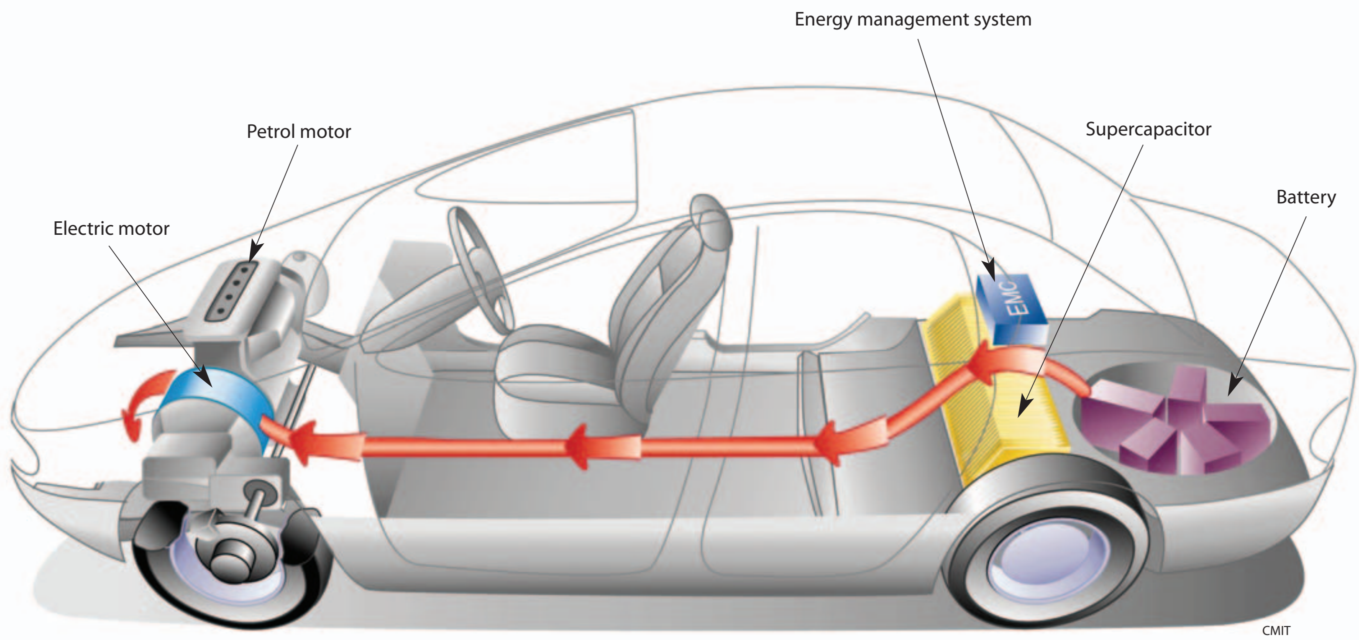


A concept diagram of CSIRO's aXcessaustralia car which is a step towards significantly reduced vehicle emissions through electro-mechanical drives and hybrid gas/electric motors that could incorporate fuel-cell technology.

Towards the forever fuel

The globe's major economic players are beginning to weigh into a hydrogen future. Steve Davidson looks at the viability considerations ahead for a transition to the new fuel economy and profiles Australia's position.

Recent enthusiasm for hydrogen fuel is understandable. It's ubiquitous, inexhaustible and produces virtually no greenhouse gases if generated using renewable energy.

Hydrogen has the potential to power our homes, vehicles, appliances and industry. According to some commentators, it could even revolutionise society by decentralising the production of energy.

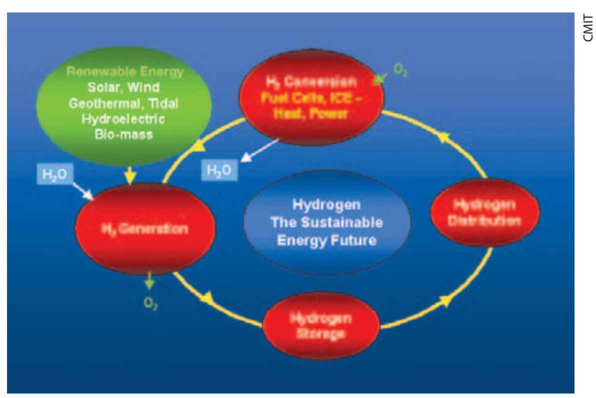
It sounds too good to be true, and indeed most experts agree that a number of problems will need to be overcome before a utopian hydrogen economy can be realised.

In 1874, with impressive vision, renowned writer Jules Verne, through one of his characters in *The Mysterious Island*, predicted that 'water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light'. However, it has taken us more than a century to begin taking hydrogen energy seriously and some scientists are still sceptical about the value of hydrogen technologies (see box on page 23).

There are three principle reasons for the hydrogen renaissance: energy security (or insecurity); energy sustainability; and health and environmental benefits. Concern about the finite nature of fossil fuel reserves, especially oil, and the fact that a growing share of remaining fossil fuels occur in parts of the world that are politically unstable, is partly driving the recent interest in a hydrogen economy. What's more, it's estimated that the time before some fossil fuels begin to run out is about the same time it would probably take to make the transition to a hydrogen economy.

Then there are the greenhouse and air quality benefits. Hydrogen is the most abundant element in the universe – comprising 75% of matter. It powers the sun, and, because hydrogen contains no carbon atoms, it produces no CO_2 or other greenhouse gases and no particulate pollution.

In fact, adoption of hydrogen will be the ultimate step in a historical 'decarbonisation' trend in which our main fuel source has progressively become lighter, cleaner and less carbon based over hundreds of years. We have gradually switched from wood, to coal, to oil,



A truly sustainable energy cycle would involve hydrogen generation by electrolysis of water using renewable energy, namely solar, wind, hydro-electric, tidal or geothermal sources, in conjunction with hydrogen storage and use in fuel cells.

Hydrogen has the potential to power our homes, vehicles, appliances and industry... it could even revolutionise society by decentralising the production of energy.

to natural gas and will, sooner or later, it seems, adopt hydrogen, the lightest element, as our main energy carrier.

It is significant also that the corporate sector is now taking an active interest in hydrogen technology. The term 'hydrogen economy' was first used, not by an environmentalist, but by General Motors, the world's largest car maker, says respected futurist and prolific author Jeremy Rifkin in his book, *The Hydrogen Economy*. In 1970, General Motors engineers began to look at hydrogen energy and, in 2000, a General Motors executive director gave a speech in which he said 'our long-term vision is of a hydrogen economy'.

Similarly, Royal Dutch Shell has stated that Shell is preparing for the 'end of the hydrocarbon age'. In all, the chairs of eight major oil and car companies have said that the world is entering the oil endgame and the start of the hydrogen era.

Forever fuel … or never fuel

All of this gives the impression that adopting a sustainable hydrogen economy is a mere formality, but there are many technical and economic challenges ahead before it becomes a reality; possibly some time between 2020 and 2050, according to most scientists. These cover the whole gamut from hydrogen production, to transport, storage and utilisation.

Production is an issue because hydrogen does not generally occur as a free element in nature; it is contained in water, fossil fuels and living organisms and needs to be extracted before it can be used as an energy carrier. Currently, most hydrogen is generated by reformation of natural gas (methane or CH_4) which strips off the carbon atoms to produce hydrogen and carbon dioxide. Using this method, the carbon dioxide will need to be captured, and possibly sequestered underground, to avoid exacerbating the greenhouse problem.

In the long term, the vision is to produce hydrogen by electrolysis of water, that is, by splitting of water into hydrogen and oxygen, using electricity from renewable wind, solar, geothermal, tidal, biomass or hydro-electric technologies. This will lead to a truly sustainable energy economy with zero emissions and an inexhaustible supply of hydrogen, 'the forever fuel'.

An Australian research contribution

CSIRO is actively involved in advancing hydrogen technologies. Research teams are conducting 'enabling' hydrogen research in a number of areas within various divisions. Hydrogen is also a common thread in all four major themes in CSIRO's newly launched Energy Transformed Flagship, one of six high-priority research and development (R&D) programs.

Dr Sukhvinder Badwal, Chief Research Scientist with CSIRO Manufacturing and Infrastructure Technology (CMIT), explains that his team and other CSIRO researchers have developed expertise in a range of relevant areas including: hydrogen generation from both fossil and renewable resources, fuel cells for converting hydrogen to electrical energy, systems integration and modelling, fluid dynamics, microtechnology, nanomaterials, catalysis, polymers and electrochemistry.

CMIT

The CSIRO has developed an efficient transition from fossil fuel to renewable energy delivery. The system produces commercial-grade hydrogen using concentrated solar energy to reform natural gas.

CSIRO is also considering setting up a National Hydrogen Centre (probably to be called Hydrogen Australia) to promote hydrogen technologies and move focused research forward (see the box on page 24).

Some of the highlights of CMIT research so far are in the area of hydrogen generation from water. Using the common process of electrolysis, water is 'split' into hydrogen and oxygen molecules using electricity in special solid-state electrolysers. Researchers are well on the way to achieving conversion efficiencies exceeding 85% in small, economical electrolysers, which could facilitate local hydrogen production.

CSIRO is aiming to have a prototype electrolyser, powered by 3–5 kilowatts, operating within about 12 months. It will eventually be used to demonstrate how renewable energy, such as solar or wind power, can be fed in to produce hydrogen that could be stored and used later in a fuel cell to produce secondary electricity.

'Using hydrogen as an energy carrier solves the inherent problem of surplus and intermittent energy availability from renewable sources such as wind, solar and tidal resources, so abundant here in Australia,' says Dr Badwal. 'Alternatively, hydrogen can be produced on-site and on-demand, using electrolysers of any size, mitigating the need for costly hydrogen transportation and distribution infrastructure … so allowing earlier adoption of a hydrogen economy.'

This so-called 'distributed generation', in which consumers produce and utilise their own hydrogen, is an exciting prospect that could supplement and even eventually replace today's centralised electricity generation at huge power stations – an energy revolution that could change the dynamics of society.

Another project in CSIRO Energy Technology has

CMIT

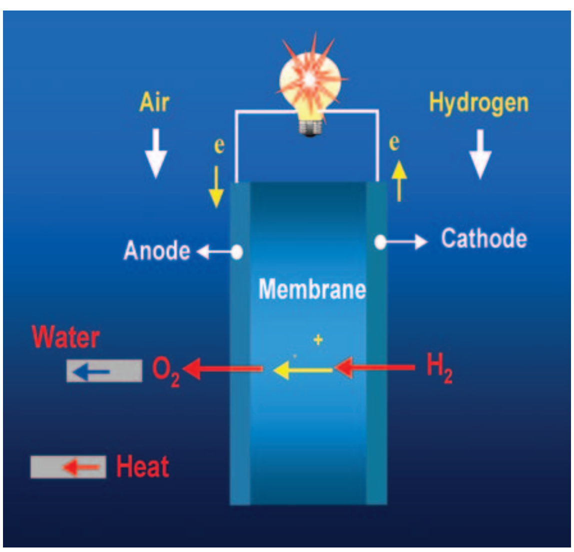
CMIT's Sarb Giddey with a working model of a hydrogen fuel-cell system. CSIRO is at the forefront of fuel-cell development.

demonstrated how, using concentrated solar energy (from a 108-square-metre solar dish), natural gas can be reformed to convert the gas to hydrogen for use in fuel cells. The novel process embeds about 20% solar energy into the hydrogen fuel produced.

Perfecting fuel cells

CSIRO is also at the leading edge of fuel-cell research and development. Fuel cells are like miniature power plants that essentially reverse the process of electrolysis. The researchers have successfully developed and operated PEM (polymer electrolyte membrane) fuel-cell stacks, in which the hydrogen recombines with oxygen on a special membrane, donating electrons to produce an electric current, but with absolutely no combustion and no greenhouse gas or pollutant emissions. A stack consists of several cells connected in series to increase the capacity of the fuel cell.

Dr Badwal says applications for PEM fuel cells include: small-scale power generation for residences and remote areas; portable power (replacing batteries) in anything from a mobile phone to a laptop computer; in a new generation of fuel-cell cars, buses, trucks,



CMIT

Fuel cells are like miniature power plants that reverse the process of electrolysis to produce electricity, without pollution.

The prohibitive cost of hydrogen technologies is often cited as evidence that the hydrogen economy is but a pipedream.

delivery vans, golf carts and wheelchairs, and for transporters at railway stations, shipyards and airports.

Dr John Wright, Director of CSIRO's Energy Transformed Flagship, points out that CSIRO has been involved in the construction of two hybrid cars, the EcoCommodore and the aXcessaustralia car, and is looking for a step change in CO_2 emissions by going from conventional cars to hybrid cars, which you can buy now, to, eventually, fuel-cell cars.

'We are strengthening our cooperation with General Motors Holden to use the hybrid car that we've developed as a basis to move into fuel-cell powered cars for Australia, and that will have a very positive environmental impact,' says Wright.

High costs and misleading myths?

The prohibitive cost of hydrogen technologies is often cited as evidence that the hydrogen economy is but a pipedream. Certainly, hydrogen vehicles and other applications are unlikely to gain a strong foothold unless their price and performance are comparable to conventional products. Enabling this is a central challenge that is perhaps not dissimilar to that facing proponents of the internal combustion engine when it emerged as a substitute for horse and cart.

Dr Amory Lovins, physicist and CEO of the Rocky Mountain Institute (RMI), an independent US research centre, argues strongly against what he calls 'twenty hydrogen myths' in a paper on the RMI website. A number of these are devoted to the question of cost.

Speaking in a US context, Lovins says it is a myth that we need ubiquitous hydrogen production, distribution and delivery infrastructure – currently impractical and costly – before, say, selling the first hydrogen car. RMI's recommended strategy is to build up hydrogen supply and demand profitably, step by step, starting now. Interlinking deployment of fuel cells in buildings and in hydrogen-ready vehicles will help make both applications happen faster.

Lovins says that studies by the Ford Motor Company indicate that a hydrogen-fuelling infrastructure based on miniature natural-gas reformers (with their own natural-gas supply) will cost about US$600 per car less than sustaining the existing gasoline fuelling infrastructure – saving US$1 trillion worldwide over the next 40 years. Thus, far from being too costly, a switch to hydrogen could well cost less than what we already do – largely because the investments needed for gas tend to be less than for oil.

Lovins also points out that nearly all significant car and oil companies have vigorous R&D programs to explore hydrogen and that many have made multi-billion-dollar investments in the hydrogen transition – presumably to make money rather than for their amusement!

Discussing safety, Lovins effectively debunks the notion, probably originating in the *Hindenberg* disaster of 1937, that hydrogen is too dangerous for common use as a fuel. He also seems to clearly discredit recent concern that hydrogen use would harm the ozone layer or the planet's climate by leaking too much hydrogen into the upper atmosphere – a case, he says, of scientists misreading references.

On the 30–50 - year timeframe for transition to a hydrogen economy, the RMI argues that hydrogen vehicles, developed since 1991, could, in principle, enter production ramp-up as soon as 2007, with aggressive investment and licensing to manufacturers. Furthermore, Deutsche Shell has said hydrogen could be dispensed from all its German fuelling stations within two years if desired. Happily, says Lovins, most of the investment in hydrogen, done right, will come from profit-seeking private-sector investments, not from tax dollars.

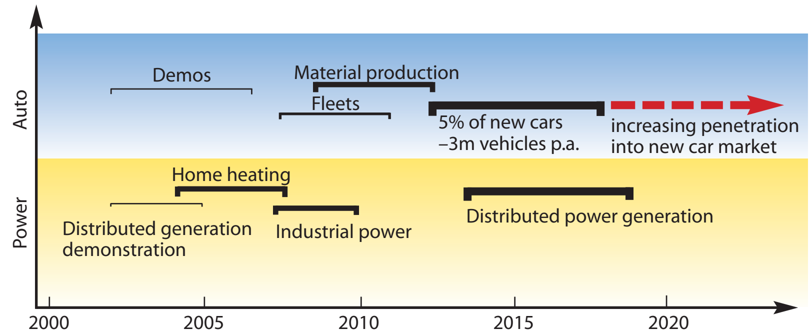
Our position in a transition

In Australia though, the R&D required to address all the technical challenges facing us if hydrogen is to win a significant share of the national or international energy mix will come at a price. With the long timeframes for any transition to greater hydrogen use, it will be difficult for any except the largest private firms to invest money in such R&D, and some of the burden of funding it may fall on the public sector, according to the National Hydrogen Study – Interim Report. Certainly, says the report, total annual investment of between $45 and $60 million dollars over the next 10 years (under a 'minimum funding scenario') is well above the current annual public sector investment in hydrogen-related R&D in Australia, of around $2–3 million. Given the probable difficulty in achieving this level of funding, the study concludes that it will be important for the research community to both attract private sector funding, and to tap into other research efforts in Australia and overseas – such as the United States Hydrogen Initiative and the Australian Coal Association's (greenhouse reducing) COAL21 coal-gasification program.

One dilemma that arises, when costs are considered, is the chicken-and-egg conundrum regarding hydrogen infrastructure and fuel. In the case of vehicles, industry is reluctant to manufacture and market cars or other vehicles if there is nowhere to refuel them, but who is going to risk putting in the necessary infrastructure for hydrogen fuel before there are enough hydrogen-powered vehicles on the road to make it worthwhile?

Perhaps the approach suggested by the RMI is one way around this dilemma: 'Instead of building a costly new infrastructure for hydrogen,' says RMI, 'we'd use excess capacity inherent in the existing gas and electricity distribution infrastructures, then make the hydrogen locally so it requires little or no further distribution.' Once this decentralised approach has built-up demand, investment in centralised hydrogen production could follow and the ideal vision of a hydrogen economy might actually materialise.

More about hydrogen:
Lovins, BA (2003). 'Twenty Hydrogen Myths'. Rocky Mountain Institute. www.rmi.org/images/other/E-20HydrogenMyths.pdf
National Hydrogen Study – Interim Report: www.aciltasman.com.au/pdf/Interim%20Report%20FINAL.pdf
Other relevant sites: www.cmit.csiro.au; www.rmi.org; www.aciltasman.com.au
Contact: Dr Sukhvinder Badwal, (03) 9545 2719



Indicative timing range for hydrogen market applications

Reproduced from the National Hydrogen Study - Interim Report 2003

Hydrogen cars: the no case

Counter to the tide of interest in hydrogen automobiles, two energy experts in the United States, David Keith and Alexander Farrell, recently argued strongly against early adoption of hydrogen cars.

Writing in the journal *Science*, Keith, of Carnegie Mellon University, and Farrell, of the University of California, say that although hydrogen is simple to produce, being a low heating-value, low boiling-point gas, it is inherently expensive to transport, store and distribute – serious drawbacks for a transportation fuel.

Although they concede that hydrogen has three big advantages – it reduces air pollution, emits no CO_2 and could reduce dependence on oil – they offer figures to back their view that there are more cost-effective solutions to all these problems.

Regarding air quality, Keith and Farrell say that using hydrogen to reduce pollution is comparatively expensive because technological innovation has already reduced emissions from conventional petrol cars to the point where they have very low emissions per unit of energy relative to other sectors and other transportation modes. This trend is likely to continue, reducing the benefit of zero-emission hydrogen vehicles.

On climate change, they argue that even if CO_2 capture and storage during hydrogen production from fossil fuels proves feasible, it will be much more cost-effective to reduce greenhouse emissions by use of new CO_2 - neutral electricity (such as wind or nuclear) than by switching to hydrogen cars.

For energy security, the two academics prefer the options of 'strategic petroleum reserves' (for example the US already stores 50 days worth of imports) and petroleum substitutes such as synthetic hydrocarbon fuels from coal or from bio-ethanol and biodiesel. Unlike hydrogen, they say, these substitute fuels will work with existing infrastructure and in existing vehicles.

The researchers conclude that although hydrogen is an attractive vision that demands serious investigation, it's 'not a sure thing.

'Transportation R&D should be broadly based, and should focus on basic enabling technologies rather than on a rush to deploy hydrogen cars.'

If we accept that there is considerable uncertainty about the optimum long-run solution to eliminating CO_2 emissions from cars, say the scientists, then early commitment to hydrogen fuel is unwise because it risks technological lock-in.

'If it were necessary to introduce hydrogen into the transportation sector, a wiser strategy would focus on transportation modes other than cars,' say Keith and Farrell. 'Hydrogen-powered heavy freight vehicles, such as ships, trains, and large trucks, could provide better air-quality benefits … and could be more easily implemented.'

CSIRO Energy Technology

AXcessaustralia's low emission car is a step-change towards hydrogen vehicle development.

Keith DW and Farrell AE (2003). Rethinking hydrogen cars. *Science* 30:1315–316.

A national hydrogen centre

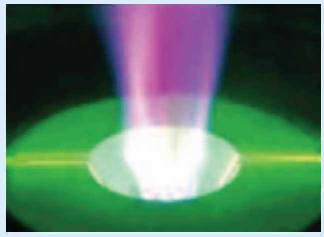
CSIRO Chief Scientist, Dr Robin Batterham, speaking at The Hydrogen Economy Conference in Broome, earlier this year, described Australia as 'a two per cent country'. We make up just two per cent of the world's intellectual effort.

Because of this, he suggests we need to focus our expertise in science and engineering in areas of R&D where we can build a critical mass, and where we expect significant improvements and break-throughs that will help to bring about a hydrogen economy. He believes that, in the big picture, we're not going to be world leaders in overall hydrogen technology, but that we can make important contributions, fill vital niches and form alliances with major players like, say, the European Union and the United States.

CSIRO's Position Paper on The Hydrogen Economy makes the point that 'Australia's investment in hydrogen-related R&D is very low, with little or no coordinated effort'. As a nation, we have relatively little understanding of hydrogen issues.

To address these shortcomings, a National Hydrogen Centre (probably to be called Hydrogen Australia) has been proposed to provide a focus for hydrogen-based activities. Initially, CSIRO is taking a leading role in helping to establish such a group. The centre under consideration is to have a strong national emphasis and will involve stakeholders from industry, educational institutes, governments and the community.

It is to have a virtual national structure and its main activities and functions will be to:



Sandia National Laboratories

Flame from the combustion of hydrogen and methane.

- promote and facilitate the early introduction of a hydrogen economy in Australia;
- act as a broker for technology development and utilisation projects;
- identify and assist local industry with establishment of business and manufacturing opportunities;
- assist with education of the public and industry and with education and training in educational institutes;
- act as a central source of information for access by academia, research institutes, industry, governments and community;
- facilitate and coordinate demonstrations of hydrogen technologies;
- assist with formulation of regulations and policy in relation to the safe generation, storage, transportation/distribution and use of hydrogen; and
- operate international alliances and links.

If it goes ahead, the centre should help to bring about business and manufacturing opportunities in various aspects of a hydrogen -energy economy and establish Australia as a leading technology provider for Asia.
Contact: Dr Sukhvinder Badwal, Chief Research Scientist, CSIRO (03) 9545 2719

Australia's future energy focus

CSIRO Energy Technology

The new National Energy Centre in Newcastle is a working demonstration of the latest renewable energy technologies.

UNDER THE NATIONAL Research Flagship, Energy Transformed, launched on 30 October, leading scientists will concentrate on Australia's future energy requirements, positioning us to develop one of the world's first hydrogen economies and a new export industry in energy technology.

The research program aims to:

- develop and implement technologies leading to near-zero emissions, power from fossil fuels and eventually, large-scale hydrogen generation;
- develop cost-effective electricity and hydrogen from renewable sources;
- increase the fuel and traffic management efficiency of urban transport, leading to an eventual transition to hydrogen-powered vehicles;

'Recent power blackouts in the United States, Italy and Denmark demonstrate that total reliance on central power generation is not a wise future option'

- double the efficiency of fuel use (natural gas and eventually hydrogen) by the generation of power/heat/cooling at point-of-use; and
- carry out energy scenario analyses to guide the research activities of the Flagship to achieve the goal of clean, cost-effective future energy for all Australians.

Launching with Energy Transformed is the $36 million CSIRO Energy Centre in Newcastle, NSW. As an international focus for energy research, the building showcases new and renewable energy technologies and represents the largest base of energy research and development in the Southern Hemisphere.

'The new centre is a distributed energy system in action,' says Acting Chief of Energy Technology, Dr Jim Smitham. 'Photovoltaic cells, gas microturbines and wind generators will initially provide most of our power, with any surplus being fed back into the main grid.'

Energy Transformed's Director, Dr John Wright, says that distributed generation will become increasingly important as the demands on national centralised generation and transmission infrastructures increase.

'Recent power blackouts in the United States, Italy and Denmark demonstrate that total reliance on central power generation is not a wise future option,' says Dr Wright.

The National Research Flagships Initiative is a partnership approach to tackling major challenges faced by Australia, and one of the largest scientific undertakings in the nation's history.

Energy Transformed:
http://www.csiro.au/index.asp?type=blank&id=EnergyTransformed