FUEL CELLS, FUELS AND FUTURE ENERGY

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Abstract

The possible use of alcohols as direct fuels for fuel cells conjures up images of instantly recharging cellphones and digital cameras from hip flasks, and of alcohol-based electricity generation plants for remote villages, and perhaps, more efficient use of alcohols as motor fuels. The reality of such images is assessed and some recent developments in fuel cells are outlined. Perspectives on the future potential of a range of non-fossil energy sources are presented and related to broad energy flow scenarios in the sugar industry.

Keywords: fuel cells, ethanol, climate change, renewable energy, electricity, fuels

Introduction

In 1839, Sir William Grove was experimenting with electrolysis of water using two electrodes in dilute sulphuric acid, with inverted test-tubes covering the electrodes to capture the hydrogen and oxygen given off. He noted that if he accumulated some hydrogen and oxygen at the respective electrodes and then disconnected the power source, electricity would flow in the opposite direction to that used for the electrolysis. This was the first observation of a fuel cell, which was initially called a gas battery. These early gas batteries were unreliable and so they received little further attention until Sir Francis Bacon developed the first practical version at Cambridge in 1950 (Cook, 2001[1]).

Compared to batteries, fuel cells have the advantage of producing much more energy per unit mass. They therefore represented appropriate sources of on-board power for space craft, and in the 1960s a 1.5 kW fuel cell was produced by an American company (International Fuel Cells) for the Apollo space craft. This unit proved very reliable, running on compressed hydrogen and oxygen and producing drinking water as well as electricity for the astronauts (Cook, 2001[1]).

Fuel cell technology continued to develop such that by the 1970s the Orbiter space craft carried a 12 kW unit which, compared to the Apollo units, produced 10 times the energy per unit volume. The reliability was such that no back-up batteries were carried and the unit ran for more than 82 000 hours on flights (Cook, 2001[1]).

The fuel cells used in space craft involve KOH, which tends to be poisoned by carbon dioxide in a terrestrial environment. Much research was therefore conducted on alternative forms of fuel cells including solid oxide, phosphoric acid, molten carbamate and proton exchange membrane (PEM) types. The PEM types had limited success on space flights (Gemini), but in 1983 the Ballard company improved the design and became world leaders in PEM fuel cells, producing units capable of 250 kW output. They soon formed alliances with major motor manufacturers whose interest in fuel cells was provoked by a Californian

[1] Cook B (2001). An introduction to fuel cells and hydrogen technology. fuelcellstore.com/products/heliocentric/INTRO.pdf (accessed Feb 2006).

‘decree’ that, as from 2003, 10% of vehicles manufactured must be zero emission vehicles (ZEVs). The ZEV programme led to the development (by Daimler-Chrysler) of a fuel cell powered car (the NECAR) that drives like a normal car but with low engine noise, no production of oxides of sulphur or nitrogen, and a fuel efficiency twice that of a standard internal combustion engine. The primary fuel is methanol, with on-board conversion to hydrogen and carbon dioxide (Cook, 2001[1]).

The huge challenge of providing hydrogen to mobile fuel cells had been overcome by the development of on-board fuel reformers that can convert various fuels, including diesel and petrol, to hydrogen. Such reformers are, however, considerably simplified if the primary fuel is methanol or ethanol. With these alcohol fuels the reformer can be incorporated into the fuel cell itself, hence the emergence of so-called direct methanol fuel cells (DMFCs) for small portable applications.

The NECAR runs on methanol and has been so successful that all major players, including Japanese and Korean motor manufacturers, have joined the California Fuel Cell Partnership. In 2002, 30 buses powered by Ballard fuel cells were introduced to 10 European cities for testing. By late 2005 they had covered more than a million kilometres and had needed less maintenance than anticipated. These fuel cell vehicles are much more expensive than conventional vehicles, but costs are declining steadily.

These and other recent energy-related developments have implications for the sugar industry.

Possible future roles of fuel cells

Direct methanol fuel cells (DMFCs) for portable power

DMFCs have advantages of:

- High energy density of alcohol compared to hydrogen
- No need for a separate reformer to convert primary fuel to hydrogen
- Unlike batteries, they do not discharge when not used
- One ‘charge’ is predicted to run a cellphone for a month
- Recharging is almost instantaneous.

Compared with other types of fuel cell they are, however, less energy efficient and more costly. For portable use the advantages far outweigh these disadvantages, and so considerable research is now focused on further development of the DMFCs. They are likely to replace batteries in cellphones, video and digital cameras, laptops and emergency back-up devices. Prototypes are already being marketed on a test basis.

Ethanol can replace methanol in DMFCs. The ethanol is slightly less efficient (more CO_2 produced per unit of hydrogen) but, unlike methanol, it has the advantage of being a renewable fuel with neutral CO_2 balance. Recent innovations include the ‘solidification’ of the alcohol fuel with a reusable additive that prevents leakage and vaporisation. If ethanol becomes the fuel of choice for DMFCs then the market for ethanol could increase substantially.

Stationary fuel cells

There is considerable development in this area with many companies involved. The main markets are in the USA and Japan, with the former being focused on uninterruptible power supply (UPS), whereas residential units (1-7 kW) are in demand in Japan. The fuel used in these devices is mainly natural gas or propane. Up-to-date market reports are available at www.fuelcelltoday.com.

One advantage of stationary fuel cells in residential applications is that the heat given off can be recovered for domestic heating. When the heat and electricity are recovered the energy efficiency (from hydrogen) is very high at about 85% (42% electrical and 43% heat). A 250 kW unit is about the size of a small bus and could provide power and hot water for about 50 Japanese households (Cook, 2001[1]).

A project of particular relevance to the sugar industry in the long term is the BioSOFC project in Europe. It involves the combination of biomass gasification and a Solid Oxide Fuel Cell to produce electricity and heat from the gas (Skreiberg, 2005). This represents a paradigm change from the current sugar industry concept of bagasse gasification feeding a combined cycle turbo-generator. In the BioSOFC system, the gas is fed directly to a fuel cell to generate electricity with very high efficiency without boilers and turbines. Heat recovery from the system could possibly be used to generate steam for sugar processing. The project has progressed to the point of operating a wood chip gasifier and successfully cleaning the gas at high temperature. European companies are aiming to produce fuel cell plants with capacity for 50 MW nominal power (up to 200 MW peak power) and electrical efficiencies of 60%. In the USA, similar research is being conducted at the National Centre for Hydrogen Technology, established in 2004 at the University of North Dakota. The challenges are considerable, but world-wide commitment and co-operation is likely to progress the technology, with implications for the sugar industry.

Climate change and energy

World awareness of impending energy shortage has been strong since the 1970s when the Club of Rome drew attention to the finite oil reserves, and the fuel crises of that time helped to emphasise the issue. In the past two years an additional force has come into play. Most of the world, including powerful governments, has now accepted the reality of climate change and the urgent need to do something about it. Natural disasters, such as the flooding of New Orleans, helped to convince people of the need to act decisively (Table 1). For example, in 2005 the British Parliament was fully supportive of plans to act urgently on climate change and agreed that it was a priority issue. The British prime minister made climate change a key theme of the UK presidency of the G8 countries and of the EU during 2005 (Winkler, 2005). Also in 2005, President Bush, in his State-of-the-Union address, announced support for a vast expansion of the country's ethanol industry, focused mainly on development of cellulose-to-ethanol technology. Part of the reason for this 'man on the moon' commitment was concern for air pollution and climate change.

Table 1. Increasing numbers and costs of climate-related natural disasters.

Decade	1950-59	1960-69	1970-79	1980-89	1990-99
Number	20	27	47	63	89
Cost (billion Euros)	33	59	106	164	506

(Data from Muencher Rueck Versicherungsgruppe,
quoted by European Council on Renewable Energies[2])

The critical world issue is no longer simply one of energy availability. This is now overlaid with a more urgent issue of mitigating man-made climate change, and the two issues dictate that there is a change in energy technologies, with concerted effort to seek alternatives to fossil fuels.

[2] European Council on Renewable Energies. Renewable energy. A key solution to climate change. www.erec-renewables.org (accessed Jan 2006)

It might be argued that South Africa is a relatively minor producer of greenhouse gases and has coal for another 200 years and therefore does not face immediate pressure to change. The country is, however, a 'skunk' in terms of climate change because production of carbon dioxide per unit of GDP is almost the worst in the world. Kyoto policy revisions due in 2012 are likely to put pressure on South Africa, Brazil, India and China (Winkler, 2005). There will probably be pressure on South African power stations to practise carbon capture and storage (CCS). Surveys have already begun to seek suitable storage sites (Engelbrecht *et al*, 2004). If this technology is adopted it will approximately double the price of electricity. If the price of electricity increases significantly and South African electricity distribution policies and technologies follow those of the UK then there will be scope for profitable electricity sales from cane farms and factories, using non-fossil fuels.

Planning for new technologies

For planning purposes, it is appropriate for the cane sugar industry to keep informed of energy trends. Ethanol production for motor fuel, and cogeneration of electricity by sugar factories are well appreciated as potential sources of revenue. As indicated by fuel cells, the changing context in which ethanol and electricity might be used in the future, alongside other energy sources, may present additional opportunities for the industry. Most countries that have produced recent energy plans have separate short-term and long-term plans, with different technologies featuring in the different time horizons. It is suggested that the sugar industry needs a similar approach, with a time horizon of at least 25 years. New technologies have inevitably taken more than 25 years to be adopted by the industry (Table 2). Active planning for new energy technologies may shorten this delay, hence the highlighting of energy technology trends in the following section.

Table 2. Examples of time delays between the appearance of a new technology and adoption of the technology by the South African sugar industry.

Date of invention	Nature of technology	Delay (years)
1952	Analytical chromatography	23
1953	DNA code elucidated	37
1960	Surveillance satellite	38
1975	Computerised supermarket checkouts	25
1975	Preparative chromatography	30+
1952	Gas turbine generator	?
1998	Sugar fuel cell (SuFuCell) patented	?

Energy trends

Increased funding of renewable energy research and training

Most countries have recently increased funding for renewable energy research and training. For example, the British Engineering and Physical Sciences Research Council (EPSRC) established an initiative called SUPERGEN (Sustainable Power Generation and Supply) which 'aims to help the UK to meet its environmental emissions targets through radical improvement in the sustainability of power'. This initiative encourages researchers to work in consortia, with the first consortia being established in 2003. The titles of the 10 consortia (Table 3) give an indication of current research directions.

Table 3. British research consortia established in 2003 to help reduce emissions.

Title of Consortium
Biomass & Bioenergy
Sustainable Hydrogen Energy
Marine Energy
Future Network Technologies
Photovoltaic Materials for 21st Century
Conventional Powerplant Lifetime Extension
Fuel Cells
Highly Distributed Power Systems
Excitonic Solar Cells
Energy Storage

Changing thoughts on the likely future contribution of renewable energies

Until recently, most energy scenarios have assumed that renewable energies will contribute only a small percentage of future energy consumption worldwide. The incentives to mitigate climate change have caused changes in thinking. In 2004, the European Council on Renewable Energy worked with its numerous associates to develop a scenario (European Council on Renewable Energies, 2006) that suggests that by 2040 as much as 48% of the world's energy requirements could be met by renewable energies. The predicted rates of growth of the various technologies are indicated in Table 4. The strong initial growth of wind, photovoltaic and solar applications is evident, with marine energy growing later.

Table 4. Predicted potential rates of growth (cumulative annual %) of various renewable energy sources on a worldwide basis (European Council on Renewable Energies[2]).

Energy source	1996-2001	2001-2010	2010-2020	2020-2030	2030-2040
Biomass	2	2	3	3	3
Large hydro	2	2	1	1	0
Small hydro	6	8	10	8	6
Wind	33	28	20	7	2
Photovoltaic	25	28	30	25	13
Solar thermal	10	16	16	14	7
Solar thermal electricity	2	16	22	18	15
Geothermal	6	8	8	6	4
Marine (tidal/wave/ocean)	–	8	15	22	21

Table 5 shows an assessment of the possible contribution of renewable energy to world energy demand in the next 35 years. Starting from the current position where renewable energy contributes 14% of world energy, it is possible to increase this to almost 50% with the major growth occurring after 2020 and with biomass playing a major role throughout the period. This scenario involves a tripling of biomass energy in the next 35 years.

Table 5. A 'high road' global renewable energy (RE) scenario (European Council on Renewable Energies[2]).

	2001	2010	2020	2030	2040	2040 RE % total
Total consumption (mill. tons oil equiv.)	10038	10549	11425	12352	13310	
Biomass	1080	1313	1791	2483	3271	25
Hydro (large & small)	232	285	358	447	547	4
Wind	5	44	266	542	688	5
Photovoltaic	0.2	2	24	221	784	6
Solar thermal	4	15	69	260	548	4
Geothermal	43	86	186	333	493	4
Marine	0.05	0.1	0.4	3	20	<1
Total Renewable	1364	1745	2694	4289	6351	48
Renewable % total	14	17	24	35	48	

If **electrical** energy is considered alone, then the renewable energy component rises to above 80% (Figure 1). Photovoltaic and wind power are seen as major contributors in the medium-term (20-30 years), with marine power developing rapidly thereafter.

The 'high road' or 'Advanced International Policies' scenario is one that depends on strong encouragement of renewable energy development through legislation, economic incentives and increased funding of research and development. An alternative scenario called the 'Dynamic Current Policies' scenario is one that is likely under current policies. This scenario has renewable energy developing to 27% of world consumption by 2040. No matter which scenario eventuates, the future development of renewable energy is likely to be rapid. The 'low road' scenario will merely be slower than the 'high road'.

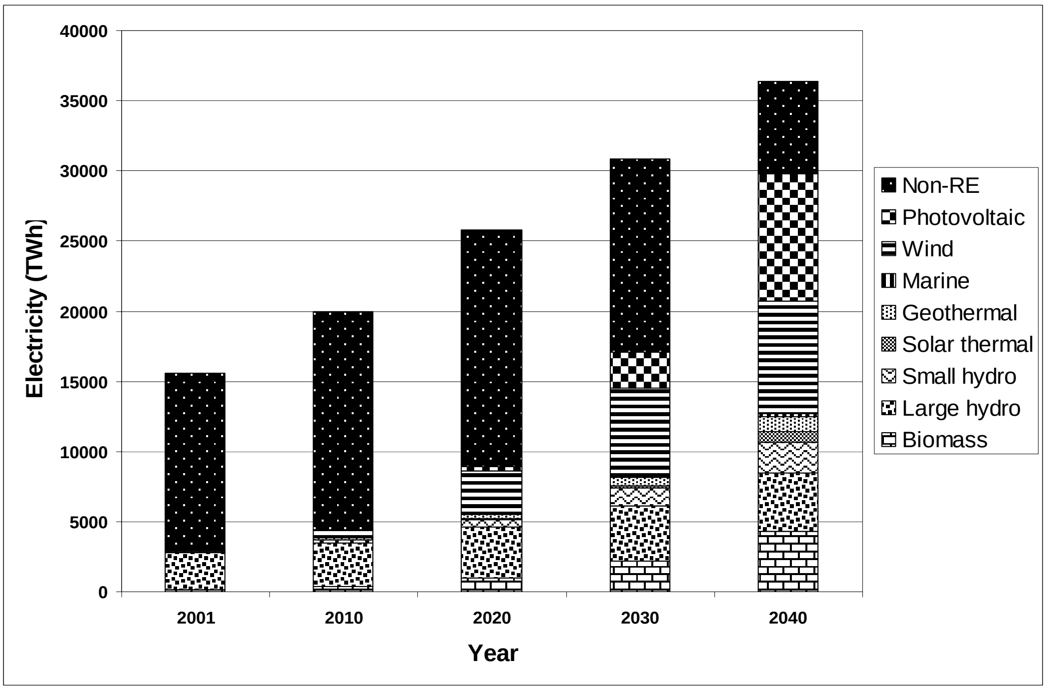

Figure 1. A 'high road' scenario for the contribution of renewable energy to world electricity generation (European Council on Renewable Energies, 2006[2]).

'Keep the nuclear option open (KNOO)'

The so-called KNOO project in the UK and in SA is part of recent energy trends, with a small modular pebble bed reactor due to be built in SA by 2007. The future of nuclear energy is uncertain – it is likely to play a significant role alongside renewable energy, but it still faces strong opposition.

Increasing opportunities for mini-suppliers and distributed generation

To accommodate renewable energy sources, it has been recognised that there is need for technologies that enable small suppliers to connect to the electricity grid via 'in-out' connections that allow selling or buying of electricity depending on circumstances. German and Japanese systems already cater for individual households and encourage the installation of photovoltaic generators on roofs of new residential buildings. The UK focus on this type of distributed generation (see Table 3) has led to rapid progress in modelling and controlling voltages throughout the grid so as to enable input from mini-sources. As a result of climate studies in the UK it is now realised that, for the grid as a whole, wind and solar power are much more consistent than previously realised – the wide geographic distribution of numerous small generators ensures good average availability of wind and sun.

Energy and the sugar industry

On farm energy flows

Sugarcane is one of the best crops for capturing energy from the sun. The energy in a standing crop is approximately as indicated in Table 6.

Table 6. Energy in components of sugarcane.

Component	Portion (t wet/t cane)	Moisture (%)	Brix (%)	Ash (%)	Energy (MJ/t LHV)	Total energy (MJ/t cane LHV)
Clean stalk	0.778	71	15	0.6	2954	2298
Tops	0.143	70	3.8	0.8	3477	497
Trash	0.079	12	2.2	1.5	15456	1221
Total						4016

Notes:
1. The cane component data is from de Beer *et al*, 1989 (ash % has been estimated)
2. The lower heat value (LHV) is calculated using the formula LHV = 18260 – 31.14 Bx % – 207.63 moisture % – 182.6 ash %

From Table 6 it is evident that perfectly topped and trashed cane would leave about 43% of its energy on the farm. Assuming an average yield of 55 t cane/ha/an, the data in Table 6 suggests that theoretically the farmer could accrue about 94 000 MJ of energy per ha in tops and trash. This is equivalent to the energy value of about 2500 litres of diesel.

Trash-to-diesel technology

Technology for converting waste (including bagasse) to diesel on a small scale is being marketed (personal communication[3]). The developers of this technology claim that, without external sources of energy, the conversion efficiency is such that the yield of diesel on dry

[3] LJ Roux, Rapax Capital (Pty) Ltd, tel. 0123478255 or 0824449807

biomass is 30%. If this proves possible then the diesel production from on-farm cane residue would be 3.4 litres/t cane. This on-farm conversion of trash to diesel has yet to be confirmed technically and economically, but it might be attractive as an alternative to cane burning. The claimed amount of diesel produced would meet about 75% of the diesel required for production and delivery of cane.

Photovoltaic energy capture vs cane energy capture

Under South African conditions the above-ground portion of cane captures about 1.1% of the solar radiation during its growth to maturity (Thompson, 1989). After harvest, the 'left behind' portion (tops and trash) contains potentially 43% of this (Table 6), meaning that about 0.5% of the solar radiation accrues as fuel on the farm. If this fuel is used to generate electricity the energy transfer from biomass to electricity is about 40%. Although the quantity is significant, it is small compared to that which Photovoltaic systems could capture if occupying the same area (Table 7).

Table 7. On-farm energy potential of trash, and comparison with photovoltaic.

Item	Quantity	Comment
Potential on-farm energy (MJ/t cane LHV)	1718	Table 6
Efficiency of conversion to electricity (%)	40	
Potential on-farm electricity from residues (kWh/t cane)	190	
Potential on-farm electricity from residues (kWh/ha.an)	10498	55 t cane/ha/an
Approx. solar radiation in SA sugar industry (kWh/ha/an)	$170x10^6$	Thompson (1989)
Approx. solar energy capture by cane (%)	1.1*	Thompson (1989)
Photovoltaic efficiency (sun to electricity %)	11	Range 9-14%**
Therefore photovoltaic potential (kWh/ha.an)	$18.7x10^6$	
Ratio of photovoltaic to tops and trash electricity	1781:1	
Ratio if photovoltaic = 0.5 x plant crop (i.e. inter-row)	89:1	

* Ranges from 0.7 to 2.0.
**www.daviddarling.info/encyclopedia/P/AE

Unfortunately the cost of photovoltaic systems is generally prohibitive but it is declining to the point where small government incentives are enough to encourage the installation of photovoltaic panels in new houses in Japan and Germany. The figures in Table 7 suggest that if farmers were to use photovoltaic energy harvesting they could sell appreciable energy. Some photovoltaic systems are being produced as roll-up fabrics that could be rolled out in the inter-row of plant crops. This is, however, futuristic – production of electricity from biomass is a more likely short-term scenario.

Wind potential

Landowners of the future could also harvest energy from wind and small-scale hydro systems. The reality of wind power is illustrated by the fact that between 1990 and 2001 the installed wind generator capacity in the European Union increased from about 1 GW to 17 GW, with plans for considerable expansion (www.ewea.org). Wind generators range in size from a few watts to 3.5 MW. The technology has a reputation for being costly in terms of capital, because the generators fail when there is no wind and therefore have to be backed up by conventional power plants. This back-up cost declines if the wind farms are part of a distributed generation system. South Africa's wind map is being redrawn for wind speeds at a height of 30 m instead of the current 10 m, because the 10 m map tends to underestimate speeds at the operating height. With the changing energy scenario, wind generation could become a source of revenue for some farmers.

Energy distribution after processing

Within a raw sugar factory the energy is channelled to the major products as shown in Table 8. With current equipment, surplus energy can be used to generate about 70 kWh of electricity per ton cane processed. Considerable capital expenditure and introduction of gas turbines could enable this to be increased to 200 kWh/t cane. The delivery of all tops and trash to the sophisticated equipment would yield a further 260 kWh/t cane (Wienese, 1999).

Table 8. Energy distribution in mill products.

Product	Tons/t cane	Approx. energy (MJ/t cane LHV)
Sugar	0.126	2080
Molasses	0.039	*250***
Bagasse	0.32	2272

**energy in fermentable sugars

Replacement of diesel with electricity

Assuming that diesel will continue to increase in price, and that the sugar industry could generate substantial amounts of electricity, it is interesting to assess the impact of replacing diesel engines with electric motors. In a futuristic scenario the electric motors on vehicles would be driven by on-board fuel cells, probably running on ethanol. In a less futuristic scenario electric tractors could run from roll-up cables, as is presently the case in mines. Major transport routes could be electrified as was the case with trolley buses in Durban until the 1960s. The infrastructure for such systems would obviously be expensive. Table 9 gives a superficial analysis of potential savings in fuel costs, excluding the on-farm infrastructure costs necessary to deliver the electricity to the vehicles. The fuel cost savings are theoretically substantial and might justify infrastructure costs in some instances. ESKOM have already conceived the idea of an electric tractor (personal communication[4]) involving simple replacement of the motors on existing tractors. Such tractors may already have attraction where electrical infrastructure exists for centre-pivot irrigation. In comparing electricity and diesel as fuels, it is important to realise that modern electric motors have energy efficiencies exceeding 90%, whereas diesel engines seldom exceed 40%.

Based on the average diesel consumption by farmers of 4.48 litres per ton cane, and taking into account the higher efficiency of electric motors, this translates to a need for 21 kWh of electricity generation per ton cane to replace the diesel with electricity. This requirement is well within the capacity for co-generation from cane (Wienese, 1999). A sugar mill with a network of powerlines to its supplying farms could theoretically represent an energy self-sufficient production system – a feature of value in the future.

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Table 9. Comparison of costs of diesel and electricity as motor fuels.

	Diesel	Electricity	Comment
Average power output (kW)	100	100	
Motor efficiency (%)	40	90	
Required power input (kW)	250	111	
Hours of operation	1	1	
Total energy input (kWh)	250	111	
Energy content of diesel (kWh/L)	10.5		
Diesel required (L)	23.8		
Cost of diesel (c/L)	325		After grower's rebate
Scenario 1 – Electricity from extended co-generation			
Cost of fuel (c/kWh)	31	33	(Wienese, 2004)
Cost of required fuel (R)	77.5	36.7	
Fuel cost saving (%)		53	
Scenario 2 – Marginal electricity or ESKOM electricity			
ESKOM electricity		25	Estimated average
Cost of required fuel (R)	77.5	27.8	
Fuel cost saving (%)		64	

Discussion and conclusions

After years of talk without much action it is evident that energy technology is now receiving serious attention. A paradigm change is taking place, with a trend towards distributed generation using a multitude of energy sources. The need for additional electricity generating capacity in South Africa is common knowledge and the need to minimise production of carbon dioxide adds urgency to the development of clean systems.

In the long-term the cane sugar industry is well positioned to benefit from energy management and marketing. With an ability to produce electricity, biofuel and biomass, and to harvest solar and wind energy, the industry should keep track of the following possibilities:

- Mini connections to the national electricity grid opening opportunities for growers and millers to sell energy, and to 'wheel' industrially generated electricity between centres.

- Developments in alcohol fuelled fuel cells that create opportunities to sell ethanol as a preferred fuel to motorists. This might become possible because the on-board fuel reformers (making hydrogen for the fuel cells) are relatively simple when alcohol is the primary fuel. The high energy efficiency of fuel cells suggests that ethanol will go much further in a fuel cell vehicle than in an internal combustion vehicle, and it is neutral in terms of carbon dioxide production.

  The impending commercialisation of fuel cells that replace batteries in portable equipment might also create a market for ethanol. Methanol currently holds 'pole position' as the fuel for alcohol fuel cells, partly because ethanol producers have shown limited interest.

- Semi-SASOL technology' for making diesel from biomass on a relatively small scale. This could create a market for tops and trash, and a profitable alternative to cane burning (with due regard to the value of tops and trash for soil conservation).

- Biomass gasification technology has relevance to electricity generation via efficient next generation combined cycle generators. Gasification may also be linked to fuel cells using the hydrogen in the gas and potentially providing a very efficient means of generating electricity from biomass.

- Replacement of diesel engines by electric motors to benefit from the lower cost of the fuel.

- American research focus on producing ethanol from lignocellulose. Success in reducing the cost of this process could provide another profitable use for fibre.

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