Hydrogen Strategies Under Uncertainty: Risk-Averse Choices for "Hydrogen" Pathway Development

*By Lorna A. Greening**

Abstract: Uncertainty about the future plays a major role in the formulation of policy options. This analysis of the total costs (private and social) with a focus on hydrogen indicates how some of this uncertainty may project into the future. Through incorporating this uncertainty into the decision process, low risk or 'risk-averse' strategies may be identified for choosing a "hydrogen" development pathway.

Introduction

Discussions of energy policy have had a major role in the legislative agenda of the last session of Congress, and may have an even greater role in the upcoming session. Since the early 1970's, many of these discussions along with the resulting energy policies in the U.S. have focused on the introduction of alternative transportation fuels and fuel efficiency policies (Greene, 1990; Kleit, 2004; Sperling, 1988; Sperling and DeLuchi, 1989). Alternative fuels have encountered many barriers to adoption. For example, bio-diesel, one of the closest substitutes for liquid transportation fuels available in terms of the use of existing vehicle technologies, is just now beginning to appear commercially. However, this fuel is on the order of 13 to 22 cents more per gallon when available, does require installation of a separate pump and tank at a re-fueling station, and depending on the blend may cause rubber or other engine components to fail in older vintage vehicles (US DOE, 2001). Therefore, some seemingly minor differences with petroleum based fuels have impeded greater penetration of the fuel. Further, although shown to be quite effective when initiated 1978, fuel efficiency standards promulgated under provisions of the Corporate Average Fuel Economy Standards Act in 1976, have lost much of their effectiveness with time. Without the re-enforcing effects of energy prices, modal shifts and declining load factors have substantially offset improvements in energy efficiency (Greening, 2004).

Most recently, hydrogen powered fuel-cell vehicles have been suggested as another alternative to the U.S. ever expanding demand for petroleum (Dearing, 2000; Sperling and DeLuchi, 1989). These studies, and many similar analyses, have identified a number of barriers to the increased use of hydrogen in transportation applications. In an evaluation of the potential for this use and R&D requirements, these barriers were summarized (NRC and NAE, 2004). As with other alternative fuels, the current operating characteristics of relatively limited driving range, and narrow requirements for ambient temperature for operation of vehicle technologies were identified as a primary barrier. Further, in the hydrogen literature, it has been suggested that even if these characteristics were improved, fuel cells would be no more efficient than a Carnot cycle (Lutz, et al., 2002). However, other researchers have provided evidence that fuel cells could be substantially more efficient than the Carnot (Cooper, 2003; Lawrence Livermore National Laboratory, 2001). Therefore, there is tremendous uncertainty concerning the operating characteristics, and the probable costs of fuel cell technologies even in the short-term.

Environmental considerations also have been been cited as a rationale for the adoption of hydrogen as a transportation fuel. However, various comparative analyses of different means of production have concluded that emissions may merely be shifted from the tail-pipe to the hydrogen production stage for some types of hydrogen production (Wang, 2002). Some methods of hydrogen production may actually increase both emissions and the total energy of the system (Neelis, et al., 2004). Although, the least expensive means of hydrogen production at the moment is natural gas reformation, greenhouse gases (GHG) are still emitted, and domestic natural gas resources are declining. The EIA forecasts approximately 15% of our natural gas consumption in 2025 will be supplied by imported LNG, most of which is expected to originate in the Middle East (EIA, 2004). Therefore, increased use of hydrogen, depending upon the means of production, may not provide the promised environmental benefits, nor lessen U.S. dependence on foreign sources of fossil fuels. These benefits maximize only when hydrogen is produced using renewable or nuclear sources, however, there are trade-offs associated with the use of those commodities particularly in the case of nuclear energy (Greening and Schneider, 2003).

Perhaps the biggest barrier to the penetration of hydrogen, which has often been cited as the overwhelming barrier, is the infrastructure requirements for hydrogen distribution. Distribution of hydrogen for transportation use is particularly difficult, owing to the need to use very high pressures or very low temperatures which greatly adds to the difficulty in storage and distribution. If a hydrogen supply chain that parallels the existing supply chain for gasoline is constructed, it has been estimated that between 4500 and 17,700 stations would be required to initiate the system with a capital investment of between \$7 and \$25 billion (Melaina, 2003). If the traditional supply chain is abandoned in favor of distributed hydrogen production and distribution, carbon sequestration becomes more difficult, and many of the environmental benefits from hydrogen are substantially reduced. Also, it should be noted that with a greater dependence on a gaseous fuel, either natural gas in the case of production or the distribution of gaseous hydrogen from central production, the fuel transportation system becomes more vulnerable to protracted disruption (Corbet, 2004). The existing liquid fuel system responds much more slowly and recovers more quickly than a gaseous based system.

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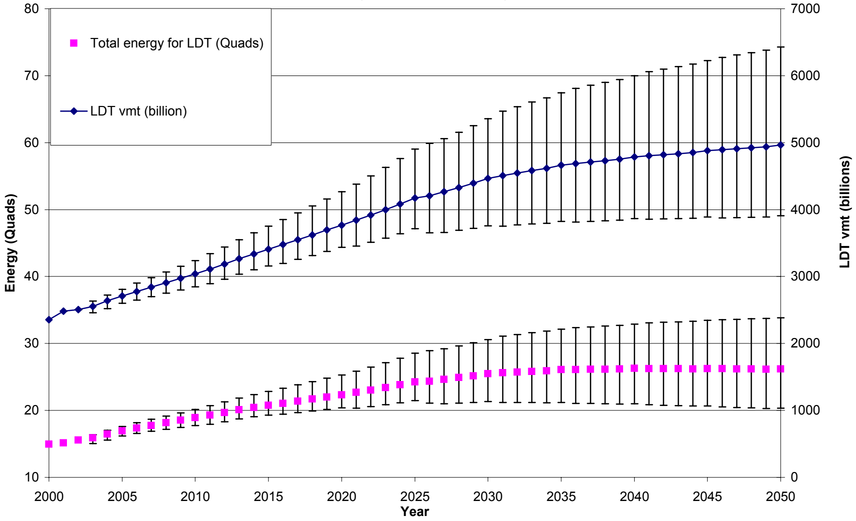
Energy and environmental policies have a number of characteristics in common, but are also dissimilar in a number of respects (Greening and Bernow, 2004). Both types of policies embody uncertainties evolving from long time frames, and capital-intensive investments (Huang, et al., 1995). However, the uncertainties associated with each stem from different sources. But, with the recognition of the nexus between energy consumption and production and the possible degradation of environmental amenities, developing coordinated approaches to energy and environmental issues has become a primary goal for the policy formulation process. The discussion presented here begins to examine how uncertainties about characteristics of potential energy policy options when combined and compared can lead to less risky or 'risk-averse' choices. Several different criteria in addition to private costs have been included in this analysis. To do this, the 'controversial' step of monetizing some of the externalities has been used. However, it should be noted that there are other well accepted means of including externalities in the decision process, and those methods are being used in further research.

Figure 1
Forecasted Light Duty Personal Vehicle Miles Traveled and Energy (2000 to 2050)



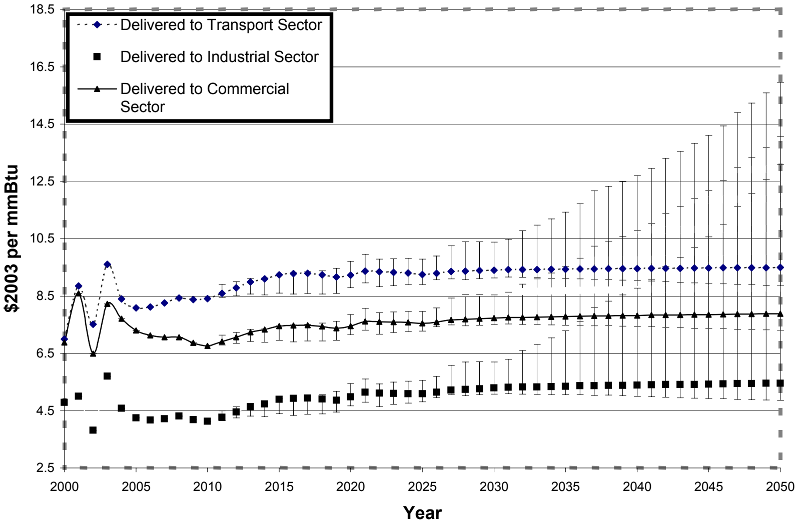
Many of the previous analyses of both the life-cycle costs and emissions have used a static approach (e.g., Ogden, et al., 2003) where fuel prices and the technological characteristics of vehicles and fuel production are assumed constant. Further, these previous analyses have not explicitly recognized the uncertainties associated with the valuation of externalities (i.e., social costs). In the work presented here, uncertainty concerning the potential prices of fuels, and technological characteristics has been explicitly recognized. In addition to market cost uncertainties, an attempt has been made to quantify other attributes, such as emissions of GHG and potential levels of imports of fossil-fuels, and provide an economic valuation. By the incorporation of other attributes in the analysis process, we begin to provide an understanding of some of the trade-offs that might be necessary in selecting one technology over another for support. As a result, policy- or decision-makers can broaden their basis for decision from just the private cost attributes.

Uncertainty and Hydrogen Choices

In order to evaluate many of the uncertainties associated with the potential development of our future transportation system, personal vehicle miles traveled (vmt), energy consumption for personal transportation, vehicle and hydrogen production technology costs, and costs for various fuel commodities were forecast out through 2050. These forecasts were developed with three cases from the Annual Energy Outlook 2004 (reference, and high and low economic growth) and long-term population forecasts from two sources (Bureau of the Census, 1996; O'Neill, et al., 2001; United Nations Population Division, 2003). As demonstrated by Figure 1 of a forecast for vmt and total energy for light duty travel, this approach illustrates the uncertainty in projecting future transportation energy needs and costs, and the impacts of the penetration of alternative transportation fuels and technologies into the future. Personal vehicle miles traveled could reach levels of between approximately 3500 and 6100 billion by 2050. Similarly, total energy consumption for this mode of transportation could reach levels of between 18 and 32 quads with an expected (or reference level) of slightly over 26 quads by 2050. These levels translate into average annual growth rates of 0.4% to 2.3% and reflect the effects of expected improvements in fuel efficiency during the forecast period.

To illustrate further the uncertainties in the analysis of the future costs of transportation alternatives, forecasts of future energy prices were prepared and incorporated into this analysis. Figure 2 provides an example of the uncertainty of prices for natural gas delivered to the transportation, commercial, and industrial sectors. This uncertainty could impact the private costs of travel to one extent or another for several different fuels including compressed natural gas and hydrogen produced from both distributed and central steam reformation. The reference case prices for natural gas assume that although domestic production of natural gas has flattened, imported supplies of LNG are readily available through 2050. The error bounds on those prices, however, begin to capture the potential effects of world competition for LNG from the developing portions of the world, the possibility that our resource estimates for recovered resources in North America are less than currently anticipated, and the over-all depletion of fossil-resources. As a result, natural gas prices could reach levels as high as 250% over forecasted reference levels in 2050, and reflect the possibility of short-falls in supply. These potential levels of price, however, do not consider the potential for fuel substitution nor acceleration of technological improvements. This same type of analysis was also performed for other fossil-fuel commodities such as the

Figure 2
Forecasted Delivered Price of Natural Gas



delivered price of coal, distillate, gasoline, and other market-based commodities.

To illustrate how these future uncertainties might impact the costs per vmt of different vehicle alternatives, Monte Carlo simulation was used to perturb the components of total costs (private and some social) of personal travel (vmt). This approach allows for a better understanding of the cumulative uncertainty in a system than might be derived from the use of individual scenarios. This analysis, also serves as the first step in development of a multi-criteria decision support framework incorporating uncertainty and additional attributes. As discussed in the following, this particular analysis includes only a very small sub-set of potential externalities from personal transportation. The inclusion of additional categories may amplify or reverse the conclusions made here. Therefore, this is an area of on-going research.

Vehicle costs and costs for production of hydrogen, and energy usage were derived from various sources. Vehicle costs and energy usage were obtained from the OTT/DOE, and are consistent with such other sources such as the AEO (EIA, 2001, 2004; Office of Transportation Technologies, 2002). Future vehicle costs and efficiency trends were projected using trends established in the Annual Energy Outlook. Costs for a selected number of hydrogen production, transportation, and delivery technologies were taken from several sources and compared with the NRC study (Amos, 1998, 2004; NRC and NAE, 2004; Simbeck and Chang, 2002). Other modeling efforts have included a greater number of production technologies (Greening and Schneider, 2004), however, for this illustration of the effects of uncertainty only a number over this range were examined.

Both vehicle technology costs and fuel efficiencies are assumed to have different rates of potential technological change depending upon the current development of a technology. Fuel price uncertainty is treated through projection of a spread of prices for each fuel commodity over the forecast horizon extending from 2000 to 2050. To incorporate some of the impacts of unpriced externalities, estimates of the potential damages from GHG and the increased or forecasted increased dependence upon imported sources of fossil fuels such as petroleum and petroleum products, and natural gas were also estimated. These two externalities have been argued by some to be particularly important for personal transportation in the U.S. (Greene, et al., 1997); however, others have argued that criteria pollutants and congestion produce greater welfare losses. As a result of this approach, we can identify technologies which may over the course of time in the face of uncertainties from a number of different sources offer lower total private and social costs on a per vmt basis. This then allows us to suggest areas of emphasis for research and development of alternative fuels, particularly hydrogen.

Emissions damages estimates were calculated for only greenhouse gases (i.e., CO_2, CH_4, N_2O, VOCs, NO_x, and CO). Different weighting schemes can be used to combine these species into a CO_2-equivalent measure. But, for this analysis, a scheme where distributions have been developed for each of the weights was used (Contadini, 2002). This captures the uncertainties associated with the climate forcing capacity of each gas (IPCC, 1996). To further incorporate these uncertainties, we have used a range of values for our proxy cost of environmental damage from GHG emissions. Following Ogden, et al (2003), a cost of carbon dioxide ranging from approximately $18 to not quite $50 per tonne of CO_2 was assigned to the CO_2-equivalent emission. This range of costs represents a 95% confidence of potential damages, and is consistent with estimated costs of achieving maximum levels of capture and sequestration. Finally, the full-fuel cycle estimates developed in GREET 1.6 were used (Wang, 2001). As a result, damages were estimated for "well-to-wheel," and thus consider all vehicle/fuel combinations on a comparable per vmt basis.

Security costs were estimated once again in a manner consistent with Ogden, et al. (2003). These authors used an estimate of between $20 and $60 billion per year to safe guard access to Persian Gulf oil. However, considering recent experience (i.e., Iraq and Afghanistan), and whether we ascribe all Middle East military costs to oil, this range may be low. Ogden, et al., use a range of between $0.35 to $1.05 per gallon of gasoline equivalent with a likely value of $0.70 estimated on the basis that 20% of U.S. oil imports originated in the Persian Gulf in 1999. Since oil is fungible with an established commodity market, any disruption would be felt in across-the-board price increases. Therefore, this risk premium was assigned to the imported share of petroleum without regard to point of origin. Further, the share of imports was forecasted out through 2050, and as a result, the oil security component of total price will increase with time for petroleum-fueled vehicles. Since imports of LNG are also expected to increase in time, they will probably be substantially from the Persian Gulf area, and will provide an increasing component of our natural gas supply, the security premium was also applied to imported LNG. As a result, this premium on a per vmt basis increases for natural gas based vehicle options (e.g., CNG dedicated, hydrogen produced from central or distributed natural gas reforming) over the forecast horizon. If other sources of energy, such as nuclear, were used in the generation of hydrogen, other issues surrounding supply security and environmental considerations would need to be included in the analysis (Greening and Schneider, 2003). However, for this analysis, those potential sources of transportation energy have been excluded.

To illustrate the relative differences between various personal vehicle technologies, Figures 3 and 4 show total costs of each of the technologies for three points in time, 2005, when all of the technologies are assumed to be fully commercialized and available to the consumer, 2025, and 2050. Error bars on the total costs for each technology reflect the uncertainties from a number of sources that have been aggregated into these estimates. Figure 3 focuses on fuel cell technologies, and reflects both private and the externality costs included in this analysis. All of these fuel cell technologies use hydrogen with the exception of reformulated gas fuel cells and internal combustion engines, both using reformulated gasoline, and the hydrogen-fuel cell technologies have the same initial investment costs and same development (i.e., technological change) trajectory. Therefore differences in total costs arise from fuel production costs, and the estimated values for emissions damages and security costs.

Figure 4 provides an overview of total costs for other vehicle options that would be considered as competitors to fuel cells. Once again the costs for an internal combustion engine using reformulated gasoline are provided as a yardstick. And, as with Figure 3, error bars on the estimates provide an indication of the potential uncertainty of the total cost estimates.

Figure 3
Total Costs for FC Technologies in Comparison to Reformulated Gasoline ICE

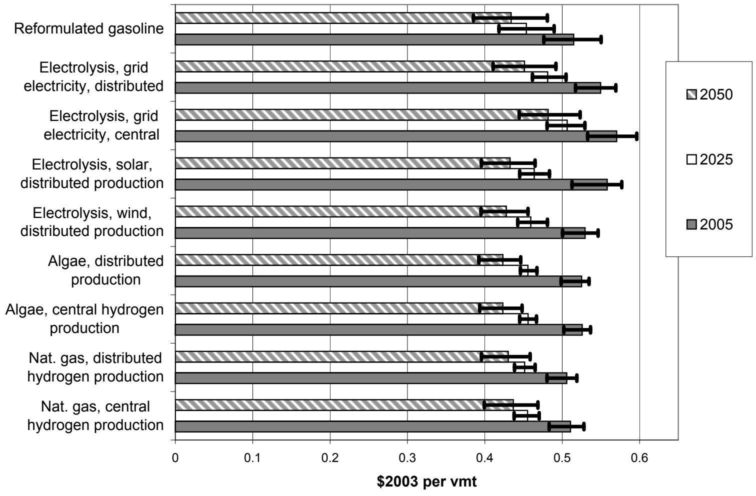
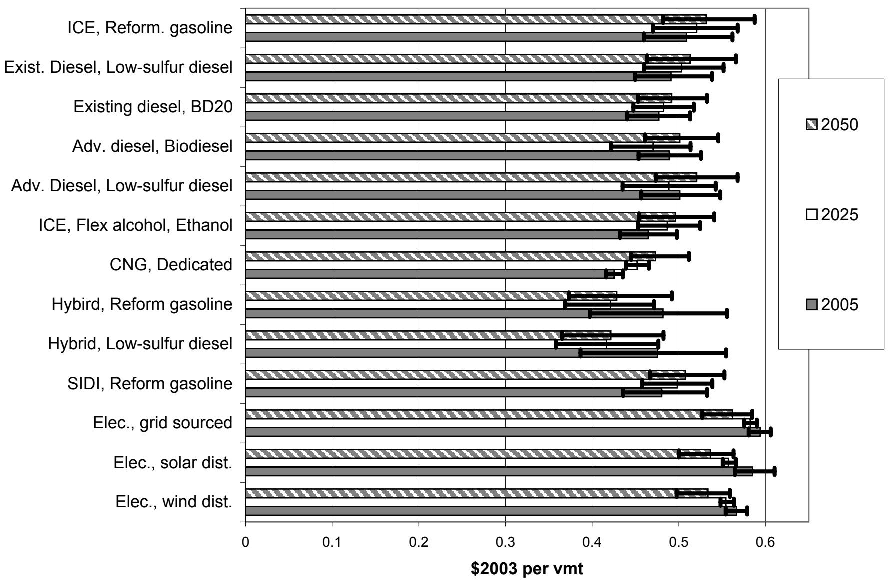


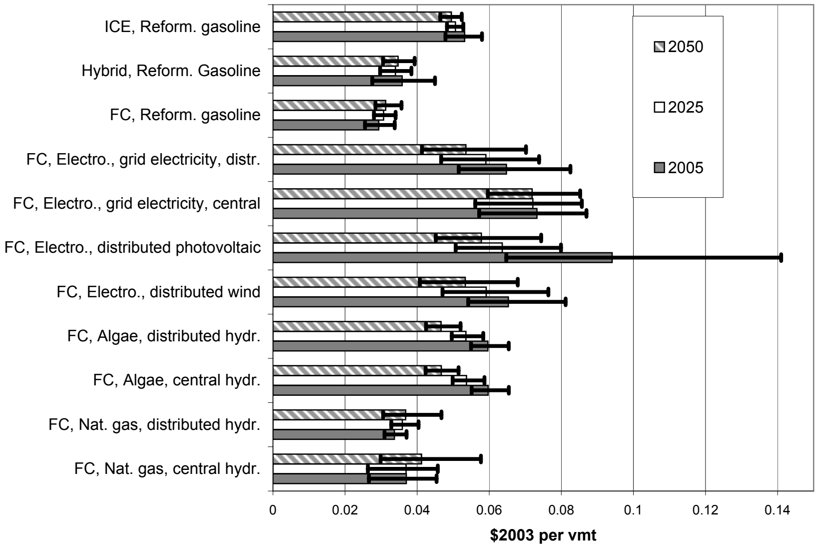
Figure 4
Other Potential Personal Transportation Options



In general as would be expected, gasoline and diesel technologies (existing, hybrid, and advanced diesel) offer a cost advantage on a per vmt basis in 2005. However, as levels of imports increase and uncertainty increases concerning potential prices of petroleum-based fuels, this advantage begins to erode. Even with anticipated increases in fuel efficiency, the potential parallel decreases in costs and improvements in operating efficiencies of renewable-based technologies along with the absence or low levels of emissions damages and security costs begin to assume an advantage. For distributed generation sources of hydrogen, renewable-based sources exhibit substantial declines in cost. These technologies have no or minimal security costs or GHG emissions damages associated with them, thus fewer sources of uncertainty. And, for some of these technologies, during the period 2005 to 2025, actually achieve lower total costs per vmt than petroleum-based options.

Figure 5 provides estimates of the range of fuel costs per vmt for the suite of fuel cell options, along with a hybrid, and an internal combustion engine, both using reformulated gasoline. Error bars once again illustrate the potential uncertainty of these costs either from projected market uncertainty or from production costs (e.g., hydrogen), and the vehicle technology fuel efficiency. All vehicles are assumed to be full-size, although this same evaluation can be performed for other vehicle sizes. Due to the relative uncertainties associated with the technological development of automotive fuel cells (both hydrogen and gasoline), the operating efficiencies of these technologies have been kept constant over the forecast horizon; however, initial costs were projected to decline. Efficiencies for the ICE and hybrid technologies improve slightly over the forecast horizon. All operating efficiencies are varied using a triangular distribution providing for a lower, expected, and upper value; this is an area of further research, and refinement of these assumptions is in progress. Hydrogen production costs with the

Figure 5
Fuel Costs for Selected Technologies



exception of the fuel inputs (e.g., electricity and natural gas) are held constant over the time horizon; however, those costs are perturbed over a range during each time increment. Holding costs constant does ignore the effects of technological change which has played a role in reducing costs for other technologies, and hydrogen production is assumed to be no different. Examination of Figure 5 indicates that fossil-fuel based technologies have the lowest cost per vmt for fuel with the least uncertainty even with the large potential spreads in projected fuel costs. Costs for fuels generated from renewables have the greatest uncertainty, but also the greatest decreases over the forecast horizon.

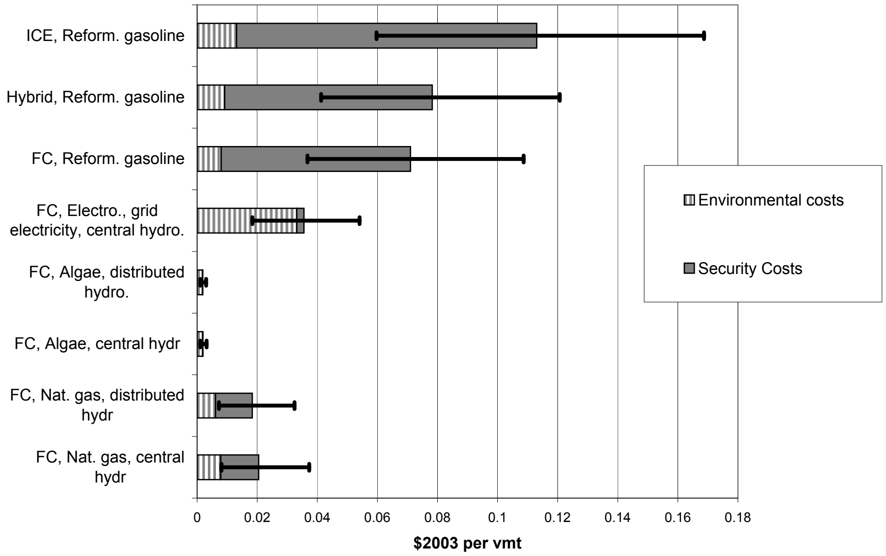
Figure 6 illustrates the potential contribution of environmental damages and security costs to total costs of selected technologies in 2050. Although fuel efficiency is improving for fossil fueled vehicles, those declines are off-set by an increase in the shares of imports expected in our fuel mix. Should shares of imports increase radically above expected levels due to say an incremental demand in natural gas or domestic resources are less than currently anticipated, then this portion of the costs per vmt will increase above these expected levels. Differences in environmental damages between renewable- and fossil-based technologies are readily seen. In the cases of distributed hydrogen production using wind and solar, no environmental or security costs are incurred. Environmental damages are greater for central production due to losses of between 5 to 10% during transmission, and between 4 and 5% from the dispensing of fuel. As a result, approximately 10 to 15% more hydrogen must be produced from central generation in order to provide one unit to the end-user. Depending upon the source of energy used, emissions damages may actually be on par or greater than more conventional petroleum-based vehicle types.

Conclusions, Policy Recommendations, and Comments on Further Work

Given the results of this initial evaluation with uncertainty for various transportation options, the following set of preliminary conclusions seems appropriate:

- If the full costs (private and social) of a vehicle mile were included in the cost per vmt, fuel cell vehicle technologies for some sources of hydrogen are probably competitive with more traditional petroleum-based technologies within the next 10 to 15 years. However, there is a high degree of uncertainty from the initial costs of a fuel-cell vehicle, operating efficiency, and fuel source.
- Uncertainties concerning transportation fuel prices and supplies may very well off-set fuel efficiency gains for petroleum- and natural-gas fueled options. Particularly, as we look further out to the future, previous polices aimed at fuel efficiency may no longer be sufficient to reduce or moderate aggregate demand for these fuels.
- Distributed sources of hydrogen provide a cost and energy advantage through avoiding the potentially costly transmission process with the accompanying energy losses. In other words, during the initial stages of development of the hydrogen economy we will probably jump out of the traditional supply chain. Further, security costs and environmental damage costs are smaller in comparison to fossil energy-based hydrogen generation sources.
- Although carbon sequestration is an option with centrally produced hydrogen, even in 2050, GHG emissions damages constitute only a small proportion of total costs for centrally generated hydrogen from algae (0.43%), natural gas (1.40%) and grid-sourced electricity (6.89%).

Figure 6
Environmental and Security Costs for Selected Technologies in 2050



Therefore, more analysis needs to be done on the tradeoffs between carbon sequestration for carbon from hydrogen generated using fossil fuels against the use of local sources of renewables for generation. The additional energy consumption from central generation of hydrogen may far outweigh the benefits.

- Alternative fuels are not all equal. Fuels such as ethanol and bio-diesel shift environmental burdens from the tailpipe to the "front-end" and can result in higher emissions of methane, a gas with a greater climate forcing capacity. Similarly, the increased use of natural gas either in compressed form or as a feedstock for hydrogen may very well lead to increased dependence on foreign sources, and may only lead to a partial environmental benefit.
- In making choices concerning future transportation options or any energy use for that matter, inclusion of externalities either through valuation or direct physical quantities is a crucial part of the analysis. Without inclusion of these attributes, decisions may be made on an erroneous basis.

For hydrogen development strategies, several insights can be drawn:

- Local sources of renewable energy (wind, solar, and biomass) provide the maximal environmental, energy, and security benefits; and, probably more so then natural gas, may lead to the initiation of the 'hydrogen' economy. As a result, a major emphasis needs to be placed on hydrogen conversion techniques for these resources. The hydrogen R&D program announced by U.S. DOE in October reflects this observation.
- Given the currently large initial costs, the uncertainty on how those costs might decline, the operating characteristics of fuel-cell vehicles and other issues surrounding the use of hydrogen, initial costs for vehicles would need to decline to levels currently found with hybrids for market penetration into fleet markets. Cost declines can be achieved to some extent through R&D. However, drawing on previous experience with alternative fuels, demonstration projects and tax subsidies will undoubtedly be required for wider spread penetration.

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Ensuring the Future Construction of Electricity Generation Plants *(continued from page 18)*

[22] The estimates of the cost of new gas-fired combustion turbines for New York City, Long Island, and upstate New York are $159, $139, and $85 per kW-year (Paynter, ER03-647-000, *op. cit.*, at 22); in New England, the same cost estimates for NEMA/Boston, SWCT, Rest-of-Connecticut, Maine, and Rest-of-Pool are $97.87, $99.16, $96.52, $87.22, and $92.34 per kW-year, respectively (*United States of America, Before the Federal Regulatory Energy Commission, Devon Power LLC, et al., Docket No. ER03-563-030*, Direct Testimony of David LaPlante, at 16).

[23] New York’s electricity consumption is more prone to spikes, which is a reflection of greater population concentrations.

[24] 1.12 times 1.038 is approximately 1.16.

[25] In New England, the level of installed capacity at which price falls to zero is not a parameter in itself, but is instead mathematically determined by the other parameters. (Stoft, *op. cit.*, at 81.)

[26] New York: 1.18 times 1.12 is approximately 1.32; New England: 1.12 times 1.15 is approximately 1.29.

[27] Stoft, *op. cit.*, at 81.

[28] The “target” level of installed capacity in New England is 5.4% above objective capability.

[29] Stoft, *op. cit.*, at 48.

[30] NYISO estimates the expected net revenues that a new combustion turbine would earn, per, year, by selling into the energy and ancillary services’ markets based on the assumption that the electric system is at its minimum capacity requirement. (Paynter, *op. cit.*, at 20.)

Creating a Commercial Environment for Energy Projects *(continued from page 20)*

Conclusion

Each of these “lessons” – and there are, of course, many others - can define a project as having positive economic impacts upon its stakeholders, or signal that the prospective investor should move on to other opportunities.

I am optimistic that the reach of global investment will continue to penetrate the barriers that older generations of managers, politicians and investors have created from their own innate conservatism and arrogance. New generations arising in the transitional economies will not have the restrictive baggage of controlling state environments and will be more nimble, creative and constructive in working with the foreign investors.

I am optimistic, too, that from our side of the world, our own investors, negotiators and entrepreneurs will be more global with their vision and constructive with the energy investment opportunities that the future will present.