text{Anode}: CH_3OH + H_2O + \rightarrow 6H^+ + 6e^- + CO_2 \tag{6}$$

$$\text{Cathode}: 6H^+ + 6e^- + \frac{3}{2}O_2 \rightarrow 3H_2O \tag{7}$$

$$\text{Overall reaction}: CH_3OH + \frac{3}{2}O_2 \rightarrow 2H_2O + CO_2 + electricity + heat \tag{8}$$

3.2.4. Phosphoric acid fuel cells (PAFC)

Phosphoric acid fuel cell (PAFC) is an intermediate-temperature FC, as it operates between 150 and 220 °C, with optimum cell temperature around 180 °C. The electrolyte of the cell is phosphoric acid H_3PO_4, hence the name PAFCs. PAFC is the commonly used FC for commercial purposes, with a higher maturity level compared to other FCs (Eapen et al., 2016). PAFCs have many advantages, such as higher tolerance to CO poisoning, and lower Pt catalyst demand compared to PEMFCs due to the higher activity, thereby reducing cost. Furthermore, they allow for the utilization of waste heat. Since PAFCs operate at higher temperatures than PEMFCs, it is a very attractive option in combined heat and power (CHP) applications (Ito, 2017). The disadvantages of PAFCs are their high cost due to the use of the Pt catalyst, long start-up time, and lower ionic conductivity. Since it is an intermediate-temperature FC, there is a limited range of cell construction material, and chosen materials should have similar thermal expansion so as not to crack the membrane electrode assembly (MEA) (Hart and Hörmandinger, 1998). The electrochemical reactions in PAFCs are similar to those of PEMFCs.

3.2.5. Molten carbonate fuel cell (MCFC)

Molten Carbonate fuel cell (MCFC) is classified as high-temperature FC, as it operates between 550 and 700 °C. The electrolyte/membrane for these types of FCs is made up of molten carbonate salt, mainly lithium and potassium carbonates. Nickel-based powders are used for both the anode and the cathode of the MCFC (Wu et al., 2016). There are a variety of fuels that can be used for MCFCs, including natural gas with oxygen or carbon dioxide as oxidants (Rosen et al., 2020). MCFCs also pose lots of advantages, such as high efficiency. They can also utilize CO_2 as an oxidant, meaning they can be used for carbon capture and storage (CCS) (Rosen et al., 2020). Noble metals are not required for MCFCs because the cell operates at a higher temperature, which makes MCFCs more cost-efficient (Kulkarni and Giddey, 2012). The main limitation of MCFCs is corrosion due to their high operating temperatures, long start-up time, limited options for materials of construction, and the complex handling of the molten carbonate liquid. The electrochemical reactions of MCFC can be summarized as follow, with an overall reaction similar to that of PEMFC:

$$\text{Anode}: CO_3^{2-} + H_2 \rightarrow H_2O + 2e^- + CO_2 \tag{9}$$

$$\text{Cathode}: CO_2 + 2e^- + \frac{1}{2}O_2 \rightarrow CO_3^{2-} \tag{10}$$

3.2.6. Solid oxide fuel cell (SOFC)

Solid oxide fuel cell (SOFC) is a common type of high-temperature FC that operates between 600 and 1100 °C (Damo et al., 2019). The solid electrolyte for SOFC can be made up of Yttrium stabilized zirconia (YSZ). There are specific requirements that must be considered for a material to be used as the cathode in SOFC, such as thermal stability, stable ionic conductivity and catalytic activity (Abdalla et al., 2018). One of the materials that fits all of these characteristics is Lanthanum Strontium Manganite (LSM) (La, Sr)MnO_3. It is, therefore, often used as the cathode for SOFCs; the anode can also be made up of nickel-based YSZ, which speeds up the hydrogen oxidation reaction (Nassef et al., 2019a).

The merits of SOFC are enormous, hence their usage in many applications. The efficiency of these types of FCs tends to be high, and the excess heat produced during the reaction can be used for cogeneration (Gandiglio et al., 2019). These FCs are functional even in the absence of noble metals, thereby making them affordable, with a long operational time up to 80,000 h (Stambouli and Traversa, 2002). Unlike other types of FCs, SOFCs allows different types of fuels to be used. Some of these fuels include methanol and biogas (Andersson et al., 2013). The main disadvanatge with SOFC is due to the high cell temperature, as only a limited selection of materials can be thermally, catalytically, and conductively stable at such high temperatures. The electrochemical reactions of SOFC are summarized as follows, with an overall reaction similar to that of PEMFC:

$$\text{Anode}: O^{2-} + H_2 \rightarrow H_2O + 2e^- \tag{11}$$

$$\text{Cathode}: 2e^- + \frac{1}{2}O_2 \rightarrow O^{2-} \tag{12}$$

The interest in FCs as a promising high-efficiency direct energy conversion tool has attracted many research works, thereby developing a wide range of FC types and combinations. Given such a wide range of the different advantages and disadvantages of different FCs, it is imperative to compare the different aspects of FCs, emphasizing on their advantages and disadvantages. Table 2 below summarizes the various points of different FCs, explaining their various advantages and disadvantages.

4. Environmental aspects of fuel cells

As discussed in the previous sections, an FC is simply a device or a tool that can convert the chemical potential or energy directly into electrical potential or energy, i.e., electricity. In this section, the different environmental aspects, i.e., benefits and impacts of utilizing FC for power generation, are discussed. The advantages and disadvantages of using FCs as a power source to drive vehicles are also discussed, and both are compared to those of conventional power generation and vehicles. The discussion is arranged according to the most common types of FCs currently in application. The main environmental aspects to be considered are associated with gaseous emissions of GHGs, as they are a common feature in both FCs and conventional power generation i.e. both utilize fuels to extract energy (Malinauskaite et al., 2019). The increase in CO_2 concentration in the atmosphere has been directly related to global warming. Along with other GHGs, NO_x has direct impacts on biota through the formation of ozone, which is a potent and microbic toxin (Jouhara et al., 2018). SO_x and NO_x damage vegetation and fauna, resulting in reduced photosynthesis, and acidic rains which damage plants and buildings, and cause severe implications for human health (Seip et al., 1991).

This discussion compares the life cycle assessment (LCA) results obtained for different FCs and conventional systems as a tool to explain the different environmental aspects of each system. The main advantage of this system is that LCAs consider the manufacturing, operation, and disposal phases of the product, i.e., the complete life cycle. However, different reference works will have a different basis, system definitions, and assumptions. Despite this, most of the reported results are usually normalized to unit power production, i.e., kWhe or MJ, which makes the comparison inarguably valid.

4.1. Environmental aspects of PEMFC

Proton exchange membrane fuel cell PEMFC is one of the oldest and most studied types of FCs, which utilize hydrogen or alcohols such as methanol and ethanol as fuel (Eisa et al., 2020; Nakagawa et al., 2011). However, the use of hydrogen fuel in PEMFCs faces many challenges. Firstly, outsourcing the non-naturally occurring hydrogen is an issue. In addition, H_2 poses some hazardous risks, such as the wide flammability range, high explosion potential, instantaneous ignition with invisible flame, high permeation rate, and causes material embrittlement (Barilo et al., 2017; Wurster, 2016). Despite these critical properties, PEMFC is an upcoming technology with many environmental advantages. Relative to other FCs, which produce CO, CO_2, and unburnt fuel, hydrogen has a high conversion to water, as well as no GHGs emissions (Verne and Cedex, 2016).

However, the whole cycle for PEMFC has to be considered in order to assess its EIs fully. The main challenge of PEMFC is to obtain hydrogen fuel, which is not present as a natural resource and has to be produced by industrial processes, mainly from coal or NG, both of which are associated with severe EIs (Stambouli, 2011). The effect of hydrogen production for PEMFC applications is significantly affecting the GHG emissions associated with PEMFC operations. Even PEMFC itself is considered as GHG-free, with low GHG emissions during its manufacturing. Fig. 4 below shows the different emissions associated with hydrogen production from different sources (Granovskii et al., 2006a). Though the emissions associated with conventional hydrogen production from natural gas H2-NG are far less than those for the production of gasoline from crude oil, it is also clear that the utilization of renewable energies as a source of energy for hydrogen production significantly helps in reducing these emissions. Wind and solar energies are very promising technologies for hydrogen production through water electrolysis (Zeng and Zhang, 2010), more specifically, seawater electrolysis (Dresp et al., 2019). The conventional routes for hydrogen production are steam methane reforming (SMR), coal gasification (CG), electrolysis, and thermochemical cycles (Stambouli, 2011). However, recent research and development efforts are focusing on the use of renewable energy to drive seawater electrolysis considering hydrogen as a means of energy storage (Saeedmanesh et al., 2018).

PEMFC has been compared to other conventional (internal combustion engine ICE) and emerging alternatives to power passenger cars. This is being viewed as one of the promising application fields for FC technology (Bauen and Hart, 2000; Hart and Hörmandinger, 1998). The comparative study, as shown in Fig. 5, clarifies the significant environmental benefits of utilizing FCs in general over other conventional and emerging solutions, such as batteries. This is evident from the relative reduction of gaseous emissions relative to the standard petrol-ICE car, which is currently the market standard.

Staffell and Ingram concluded that PEMFCs and AFCs have much lower cumulative impacts in manufacturing for a single FC stack than for 10-years power stacks relative to PAFC and SOFC types (Staffell and Ingram, 2010). Pehnt performed a detailed analysis of a 75 kW_{el} mobile and 275 kW_{el} stationary Polymer electrolyte fuel cell (PEFC),- a type of PEMFC, for power generation and vehicle application. Different power mixes were utilized, and the recycle option for noble metals was analyzed as well (Pehnt, 2001). The analysis showed that the mobile stack has much less non-renewable primary energy, global emissions, local emissions, global warming, and acidification relative to the stationary stack for each kWh_{el}. The analysis was expanded to compare the performance of fuel cars using hydrogen and methanol sourced from NG as a fuel. This analysis showed that hydrogen had less EIs of non-renewable primary energy, global emissions, local emissions, global warming, and acidification relative to methanol for each km driven. The analysis also showed that most of the EIs were due to the operation phase due to fuel synthesis.

Sørensen performed a total LCA for PEMFC car, using H_2 sourced from NG and wind energy in comparison to diesel and gasoline car types, (Sørensen, 2004). The results showed lower energy requirements of 1.74 and 1.6 MJ/km for the PEMFC and diesel car, compared to 3.54 for the gasoline car, with similar results obtained for the acidification impact. However, the PEMFC-wind showed a substantially lower global warming impact of 34 gCO_2-eq/km compared to 97, 120, and 262 gCO_2-eq/km for the diesel, PEMFC-NG, and gasoline car, respectively. Schäfer et al. compared the LCA of fuel cell engine/electric hybrid vehicles, using hydrogen and gasoline as engine fuel, and hydrogen FC (Schäfer et al., 2006). The FC-hybrid vehicles showed substantially lower GHG emissions and energy use per km driven, despite of the higher cost, approximately \$0.25/km, compared to about \$0.19/km for gasoline and diesel vehicles. The authors concluded that the time required for a significant fleet impact could be up to 55 years for FC vehicles with H_2 storage onboard, compared to 35 years for gasoline engine/battery hybrid vehicles. This further highlights the importance of the economic analysis of the technology, which is currently the main barrier preventing the implementation of FCs in a wide range of applications, despite their many advantages and environmental benefits.

Granovskii et al. performed a detailed LCA for hydrogen PEMFCs and gasoline vehicles. The LCA showed that FC vehicles have a 25–30% higher efficiency compared to gasoline vehicles mainly referring to fossil fuel energy consumption and GHG emissions (Granovskii et al., 2006b). The authors also showed that H_2 sourced by the employment of wind energy had the lowest impacts. However, this was very sensitive to energy cost. Wagner et al. obtained similar results, which concluded that an FC car with an electric motor had CO_2 emissions in a range between 55 and 60 g/km when H_2 sourced by wind and solar thermal, compared to 140 and 200 g/km when sourced from wood and NG respectively. They were also lower than those for methanol as

Table 2
Summary of operational aspects, advantages, and disadvantages of most prominent fuel cells.

		PEMFC	AFC	PAFC	DAFC	MCFC	SOFC
Ref.		(Wang et al., 2020)	(McLean et al., 2002)	(Stonehart and Wheeler, 2006)	(Alias et al., 2020)	(Antolini, 2011)	(B. Yang et al., 2020b)
Catalyst layer		Pt	Pt or Ni Alloys	Pt	Pt/Ru (1:1)	Ni or Ni-based Alloys (Transition metals)	
Membrane/electrolyte		Nafion	Alkaline	Phosphoric Acid	Nafion	Molten Carbonate	Yttria Stabilized Zirconia (YSZ)
Fuel			H_2		Methanol, ethanol..	H_2/CO/CH	
Optimum operating temperature		~80 °C	23–70 °C	180 °C	> 60 °C	550–700 °C	700–1000 °C
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 CO_2	• No CO_2 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 • High activity • Supports internal reforming	
Disadvantages		• Slow oxygen kinetics • Heat and water management • CO poisoning • Requires high purity H_2	• Intolerance to CO_2 • Requires pure O_2	• 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 • Cathode dissolution • Long start-up time • Limitation in material selection • Hard to handle liquid electrolyte	
Electrical Efficiency[a]	C	50–70%	60–70%	55%	20–30%	55%	60–65%
	S	30–50%	62%	40% Co-gen: 90%	10–25%	45–55%	55–60%
Power Range		1 W-500 kW	10 W-200 kW	50 kW-1 MW (250 kW Module typical)	100 mW-1 kW	<1 kW-1 MW (250 kW Module Typical)	5 kW-3 MW
Applications		• Backup power • Portable power • Small distributed generation • Transportation	• Submarines • Military • Spacecraft • Backup power	Distributed generation	Electronic devices (Laptops and Phones)	• Auxiliary power • Electric utility • Large distributed generation	
Cost ($/W)		50–100	–	4–4.5	125	–	–

[a] C = Cell, S = system/stack.

fuel sourced from NG and miscanthus with 180 and 70 g/km, respectively (Wagner et al., 2006). Ally and Pryor showed that FC bus transportation systems could achieve a reduction of more than 50% in GHG emissions, primary energy demand, and photochemical ozone creation compared to diesel bus systems, and confirmed the substantial benefits of sourcing H_2 fuel from renewables for a significant reduction in EIs (Ally and Pryor, 2007). Similarly, the environmental relevance of the manufacturing stage of PEMFCs in automotive applications was assessed, showing that PEMFCs, in general, have lower EIs, with respect to energy requirements, global warming, and acidification effects compared to diesel and gasoline ICE (Garraín et al., 2011).

Hussain et al. performed a preliminary LCA comparison between PEMFC and gasoline-powered automobiles, considering both feedstock and fuel (production and transportation). H_2 was used for PEMFC,

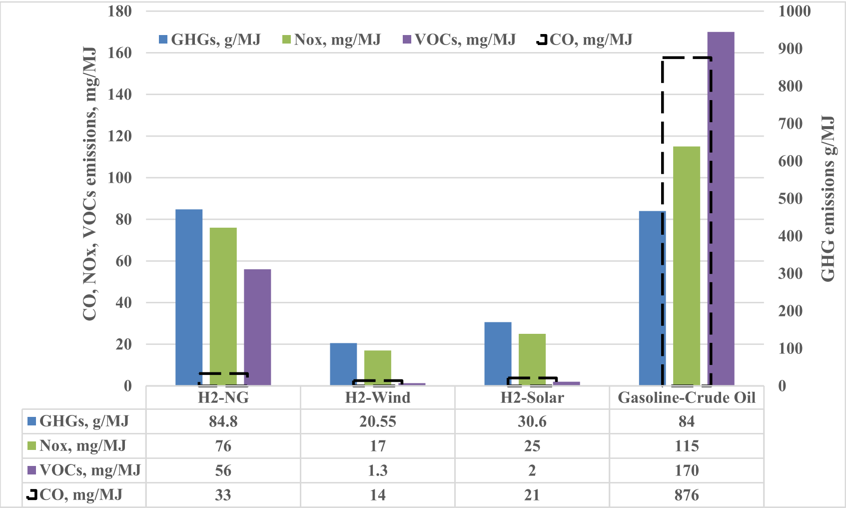

Fig. 4. GHG and gaseous emissions associated with different hydrogen production technologies compared to gasoline (Granovskii et al., 2006a). (H2-NG = hydrogen from natural gas, H2-Wind/Solar = hydrogen from water electrolysis powered by wind/solar energy, respectively).

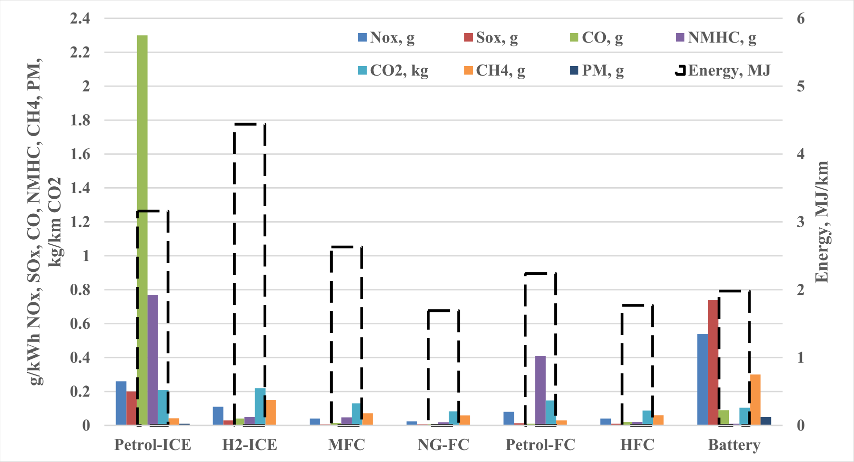

Fig. 5. Gaseous emissions and energy of FCs as compared to other power sources for passenger cars. (ICE = internal combustion engine, MFC/HFC = methanol/hydrogen fuel cell, NG = natural gas, FC = fuel cell) (Bauen and Hart, 2000; Hart and Hörmandinger, 1998).

while gasoline was used for ICE. Vehicles were also thoroughly analyzed, with particular regard to material production, assembly, distribution, use, and disposal. The data is presented in Table 3 below (Hussain et al., 2007). The table shows that most PEMFC energy consumption and GHG emissions are due to feedstock and fuel, rather than FC itself. Conversely, it is the opposite in the case of gasoline ICE vehicles. Ahmadi and Kjeang compared the LCA of H_2 FC passenger vehicles in different Canadian provinces, showing up to a 90% reduction in GHG emissions compared to gasoline-powered vehicles, at almost 40–50% of their lifetime cost (Ahmadi and Kjeang, 2015). Evangelisti et al. performed a comprehensive LCA of the H_2 PEMFC system and compared it to a conventional ICE and battery-electric vehicle (B-EV) for passenger class vehicles (Evangelisti et al., 2017). The analysis showed high EIs from the FC vehicle, mainly related to the FC production processes due to the H_2 and FC stack. However, the FC had both lower global warming and abiotic depletion impacts than the ICE, and is comparable to that of B-EV, with opportunity for a 25% reduction in EIs for the FC vehicle.

Chen et al. performed an LCA for H_2 PEMFC vehicles with careful consideration to detailed components. The LCA concluded that 94% of coal consumption as an energy source is for usage and scarping stages (Chen et al., 2019). 80% of NG usage was for raw material acquisition and usage. The work also revealed that almost 77% of CO_2 emissions were due to the usage stage, followed by 11 and 7% for scraping and raw material acquisitions, respectively. Similar results were obtained for other gaseous emissions, except for NMVOC, which was 99% due to raw material acquisition. Yang et al. compared the LCA for FCs, Electric vehicles EVs, and conventional ICEs (Z. Yang et al., 2020a). The results showed that EVs had the highest energy consumption and GHG emissions, almost 1.4 and 1.2 times those of FCs. The lowest value obtained was that of ICE. The higher EIs of both EV and FC, unlike ICE, were mainly due to battery production for EVs and the fuel cycle for FCs.

Table 3
Energy consumption and GHG emissions for PEMFC and gasoline ICE vehicles (Hussain et al., 2007).

	Energy consumption, GJ		GHG emissions, ton CO_2	
	PEMFC	ICE	PEMFC	ICE
Feedstock	130	70.6	24.75	4
Fuel	640	150	107.25	12.7
Vehicle	276.3	896.7	5.39	64.4
Total	1046.3	1117.3	137.4	81.1

In PEMFCs, a Pt catalyst is commonly used, to significantly reduce different EIs. Pt, being a noble metal, is costly, with complex and energy-extensive mining and extraction processes, hence, it makes up most of the FC cost. As a result, many efforts have been devoted to totally or at least partially replace this costly metal with cheaper, but equally effective, alternatives. Notter et al. showed that the use of multi-wall carbon nanotubes MWCNT as carbon support, enhanced the catalyst activity, resulting in about 27% savings in Pt use. In turn, this resulted in an approximately 20% overall increase in efficiency in the PEMFC for micro-combined heat and power (μ-CHP), showing a substantial reduction in EIs related to PEMFC manufacturing (Notter et al., 2015). Bachmann et al. performed an LCA for a domestic scale FC-μCHP for single-family and multi-family uses. The LCA showed that it can eliminate up to 10% in GHG emissions at 6000 h/year load, and can increase up to 48% at 7000 h/year load, the equivalent of 3.6 t of CO_2-eq emissions (Bachmann et al., 2019).

The previous discussions exploring different literature sources have clearly shown the environmental benefits of using PEMFCs in its different variations. In addition, the studies have shown that the major EIs of FCs are either associated with the manufacturing phase, more specifically for electrocatalyst, or for sourcing the H_2 fuel. These EIs can be reduced either by developing Pt-free or precious metal-free electrocatalysts for PEMFCs. The new developments in Earth-abundant metals and carbonous material used for electrocatalysis of different electrochemical processes seem to be potential candidates to resolve this challenge. The use of renewable resources to drive the process of sourcing H_2 fuel provides a good pathway for further reducing the EIs associated with fuel sourcing for PEMFCs. Collectively, these solutions aim to minimize the EIs associated with PEMFCs, thereby making them more environmental-friendly. However, the economic assessment of the overall process should be carefully considered, so as to make the PEMFC economically attractive.

4.2. Environmental aspects of phosphoric acid fuel cell PAFC

A phosphoric acid fuel cell PAFC is considered as one of the well-developed medium temperature FCs, usually working between 160 and 220 °C (Stambouli, 2011). As with all Hydrogen-based FCs, one of the significant environmental benefits of PAFCs is that they only produce water, without any other reaction products. Furthermore, the waste heat produced can be recovered and utilized as low-grade waste heat with the appropriate waste heat recovery WHR device (Khanmohammadi et al., 2020). The hydrogen used as fuel in PAFCs can be sourced either as hydrogen gas or from hydrocarbons or as hydrogen-containing fuel (Stambouli, 2011).

The groups of Hart and Hormandinger, and Bauen and Hart performed an extensive work, comparing solid polymer fuel cells SPFCs (a type of PEMFC) and PAFC to conventional technologies for different applications (Bauen and Hart, 2000; Hart and Hörmandinger, 1998). Figs. 6 and 7 below show the LCA comparison between these technologies for two main applications, namely transportation via vehicles and buses, and commercial power generation. The figures show clearly that SPFCs and PAFCs are more environmentally friendly, and result in far lower emissions compared to conventional vehicles and power generation technologies, with reductions amounting to 26–97.4% across the different EI categories.

Rooijen performed a comprehensive LCA for the PureCell™ Model 200, which is a 200 kW PAFC with a lifetime of 85,000 h (van Rooijen, 2006). The analysis showed that the operation phase is the major contributor to the different EIs with about 98%, mainly due to NG input and reforming, while only 1.45% being due to the manufacturing phase. Staffell and Ingram compared commercial AFCs and PEMFCs (250 kW Ballard-Alstrom CHP system and 10 kW PlugPower GenSys CHP stack), PAFC (200 kW UTC PureCell CHP system), and SOFC (1 kW Sulzer Hexis system and 24 kW Siemens stack) (Staffell and Ingram, 2010). The results showed that PAFC was next to PEMFC in terms of lower cumulative normalized impacts of manufacturing for ten years of operation, followed by AFC, and lastly, SOFC. The major EIs of PAFC, similarly to PEMFC, are still associated with the materials of construction, as thermally and chemically stable materials are still required to withstand the higher operating temperature and acidity of the phosphoric acid electrolyte. Platinum, fortunately, is not a necessary electrocatalyst for PAFC. However, other precious metals such as nickel are still required, which nonetheless adds to the EIs.

4.3. Environmental aspects of molten carbonate fuel cell MCFC

Molten carbonate fuel cell MCFC is another promising FC technology that operates at high-temperature ranges. MCFC is considered a complex FC among the modern FCs, utilizing molten salts of lithium and potassium carbonate as an electrolyte. CO_2 is produced at the anode and consumed at the cathode, working at temperatures of 650 °C so that it can be paired with gas or steam turbines for additional power generation and utilization of waste heat (Wu et al., 2016). Simplified input/output balances for MCFC are presented in Fig. 8 below (adapted from Mehmeti et al., 2018), showing the fuel input, along with energy and emissions output (Mehmeti et al., 2018). As shown, the MCFC has a thermal efficiency of about 77%, and electrical energy conversion of about 44%, producing about 3340 MWh and 3400 GJ, with waste heat recovery of 948 GJ.

Mehmeti et al. summarized the LCA studies performed on MCFC using different methods and functional power units, again highlighting that LCAs are a very useful tool for investigating all of the comparative resources consumption, emission, and EIs for new technologies, such as MCFC(Mehmeti et al., 2016). Lunghi and Bove performed a detailed LCA study of an MCFC stack. It showed that during the MCFC manufacture phase, most of the EIs such as acidification, global warming, and energy resources resulted mainly from anode and cathode manufacturing, accounting for about 75–95% of the total impacts (Lunghi and Bove, 2003). The study was further extended to a comprehensive LCA study, including the operational phase of MCFC, utilizing landfill-gas (LFG), which contains mainly CH_4 of more than 50% and CO_2, as compared to natural gas (NG) for power generation (Lunghi et al., 2004). The study showed that LFG has a clear advantage over NG, with only 10–15% CO_2-eq and only 40% of SO_2-eq compared to NG, with substantially less negative impacts on human health, ecosystem quality, and resources.

Raugei et al. performed a multi-criteria LCA of 0.5 MW MCFC and compared it to other conventional power generation sources, utilizing NG as fuel (Raugei et al., 2005). The results obtained showed that an MCFC compared to a semi-closed combined cycle gas turbine (SCGT/CC), a combined cycle gas turbine (NGCC) with cogeneration, and a dual steam turbine and gas turbine ST + GT with cogeneration had less EIs. These conclusions further emphasize the more environmental-friendly nature of FCs in general compared to conventional power generation technologies. These results also confirm the crucial impact of the electrocatalyst on the overall EIs of FC, hence why developing a cost-effective and efficient electrocatalyst are essential for expanding the application of FC to different areas.

4.4. Environmental aspects of solid oxide fuel cell SOFC

Solid oxide fuel cell SOFC is considered one of the most promising FC technologies. It has been under development for some time with a high market penetration potential. One of the main advantages of SOFC over others that it is an all-solid-state cell, meaning it can withstand high pressures to obtain high chemical reaction rates (Abdelkareem et al., 2019b). A simplified mass and energy balance for the SOFC is shown in Fig. 9 below (adapted from Lee et al., 2015), based on the use of liquified natural gas (LNG) as fuel, to have a better understanding of the basic

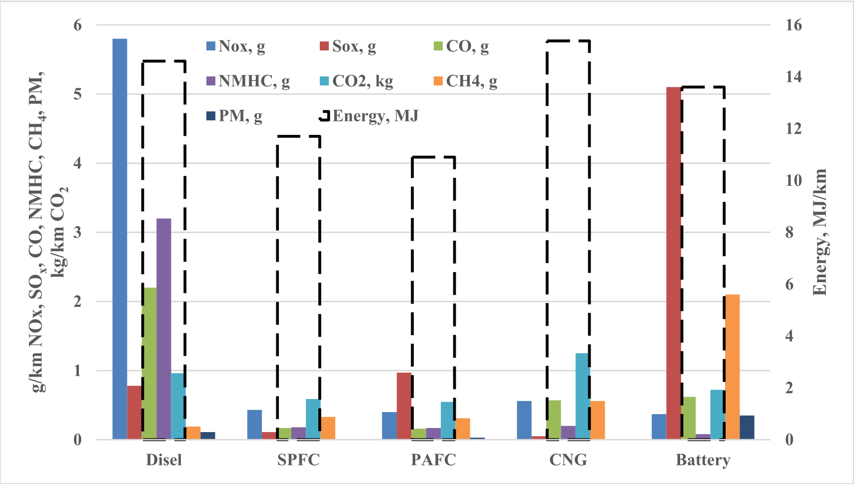

Fig. 6. The gaseous emissions and energy of FC and batteries relative to conventional diesel bus technology. (SPFC = solid polymer fuel cell, PAFC = phosphoric acid fuel cell, CNG = compressed natural gas) (Bauen and Hart, 2000; Hart and Hörmandinger, 1998).

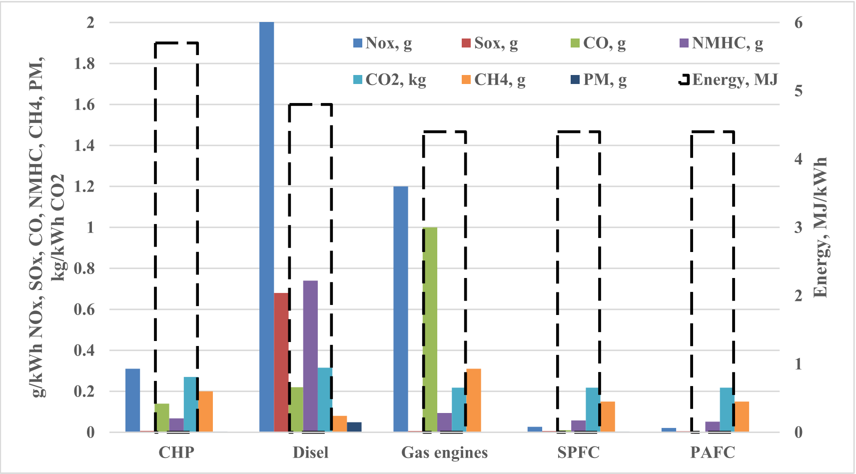

Fig. 7. The gaseous emissions and energy of FC and engines relative to large commercial combined heat/power (CHP = conventional heat/power, SPFC = solid polymer fuel cell, PAFC = phosphoric acid fuel cell) (Bauen and Hart, 2000; Hart and Hörmandinger, 1998).

principles of SOFC operation (Lee et al., 2015). P. Zapp previously tried to perform an environmental analysis of SOFC in comparison to a 10 MW gas turbine and reported that there is a lack of data, which should be obtained upon expanding the work on SOFC (Zapp, 1996). Stambouli and Traversa later made an overview of SOFC as an efficient and environmentally clean energy source (Stambouli and Traversa, 2002). Seip et al. indicated that for a 200 MW power plant at 7000 h/year, SOFC has a lower annual fuel consumption of 84^*10^9 MJ, compared to 126^*10^9 and 252^*10^9 MJ for NG and coal respectively, which is mainly attributed to the higher efficiency of SOFC (Seip et al., 1991). SOFC has proven to be environmentally friendly when compared to other power generation technologies, with far less impacts on the environment (Damo et al., 2019).

The presiding environmental aspect of SOFC is the reduced air pollution, through both a reduction in CO_2 emissions and the elimination of CO, NO_X, SO_x, PM, and organic compounds. This was firstly confirmed by the work of Seip et al. (Seip et al., 1991), and later by the works of Hart and Hörmandinger (Bauen and Hart, 2000; Hart and

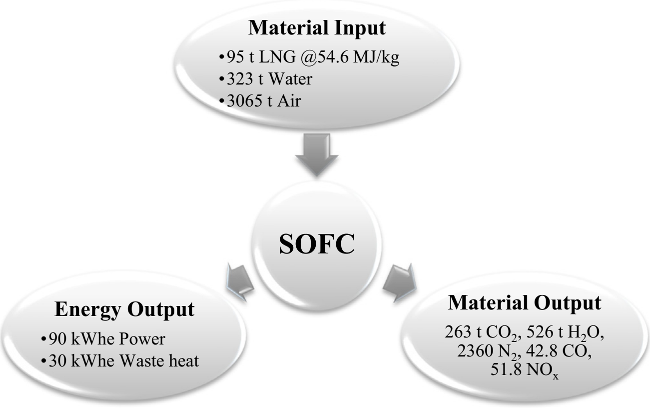

Fig. 9. Simplified material and energy balances for SOFC operation (Basis 1 year of operation) (Lee et al., 2015).

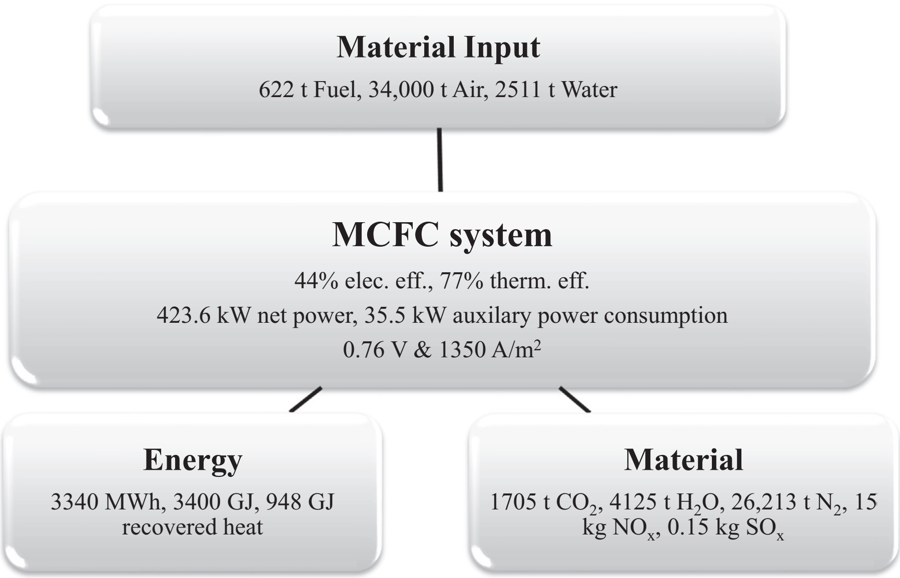

Fig. 8. Simplified material and energy balances for MCFC operation (Basis 1 year of operation) (Mehmeti et al., 2018).

Hörmandinger, 1998), Stambouli and Traversa (2002), and more recently, has also been confirmed by Stambouli (2011). Casas et al. showed that the integration of SOFC in the sugar-ethanol industry for power generation, resulted in a reduction of about 52–55% in GHG emissions, 60–64% non-renewable resource utilization, and a higher renewability index of 0.93, and an exergy efficiency of 38% (Casas et al., 2011).

Table 4 below shows the emissions associated with SOFC operations compared to those of fossil fuels, from two different studies. The table shows that generally, SOFC has much lower GHG emissions compared to fossil fuels in general, and to coal in particular, being the least environmentally friendly fossil fuel. NG was classified as the cleanest fossil fuel. The use of H_2 as fuel resulted in more CO_x emissions than the direct use of NG, which is mainly due to the reforming processes necessary to obtain H_2. However, the use of NG for SOFC resulted in SO_x and NO_x emissions. In another study, SOFC used for power generation resulted in a reduction of about 22% CO_2, 94.1% NO_x, 95.9% SO_x, 97.2% CO, 24% non-methane hydrocarbons NMHC, 22% methane HC (NMHC and HC together are the organic compounds OC), 25% PM, and 22% energy consumption, compared to conventional heat and power generation (Bauen and Hart, 2000; Hart and Hörmandinger, 1998). This has been further affirmed for different hybridizations of SOFC (SOFC/μ-gas turbine, SOFC/gas turbine/steam turbine, and SOFC/steam turbine injection gas), which resulted in 86–89% reduction in annual CO_2 emissions, compared to conventional power generation, as energy efficiency increased from 25-30% for the conventional system to 60–65% for the SOFC hybrid system (Damo et al., 2019).

The environmental impacts of SOFC depend mainly on the type of fuel used, as well as how the fuel has been produced, in order to have an acceptable life cycle assessment for its power production. A recent study by Bicer and Khaled assessed the different EI categories (Bicer and Khalid, 2020). Fig. 10 below shows that H_2 produced using renewable wind energy for water electrolysis, whether for direct use as H_2 fuel, or through ammonia, resulted in lower EIs compared to NG, and NG-derived fuels, such as H_2, ammonia, and methanol. Mortazaei and Rahimi compared SOFCs operating by gas obtained from municipal solid waste, either through the digester, i.e., D-SOFC, or through a gasifier, i.e., G-SOFC (Mortazaei and Rahimi, 2016). It was concluded that D-SOFC has a higher exegetic efficiency of 43.2%, and lower CO_2 emissions of 17.87 t/MWh, compared to 37.7% and 21.3 t CO_2/MWh for G-SOFC, respectively.

Lin et al. integrated an LCA with thermodynamic analysis to explore the utilization of biofuels for sourcing H_2 for SOFC (Lin et al., 2013). Biodiesel from waste cooking oil as feedstock showed the lowest total energy use of 9.6 MJ, while methane from municipal solid waste showed the lowest fossil energy use of 0.37 MJ and total GHG emissions of 0.09 kg-CO_2 eq. Mortazaei and Rahimi expanded their previous work to compare the performance of SOFC for power generation (P), combined heat + power generation (CHP), i.e., cogeneration, and combined cooling + heating + power (CCHP), i.e., trigeneration (Mortazaei and Rahimi, 2016). The results showed that upon increasing the generation level, the energetic efficiency increased, while exegetic efficiency and CO_2 emissions decreased for both D-SOFC and G-SOFC systems. Dual utilization of both electrical and thermal energies, i.e., SOFC-CHP compared to only power SOFC-P resulted in an increase of the energy efficiency by 20–25%, which in turn resulted in a reduction in different EI categories by 10–30%, as shown in Table 5 for the main EI categories (Longo et al., 2019).

Rillo et al. performed a comprehensive LCA for biogas-fed SOFC sourced from sewage treatment (Rillo et al., 2017). The analysis showed that SOFC was very competitive, with substantially lower EIs of about 30–50% when compared to conventional combined heat and power generation. This is mainly due to the higher efficiency of 52%, compared to 27 and 29% for the internal combustion engine and micro gas turbine, respectively. The integration of SOFC with other conventional power generation, such as micro-gas turbine SOFC/μGT, gas turbine and steam turbine SOFC/GT/ST, and steam injector gas turbine SOFC/STIG have shown to further reduce the levelized cost of energy (LCOE) and CO_2 emissions, while increasing the efficiency and power produced (Roshandel et al., 2018). Gandiglio et al. analyzed the LCA of SOFC integrated with a wastewater treatment plant WWTP, to utilize the biogas produced from the anaerobic digester in biological treatment for combined heat and power CHP (Gandiglio et al., 2019). The SOFC was able to produce 174 kW_{el}, almost 25% of plant power demand, and heat of 90 kW_{th} both self-consumed in the plant, along with a 20–30% reduction in five out of seven EI groups, including global warming potential and energy demand.

Lee et al. performed a detailed environmental impact assessment (EIA) of SOFC-based combined heat and power generation systems, using the LCA approach (Lee et al., 2015). The LCA showed that SOFC stack is the main contributor to the associated EIs of SOFC, with about 72% for manufacturing, and 28% for balance-of-plant (BOP). For the SOFC operation, however, the main contributor was fuel input, with about 80–90%. Recent work performed a detailed LCA for a SOFC system fueled by biogas sourced from wood chips, wood pellets, and *Miscanthus* pellets. The study showed that fuel production and transportation contribute about 23–99% to the different EI categories. However, the LCA revealed that biogas-fed SOFC has about 37–95% lower EIs when compared to conventional natural gas, combined heat, and power generation (Moretti et al., 2020).

4.5. Comparative assessment of the environmental aspects of different FCs

From the previous discussions, it is evident that the use of the previously discussed fuel cell types for the indicated applications of power generation or combined heat and power generation, as well as for transportation by powering different vehicles, has resulted in a substantial reduction of EIs. In other words, it has resulted in huge environmental benefits, which are supported by the different life cycle assessment LCA studies. The main environmental benefit of the use of FCs is the significant reduction in emissions to the atmosphere and other EI categories, as studied in LCA. However, it was concluded as well that the fuel cycle, i.e., fuel source and production method, has a substantial effect on these benefits. Questions have been raised on the comparison between the EIs of different types of FC in comparison to one another. Unfortunately, as the current studied FCs systems have different natures, working principles, specifications, fuels, operating conditions, etc., it is difficult to obtain a unified comparison between these systems.

One approach that can be taken is to compare the different FC systems, with regards to their primary function, i.e., power generation, and compare the different EIs. A. Mehmeti et al. compared the different EIs of MCFC, SOFC, and PEMFC compared to μ-Gas turbine μGT, and combined heat and power CHP (Mehmeti et al., 2018). Table 6 below clearly shows that in almost all the EI categories, the FCs are more environmentally friendly and less harmful to the environment compared to conventional power generation systems. FC inter-comparison showed that MCFC and SOFC are relatively more environmentally friendly compared to PEMFC, in most of the categories. This may be due to the impact of the fuel cycle associated with PEMFC when utilizing high purity H_2 as fuel, as well as the use of the precious Pt catalyst. In contrast, MCFC and SOFC can utilize the fuel directly because of the internal reforming capability, without the need for precious metals for the electrodes.

5. Conclusions

Fossil fuels are the primary sources for energy supply worldwide, representing about 80% of the current global energy supply. However, the dependence on fossil fuels has been declining over the years, with more attention given towards utilizing cleaner technologies, such as: hydropower, renewable energies, biomass, waste, and, more importantly, fuel cells. Fuel cells (FCs) are simple devices that directly convert chemical energy into electrical energy, which explains both their higher energy conversion efficiency and minimum energy loss as heat. Although FCs have been widely investigated, with proven eco-environmental benefits

Table 4
Comparison of annual air emissions from fossil fuel and SOFC for power generation.

Air emissions	CO_2, t	SO_x, t	NO_x, t	CO, t	PM, t	OC, t	Ref.
Fossiel fuel	1840	12.74	18.85	12.80	0.23	0.21	Basis 1650 MWh/year (Stambouli, 2011; Stambouli and Traversa, 2002)
SOFC[a]	846.3	–	–	0.03	–	–	
Coal	$1.4*10^6$	5300	1500	–	500	–	Basis 200 MWh/year (Seip et al., 1991)
Natural gas	695	10	325	–	3	–	
SOFC[b]	460	7	0.8	–	2	–	

[a] Fueled by hydrogen.
[b] Fueled by natural gas.

Table 5
Comparision of SOFC-P and SOC-CHP generation per 1 MJ electrical power (Longo et al., 2019).

Environmental impact	SOFC-CHP	SOFC-P
Cumulative energy demand CED, Mj	10.5	12.1
Global warming potential, GWP, g Co_2-Eq	620	709
Ozone depletion OD, μg CFC-11-Eq	77.3	91.1
Particulate matter formation PM, mg $PM_{2.5}$-Eq	38.9	43.5
Photochemical ozone formation POF, mg NMVOC-Eq	489	575
Acidification AC, μmol H^+-Eq	645	735
Freshwater eutrophication FE, mg P-Eq	18.3	21.3
Marine eutrophication ME, mg N-Eq	84.2	103
Water resources depletion WRD, L Water-Eq	38.5	42.0

compared to conventional power generation systems, there are certain environmental aspects that still have to be thoroughly discussed. P. Zapp, in 1996, introduced one of the first environmental analysis of solid oxide fuel cells, introduced by the statment that “Nowadays, for a new technology to be successfully introduced, it should compete not only in terms of economy but also in terms of ecology.”

In this work, a review was conducted for the different environmental aspects of FCs, such as global warming potential, gaseous emissions, and many others. The review considered the most used FCs, such as proton exchange membrane fuel cell PEMFC (that includes hydrogen FC, alkaline FC, and direct alcohol FC), phosphoric acid fuel cell PAFC, molten carbonate fuel cell MCFC, and solid oxide fuel cell SOFC. The environmental benefits of using different types of FCs are evident, mainly for FC operation. However, when considering the life cycle assessment (LCA) for FC, it still poses some environmental impacts that ought to be addressed, in addition to the economic barriers. Most of the LCAs performed on FCs have shown that most of the environmental impacts are associated with construction and manufacturing or material acquisition. This is because precious metals, such as Pt for the electrocatalyst for low-temperature FCs, in addition to thermally and chemically stable material for medium- and high-temperature FCs are the significant contributors. In addition, fuel sourcing, like in the case of hydrogen, contributes significantly to the operation phase of the LCA. Interestingly, both factors are significant contributors to FC cost as well. So, developments in both will help to overcome both environmental and economic barriers, and widen the potential application of FCs in many fields. Both the fuel and its source have a substantial effect on the environmental benefits of FCs, with extensive benefits for sustainable and renewable sourced fuels, such as bio-based fuels, and H_2 from water electrolysis using renewable energies. This, in turn, will help minimizing the EIs associated with fuel sourcing, along with aiding the development of cost-effective electrocatalysts that will collectively help minimizing the EIs of FCs, making them more environmentally attractive and cost-efficient.

However, when comparing different FCs to one another, it is hard to make decisive conclusions for the relative environmental benefits, with respect to each FC type. This is mainly because different studies have a different basis and life cycle inventory for the different types of FCs. This, along with the differences in nature and working principles for different FCs. Accordingly, there is a need to perform a standardized performance analysis of different fuel cells to have good insight for FC inter-comparison.

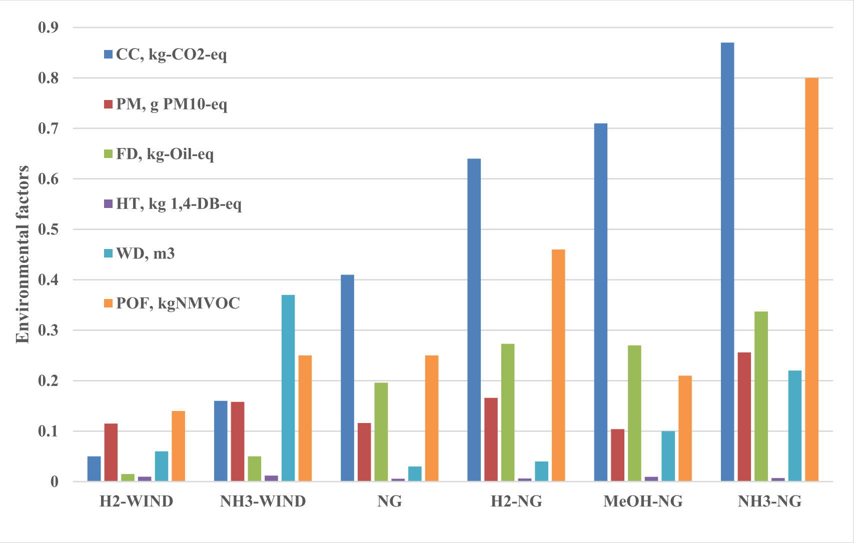

Fig. 10. Environmental factors for SOFC utilizing different fuels per 1kWhe power produced (Bicer and Khalid, 2020). (CC = Climate change, kg CO_2-eq; PM = particulate matter, kg PM_{10}-eq; FD = fossil depletion, kg oil-eq; HT = human toxicity, kg-1,4-DB-eq; WD = water depletion m^3; POF = photochemical oxidant formation as non-methane volatile organic carbon NMVOC, kg-NMVOC).

Table 6
Comparision of the normalized environmental impacts of PEM, SOFC, MCFC, μ-GT, and CHP per kWhe.
Adapted from (Mehmeti et al., 2018).

Environmental impact	PEM 2 kW	SOFC 125 kW	MCFC 500 kW	μ-GT 100 kW	CHP 160 kW
Global warming potential GWP, kg CO_2-eq	0.752	0.523	0.549	0.736	0.777
Stratopsheric ozone depletion ODP, μg CFC-11-eq	0.204	0.142	4.11	0.280	0.458
Particulate matter formation PM, mg $PM_{2.5}$-eq	189	83.3	135	99.8	115
Photochemical oxidant formation POF, mg NO_x-eq	716	516	445	1243	954
Terrestria acidification potential TAP, mg SO_2-eq	700	330	506	798	509
Freshwater eutripication potential FEP, mg P-eq	21.8	12.1	9.81	6.99	8.34
Mineral resources scaricity SOP, g Cu-eq	2.20	0.830	0.612	0.509	0.426
Fossil resources scaricity FFP, kg oil-eq	0.263	0.184	0.187	0.259	0.269
Water consumption potential WCP, l water	204	101	85.4	61.9	51.7
Cummulative excergy extractions from natural environment CEENE, MJ_{ex}	12.225	8.509	8.845	11.878	12.357

CRediT authorship contribution statement

All authors have equal contribution.

Declaration of competing interest

The authors declare that there is no conflict of interest of the current work.

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