False Optimism for the Hydrogen Economy and
the Potential of Biofuels and Advanced Energy Storage
to Reduce Domestic Greenhouse Gas Emissions

By

Rory Foster

Submitted to the Department of Mechanical
Engineering in Partial Fulfillment of the Requirements
for the Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology
[June 2004]
May 2004

Signature of the author ______________________________
Department of Mechanical Engineering
May 6, 2004

Certified by ______________________________
Stephen Connors
Director, Analysis Group for Regional Electricity Alternatives
MIT Laboratory for Energy and the Environment
Thesis Supervisor

Accepted by ______________________________
Ernest G. Cravalho
Chairman, Undergraduate Thesis Office

False Optimism for the Hydrogen Economy and
the Potential of Biofuels and Advanced Energy Storage
to Reduce Domestic Greenhouse Gas Emissions

By

Rory Foster

Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science

Abstract

Discussion of the general domestic energy situation addresses the motivations which underlie the push for an hydrogen energy economy. The validity of claims about such a hydrogen economy and the official DOE position regarding such are evaluated, and then discarded as overly optimistic given the inherent physics of the required production and transportation processes.

Biomass is then introduced as a potential source of greenhouse gas reduction in both stationary and mobile applications for the near term future (10-25 years). Combined renewable power (mainly solar and wind power) and attached energy storage to buffer the inherently fluctuating supply is also discussed, and recommended as potential zero-emission power generation technology for the long-term depending on the advances in photovoltaics, wind power and pumped liquid electrolyte battery technology.

Thesis Supervisor: Stephen Connors

Title: Director, Analysis Group for Regional Electricity Alternatives, MIT Laboratory for Energy and the Environment

Introduction:

Clearly the United States is approaching a crossroads of energy policy, or at very least a series of forks in the energy road at which policy makers must reevaluate the chosen directions of investment, education and research. Domestic energy demand continues to grow as does the world's largest and most dominant economy; and as energy usage increases, so will the problems intrinsically linked with reliance on fossil fuels such as coal, oil, and natural gas (NG). Political instability in fossil fuel rich nations embroils domestic energy in global conflict and strife; harvestable fossil fuel is ultimately limited and finite in supply; and, most significantly of late, environmental pollution from fossil fuel combustion byproducts such as sulfur and nitrogen oxides (SO_x and NO_x) and greenhouse gases (GHG) like methane (CH_4) and carbon dioxide (CO_2) threaten worldwide ecological and climatic effects. Sulfur and nitrogen compounds produced by fossil fuel combustion contribute to acid rain and to increasingly detrimental fine particulates; while GHG, especially CO_2, are undeniably beginning to affect global temperature and local ecologies in significant ways. Faced with these difficulties, it behooves a responsible and forward-looking nation to consider its energy future in realistic and intelligent planning; planning that respects all factors of a future energy economy.

Since the early 1950s the promise of a clean, efficient, sustainable, domestic hydrogen (H_2) energy economy has tantalized the environmentally inclined; and discussion, preparation and planning have only intensified in recent years. In the visions of some, hydrogen could be derived from clean, renewable power sources (i.e. the sun and wind), and coupled with 'clean' power conversion technologies like fuel cells (FC), for an unlimited supply of useful energy – all with only water as an emission. However, under the scrutiny of scientific analysis, the short term hydrogen economy (HE) is burdened by more problems than can be justified by merely the idealism and enthusiasm of its proponents. Hydrogen could play an important role in long-term (50-100 yeas) planning if hybrid/battery storage research fails to advance; however, for the shorter term, the increasing integration of other environmentally sound technologies, such as the processing of Biomass into biofuels and the combination of energy storage with renewable-source power plants, shows greater (and more scientifically founded) promise for the mitigation of CO_2 and other emissions.

This paper will discuss the current energy state of the United States, and the promise and problems inherent to a pure H_2 economy. It will then present various technologies for Biomass processing and utilization and the potential of energy storage systems to eliminate the supply problems of renewable solar and wind power plants. Due to the shortcomings of H_2 production and distribution, it should be biofuels and fixed battery storage systems that dominate near-term conservation efforts.

U.S. Energy Picture

From U.S. Department of Energy (DOE) estimates, the United States is currently proprietor to roughly 22.4 billion barrels of proven oil reserves, and produces on average 7.9 million barrels per day (mmbd) of which 5.7 are crude oil. This production, however, cannot satisfy the daily energy demand of the world's largest economy: which requires total gross oil imports of 11.4 mmbd during 2002 (about 58% of the total U.S. oil demand). 40% of this import total was purchased from OPEC nations, and roughly 20% from the Persian Gulf – areas of increasingly troublesome political strife. Oil production and imports, as well as the major sources of U.S. oil are displayed in Figures 1 and 2. Petroleum and petroleum products account for 39% of domestic energy consumption. [1]

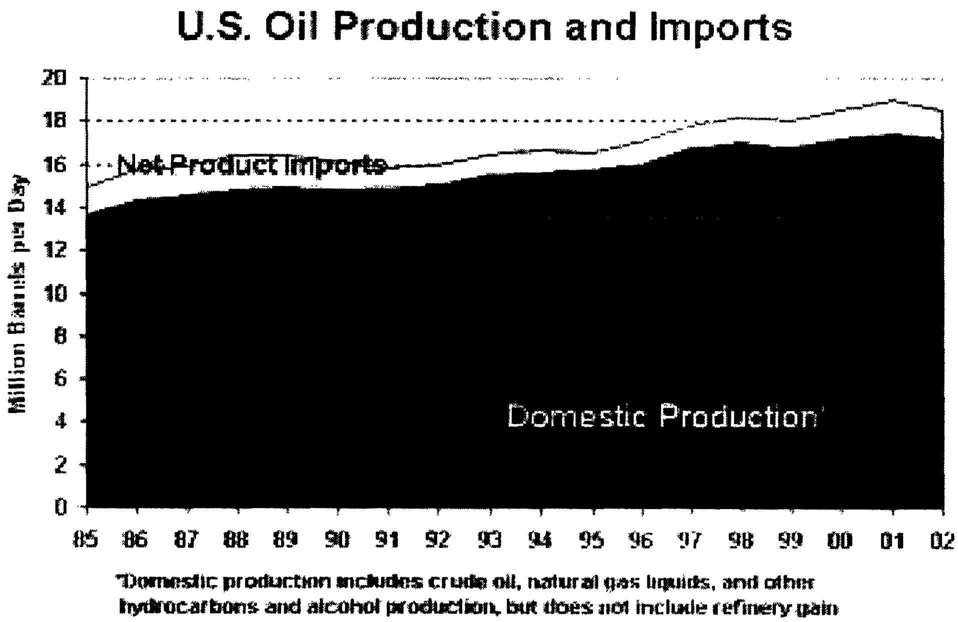

Figure 1: U.S. Oil Production and Oil Imports Comparison from 1985-2002 [1] Note the growing percentage of the total oil demand which is satisfied by imports

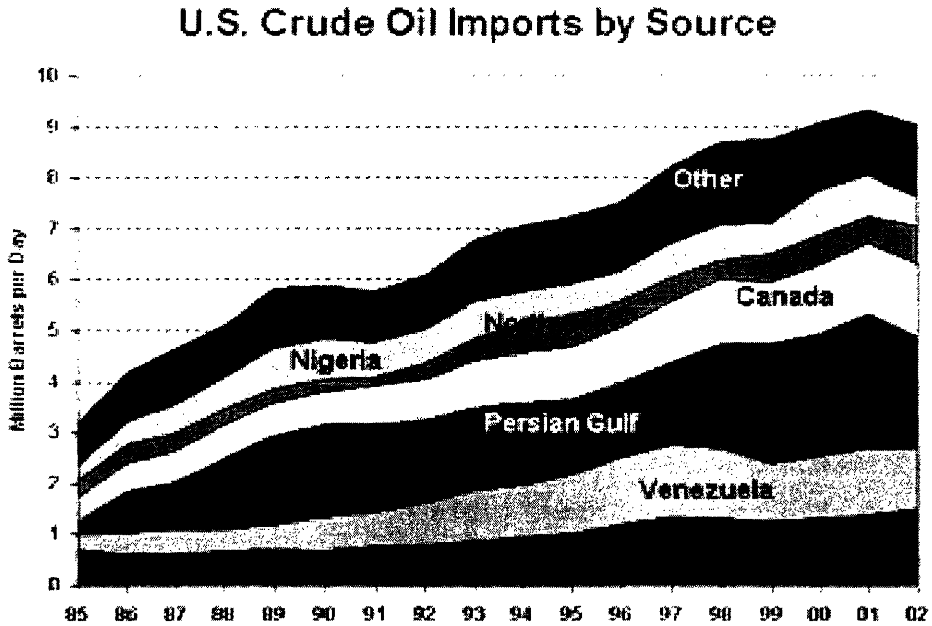

Figure 2: Crude Oil Imports, Comparison of Sources 1985-2002 [1] The proportion of imports from the politically unstable Persian Gulf has decreased in the recent years. However, other areas of increasing importance – Nigeria and Venezuela – suffer from increasingly unstable political situations as well.

The demand for refined oil for gasoline and diesel internal combustion engines (ICE) and the accompanying increase in GHG emissions provide a major target for the proposed H_2 Economy. The U.S. is an automobile nation, with the average driving distance per car topping 12,000 miles a year, at an average consumption of 4.8 gallons of gasoline per 100 miles (21 miles per gallon). [1] The sizable proportion of oil supplied to the transportation sector, as compared to all other sectors is represented in Figure 3; clearly a shift in automobile efficiency technology could afford the U.S. considerable freedom from foreign oil dependence in addition to the GHG mitigation effects.

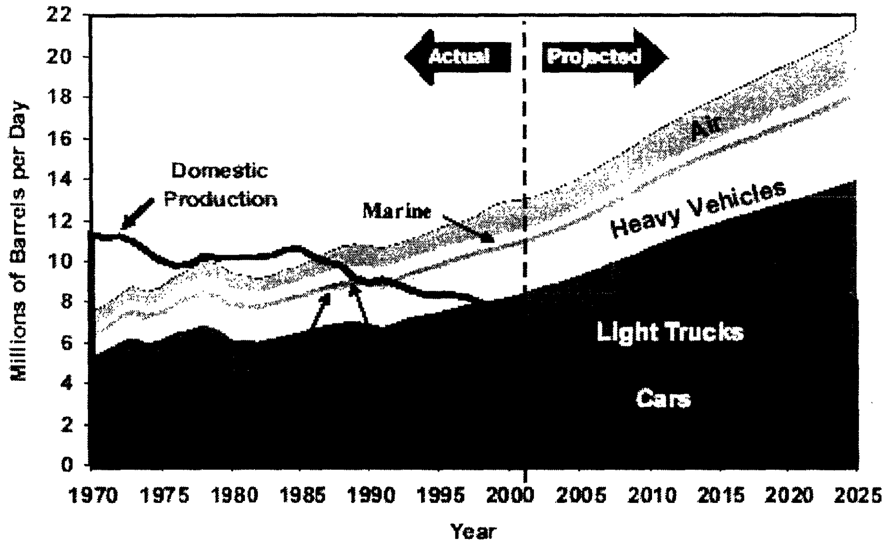

Figure 3: Division of oil demand by demand sector [2] The ground transportation sector accounts for more than the total oil imports from Figure 2.

Natural Gas

Natural Gas is an inherently cleaner burning fuel than gasoline or coal, and the U.S. enjoys proven NG reserves of 183 trillion cubic feet (3.3% of world's reserves). NG provides for 24% of the U.S. primary energy requirements and has seen recent surges in application, from NG-powered bus fleets to NG combined cycle power plants. Imports of NG are mainly from Canada, [1] which is generally free from the political strife that routinely plagues many of the major petroleum exporters. However, NG prices have risen by as much as 60% from 2002 values, making NG a less economically attractive option for pollution mitigation than it was 5 years ago.

Coal

Coal accounts for roughly 24% of total domestic energy usage, most of this in the electric power production sector. [1] However, coal suffers from substantial GHG and non-GHG emission levels, and along with vehicle emissions contribute to the nearly 60% of Americans who live in highly polluted areas and/or suffer from detrimental pollution-related health effects. [2] 1091 Million short tons of coal were produced domestically in 2003, down 3% from 2002, however coal imports account for only 2% of total domestic consumption. [1]

Electricity Needs

The United States generates and consumes approximately 3836 billion kWh (BkWh) of electrical energy each year, the percentage production of which is presented in Table 1.

Table 1: Percentage distribution of U.S. electricity production

Electric Power Source	Percentage of total production
Coal	52
Nuclear	21
NG	16
Hydro	7
Oil	2
Other (wind, solar, etc)	1

The total installed electric generating capacity in 2001 was 813 GW, with 74% thermal, 12% nuclear, 12% hydro and 2% 'renewables.' [1]

Renewable energy has played a minor role thus far in U.S. electrical generation, with about 6% of the 2002 total energy demand coming from renewable sources. Hydropower comprises the majority of this share, accounting for 45% of the total, with biofuels, wind, solar and geothermal making up the rest. A National Renewable Energy Laboratory report suggests that solar power (photovoltaics – PV) could potentially provide 15% of the peak U.S. electricity capacity using current technologies; however, growth of renewable power generation has been slow, with the exception of wind power, which boasts a current domestic capacity of 4100 MW and estimated 10% annual growth. [1] One reason for the slow market penetration of the seemingly attractive (quiet, non-polluting, unobtrusive) energy sources is that solar and wind power suffer from unavoidable supply problems. The sources, sun and wind, are naturally intermittent, and although solar-power supply (sunlight) is roughly coincident with peak demand times, neither solar nor wind power can independently supply reliable, utility-scale power. [3] However, given the tremendous polluting effects of fossil fuel power generation, the environmental difficulties facing the United States (see below), and the potential for renewable energy and battery technology development [4], long range planning should include drastic increases in renewable power generation.

Environment

The U.S. enjoys the lion's share of the world economy (25%), but is also the world's largest anthropogenic GHG producer (24% of total carbon emissions, the majority of which are in the form of CO_2). By DOE estimates, carbon emissions in the U.S. will reach 1624 million metric tons in 2005, an increase of 18% from 1990. Serious health and environmental problems are of course associated with the non-trivial emission of CO, NO_x, SO_x and volatile organic compounds (VOC) – each associated with combustion of fossil fuels; however, CO_2 emissions (currently estimated at 5.5 metric tons per capita per annum) are of primary environmental concern and comprise the majority of polluting emissions by mass. As demonstrated by Figure 4, carbon emissions have increased almost identically with energy demand for the years 1974-2001 [1], so for the continuously growing domestic economy, increasing GHG emissions promise to continue. The majority of these CO_2 emissions result from electric power generation, and as seen in Figure 5, which displays the value of several key polluting emissions divided by emitting sector, transportation plays a secondary role to electric power generation as a CO_2 source. Of note also, is the tremendous dominance of CO_2 as a pollutant by mass when compared with CO, NO_x and VOCs.

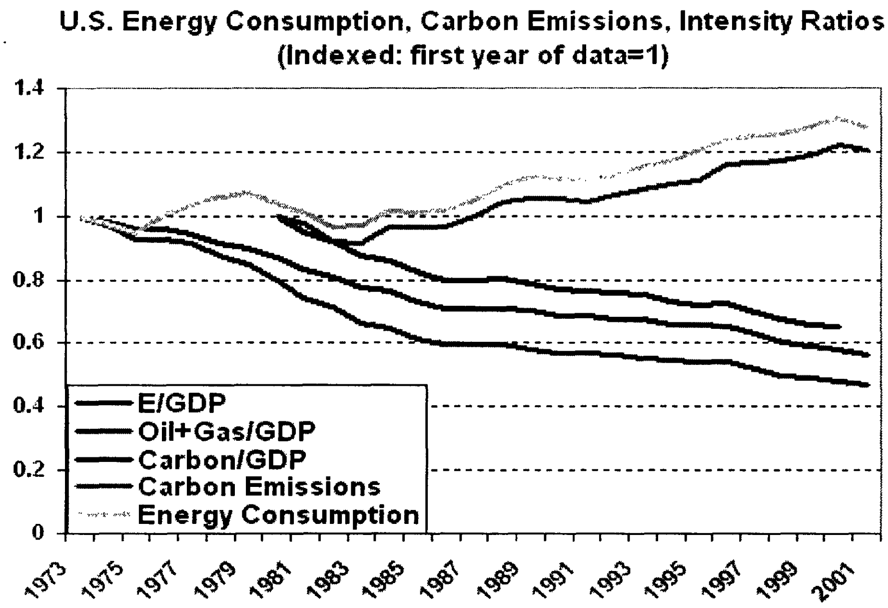

Figure 4: Carbon Emissions and Energy Demand 1973-2001 (Normalized to first year Values) [1]

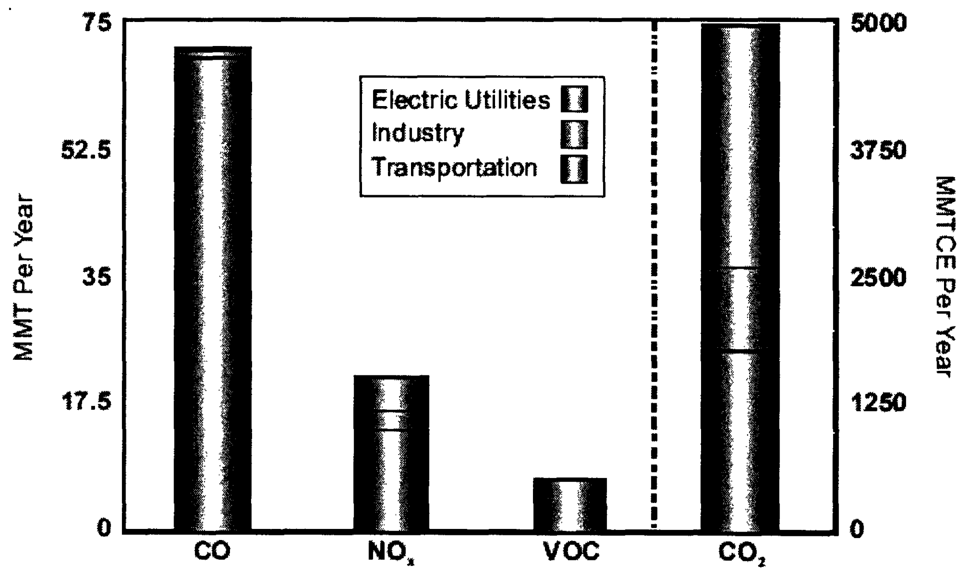

Figure 5: Polluting emissions divided by emitting sector [1]

Of encouraging interest in Figure 4, is the general decrease in energy usage and carbon production when both figures are normalized to the Gross Domestic Product (GDP), which suggests a generally increasing efficiency in energy usage and associated CO_2 production. However, carbon emissions will continue to increase with the inevitably increasing domestic energy consumption, regardless of the energy conversion efficiency: as U.S. energy demand continues to grow in the future, so will CO_2 and other emissions, as well as the associated detrimental environmental and health effects.

Of considerable environmental concern are not so much the direct effects of increased atmospheric pollutants like CO_2 and other GHG, but rather the associated global climate change (indicated most prominently by rising global average temperature) that these pollutants effect. Data collected by biologists Cook and Schweingruber [5] show a remarkable short-term correlation between increasing worldwide industrialization since 1900 (i.e. increasing GHG emissions) and the general rise in global temperature (Figure 6).

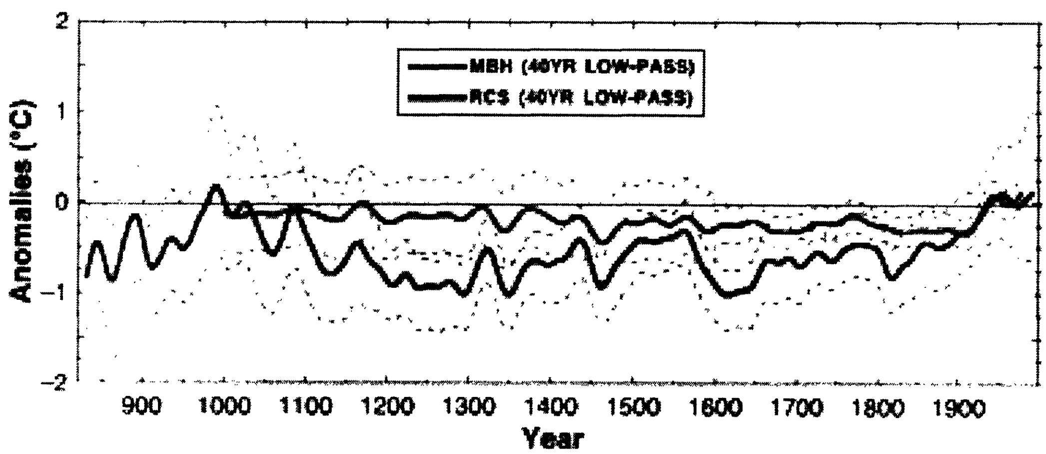

Figure 6: Global temperatures 900-2000. Note the rapid increase from 1900 on of the data from both temperature acquisition methods, corresponding to the industrial revolution and a marked increase in atmospheric CO_2. [5]

Problems with the Cook-Schweingruber model, have been raised, and its validity is contested by some. [6] The main contention, however, seems aimed more solidly at the magnitude of the actual danger facing the species subject to these climatic changes; there has been little supportable criticism of the actual temperature data and its connection to CO_2 levels as shown in Figure 7. There is an apparent, marked and undeniable correlation between CO_2 levels and global temperature increase.

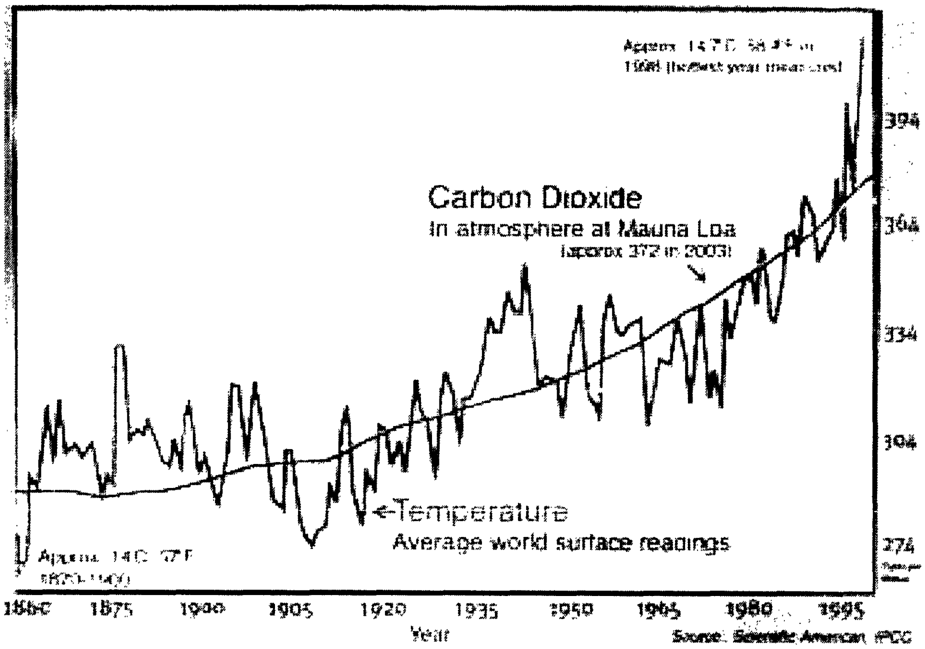

Figure 7: Global Temperature overlay on levels of atmospheric CO_2 [7]

The tremendous and still increasing output of GHG into the atmosphere threatens to have serious and possibly irreversible environmental effects, including but not limited to rising sea-levels, unpredictable and sometimes destructive weather patterns, and considerable local ecology disruption (such as selective extinctions and general lack of biodiversity). The final effects of the GHG driven global warming trend are as yet uncertain, but a sound energy strategy should make every attempt to reverse emissions and, hopefully, the increasing temperature trend. Environmental motivation is perhaps the highest among those which inspired the H_2 economy, and is certainly the driving force behind the ever-increasing amount of expensive emissions regulation.

H_2 Economy: Potential and Problems

Solutions to the CO_2/GHG problem have been suggested from a variety of sources, but none as adamantly, as optimistically, or as universally as a pure Hydrogen Economy (HE), in which hydrogen would replace all non-renewable fossil fuels as the dominant energy carrier: not only would hydrogen power our cars, trucks and trains, but also our industry and our homes. The United States Government is strongly supportive of such a proposed economy, as indicated by the focus that President Bush afforded the subject in his 2003 State of the Union Address:

> With a new national commitment, our scientists and engineers will overcome obstacles...so that the first car driven by a child born today could be powered by hydrogen and pollution-free. Join me in this important innovation to make our air significantly cleaner and our country much less dependent on foreign sources of energy.
>
> –President George W. Bush, January 18, 2003 [8]

The executive and legislative branches, in their funding and policy decisions are attempting to focus the nation onto a near-term, all-Hydrogen energy infrastructure; despite their apparent confidence, however, there is reason to question the validity of their position, and after even a cursory scientific interrogation of the facts, the future of hydrogen will become considerably more cloudy and indiscernible than is indicated by president Bush's optimistic speech. Following sections will discuss the general characteristics of hydrogen and the way in which those properties make HE appealing yet also sometimes prohibitively difficult and even recklessly inefficient.

Hydrogen: Properties

Despite being the lightest and simplest element, hydrogen is widely recognized as the most abundant substance by mass in the universe. However, due to its high volatility, pure hydrogen cannot be found in a natural environment and must be synthesized (and purified) from various sources. Current technologies can derive pure hydrogen gas through electrolysis of water, reformation of methane (NG) or liquid petroleum, hydrolysis of chemical carriers like $NaBH_4$, or gasification and reformation of either coal or biomass material. Nearly 80% of H_2 produced today is synthesized from NG, and most industrial hydrogen use is in the realm ofpetroleum refining (hydrocracking). Fuel cells, which the U.S. government predicts will be the work-horse of the future H_2 Economy, today account for less than one percent of all hydrogen usage. [9]

Due to its low molecular weight, hydrogen must be compressed in order to store significant amounts of energy, with typical modern technology effecting compression losses on the order of 25% for compression to 10000 psi (68.9 MPa): at this high pressure, hydrogen has a material density of roughly 0.04 kg/L and a chemical-energy density of roughly 4.5 MJ/L, which can be contrasted with an energy density of roughly 46 MJ/L for un-pressurized, liquid gasoline. [10] By weight, however, hydrogen has the highest energy content (121 kJ/g) of any known fuel, a statistic that does much to drive HE optimism.

Producing Hydrogen

Steam reforming uses thermal energy to separate hydrogen from the carbon components in methane and methanol, followed by the reaction of these produced fuels with steam on catalytic surfaces. The first step of the reaction changes the available carbon-fuels to water and carbon monoxide and a second step (known as a shift reaction) changes the CO and water to carbon dioxide and H_2. Temperatures required for steam reforming are 200° C or greater, and steam reforming currently costs approximately \$7/GJ in large plant production. [9] The cost values of this analysis rely on low estimates of NG prices, however, which may no longer be valid for at least the short-term future.

Electrolysis, a different method of hydrogen production that uses electricity to split water into hydrogen and oxygen, requires 1.24 V for the separation of pure water at 25° C, and

65.3 Watt-hours of energy for each mole of H_2 produced. This equates to roughly 4.8 kWh (290 J) per cubic meter of H_2 produced at standard temperature and pressure. [8] Electrolysis has been proposed as the main HE production method due to the total absence of CO_2 output inherent to other conversion technology like steam reforming of NG or biomass gasification.

Other production processes which may see future application include steam electrolysis (separation of water at 2500° C), thermochemical splitting of water with bromine or iodine, and photoelectrochemical processing – a mimicry of photosynthesis in which a soluble metal complex in aqueous solution converts solar energy to electrical charge that splits water. Ongoing research at Oak Ridge National Labs (DOE) and the University of Tennessee to develop photosynthesis driven production – still in expensive developmental stages due to the cost of a necessary catalyst – and other biological processes represent the diversity of H_2 production research. Biological anaerobic fermentation of biomass into methane or ethanol for gasification, and chemical processes such as the low temperature catalytic process being pioneered at the UW-Madison [11] also show potential as efficient conversion methods.

Uses of Hydrogen

Direct burning of hydrogen as a liquid or gas is feasible and has been historically useful – modern day NASA missions are primarily fueled by combustion of liquid hydrogen, and in the early 20th century, the combustive use of 'town gas,' which is primarily H_2 and CO, was widespread. FreedomCAR projects have also demonstrated the feasibility of burning hydrogen as a replacement for gasoline in only slightly modified IC engines. [9] A higher flame speed and lower detonation temperature means that hydrogen burns hotter and takes less energy to ignite than gasoline. Furthermore, the ignition of hydrogen results in generally carbon free exhaust, the primary component of which is pure water. (Due to the high combustion temperature however, production of NOx can still be significant when H_2 is burned with air.)

Despite the superficial advantages of direct combustion, however, the most promising hydrogen utilization technology appears to be the PEM hydrogen fuel cell (Figure 8), which utilizes a selectively permeable membrane to temporarily separate the electrons and protons of hydrogen atoms, thereby producing electrical current. Such fuel cells are already used in many applications including several experimental fleets of hydrogen FC vehicles across the country. Honda and BMW have already established H_2 fueling stations for their PEM FC vehicles, including an integrated photovoltaic array in Torrance, CA that produces enough hydrogen to power one fuel-cell vehicle (this installment utilizes additional electricity from the grid, though, to supplement the generated solar power). [9] By most estimates of HE supporters, PEM fuel cells will soon replace ICE as the dominant transportation-power technology of the hydrogen economy.

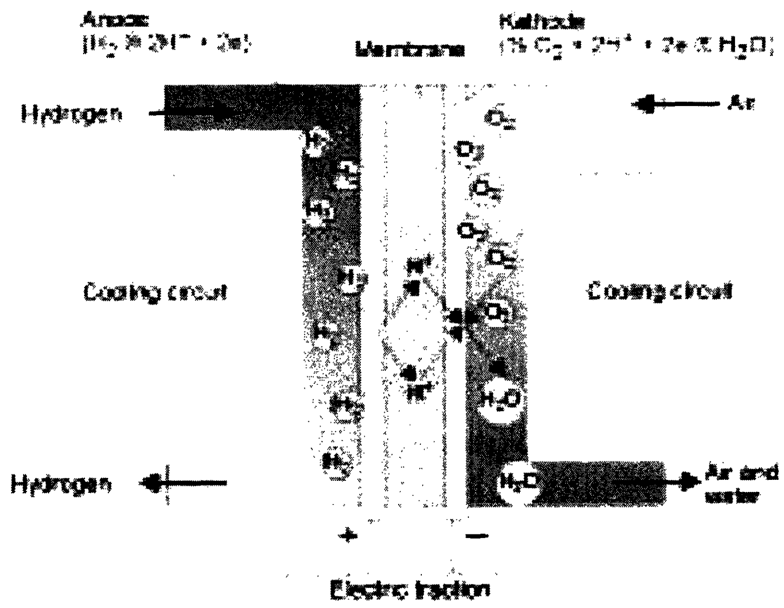

Figure 8: Proton Exchange Membrane (PEM) Fuel Cell [12] Hydrogen from the left is separated by the selectively permeable membrane. The proton moves across the membrane but the electron is forced to ravel around the circuit before recombining with the proton and incoming air to produce exhaust water.

Storing Hydrogen

In order for hydrogen utilization technology like fuel cells to be useful, hydrogen must be not only produced, but also stored in significant quantities. H_2 has a boiling point of -253° C, and with current technology requires an initial investment of 25%-30% of its energy content to effect condensation: to cool only 500 g of H_2 requires over 5 kWh of energy. Refrigeration is a storage method with the natural advantages of high energy density and low storage pressure, but requires expensive and bulky cryogenic equipment. Liquid hydrogen must also be vented to prevent explosion, resulting in additional useful-energy losses. Compressive storage of hydrogen provides an alternative option, but it too requires significant energy investment compared to the amount of energy practically stored, and also introduces the dangers typical of a highly volatile, highly pressurized gas. Neither method is, therefore, especially attractive for consumer applications such as home or vehicle power systems.

Current research is exploring the potential of high-density synthetic storage, through which metal and composite structures (carbon nano-tubes, etc) could possibly retain large amounts of H_2 by weight. One example of such promising technology are the polyethylene encapsulated sodium-metal pellets pioneered by Power Ball Technologies [13] – in which the stored energy density of hydrogen can exceed 7 times that of a compressed H_2 storage tank at 3000 psi (~ 204 atm). These synthetic storage technologies are still in developmental stages however, and have shown to be still far too heavy to be truly economical.

US DOE Hydrogen Posture Plan

To promote its vision for the future of the energy economy in the United States, the Department of Energy (DOE) has released a Hydrogen Posture Plan, [14] which outlines the short and long term goals which the DOE believes will culminate in a nationwide HE. Motivating the policies and decisions of the document are three major considerations: 1) a belief that it is in the best interests of the country to wean itself from foreign energy sources; 2) the need to transition from the GHG producing combustion of fossil fuels to renewable and clean energy sources; and 3) a strong optimism about the capabilities of hydrogen to address both of these key issues. The third consideration is the most tenuous, and the least essential to a secure and clean energy future, but despite the technical difficulties associated with H_2 production, delivery, storage, conversion and even end-use applications, DOE is confident that a HE is a feasible alternative to fossil fuels and should be attainable within 30-40 years.

Full realization of HE would entail the following technological and economic capabilities [14]:

1. On-board vehicle storage with 9% capacity by weight to allow 300 mile driving range

2. At pump costs per unit energy of H_2 equivalent to those of gasoline

3. PEM Fuel Cells at costs of roughly \$30-\$45 per kW

4. Zero emission coal-fired power plants (achievable through carbon sequestration)

5. Sustainable wind/solar-power based electrolysis capable of supplying the national demand for transportation hydrogen

6. Delivery technologies at per unit energy prices equivalent to those of gasoline

Some of these recommendations are approaching states of reasonable feasibility, as demonstrated in Santarelli and Macagno's discussion of solar-powered production of hydrogen. [3] The scale of the system discussed in [3] however is still far below that required for a national HE as are other vital technologies similarly deficient – a fact which the Posture Plan acknowledges in its aggressive research and funding recommendations. Such funding and resource allocation should depend on the demonstrated feasibility of HE, however, a consideration which is notably absent from [14].

A second pro-HE document, [2], authored and issued by the DOE funded Hydrogen Technology Advisory Panel (HTAP), complements the vision of [14] with specific timeline recommendations for the full integration of H_2 as an all-purpose energy carrier. In the near term (10-20 years) [2] recommend the primary use of H_2 as a traditional combustive fuel, to be mixed with NG in IC engines to improve engine performance and decrease pollution. Nahmias et al postulate that near-term hydrogen will be produced mainly by advanced steam reforming of NG, requiring, therefore, the sequestration of the resultant CO_2 in order to effect actual decreases in domestic GHG emissions. By [2], the fuel cell has little recommended role in the near term H_2 Economy.

In the long term (25-50 years), [2] predicts that advancing research should yield efficient and CO_2 neutral (zero net carbon emission) thermochemical, photobiological, and photoelectrochemical processes, (such as those discussed previously) through which hydrogen can be cheaply and expansively produced. Necessary storage will be facilitated primarily by advanced metal hydrides, carbon nanostructures and other high density/low weight synthetic storage technologies. The proposed distribution infrastructure for transportation H_2 will be compressed or liquid H_2 tanker trucks and H_2 pipelines akin to those in place for present day NG transport.

Various production facilities and general capabilities which [2] proposes as necessary for HE are presented in Figure 9. The bottom half of the figure presents the energy requirements for sustainable water-electrolysis or nuclear powered thermo-chemical production of H_2, another possibility discussed in [2]. The footprints of these energy systems are of considerable size and are resource intensity, yet they would provide the hydrogen necessary for the transportation industry only. They also do not include the hydrogen production that would be necessary to power the proposed distribution infrastructure of pipelines and tanker-trucks.

Resource	Needed for Hydrogen[a]	Availability	Current Consumption	Consumption with Hydrogen Production (factor times current)	Construction/ Footprint Required
REFORMING AND/OR PARTIAL OXIDATION[b]					
Natural Gas	95 million tons/year	28 billion tons (technically recoverable as of 1/2000)	475 million tons/year	1.2	400 dedicated hydrogen plants (100 MMSCF of hydrogen per day)
Biomass	400-800 million tons/year	800 million tons/year of biomass residue and waste, plus 300 million tons/year of dedicated crops[c]	200 million tons/year (3 quads for heat power & electricity)	2-4	400-600 dedicated hydrogen plants
Coal	310 million tons/year	126 billion tons (recoverable bituminous coal)	1100 million tons/year (all grades)	1.3	280 dedicated hydrogen plants
WATER ELECTROLYSIS[d]					
Wind	555 GW_e	3250 GW_e	4 GW_e	140	Available capacity of North Dakota (Class 3 and above)
Solar	740 GW_e	SW U.S.: 2.300 kWh/m^2-year	<1 GW_e	>740 times current	3750 sq. miles (approx. footprint of White Sands Missile Range, NM)
Nuclear	216 GW_e	n/a	98 GW_e	3.2	200 dedicated plants (1-1.2 GW_e)
THERMO-CHEMICAL					
Nuclear	300 GW_{th}	n/a	0 GW	n/a	125 dedicated plants (2.4 GW_{th})

Figure 9: Energy Requirements for a devoted H_2 Economy [2] Construction footprints are of considerable size

To facilitate achievement of the recommended timeline, in order to "realize the country's hydrogen future," [2] calls for a yearly increase in funding well beyond the $1.2 Billion Hydrogen Fuel Initiative already on the table.

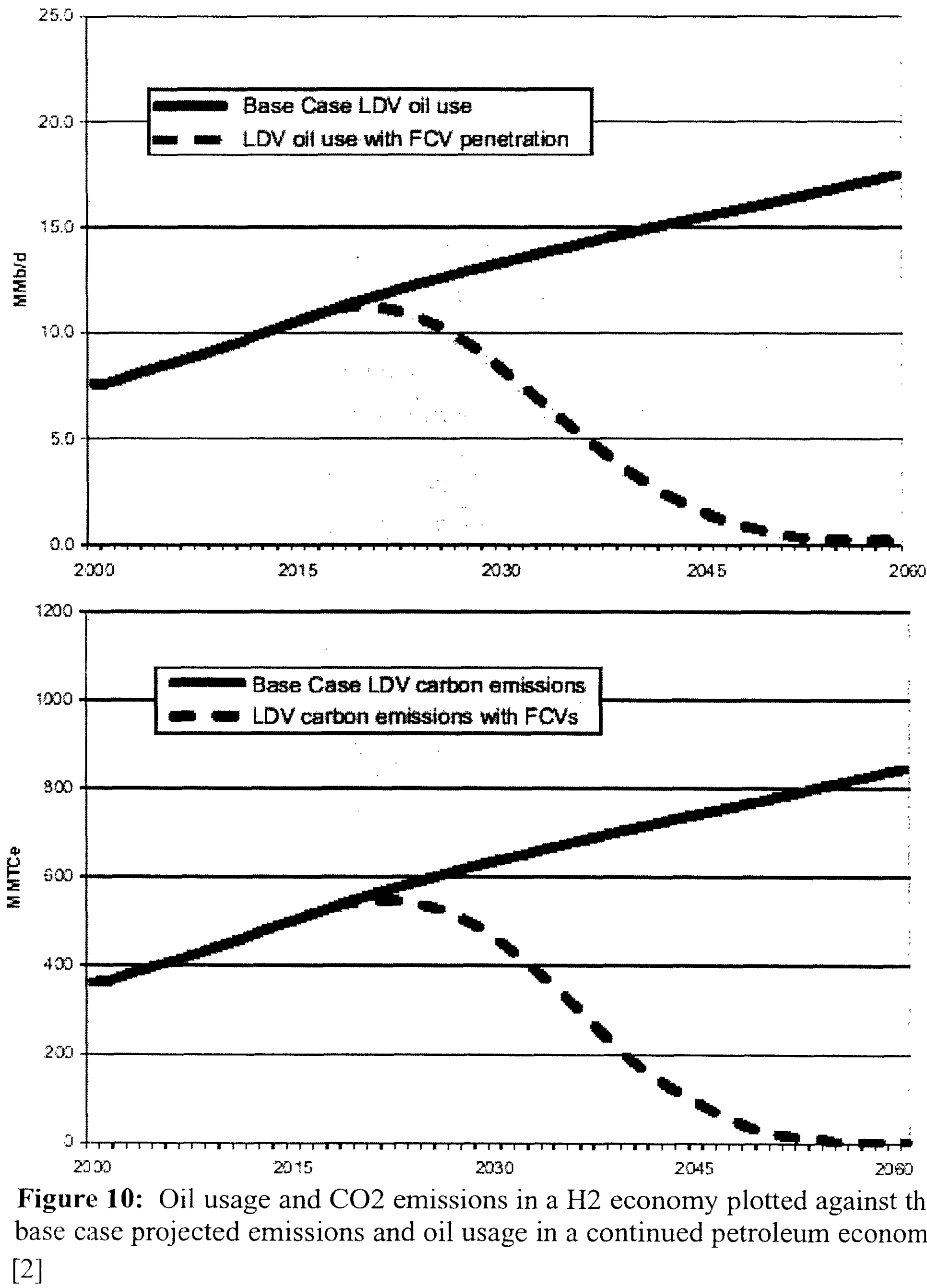

Figure 10: Oil usage and CO2 emissions in a H2 economy plotted against the base case projected emissions and oil usage in a continued petroleum economy [2]

The payoff of this additional yearly investment should be realized by roughly 2020, at which point, given the proposed developmental timeline, both vehicle petroleum use and net vehicle CO_2 emissions should begin to decrease from the base-case projection (i.e. FC vehicles will begin to achieve significant market penetration). By 2040 net vehicle carbon emissions should have been reduced by more than 500 million metric tons through the use of hydrogen powered vehicles; CO_2 emissions and vehicle petroleum demand are predicted to reach zero (or near zero levels) by approximately 2050. Figure 10 shows this predicted progress in petroleum use and CO_2 emissions versus the projected base case of improved ICE efficiency.

Problems with the H_2 Economy

The DOE Vision and HTAP projections for the HE are exciting – imagine a world in which the only emissive element of consequence, in all of our energy applications, is pure, clean water. The mere possibility has galvanized mass groups of constituents into a clean-energy optimism that is genuine and committed;, and in many ways, the first vestiges of the H_2 Economy seem to have passed from mere vision into definitive reality: the Humbolt State University's Schatz Energy Research Center, for example, recently implemented a combined photovoltaic/hydrogen power configuration that requires little supervision or maintenance and which can run in complete isolation from the general electric grid [8]: a 9.2 kW PV array provides the main daytime power-source to aerate the center's fish tanks, while surplus power is diverted to a 7.2 kW bipolar alkaline electrolyzer . With near-complete autonomy, the system produces 25 liters of H_2 (STP) per minute which is then reconverted by a 1.5 kW PEM fuel cell to provide compensating compressor power when the sun is covered or down.

Yet neither [14] nor [2] addresses the short- or long-term scientific feasibilities of HE. As fantastic and promising as the Schatz Center plant may seem, there are considerable physical problems (addressed extensively in [15]) that plague, and may ultimately condemn, the HE dream. Bossel et al raise critical and strikingly basic scientific issues with the almost reckless optimism of the DOE Vision and other H_2 proponents. The reality of the physics of hydrogen production, storage, transport and utilization on the large scale eventually limit the efficiency of the necessary processes to such low values as to cast serious doubt onto the feasibility and wisdom of policies which pursue such an energy infrastructure. Hydrogen is an energy carrier, not a fuel, and it can be seriously argued that there is no sound reason to employ such an energy middle-man.

To begin, consider the existing grid that provides electric power to our homes, offices, factories, schools, and shopping malls. What compelling reason can be offered to replace (as has been suggested by many proponents of hydrogen) such a grid with a hydrogen infrastructure? Two simple, inexpensive metal wires can carry electricity with efficiency of over 90% in most cases, resulting in a loss of only 1 kWh in transmission for every 10 produced. [15] Yet at the most optimistic estimates, transmission of the same energy by H_2 results in efficiencies of less than 30%: a loss of over 7 out of every 10 kWh produced. (Energy lost between well and consumer in the fossil fuel economy is about 12% for oil and 5% for NG. [1])

This inherent inefficiency is often overlooked by proponents of hydrogen, who (rightly) claim that hydrogen gas contains more energy per weight than any other fuel. The reality, however, especially in the case of such a naturally diffuse gas as hydrogen, is that transportation considerations are driven by volume, not by weight. Figure 11 displays the effects of this reality, in which hydrogen has the highest energy content (High Heating Value) by mass, but literally the lowest energy content by volume at equivalent pressures. In order to approach the energy density of methane at roughly 200 atm, hydrogen must be either liquefied, or compressed by nearly 4 times. At comparable pressures, hydrogen contains over 3 times less energy per cubic meter than methane and yet the energy required to compress hydrogen to useful pressures would require as much as half of the energy content – just for compression; liquefaction is better in efficiency, but not significantly, with theoretical large scale plants being able to produce liquid hydrogen with only 75% efficiency (currently available plants can do no better than 60%).

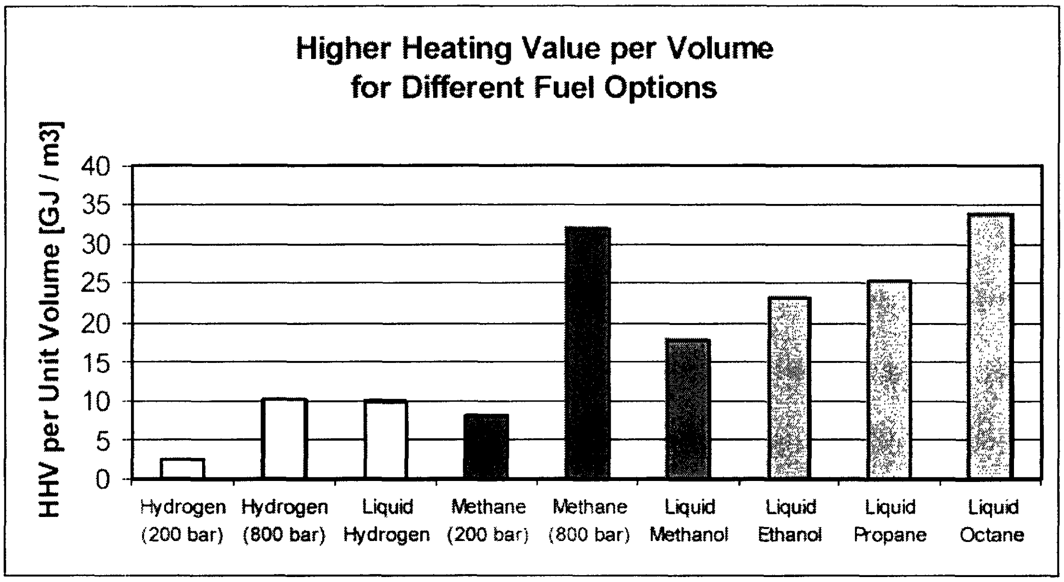

Figure 11: Energy content of various fuels by weight. [15]

The naturally low energy content per volume of Hydrogen compounds itself with the inefficiencies of pipeline delivery (the proposed distribution method for fixed-application hydrogen) to render the pipeline concept – and the vision of large-scale hydrogen distribution to cities – not just impractical, but very nearly physically impossible. Using universally accepted methods for pumping power calculation, it can be shown that ratio of theoretical pumping power for hydrogen (N_{H2}) to that for methane (N_{CH4}) is no less than 3.13 to 1 (Equation 1). [15]

$$\frac{N_{H2}}{N_{CH4}} = \left(\frac{\rho_{H2}}{\rho_{CH4}}\right) \cdot \left(\frac{v_{H2}}{v_{CH4}}\right)^3 \tag{1}$$

The necessary addition of pipeline compressors (which are generally powered by a small portion of the fuel within the line) and the inevitable flow leaks, together cause pipeline distribution of hydrogen to essentially lose any semblance of feasibility. Figures 12 and 13 demonstrate the tremendous inefficiencies of a hydrogen pipeline versus NG.

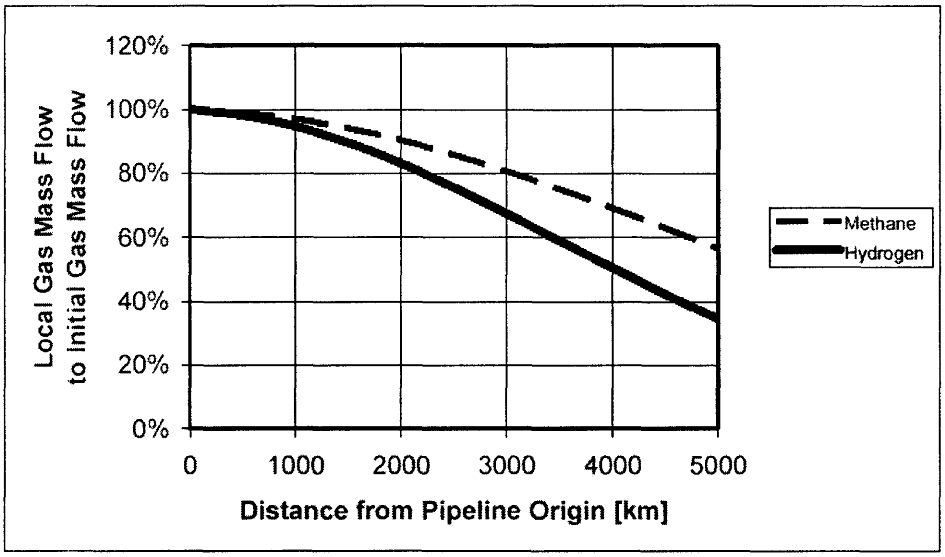

Figure 12: Loss of fuel mass as a function of pipeline length [15]: Hydrogen suffers from this phenomenon significantly more than does NG.

So in addition to driving the cost of energy (per watt) to at best nearly double that for electricity [15], the inherent inefficiency of hydrogen production and a hydrogen pipeline would require an truly irresponsible investment of resources for even marginal feasibility. For the conceivable future, hydrogen will never replace electricity as an energy carrier for stationary applications. What remain to HE then, are the localized use of hydrogen for energy storage (as at the Humbolt State facility) and the utilization of hydrogen fuels cells (FC) for transportation. The former application may have merit as demonstrated by [8], but there are other (more worthy) options to be considered and it still remains to be shown that the outlook for H_2-powered transportation is little better than that for pipeline distribution.

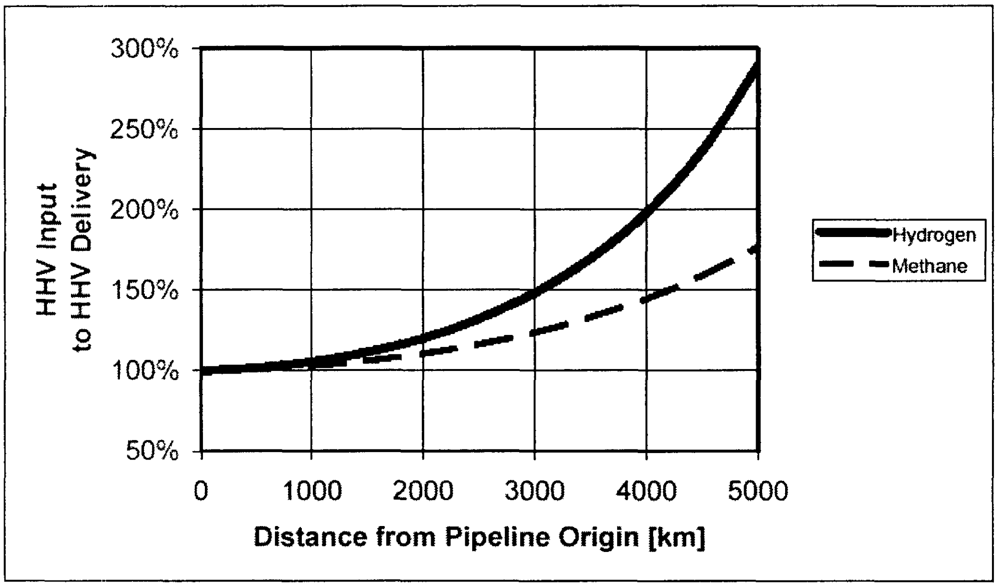

Figure 13: Percent ratio of energy required for delivery to energy actually delivered: Hydrogen again suffers tremendously in comparison to NG.

The first obvious solution to the pipeline problem in a national hydrogen-powered transportation infrastructure is to use tanker trucks in a system analogous to the current gasoline/filling station system, but it will become quickly apparent, that there are as many efficiency problems with a tanker truck distribution system as there are for a pipeline system. Road delivery of compressed hydrogen at 20 MPa would require roughly 39.6 metric tons of vehicle for a delivery payload of only 400 kg of gaseous H_2 at 20 MPa(only a 1% yield by weight); and yet this is an optimistic number based on prognostic assessment of future transportation technology: current trailers could deliver only about 288 kg total at 20 MPa. On the return trip then, based on these figures, the H_2-transport truck is driving empty of payload but with essentially the same road weight as when it was full. It is striking to compare this to the NG standard, under which a similarly equipped truck could carry 3000 kg (only 2400 kg actually delivered). [15]

Liquid hydrogen is nearly as problematic for tanker transport: its density is roughly equal to that of Styrofoam (70 kg/m^3), implying that a standard trailer truck, with the necessary cryogenic and safety equipment could carry only about 2100 kg of liquid H_2. [15] Roughly 15 tanker trucks of H_2 would be required to equivalently stock a filling station now serviced by only 1 truck full of diesel today.

The final suggested solution then for providing H_2 as a transportation fuel, in the light of the demonstrated delivery inefficiencies, is to generate the necessary hydrogen on-site as the demand requires. Yet current technology seems to render this option relatively unattractive as well, because the energy necessary for the electrolysis could be derived currently only from fossil fuel sources [15] (drastic improvements in PV and wind power technologies would be needed to change this). With conversion efficiencies yet at best only 50%, electrolysis production of H_2 for FC vehicles would result in increased GHG emissions.

There are still possibilities to salvage the supply problem, and even the problems of onboard storage which transportation vehicles will share with delivery vehicles could potentially be overcome by future research and developments in physical metal hydrides, carbon nanostructures, and other synthetic storage systems such as PowerBalls [13]. Even were these advances to materialize, though, according to an MIT e-lab report [16], nationwide implementation of a hydrogen FC-vehicle economy would not significantly affect the overall GHG emissions of the United States by 2020: mandated tailpipe emissions of ICE vehicles for 2020 (assuming evolutionary improvements in efficiency), would be such a small equivalent portion of the total domestic GHG output that their elimination through HE (or any other method) actually would have little significant environmental effects. Additionally, [16] reports that the total energy (and therefore, in the short term, the total GHG output) required to manufacture, maintain, supply fuel for and eventually decommission a diesel ICE hybrid, is essentially no different from the energy and CO_2 emissions required to manufacture, maintain, supply fuel for and eventually decommission a fuel cell vehicle. Therefore improving the efficiency and overall emissions of other energy sources (electric power plants, etc.) would be a considerably wiser and more important investment of both capital and research efforts than will FC and H_2 research.

Biomass for the Future

Hydrogen may have a place even in vehicle power in the long term, but in the short term, that place does not correspond to the DOE Vision [14] or the HTAP recommendations [2]. Returning to the underlying motivations of a H_2 economy – to significantly reduce the GHG emissions of the United States – and considering the analysis and recommendations above, it would be prudent to alter the short term hydrogen goals in three significant ways:

1. Advance hybrid and battery research for transportation power, forsaking the short term vision of a FC vehicle dominated pathway

2. Employ innovative fuels and technologies to reduce GHG output from existing power plants.

3. Explore methods by which hydrogen or other energy storage methods can help effect eventually sustainable power generation using renewable energy sources.

One potential source of inspiration and optimism with regard to each of these three goals, is the increased production and modification of biomass: as a potential source of hydrogen, and as a source of non-traditional direct-combustion fuels, biomass promises to play a more significant role in the near future than the fuel cell technologies propounded by H_2 Economy advocates. This section will discuss, with the ultimate motivation of decreasing short term GHG emissions, both potentials for biomass in conjunction with combined renewable-power/energy-storage systems.

Wood, the largest source of bioenergy to date, [17] has been used to provide heat for thousands of years, but there are many other types of biomass — such as residue from agriculture or forestry, and the organic component of municipal and industrial wastes — that can now be used as an energy source. Bioenergy resources are attractively replenishable through the cultivation of energy crops, such as fast-growing trees and grasses, called bioenergy feedstock. Switchgrass, for example, offers a theoretical net energy gain of 330% due to a 10 year planting cycle and low chemical fertilizer needs. [18]

Unlike other renewable energy sources, biomass can be converted directly into liquid fuels, the two most common of which are ethanol – an alcohol synthesized by the fermentation of high-carbohydrate biomass such as corn – and biodiesel – an ester made using primarily vegetable oils, animal fats, algae, or even recycled cooking grease. (Biodiesel can be used as a diesel additive to reduce vehicle emissions or in its pure form to fuel a vehicle.) Biomass can also be burned directly with little preliminary processing to produce steam for electricity production or manufacturing processes, or it can be chemically converted into a fuel oil, which is burned like petroleum to generate electricity.

Another possibility for biomass use involves gasification systems, which use high temperatures and/or catalysts to convert biomass into a gaseous mixture of hydrogen, carbon monoxide, and methane. The gas can be used to fuel a turbine or can be purified as a CO_2 neutral source of hydrogen. [17] (The processes are theoretically CO_2 neutral because the carbon contained within biomass is drawn primarily from atmospheric CO_2; although, for the short term, in which transportation and processing power are derived from fossil fuel resources, fully encompassing system boundaries require non-zero CO_2 emissions.)

Biomass for H_2

The first area of biomass potential to be discussed is the use of biomass sources to provide hydrogen. Eventually this may become important to transportation, but as demonstrated in the criticism of HE above, the primary application of these technologies will be in sustainable, renewable source power generation. Readily available biomass can be converted to hydrogen using electrical or thermal energy, which could in turn be derived from renewable sources like wind power or photovoltaic plants. The hydrogen could then be stored as a compensating reserve against the inevitable fluctuations of renewable power. The feasibility of such a system has already been demonstrated by Jurado and Saenz [19] in their mathematical analysis of a combined wind power/biomass gasification system.

Hemmes et al demonstrate different feasibility in [20], eventually concluding that centralized production of hydrogen from biomass with a pipeline distribution infrastructure is the most economically appealing Dutch response to the GHG emissions problem. [20] fails to recognize the inherent problems with pipeline distribution, but does satisfactorily demonstrate the ability of biomass to supply an entire country's hydrogen needs.

Obviously, significant research will be required before the biomass-hydrogen chain becomes truly feasible. For example: the distribution infrastructure necessary for a sustained supply of gasification feedstock needs serious development as do reliable feeder systems for pressurized gasifiers; and H_2 selectivity from gasification products also needs improvement. However, current research shows significant promise for the large scale, economic conversion of biomass to H_2 using Super Critical Water (SCW) gasification, or even low temperature catalytic processes:

- SCW gasification shows potential for efficient conversion of even very wet biomass (>80% moisture by weight) into extremely clean gas – free of tars and other contaminants – that is tremendously rich in H_2 (50-60% by volume). In addition the products are emitted at high pressures, saving expensive compression for the necessary eventual storage of the H_2. [21]

- According to Cortright, [11], hydrogen can also be produced from sugars and alcohols at temperatures near 500 K in a single-reactor, aqueous-phase reforming process utilizing a platinum-alloy catalyst. Improvements are acknowledged as necessary to prove the process practically useful, but it appears to have promise: Peak H_2 selectivity is nearly 99% for methanol, 96% for ethylene glycol, 75% for glycerol, 66% for sorbitol, and 50% for glucose. Such a system could theoretically harness waste heat from a CO_2-free nuclear plant to produce large amounts of H_2 relatively cheaply.

The potential for these conversion methods is significant and is generally overlooked by [14] in its planning and vision; but the research required for their economical implementation, as well as the questionable merit of *any* H_2 system, precludes their short-term implementation. Processed biofuels offer more appealing opportunities for short term GHG reductions.

Biomass for Traditional Fuels and GHG Mitigation

Biomass to H_2 conversion may be of dubious practical worth, but this is not so for processed biofuels. It has been shown that bio-fuels emit less GHG over the entire fuel cycle than petroleum based combustion-fuels, however concerns have been raised regarding other emissions, including particulates, sulfides and other compounds. Durbin et al, [22] demonstrate the potential for biodiesel driven GHG emission reduction in diesel ICE vehicles ,without significant increase in other emission factors. Using standard Federal test procedures (FTP), the authors investigate the environmental performance of four types of diesel fuels: a 10% aromatic diesel fuel (characteristic of the Reference Diesel Fuel – RDF – for CA); a 100% biodiesel fuel from Taurus Lubricants; a blend of 80% RDF and 20% biodiesel; and a synthetic diesel fuel from Mossgass Ltd. Figures 14-17 demonstrate the equivalence of tailpipe emissions from biodiesel and bio-blends in a 1996 Dodge Ram, 1995 Ford F350, 1988 Ford F250 and a 1990 Dodge Ram. Particulate emissions are noticeably higher for the bio-fuels in one older non-catalyst model only, while all other emissions are comparable to the reference diesel. Improved catalytic converter technologies and ICE efficiencies should validate bio-fuels as immediately attractive GHG-reducing alternatives to gasoline/diesel and to the questionable hydrogen economy.

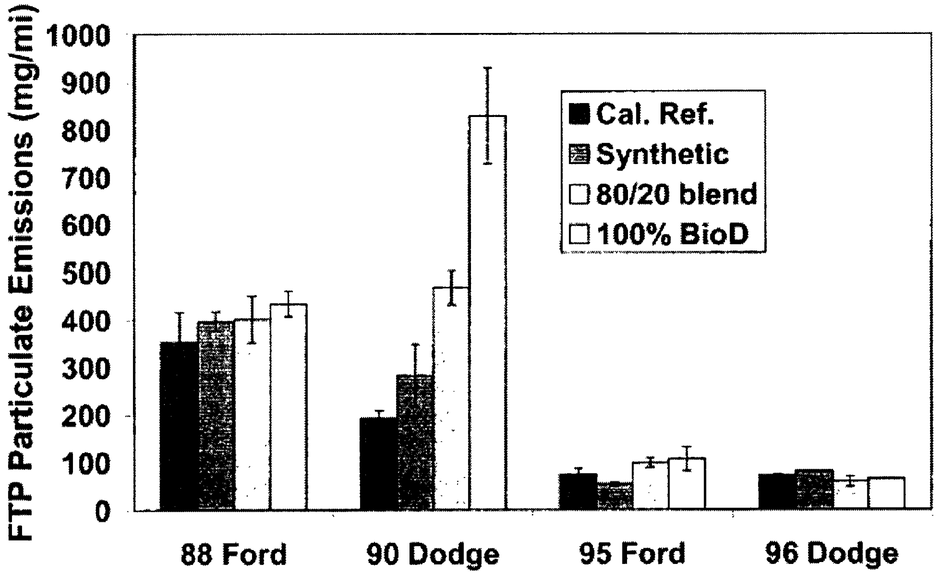

Figure 14: Particulate Emissions from Biofuels [22]

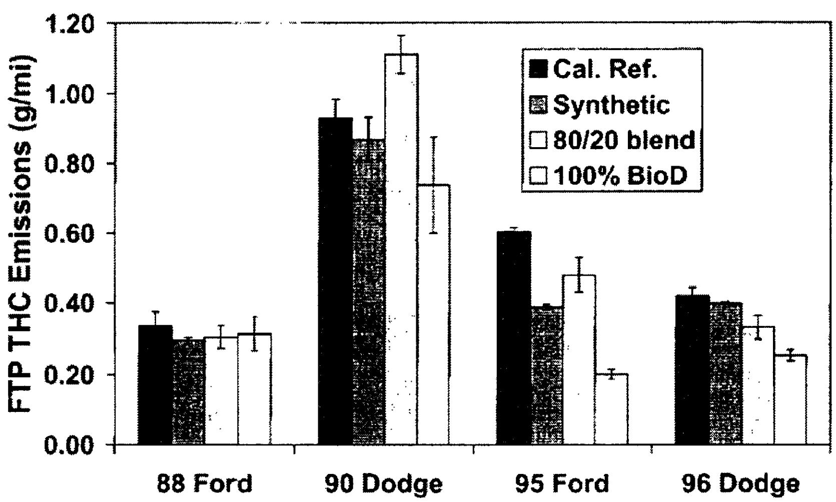

Figure 15: THC Emissions from Biofuels [22]

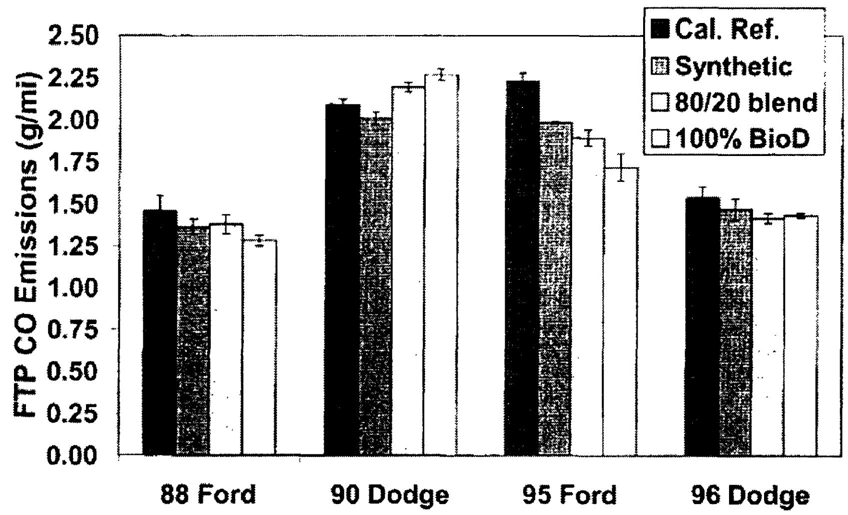

Figure 16: CO Emissions from Biofuels [22]

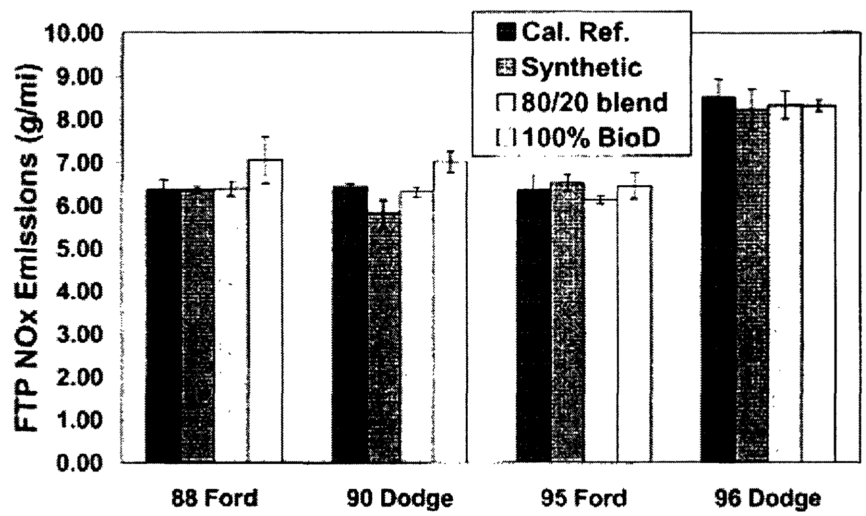

Figure 17: NO_x Emissions from Biofuels [22]

Biomass Power Plants in Europe

Biomass and biofuels do not show promise in ICE vehicle applications alone. Power generation using renewable bio-materials shows tremendous environmental promise as well. Groscurth in [23] presents several cases of actual biomass usage across Europe in reference to comparable non-biomass plants. Real-time CO_2 emissions decrease in only one test case (with comparison to the reference case), however, most biomass cases are presented as significantly lowering NO_x and SO_2 emissions, in some cases by up to nearly 96%. Additionally, when CO_2 equivalents - CO_2 emissions plus the weighted emissions of CH_4 and $N0_2$ – are considered, each Biomass case fared significantly better than its reference case. [23] further concludes that the high CO_2 emissions of the biomass cases are related more to the conversion technology than to the fuel itself; developing technologies such as porous-burner combustion [24] have potential to mitigate the GHG emissions significantly even with comparison to the results of [23]. Furthermore, the authors conclude that with the exception of one test case (in which biogas replaces NG in Denmark), the global warming mitigation effects are also marked by decreases in traditional non-GHG pollutants and therefore accompanied by increases in quality of life through generally positive health effects.* The cumulative result of the biomass benefits, along with the consideration that much of bio-fuel carbon was initially sequestered from atmospheric CO_2, suggests that biomass power plants should have substantial prominence in the near future.

Additional problems with Biomass are introduced in [23], however, including the potential ecological effects of larger plant harvests and increasingly intensive farming. With respect to these environmental problems, [23] recommends direct burning of

* According to [23], gas turbines and the combinations of boilers and steam turbines are a preferable option for biomass as compared to internal combustion engines, due to the problematic emissions of NO_x and methane from the IC engines. However, in areas of low demand densities it may only be economically feasible in the near future to utilize the ICE plants for cogeneration which essentially represents, then, a trade-off between lowering CO_2 and GHG emissions and the localized health effects of increase NO_x.

biomass residues (such as sawdust and wood chips) as preferable to the processing of crops, and perennials, as preferable to annuals, due to the additional efforts required to cultivate annual crops and the complexities of fuel preparation involved with converting non-residue biomass into convenient biofuels. These recommendation are corroborated by Bauen in [25], which demonstrates the potential of sugarcane residue to both heat and power sugarcane processing facilities, and by Talvitie et al in [26], which discusses the promising possibility of combusting sawdust for energy production (dependent on the recent advances of drying technology.) The effect of biomass crops on biodiversity and on water and soil quality are not addressed by this paper, and may become significant if biomass utilization increases to a larger scale. In that case, these problems must be addressed early on.

Gustavsson et al, [27], present comparable analysis (although of a more theoretical nature) of the potential for biomass in electricity and heat production in Sweden. Biomass is shown by [27] to require an initial investment and fixed and variable operating costs on the order of coal for medium-scale power plants. For larger scales, Biomass is not as efficient and is more expensive than any other fuel in Cogeneration and Condensing plants, but for similar capacity Boiler/Heat Pump plants the costs associated with biomass are again comparable to coal, again suggesting strong potential for fossil fuel replacement. Transportation gains are given only brief analysis by [27], in which ethanol is accorded the highest output yield of any of the bio-fuels analyzed, and similarly, one of the lowest production and distribution/storage costs. Use of ethanol is calculated to have a 15% increase in efficiency for light duty vehicles, and negligible change for heavy duty vehicles, with an additional investment of only \$520 and \$1900 respectively per vehicle to convert each from fossil fuels to ethanol.

Reduction of CO_2 emissions is slightly higher, and the cost of that reduction, slightly lower, for large scale plants versus medium scale plants. Generally the reduction is largest and the costs lowest when biomass replaces coal, and the reduction smallest and the costs highest when biomass replaces NG. [27] Table 2 shows cost estimates for various types of biomass sources, of which Gustavson et al generally recommend Salix, a short-rotation woody species, for both ecological and economical considerations. Their data applies specifically to the Swedish situation, but comparisons have been drawn between availability of Salix in Sweden and that of poplar in the Midwestern United States.

Table 2 Costs of Biomass Fuels in Sweden per MWh

Biomass Energy Crop	Production Costs (\$/MWh)	Transportation Costs (\$/MWh)	Total costs (\$/MWh)
Rape, seed	43	1.7	45
Winter wheat, grain	29	1.7	31
Reed canary-grass	13	4.0	17
Lucerne	12	4.0	16
Salix	10	2.3	12
Logging Residues	8.8	2.3	11
Straw from food product	7.6	4.0	12

[27] suggests a near-future scenario for Sweden in which 80% of coal and heavy fuel oils are replaced in large scale plants and 20% replaced in medium-scale plants. 50% of NG and LPG are substituted out of both large-scale and medium scale plants. Such measures

are projected to result in carbon mass reductions of over 50% of the present values as biomass is increased to 150 TWh/year, but will require an increase in costs of nearly \$350/ metric ton CO_2. With respect to Figure 5, and in conjunction with widespread application of ICE-hybrid technologies [28], the analysis of [27] offers tantalizing and scientifically verifiable potential to significantly reduce short-term CO_2 emissions.

In this particular analysis, the energy used for transportation of biomass in trucks is assumed to be small – about 1% of the total energy yield of the product for transportation of less than 50 km. [27] This assumption would not be particularly valid for the United States, which has a much more expansive biomass establishment and infrastructure than a small country like Sweden, however, if tail-pipe emissions are correspondingly reduced with bio-fuels, the analysis above should retain it's validity and promise.

A study by Kumar et al on the use of biomass in Vietnam, [29], provides even more encouraging conclusions about the potential of biomass to reduce GHG emissions. Exploring five specific options for replacing petroleum fuels with biomass, [29] concludes that the immediate potential for CO_2 reduction in Vietnam is over 3.5 Billion kg per year, with one option actually reducing CO_2 at a negative cost due to the high comparative price of fossil fuels with respect to locally produced biomass. Results are presented in Table 3, with the definitions of options 1-5 to precede:

- Option 1 – replacement of coal stoves with biomass
- Option 2 – replacement of LPG and kerosene stoves by biogas stoves
- Option 3 – replacement of gasoline by ethanol in cars
- Option 4 – replacement of coal by wood in industrial boilers
- Option 5 – substitution of fossil fuel power plants by package of Biomass Energy Technologies (BETs)

Table 3: CO_2 Reduction using Biomass in Vietnam [29]

	Option 1	Option 2	Option 3	Option 4	Option 5
Emission Mitigation Potential (million kg)	1363.40	113.57	131.63	2185.10	10830
Cost/emission reduction ($/Mg CO_2)	48.80	114.89	59.79	49.81	-45.59

Although the adaptation of these options in the U.S. would not be easy, or even in some cases practical, the general promise of the study is apparent. Certainly there is potential to employ biomass residue or even short-growth forest products in cogeneration heat/power plants, and biofuels in both plants and ICE vehicles, all with immediate, significant GHG-reducing effects: the combination of biofuels with hybrid cars could increase the average U.S. vehicle gas mileage to over 40 miles per gallon, decreasing transportation GHG output by over half. [28] (Combined with the analysis of [16], this amounts to tremendous gains in vehicle cleanliness.) To ignore this short term potential for GHG reduction in a blind race towards a dubious HE would be foolhardy.

Combined Power Generation:

Although biofuel-powered electric utilities would deliver appreciably reduced CO_2 emissions, they are a far cry from the zero-emission plants towards which energy policy should eventually aim. It would be, therefore, as inappropriate to end the analysis of appropriate short term technology with biomass as it would be to recommend HE without real scientific analysis of its principles and potential. There is significant potential for combined power generation and energy storage plants to make renewable source power plants (wind and solar, especially) practical, large-scale power sources within 25-30 years. [19]

As previously discussed, a major problem with PV and wind power is that the supply is unsteady and has difficulty responding to the inherently unpredictable demand. Solar and wind power can decrease unexpectedly, as a function of unpredictable micro-scale weather patterns and so must also be coupled with environmentally sound energy storage systems in order to provide an economically practical power supply. Of the three options to be discussed here – pumped hydro-storage (PHS), compressed air energy storage (CAES), and battery energy storage systems (BESS) – only pumped hydro storage is in current extensive use in the U.S. [30] – yet there is an untapped and possibly great potential for employing CAES and especially BESS in the continued reduction of GHG emissions.

Denholm and Kulcinski, in [30], present life-cycle analysis (analysis of total energy and GHG emission requirements for the entire life-cycle – construction through demolition – of a power plant) for each of these energy storage systems; [30] eventually points towards BESS as the most appealing long term renewable-source coupled-storage power plants.

Pumped Hydro Storage [30]

Pumped Hydro Storage uses surplus power from the primary generation source to pump water from a lower to an upper reservoir. When power demand exceeds supply, the water from the upper reservoir is released through a hydro-electric turbine to supplement the primary generation plant. Several PHS systems are presently in operation in the U.S., with possible round trip conversion efficiencies of 70%-85% (most plants actually operate in 75%-80% range). Sizes of the plants often approach or exceed 2000 MW, requiring construction and modification of two or more reservoirs and multiple dams. In a few cases the lower reservoir can be a river or existing lake, however, underground caverns could also be utilized. PHS systems have very small ramp-up times allowing for quick response to real-time demand fluctuations.

CO_2 emissions due to the decay of biomass under the flooded area, and the lost CO_2 sequestration of the flooded area (dependent on reservoir size, previous vegetation and climate) are contestably non-negligible, but should still be significantly smaller in absolute scale than the CO_2 emissions reduction achieved through the use of the renewable generation system (assuming that PHS is indeed implemented alongside a PV or wind-power array). The net efficiency of an average PHS system, accounting for line losses, transformer cycles and inherent mechanical efficiencies is 74%.

CAES Systems

In a compressed air energy storage system, during low demand periods, compressors pump air into a large storage facility such as an underground cavern or salt-dome. Later this air is extracted through a high-pressure expander which captures some of the contained energy. The air is then mixed with fuel (such as NG) and combusted in a low-pressure gas turbine expander, the exhaust heat of which can then be captured to pre-heat the stored air. Such a system, like PHS, allows for fast ramping rates to allow for responsive load following as well as potentially fast compensating response to intermittence of renewable energy sources. Cavern leakage rates are negligibly small, and typically do not contribute to system inefficiency. There is, at present, only one operating CAES system in the U.S. – a 110 MW, 26 hour Alabama Electric Cooperative facility in McIntosh, Alabama. [30]

Due to the required use of fossil fuels, CAES systems produce more energy than they consume (unique among the discussed storage options) providing an energy ratio – energy invested to energy delivered – between 0.75 and 0.85. 1 GWh of electricity from a CAES system requires only 0.735 GWh of electricity and 5246 GJ of thermal energy (NG). [30] The use of a fossil fuel makes this system appealing from an efficiency perspective, but also less attractive from an emissions perspective (as compared to PHS and BESS). CAES systems make efficient use of natural formations without significant local ecological impact (unlike PHS), but in the long term, the CO_2 emissions and non-sustainability, both due to the NG requirement, should eventually render the system obsolete. Short term prospects, though, are promising, and [30] reports that future sites have been planned in Norton, Ohio and in the southern U.S.

BESS

Battery storage is another attractive option for renewable-power/energy-storage coupling, but has acquired a generally poor reputation, mainly on behalf of lead acid batteries: these suffer from marginal economic benefits when compared to, for example, diesel generators. Lead-acid batteries have, as well, an unacceptably limited life-time, which tends to decrease rapidly whenever the batteries are discharged past 30% of capacity. There are only two lead acid BESS currently in operation in the U.S., one in Puerto-Rico (at 20MW and 14MWh), and one in Chino, CA (10MW, 40 MWh). Possibilities are exciting for other battery technologies however, especially pumped liquid electrolyte (PLE) flow batteries which utilize vanadium-acid, sodium-bromide/sodium-polysulphide (Regenesys), or zinc-bromide. Batteries which employ one of the first two electrolyte pairs are sometimes referred to as Regenerative Fuel Cells, as they use an ion-exchange membrane similar to that used by PEM fuel cells. These systems seem to be extremely adaptable to large-scale energy storage, having:

- High depth of discharge - ~100%
- High cycle life (5000+ cycles)
- Flexibility in both capacity and discharge rate

- Reduced maintenance requirements
- Easily measured state of discharge
- Non- or low- toxicity components
- Size and shape flexibility
- Negligible hydrogen production (no venting or ventilation required). [30]

A typical flow battery configuration is presented in Figure 18: large reservoir tanks store the electrolytes, which are pumped through the regenerative fuel cell in order to facilitate charging/discharging of the battery system.

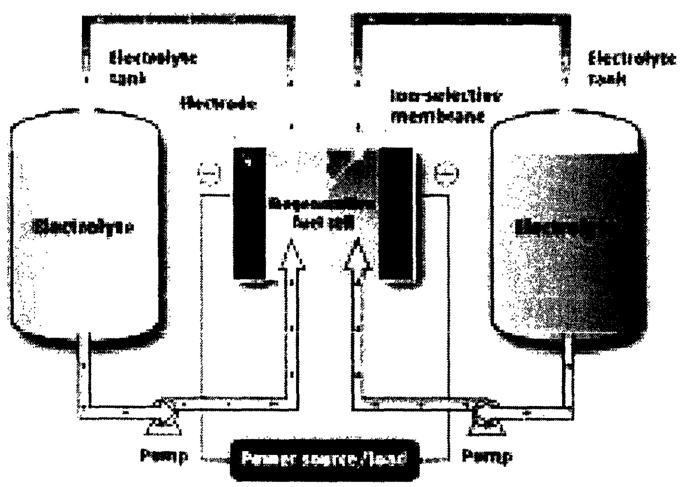

Figure 18: Pumped Liquid Electrolyte Battery Configuration [30] Such as system could be theoretically scaled to almost any size required for industrial applications

The inherent electrical cycle efficiency of PLEs is near 90%, especially for the vanadium systems. However, mechanical flow and pump energy consumption decrease overall efficiency by up to 3% more. Still, delivery of 1 GWh from a vanadium battery requires only 591 GJ in addition to the primary generation. [30]

BESS store and produce direct current, so additional inefficiencies must be accounted for in the AC-DC converters (around 4%); however, PLEs especially offer themselves as exceptional possibilities for combined renewable power generation/power storage. Additionally, while there promises to be little improvement in the efficiencies and capacities of CAES and PHS systems in the near future, battery installations in general show considerable possibility for near-term technological development and coupled with PV and wind power advances, [19], could potentially provide realistically emission-free power plants.

Conclusions:

As environmental and sustainability problems worsen, honest and rigorously scientific consideration of the costs and benefits of various energy technologies will be necessary for the efficient domestic transition to a lower (and eventually zero) GHG-emitting economy. Analysis methods like Kulcinski's Life-Cycle Analysis (LCA) in [30], or the comparative indicators suggested in Afgan et al [19], will provide useful tools for choosing the most appropriate technologies for both short-term local use and long-term national planning.

By all such scientific analyses, hydrogen must play a significantly smaller role in both the short- and long-term future than most of its supporters would like or imagine. In the short-term, biomass/biofuel and hybrid vehicle technologies [28] can be demonstrated to offer a more efficient and potentially cleaner energy option for mobile applications. Stationary power production and utilization should continue to rely on the existing electric-grid infrastructure, with biomass implementation increasing in the short-term. In the long term, PHS and BESS show the greatest potential of non-nuclear technologies to buffer the supply inadequacies of renewable power generation while operating with reduced or even eventually zero net CO_2 emissions. (Figure 19)

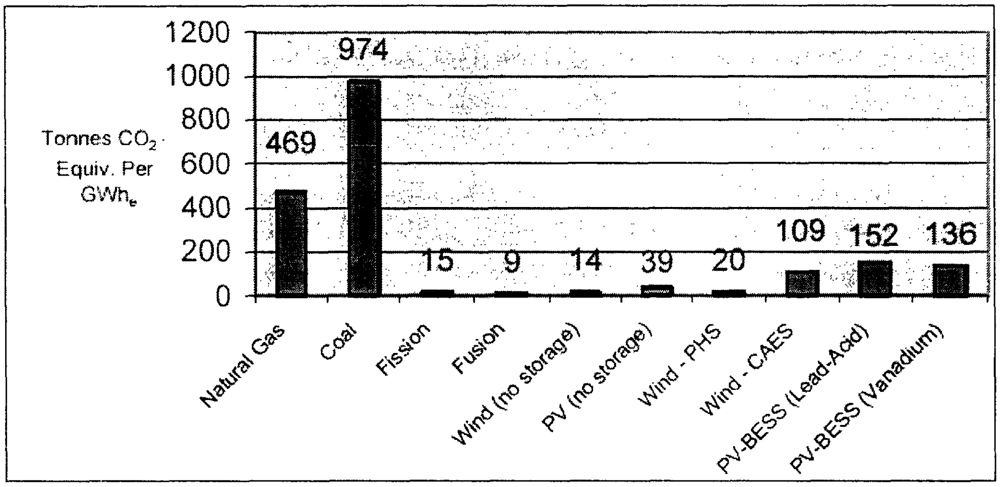

Figure 19: CO_2 emission per GWh energy produced [30]. LCA relies on current CO_2 emission-rates to calculate construction / materials / maintenance emissions and will therefore yield indeterminately lower values for future analysis, as a larger percent of grid power can be considered to come from low to zero emission sources. (It is important to realize that this lowest value for emissions is theoretically zero only for nuclear power and for combinations of PV, wind, PHS and BESS systems; nuclear power analysis will be left for later discussions.

References

[1] - DOE. "United States Country Analysis Brief – Energy". www.eia.doe.gov/emeu/cabs/usa.html, 23 October 2003 [30 March 2004]

[2] - Nahmias et al, "Realizing a Hydrogen Future," Hydrogen Technolgoy Advisory Panel Publication 2003 Recommendations

[3] - Santarelli, Macagno, "Hydrogen as an energy carrier in stand-alone applications based on PV and PV-micro-hydro systems," Energy, 20 (2004)

[4] - Zumerchik, "Batteries," in McMillan Encyclopedia of Energy 1, Zumerchik ed. New York, Ogden Publishing, 2001 pp 115-124

[5] - [Esper, J., E.R. Cook, and F.H. Schweingruber, 2002. Low frequency signals in long tree-ring chronologies for reconstructing past temperature variability, *Science,* **295,** 2250-2253

[6] Pat Michaels [Extinguishing Extinction Hysteria, http://www.greeningearthsociety.org/wca/2004/wca_15d.html, (4/25/2004)

[7] - [World View of Global Warming, Gary Braasch, from Scientific American, http://www.worldviewofglobalwarming.org/, 25 April 2004 (30 April 2004)

[8] - Bush's State of the Union speech, 29 January 2003, (30 April 2004) http://www.cnn.com/2003/ALLPOLITICS/01/28/sotu.transcript/

[9] - Office of Energy Efficiency and Renewable Energy. "Hydrogen Fuel." www.eere.energy.gov/consumerinfo/refbriefs/a109.html, 30 March 2004 (1 April 2004)

[10] – Energy Equivalents of Various Fuels, http://www.nafa.org..., 30 March 2004 (30 April 2004)

[11] - Cortright, Davda, Dumesic, "Hydrogen from catalytic reforming of biomass-derived hydrocarbons in liquid water," Nature, 418, 29 August 2002 pp 964-966

[12] – PEM Fuel Cell http://www.fuelcellbus.com/eimage/ezelle.gif

[13] – The PowerBall Concept, http://www.powerball.net/concept/index.shtml, 16 April 2004

[14] – DOE Hydrogen Posture Plan 2002

[15] - Bossel, Eliasson, Taylor, "The Future of the Hydrogen Economy: Bright of Bleak?," presented at the 2003 Fuel Cell Seminar, 2003.

[16]- Weiss et al, "Vehicles and Fuels for 2020: Assessing the Hydrogen Fuel-Cell Vehicle," MIT E-Lab Research Reports, January-March 2003, 1-5

[17] http://www.eere.energy.gov/RE/bio_basics.html 02/04/2003

[18] – Mowery, "Biofuels," in McMillan Encyclopedia of Energy 2, Zumerchik ed. New York, Ogden Publishing, 2001 pp157-166

[19] - Jurado, Saenz, "Possibilities for biomass-based power plant and wind system integration," Energy, 27, 2002, pp. 955-966

[20] - Hemmes, Groot and Uil, "Application Potential of Biomass Related Hydrogen Production Technologies to the Dutch Energy Infrastructure of 2020-2050". *ECN Biomass*, April 2003

[21] - Babu, "Biomass gasification for Hydrogen production – process description and research needs," Gas Technology Institute Publication, 2004.

[22] - Durbin, Collins, Norbeck, Smith, "Effects of Biodiesel, Biodiesel Blends, and a Synthetic Diesel on Emissions from Light Heavy-Duty Diesel Vehicles," Environmental and Science Technology, Vol 32 No. 3, 2000, pp. 349-355

[23] - Groscurth et al. "Total costs and benefits of biomass in selected regions of the European Union," Energy, 25, 2000, pp 1081-1095

[24] Bakry, Genenger, Schmidt, Trimis, "Low Emission Combustion of Vegetable Oils with the Porous Burner Technology," in New and Renewable Technologies for Sustainable Development, Afgand and Carvalho, Eds. Boston, Kluwer Academic Publishers, 2002, pp.541-551

[25] Bauen, "Sustainable Heat and Electricity from Sugarcane Residues Gasification in Brazil," in New and Renewable Technologies for Sustainable Development, Afgand and Carvalho, Eds. Boston, Kluwer Academic Publishers, 2002, pp. 429-441

[26] Talvitie, Sierila, Oksanen, Miettinen, "Combustion of Sawdust," in New and Renewable Technologies for Sustainable Development, Afgand and Carvalho, Eds. Boston, Kluwer Academic Publishers, 2002 pp. 569-579

[27]- Gustavsson, Borjesson, Johansson, Svenningsson, 'Reducing CO2 Emissions by Subsittuting Biomass for Fossil Fuels,' Energy, Vol. 20, No. 11, 1995, pp. 1097-1113

[28] - Fairley, "Hybrid's Rising Sun," Technology Review, April 2004, pp. 34-42

[29] - Kumar, Bhattacharya, Pham, "Greenhouse gas mitigation potential of biomass energy technologies in Vietnam using the long range energy alternative planning system model," Energy, 28 627-654, (2003)

[30] - Denholm, Kulcinski, "Net energy balance and greenhouse gas emissions from renewable energy storage systems," Energy Center Publications, June 2003