Kicking the oil addiction

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Kicking the oil addiction

Powering your car with hydrogen may sound far-fetched. However, it is actually a realistic alternative to petrol and diesel that could help in the fight against climate change, argue **Yaakov Vilenchik**, **Emanuel Peled** and **David Andelman**

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Few people were left unaffected by the soaring oil prices of summer 2008. Motorists were the hardest hit as the price at the pumps reached an all time high, but nobody could avoid paying more for their food as higher transport costs were passed on from the retailer to the consumer.

Since then, oil prices have fallen substantially, thanks in part to a deep global recession that has suppressed energy demand. However, there is no reason why the cost of a barrel of oil will not rise again to fresh highs. While producers continue to reassure us that we need not worry about the future supply of oil, global production could nevertheless peak before the middle of this century, and if that happens, prices will rocket as demand fails to keep pace with supply.

If we are to avoid being at the mercy of fluctuating oil prices, then we must develop alternatives to petrol and diesel engines. There is not a long list of realistic alternatives, but two options are worthy of serious consideration: rechargeable batteries and fuel cells, both of which can power electric cars. Neither of these emit greenhouse gases and could therefore have a big impact on the fight against global warming. Road transport, after all, currently accounts for about 16% of global carbon-dioxide emissions, according to the International Organization of Motor Vehicle Manufacturers.

The rechargeable battery has several advantages: high efficiency; low wear and tear; and a relatively quiet, clean operation. Batteries based on lithium technology have also improved hugely over the last few years, now being lighter, smaller and longer lasting. These batteries are just starting to be tested in hybrid vehicles, such as the Toyota Prius, where the battery is used in tandem with a small, economic combustion engine operating at constant speed. Braking recharges the battery, which helps to reduce fuel costs by two-fifths and lowers greenhouse-gas emissions. However, the small batteries in hybrid electric vehicles are not enough to trigger a real ecological revolution, which will only come from electric cars being powered solely by rechargeable batteries.

Although genuine electric cars do exist, they have several weaknesses: their cruising range is limited to about 250 km because the batteries are heavy and cannot store much energy; the batteries can only operate over a narrow temperature range; the vehicle cannot be used when the battery is exhausted; recharging takes several hours; and many cycles of discharging and recharging of the battery degrades its performance. In addition, there are safety concerns, because internal shorting and high temperatures can cause a spontaneous reaction between the electrodes and the electrolyte that ultimately destroys the battery. Plus, electric cars cost a lot. Despite these weaknesses, hybrid and battery-operated electric vehicles will have an important role to play in reducing the use of oil.

A fuel cell is arguably a better option for powering a car because it shares many of the strengths of a battery while addressing its weaknesses. Unlike a battery, the chemical energy of a fuel cell is not stored inside it but fed continuously from an external source of fuel, such as a hydrogen tank built into a vehicle. This difference is invaluable because a fuel-cell-powered vehicle can travel further than its battery-powered rival, and because refuelling with hydrogen is almost as simple as topping up a tank with petrol.

Fuel-cell cars can also be lighter than their battery-powered cousins. A range of about 500 km is possible with a 130 kg, 300 litre tank that can hold 6 kg of hydrogen. In comparison, a lithium-ion battery car would need an 800 kg battery occupying a volume of 650 litres to travel the same distance. Fuel cells also outperform batteries in terms of their operating temperature range, and they could supply power ranging from watts through megawatts, which would allow them to be used in many applications unrelated to transportation. Despite all the advantages of fuel cells, they do also have some disadvantages, as will be detailed later, and it is still not clear which of these two technologies will dominate in the long run.

The principal challenges with fuel cells are to find materials and processes that can make the devices more efficient and economically viable, so that they can compete with petrol and diesel engines. Interestingly, many of the world's leading car manufacturers are working towards this goal, and concept cars have been built by General Motors, Toyota, Mercedes Benz, Fiat and others. General Motors has also gone one step further by producing a fleet of about a hundred Chevrolet

At a Glance: Fuel cells

- Fuel cells and batteries are realistic alternatives to the internal combustion engine and could help to reduce road-transport greenhouse-gas emissions, which currently contribute one-sixth of the entire global carbon-dioxide output
- Hydrogen provides the fuel for the electrochemical cell, reacting with oxygen to produce electrical energy, water and heat
- The theoretical efficiency for a fuel cell, which is governed by the laws of thermodynamics, is almost 100%, although in practice efficiencies are limited to 70%
- Industrial manufacture and transportation of hydrogen is well established, but costs must fall and roadside availability rise if hydrogen is to become an attractive alternative to petrol and diesel

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General Motors

Vroom, vroom General Motors has produced a fuel-cell-powered car based on its Chevrolet Equinox model. It has a top speed of 160 km per hour, and can go from a standing start to 100 km per hour in 12 s.

Equinox fuel-cell-powered cars that have clocked an aggregate of more than a million miles. This US manufacturer is keen to study the performance of these cars and discover the reactions of drivers and their passengers. It hopes to put a few thousand vehicles on the road in the coming decade.

Generating green electricity

Although fuel cells vary in design, materials, working temperature range and output power, they all share the same operating principle. The process begins at an anode, where a hydrogen molecule is split into two hydrogen ions and two electrons. The hydrogen ions (protons) are then swept to a cathode by an electric field and concentration gradients between the two electrodes. During this journey they pass through a negatively charged membrane that is a proton conductor (see figure opposite). However, the electrons that have been separated from the hydrogen molecules at the anode cannot pass directly through the cell because its membrane is an electronic insulator that blocks their passage. The resulting charge separation produces a voltage between the two electrodes that is equivalent to the output voltage of the cell. It has a maximum value of 1.23 V, but by connecting several (up to a few hundred) cells together in series it is possible to produce far higher voltages.

If an external circuit is connected between the cell's two electrodes, those electrons that were blocked by the membrane can now flow through this external load from the anode towards the cathode. At this electrode, water is created by a chemical reaction between oxygen molecules from the air that are broken down into oxygen atoms, hydrogen ions that pass through the cell itself, and electrons that pass through the external circuit. As the amount of chemical energy stored in the water molecules is less than that of the hydrogen and oxygen molecules, the energy difference gives rise to electric energy that can power any external device.

In this respect the analogy with an electric battery is evident. They both transform chemical energy into electrical energy, although in a fuel cell the chemical energy is not accumulated within but supplied via an external reservoir of hydrogen. Fuel cells also use a catalyst, because the reaction rates at bare carbon electrodes would otherwise be too slow to generate much electricity. A lot of attention has been devoted to developing catalysts that coat the electrodes, increase oxidation and reduction rates, and ultimately magnify the current supplied to the external circuit.

Comparing efficiencies

Fuel cells are very efficient, typically converting 50–70% of the chemical energy stored in hydrogen and oxygen into electrical energy. However, not all of this electrical energy can be converted into mechanical energy in an electric engine: usually about 10% is lost from this process, while for vehicles energy is also wasted due to phenomena like aerodynamic drag and tyre friction. Fuel-cell vehicles therefore have an overall efficiency of about 35–40% (tank to wheel), which is much higher than the roughly 15% efficiency (tank to wheel) of a typical combustion engine, even though this is a far more mature technology.

Fuel cells do not just have the edge over combustion engines in practical terms; they are also capable of far higher theoretical efficiencies. The peak efficiency for a combustion engine – or a steam engine for that matter – is governed by the second law of thermodynamics, which states that the entropy of a closed system can remain constant or increase but will never decrease. Combustion engines work by converting the chemical energy stored in the fuel into heat, which is considered to be an "entropic" form of energy. Heat is then converted into mechanical work, a much more "ordered" form of energy, and during this process the

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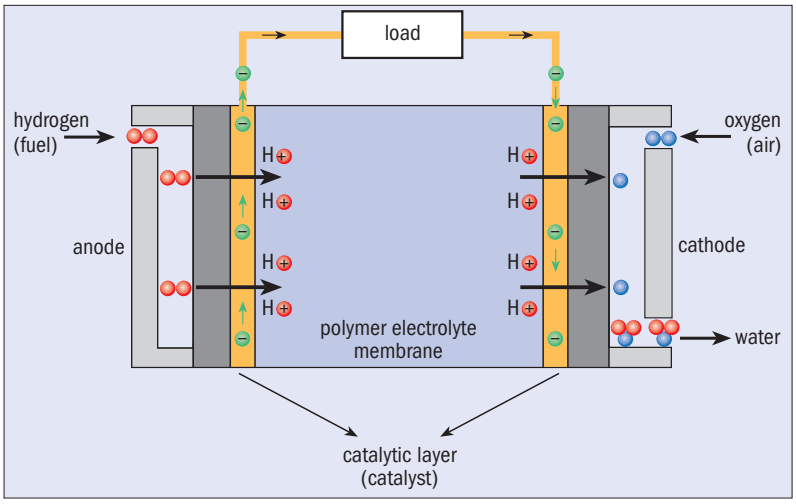

Bubbling away A fuel cell generates electricity by reacting oxygen, hydrogen ions and electrons (artist's impression, left). The hydrogen ions generated at the anode are swept through a membrane to the cathode. The membrane is often made from a polymer called Nafion, which has a Teflon skeleton with negatively charged groups of sulphur trioxide attached to it. This membrane is impermeable to electrons generated at the anode, which are routed to the cathode via an external circuit that is powered by the cell.

entropy associated with the engine diminishes. Since the second law forbids an entropy reduction, a lot of energy goes on increasing the entropy of the environment by heating. Moreover, the chamber of a combustion engine gets very hot, which means that a lot of the thermal energy is "carried away" and wasted by the necessary cooling system. In addition to this, extra thermal energy is also lost through the emission of hot exhaust fumes.

In comparison, the gentle and slow conversion of chemical energy to electric energy by a fuel cell has a *theoretical* efficiency of almost 100%. This is because fuel cells are not heat engines and the slow oxidation, electrochemical processes generate little heat. At low operating powers real cells can get remarkably close to this upper limit, but crank up the output power and efficiency plummets because more heat is generated.

To fully compare efficiencies of vehicles powered by fuel-cell and combustion engines, one should also consider the efficiency of producing or exerting the fuels – petrol, diesel or hydrogen. This comparison is not straightforward, however, because hydrogen can be produced in a variety of ways with different efficiencies and by-products.

The bigger picture

While the fuel cell is not perfect, it certainly appears to be a great and efficient source of energy – its only by-product is water, while hydrogen, the only fuel it needs, appears in great abundance on Earth. However, fuel cells have some shortcomings too. For example, hydrogen gas has to be produced, compressed and stored, and although each of these steps is reasonably efficient, traditional processes employed for these tasks generate greenhouse gases. Another downside is that although hydrogen is all around us – it is the third most abundant element on the Earth's surface – hydrogen gas, which is needed to make a fuel cell, has a concentration of less than one part per million in air.

Fortunately, industrial hydrogen production is well established. It is used in oil refineries to help remove sulphur contaminates from oil and aid the cracking of hydrocarbons. It is also employed in the production of ammonia and other chemicals. In fact, the volume of hydrogen produced is so large that its manufacture accounts for about 2% of global energy consumption; if it was exclusively used to provide fuel for the automobile industry, then it could power one-fifth of the world's cars.

Hydrogen is usually manufactured from petroleum and natural gas. It is expected that in the near future the hydrogen economy will be based on these processes, although they are not the perfect solution in terms of air pollution. This solution will push forward massive use of hydrogen and will enable the transition to production of "cleaner" and "greener" hydrogen. Although carbon dioxide is created as a by-product, the good news is that its emission can be supervised and controlled far more efficiently than that of the greenhouse gases produced by combustion engines.

There are also promising alternative methods for producing hydrogen, including controlled heating of biomass in an oxygen and water-vapour atmosphere. Although this generates greenhouse gases, the vegetation that is used started life as a consumer of carbon dioxide, thanks to photosynthesis. It is also worth noting that these materials would emit greenhouse gases even if they were simply left to rot and decompose naturally. Another clean approach to hydrogen production involves using solar, wind and nuclear sources to produce the power needed to break down water by electrolysis. However, this technology is still in its infancy and currently production costs are still very high.

Another problem with hydrogen is that the gas is difficult to work with, as it is volatile and highly flammable. To make matters worse, the flame associated with hydrogen is almost impossible to observe, and the gas can ignite in a wide range of concentrations. But despite these concerns, many industrial facilities routinely store and handle hydrogen without accidents and the same precautions can be used when dealing with hydrogen tanks in fuel-cell systems. As for the fuel-cell stack itself, the gas content inside it is relatively small, so it is not considered to be a major safety issue.

Another downside of hydrogen is that it is compli-

Fuel cells for electronic gadgets?

The last decade has witnessed tremendous growth in the sales of mobile phones, laptops and other portable electronic devices. To meet the growing demands for powering these products, significant effort has been devoted to improving the performance of rechargeable lithium and nickel batteries. However, this technology will struggle to meet the demands of the next generation of devices, which will require lighter energy sources that can provide more power for longer – so that you will not have to recharge your mobile phone as frequently, even though it will use more power than older models.

Although fuel cells are a potential successor to batteries, it is a challenge to use hydrogen fuels in the microelectronics industry. Storing pressurized hydrogen gas is complicated and expensive, and engineers devising vessels for such applications also need to fulfil the demand for a low-weight fuel cell. Using compressed hydrogen safely in a portable device is also much more difficult than in a vehicle, which offers far more room for installing control systems that substantially decrease the risk of the hydrogen handling.

To address this particular concern, many of today's manufacturers of portable fuel cells use liquid alcohol (mainly methanol but also ethylene glycol), even though this makes the cell less efficient. Two examples of this type of technology can be seen in the figures here. One of these cells has been developed by one of the authors (EP) and can power a small portable computer for six hours (top). Another cell architecture was developed by researchers at Fujistu, with 18 cm^3 of methanol being sufficient to charge three lithium batteries (bottom). Other companies such as Toshiba, Motorola, Samsung and NEC are also investing in this type of energy source for use in their portable products, so it may not be long before laptops and mobile phones are fuelled by alcohol.

cated and expensive to transport. Before it is moved from place to place it is usually either compressed to 700 atmospheres or converted to a liquid by chilling to a temperature of 20 K. Storing hydrogen in these forms is energy costly and also requires containers that can withstand very high pressures or maintain very low temperatures, which partly explains why hydrogen is pricier than petrol and diesel. It therefore makes sense to produce the gas locally, and to select the most appropriate manufacturing technology from the wide range of processes that are available. So in sunnier climes and isolated regions, for example, solar energy could be used to manufacture the hydrogen by breaking down water.

Fuelling the transition

Encouraging motorists to switch from a conventional car to a fuel-cell-powered equivalent will also require improvements to the efficiency and lifetime of fuel cells. The membrane used in the cell contains nanoscopic water channels through which hydrogen ions pass, but these can dry out when ions going through the channels carry some water molecules along with them. The cell then becomes less efficient, although this can be remedied by applying a pressure gradient between the electrodes to drive the water back into the membrane, or by enriching the fuel with water vapour that is absorbed by the membrane and prevents the water channels from drying out. Another opportunity for improvement is the catalyst in the cell, which is usually made from 3–5 nm particles of platinum – an extremely rare and expensive metal. If more efficient catalysts can be manufactured, this could slash the amount of platinum needed for each fuel cell and so save considerably on production costs.

But the main barrier to fuel-cell growth is economic, not technical. Hydrogen is more expensive than fossil fuels, and fuel cells cost about five times as much to make as combustion engines. Closing both of these gaps are key challenges, and addressing them will require the mass production of fuel-cell vehicles. At the moment it is difficult to see how that can happen. More filling stations are needed to increase the public's interest in hydrogen-operated vehicles, but the gas companies are reluctant to roll out this infrastructure until they are assured of an economic return on their investment.

Today, most fuel-cell vehicles that exist provide local and regional transportation, because they cannot venture far from their filling stations. Globally, there are only about 100 such stations, most of them located in cities, industrial zones or testing grounds. This limited uptake is still very valuable, however, because it is a great test bed for this technology, providing an important milestone on the road towards a hydrogen economy.

If oil prices rocket again in the years to come, this could ignite sales of electric vehicles. And as demand for hydrogen grows, production costs will fall and reduce the costs of this form of transportation. If the price per unit energy of hydrogen were to fall to twice that of petrol or diesel – a realistic goal – then the greater efficiency of the fuel cell, compared with that of the combustion engine, would offset the higher cost of the hydrogen. And that could give all of us the opportunity to enjoy the pleasure of motoring without the guilt of greenhouse-gas emissions. Let's hope that this dream will become a reality over the coming years. ■

More about: Fuel cells

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