Draft 4/13/2007

Australian Petroleum Production and Exploration Association

Adelaide 16 April 2007

The Future Environment for Energy Business

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Thanks to Belinda Robinson and the Australian Petroleum Production and Exploration Association for this opportunity to speak with you about the future environment for the energy business. [**Slide 1**]

Oil has blessed my career. The profits of the Standard Oil Company allowed John D. Rockefeller in 1901 to establish the institute that became the university specialized in sciences where I have worked for more than 20 years. Let me also point out that John D. Rockefeller did far more to save whales than Greenpeace. The innovations of the petroleum industry beginning with Colonel Drake's discovery of abundant supplies in Pennsylvania in 1859 led speedily to the collapse of the whaling fleet in the early 1870s. Whaling was primarily an oil industry, not a meat industry. Had worldwide whaling continued at its mid 19^{th} century pace for even one or two decades more, humans might well have extinguished many whale species. This anecdote about whaling is not tangential. Rather, it illustrates my central message: the *substitution* of an environmentally and economically superior product.

I will not keep you in suspense about the next product for your industry. The product is methane, CH_4, with its rich energy per carbon atom. APPEA also foresees methane's coming dominance in its March 2007 Submission to the Prime Ministerial Task Group on Greenhouse Gas Emission Trading. **[Slide 2]** A photo of a lake of liquid methane on Saturn's largest moon shows non-biological methane is astoundingly abundant there, as it will prove to be on Earth, a point to which I will return.

Here let me introduce the most important trend in the environment for the energy business, namely *decarbonization*. I need not say to APPEA that hydrocarbons are a mix of carbon (C) and hydrogen (H) [**Slide 3**], but perhaps I can bring a new *historical* appreciation to their changing roles. On average, when one removes the water, biomass fuels such as wood and hay have a ratio of about 40 Cs to 4 H. (Charcoal, by the way, is essentially pure C.) Coal comes in many shades but typically has about 8 Cs for each 4 H. APPEA's prime products, like gasoline and jet fuel, average about 2 C for each 4 H. Methane, as mentioned, burns only 1 carbon for each 4 hydrogens, $1/40^{th}$ the ratio of wood.

Almost 25 years ago, my colleagues and I put all the hydrocarbons humans used each year for the past two centuries in a hypothetical gigamixer and plotted the history of fuel in terms of the ratio of C to H **[Slide 4**]. To our surprise we found a monotonic trend toward decarbonization. The figure shows carbon losing market share to hydrogen as horses losing to cars or typewriters losing to word processors. The slow process to get from 90% C to 90% H in the fuel mix should take about 300 years and culminate about 2100. Some decades have lagged and some accelerated but the inexorable decline of carbon seems clear. Times make the man. John D. Rockefeller surfed on this long wave. So do Lord Browne and Al Gore. Successful people and companies ride the wave of history and arrogate fame and money. I hope people in this room will do so.

Over the past 20 years decarbonization has entered the vernacular, and the broker Merrill Lynch even has a decarbonization mutual fund. A variation [**Slide 5**] of decarbonization showing the kilos of carbon per unit of energy integrates fuel switching with increases in efficiency, that is, technical progress, for example better motors. The variation of carbon per GDP further integrates energy with consumer behavior, that is, whether consumers favor energy with their marginal dollar. The decarbonization lines always point down for C and up for H.

One naturally asks why. The explanation is that the overall evolution of the energy system is driven by the increasing spatial density of energy consumption at the level of the end user, that is, the energy consumed per square meter, for example, in a city. Finally, fuels must conform to what the end user will accept, and constraints become more stringent as spatial density of consumption rises. Rich, dense cities accept happily only electricity and gases, now methane and later hydrogen. These are the fuels that reach consumers easily through pervasive infrastructure grids, right to the burner tip in your kitchen.

Ultimately the behavior of the end user drives the system. When the end user wants electricity and hydrogen, the primary energy sources that can produce on the needed scale while meeting the ever more stringent constraints that attend growth will eventually and inexorably win. Economies of scale are a juggernaut over the long run.

One contributor to economies of scale is the heat value of the fuel per kg. [S**lide 6**]. Replacing brown coal with methane raises the energy per ton of fuel as it decarbonizes. Thirteen railroad cars of biomass such as switchgrass equal about one railcar of coal and half a car of oil. Economies of scale match best with technologies that grow smaller even as they grow more powerful, as computer chips, electric motors and power plants all have done.

I mentioned dense cities as the final arbiter of the energy system. Energy demand is far denser in some places than other as artificial lighting displays. [**Slide 7]** shows light at night in 1996. The bright city lights of the USA, Europe, and Japan glow and most of the rest is dark. The next [**Slide 8]** shows how Earth would glow if all of today's 6.4 billion people lit bulbs like today's Americans. The third **[Slide 9]** shows where the increases would occur, that is, the latent electricity demand. The story would be the same for fuels for mobility. Demand growth is concentrated in South and East Asia. Australia already prospers from serving energy to these markets. As the slide shows, India and eastern China may essentially be considered vast incipient conurbations that will require ultra-clean fuels as the spatial density of their energy consumption soars.

India and China are the future environment for energy business. In about 1930 the writer Gertrude Stein remarked that America was the oldest country in the world because America had been in the 20th century longer than any other country. In 2007 jet-setters know that Singapore and Shanghai have been in the 21st century longer than Los Angeles or New York. Make sure you keep your minds on the magnetically levitated train of Shanghai and the chilling of Singapore, not the blah-blah of Brussels and Washington DC nor the windmills of Denmark.

By the way, the upstream oil and gas industries should not fear rising end-use efficiency. First, the unmet global demand is probably at least 4 times today's energy consumption, so even a doubling of efficiency leaves a market that will double in size. Or consider that a European car of the mid 1950s did about 14km per liter of gasoline as most cars do now with engines 5 times more powerful; the progress went into performance of some kind, not saving energy or even increasing mean speed, which traffic keeps around 40 km per hour.

Moreover, people tend to work within money budgets for goods such as mobility. For example, people in all societies spend about 13-15% of their discretionary income on travel. If consumers become richer or traveling by car becomes more efficient and thus cheaper, the happy individuals transfer the surplus or saving to, for example, purchase of air tickets. Taxing mobility and energy temporarily allows governments to seize more of the travel money budget, but over the long run, humans instinctively maximize their range and thus access to resources. Mobility will keep increasing about 2 percent per year [**Slide 10**] as they substitute better machines, that is, machines that offer low cost speed. Americans still average only a about a minute per day in airplanes, while a person who flies about 150,000 km per year, as many APPEA attendees probably do, averages about 40 minutes per day. Even super-efficient planes will form an immense growth market for your fuels as more people join the jet set.

What are the most promising ways for the energy system to meet the next round of consumer demands amidst fears about global climate change? For electricity, I propose generation companies and their suppliers should develop very large zero-emission power plants or ZEPPs. Operating on methane, a ZEPP puts out electricity and carbon dioxide that can easily be sequestered. A company called Clean Energy Systems in Bakersfield California already has a prototype of 5 MW and is working on models for 50 MW and 500 MW. One design fittingly uses CO_2 as an operating fluid [**Slide 11]**. Japanese colleagues calculate a ZEPP could reach 70% efficiency, green indeed compared to the 30% of today's coal plants with accompanying saving of carbon emission. My dream is a 5 GW ZEPPs, super fast, operating at high temperatures and high pressures and thus super compact, so the ZEPPs could fit comfortably within the existing infrastructure [**Slide 12].**

Efficiency must be reckoned in space as well as energy and carbon. To me the essence of green is No New Structures, or at least few new visible ones. Like computers and the internet, the energy system to be deeply green should become more powerful and smaller. [**Slide 13**] During the 20th century, electric generators grew from 10 to 1 million kW, scaling up an astonishing 100,000 times. Yet a power station today differs little in the space it occupies from that of 50 or 100 years ago. For a ZEPP in a few decades, think of a space shuttle engine that might operate for 300,000 hours. A couple of thousand ZEPPs around India and China would be good customers for APPEA. How can China and India multiply their power by 5 or 10 unless the new system fits into a small footprint?

As the sample ZEPP design hinted, from an engineering point of view, oxy-fuel combustion is essential for capturing and sequestering the carbon dioxide efficiently [**Slide 14**]. Post-combustion and pre-combustion approaches suffer badly compared to direct stoichiometric combustion with oxygen. Air separation is going to become a vast industry. I hope APPEA members prosper in it. And of course, the requirement for less carbon dioxide emitted will increase carbon sequestration. While methane consumption grows, we won't permit ourselves to dispose much of its carbon in the air. Fortunately, carbon capture and sequestration for methane is half or less the problem for coal.

What might future cumulative demand for hydrocarbons total? The history of decarbonization hints that humanity might use in round numbers 100 billion tons more of coal and 200 billion tons coal equivalent more of oil. Astonishingly, we might use 1000 billion tons coal equivalent of methane. I would not be surprised by a peak use, say in 2060, of 30 x 10^{12th} cubic meters, a rate reached by sustained 4% yearly growth.

Where will the methane come from? Here let me introduce a heresy. [**Titan Slide again 15**] I reject the notion of "fossil" fuels, which implies that petroleum derives from the buried and chemically transformed remains of once-living cells. This theory relies on the long unquestioned belief that life can exist only at the surface of Earth. In fact, as the late Thomas Gold of Cornell University showed, a huge, deep, hot biosphere of microbes flourishes within Earth's crust, down to the deepest levels we drill. The microbes can be justified only by diffuse methane welling from the depths.

Consider instead an upwelling theory for coal, oil, and gas. The primordial, non-biological carbon comes in the first place from the chondritic meteorites that help form Earth and other planetary bodies. The abiogenic carbon, which clearly abounds on such planetary bodies as Titan, enters the crust from below as a carbon-bearing fluid such as methane, butane, or propane. Continual loss of hydrogen brings it closer to what we call petroleum or coal. Oil is very desirable to microbes, and the deep hot biosphere adds their products to the hydrocarbons. These bioproducts have caused us to uphold the belief that the so-called fossil fuels are the stored energy of the Sun. I believe they are not the stored energy of the Sun but primordial hydrocarbons from deep in Earth. And they keep refilling oil and gas reservoirs from below. The alternate theory of the origins of gas, oil, and coal will revolutionize Earth sciences over the next 2-3 decades, and lift estimates of resource abundance.

New theory will also help reveal resources in little explored places, such as the continental margins **[Slide 16]**. I am part of a worldwide network of scientists including many outstanding Australians who are in the midst of a decade-long effort to complete the first ever global Census of Marine Life. One of our projects is focused on communities of life around cold seeps of methane on continental margins. These cold seep communities may be ubiquitous. They are plentiful in the Gulf of Mexico [**Slide 17]**), near the potentially giant Jack Field touted in September 2006. The methane clathrates have attracted much attention in recent years, but perhaps we need a more embracing theory of the margins in which outgassing methane occurs all along the margins and creates not only the clathrates and the startling life on the margins but vast ribbons of opportunity for offshore exploration. So, much of the frontier of methane production may well look like Norway's Storegga plan. [**Slide 18**]

As Australians know, working in the oceans brings immense responsibility. The oceans are beautiful beyond imagination [**Slide 19**]. But we have already squandered many riches of the oceans, and we do not want to squander or harm more. A recent Census of Marine Life expedition south of Crete found more trash than life at 4000 meters depth [**Slide 20**]. Thus to maintain their license to operate, energy industries of exploration, production, and transport must gain a culture of supreme respect. [repeat slide 20 as **Slide 21**]. The energy industries should become leading stewards of marine life, supporting creation of protected areas, research, and monitoring, while operating perfectly where society does permit operation.

So far, my messages have been about substitution, decarbonization, methane, India & China, ZEPPs, and offshore. I must also comment on APPEA's core market of mobility.

Numerous companies and labs work on hydrogen cars with revamped internal combustion engines and fuel cells for clean propulsion. While both of these approaches will likely succeed, problems persist, for example with the ability to store enough energy onboard. In the interim, I urge more attention directed at a small analogue to the ZEPP, a zero-emission piston engine system using ordinary fuel and an ordinary piston engine. The key again is oxygen separation, this time onboard in an Ion Transport Membrane Reactor that companies like Air Products and Norsk Hydro are developing on a much larger scale for electric power plants. A combustible mixture enriched by oxygen could increase the fuel charge in the cylinder in a lean-burn diesel engine. An additional afterburner could use the excess of oxygen to add power. The effective power of a typical turbo diesel might increase from about 50 kW to about 200 kW, and motor efficiency rise from about 35% to about 50%, a very green machine.

Moreover, converting the vehicle fleet to zero emissions would not require changed fuel supply or engines. The gaseous emission would be converted onboard into liquid, which would be discharged in the fueling station and then sequestered. The principle challenges are extra weight for the membrane reactor and the liquid CO_2 stored onboard, which might total 250-300kg.

All my enthusiasm for methane will not complete decarbonization. The completion of decarbonization ultimately depends on the production and use of pure hydrogen. Already hydrogen is a thriving industry, essential to the downstream processing of APPEA's petroleum. In 2006 world production exceeded 45 billion standard cubic feet per day, equal to 80,000 MW if converted to electricity. US production, which is about 1/3 of world production, multiplied tenfold between 1970 and 2003 [S**lide 22]**. Over 16,000 kilometers of pipeline transport H_2 gas for big users, with pipes at 100 atmospheres as long as 400 kilometers from Antwerp to Normandy. High pressure containers such as tube trailers distribute the liquid product to small and moderate users throughout the world. With production experience, the hydrogen price is falling [S**lide 23]**. In fact, H_2 is already near prices to which energy consumers are accustomed [**Slide 24]**.

About hydrogen, the fundamental question then becomes, "Where will large quantities of cheap hydrogen come from?" Methane and water will compete to provide the hydrogen feedstock, while methane and nuclear will compete to provide the energy needed to transform the feedstock into hydrogen.

Steam reforming is already a venerable chemical process for making hydrogen from methane. In the near term because methane abounds, steam reforming of methane, using heat from methane, will remain the preferred way to produce hydrogen. Moreover, because much of the demand for hydrogen is within the petrochemical industry, nepotism gives methane an edge. But increasingly, as markets demanding hydrogen grow, carbon-free nuclear's chance to compete as the transformer improves.

While methane and nuclear will inevitably compete to provide energy for hydrogen manufacture, they can also fruitfully cooperate. Here let me share a big technological idea, methane-nuclear-hydrogen (MNH) complexes, first sketched by Cesare Marchetti. Much methane inevitably travels through a few giant pipeline clusters. These methane trunk routes are attractive places to assemble MNH industrial complexes. Here, if one builds a few nuclear power plants and siphons off some of the methane, the nuclear plants could profitably manufacture hydrogen to re-introduce into the pipelines, say up to 20% of the composition of the gas in the pipeline. This decarbonization would enhance the value of the gas. Meanwhile, the carbon separated from the methane would become CO_2 to inject into depleted oil and gas fields and help tertiary recovery. Distributed around the world, the hydrogen mixture would accustom users to the new level of decarbonization and start the capillary distribution of hydrogen for cars.

Over the next 10-15 years, I will keep my eye where much gas flows and see whether these regions begin to integrate with nuclear power. The experience of working with hydrogen from methane will benefit the nuclear industry as it puts nuclear plants at the nodes of the webs of hydrogen distribution, anticipating the eventual shift from CH_4 to H_20 as a feedstock. The methane-nuclear-hydrogen complexes can be the nurseries for a beautiful future generation of the energy system.

So my next message is, “Prepare to ally with uranium.” Uranium is 10,000 to 100,000 times as compact as methane [**Slide 25]**. While the competition will take another century or so, finally nuclear energy remains the overwhelming favorite to produce the hydrogen and electricity that Bangalore and Shanghai will demand.

What about the so-called renewable forms of energy? They may be renewable, but calculating spatial density proves they are not green. The best way to understand the scale of destruction that hydro, biomass, wind, and solar promise is to denominate each in watts per square meter that the source could produce [**Slide 26**]. In a well-watered area like Ontario, Canada, a square kilometer produces enough hydroelectricity for about a dozen Canadians, while severely damaging life in its rivers. A biomass power plant requires about 2500 sq km of prime Iowa farmland to equal the output of a single 1000 MW nuclear power plant on few hectares. Windmills to equal the same nuclear plant cover about 800 square km in a very favorable climate. [**Slide 27**] Photovoltaics require less but still a carpet of 150 sq km to match the nuclear plant. The spatial ratio for a Toyota rather than a large power plant is equally discouraging. A car requires a pasture of a hectare or two to run on biofuels, unwise as the world’s vehicle population heads toward 1 billion. No economies of scale adhere to any of the solar and renewable sources, so trying to supply India or eastern China would require increases in infrastructure that would overwhelm these already crowded lands.

Moreover, the photovoltaics raise nasty problems of hazardous materials. Wind farms irritate with low-frequency noise and thumps, blight landscapes, and whack birds and bats. And, solar and renewables in every form require large and complex machinery to produce many megawatts. While a natural-gas combined cycle plant uses 3.3 MT steel and 27 m^3 concrete, a typical wind energy system requires construction inputs of 460 MT of steel and 870 m^3 of concrete per average MW(e), about 130 and 30 times as much. Bridging the cloudy and dark as well as calm and gusty weather takes storage batteries and their heavy metals. Burning crops inflates the price of food.

Renewable energies also invoke high risk as sources of supply in a changing climate. Clouds may cover the deserts investors covered with photovoltaics. Rain may no longer fall where we built dams and planted biomass for fuel. The wind may no longer blow where we build windmills. Maybe we should put windmills on railcars, as Ronald Reagan wanted to put Peacekeeper intercontinental ballistic missiles on railcars rather than in silos. Without vastly improved storage, the windmills and photovoltaics are supernumeraries for the coal, methane, and uranium plants that operate reliably round the clock day after day.

We live in an era of mass delusion about solar renewables, which will become an embarrassing collection of stranded assets. But let's use our intelligence and resources to build what will work on the large scale that matters for decarbonization rather than to fight irrationality. Humans are not rational after all, and the environment for the energy business never will be.

In this regard, the matter of taxes and trading schemes is tricky. The arithmetic is simple. At say, $30 per ton of carbon, the present global emission of 7 billion tons of carbon could bring $210 billion in annual revenues for governments, a tempting amount about 4 times the annual budget of the entire UN system. The world economy can probably afford it. After all, the total is not much larger than the annual sales of WalMart. But the outcome of the taxes and trading will almost certainly bear little relation to what experts forecast. I will wager the main beneficiaries will be lawyers, accountants, financial intermediaries and administrators, not people suffering from changing climate.

Still, what does matter is keeping energy cheap for end-users. To adapt to climate change, cheap energy matters enormously. Especially important is that cheap energy can translate into cheap water, for example, through pumping or desalination. Cheap energy also means people can range further in search of jobs and income.

So, my messages for APPEA's upstream community have been substitution, decarbonization, methane, India & China, compact very powerful ZEPPS for electricity, mini-ZEPPS for cars, offshore operations, entering into the hydrogen business on your own and in alliances with nuclear, and a benign attitude toward the ill-starred renewables while focusing on the greener strategy of a compact energy system that harms neither land nor sea.

In closing, let me return to John D. Rockefeller. Rockefeller, like the Medicis before him and Bill Gates more recently, achieved immortality through business acumen linked to philanthropy, notably in sciences and art. If I visit with APPEA again in 10 years, I hope your business acumen will have led you to change your name to the Australian Methane Production and Sequestration Association [**Slide 28**] and to prosper on the path of decarbonization, while your concern for public benefit and immortality will have caused you to be generous to the sciences and especially to the oceans, from which much of your wealth will be drawn.

Acknowledgement: This talk is dedicated to the 95th birthday of Chauncey Starr, founder of the Electric Power Research Institute. Thanks to Cesare Marchetti, Nadja Victor, Paul Waggoner, and Evgeny Yantovski.