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The Re-Imagination of Electrochemical Power: A Global Awakening and Thoughts from Obafemi Awolowo University, Ile-Ife.

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Abstract

From its humble beginnings as Alessandro Volta's "voltaic pile", electrochemical power (EP) has been powering paradigm shifts in technology for the past 150 years. From the life-support systems in manned space exploration of the 1960s, to the electric vehicles of the last 20 years, EP has been the unsung hero. EP is enjoying renewed focus and a flurry of R&D activities in today's resource-constrained and environment-conscious world that is urgently looking for a "silver-bullet" for its global warming and pollution problems. This paper discusses the impetus for the renewed interest in EP, with emphasis on its storied high operating efficiencies and green credentials, compared with traditional power production systems. It highlights the impact of cumulative years of EP R&D, the basic electrochemistry of mature EP systems, the global energy conundrum and the steady permeation of EP into the global energy mix. Recent re-imagination trends of EP into applications hitherto the preserve of traditional power technologies and novel applications outside of its native scope of portable and reserve power were also discussed. In view of the inevitable global shift towards EP as a veritable future energy source, the urgent need for a strategic local R&D focus on EP in Nigeria was emphasised. In view of this, the research efforts and direction of our team at the Department of Materials Science and Engineering, Obafemi Awolowo University, Ile-Ife are presented and put in context.

Keywords: Energy, Battery, Electrochemical, Fuel Cells

1. Introduction: Historical Overview

Since the invention of the voltaic pile by Alessandro Giuseppe Volta in 1800 (Decker, 2005), the ascent of electrochemical power and it's coming of age was only a matter of time. The 19th century saw a flurry of innovations in basic electrochemical energy research. The Hydrogen – Oxygen Fuel Cell in 1839 (Takamura, 2009), Lead-Acid Battery in 1859 and Direct Carbon Fuel Cell in 1895 (Battery Association of Japan, 2015). However, in those early days, electrochemical power was an invention without a market. Applications areas were restricted to research laboratories and the technology was considered too expensive.

Rapid innovations in automobile engineering and aircraft communication underscored the need for portable power and this further received a boost during the Second World War. The first real foray of electrochemical power into the consumer market occurred in 1940 when Herman Anthony was awarded a patent for a leak-proof battery (Alfred, 2012). This was a marked improvement over the hitherto standard 'zinc-carbon' batteries which have a tendency to burst due to the swelling of the zinc. This invention was timely for the allied war effort of World War II and powered everything from mine detectors, signalling lights and radio transmission sets. The post war economy saw the introduction of the first truly portable consumer devices like transistor radios and torch light which spurred the large-scale interest in electrochemical power.

The final conviction needed by the scientific community and the consuming public of the viability and reliability of electrochemical power came with the first manned space missions of the 1960s. Communication and life-support systems of the Soviet and American missions were powered by electrochemical power. Indeed, Neil Armstrong and Buzz Aldrin's Extra Vehicular Activity on the lunar surface was powered entirely by electrochemical power.

Electrochemical power has been silently powering the world's industrialisation since the turn of the last century. It has been for years the uncelebrated hero that get your car started when you turn the key, that is powering the wristwatch on your wrist, the mobile phone in your pocket, providing crucial back-up power for the base-stations managing the calls and data traffic, the cardiac pacemaker implanted in the human body enabling many with deadly heart diseases to remain alive today, to mention just a few.

The eventual coming of age of electrochemical power is inevitable due to its inherent high efficiencies, flexibility of operating conditions and configurations and its generally environment-friendly credentials. Costs have been lowered by decades of research into the use of less-exotic materials, more efficient catalyst utilisation and scalable, simplified production methods.

The time may be apt to declare that electrochemical power has come of age. The 2019 Nobel Prize for Chemistry was awarded to the trio of researchers in the field of electrochemical power. Finally, it seems, according EP the recognition it deserves as the world looks at solving the present-day energy conundrum and seek viable energy alternatives for the next 100 years.

2. The Basic Chemistry of Electrochemical Power

In general, electrochemical power systems consists of a cathode and anode separated by an electrolyte (Bard and Faulkner, 2001). This is illustrated in Figure 1. The main distinguishing feature between an electrochemical reaction occurring in a cell and a redox reaction is that oxidation and reduction do not occur at the same place. Rather they are separated by the electrolyte, forming half-cell reactions at the cathode and anode (Newman and Thomas-Alyea, 2004). In a chemical redox reaction. The electrolyte is an ionic conductor and does not permit the conduction of electrons. The electrons flow in an external circuit in which they do work.

An electrochemical system capable of providing electrical current is referred to as a galvanic cell (Hamnett, 2003). These type cof ells can be classified into three groups:

Primary cells: These are cells in which the reaction is non-reversible. Hence, after the fuel is consumed, the cell has to be mechanically refilled. The very first galvanic cell was the voltaic pile invented by Volta in 1800.

Secondary or rechargeable cells: In this group of cells the reaction is reversible. They have two operation modes; discharge (producing electrical energy from chemical energy) and charge (converting electrical energy to chemical energy). The fuel and oxidant are contained inside the cell.

Tertiary or fuel cells: In this group of cells the fuel is supplied externally. The preceding two categories of galvanic cells are energy storage devices. Tertiary or fuel cells, however are energy conversion devices, that is, they would continue to operate for as long as the supply of oxidant and fuel are maintained.

The key parts of an electrochemical cell are as briefly described:.

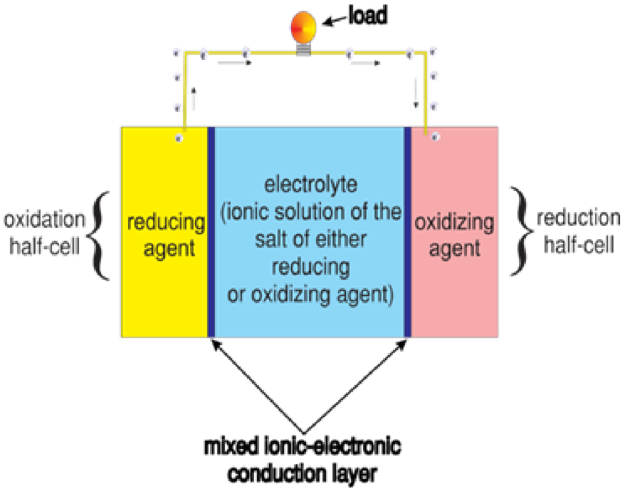


Figure 1: Basic Schematic of Electrochemical Energy Conversion

Electrolyte: It serves to separate the anode and cathode so as to prevent a spontaneous reaction of their reactants (Bagotsky, 2005). It also serves as a pathway for the internal flow of charge carriers within the cell via its ionic species. The electrolyte must however be a poor electronic conductor to prevent internal short circuiting inside the cell. Another important role of the electrolyte is transport of ions to or from the triple phase boundary (TPB) region where the cell's redox reactions occur.

Anode: The anode is the oxidation half-cell which provides free electrons. It is the negative pole in the cell. The anode, normally, must have good electronic conductivity in order to connect with external electrical circuitry (Newman and Thomas-Alyea, 2004). Or alternatively, it must have suitably placed current collectors in the vicinity of TPB reactions capable of conducting free electrons to an external circuit.

Cathode: The cathode has similar specifications the as the anode, the difference is that reduction reaction takes place there. The reduction reaction consumes the free electrons produced in the anode after their round-trip through the external circuit. This imparts on the cathode a net positive charge as a consequence. It has to meet the same conditions for electronic conductivity as the anode. However, the reducing environment on the cathode and the oxidising environment on the anode usually necessitates the use of separate materials for current collectors (Klotz, 2014).

3. Common Electrochemical Power Technologies

Some common and mature EP technologies that have been widely adopted are presented as follows.

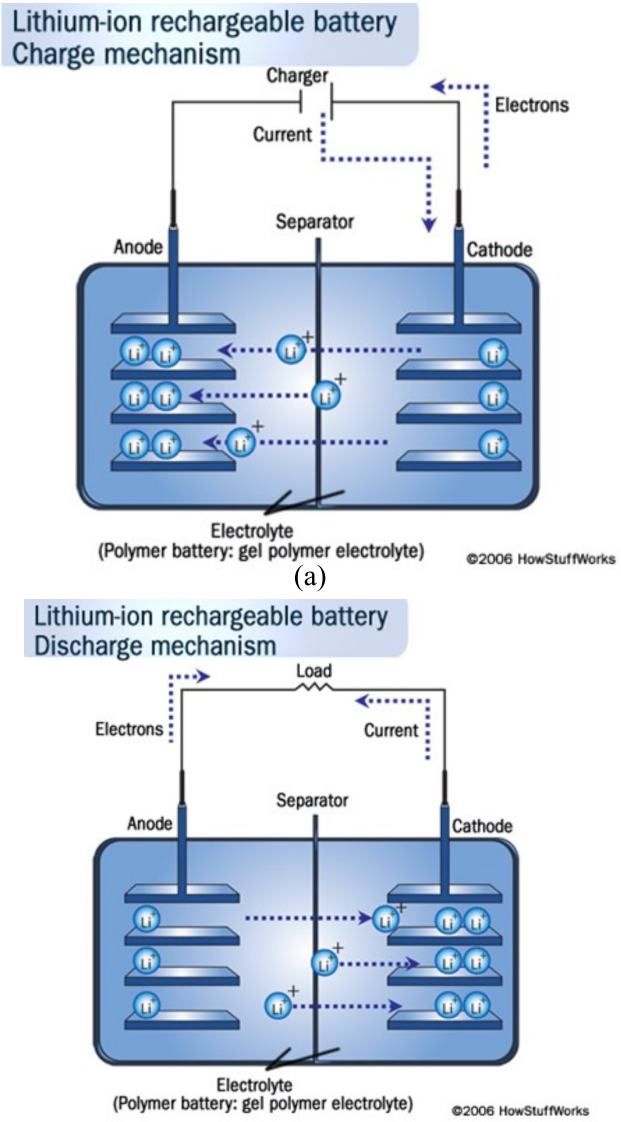
3.1 Lithium-Ion Battery

Lithium-ion batteries make use of the process of intercalation to sequester lithium ions into the structure of electrode materials. Figure 2 illustrates the intercalation during charging and discharging of Li-Ion batteries.

3.1.1 Positive electrode (cathode) and negative electrode (anode) materials

Lithium-ion batteries can be classified based on to the composition of their cathodes. These include: Lithium Cobalt Oxide, Nickel Cobalt Aluminium, Nickel Manganese Cobalt, Lithium Manganese Oxide, Lithium Iron Phosphate.

Anode Materials: Graphite in various formulations is generally used for the anode in commercial cells. Lithi-



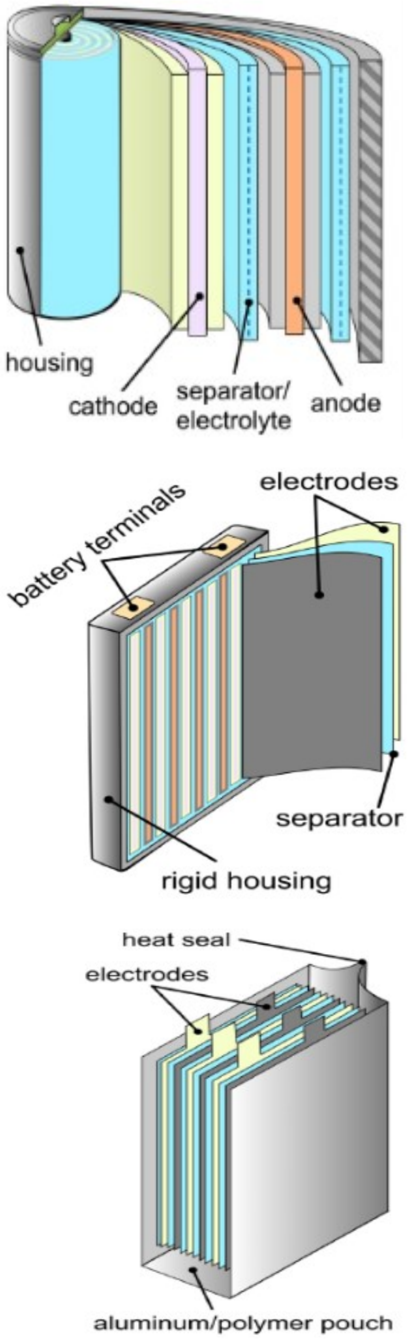
(a)

(b)

Figure 2. Intercalation during charging (a) and discharging (b) of Li-Ion batteries (upsbatterycenter.com, 2014).

3.1.2 Cell construction

Lithium-ion cells can be made into rigid cylindrical, prismatic and pouch product shapes as shown in Figure 3. The cylindrical cells are the most well-established amongst the various forms. Prismatic cells have long been associated with mobile phones and other consumer electronics. Pouch cells are relative newcomers and are similar in appearance to prismatic cells. They use a thin, flexible laminate in place of a rigid housing.



(a)

(b)

(c)

Figure 3. (a) Cylindrical (b) Prismatic and (c) Pouch Lithium -ion cells (Schatz Energy Research Centre, 2019)

um ions are intercalated in between carbon sheets in the graphite during the charging of the cell and are released during cell discharge.

3.2. Nickel Hydrogen Battery

Nickel Hydrogen batteries combine Ni-Cad battery and fuel cell technologies and can be considered as hybrid batteries. It uses hydrogen gas at high pressures to replace the cadmium electrode. They were developed mainly for use in space applications. They are still favoured for energy storage in many satellites today. Application areas include aerospace, International Space Station (ISS) and the Hubble Space Telescope

3.2.1 Cathode and anode materials

Cathode: Nickel Hydrogen cells use a similar positive electrode as Nickel Cadmium cells (Nickel hydroxide) and alkaline potassium hydroxide electrolyte.

Anode: Nickel Hydrogen cell uses H_2 as the active material for the negative electrode. The anode resembles a fuel cell electrode. When discharged, H_2 is absorbed by Nickel hydroxide (to form nickel oxy-hydroxide). Hydrogen gas remains within the cell during charging, attaining very high pressures of up to about 70 bar.

3.2.3 Advantages and shortcomings

Some advantages of the nickel-hydrogen battery include lightweight with high gravimetric energy density, high cycle life (50,000 cycles is typical), virtually maintenance-free with 15 years lifespan and is capable of deep-discharge. However, the shortcomings are low volumetric energy density due to the use gaseous hydrogen, high self-discharge rate, high pressure and robust storage container (due to gaseous hydrogen) and limited applications due to high cost.

3.3 Sodium Sulphur Battery

The electrolyte of the sodium sulphur battery is beta alumina solid electrolyte (BASE). This electrolyte comprises of alternating, closely and loosely packed layers. The loosely packed layers contain mobile sodium ions which are the conduction planes.

The mobile cations are conducted primarily within the conduction layers. At 300°C, beta alumina displays a Na+ conductivity of 0.2–0.4 S/cm making it a good solid-state Na+-conductor.

Liquid sodium is the anode while the molten sulphur is the cathode. A Tubular sodium sulphur battery is shown in Figure 4.

3.4 Disadvantages

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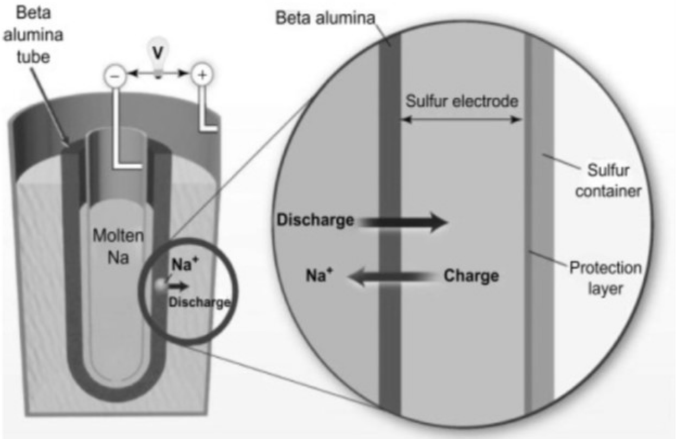


Figure 4. Tubular sodium sulphur battery (Shripad, 2019)

3.5 Lead-Acid Battery

The lead-acid battery was first proposed in 1859 by French physicist Dr. Plante (Day, 2019). It was the first type of rechargeable battery and is still relevant today in stationary power, automobile auxiliary power units and wheeled mobility aids. In the lead-acid battery, lead is the anode while lead dioxide is the cathode. A sulphuric acid-water solution serves as the electrolyte.

Lead-battery can be classified into two groups: Flooded type, relatively cheap and common in automotive and industrial applications; Sealed type, also referred to as Valve-Regulated Lead-Acid. This type is being adopted for stationary power.

The power and energy capacities of lead-acid batteries are functions of the size and geometry of the electrodes. Power capacity is improved through an increase in the surface area of each electrode.

The low-cost and high power coupled with the ease of recyclability are advantages of the lead-acid batteries. A major drawback however is the decrease in usable capacity when high power is discharged.

3.6 Fuel Cell

A fuel cell is an electrochemical cell, which can continuously convert the chemical energy of a fuel and an oxidant to electrical energy. It promises higher efficiency power generation with low environmental impact. Fuel cells are reliable and require low maintenance. NASA's Space Shuttle Orbiter fleet had a single fuel cell stack, with no backup, as the sole source of electricity and drinking water (NASA, 2010). The basic chemistry of fuel cell is very similar to those of electrochemical cells, it is illustrated in Figure 5.

In a fuel cell, the chemical energy is provided by a fuel and an oxidant which are stored outside the cell while the chemical reactions occur inside the cell. Steady power is guaranteed from the cell as long as the supply of fuel and oxidant is maintained. This is a sharp contrast with primary and secondary batteries where the chemical energy is stored inside the cell and the battery must be thrown away or recharged once the fuel and oxidant are depleted. Though fuel cells could, in principle, process a wide variety of fuels and oxidants, of most interest today are those fuel cells that are readily available and use ambient air as the oxidant. The most popular fuel cell today is the Polymer Electrolyte Membrane Fuel Cell (PEMFC or PEM). This fuel cell type is

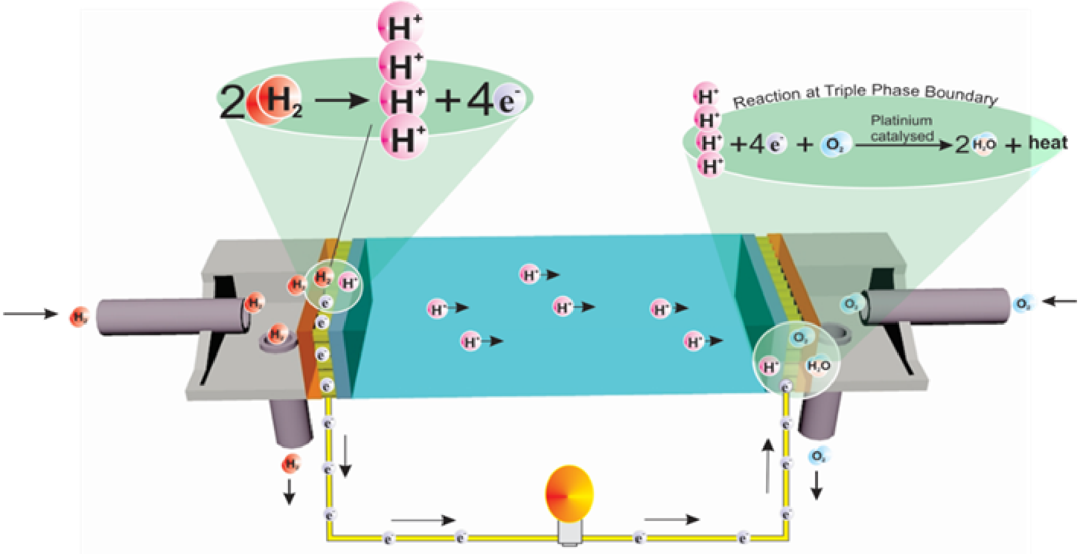


Figure 5. Principle of the Hydrogen fuel cell

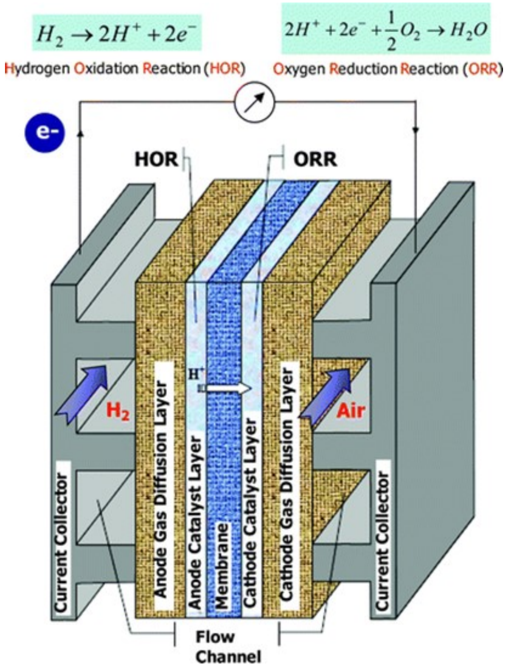


Figure 6. Schematic illustration of a polymer electrolyte fuel cell (Mukherjee et al., 2010)

3.6.1. Fuel cell types

Fuel cells are typified by the temperature of operation, the type of electrolyte system in place or the type of fuel. Based on operating temperature (T) fuel cells can be categorised as:

Low-temperature fuel cells (T<300°C): examples include Polymer electrolyte membrane fuel cells (PEM) with T<100°C and Phosphoric Acid Fuel Cell (PAFC) with T~205°C.

Intermediate temperature fuel cells (300°C<T≤650°C): an example is the molten carbonate fuel cell (MCFC) with T of about 650°C

High temperature fuel cells (800°C≤T≤1000°C): an example is the solid oxide fuel cell (SOFC) with T of about 800 °C.

Based on the type of electrolyte, the categorisation is more diverse more instructive as it provides information about the cells' electrochemistry. This includes:

i. Polymer Electrolyte Membrane (PEM);
ii. Alkaline Fuel Cell (AFC);
iii. Phosphoric Acid Fuel Cell (PAFC);
iv. Molten Carbonate Fuel Cell (MCFC);

v) Solid Oxide Fuel Cell (SOFC).

Based on the type of fuel, fuel cells can be categorised as:

Direct Methanol Fuel cell (DMFC)
Direct Carbon Fuel Cells (DCFC)
Microbial Fuel Cell (MFC)

3.6.2. Spin-Off from Fuel Cell Technology: The Metal-Air Battery

The quest for energy storage systems with high energy density has led to renewed interest in the metal -air battery. This class of cells benefit from the absence of an on-board store of oxidant. This frees up space within the cell for the increase in the volume of metal (anode) that can be packaged in the cell. The oxidant is the ambient surrounding air and it is reduced at the air cathode. Metal-air cells have to be mechanically recharged when the anode is depleted. Several types have been proposed, such as lithium-air, sodium-air, zinc-air, magnesium-air, aluminium-air and potassium-air batteries. All of them have very high theoretical energy density about 2-10 folds higher than that of lithium-ion batteries and enables a much lighter cell. Thus metal-air cells are promising candidates for next-generation power of electric vehicles (Linden, 2002).

4.0 The Global Energy Conundrum

Population growth and rapid economic development is expected to accelerate global energy demand considerably in the years to come (EIA, 2007). Many countries are actively upgrading the lifestyle of their people from peasant and agrarian to more urbane and industrial living. The largest of these increases in demand for energy will take place in third world countries. Due to this, global energy consumption should likely increase between 46 to 58 percent from 2004 to 2030 (EIA, 2007), ostensibly due to improved way of life of the people.

The situation in industrialized countries is not expected to be so dramatic. Here, national economies are more mature and population growth is relatively low. Thus, the demand for energy is expected to grow at a lower rate of 0.9 percent per year.

4.1 The Climate Emergency

There is general consensus that the planet is warming up, and a switch to cleaner energy is now more politically correct. Despite all the progress made in recent years to effect the switch, the world is still struggling to hit the pause button on the global climate emergency. It seems the centuries old habit of relying on cheap carbonaceous fuels is difficult to kick. As a consequence, the world is actually moving in the wrong direction with regards to halting its dependence on fossil fuels. The BP Statistical Review of World Energy (2019) aptly summarises the present scenario:

Oil consumption increased by 1.4 million barrels per day
Globally, oil production increased by 2.2 million barrels per day.
Average refinery utilization reached to its highest level since 2007

Global carbon emissions are not falling, rather increased up by 1.7 % in 2018 (IRENA, 2019). Also, subsidies to fossil fuels increased by 11% between 2016 and 2017 translating to $300 billion a year. The silver lining for clean energy in the midst of all this was that as of April 2020, in America (a major carbon emitter) more of the electricity was traceable to clean energy than coal for the very first time ever (Institute for Energy Economics and Financial Analysis, 2020). However, the Global Sustainability Report (International Symposium on Renewable Energy and Sustainability, 2020) still showed total renewable energy investments (minus hydropower) was about $288.9 billion in year 2018 — a figure that is less than the subsidies for fossil fuel and an 11 % reduction from 2017.

4.2 Current Status of Global Renewable Power

The rise of renewable energy is seemingly unstoppable in the power sector, with the electricity sub-sector leading the way. Globally, the installed renewable energy capacity has surpassed the combined new fossil fuel and nuclear capacity. This has persisted for the past four years. In 2018, about 181 GW of new renewables capacity was installed (Roberts, 2019).

Solar photovoltaics (PV) are the most prominent renewable energy technology so far. Solar PV makes up the majority of additional capacity of deployed renewable power technology. In 2018, it topped with about 55% of installed capacity, while wind and hydropower followed at 28% and 11% respectively (Roberts, 2019). One can say that the growth in renewable power as a whole globally is tied to the growth of solar PVs.

Renewables are beginning to make impact on electricity, albeit still small. All the growth and investments in renewables are beginning to be impactful. Renewables now constitute over a third of the global installed capacity that is, more than 26 % of global electricity generation (REN21, 2019).

Outside of electricity generation, renewables are however not doing so well. Whereas renewables constitute about 26 % of global electricity, however they are still less than 10 % of the energy used for heating and cooling and just 3 % of transportation energy (REVE, 2019).

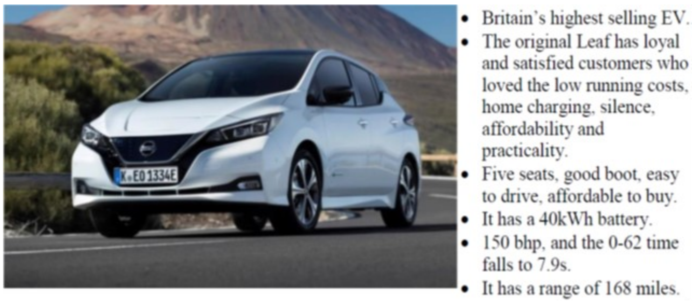
To put the situation further into context, heating and cooling consume 51 % of global energy and mostly run on natural gas and oil, while transportation which consume 32 % mostly run on petrol and diesel (Prescriptive Data, 2019).

5. The Re-Imagination of Roles for Electrochemical Power

Roles that were hitherto the strongholds of traditional power conversion technologies are now being taken over by EP. These are discussed below.

5.1. EP in Automobiles

Cleaning up the automobiles sector of polluting carbonaceous fuels for long has been a challenge. However, in the last decade, there has been a surge in momentum. This is evidenced in the scale-up of Electric Vehicle (EV) development and lower battery costs. A total and global shift towards electrification of the automobile sector is underway with many countries passing legislation to phase-out the internal combustion engine by the middle of this century. As of 2018, electric passenger cars rose 63% globally compared with 2017 (IEA, 2019). China and Norway lead the rest of the world, in ambitious EV programs. This drive is being aided by the continual drop in battery cost due to concerted R&D efforts and maturing of system component technologies. The cost of EV batteries dropped by 73% between 2010 and 2016 (IRENA, 2017). At year-end 2016, the total stock of electric cars had reached 2 million (IEA, 2017). Smaller EVs (two and three wheelers) have had their numbers surpass 250 million globally, while about 300 000 electric buses ply the streets of China (IRENA, 2017). Figures 7 to 9 show some of the pioneering EV models leading the renewed charge in the EV market.

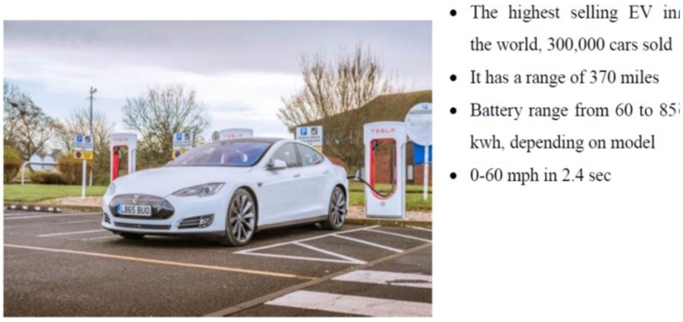


- Britain's highest selling EV.
- The original Leaf has loyal and satisfied customers who loved the low running costs, home charging, silence, affordability and practicality.
- Five seats, good boot, easy to drive, affordable to buy.
- It has a 40kWh battery.
- 150 bhp, and the 0-62 time falls to 7.9s.
- It has a range of 168 miles.

Figure 7. 2018 Nissan leaf (Second Generation) (BBC Top Gear, 2020)

- The car drives its front wheels with a 118 bhp, 194 lbft electric motor
- It has a 28kWh lithium-ion polymer battery.
- In Eco and Normal mode, this means 0-62 mph in 10.2 seconds.
- Maximum claimed range is 174 miles

Figure 8. Hyundai Ioniq Electric (Williams, 2016)



- The highest selling EV in the world, 300,000 cars sold
- It has a range of 370 miles
- Battery range from 60 to 85 kwh, depending on model
- 0-60 mph in 2.4 sec

Figure 9. Tesla Model S (Car Magazine, 2018)

5.2 EP in Aeroplanes

EP faced significant difficulties making an in-road into the aviation sector. This is due to two factors: Safety concerns of state-of-the-art lithium-ion battery and the low energy density of existing rechargeable battery technologies:

i. Safety concerns of Lithium-ion battery:

Safety concerns of state-of-the-art lithium-ion battery, the most promising candidate for the aviation sector, gives cause for concern and keeps regulators reluctant to grant approval for its large-scale deployment in the aviation sector in general. These safety concerns stem from the risk of internal short-circuit between electrodes due to production defects and dendrite growth. This is further exacerbated by the use of organic aprotic electrolytes which are highly flammable. This increases the flammability and explosion risks of the lithium-ion battery. This nightmare scenario was played out in United Parcel Service 747 cargo flight carrying 80,000 lithium-ion batteries en route to Dubai in September 2010 (The Associated Press, 2014). The lithium-ion batteries experienced thermal-runaway, and a mid-air fire and explosion in the battery pack occurred. This caused the plane to crash-land with very tragic outcomes.

ii. Low energy density:

This a major stumbling block in the application of lithium-ion battery in the powering of aeroplanes. The intercalation required to make the lithium-ion battery rechargeable severely restricts the density of lithium that can be sequestered inside the cells. An inordinately large number of Li-ion cells would thus be required to power an aircraft propulsion system. This, coupled with the weight of an electric propulsion system makes the deployment of EP in aeroplanes slow to really take off.

However, these challenges notwithstanding, R&D into the use of EP in aeroplanes is unabating. The new Boeing 777 has an on-board Li-ion power bank (Saft, 2018) while an EP-powered Airbus E-Fan prototype, successfully crossed the English Channel on the 10th of July 2015 (see Figure 10).

5.3. Application of EP in Motorcycles

The low power density of EP systems such as Li-ion is especially problematic in motorcycle propulsion. This is because there is limited on-board space in the motorcycle chassis to stack enough cell units to satiate the demand for range and assuage range anxiety. These concerns are however being addressed by the use of regenerative braking and smaller, energy-efficient induction motors. These have made the deployment of EP in motorcycles feasible. Harley Davison motorcycle have recently debuted the "LiveWire" electric motorcycle (Kamli, 2019) shown in Figure 11.

5.4 Storage for Stationary Power and Distributed Generation

Electricity storage enables a high degree of flexibility in stationary power and distributed generation. EP provides the means for electricity storage, and this has the prospect of radically changing the dynamics of future energy mix. Storage brightens the outlook of very large array solar PV, solar thermal, wind and other energy technologies prone to seasonal or even daily fluctuations in peak output. Electricity storage will even be more important in the future with the deeper penetration of EVs. The much vaunted 100% renewable minigrids require cheap EP storage on rapidly improving batteries and other technologies.

Globally, battery capacity for stationary power is currently about at 11 GWh. This is expected to grow to about 100 GWh to 167 GWh by 2030. According to IRENA (2017), energy transition by 2050 will lead to more than 80% of the world's electricity supply to be derived from renewable sources with Solar PV and wind power constituting about 52%.

Electricity storage capability can help to reduce strain on the existing transmission network, deferring the need for major investments in infrastructure. With the very high shares of wind and solar PV expected beyond 2030, the need for long-term reliable and affordable energy storage becomes pertinent to smoothen supply fluctuations.

5.4.1 Home Battery

The home battery sphere is a burgeoning area of application of EP to medium-sized homes. This space has LG Chem Ltd. and Tesla Powerwall as the leading exponents. LG Chem Ltd. Is a major player in the lithium-ion battery industry, with about 29,000 employees globally. It's Residential Energy Storage Unit (RESU), shown in Figure 12, consists of 400 volt and 48 Volt options. Tesla's Powerwall (Figure 13) combined with solar PV, will continue to power the home and recharge. Powerwall's usable capacity is 13.5 kWh and costs about $ 6700 (Solar Guide, 2020).

5.4.2 Large scale grid storage

Large scale grid storage is now a reality with EP. Large scale grid storage is used primarily to level loads in peak periods and to store excess power during off-peak. These have proved vital in fast growth population centres areas with that require urgent roll-out of power solutions. The largest battery bank in the world with a capacity of 129 MW was built by Tesla in Hornsdale, South Australia (Figure 14). It can serve 30,000 homes for one hour, though it is intended for use in the support and stabilisation of existing electricity supplies (BBC, 2017). These mega-sized installa-

Figure 10: Airbus E-Fan prototype crossing the English Channel on July 10, 2015 (Gorrasi, 2019).

- The LiveWire motorcycle features a high-voltage battery (Rechargeable Energy Storage System)
- Range is 98 Miles (158 km)
- 0 – 60 mph in 3 sec

Figure 11: Harley Davidson LiveWire (Kamli, 2019)

Figure 12: LG Chem's RESU installed for residential power (Casey, 2019)

Figure 13. Tesla Powerwall (Golson, 2017)

Figure 14: The world's largest lithium-ion battery installation, Tesla's 129 MW/h Megapack in Hornsdale, South Australia (CleanTechnica, 2020).

tions are popping-up in many places as existing grids struggle with increased demand for power.

6. Thoughts from Obafemi Awolowo University, Ile-Ife

The team at Obafemi Awolowo University, Department of Materials Science and Engineering has been focused for the past decade on the development of the alkaline fuel cell (AFC) technology. The decision was made early on for the following reasons:

i) The electrolyte is readily and cheaply available locally. This is very significant. The main competing low-temperature fuel cell, the PEM, relies on expensive solid polymer electrolyte, Nafion®. This solid electrolyte cannot be used in the completely dry state, it requires some degree of hydration to realise its ionic conductivity. However, too much hydration will result in electrode flooding, too little will increase ohmic resistance. The PEM is also susceptible to mechanical tear and the very real danger of reactant crossover.

ii) The main problem of the alkaline electrolyte is it contamination by carbon dioxide. CO_2 forms potassium carbonate which blocks the pores of the GDE. However, this problem only occurs when ambient air is used as the oxidant stream instead of pure oxygen. The problem of the carbonate formation is easily solved in the mobilised AFC system where the circulating electrolyte is passed through a filtration system at the end of every cycle.

iii) The AFC technology is fully mature and it is the fuel cell that has proved its reliability the most of all the fuel cell systems. It was the ONLY power unit, without backup, on-board the US Space Shuttle orbiter fleet. It was relied upon to provide power and water for manned space missions that can last up to two weeks at a time.

The quest to use less exotic and expensive materials and readily available material has been a major consideration. It was considered that long-term viability of the EP power in the country will have to depend of materials that are not difficult to procure locally.

The team was also interested in developing sustainability and competencies in the design and construction of custom fixtures and instrumentation. This is because in EP research, there are often no turnkey solutions and fixtures to conduct test and evaluation of cell. Hence building custom circuits and test fixtures were prioritised from the beginning. Key milestones attained are presented in the following sections.

6.1 Development of Button Cell Apparatus and Test Station

A test station was designed and constructed for the evaluation of AFC at different electrolyte concentrations and temperature. AFC button cells can be evaluated from room temperature to 90°C. The unit comprised of a button cell test apparatus with variable electrolyte distance, an electrolyte heater and electronic load. These were reported by Aremo *et al* (2015) and are shown in Figures 15 and 16. This coupled with custom button-cell fabrication fixtures and methods enabled the production of mesh-supported 3-ply gas diffusion electrodes.

6.2 Development of Conventional Gas Diffusion Electrode

Based on the works of Gharibi *et al*. (2005), conventional 3-ply gas diffusion electrodes for oxygen reduction reactions (ORR) were produced. This was fabricated around a nickel-plated woven mesh current collector produced locally as shown schematically in Figure 17. The performance of the GDE at different carbon-supported platinium electrocatalyst concentrations, different electrolyte concentrations and different electrolyte temperatures were evaluated in aluminium-air configuration using the test station previously developed and were reported by Aremo *et al*. (2015). The polarisation curve for the GDE between 1 and 5 M KOH is presented in Figure 18.

6.3 Co-deposition of Composite Nickel-Graphite Thick Film

A novel co-deposition route for the co-deposition of nickel and graphite was developed. This was reported by Aremo *et al.* (2019) and it is illustrated in Figure 19. The film shown in Figure 20 has been trialled for the production of advanced air-cathodes and showed promise in facilitating ORR.

6.4 Cell Miniaturisation

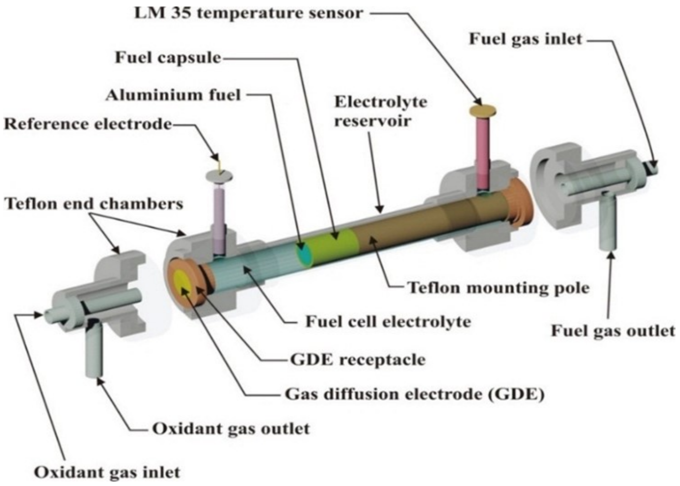


Figure 15. Button-cell test apparatus (Aremo *et al.* 2015)

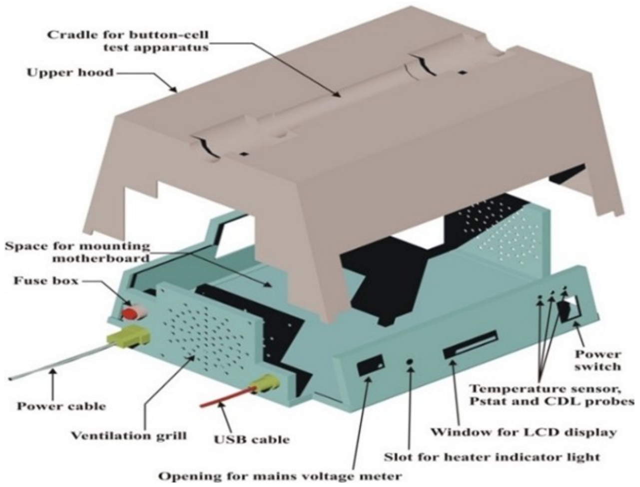


Figure 16. Exploded assembly of Test Station (Aremo *et al.* 2015)

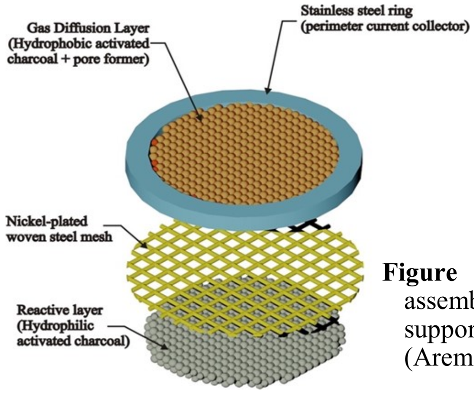


Figure 17. Exploded assembly of a mesh-supported GDE (Aremo, 2012)

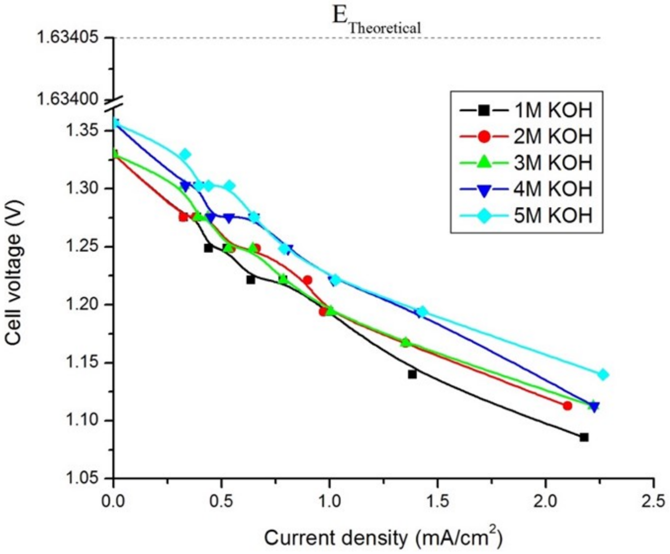


Figure 18. Polarization curves for Al-air cell (room temp.) between 1 and 5M KOH (Aremo *et al.* 2015)

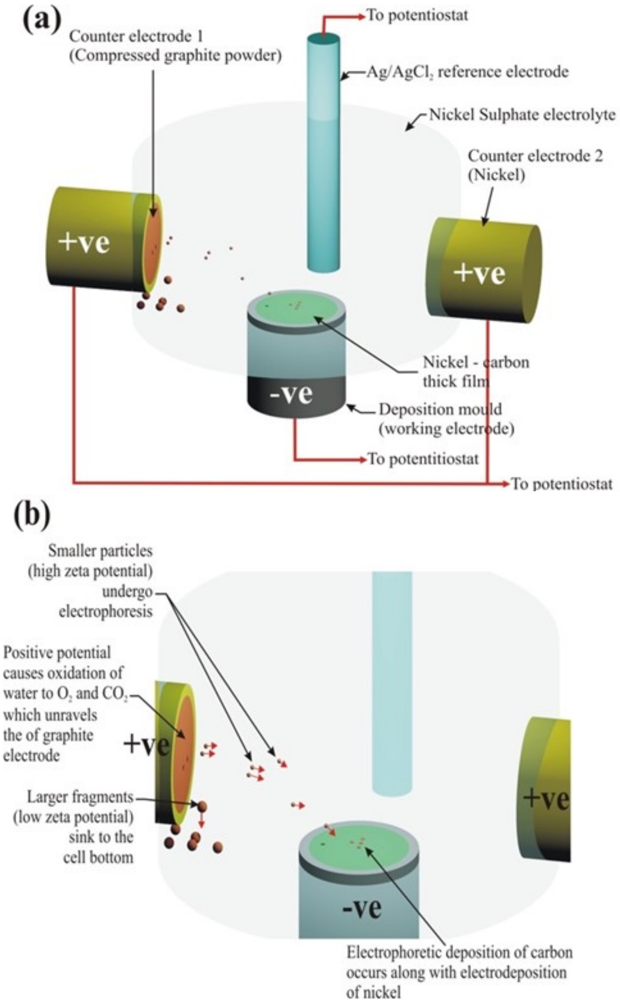


Figure 19. Setup for potentiostatic co-deposition.

Miniaturisation is being pursued earnestly and a few prototypes have been produced. These include a small-footprint 17 × 5 mm unit and a mechanically rechargeable unit. Both of these configurations are based of zinc-air cell. This is shown in Figure 21. Further work on improved electrolyte chemistry and catalyst utilisation is on-going for these prototypes.

6.5 Enhancement of Output Current Density from the Cell

Low output current is the bane of air-breathing metal-air cells. This is because current is directly proportional to the effective surface area of the electrodes. The output current of a zinc – air cell was significantly enhanced by developing a 3D zinc-entrained anode. This was reported by Okuwa *et al*. (2019). SEM micrograph showing the entrained zinc in an activated charcoal matrix is shown in Figure 22, while the polarisation curves for the 3D anode and a conventional one is shown in Figure 23.

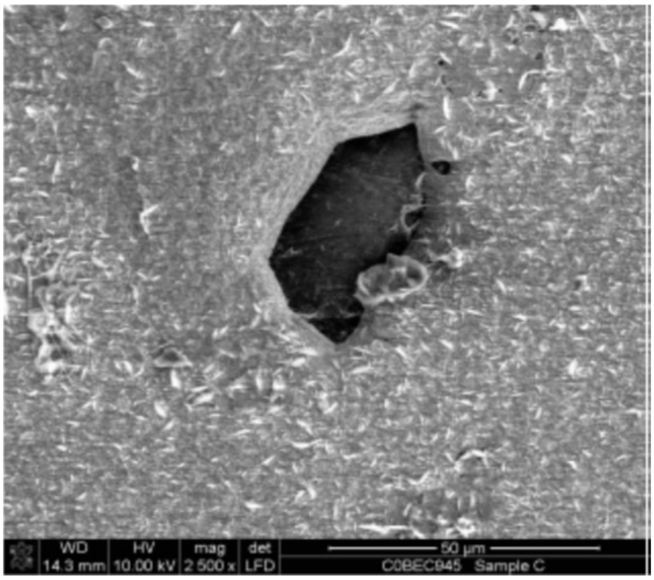


Figure 20. SEM micrograph (2500×) showing co-deposited graphite in a nickel matrix (Aremo *et al*., 2019)

6.6 Future Trajectory

Our team is desirous of pursuing the following strategic R&D trajectory in the short and medium term:

High energy density, low-cost MAFC: At present, metal-air systems only serve in fringe, low-power applications such as hearing aids because of their typical low-current output. The prospect of high current output in metal-air cells was highlighted by Okuwa *et al*. (2019) through the development of 3D zinc-entrained anode. This will be a focus in the short-term and will be developed further for mainstream, non-technical end users. This will occur with the development of cheap stack construction materials to

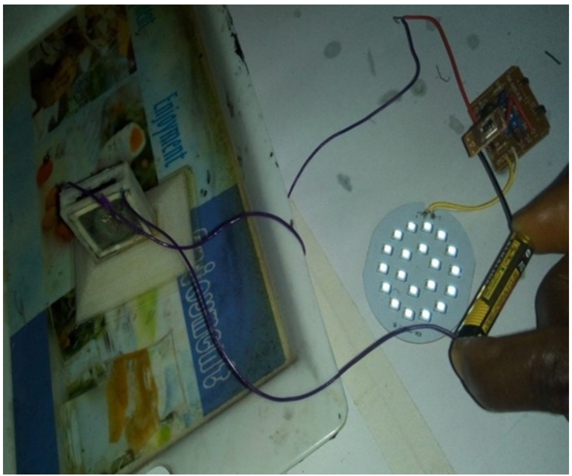


Figure 21. Miniaturized (25 by 25 by 4 mm) 1.4 V zinc-air cell Zn – air in series with a primary cell powering a lamp

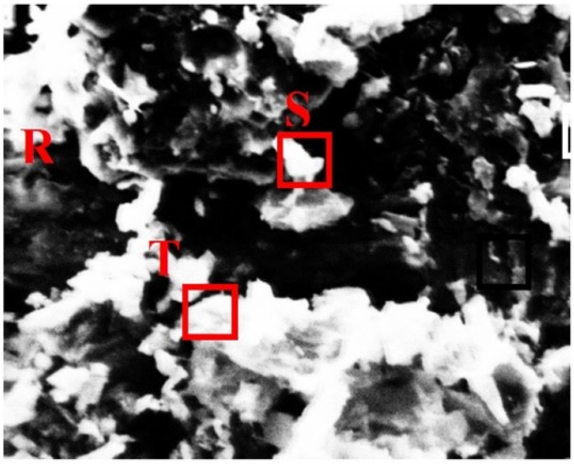


Figure 22. SEM micrograph of entrained-zinc anode at 1000× (Okuwa *et al.* 2019)

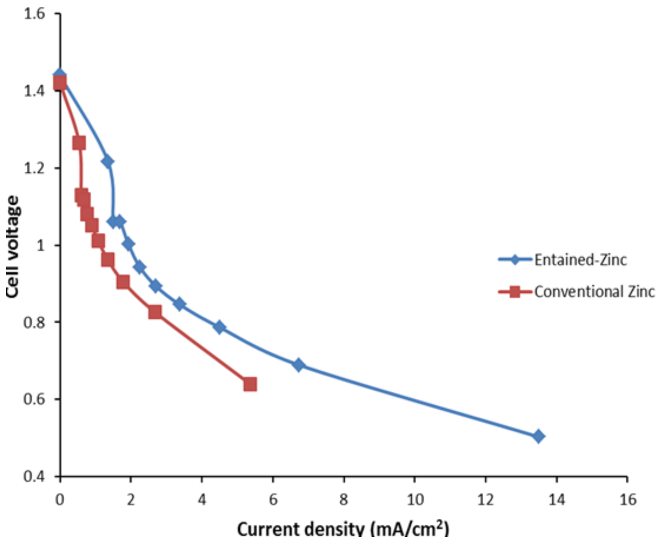


Figure 23. Polarisation Curve Comparing the performance of Entrained-zinc and Conventional Zinc Anode (Okuwa *et al*, 2019)

make it competitive with existing primary cells technology.

Kilowatt-scale EP fuel cells: Kilowatt-scale fuel cell stack providing power for residential users will be a focus in the midterm. This will additionally serve as a test bed for the development of utility support and mini-grid EP systems. These systems such as power conditioning and balance of plant are considered invaluable for grid-scale EP.

Alternative fuels: Development of alternative fuels such as bio-derived fuels from the by-products of agricultural processing is being investigated. This will further cement the “green” credentials of the fuel cell EP system.

Robust multi-disciplinary team building involving academia, graduate and undergraduate students, together with industry partners are necessary in the attainment of these goals. This is being earnestly cultivated.

7.0 Conclusions

There is no doubt that the forward march of EP into the future is unstoppable. In fact, the future is now! The EP takeover is quietly occurring all around us. Hybrid electric vehicles are now commonplace and the proliferation of solar PV augmented with cheap EP storage is encouraging more households to jump on the renewable energy bandwagon.

There is need for concerted efforts to support R&D and the local production of core EP technologies such as batteries and BOP. The country cannot afford to be left behind. Virtually all the batteries used at all levels, from TV remote control to laptops and automobiles are imported. This has to change to forestall the country’s perpetual reliance on external entities for its future energy needs. EP is a multi-billion-dollar industry, and the employment potentials are immense. A foray into EP development in the country will be a win-win for both the environment and the citizenry.

Electrochemical power is only just getting started in the permeation of modern society. It is of utmost importance that Nigeria is not left behind.

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