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Fundamentals, Characteristics and Applications of Fuel Cells

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Abstract

Energy is central to achieving the interrelated economic, social and environmental aims of sustainable human development. The generation of energy by clean, efficient and environmental-friendly means is now one of the major challenges for engineers and scientists. This paper focuses on energy-related solution to global warming, air pollution mortality and energy security. However, it provides a review on fuel cell technology with a focus on fundaments, types and applications of fuel cells. Fuel cells are electrochemical devices which combine hydrogen and oxygen to produce electricity, heat and water. A fuel cell is composed of three active components: a fuel electrode (anode), an oxidant electrode (cathode), and an electrolyte sandwiched between them. Water and thermal management are key areas in the efficient design and operation of fuel cells. It was discovered that fuel cells have many inherent advantages over conventional combustion-based systems and such advantages among others are reduced harmful emissions, high efficiency, less pollution, fuel flexibility, excellent load response, high thermodynamic efficiency, modularity and scalability, quiet and static nature, water and cogeneration applications and wide range of applications. Hence, fuel cells make a valuable contribution to future power generation facilities. They improve the flexibility and increase the options for many applications, such as stationary power (emergency back-up power supply, remote-area power supply (RAPS), distributed power/combined heat and power (CHP) generation), transportation applications (auxiliary power units (APUs), Light traction vehicles (LTVs), aerial propulsion, marine propulsion) and portable applications (portable power generators, consumer electronics, portable military equipment, battery chargers, miniature toys, kits and gadgets). It is concluded that fuel cells are attractive, efficient and effective options for stationary building applications because of their high electrical efficiency, low emissions, silent operation and flexibility of fuel use.

Keywords

Energy Security, Sustainable, Global Warming, Air Pollution Mortality, CO_2 Emission

1. Introduction

Humanity is currently facing a future of dwindling reserves of fossil fuels, rising energy demand and a greater understanding of the environmental impact by the use of fossil fuels. It is now of global importance that greenhouse gas (GHG) emissions associated with energy production are substantially reduced in order to limit the effects of climate change and environmental pollution. However, a fuel cell is proposed as a suitable and an appropriate energy source. A fuel cell is an electrochemical device that converts the chemical energy of a fuel directly into electrical energy. The one-step (from chemical to electrical energy) nature of this process, in comparison to the multi-step (e.g. from chemical to thermal to mechanical to electrical energy) processes involved in combustion-based heat engines, offers several unique advantages. For instance, the current combustion-based energy generation technologies are very harmful to the environment and are predominantly contributing too many global concerns, such as climate change, ozone layer depletion, acidic rains, and thus, the consistent reduction in the vegetation cover.

Fuel cells, on the other hand, provide an efficient and clean mechanism for energy conversion. Additionally, fuel cells are compatible with renewable sources and modern energy carriers (i.e., hydrogen) for sustainable development and energy security. As a result, they are regarded as the energy conversion devices of the future. The static nature of fuel cells also means quiet operation without noise or vibration, while their inherent modularity allows for simple construction and a diverse range of applications in portable, stationary, and transportation power generation. In short, fuel cells provide a cleaner, more efficient, and possibly the most flexible chemical-to-electrical energy conversion. The reasons for the late evolution of fuel cells can be reduced to mainly economic factors, material problems and certain inadequacies in the operation of electrochemical devices. The world population increase requires bigger, more powerful and finely distributed power distribution. Furthermore, with a newly deregulated electrical power market in many industrialized countries, a new tendency to increase its flexibility by employing distributed power has emerged. It is expected that decentralized power plants will reduce both the overall capital investment for the installer and improve efficiency due to co-generation of electricity and heat. The first successful application of fuel cells was achieved with the space technologies. An electrical energy conversion device, which can provide electricity, heat and portable water was significantly more convenient compared to existing power sources such as batteries.

Fuel cells have recently been identified as a key technological option on route to a future low carbon built environment. This is because of the ability of fuel cells, depending on hydrogen production technique, to produce electrical power with little or no emission of harmful pollutants such as CO_2 [1, 2]. Furthermore, fuel cells produce useful quantities of heat when generating electricity, thus they are of particular interest for combined heat and power (CHP) and combined cooling heat and power (CCHP) applications, also known as tri-generation systems [3, 4]. In CHP and tri-generation systems, the often wasted heat created in the electrical generation process is utilized in a useful process such as space heating or cooling and this heat can be used to either produce more electricity (in a gas or steam turbine for instance) or to accommodate the plant with heat and warm water. This offers the potential to bring about improved system overall efficiency and thus increased energy savings [5].

2. Fundamentals of Fuel Cell

Fuel cells are electrochemical devices which combine hydrogen and oxygen to produce electricity, heat and water. Fuel cells are attractive options for stationary building applications because of their; high electrical efficiency, low emissions, near silent operation and flexibility of fuel use. Because fuel cells produce heat when generating electricity, they are of specific interest for CHP and tri-generation systems, particularly in the domestic built environment. Owing to the variety of types of fuel cells and their modularity, fuel cells have the ability to cover a range of building applications from a single family home to an entire hospital [2]. By combining hydrogen and oxygen in electrochemical reactions, fuel cells have the potential to produce electrical power without the emission of environmentally damaging pollutants such as CO_2. Furthermore the exothermic nature of the electrochemical reaction makes fuel cells ideal candidates for CHP applications.

2.1. Fuel Cell Operation

Fuel cells, like batteries, convert the chemical energy residing in a fuel into electrical energy on demand. As in batteries and other electrochemical cells, fuel cells consist of an anode, where oxidation occurs, a cathode, where reduction occurs, and an electrolyte, where ions carry the current between the electrodes. Fuel cells differ from batteries in that the fuel and oxidant are not contained within the fuel cell compartment but supplied continuously from an external source. In a real sense, fuel cells are like internal combustion engines, as they operate only so long as the fuel is supplied. Fuel cells are not electrically recharged, but after use, the tank is refilled with fuel. From an operational point of view, the fuel of choice is hydrogen gas, with the exhaust gas being water. Other fuels and hydrocarbons must be converted to hydrogen for use in a fuel cell. The direct conversion of fuels such as CH_3OH and CH_4 is possible under certain conditions. Each type of fuel cell has a unique set of processes and reactions to describe its operation.

2.2. Electrodes

The anode and cathode have the function of allowing the gas to diffuse from the gas channel to the electrolyte. Every electrode faces the gas channel on one side and the electrolyte on the other. On the electrolyte side, an electro-catalyst, whose function is primarily to favor the gas reaction, is placed. Since the electrolyte is in a liquid form, and to expel the produced water, electrodes need to be hydrophobic. This is generally achieved, by immersing the backing layer into a polytetrafluoroethylene (PTFE) solution. PTFE is also used as a binder, in order to prevent pore flooding. In addition, electrodes need a good electrical conductivity, to enable electrons to flow through them without significant resistance, from the catalyst layer to the current collector (anode) or vice versa (cathode). A fuel cell is composed of three active components: a fuel electrode (anode), an oxidant electrode (cathode), and an electrolyte sandwiched between them. The electrodes consist of a porous material that is covered with a layer of catalyst (often platinum). Molecular hydrogen (H_2) is delivered from a gas-flow stream to the anode where it reacts electrochemically. The hydrogen is oxidized to produce hydrogen ions and electrons, as shown in Equation 1:

$$H_2 => 2H^+ + 2e^- \qquad (1)$$

The hydrogen ions migrate through the acidic electrolyte while the electrons are forced through an external circuit all the way to the cathode. At the cathode, the electrons and the hydrogen ions react with the oxygen supplied from an external gas-flow stream to form water, as shown in Equation 2:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- => H_2O \quad (2)$$

The overall reaction in the fuel cell produces water, heat and electrical work as shown Equation 3:

$$H_2 + 21O_2 => H_2O + W_{ele} + Q_{heat} \quad (3)$$

The heat and water by-products must be continuously removed in order to maintain continuous isothermal operation or ideal electric power generation. Hence, water and thermal management are key areas in the efficient design and operation of fuel cells. Fuel cells and batteries are quite similar in the sense that they are both electrochemical cells that consist of an electrolyte sandwiched between two electrodes. They both use internal oxidation–reduction reactions to convert the chemical energy content of a fuel to DC electricity. However, the composition and role of the electrodes differ significantly between the two energy devices. The electrodes in a battery are typically metals (e.g., zinc, lead, or lithium) immersed in mild acids. In fuel cells, the electrodes (i.e., catalyst layer and gas diffusion layer) typically consist of a proton-conducting medium, carbon-supported catalyst, and electron-conducting fibers. Batteries are used as energy storage and conversion devices, while fuel cells are used for energy conversion only. A battery uses the chemical energy stored in its electrodes to fuel the electrochemical reactions that give us electricity at a specified potential difference. Thus, a battery has a limited lifetime and can only function as long as the electrodes material is not yet depleted.

2.3. Types of Fuel Cells

Fuel cells are often categorized by the type of electrolyte. This is determined by the type and purity of the fuel and oxidant used and the operating temperature. There are currently six types of established fuel cells [6]: Proton Exchange Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Direct Methanol Fuel Cell (DMFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC). The first three fuel cells are classified as low temperature (80–250°C), whilst the remaining three are medium to high temperature (250–1000°C). The operating temperature is often a significant factor when determining which type of fuel cell should be used in a particular application. This is due to a number of factors including; heat usability, start-up time and ability to vary output. Of the six fuel cell variants listed above, the low temperature PEMFC and the high temperature SOFC demonstrate the greatest promise for early market application, attracting the most attention and investment in building application projects [2, 7, 8].

2.3.1. Proton Exchange Membrane Fuel Cells (PEMFC)

PEM fuel cells use a proton-conducting polymer membrane as an electrolyte. They are low temperature fuel cells, generally operating at 85-105°C and were the first to be used in space. A major breakthrough in the field of PEM fuel cells came with the use of Nafion membranes (DuPont). These membranes possess a higher acidity, concurrently conductivity and are far more stable than the polystyrene sulfonate (PSS) membranes. Nafion consists of a polytetrafluoroethylene-based (PTFE) structure which is chemically inert in reducing and oxidising environments, in contrast to the PSS membranes.

2.3.2. Alkaline Fuel Cell (AFC)

The AFC has the advantage of exhibiting the highest electrical efficiencies of all fuel cells but it works properly only with very pure gases which is considered a major restraint in most applications. The KOH electrolyte which is used in AFC's (usually in concentrations of 30-45 wt.%) has an advantage over acidic fuel cells which is that the oxygen reduction kinetics are much faster in alkaline electrolyte than in acid making the AFC a very attractive system for specific applications.

The direct methanol fuel cell is a special form of low temperature fuel cell based on PEM technology. It operates at temperatures similar to PEMFC, although it can also run at slightly higher temperatures in order to improve the power density. In the DMFC, methanol is directly fed into the fuel cell without the intermediate step of reforming the alcohol into hydrogen. Methanol is an attractive fuel option because it can be produced from natural gas or renewable biomass resources. It has the advantage of a high specific energy density (since it is liquid at operating conditions) and it is assumed that the existing infrastructure for fuels may be adapted to methanol. The DMFC can be operated with liquid or gaseous methanol/water mixtures.

2.3.3. Phosphoric Acid Fuel Cell (PAFC)

The phosphoric acid fuel cell is thus far the most advanced system regarding commercial development. It is mainly used in stationary power plants ranging from dispersed power to on-site generation plants. Power plants based on PAFCs are being installed worldwide with outputs ranging from 5±20 MW supplying towns, cities, and shopping malls or hospitals with electricity, heat, and hot water. The advantages of the PAFC are its simple construction, its stability both thermally, chemically, and //electrochemically, and the low volatility of the electrolyte at operating temperatures (150-200°C). These factors probably assisted the earlier deployment into commercial systems compared to the other fuel cell types. At the beginning of PAFC development diluted phosphoric acid was used in PAFCs to avoid corrosion of some of the cell components. Nowadays with improved materials available for cell construction the concentration of the acid is nearly 100%. The acid is usually stabilized in a SiC-based matrix. The higher concentration of the acid increases the conductivity of the electrolyte and reduces the corrosion of the carbon supported electrodes.

2.3.4. Molten Carbonate Fuel Cell (MCFC)

One advantage of the MCFC is the possibility to allow for internal reforming due to the high operating temperatures (600-700°C) and to use the waste heat in combined cycle power plants. The high temperatures improve the oxygen reduction kinetics dramatically eliminating the need for very high loadings of precious-metal catalysts. The molten carbonate (usually a LiK or LiNa carbonate) is stabilized in a matrix ($LiAlO_2$) which can be supported with Al_2O_3 fibres for mechanical strength.

2.3.5. Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cells employ a solid oxide material as electrolyte and are, thus, more stable than the molten carbonate fuel cells as no leakage problems due to a liquid electrolyte can occur. The SOFC is a straightforward two-phase gas-solid system so it has no problems with water management, flooding of the catalyst layer, or slow oxygen reduction kinetics. On the other hand it is difficult to find suitable materials which have the necessary thermal and chemical stability properties for operating at high temperatures.

3. Characteristics and Features

Fuel cells have many inherent advantages over conventional combustion-based systems, making them one of the strongest candidates to be the energy conversion device of the future. They also have some inherent disadvantages that require further research and development to overcome them.

3.1. Reduced Harmful Emissions

The only products from a fuel cell stack fueled by hydrogen are water, heat, and DC electricity. And with the exception of controllable NOx emissions from high-temperature fuel cells, a hydrogen fuel cell stack is emissions-free. However, the clean nature of a fuel cell depends on the production path of its fuel (e.g. hydrogen). For instance, the products of a complete fuel cell system that includes a fuel reformation stage include greenhouse emissions (e.g., CO and CO_2). When the hydrogen supplied to the fuel cell is pure (i.e., not reformation-based hydrogen which is always contaminated with COx), the durability and reliability of the fuel cell significantly improve in comparison to when we run the fuel cell on reformation-based hydrogen. This is one of the most important advantages of fuel cells in comparison to heat engines, i.e., fuel cells are inherently clean energy converters that ideally run on pure hydrogen. This fact is actually pressingly driving researchers and the industry to develop efficient and renewable-based hydrogen generation technologies based on clean water electrolysis to replace the conventional reformation-based ones. Systems that integrate renewable-based hydrogen generation with fuel cells are genuinely clean energy generation and conversion systems that resemble what the energy industry is striving to achieve.

3.2. High Efficiency

The amount of heat that could be converted to useful work in a heat engine is limited by the ideal reversible Carnot efficiency, given by the following equation:

$$\eta_{carnot} = \frac{T_i - T_e}{T_i} \tag{4}$$

where T_i is the absolute temperature at the engine inlet and T_e is the absolute temperature at the engine exit. However, a fuel cell is not limited by the Carnot efficiency since a fuel cell is an electrochemical device that undergoes isothermal oxidation instead of combustion oxidation. The maximum conversion efficiency of a fuel cell is bounded by the chemical energy content of the fuel and is found by:

$$\eta_{rev} = \frac{\Delta G_f}{\Delta H_f} \tag{5}$$

where ΔG_f is the change in Gibbs free energy of formation during the reactions and ΔH_f is the change in the enthalpy of formation (using lower heating value (LHV) or higher heating value (HHV). In light vehicles, for instance, the efficiency of a fuel cell-powered car is nearly twice the efficiency of an internal combustion engine-powered car.

3.3. Modularity

Fuel cells have excellent modularity. In principle, changing the number of cells-per-stack and/or stacks-per-system allows us to control the power output of any fuel cell system. Unlike combustion-based devices, a fuel cell's efficiency does not vary much with system size or load factor. In fact, as opposed to conventional power plants, fuel cells have higher efficiencies at part loads compared to full loads. This would prove advantageous in large-scale fuel cell systems that would normally run on part-load instead of full load. Additionally, the high modularity of fuel cells means that smaller fuel cell systems have similar efficiencies to larger systems. This feature greatly facilitates the future integration of fuel cells in small-scale distributed generation systems, which hold a great potential in the power generation industry. It is worth noting; however, that reformation processors are not as modular as fuel cell stacks. This presents another reason to shift to renewable-based hydrogen production technology.

3.4. Static Nature

Due to its electrochemical nature, a fuel cell stack is a static silent device. This is a very important feature that promotes the use of fuel cells for auxiliary power and distributed generation applications in addition to portable applications that require silent-operation. The fact that a fuel cell system has very few dynamic parts (and hence, almost no vibrations) makes fuel cells design, manufacturing, assembly, operation, and analysis simpler than that of heat engines. Nevertheless, for fuel cell systems that use compressors instead of blowers for the oxidant supply, noise levels can noticeably increase. As such, fuel cell designers tend to avoid using compressors due to their high parasitic load, noise production, cost, weight, volume and complexity relative to fans and blowers. For instance, in a conventional urban bus, most of the noise is generated from the diesel engine. A fuel cell stack, on the other hand, is a completely silent device. As such, the noise level from a fuel cell bus could be significantly lower than a conventional bus provided that the fuel cell system's balance-of-plant (BoP) components are reasonably quiet. The static nature of a fuel cell also reflects on its low maintenance requirements in comparison to competing technologies such as heat engines, wind turbines and concentrated solar power (CSP) plants.

3.5. Range of Applications and Fuel Flexibility

Fuel cells have diverse applications ranging from micro-fuel cells with less than 1W power outputs to multi-MW prime power generation plants. This is attributed to their modularity, static nature and variety of fuel cell types. This qualifies fuel cells to replace batteries used in consumer electronics and auxiliary vehicular power. These same properties also qualify a fuel cell to replace heat engines used in transportation and power generation. Fuel cells are also highly integrable to most renewable power generation technologies. Fuel cells that operate on low-temperature ranges require short warm-up times, which is important for portable and emergency power applications. While for fuel cells that operate on medium-to high-temperature ranges, utilization of waste heat both increases the overall efficiency of the system and provides an additional form of power output useful for domestic hot water (DHW) and space heating residential applications or CHP industrial-level applications. Fuels for a reformation-based fuel cell system include methanol, methane and hydrocarbons such as natural gas and propane. These fuels are converted into hydrogen through a fuel reformation process. Alternatively, direct alcohol fuel cells (e.g. direct methanol fuel cells) can run directly on an alcohol. And even though fuel cells run best on hydrogen generated from water electrolysis, a fuel cell system with natural gas reformation also possesses favorable features to conventional technologies.

3.6. High Cost

Fuel cells are expensive. Experts estimate that the cost-per-kW generated using fuel cells has to drop by a factor of 10 for fuel cells to enter the energy market. Three main reasons behind the current high cost of fuel cell stacks are: the dependence on platinum-based catalysts, delicate membrane fabrication techniques and the coating and plate material of bipolar plates. While from a system-level perspective, the BoP components such as fuel supply and storage sub-systems, pumps, blowers, power and control electronics and compressors constitute about half the cost of a typical complete fuel cell system. More specifically, whether renewable- or hydrocarbon- based, the current hydrogen production BoP equipment are far from being cost-effective. Technological advances in contaminate removal for hydrocarbon-based technologies are essential if the cost of fuel cell systems is to meet planned targets. Nevertheless, if fuel cells successfully enter the mass production stage, their costs are expected to significantly drop and become consumer-affordable due to the fact that manufacturing and assembly of fuel cells is generally less demanding than typical competing technologies, such as heat engines.

3.7. Low Durability

The durability of fuel cells needs to be increased by about five times the current rates in order for fuel cells to present a long-term reliable alternative to the current power generation technologies available in the market. The degradation mechanisms and failure modes within the fuel cell components and the mitigation measures that could be taken to prevent failure need to be examined and tested. Contamination mechanisms in fuel cells due to air pollutants and fuel impurities need to be carefully addressed to resolve the fuel cell durability issue.

3.8. Hydrogen Infrastructure

One of the biggest challenges that face fuel cells commercialization is the fact that we are still producing 96% of the world's hydrogen from hydrocarbon reformation processes [9]. Producing hydrogen from fossil fuels (mainly natural gas) and then using it in fuel cells is economically disadvantageous since the cost-per-kWh delivered from hydrogen generated from a fossil fuel is higher than the cost-per-kWh if we were to directly use the fossil fuel. Thus, promoting renewable- based hydrogen is the only viable solution to help the shift from a fossil-based economy to a renewable-based, hydrogen-facilitated economy.

Moreover, development of hydrogen storage mechanisms that provide high energy density per mass and volume whilst maintaining a reasonable cost is the second half of the hydrogen infrastructure dilemma. Any widely-adopted hydrogen storage technology will have to be completely safe since hydrogen is a very light and highly flammable fuel that could easily leak from a regular container. Metal- and chemical- hydride storage technologies are proving to be safer and more efficient options than the traditional compressed gaseous and liquid hydrogen mechanisms. However, more research and development are needed to reduce the relatively high cost of the hydride storage technologies and to further improve their properties.

3.9. Water Balance

Water transport within a fuel cell is a function of water entering with inlet streams, water generated by the cathodic reaction, water migration from one component to another and water exiting with exit streams. Generally speaking, a successful water management strategy would keep the membrane well-hydrated without causing water accumulation and blockage in any part of the membrane electrode assembly (MEA) or flow fields. As such, maintaining this delicate water balance inside a PEMFC over different operation conditions and load requirements is a major technical difficulty the scientific community is required to fully address [10]. Flooding of the membrane; water accumulation in the pores and channels of the gas diffusion layer (GDL) and flow fields; dryness of the membrane; freezing of residual water inside the fuel cell; dependence between thermal, gases and water management; and humidity of the feeding gases are all subtle and interdependent facets in the water management of a PEMFC [11].

Improper water management within a PEMFC leads to both performance loss and durability degradations as a result of permanent membrane damage, low membrane ionic conductivity, non-homogeneous current density distribution, delamination of components, and reactants starvation. As such, water management strategies range from direct water injection to reactant gases recirculation [10]. The performance evaluation of a water management technique could be accomplished using empirical liquid water visualization micro- and macro- scale numerical simulation [10]. Nonetheless, fundamental understanding and comprehensive models of water transport phenomena within a fuel cell are highly needed in order to develop optimized component designs, residual water removal methods and MEA materials according to application requirements and operation conditions [11].

4. Applications of Fuel Cell

Fuel cells hold promising potential to become competitive players in a number of markets due to their broad range of applications. And as a result of their high modularity, wide power range and variation of properties among different types, fuel cells have applications ranging from scooters to large co-generation power plants as fuel cells can theoretically be used for any energy-demanding application. Efforts towards the commercialization of fuel cells in the portable electronics, stationary power generation and transportation sectors are well underway. In fact, worldwide shipments of fuel cells increased by 214% between the years 2008 and 2011 with fuel cells becoming an emerging competitor in the back-up power for telecommunication networks market [12], material handling market [13, 14] and the airport ground support equipment market [15]. The global fuel cell industry market is expected to reach $19.2 billion by the year 2020 with the United States, Japan, Germany, South Korea, and Canada acting as the flagship countries in the development and commercialization of fuel cells [16].

4.1. Stationary Power

Fuel cells can play an integral part in the residential, commercial, and industrial stationary power generation sectors. They are utilized for both grid-independent (also known as stand-alone) and gird-assisted power supply. Stationary fuel cell applications include emergency back-up power supply (also known as uninterrupted power supply (UPS)), remote-area power supply (RAPS), and distributed power or CHP generation.

4.1.1. Emergency Back-up Power Supply

Due to their high energy and power densities, high modularity, longer operation times (2–10 times longer than currently-used lead-acid batteries), compact size, and ability to operate under harsh ambient conditions, fuel cells are becoming an encouraging alternative for batteries in the EPS market, especially in the telecommunications market, with PEMFCs and DMFCs as the dominantly-chosen fuel cell types [12]. Due to the fact that the EPS market requires high reliability but not necessarily high operational lifetimes, fuel cells found EPS to be one of its most successful markets. Other fuel cell EPS markets include hospitals, data centers, banks, and government agencies. In all these markets, the continuation of a power supply (typically between 2 and 8 kW) is critical, when grid power is unavailable.

4.1.2. Remote-Area Power Supply (RAPS)

In grid-isolated locations, such as islands, deserts, forests, remote technical installations, holiday retreats and remote research facilities, providing power could be problematic. Such locations fall under the remote-area power supply (RAPS) category. Usually, providing power to rural and urban off-grid locations using RAPS solutions is more economical than extending electric grid power lines. This is especially true for rural areas where the geographical nature of rough terrains (forests, mountains, etc.) makes grid extensions an unrealistic approach.

4.1.3. Distributed Power/CHP Generation

Fuel cells could serve as the means to make the shift from large centralized power generation to decentralized distributed generation. Due to their static nature, lower emissions and high efficiency; fuel cells could be used for residential electric power or CHP distributed generation either on a household basis [2, 17, 18] or a larger residential blocks basis [19, 20]. A residential CHP fuel cell system could range from a few kilowatts to a few megawatts depending on the targeted basis load. A residential CHP fuel cell system will be able to provide electric power, space heating and domestic water heating requirements. Cooling could also be added to power generation and heating (known as combined cooling, heating, and power (CCHP) systems) if an absorption chiller, thermally-driven heat pump, or an appropriate technique is integrated with the system to utilize the waste heat of the fuel cell stack in a dual-mode heating/cooling cycle [21, 22]. CHP and CCHP systems could reach overall efficiencies as high as 80% [17, 22]; however, further studies to resolve the technical challenges and reduce capital cost in addition to funding for experimental validation remain highly needed.

The most important attributes of fuel cells for stationary power generation are the high efficiencies and the possibility for distributed power generation. Both low-temperature and high-temperature fuel cells could, in principle, be utilized for stationary applications. The low-temperature fuel cells have the advantage that usually a faster start-up time can be achieved. The needed operating time for the stationary application is about 40,000 hours, which may be a challenge for fuel cell systems. The high-temperature systems such as SOFC and MCFC generate high-grade heat which can directly be used in a heat cycle or indirectly used by incorporating the fuel cell system into a combined cycle. SOFCs and MCFCs also have the advantage that they can operate directly on available fuels without the need for external reforming. For a small distributed power system, e.g., single-home or multiple-home power generation, a PEM, SOFC, or PAFC combined with a heat cycle could be used to provide all the needs for a home. The PAFC start-up time is much lower than this for high-temperature systems, which makes it more attractive for small-power generation.

The heat generated by the fuel cell system can be employed for heating and providing the home with hot water. The PAFC produces enough steam to operate a steam reforming system whereas the PEM system due to its lower operation temperature is not able to supply the necessary heat. Small power plants in the range above 250 kW can be operated by high-temperature fuel cell systems. The high grade heat obtained from these systems can be exchanged at a broad temperature range leaving the possibility of direct heat use or further electricity generation by steam engines. The start-up time of these systems are longer than for low-temperature systems but the advantages of being able to operate the system without external reforming and the higher efficiencies of SOFCs and MCFCs makes these systems more suitable for large-scale power plants.

4.2. Transportation Applications

The transportation industry is one of the main power houses in the development of clean energy technologies. This is due to the fact that the transportation industry is responsible for 17% of the global greenhouse gas emissions every year [23]. The industry's outlook is to invest in technologies that would offer both significant reductions in harmful emissions and better energy conversion efficiencies. Accordingly, the current complete dependence on combustion-based technologies that utilize fossil fuels in heat engines makes the development of environmentally-benign transportation alternatives a necessity rather than an option. This is where fuel cells come into the picture. Fuel cells offer the transportation industry near-zero harmful emissions without having to compromise the efficiency of the vehicle's propulsion system. In fact, fuel cells have demonstrated efficiencies (from 53% to 59%) that are almost twice the efficiencies of conventional internal combustion engines [24] When we add advantages such as static operation, fuel flexibility, modularity and low maintenance requirements; fuel cells become an ideal future alternative for current combustion engines. That is, if durability, cost, hydrogen infrastructure and technical targets are met on-schedule. This is why using fuel cells in various means of transportation, with a focus on light-duty passenger cars, has been one of the main drivers for fuel cell R&D in the past decade. We will classify fuel cell applications that fall under the transportation category into the following markets: auxiliary power units (APUs), light traction vehicles (LTVs), light-duty fuel cell electric vehicles (L-FCEVs), heavy-duty fuel cell electric vehicles (H-FCEVs), aerial propulsion, and marine propulsion.

4.2.1. Auxiliary Power Units (APUs)

An on-board auxiliary power unit is used for the generation of non-propulsive power in any vehicle. Unlike portable power generators that could be used on-board of recreational vehicles (RVs), boats, etc., an APU is built into the vehicle. An APU provides power for air conditioning, refrigerating, entertainment, heating, lighting, communication, and any electrical appliances in any car, boat, ship, locomotive, airplane, truck, bus, submarine, spaceship, military vehicle, or any other vehicle with on-board energy needs. However, leisure yachts, plane and cars [25]; heavy-duty trucks [26-28]; utility and service vehicles; law enforcement vehicles; and refrigeration vehicles present the most promising markets for APUs due to their high on-board electrical energy demand [29-31]. Leisure and recreational vehicles in Fuel cells as APUs produce significantly less emissions, cause no acoustic pollution, have short start-up times and have higher efficiencies.

4.2.2. Light Traction Vehicles (LTVs)

Light traction vehicles (LTVs) include scooters, personal wheelchairs, electric-assisted bicycles, airport tugs, motorbikes, golf carts, etc. in addition to material handling vehicles and equipment. Material handling vehicles and equipment include forklifts, tow trucks, pallet trucks, etc. and fall under the LTVs category. Forklifts have been the most successful demonstration of fuel cells in the transportation sector and one of the most successful demonstrations for fuel cells overall. Forklifts and other material handling vehicles and equipment are exhaustively used in the warehousing and distribution industry.

4.2.3. Aerial Propulsion

Other applications for fuel cells include the space and aviation industries with small unmanned aerial vehicles (UAVs) being the main focus for fuel cells in the aerial propulsion sector. UAVs are mainly used for surveying, surveillance and reconnaissance purposes due to their stealth nature and lack of risk to human life. And with the ever-increasing interest in UAVs by military authorities and commercial parties, the development of more durable and reliable propulsion systems is a necessity. Fuel cells (mostly PEMFCs with few SOFCs) are clearly becoming the ideal candidates for powering future UAVs. The stealth nature of UAVs is facilitated by fuel cells' static operation and low heat dissipation, two advantages over UAVs with internal combustion engines. And even though batteries share those two advantages with fuel cells, the low energy density and large weight of batteries make fuel cell UAVs superior to UAVs with batteries. The lighter weight and higher energy density of fuel cells allow for greater mission range and endurance as compared to an average of one hour for battery UAVs [32]. Additionally, the modularity of fuel cells makes them promising to use for small-scale applications such as UAVs, contrary to combustion engines that suffer from low efficiencies when designed for small-scale applications.

4.2.4. Marine Propulsion

Even though the most common use for fuel cells in the marine industry is as APUs on-board of boats and yachts, as previously mentioned, promising future marine propulsion markets for fuel cells exist in submarines, ferries, underwater vehicles, boats, yachts and even cargo ships. Fuel cells provide their regular benefits for ships and ferries, such as low emissions, high efficiency and static operation. However, issues related to reliability, lifetime, shock resistance and tolerance to the salt content of sea air are yet to be resolved.

4.3. Portable Applications

Portable applications for fuel cells are mainly focused on two main markets. The first is the market of portable power generators designed for light outdoor personal uses such as camping and climbing, light commercial applications such as portable signage and surveillance, and power required for emergency relief efforts. The second is the market of consumer electronic devices such as laptops, cell phones, radios, camcorders and basically any electronic device that traditionally runs on a battery. Portable fuel cells typically have power ranges between 5 and 500W, with micro-fuel cells having power outputs less than 5W and more demanding portable electronics reaching the kW-level. Unlike stationary fuel cells, portable fuel cells could be carried by an individual and used for a variety of applications. The modularity and high energy density of fuel cells make them strong potential candidates for future portable personal electronics. Moreover, portable military equipment is another growing application for portable direct methanol fuel cells (DMFCs), reformed methanol fuel cells (RMFCs) and PEMFCs due to their silent operation, high power and energy density, and low weight compared to current battery- based portable equipment [33, 34].

In addition to lower weight and higher energy density, the fact that fuel cells do not require recharging from an electricity source makes them more favorable in comparison to batteries in the future portables market. However, their cost and durability are yet to meet set targets. For small power applications like laptops, camcorders, and mobile phones the requirements of the fuel cell systems are even more specific than for vehicle applications. Low temperatures are necessary and therefore PEM fuel cells are chosen. Possibilities for fuel cell systems are the combination of PEM with hydrogen storage by hydrides or gas cartridges or the direct methanol fuel cell. This type of fuel cell will be employed in portable phones and can be adjusted for other portable applications. The requirements for portable applications are mostly focused on size and weight of the system (as well as the temperature). Other fuel cells are, therefore, not suitable for this kind of applications. Portable devices need lower power than other fuel cell applications and, thus, DMFC systems may be well suited for this kind of applications.

5. Conclusions

Fuel cells will make a valuable contribution to future power generation facilities. They improve the flexibility and increase the options for many applications, such as distributed power, vehicle propulsion, and portable devices. Their main property is the high electrical efficiency compared to other energy conversion devices. Both the low-temperature and the high-temperature fuel cells have their advantages and disadvantages depending on the application. Sometimes, they can both be implemented in similar applications. The modularity of fuel cells makes them quite flexible as the power needed can easily be attained by changing the number of modules. Fuel cell systems are commercial products in many areas, such as stationary application and some small power devices (power for traffic signs). The imminent commercialization of fuel cells in areas of high turnover, such as vehicle propulsion, battery replacement, and stationary power generation, has accelerated the research and development dynamics considerably.

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