CLEAN ENERGY

A. Q. CONTRACTOR

A significant source of air pollution, so visible in our urban centers, is emissions from motorized vehicles. This article describes a clean energy approach to vehicular transport. Solar energy can be harnessed to produce hydrogen, which can be converted to electricity on-demand to drive electric vehicles.

Humans, most likely, first started harnessing energy for their use by learning to keep fires (discovered accidentally) alive. The fuel to feed these fires may have initially consisted of dead leaves, twigs and branches from the forest floor. Once the technology for the necessary tools became available, humans may have graduated to chopping down trees for fuel. With the discovery of coal and peat, we had access to fuels with much greater energy density (amount of energy stored per unit volume of a given mass of substance) in seemingly limitless supply. Coal powered the Industrial Revolution in 18th century Europe. Early automobiles were powered by steam engines which used coal as fuel. The invention of the internal combustion engine made liquid fuels like gasoline or petrol important. The discovery of vast reserves of oil has transformed almost every aspect of modern life to such an extent that we have become addicted to it.

Our consumption of energy has increased significantly. In fact, per capita energy consumption is considered one of the measures of 'development'. However, today, as the consequences of this excess are being experienced in terms of air quality, Global Warming and Climate Change, we need to seek 'cleaner' fuels.

Deriving energy from hydrogen

Ideally, a fuel should combine two properties — high energy density, and the ability to burn cleanly and efficiently. Of course, there can be no such thing as an 'ideal' fuel. While carbonaceous fuels — like coal, oil and gas — have high energy densities; 'clean' fuels do not produce greenhouse gases (GHGs), suspended particulate matter (SPM), or oxides of sulphur and nitrogen (refer **Box 1**). Among the many alternatives we are currently exploring, hydrogen appears to be

Box 1. GHGs and SPMs:

Greenhouse gases (GHGs) refer to those gases in the Earth's atmosphere that absorb infrared rays reflected from its surface, preventing them from escaping into space. Their heat-trapping ability results in an increase in surface and atmospheric temperatures. Examples include water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4).

Suspended particulate matter (SPM) is an insoluble mixture of liquids and solids suspended in the atmosphere. Composed of dust, ash, pollen or smoke, SPM is a major contributor to air pollution.

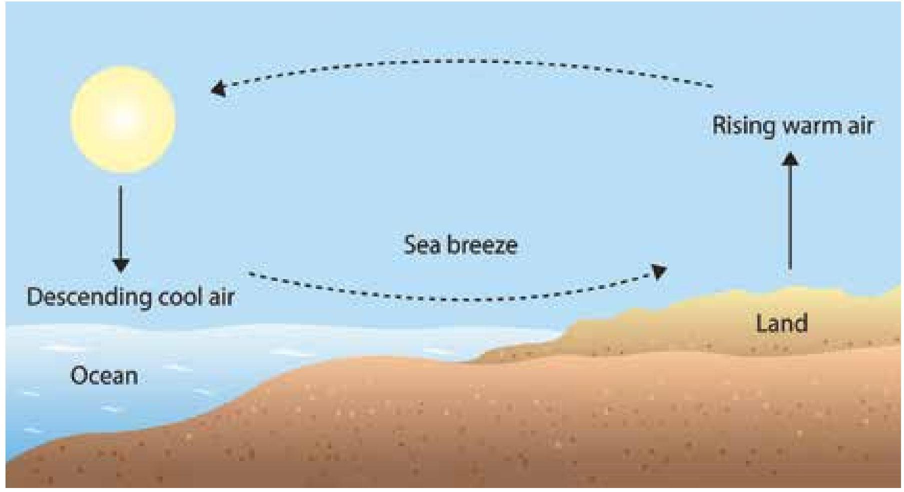


Fig. 1. Local winds are produced by the differential heating of land and sea by the Sun.

Credits: Adapted from an image by Crystal Wicker on Weather Wiz Kids. URL: http://www.weatherwizkids.com/weather-wind.htm.

promising as a clean fuel. It has a high energy density — almost three times as much as oil per unit weight. Also, on combustion in air, it produces water, not GHGs or SPMs.

The idea of using hydrogen as a source of energy was first proposed by J. B. S. Haldane in 1923. Then, in 1970, John Bockris used the term 'Hydrogen Economy' to describe the possibility of a global economy powered not by carbonaceous fuels, but by hydrogen. This calls for the invention of new technologies for the production, storage and utilization of hydrogen as a fuel. Unfortunately, molecular hydrogen is not freely available in nature. While it can be produced by splitting water into hydrogen and oxygen by electrolysis, how does one derive electricity from it in a manner that does not harm the environment?

Like with most things, nature provides a clue — the Sun is the ultimate source of energy for all life on Earth. Thus, energy can be harvested directly from sunlight using devices called photovoltaic (PV) cells; or, indirectly from wind power, produced as a result of the uneven heating of the earth's surface by the Sun (refer **Fig. 1**).

The energy harvested through either of these approaches can be converted to electricity (refer **Fig. 2**). Solar energy may need to be stored for use at night or on days with poor sunlight. Chemical storage as hydrogen is one of the most stable ways of doing this. Another option is to use the electrical energy from PV cells to charge a secondary battery like the lead-acid batteries used in automobiles, or a version of lithium cells used in portable devices (e.g. mobile phones, laptops etc).

Electricity can be stored in rechargeable batteries or used to electrolyze water to produce hydrogen and oxygen (refer **Fig. 3**). While burning hydrogen in a combustion engine would be too dangerous for normal use, it can be 'combusted' in a fuel cell to produce electricity as and when required.

Photovoltaic (PV) cells

These are devices capable of converting the energy from sunlight (~photo) into electricity (~voltaic) through a phenomenon called the Photoelectric effect (refer **Fig. 4**). In this phenomenon, certain materials release or eject electrons or ions (charge carriers) upon being exposed to electromagnetic radiations (such as visible light, ultraviolet, infrared etc.). Capturing the released charge carriers produces an electric current.

Since silicon has a band-gap that is close to optimum for the absorption of solar photons (refer **Box 2**), almost

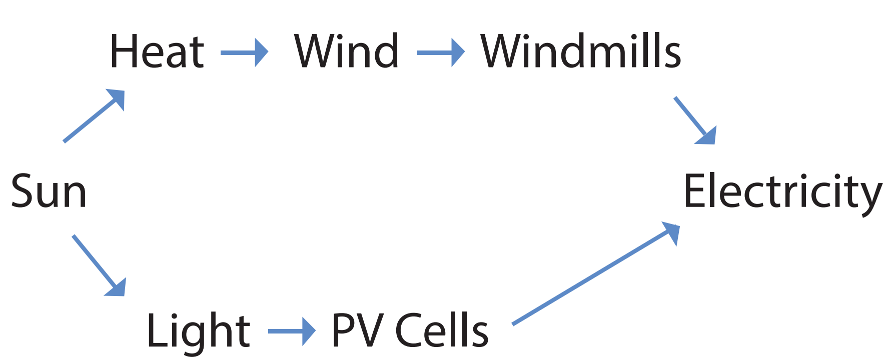


Fig. 2. Harvesting solar energy to produce electricity.

Credits: A. Q. Contractor. License: CC-BY.

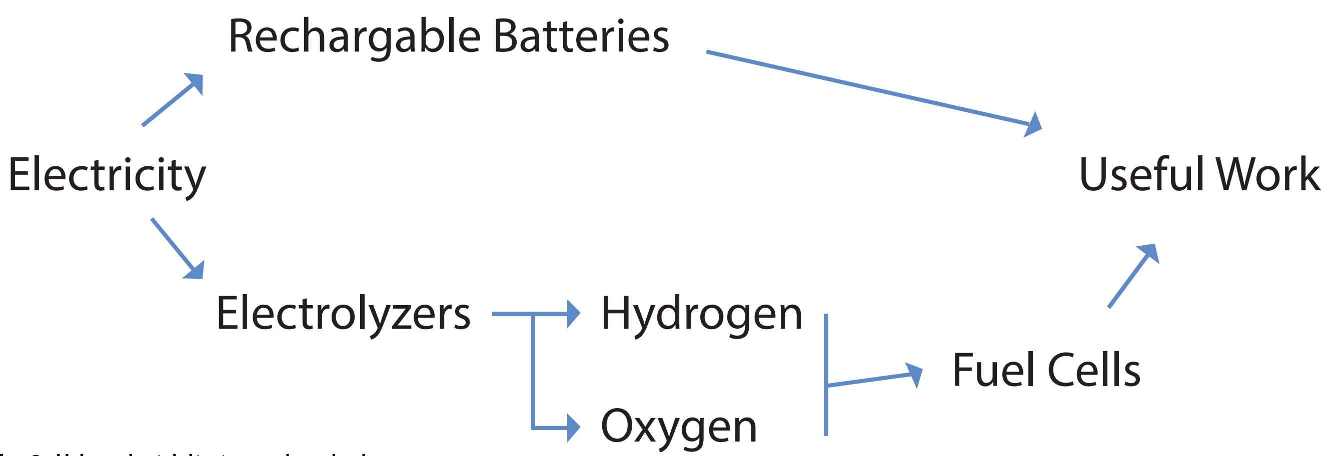


Fig. 3. Using electricity to produce hydrogen.
Credits: A. Q. Contractor. License: CC-BY.

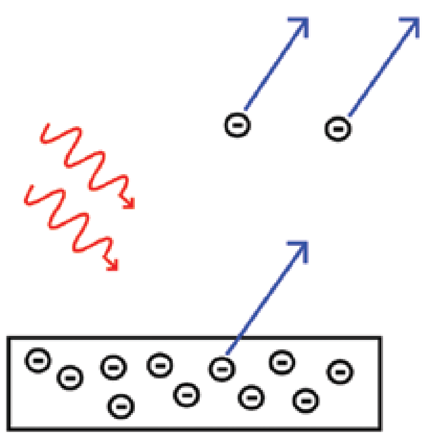


Fig. 4. The photoelectric effect.
Credits: Wolfmankurd, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Photoelectric_effect.svg. License: CC-BY-SA.

all commercially available PV cells are based on crystalline silicon. In a silicon-based PV (Si-PV) cell (refer **Fig. 7**) cell, silicon atoms absorb a photon to release an electron. While the electron drifts to the surface and is conducted away through the silver (Ag) contact, the positively charged electron hole it leaves behind (refer **Fig. 8**) drifts to the aluminum (Al) contact, resulting in the flow of electric current from Al to Ag (refer **Fig. 9**). Since one silicon PV cell produces less than 1 V of electric potential, several of them are aggregated together in a modular form to produce higher voltage.

Box 2. Band gap and Photoelectric effect:

For a material to show the photoelectric effect, the energy required by excited electrons to cross the energy gap between its valence (lower energy electron orbital) and conduction (higher energy electron orbital) bands has to match the energy of a photon (refer **Fig. 5**). The more the number of electrons in the conduction band, the greater the electrical conductivity of the material. While the band gap in insulators is too high, the free electrons in conductors move too randomly to produce an electric current. Thus, it is in semiconductors, with their intermediate band gap, that charge carriers can be excited most effectively (refer **Fig. 6**).

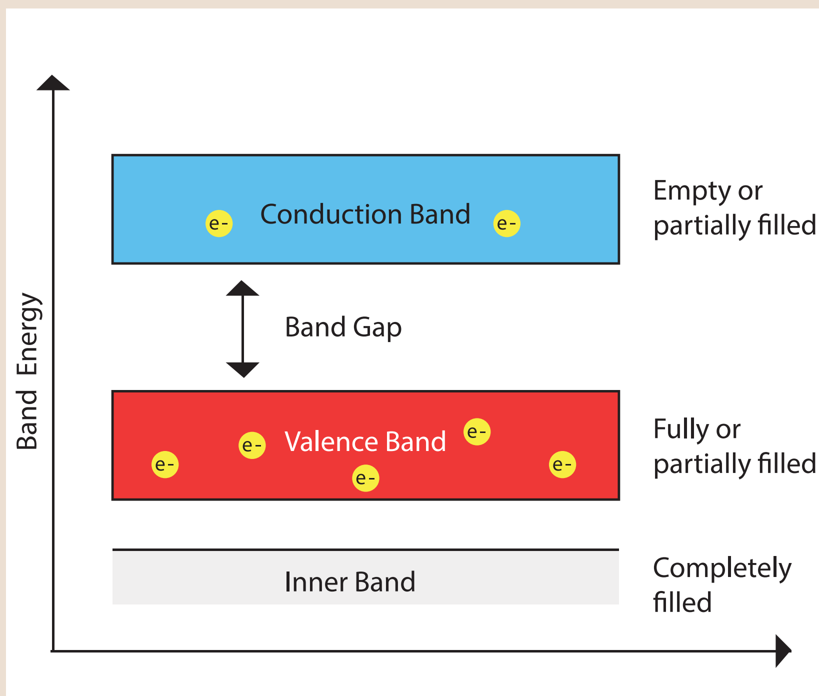


Fig. 5. The energy gap between the valence and conduction bands.
Credits: Adapted from an image on Physics and Radio Electronics. URL: http://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/semiconductor/hole.html.

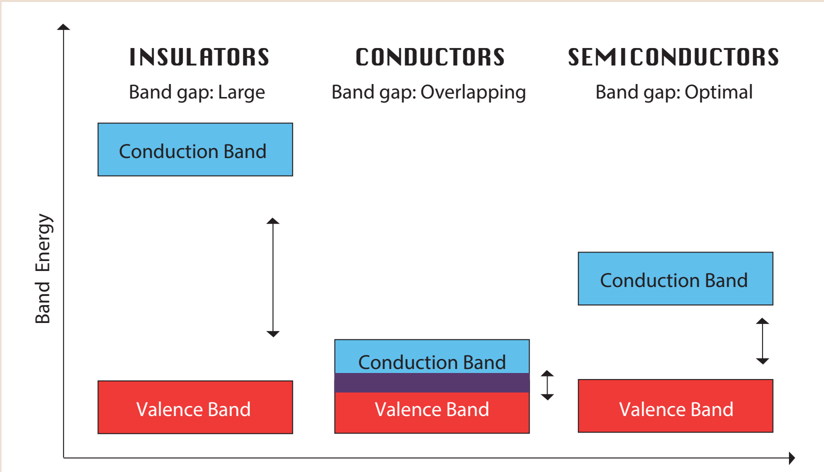


Fig. 6. **The energy gap in a semiconductor makes it the most effective material in a PV cell.**

Credits: Adapted from an image by Pieter Kuiper, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Isolator-metal.svg.

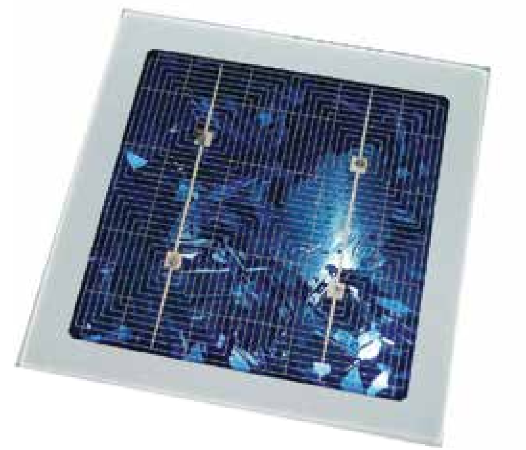


Fig. 7. **A polycrystalline silicon-based solar cell.**

Credits: Nosferatu it (modified by Rogilbert) Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:4inch_poly_solar_cell.jpg. License: CC-BY-SA.

Solar photovoltaic cells have now become a fairly common sight, particularly in street lighting. Panels of Si-PV cells are becoming a popular option for lighting in remote areas that are not connected to the grid, or do not receive an adequate power supply.

Electrolyzers

In the late 18th century, it was shown that water could be electrolyzed to decompose it into gaseous hydrogen and oxygen in the proportion 2:1. This reaction is the basis of modern electrolyzers.

In a typical water electrolyzer (refer **Fig. 10**), a proton-conducting membrane separates the cathode and anode compartments. Electron holes oxidize water to protons and oxygen gas at the anode, while their electrons are accepted by protons from the acidified

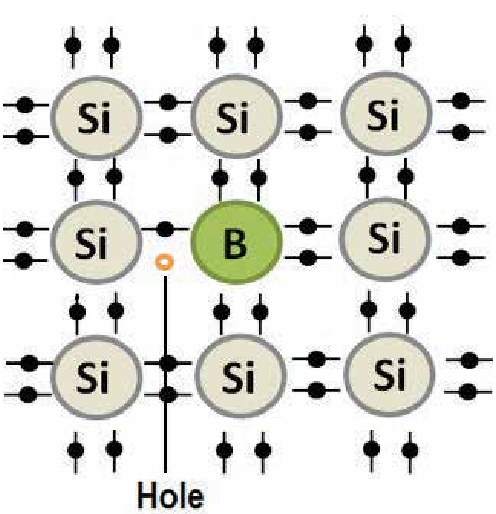


Fig. 8. **The release of an electron from a silicon crystal lattice creates a hole.**

Credits: J.M.K.C. Donev et al. (2018). Energy Education - Electron hole [adapted from HyperPhysics, (August 20, 2015): P and N-Type Semiconductors (http://hyperphysics.phy-astr.gsu.edu/hbase/solids/dope.html)]. URL: https://energyeducation.ca/encyclopedia/Electron_hole. [Accessed: August 28, 2018] License: CC-BY-SA.

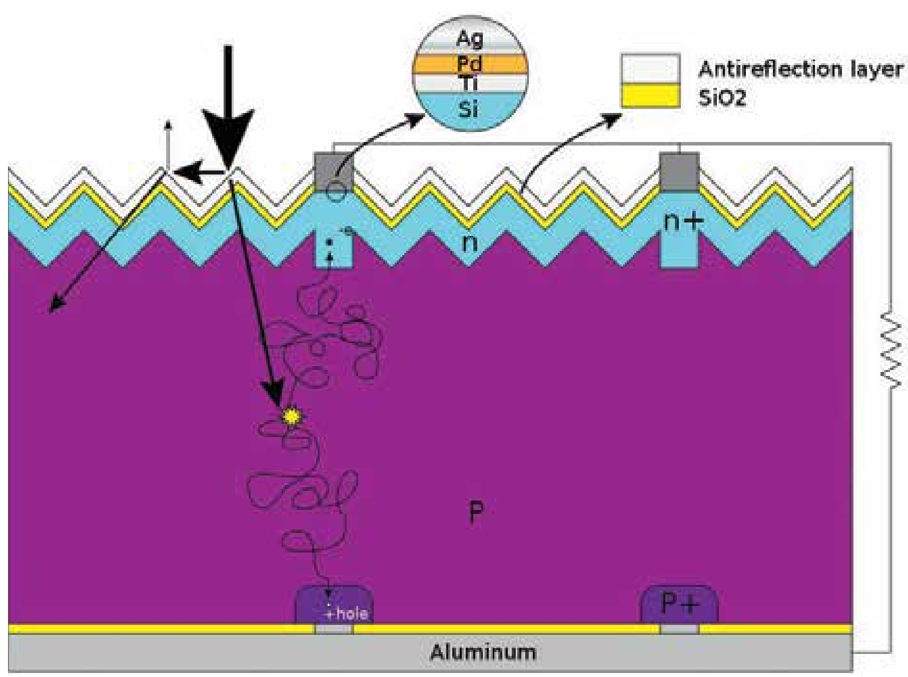


Fig 9. **A cross-section of an Si-PV cell.**

Credits: Cyferz, Wikimedia Commons. URL: https://commons.wikimedia.org/w/index.php?curid=17902127. License: CC-BY.

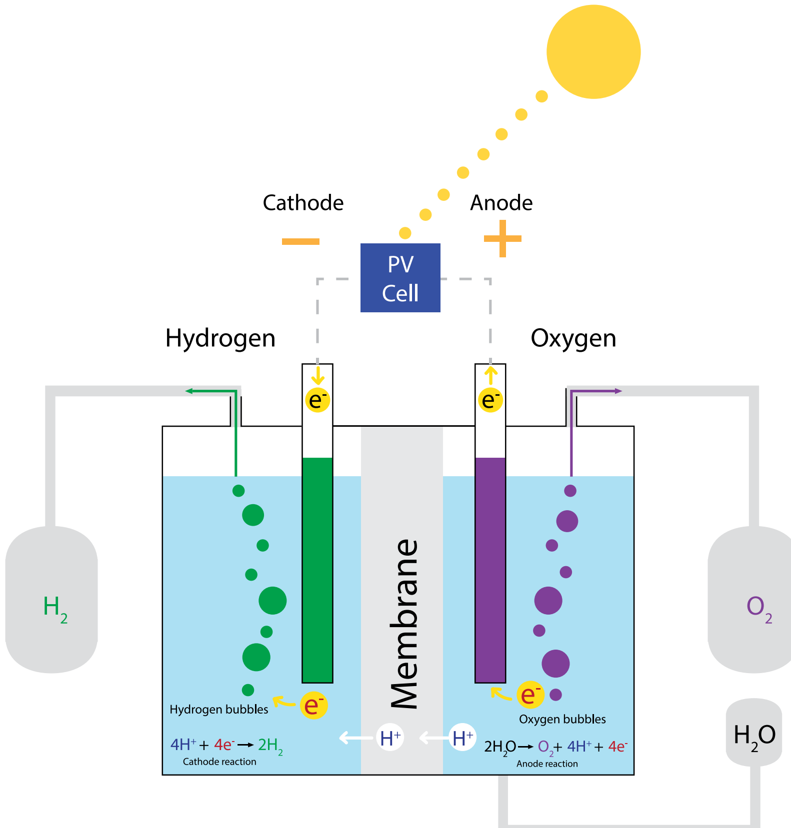
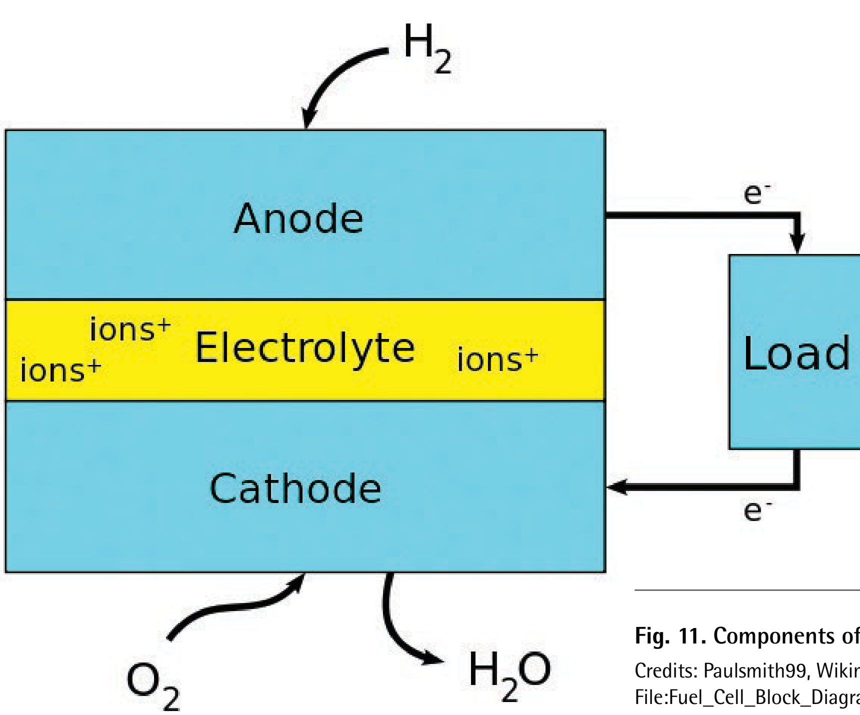


Fig. 10. Schematic of a typical water electrolyzer working on a DC current generated by a PV module.

Credits: Adapted from images by The Office of Energy Efficiency & Renewable Energy, The U.S Department of Energy (URL: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis) and DavidIfritz, Wikimedia Commons (URL: https://commons.wikimedia.org/w/index.php?curid=26251918).



water to produce hydrogen gas at the cathode. Water is continually fed into the electrolyzer to maintain the balance of the volume consumed. The two gases can be stored under pressure in cylinders, or in the lattice of a suitable storage material.

Fuel cells

These devices convert the energy from chemical reactions to electricity and heat. Any fuel cell consists of three adjacent segments — an anode, an electrolyte, and a cathode (refer **Fig. 11**). Chemical reactions occur at each of the two interfaces of this assembly.

Fuel cells can vary depending on the nature of the electrolyte they use. For example, the electrolyte in a proton-exchange membrane (PEM) fuel cell is in the form of an acidic, water-based polymeric membrane (refer **Fig. 12**). Electricity is produced from the energy released by combining oxygen (from the air) with molecular hydrogen (stored in a pressurized cylinder or tank). Since this reaction produces a potential difference of only about 1.23 V between the cathode and the anode, higher voltages are obtained by aggregating many fuel cells together in a modular arrangement similar to that used in PV cells.

$2H_2 + O_2 = 2H_2O$; $\Delta G = -237$ kJ mol^{-1}; 1.23 V

Clean energy for transport

The transport industry is a major contributor to environmental pollution, particularly in urban areas. In fact, the crisis caused by vehicular emission in cities in China and India is frequently a subject of news headlines!

Electric vehicles are being considered as part of a broader strategy towards reducing vehicular emissions that includes improvements in mass transit systems. In fact, some of the earliest cars

Fig. 11. Components of a fuel cell.

Credits: Paulsmith99, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Fuel_Cell_Block_Diagram.svg. License: CC-BY.

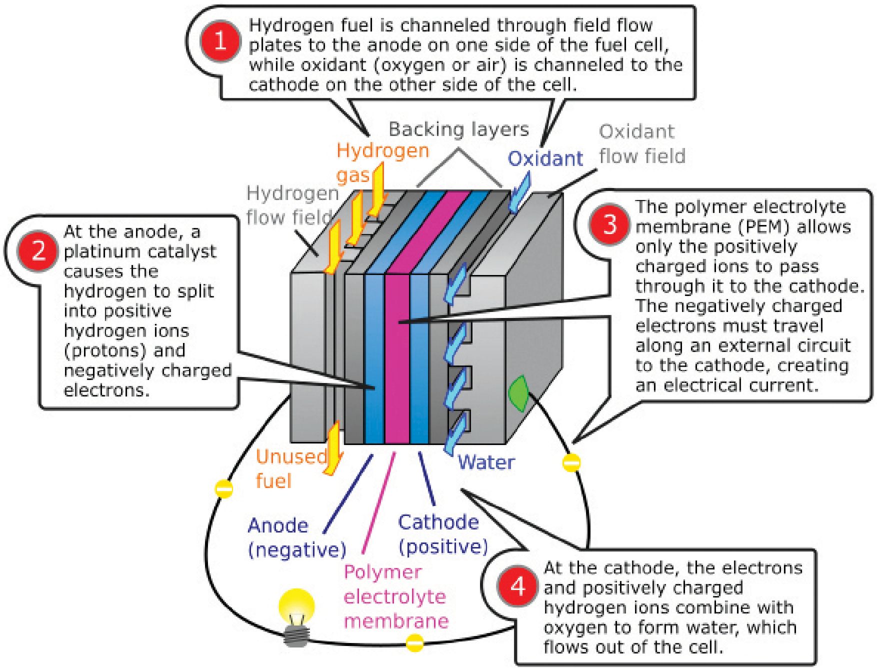


Fig. 12. A proton exchange membrane (PEM) fuel cell.

Credits: Jafet, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File%3APEM_fuelcell.svg. License: Public Domain.

to be built, like Thomas Parker's model in 1895, were also electric! Conceptually, these early models of electric cars are not very different from their current counterparts – both operate on rechargeable batteries. Current models are, however, built with light-weight material, and powered by batteries with much higher energy density and efficiency. Fuel cells could potentially replace rechargeable batteries in electric vehicles.

As of 2011, about 100 fuel-cell based buses have been deployed around the world, with 39-141% greater fuel economy than natural gas or diesel powered buses (refer **Fig. 13**). The use of fuel cells in the automobile sector is a relatively more recent development – the first model was introduced in the market in 2015 (refer **Fig. 14**). While the fuel economy of fuel cell powered cars seems comparable to those powered with rechargeable batteries, the latter tend to have lower range. For example, a 2016 model of a fuel-cell-powered car has a fuel economy of more than 28 km/l, and a range as high as about 500 km.

To conclude

The idea of using hydrogen as a fuel is still very young. As with other new technologies, it will need to overcome several challenges to become a reality. For example, fuel cells are just beginning to make their appearance in applications like fully electric or hybrid cars. The generic advantages of this application is the high energy conversion efficiency, silent operation and zero GHG emission associated with fuel cells. However, these vehicles are, at present, very expensive. While mass production is

Fig 13. A fuel cell powered bus – Toyota FCHV Bus (Expo 2005 Aichi Japan specification).

Credits: Gnsin, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:TOYOTA_FCHV_Bus.jpg. License: CC-BY-SA.

Fig. 14. The first fuel-cell powered automobile to be introduced in the market – a 2015 Toyota Mirai sedan.

Credits: Turbo-myu-z (modified by Mariordo), Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Toyota_mirai_trimmed.jpg. License: CC-BY-SA.

expected to reduce per unit costs of manufacturing, it is also likely that as more stringent emission standards come into force, the value of clean energy vehicles will begin to justify its additional cost.

Of course, this is only **one** sector of our energy economy. Tackling air pollution and climate change will require similar innovations in other sectors as well.

Note: Credits for the image used in the background of the article title: Automobile exhaust by Ruben de Rijcke, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Automobile_exhaust_gas.jpg. License: CC-BY-SA.

A. Q. Contractor is a former Professor of Chemistry at the Indian Institute of Technology Bombay (IITB), Mumbai, and Dean, College of Engineering, Dhofar University, Oman. He can be contacted at aqcontractor@iitb.ac.in.