Averting climate catastrophe?

by Dr Richard Pike

Dr Richard Pike was Commissioning Engineer at Sullom Voe 1980 – 1982, returning in 1986 for two years as Technical Manager. He is currently Chief Executive of the Royal Society of Chemistry. In June 2008, he gave a public lecture to a packed audience at the Shetland Museum and Archives on 'Chemistry, Energy and Climate Change'. The event was sponsored jointly by the Royal Society of Chemistry, Institution of Engineering and Technology, and the Unst-based company PURE Energy Ltd. Here Dr Pike summarises the key messages on this increasingly important topic.

Shetland – A Microcosm of Global Energy Provision

Shetland shows an extraordinary diversity in the range of energy and environmentally-related activities it is progressing, from the Sullom Voe Terminal, at one stage Europe's largest oil and gas processing facility, to wind farms and potentially tidal schemes in its surrounding fast-flowing waters. Unst has the only fully-operational car in the world powered by hydrogen derived locally through the electrolysis of water, drawing on the output from wind turbines. Lerwick has a novel hot-water ring main powered by the combustion of refuse from Shetland, Orkney and offshore oil and gas facilities, which provides, through heat exchangers, domestic and industrial heating to many premises in the town.

To the south, on the Scottish mainland, are nuclear facilities. Within just a few miles is representation of much of the global energy business of the future. How does all this fit into the wider context, and what is the role of the UK in addressing the momentous challenge facing us?

Some Random Facts

Nothing focuses the mind more than a few random facts, which nevertheless underlie some key messages. Did you know that around 30% of energy available at source is lost before it reaches the end-user? Some of this is due to the way electricity is generated and to losses over hundreds of miles of power transmission. In the two other major sectors of heating and transport, fuels continue to be used inefficiently.

If we consider just power generation and heating, 42% of consumption for these end-uses is for the space heating of buildings, and one-third of this is lost through windows.

Also, transportation represents 74% of UK oil usage, but only 25% of carbon emissions. This is because gas dominates power generation and heating, whereas petrol, diesel, kerosene and fuel oil, the principal products from petroleum, are used predominantly for vehicles, planes and ships. It implies that even halving car emissions (just one of the three transportation sectors) will have a relatively small effect on the national carbon footprint.

Finally, the European Union Directive to achieve, by 2010, a 5.75% substitution of petrol and diesel by biofuels would require 19% of arable land to be converted to fuel-crops, if provided solely from within the EU. This raises important issues over the need to understand the quantitative impact of governmental directives, and the risks of unintended consequences in decision-making.

The Key Issues

Long-term provision of energy, while addressing the environmental issues and potential climate catastrophe within the next few decades, will be the key challenge for the immediate future.

The chemical sciences can provide the understanding and routes to implementation, to deliver ultimately energy that is secure, affordable and sustainable.

Saving energy is important, but we need to nurture and harness far more effectively research skills throughout the country and internationally. Crucially, nothing will happen without vision, and delivery mechanisms and funding to bring about implementation.

The world picture often surprises people. Despite many fine words, 80% of the total energy for power, heating and transport still comes from the fossil fuels of oil, coal and gas. Around 7% additionally is from nuclear power stations, 3% from renewables such as solar, wind, tide, hydro and geothermal, and the remaining 10% from biomass.

This 10% figure is deceptive, because most is represented by the traditional burning of wood and agricultural waste, while only 1~2 percentage points are covered by more sophisticated biofuels such as ethanol or bio-diesel.

Total annual energy demand in the world is equivalent to 11.1 billion tonnes (Gt) of oil. As much as 80% is based on hydrocarbon fuels formed hundreds of millions of years ago. That fact, coupled with the economic and political strength of the energy industry, illustrates the challenge facing us. Contrary to popular perceptions, oil and gas will be readily available into the next century, and coal still longer. We cannot rely on these resources running out as the solution to climate change; instead, bold decisions must be made to curtail their use, unless the associated carbon dioxide emissions can be reduced markedly through carbon capture and storage (CCS).

This has to be complemented by enhanced use of renewables and nuclear sources, together with improved efficiency, and a rigorous fiscal and regulatory framework to promote these, while applying sanctions for unauthorised carbon dioxide releases.

Hydrocarbon fuels contain a large proportion of carbon, and with combustion and increasing deforestation, approximately 8.8 Gt of carbon (mainly within carbon dioxide) is released into the atmosphere each year. Of this, about 40% stays in the air, while the remainder dissolves in the oceans.

Although the mass of the Earth’s atmosphere is enormous (5.3 million Gt), it is the permanent annual transfer of 3.5 Gt of carbon that lies at the heart of global warming. Calculations show that if this were to continue unabated to the end of this century, the average temperature rise throughout the world could be as much as 6 degrees Celsius (6°C). This is because carbon dioxide absorbs the infra-red radiation from the Earth’s surface that results from the latter’s exposure to the sun’s ultra-violet rays each day.

The implications of not addressing this almost defy comprehension. They include mass migrations of human and animal populations, dislocation of society, food and water shortages, war and possibly a billion deaths.

The Hydrogen and Electricity Economy

There is no single solution that can be applied to all countries. Hydrocarbons could continue to play a major role, provided applications were linked to CCS. Conversely, some countries may choose to let renewables and nuclear dominate, depending on technology, economics, social and ethical priorities.

The scale of CCS should not be underestimated. Every tonne of carbon in a hydrocarbon fuel is converted to about 3.7 tonnes of carbon dioxide on combustion, and therefore capturing all emissions globally represents close to 100 million tonnes of the gas *each day*. This compares with the size of a typical world-scale liquefied natural gas (LNG) plant, which produces 10 million tonnes *each year*.

Extensive use of hydrocarbons with CCS would involve generating electricity centrally for conventional power, transport and heating. (Local, small-scale capture of carbon dioxide on vehicles and from buildings is considered impracticable.) There will be circumstances where using the electricity to electrolyse water at the power station, and transporting the resulting hydrogen by pipeline (say) for combustion elsewhere, may be more attractive.

This thinking forms the basis of the so-called ‘electricity and hydrogen economy’, where hydrocarbon fuels could continue to be used with only very limited release of carbon dioxide emissions. Key technologies needed to make this successful are:

(1) large, commercial-scale proof of CCS (typically using depleted oil or gas fields, or other geological structures for carbon dioxide storage);
(2) economic, large-scale storage for electricity and hydrogen.

With the latter storage issues addressed, electricity from other sources, such as renewables (and particularly the abundance of solar) and nuclear, could be integrated readily into a less centralised carbon-free energy infrastructure, with or without the hydrogen option.

Myths of Some ‘Clean Fuels’

Mention of clean fuels, and particularly ‘clean coal’, conjures up in the minds of many something that is environmentally friendly, and even carbon-free. Rarely could there be a greater misconception.

Conventionally, ‘clean fuel’ refers to the process by which oxides of sulphur (SOx) and nitrogen (NOx), usually resulting from the combustion of hydrocarbons, are removed, or the routes to their formation blocked. This improves air quality and reduces the prevalence of acid rain, but has *no* material impact on the quantity of carbon dioxide emitted into the atmosphere from the burning of the hydrocarbons –unless CCS is also adopted.

More significantly, gas-to-liquid (GTL) and coal-to-liquid (CTL) technology allows natural gas or coal to be converted to diesel, or even jet fuel, for vehicles and aeroplanes. The derived liquid fuel is also free of SOx and NOx – but at a price. Typically, 40% of the feedstock of natural gas or coal is used to provide energy for the conversion process, so that only 60% emerges as the final liquid product.

Since carbon dioxide is emitted at both the manufacturing sites (typically in the Middle East and East Asia) and from the vehicle or aeroplane, the total emissions per mile are far greater than those from conventionally produced fuels! And you may wonder where the sulfur goes that was originally in the feedstock. It finishes up at the manufacturing site, sometimes contaminated with heavy-metal catalysts, where disposal poses further environmental issues.

This highlights the need for more efficient conversion technologies through catalyst development, and the adoption of life-cycle analysis (LCA) to examine the overall process of energy provision and its environmental impact. There is always the risk that solving an issue at one end of the supply chain merely creates another problem elsewhere.

Alternatives To Hydrocarbons

The largest single sector providing globally an alternative to the use of hydrocarbons is nuclear energy.

Operationally, this is ostensibly carbon-free, but carbon dioxide is evolved in the manufacture of the concrete that is a significant component of the installation of a nuclear power station.

Typically, uranium and plutonium (in the form of their oxides) provide the main feedstock, and yet only around 4% of this is radioactively changed in the reactor, with a surprisingly high 96% of the fuel remaining completely unaltered.

Recovery of the spent fuel and nuclear re-processing are all about the complex separation of those elements that can be used as further feedstock (uranium and plutonium), from radioactive material that has no further use, and ultimately must be stored safely for thousands, even millions of years. This is the key scientific challenge, addressing waste encapsulation, environmental and biological monitoring, and long-term risk management.

Additionally, we need to explore more efficient ways of obtaining energy from radioactive materials, such as the conversion from uranium to plutonium in so-called fast-breeder reactors. And there remains the still-elusive goal of hydrogen fusion, that could provide almost limitless energy in converting hydrogen (from the electrolysis of water) into helium! Operational safety will be paramount in design-thinking.

Many commentators see long-term sustainability based on energy from the sun, which falls principally into two categories:

> (1) photo-voltaic devices, based on thin-film silicon panels or alternatively polymer sheets, which provide initially direct-current electricity. This can be used to generate hydrogen, or converted to alternating current for transmission and use in heating, electrical appliances and ‘truly green’ cars.
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> (2) concentrated solar power (CSP), using hundreds of mirrors to focus the sun’s rays onto water flowing in a transparent pipe, to generate steam that drives turbines in a power station. This electricity is alternating, but can be rectified to provide the direct current needed for electrolysis, should a hydrogen route be adopted.

What we can use worldwide from the sun’s rays is limited by the global annual average of the energy that can be captured at the Earth’s surface. The key figure is 174 watts per square metre but the local average will be higher nearer the equator and lower at the poles.

This figure represents principally the outcome of the difference between energy reaching the outer regions of the Earth’s atmosphere, and what is reflected back into space from clouds and the Earth’s surface, itself.

Conversion of this solar energy to electricity through photo-voltaic devices is approaching 20%; for CSP it is even higher. To put this into context, an area of land the size of a large living room would power a single one-kilowatt bar of an electric heater. The scientific challenge for the future is to increase efficiencies still further, and develop new materials for durability and sustainability.

Wind energy ultimately derives from temperature differences in the lower atmosphere generated by the sun’s rays, while tidal energy draws on the gravitational fields of both the sun and moon. Hydro-electric power also relies on the sun driving the water-cycle by evaporating water from the oceans, for it to fall later as rain to be collected within rivers and lakes that can be dammed. Allowing the water to flow through turbines in the dam structure enables electricity to be generated.

The use of geothermal energy, which is particularly prevalent in Iceland, draws on hot water and steam that has been heated underground. This typically occurs through a combination of the natural increase in rock temperature with depth, and local ‘hot spots’ associated with volcanic activity where the liquid magma is closer to the Earth’s surface.

Water may be drawn from a naturally occurring hot aquifer, or pumped underground to be heated. Depending on the application, this will either be used directly, or passed through heat exchangers to heat a separate loop of water or steam for the eventual end-use. In this way, geothermal sources can provide for domestic heating, public swimming pools and steam for electricity generation.

The Biofuel Question

Debate on biofuels has become extremely topical. So-called ‘first generation’ biofuels fall into two categories: those producing ethyl alcohol (or ethanol) from the fermentation of starch and sugar, and those yielding biodiesel through the esterification of plant oils. Controversially, these are based on crops that can be used alternatively as food.

These are currently most prevalent, but ‘second generation’ developments draw on the whole plant, and are designated lignocellulosic biofuels, typically based on miscanthus, poplar and willow, and waste from urban, agricultural and forestry sources, which do not compete with food. Importantly, the final output is rarely solely fuel, but a slate of refinery-type products from a biomass-to-liquid (BTL) process not unlike the GTL and CTL routes referred to earlier.

Finally, there are ‘third generation’ biofuels that are still in the very early stages of development, and where the overall efficiencies and wider environmental consequences remain uncertain. The most loudly-heralded of these is the cultivation and use of algae.

The most controversial aspect of biofuels is the way high-level governmental decisions have been made without adequate scrutiny of yields, economics, life-cycle analysis or potential unintended consequences. At best, first-generation biofuels yield about 4 tonnes of liquid per hectare, which is an area of 10,000 square metres – a square 100 metres by 100 metres.

However, when the use of fossil-based agricultural fuel, fertiliser and transport is incorporated, the overall yield falls significantly, and still more so if the energy for processing also is in this category. A net operational yield of 1~2 tonnes per hectare of biofuel might be typical, even for a modern BTL plant in the UK. With biofuel having an energy value of 30 billion joules per tonne, this means that far less than one percent (and as low as one-tenth of this) of the available energy from the sun is being converted to fuel.

Here lies the real dilemma with biofuels. In stark terms, if the UK were dependent on its own production, for every one percent of petrol and diesel substituted with biofuel, one percent of the UK land area would have to be dedicated to the cultivation of these fuel-crops.

A further issue is that in some countries farmers are being subsidised to clear woodland for biofuel production. When established bushes and trees are burnt down in this way, up to 200 tonnes per hectare of carbon dioxide is emitted into the atmosphere that would have otherwise been ‘captured’ from the air for many years within the wood of the plant. The subsequent cultivation and use of biofuels from the same area effectively avoids the emission of typically 3~4 tonnes of carbon dioxide from fossil fuels. The ‘carbon payback’ period is therefore many decades. Numerous projects, where both the farmer and car driver are being subsidised, distort the economic and technological drivers of the business, and are likely to have an overall negative effect on the environment.

Far more work must be done on the science and commercialisation of biofuels before large-scale commitments are made. The whole sector could become a technological dead-end, for reasons expanded on below.

The Balance of Resources

Integration of land, sea and air resources will be essential in the future. The likelihood of increased alternating current generation through nuclear power stations, and gas, oil and coal facilities (with CCS), will place priority on utilising the waste heat from these units for domestic and other industrial applications.

It is a curious consequence of fundamental thermodynamics that electricity can be generated in this way only if some of the heat from combustion of the fuel (typically, over half) is ultimately rejected from the facility into the sea or nearby river. In some countries, where the power station is close to an urban development, this waste heat can be used instead for space heating and hot water through a network of pipes. It rarely occurs in the UK, because of the separation between towns and generating facilities, and yet wider application of this concept would significantly reduce national fuel requirements.

Further optimisation lies particularly in the use of land. Energy-for-energy, solar devices require around 50~100 times less land area than biofuels because of the extraordinarily low conversion efficiencies of the latter route.

There is, however, an important contrast: biofuels are relatively low technology, easy to cultivate, and yield products that are readily blended with fossil-fuel products, and can share some of their distribution infrastructure. Solar devices are relatively high technology and capital intensive, and yield outputs of electricity and hydrogen in a way that requires radical change in end-use and distribution. There is the risk that investment in this long-term sustainable route will be delayed through focusing on the illusory, easily-won benefits of biofuels.

The picture would not be complete without the need to optimise further land-use for wind and tidal energy, and other renewables, taking account of food crops, and social, ethical and life-style requirements of urban and rural populations, and associated infrastructures.

Finally, there is the crucial question: since fossil hydrocarbons are finite, should we not be accelerating the use of alternatives, so that hydrocarbons are restricted to manufacturing high-value products rather than merely being burned? These include medicines and polymers, and other speciality chemicals.

The Need for Decisiveness

Oil alone represents 34% of energy provision, with coal and gas together being 46%. These are all massive global industries and, as indicated, the framework will need to be in place internationally, to provide direction on limiting the impact of hydrocarbons, through curtailment or the use of CCS, and to promote other low-carbon alternatives.

Despite the signing of agreements and protocols, the major users of energy continue to send mixed messages, which heightens the risk that a clear plan with milestones will not emerge until too late. There is insufficient recognition of the dangers, no coherent vision for the future, and a lack of understanding of the next, short-term steps to achieve this. Unless these three elements are all brought together, nothing substantive will happen.

Melting of the permafrost due to global warming is seen as an opportunity to drill for still more oil. New coal-fired power stations are being sponsored even though, energy-for-energy, these produce twice as much carbon dioxide as natural gas. Also, oil producing countries are importing cheap coal to generate electricity, so that the natural gas that would normally be used can be re-injected into reservoirs to enhance the production of oil at its current high price.

Within the UK we have seen CCS projects delayed, to the extent that there is still no completely proven integrated system in the world – although there is reasonable confidence in the separate components. Furthermore, wind farm projects have been cancelled through public pressure or lack of commercial attractiveness.

Many people have the reservation that even if the UK were to become completely carbon-free, the hydrocarbon dependence of the world would fall from 80% to just 78%. This should not deter us from taking a lead, and promoting the essential changes needed to the rest of the world, in collaboration with the more enlightened countries.

Science And Education

Science will have to play a key role in addressing the issues raised here. Thinking further ‘out of the box’ yields ideas such as using the carbon dioxide already in the atmosphere to manufacture fuels such as alcohols, drawing on the energy of the sun. Somehow recycling around just one-fiftieth of the carbon in the atmosphere each year would provide all the energy the world needs. Plants do a portion of this already, albeit very inefficiently, but there may be the potential for synthetic devices to undertake this.

Genetic modification has been cited as a way of naturally enhancing the capture of carbon dioxide by plants or marine organisms such as plankton, but this raises important scientific, bio-security and ethical issues.

There has to be the realisation that carbon dioxide must be stored for thousands of years. Both synthetic and biological devices will have to be prevented from degrading or decaying to avoid the release of the gas. In this sense, we will be passing on a legacy to our descendents as potent as radioactive waste from our nuclear power stations.

The key role of science will be in handling the whole supply chain for energy, from the discovery and development of resources, through to conversion technologies and finally to waste management, with this last step covering everything from CCS to recyclability and nuclear fuel re-processing.

But all this cannot exist in isolation: education will be essential to provide the knowledge and skills to support future developments, and tackle the greatest challenge facing mankind. Within the UK, this means having energy and environmental issues permeating the whole of society. There must be more qualified science teachers in the secondary sector, in particular, and sufficient funding for teaching and research.

Overall, science education must be both intellectually rigorous and creative, to meet the needs of the country, and energy issues must be seen as business opportunities, rather than just problems. The next ten years will be critical!

We would welcome debate on the issues raised in this article. If you wish to send us your views, then you can contact us via the following e-mail address: campaigns@rsc.org