Hydrogen in the Energy Economy

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1.0 Introduction

In 2003, when General Motors demonstrated HydroGen3 at the Tokyo auto show, the $1M price tag for the minivan evoked nostalgia in those old enough to remember DEC's desktop computer, PDP1 priced at $120,000 in 1960. Michael Ramage, former VP of ExxonMobil Research and Engineering commented that, "we face a chicken and egg problem that will be difficult to overcome." Bernard Bulkin, former Chief Scientist at BP echoes the 'chicken and egg problem' as the "need for a massive hydrogen infrastructure to deliver the goods." Pessimism about hydrogen as fuel persists, nearly a decade later. General Motors does not trumpet claims about hydrogen anymore but introduced electric vehicles in the US, for example, the Chevy Volt, powered with batteries from A123 Systems at a price of about $45,000 to buy or just above $10 per day for a 36 month lease, in select markets.

In other words, the pipe dream about filling stations and fueling services – the bread and butter (with jam) for the global petro merchants stands in the way of new investments necessary for the distribution of hydrogen as a transportation fuel. Perhaps the latter may explain, in part, the tone from US National Academy of Science (NAS) and American Physical Society (APS) reports that the hydrogen economy challenges are enormous and "the transition to a hydrogen economy, if it comes at all, will not happen soon." Predictions are difficult to make, especially about the future, but the recent report (chaired by Michael Ramage of ExxonMobil) from NAS, an august society of thinkers, stopped short of saying it is impossible. The facts may be genuine but one must wonder about the quality of vision of the leadership that is bound to retard the progress toward the economic prospects and environmental benefits from use of hydrogen as a fuel. It may not be a panacea but hydrogen even with its risks may effectively curtail the bulk of the emissions to aid the environment.

Today, the world uses about 15 terawatts of energy. Approximately 80% is derived from carbon dioxide emitting fossil fuel. To keep the Earth's average temperature low enough to prevent eventual sea level increases (projected to be from 8 meters to 35 meters) and sustain 3% annual economic growth, we will need between 10 and 30 terawatts of new carbon-free power by 2050.[1]

For fossil fuel enthusiasts, the Middle East spells geopolitical doom because it cannot sustain the global demand for oil even if peace was offered a fighting chance. A decade ago economists were confident that demand for oil was stagnating at 70 million barrels per day (bpd). Our current global consumption is approaching 100 million bpd (US uses nearly 25%). Global growth, especially in India and China, will push demand for oil over the 120 million bpd mark by 2030, according to the International Energy Agency (IEA). For such demand to be met, one assumes "boundless Middle East oil" output to grow by more than 30 million bpd. Saudi Arabia's comforting "trust me" statements about its oil reserves (jumped to 280 billion barrels in 1988 from 110 billion barrels in 1978) and production capacity (sustain 10-15 million bpd for at least another half century) are highly suspect since these numbers have never been subject to any third party audit or any report on how the reserves stack up on a field-by-field basis. In 2000, 90% of Saudi Aramco's oil was produced from 6 fields. The 3 most important fields producing 80% of Saudi oil (total production is about 10 million bpd) were discovered in 1940, 1948 and 1951 (Matthew Simmons). In the next 25 years, additional supply of oil may grow at a rate less than the estimated increase in demand (20 million bpd). Oil output of about 100 million bpd may result in oil shortages of about 20% or more by 2030.

Discovery teams in search for new resources are accelerating their missions but success is rather scarce and expensive. Hope drifts from oil sands (tar sands) of Fort McMurray (Alberta, Canada) that cover an area of 58,000 square miles. It is expected to yield 174 billion barrels of oil (active through 2025). At the current rate of consumption of oil by the US (more than 20 million barrels per day of which 60% is imported and represents 25% of global demand), the Canadian reserves will be depleted in two decades even if Canada chooses to sell every drop of oil from tar sands to the US. The estimated 500 million barrels of oil found in Utah (USA) may suffice for less than three weeks.

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[1] Jim Hansen, Goddard Institute for Space Studies, NASA in MIT Technology Review (07-08/2006)

The discovery of "Tahiti" deep sea oil field by Chevron in the Gulf of Mexico may add about 500 million barrels [2] or another three weeks. The Minerals Management Service of the US Government estimates 44 billion barrels of oil (5 year supply) remains to be discovered in the Gulf of Mexico.

Emergency oil stores are inconsequential. Rokkasho, an oil-storage site in Honshu holds 30 million barrels of oil. It is barely enough to supply one week's worth of domestic demand. Rokkasho is also dominated by giant wind-turbines but Rokkasho's fresh sea breeze can operate the turbines 20% of the time and may not produce enough power to make up for energy consumed in their construction. The industrial world is vulnerable to oil supply disruptions in the Middle East. The economic progress in developing countries will be retarded by energy crisis and it will jeopardize the already dubious UN Millennium Development Goals (MDG) to reduce global poverty by half by 2015. The promise of oil from the Middle East and UN's plight to reduce poverty may be utopian dreams unless the vision of hydrogen as a fuel is a part of the answer to global demand for energy. A report published in 2001 by Sir David King, then Chief Scientific Adviser to British PM Tony Blair advocated a fast track for fusion development. The experimental nuclear fusion reactor ITER housed in Grenoble (France) is far from commercial production. Fusion-generated electricity may not reach the grid until around 2050 and it will be expensive, at least through the end of the 21^{st} Century.

One fusion reactor uses Hydrogen and Boron-11 as fuel. Hydrogen is obtained by electrolysis of water and Boron deposits are plentiful (140 million tons in California, 500 million tons in Turkey). A 100 mega-watt plant would burn 200 grams of Boron a day, as opposed to 700 tons of coal [3] to power a similarly sized coal-burning plant. Better yet, this type of fusion reactor emits no radiation. In addition, because the reactor is safe and clean, it is possible to build small neighborhood power plants or even have a portable domestic fusion reactor right in your back yard, eliminating wasteful long distance electricity transport (60% of energy is wasted as heat during power transmission).

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[2] Chevron claims that it could cost $3.5 billion to develop the "Tahiti" oil field that may yield 500 million barrels of crude petroleum. The exploratory vessel, *Deep Seas*, leased from Transocean, costs $250,000 and including a team of 170 it is $500,000 per day.

[3] The annual amount of carbon dioxide released from burning fossil fuel is projected to increase from 24 billion metric tons in 2002 to 33 billion metric tons in less than 10 years (by 2015). Coal presents the world's single largest opportunity for carbon dioxide mitigation. Coal generates 37% of the global fossil-fuel related emissions, in second place, after oil (42% from oil). In the US, coal contributes 51% of electricity but 81% of carbon dioxide related to power generation. Overall, 40% of global electricity is generated from coal-burning plants that spews twice as much as carbon compared to natural gas (kilowatt for kilowatt). World Coal Institute estimates there are 164 years worth of coal in the ground compared to 40 years store of oil (through 2050). According to the Natural Resources Defense Council, the enthusiastic coal mining countries are US, India and China. More than fourteen hundred 500-megawatt coal powered plants are planned worldwide by 2020, of which 140 are in the US. (Source: MIT Tech Review 07-08/2006)

The investment necessary to transform this vision into reality is not there, even though evidence suggests billions of dollars worth of government investment in hydrogen fuel projects in US, EU and Japan. Some of this money was spent on perfecting procedures to break down natural gas into hydrogen and carbon dioxide with substantial wastage as heat (~15% of energy). According to Pete Devlin of the US Department of Energy, it costs $5 to produce the amount of hydrogen that releases as much energy as a gallon of gasoline. At current US gas prices approaching $4 per gallon and crude in excess of $100 per barrel the writing is on the wall. It may be increasingly attractive to consider a dumpster sized hydrogen generator at about $400,000 from H2Gen Innovations (Alexandria, VA).

Dr Joseph Romm, former Acting Assistant Secretary for Renewable Energy at the US Department of Energy told the US Congress (House Science Committee, 03/04) that, "if we fail to do so because we have bought into the hype about hydrogen's prospects – we will be making an unforgivable national blunder." Perhaps promoting hybrids and biofuel from biomass and corn ethanol makes some sense but the price of food (staples) are at an all time high due to the use of vegetation for fuel production.

The gobal hydrogen endeavor is lacking direction and leadership. It is necessary to articulate an unambiguous goal unencumbered by the geopolitical ramifications that surround any such profound economic change. Use of hydrogen as a fuel may enable our energy independence [4] from fossil fuel.

1.1 Electrolysis

A simple process that can catapult the hydrogen economy to the forefront of global progress comes from the same man who invented the electric motor, two centuries ago. Michael Faraday, born on 22 September 1791 in Newington (UK), invented the dynamo in 1831 which led to the invention of the electric motor and the revolution [5] that followed. In 1832, he started work on electrochemistry that led to the discovery of the principle of electrolysis. He lived to see the first isolation of Lithium by electrolysis by his mentor, Humphrey Davy. Faraday died on 25 August 1867 in Hampton Court and is buried in the Highgate Cemetery in London. What we should not bury is the idea of generating hydrogen from electrolysis of water, engineered as a domestic appliance for use in every garage.

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[4] Datta, S. (2011) Energy Self-Sufficiency: Can Micro-scale Energy Autonomy Catalyze an Energy Agnostic Global Economy? http://dspace.mit.edu/handle/1721.1/59804

[5] Paul A. David and Gavin Wright (2003) *The Economic Future in Historical Perspective* (Oxford University Press)

Hydrogen generation [6] from water to replenish solid hydrogen storage in automobiles is possible. Electrolysis of water in your garage to generate hydrogen to replenish hydrogen storage tank in your automobile ("gas tank") could eliminate the trillion dollar investment necessary to re-tool the infrastructure for generation and delivery of hydrogen fuel. If electrolysis is successful and portable hydrogen generators are in every garage, there may not be an "oil industry" or behemoths to reap the financial largesse from petroleum oligopoly. President John F Kennedy, threatened by the Sputnik, challenged the nation (USA) to put a 'man on the moon' within a few years. It did happen. We need leadership who can articulate unambiguous universal agenda to challenge the research community to focus on developing efficient commercial portable electrolyzer compatible with solid hydrogen storage systems. If automobile usage, alone, could become independent of fossil fuel, imagine the impact on the global economy, decreasing oil prices and the potential economic benefits.

The economic revolution due to hydrogen may trigger resistance from uninformed about the source of energy for electrolysis. Boosting safe nuclear (fission) energy production still suffers from the ignorance of the public. Fukushima, Chernobyl and Three Mile Island are used [7] to stoke public fears. UK obtains a fifth of its power from nuclear plants and all but one (Sizewell) will be decommissioned by 2023. Nuclear fusion is on its way from ITER (France) and others [8] perhaps sooner than expected.

1.2 Scientific Hurdles

By using energy (solar, wind, wave, nuclear, hydroelectric, geothermal) we can convert water to yield hydrogen in an electrolyzer and reverse the process in a fuel cell to obtain electrical energy from hydrogen. Energy required to produce hydrogen by electrolysis is 32.9 kWhr per kg. For 2g of hydrogen (one mole) the energy is ~ 0.0660 kWhr/mole. For commercial electrolysis systems which operates at 1 A/cm^2, 1.75 volts is required. It translates to 46.8 kWhr/kg and an energy efficiency of 70%. Lowering the voltage for electrolysis increases the energy efficiency. R. P. Viswanath and his team at the Indian Institute of Technology in Madras claims to have split water into hydrogen and oxygen at the lower potential of 0.9 volts using a compartmentalized electrolytic cell. The current efficiency increases to 135%. It may be a significant disruptive advance, if it is reproducible.

[6] Richard Bourgeois and his team at GE Global Research (Niskayuna, NY) have built a low-cost mass-manufacturable electrolyzer using a GE plastic (Noryl) resistant to corrosive electrolytes. It produces hydrogen via electrolysis for $3 per kilogram and is functionally equivalent to a gallon of gasoline (current price of gasoline is $4 per gallon).

[7] *The March of Unreason* by Dick Taverne

[8] *Colliding Beam Fusion Reactor* by N. Rostoker, M. Binderbauer, H. Monkhorst in Science (1997) 278 1419

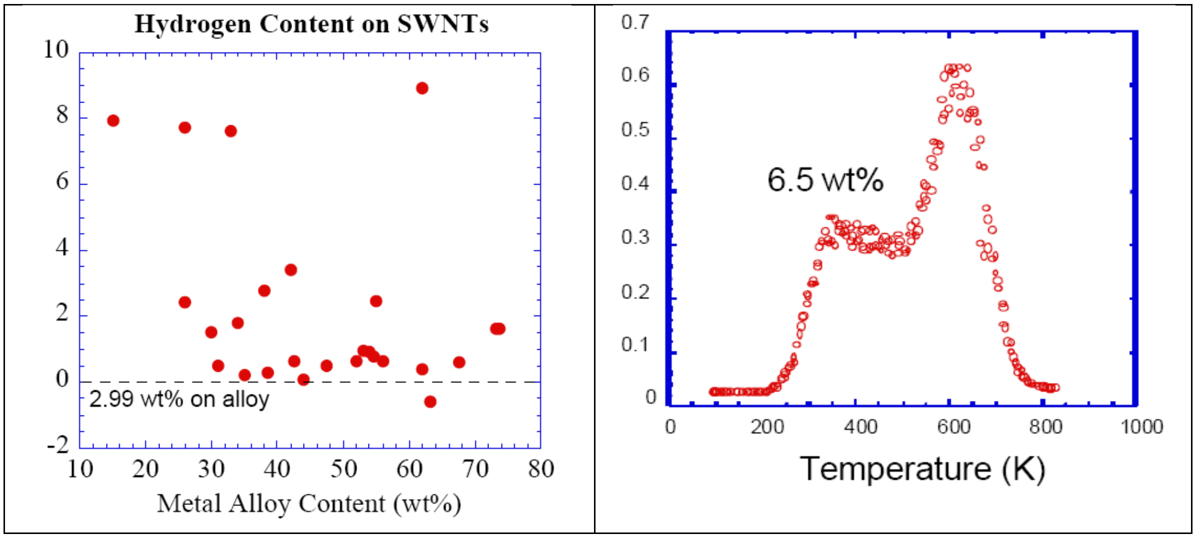
In an ideal case, fuel energy from hydrogen is converted to electrical energy at an efficiency of 80% or more. This is greater than the ideal efficiency of a generating facility which burns hydrogen and uses heat to power generator. Fuel cells currently may not approach >80% efficiency but are still more efficient than electric power plants which burns a fuel. In comparing the fuel cell process to its reverse reaction (electrolysis of water) it is useful to treat the enthalpy change as the overall energy change. Gibbs free energy is necessary to drive the reaction. In electrolysis and fuel cell pair, 237 kJ energy is required to drive electrolysis and the heat from the environment will contribute 48.7 kJ. In the fuel cell, 237 kJ is regained as electrical energy (48.7 kJ escapes as heat but may be recaptured). The search for nano-catalysts with greater surface to volume ratio which can improve efficiencies in the electrolysis/fuel cell paradigm are key areas for research in material science and thin films.

John Peters and Lance Seefeldt of Utah described the structure of an enzyme found in *Clostridium pasteurianum*. CpI is a hydrogenase, which uses iron atoms to catalyze hydrogen (waste) production from protons and electrons. The enzyme active site, tethered to a substrate, may improve hydrogen production efficiencies. Non-platinum catalysts [9] are also of increasing significance.

Safe, non-toxic, cost-effective on-board solid hydrogen storage solutions are emerging from traditional materials (sodium borohydride) as well as nano-materials (nanotubes). Catalysts (doped nanotubes) that can improve storage capacities above the recommended 6.5% (storage by weight) will be a boon to this fuel system. Solid sodium borohydride currently can store 10.5% hydrogen [10] by weight. Carbon single-wall nanotubes (SWNT) and other nano-structures exhibit hydrogen storage capacities at room temperatures. Capacity for adsorption of hydrogen by SWNT is about 8% by weight. A method for growing SWNTs by vapor deposition from methane holds promise when scaled-up to produce SWNTs for $1 per kilogram.

[9] G.W. Huber, J.W. Shabaker and J.A. Dumesic. 2003. Raney Ni-Sn Catalyst for H_2 Production from Biomass-derived Hydrocarbons. *Science* **300** 2075–2077

[10] One kilogram of solid $NaBH_4$ reacted with 950gm of water yields 213.5g of hydrogen gas or 24,230 BTU = 7.1 kWh = 25,560 kJ (1 kg of hydrogen = 119,600 kJ which is a close equivalent to 1 gallon of gasoline = 121,300 kJ).



HYDROGEN STORAGE IN CARBON SINGLE-WALL NANOTUBES
Proceedings of the 2002 US Department of Energy Hydrogen Program Review
A.C. Dillon, K.E.H. Gilbert, P.A. Parilla, J.L. Alleman, G.L. Hornyak, K.M. Jones, and M.J. Heben

1.3 Solution Space

Standardization of form for fuel cells and mechanism to replenish with hydrogen from portable electrolyzers may be as simple as inserting a tube to feed hydrogen to adsorbent in the on-board storage tank or solid material that can be stored in the hollow frame of an automobile. When the domestic electrolyzer is not available (vacation to distant location), electrolyzer outlets may be ubiquitous in stores, grocery chains, restaurants or charged fuel cells can be exchanged just as cooking gas is available in tanks in most corner stores. GPS-RFID-UWB linked hydrogen sensor tagged fuel cells can help track and trace customer issues, inventory, billing operations, as well as monitor fill-status and safety of the hydrogen system, especially to prevent leaks.

This discussion about hydrogen as a renewable fuel highlights transportation. In most industrialized nations, it is about 20-25% of total energy. Successful implementation of hydrogen as a fuel reduces need for fossil fuel by the same amount. Residential and commercial use is another 20-25% while industrial uses claim almost half of the energy output. Fusion reactors are one answer but are still a few decades away and may not be even necessary if energy self-sufficiency is allowed to flourish.

There may be a interim "STAR" solution. Sealed, transportable, autonomous reactors (STAR) can generate power from nuclear fission without refueling or maintenance. It is a choice that is available now and those who will keep it out of the hands of those who need it the most may wish to consider the odds. By the time you finish reading the rest of this article, several children will have perished from malaria. In Africa, a child dies every 30 seconds from malaria, alone. Improvements in sewer and sanitation can eliminate this morbid statistic. Lack of energy is the gatekeeper in the 'south' nations. STAR reactors may be a rapid and short term answer to this agony. STAR was developed by the Lawrence Livermore National Laboratory in California, to be transported to a site and generate power for decades (current estimate is 30 years). When the fuel is spent, it can be retrieved from the site and disposed under proper supervision since there is no option in a sealed STAR for recharging the fuel rods depleted of fissile isotopes (usually commercial operators replace fuel rods every few years). A tamper-proof casket eliminates the risk of extracting fissile material. An even better reason to use STAR in 'south' nations is the ability to produce versions capable of generating 100 or 10 megawatts of electricity compared to the conventional nuclear stations that produce about one gigawatt. Without an extensive electricity grid, the output from a conventional nuclear station is wasted due to lack of distribution infrastructure. STAR units producing 100 megawatts may be 15 metres tall, 3 meters in diameter and weigh 500 metric tons. A lighter, 200 metric ton version may produce 10 megawatts of electricity. Nuclear fuel, liquid lead coolant and a steam generator is sealed in the housing along with steam pipes ready to hook up to an external generator turbine.

1.4 One Shoe Fits All?

Nuclear energy *cannot* become the 'one shoe fits all' solution. It is a solution at hand and one that will empower the 'south' nations to see some light at the end of the tunnel. It is important that national policies commit to concomitant exploration of energy self-sufficiency and renewable energy which can improve our environmental quality as well as the economy. Encouraging advances include (Intelligent Energy, UK) a motorcycle which runs on hydrogen fuel cells, attains speeds of up to 50 mph and travels for 100 miles before refueling. Tokyo Gas launched (2005) a residential fuel cell project where a home-owner can lease an unit that extracts hydrogen from natural gas and uses it to generate electricity to meet 60% of the demand and reduce the annual greenhouse gas emissions by 40% for a 4-person household (10 year lease costs 1 million Yen).

Developments from super-conductivity research are helping to produce better fuel cells. New thin film solid oxide fuel cells (SOFC) offers catalyst-independent operating temperatures of less than 500^0 C. At less than 1 micron thin and an output of about 1 volt, a stack of SOFC equivalent to two soda cans may produce more than 5 kilowatts (enough to power one or more typical households). Connected to a homeowner's natural gas line, this stack operates at an efficiency of about 65%, a two-fold increase in efficiency over conventional power plants.

Plankton fuel cells, energy from spinach, biofuels from metabolic engineering, butanol from photo bio-reactors, carbon sequestration and natural forces (air, water, wave, solar) to generate energy are all likely to be more or less viable in specific use cases and environments. Costa Rica claims to derive 92% of its energy from renewable sources. It is vital to pursue these and other emerging 'green' sources of energy while we continue to support options available at hand to immediately provide energy for the emerging economies. The sooner the impoverished countries are economically mature, the sooner they can contribute to invest in the global plight for alternative 'green' energy to reduce fossil fuel dependency and approach the Holy Grail of energy self-sufficiency.

1.5 Ethanol Economy

With 40% of operating automobiles **not** running on petroleum, Brazil has demonstrated that it is the global leader in the use of ethanol without government subsidies. Alcool (ethanol) as an alternate fuel for cars, buses and other motor vehicles is in use. 75% of all vehicles sold in Brazil are flex fuel vehicles (FFV introduced in 2003) that can run on ethanol (E100) or gasoline or a mix. Commencing with ideas and idealism that sprouted during 1970-1975, Brazil boasts of ***manufacturing energy*** to the tune of 7 billion gallons of ethanol in 2010 (13 billion gallons produced by US in 2010). Brazil is manufacturing energy from sugar (sugarcane) and pays for plant operation using energy obtained from burning biomass. This is a true paradigm shift because till recently energy was traditionally associated with discovery and mining (oil, coal, natural gas). While "sugar farmers" in the EU are sparring over the size of "hand outs" (subsidies), sugar is effectively used as an energy cash-crop in a novel entrepreneurial zeal just a few thousand miles, south. However, the use of food sources for fuel may not be sustainable and evidence of higher food prices are igniting the food vs fuel debate.

To use ethanol as a near carbon-neutral biofuel remains on the agenda for some nations. India planned to mandate E20 (20% ethanol by volume) by 2011 but has postponed it to 2017. Gallon for gallon it is competitive with gasoline even if crude prices drop to $40 per barrel. Corn, sugarcane, sorghum and the oil-weed, *Jatropha curcas*, are common agricultural raw materials that can be chemically processed to yield liquid fuel but doubts persist whether they are sustainable over time.

The convergence of energy scientists with chemists and biologists are likely to unveil new vistas. Converting cellulose to ethanol is a two-step process. First, the long chains of cellulose must be broken down to basic units (glucose, fructose or other sugars) and second, fermenting those sugars into ethanol. In nature, fungi and bacteria secrete enzymes (cellulase) that hydrolyzes cellulose to "free" the sugars. Yeasts ferment the sugars to produce alcohol. With the tools available from chemistry, biochemistry, molecular genetics, recombinant DNA and bio-engineering, it is possible to improve the efficacy of the microorganisms for production of cellulosic ethanol. Genetic engineering to yield strains of yeast (*Saccharomyces cerevisiae*) that tolerate higher concentrations of ethanol [11] in a fermentation reactor and can survive on cellulose alone [12] may help the ethanol economy. The strides made by synthetic genomics may make it possible to engineer an existing microorganism [13] with an artificial chromosome to harbour genes for the enzymes necessary to direct a high yield manufacturing process to produce ethanol from cellulose or photosynthetic production of butanol. Other short chain hydrocarbons, pentanol produced by metabolic engineering and methanol [14] from differential compression and fractionation are contenders for the future of liquid fuel.

[11] Greg Stephanopoulos of MIT has developed a yeast strain that claims to tolerate 50% more ethanol.

[12] Mascoma (Cambridge, MA) engineered a thermophilic bacteria to optimize the kinetics of cellulase and whose only fermentation product is ethanol.

[13] Synthetic Genomics, a start-up in Rockville (Maryland, USA), founded by Craig Venter, is exploring *Mycoplasma genitalium*, a microbe which dwells in the human urinary tract and has the smallest genome (517 genes) of known life form (except viruses), to produce task-specific genetic pathways (for example, the two steps or tasks necessary to breakdown cellulose to produce ethanol) in much the same way that software is loaded on to a computer's operating system. Instructions from the software could be used to create spread sheets or word processing. Similarly, the "biological software" introduced in the genome of *Mycoplasma genitalium* would instruct the microbe (the cell) to break down cellulose to produce ethanol.

[14] *The Methanol Economy* by George A. Olah, Alain Goeppert, G. K. Surya Prakash (Wiley-VCH, 2006)

1.6 Outsourcing Energy-Self Sufficiency

Manufacturing energy may lend itself to the practices of near-shoring, off-shoring and outsourcing, classical strategies used in global supply chain management. For example, Singapore leased an island for 999 years from Indonesia to set up a chemical processing facility. Leasing a few islands from Indonesia may not be an absurd idea given that it is the world's largest archipelago with 13,667 islands nestled between Asia and Australia, spanning 3200 miles along the Equator from east to west (almost the expanse of US) and 1100 miles from north to south. In addition to an abundance of plant (cellulose), these tropical islands are suitable for growing sugarcane or sorghum. But it is most important as a high insolation zone which enables photosynthetic production of short chain hydrocarbons (butanol, pentanol) by cyano-bacteria or micro-algae in photo bio-reactors. The latter is a step toward energy manufacturing from non-vegetative sources and uses sun light and carbon dioxide from the atmosphere. Entrepreneurial organizations or nations may off-shore photo-butanol or photo-glucose manufacturing in Indonesia or in the State of Bihar in India with high insolation.

1.7 Concluding Comments

The potential of hydrogen as a fuel in the portfolio of energy is slow to materialize. For example, the focus has shifted from hydrogen vehicles to electric automobiles. For the hydrogen economy to take hold, further developments are necessary. In the interim we must decrease our dependency on fossil fuels but must not create an unsustainable dependency on vegetation or food sources as a significant source of liquid fuel. Energy independence and energy self-sufficiency are both attainable [15] from renewable sources through a convergence of bio-technology, metabolic and chemical engineering.

[15] If my theory of relativity is proven successful, Germany will claim me as a German and France will declare that I am a citizen of the world. Should my theory prove untrue, France will say that I am a German and Germany will declare that I am a Jew.
(ALBERT EINSTEIN, Address at the Sorbonne, 1936)