Which way to energy utopia?

The vehicles of the future will almost certainly be powered by hydrogen. But no one is sure exactly how to get drivers to kick their fossil-fuel habit. Mark Schrope weighs up the options.

Imagine a world in which everyone uses all the energy they want, yet dependence on oil, with its attendant smog and greenhouse-gas emissions, is a thing of the past. This utopia is plausible — many would say probable. It is one in which hydrogen, rather than fossil fuels, is central to our energy economy.

In the most ambitious vision, all the hydrogen we need would be liberated from water using renewable energy sources. Burning it, or using it in battery-like fuel cells that produce electricity, would allow the gas to power everything from buildings to cars. Fossil fuels would be almost totally removed from the energy equation.

Although this is seen by most as the best outcome, the way forward is far from clear. The basic technology needed already exists. But renewable energy sources are not mature enough to provide all the hydrogen we would need, so alternative methods are under consideration (see 'Cranking up the hydrogen flow', opposite). And it remains unclear how best to lure people away from conventional cars and into hydrogen-powered alternatives.

The transport sector is seen by experts as central to the hydrogen economy. It is the main driver of oil dependence — something the developed world wants to reduce, given the vulnerability of supplies to conflict and political disturbance in oil-exporting nations. Exhaust gases from vehicles also damage air quality, and transport as a whole is responsible for around a

It's a gas: a prototype hydrogen-powered vehicle from BMW refuels during testing.

third of all greenhouse-gas emissions.

Debate is now raging over which technologies should be used as stepping stones to a hydrogen future for vehicles. If the politicians, companies and environmentalists involved can reach a consensus, the prize is huge: cars and buses that emit nothing more than water vapour.

Burning issues

Vehicles could use hydrogen in a variety of ways. Some researchers favour the introduction of electric cars powered solely by fuel cells, which combine hydrogen and oxygen to produce electricity. Others say that conventional car engines can be converted to run on hydrogen with relatively minor modifications. Experts are also split over whether, as an interim step towards a full hydrogen economy, vehicles should initially use on-board equipment to extract hydrogen from fossil fuels.

Infrastructure issues play a big role in the debate over which approach should be taken. The lack of an existing system for storing and distributing hydrogen presents a dilemma. Car manufacturers do not want to sell

vehicles that people cannot fuel, and energy companies do not want to spend money developing a hydrogen distribution infrastructure when there are no hydrogen cars on the road. The equation becomes more complicated with fuel cells because they have yet to be produced in large numbers and their long-term reliability has not been proven.

This deadlock could be broken by 'reformers', which would allow hydrogen cars to run on fossil fuels. Reformers can break down the hydrocarbons in fossil fuels and so liberate hydrogen. Natural gas, for example, can be reformed by heating it together with water and a nickel-based catalyst. The result is a series of reactions whose products are carbon dioxide and hydrogen. Other fossil fuels, including petrol or gasoline, can be reformed in a similar way.

Hydrogen cars fitted with reformers would still run on petrol, but would reform it into hydrogen. Advocates of the technology say that this would give car companies the confidence to produce the vehicles, and so provide a fresh impetus for fuel-cell development. Several car manufacturers, including General Motors and DaimlerChrysler, are

Powerhouse: cars running on hydrogen fuel cells emit nothing more than water vapour.

now working with Ballard Power Systems, a fuel-cell producer based in Burnaby, near Vancouver, to develop vehicles that are powered by fuel cells fed by reformers.

But reformers still produce carbon dioxide, and for many environmentalists, this is enough to rule them out. "If you are going to move to a technology that allows you to have literally no pollution, why would you want to salvage the pollution in the process of switching?" asks Dan Becker, director of the global warming and energy programme at the Sierra Club, a San Francisco-based environmental organization. "It's like a nicotine patch that causes cancer."

Hydrogen vehicles with reformers are also technologically more complex and costly to build than straight fuel-cell cars, argues Robert Williams of the Center for Energy and Environmental Studies at Princeton University in New Jersey.

Reformed character

Some argue that these objections could be reduced by using methanol, rather than petrol, to power reformer vehicles. Reforming methanol, a low-mass alcohol that is liquid at room temperature, is more efficient than the process for petrol, as the hydrogen can be extracted at a lower temperature. It also produces fewer greenhouse-gas emissions. And because methanol can be produced from coal and natural gas, it could also reduce dependence on oil.

But methanol would need new infrastructure to distribute it. As a liquid, the changes required would be less than for hydrogen. A distribution system for ethanol, another liquid alcohol, is already in place in Brazil, where the fuel is produced from sugar cane. But, critics argue, developing a methanol distribution network would take us no closer to the hydrogen system that most agree is the ultimate goal.

Like petrol, methanol is poisonous. But it has only a slight odour and mixes easily with water, raising the risk that it could contaminate water supplies without people knowing. Another drawback of all reformer systems is that they currently require several minutes' heating before they can operate — far too long for drivers who expect to get in their cars and go instantly.

Given these problems, some experts argue that the most sensible route to a hydrogen economy is to tackle the infrastructure issue head on. With proper planning, says Williams, a hydrogen infrastructure could be created gradually and economically. Fleet vehicles, such as city buses, government vehicles and delivery trucks, would be the starting point. Because all the vehicles return to the same place every night, only one refuelling station would be needed for each fleet. Prototype projects of this type are currently under way in several European

Conventional internal combustion engines could be converted to burn hydrogen with fairly minor alterations.

countries and the United States.

Williams suggests that governments could then encourage further dissemination of the technology by requiring vehicle manufacturers to sell a certain number of fuel-cell cars every year. A related scheme is being used by the California state government to encourage sales of conventional electric vehicles. Governments could also help by offering drivers the chance to earn income-tax credits if they buy hydrogen vehicles. As use grows, the energy companies would have more incentive to expand the hydrogen distribution system.

Such a plan could get hydrogen-powered vehicles powered by fuel cells on the road, but

others argue that the process would be quicker if hydrogen were burned instead. All conventional engines powered by petrol, from turbines to cars, could be made to burn hydrogen with fairly minor alterations. Both Ford and BMW have developed vehicles that use hydrogen to power modified internal combustion engines (ICEs). Hydrogen ICEs still have to face the problem of developing an infrastructure for hydrogen distribution, but because only minor re-engineering of vehicles is needed, large-scale production would be cheaper and quicker than producing fuel-cell cars. Bob Natkin, leader of Ford's hydrogen ICE programme at the company's laboratories in Dearborn, Michigan, says he could have a hydrogen ICE available in three to five years. BMW is running on a similar timetable.

Work on modified ICE prototypes suggests that they will use hydrogen less efficiently than fuel cells. But their performance could be improved by using a 'hybrid' engine that also uses battery power. Petrol-run hybrid cars, which use batteries in conjunction with ICEs, already exist. Although they consume fossil fuels, their efficiency is around twice that of normal petrol vehicles. Hybrid vehicles running on

Cranking up the hydrogen flow

Going green: algae could be used to split water and so meet hydrogen demand.

organization that brings together academics and industry representatives interested in hydrogen technology. Reforming could be extended to any fossil fuel, or even plant matter, as an interim solution to the need for hydrogen.

But researchers are also working on methods for hydrogen production that avoid fossil fuels altogether. John Turner of the National Renewable Energy Laboratory in Golden, Colorado, leads one of several groups investigating photoelectrochemical systems. These combine photovoltaic materials, which use light to produce electricity, with electrolyzers, which split water. Rather than using a solar cell to generate electricity, which is then fed to a separate electrolyser, Turner's team aims to create single devices that can split water once submerged and illuminated.

Another group at the same lab is studying the green alga *Chlamydomonas reinhardtii*, which uses sunlight to split water and produce hydrogen and oxygen, in the hope of scaling up the process to create cultures of algae that can produce industrial levels of hydrogen.

Producing hydrogen is not difficult — passing electricity through water generates hydrogen at the negative electrode and oxygen at the positive electrode. But with existing renewable energy technologies not ready to deliver the electricity needed, other methods are needed.

'Reforming', or 'cracking', natural gas is currently the cheapest and most common method of hydrogen production. The technique is used by petrochemical companies to generate the hydrogen used in the synthesis of a variety of useful compounds. Using industrial-scale crackers, BP alone produces enough hydrogen to run over a million fuel-cell cars, says Jeff Rinker, the company's general manager for hydrogen and chair of the National Hydrogen Association, a Washington-based

Ray of hope: John Turner wants to use solar power to generate hydrogen.

W. GRETZ/NREL

R. PETERSON/NREL

Convertibles: hydrogen fuel tanks feed a converted internal combustion engine.

► hydrogen ICEs could achieve around 80% of the efficiency of fuel-cell vehicles, says Jay Keller, manager of the hydrogen programme at Sandia National Laboratories in Livermore, California. Modified ICEs do produce additional emissions of gases such as nitrogen oxides, which are pollutants and greenhouse gases, but Natkin says the emissions from his prototypes are already well below those from normal engines and could be reduced to close to zero.

Williams says that introducing the hybrid hydrogen ICE vehicles would offer the chance to work with a hydrogen infrastructure in preparation for the full-scale introduction of fuel cells. They would then be phased out over time.

These plans sound promising, but one major problem — that of storing hydrogen fuel — has to be overcome first. The Partnership for a New Generation of Vehicles, an initiative that brings together the US government and vehicle manufacturers with the aim of developing environmentally friendly vehicles, estimates that to satisfy consumer demand a car needs to run for around 600

kilometres on a single tank of fuel. Using current fuel-cell technology, around 5 kilograms of hydrogen would be needed to travel this distance. But this would require a pressurized tank of roughly 180 litres — far too large for family cars, which have tanks that hold an average of about 50 litres. Buses need even larger tanks but, unlike cars, have the space in which to put them.

Higher pressures can be used to cram the hydrogen into a smaller volume, but, as with any pressurized gas, this increases the risk of explosion, so numerous alternatives are under development. Storage density could, for example, be increased by adding metal hydrides to the tanks. These absorb hydrogen molecules, increasing hydrogen density without increasing pressure. The hydrides release the hydrogen when heated, allowing fuel flow to be controlled. Carbon nanostructures, such as nanotubes, could potentially be used in a similar way.

Tanked up

Researchers are currently trying to increase the amount of hydrogen these metal hydrides and nanotubes can hold. In many cases, commercial secrecy prevents the exact figures from being revealed. But Sigmund Gronich, who leads the US Department of Energy's Hydrogen Program Team, says that some government-funded groups have created mixtures of metal hydrides and hydrogen in which the hydrogen makes about 5% of the weight of the two. This would get the size of a fuel tank required for 600 km of motoring down to around 100 litres.

Although this is still too large for a family car, Keller argues that it could serve as a practical storage density if drivers can be convinced to accept the need to fill up more frequently. He suggests that a target of 320 km per tank, or around four hours' continuous driving, is reasonable. This would require a more practical 55-litre tank, at current hydride storage densities.

Meanwhile, some groups have claimed hydrogen-storage figures of 8% by weight for nanotubes, although others have found their claims hard to replicate (see *Nature* **410**, 734–735; 2001), and it is unclear how successfully these laboratory experiments would scale up into commercial fuel tanks. But with interest in both storage mechanisms currently intense, many in the field remain confident that the problem of hydrogen storage will be cracked.

With so many different approaches being pursued, some have argued that the money and time being ploughed into hydrogen research would be better spent on a more focused range of projects. Environmentalists add that oil and car companies need to invest more in the field. But overall, the drive for hydrogen power seems to be gaining momentum.

In Iceland, for instance, non-governmental groups and researchers, with the support of companies such as Ballard and Daimler-Chrysler, are working on a plan that would almost totally remove fossil fuels from the country's economy within 30 years. Iceland is in a unique situation. Vehicles will be powered by methanol — which can be derived from a by-product of the country's metal-production industry. Electricity needs can be met by abundant geothermal sources. The route to a hydrogen economy is not so straightforward elsewhere, but hydrogen supporters say that everyone will learn from Iceland's experience.

Charles Stone, a vice-president at Ballard, is in no doubt that other countries will follow Iceland's lead. "The goal of getting to a hydrogen-based system is so compelling, and the people involved in this are so ingenious, that I'm very confident we'll get there," he says. ■

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US Department of Energy Hydrogen Program

► www.eren.doe.gov/hydrogen/program.html

Partnership for a New Generation of Vehicles

► www.uscar.org/pngv

Desert manoeuvres: last year's Clean Energy World Tour, which demonstrated hydrogen-powered vehicles, started in Dubai.