

### **III.3 Integrated Assessment of Energy Technologies**

#### **Investigators**

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#### **Background**

The research involved two related areas of examination. The first, “Assessing the Value of New Energy Technologies”, focused on two main tasks:

- Developing ways to represent the performance and costs of new energy technologies at representative years in the future probabilistically with and without GCEP support.
- Develop a prototype portfolio valuation model designed to give a probabilistic representation of the contribution of resources invested in each GCEP program area to the overall value of the GCEP portfolio.

The second, “Modeling the Transition to a Hydrogen Economy”, focused on two main tasks:

- Developing a set of unit costs and unit carbon dioxide emissions associated with various technologies that could be used to supply hydrogen for use in light duty vehicles.
- Modeling several quantitative scenarios of the introduction and growth of hydrogen use in light duty vehicles, examining the consequences for economic and environmental impacts as well as impact on other U.S. natural resource use.

These two related areas will be examined separately in the next two sections of this report, entitled “Results: Assessing the Value of New Energy Technologies” and “Results: Modeling the Transition to a Hydrogen Economy”.

#### **Results: Assessing the Value of New Energy Technologies**

##### Advanced Technology Representation

This task has involved alternative ways of representing the performance and cost of fundamentally new energy technologies with and without GCEP funding. So far this has involved assessments of the probability of demonstrating the technical feasibility of the technology and separate assessments of the probability distributions over the cost of employing these technologies to reduce carbon emissions at future dates of interest. We have experimented with triangular, uniform and lognormal distributions.

Also important in projecting the costs of new energy technologies are projected shifts in the assessed distributions over time and decreases in costs with level of implementation resulting from limits on the rate of introduction diffusion considerations, as well as siting, intermittency of availability, and resource supply considerations. Land use, water use, and noble metal availability are examples of resources whose prices may increase if demand for them increases significantly to support the introduction of new energy technologies.

Obviously these assessments require a great deal of input from technical experts in the areas being assessed. So far we have been using our own somewhat limited expertise in the technology areas together with our strong traditional expertise in probabilistic risk assessment and system economics, but we are starting to interact with GCEP's central systems group and technology assessment staff to bring in their expertise. We hope to involve experts in specific technologies and relevant areas of scientific research here at Stanford and the research community at large in this endeavor. Particularly valuable here will be input from technical experts at the sponsoring companies.

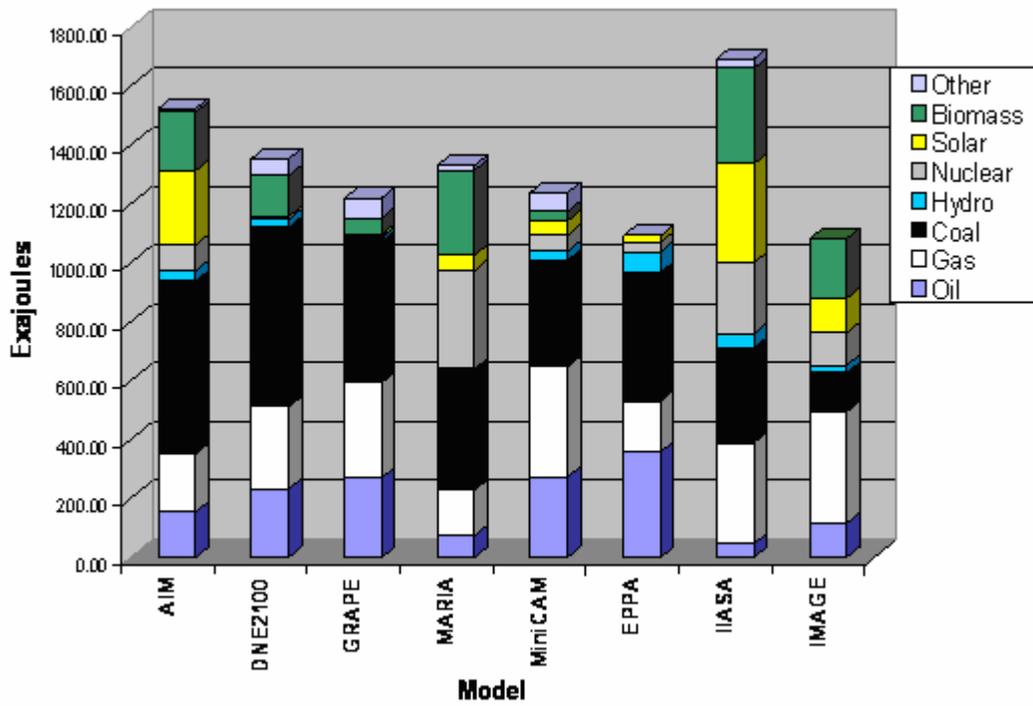
#### Portfolio Valuation

Given information regarding the characteristics of the new energy technologies resulting from R&D (expressed via probability distributions over costs and performance at specific future dates of interest), assessments of the value of that new technology depend on what other new technologies have been developed, the rate of improvement in existing technologies, and conditions in energy markets. Conditions in energy markets are reflected in energy prices and depend on many factors including population levels, economic output, the structures of the world's economies, resource availabilities, energy producer (and especially oil exporter) behavior, the set of available technologies for producing, transforming and consuming energy, and government energy, economic, and environmental policies.

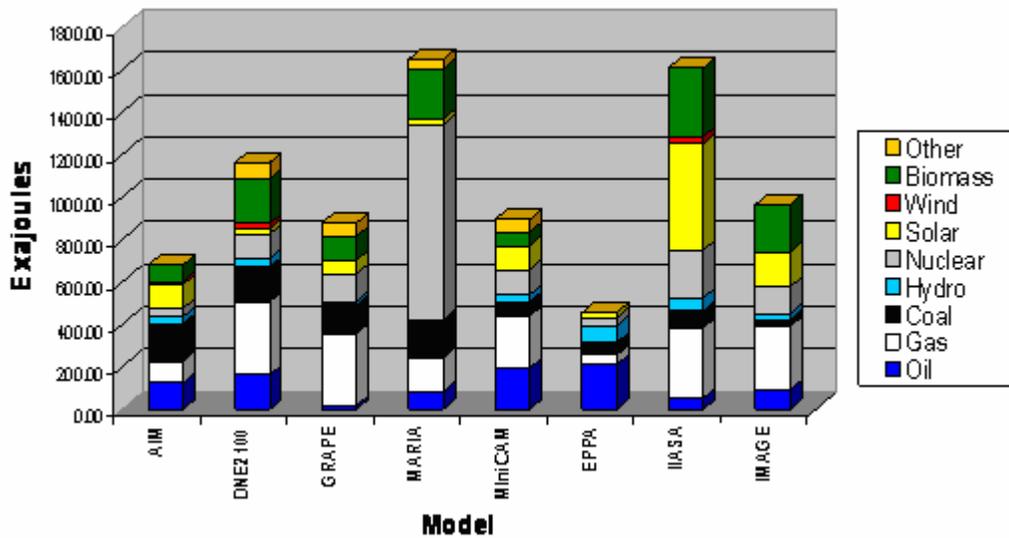
The key factors that determine the future value of new energy technologies are highly uncertain and the relationships between them can be quite complex. One approach to energy policy assessment is to run sensitivity analysis on external factors through models of the energy system. Figure 1 and Figure 2 show the primary energy mix for 2100 projected by a number of prominent large-scale energy models for a reference case (a different modeler chosen reference case for each model) and a case in which the atmospheric concentration of CO<sub>2</sub> concentration in the atmosphere is limited to 550 ppm.

The changes between the two diagrams are motivated by a tax on carbon that starts at about \$10 per ton in the early part of the century and reaches \$200 to \$400 per ton by 2100 (depending on the model and its reference scenario). Results like these are extremely illuminating, but consider only one reference scenario for one set of parameter values for each model. There are extremely large uncertainties about both over the course of a century and these uncertainties can have a significant impact on how we value the products of long-term R&D on new energy technologies.

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**Figure 1.** Reference Case World Primary Energy in 2100



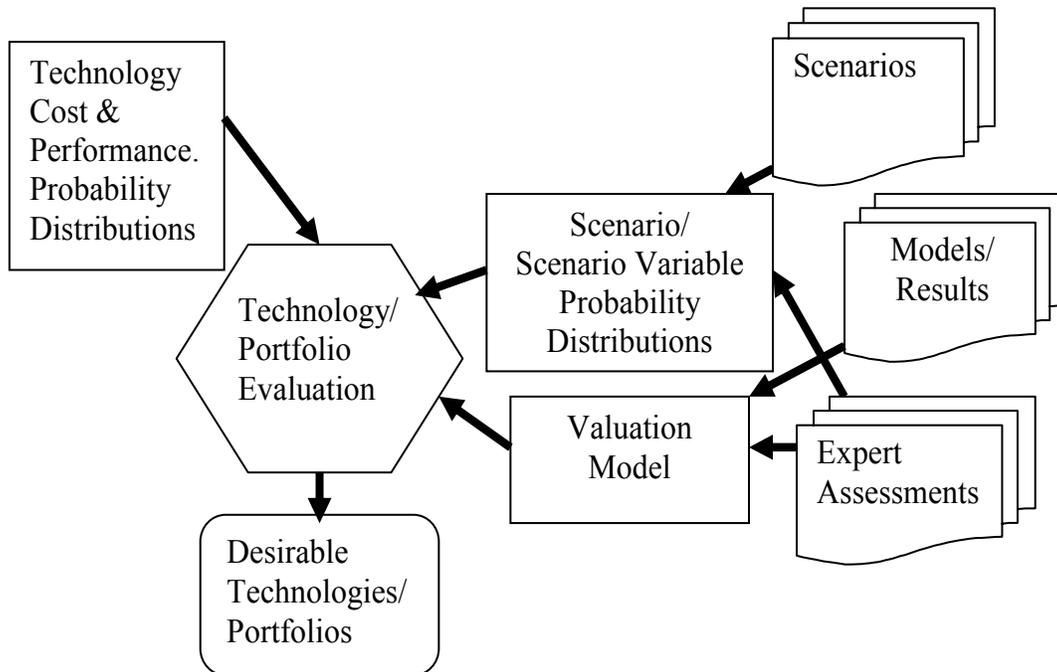
**Figure 2.** World Primary Energy in 500 ppm case in 2100

#### Design Criteria for Evaluation Framework

Last year preliminary design criteria for the evaluation framework were developed.

It was recognized that large-scale energy system models are often designed for purposes other than long-run energy technology assessment and, therefore, include enough complexities so as to make extensive sensitivity analyses, let alone formal uncertainty analyses infeasible. The approach here is to use reduced form energy models (calibrated to the more large-scale models) as the central element of an uncertainty-oriented technology evaluation approach. We expect to use literature reviews and expert assessments to develop probabilities distributions about key inputs to the models. This is crucial because these inputs are generally more important determinants of the values of the new technologies than the parameters included in the models.

Our experience with thousands of energy system scenarios and hundreds of models over the years enabled us to identify the important drivers of the valuation equations and calibrate them to available modeling results. In addition, we know what information to seek via expert assessments, e.g., ranges of possible economic growth rate assumptions, fossil fuel resource base estimates, evolution of conventional energy technologies, oil exporter behaviors, etc. It will take some time to develop the full assessment system. In the interim, rather than working with all the uncertainties independently, we are working with a set of integrated probabilistic scenarios. These scenarios represent a wide range of future states of the world and be mutually exclusive and collectively exhaustive so that probabilities can be assigned to them. This enables us to compute values for the new technologies across a wide range of possible technological and socio-economic futures. Figure 3 shows the key elements of the technology evaluation system.



**Figure 3.** Schematic Diagram of Technology Evaluation Process

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We are designing these scenarios to be as informative as possible about the efficacy of the GCEP R&D portfolio. For example, they range from a (relatively low probability) case where there is no future concern about climate change to one in which (say twenty years from now) where climate change is perceived to be a (relatively low probability, but plausible) much more serious problem than currently expected. In the former case, only a small number of low-/non-carbon emitting technologies (e.g., perhaps advanced-technology combustion engines) will be adopted, whereas in the latter many low-/non-carbon emitting technologies that are more expensive than conventional carbon emitting technologies will be adopted. This comparison illustrates the “option value” associated with the development of new technologies. If new technologies are developed they can be introduced and diffused if they are needed, but kept “on the shelf” (and perhaps put into further development to make them more economical) if they are not needed.

The valuation model will also evolve over time from a simple two sector, five region specification with sensitivities on parameter values to a more sophisticated system with greater detail and inputs calibrated to more complex models, estimated from primary data and/or obtained via expert assessments. Uncertainty about the cost and performance of the technology being evaluated, and of the technologies with which it might compete are initially being represented by sampling from probability distributions over those characteristics. Over time more sophisticated ways of incorporating the actual probability distributions into the analysis will be adopted, and the R&D effort will be broken down into stages reflecting the logical technical challenges that need to be met to bring the technology to fruition as well as the option to improve it over time. This information will allow us to look at the optimal R&D portfolio more fully as a sequential decision making problem over time where stages of the R&D on a particular technology may be pursued with subsequent stages either canceled or accelerated depending on how the energy system and the climate problem evolve.

Finally the technologies are to be evaluated in groups in hopes of finding the most valuable portfolio(s) of technology options given the uncertainties about technology costs and performances, scenario variables, and valuation model parameters. Here we will consider using the whole portfolio as a hedge against future uncertainties as well as using individual elements of the portfolio as hedges against lack of technical or economic success in the other elements of the portfolio.

#### Prototype Valuation Framework

This year we have worked on putting together a prototype valuation model. Although this model is not quite yet ready to be used in the technology assessments, the basic structure seems workable, developing it has revealed a number of challenges that will need to be met to develop a more useful, and some basic insights can be illustrated semi-quantitatively. We start with information regarding the characteristics of the new energy technologies resulting from R&D (expressed via probability distributions over costs and performance at specific future dates of interest as described above). Assessments of the value of that new technology depend on what other new technologies have been developed, how fast existing technologies are improved, and conditions in energy

markets. Thus, these evaluations require a type of “integrated assessment” of all technologies under all possible market conditions. The basic approach pursued in the design of the prototype evaluation system has been initially divide the world up into two parts: (1) what the GCEP Portfolio can provide in terms of supplies of carbon energy substitutes at various price levels, and (2) what the world might demand of this portfolio under a wide range of future energy market futures. Obviously both the technology assessments and market assessments are very complex and highly uncertain.

The preliminary assessment systems starts with a highly simplistic and aggregate representation of key elements, but is designed in a way to which more detailed information from any source can easily be added as necessary (in modeling parlance this framework has been designed to be highly scalable). The value of each individual GCEP research program is evaluated in terms of its contribution to the value of the whole GCEP portfolio which is in turn evaluated in terms of its contribution to key energy sectors in key world regions in the future. A globally aggregated version of this framework is described here in some detail, followed by a description of the level of geographical and sectoral disaggregation, and dynamics currently being incorporated in the prototype assessment framework.

The simplest aggregated version of the framework looks at the GCEP enabled supply and rest-of-world demand for non-carbon energy at various future dates of interest. The supply side of the framework consists of the collection of stochastic GCEP R&D program supply curves described above. Initially these consist of a single subjective probability of technical success of the program and a probability distribution over the cost of employing the new technology commercially.

The demand for non-carbon energy takes into account possible future conditions in the global energy system including the implications of alternative fuel price scenarios, improvements in non-GCEP technologies (through learning over time, with respect to non-GCEP R&D funding, and with respect to cumulative experience), critical materials or infrastructure constraints on the rates of new technology adoption, economic growth rates, structural changes in the global economy, and government policies including those directly related to climate change. Forecasting how all these factors will work towards creating a market for advanced non-carbon technologies is extremely complicated and highly uncertain. But it is just this wide range of possible outcomes that can create a very large value for advanced technology development.

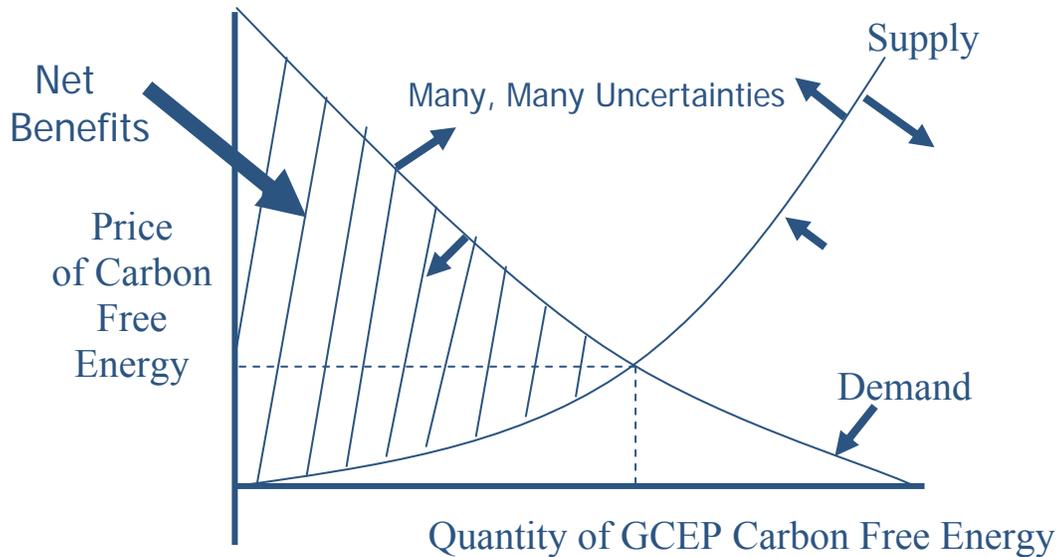
Conceptually one could construct these demand curves for non-carbon energy by taking any of the leading global energy models and for one set of model parameters, one set of model drivers and one set of policies and add a fictitious source of non-carbon energy at a very low price and observe the demand for it, subsequently increasing the price again and again until none is demanded. In this way a demand curve for non-carbon energy for one model implemented state of the world could be developed. Since the focus of GCEP is on long-run pre-competitive R&D to help prepare for a very wide range of future states of the energy system it would be cumbersome and probably infeasible to run a large-scale model thousands of times to develop the demand side of

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the framework. In addition, large-scale models may impose too much structure on the world energy system to be appropriate for this task. Thus, we start with very aggregated energy system models which can be calibrated to the existing set of large-scale energy models, but also take inputs from a number of other sources including relevant empirical work and expert opinion. This information is also integrated into uncertainty representations (i.e., probability distributions) for demand factors that are similar to the new technology supply uncertainty specifications described above. Given probability distributions for the demand for non-carbon energy in the future and for the supply of each technology included in the GCEP portfolio, stochastic simulation techniques are used to generate thousands of possible supply demand equilibria each including a level of contribution by each technology in the portfolio.

There is a wide range of net benefit measures that could be used to quantify the benefits of the GCEP portfolio for each supply and demand realization. One frequently used metric that is convenient for illustrative purposes here is the increase in net surplus to the economy resulting from the new technologies. For simple supply and demand curves such as those shown in Figure 4 the net surplus gain can be computed as the area under the demand curve less the area under the supply curve. The area under the demand curve represents the total value of the new technologies to consumers and intermediate goods producers while the area under the supply curve represents the total draw on societal resources required to produce the alternative energy. Net surplus is maximized at the point where supply equals demand (also known as the market equilibrium) because to the left of the point the marginal area under the demand curve exceeds the marginal area under the supply curve and that relationship reverses to the right of the market equilibrium point. Using the net benefits triangle is thus easy to calculate the net benefits of the GCEP portfolio for one particular set of technology outcomes and one particular future state of the world energy system. Given the complexities and uncertainties involved though this set of calculations might need to be repeated thousands to millions of times to capture the effect of the full range of outcomes.

Initially this capability will be implemented through Monte Carlo Simulation in which each probability distribution is sampled through the use of appropriate random number generators. For example if an R&D project on a new technology has a .2 chance of demonstrating the technical feasibility of a new carbon free energy technology, a random number between 0 and 1 is generated and the technical demonstration is assumed to be successful if that number is .2 or less and unsuccessful otherwise. Then the cost of the new technology is determined by another random draw used to pick an outcome corresponding to that probability number in the cost distribution for that technology. For example, if .5 is drawn the mean of the probability distribution over future costs is selected. The process is repeated over all the uncertainties many times over to generate probability distributions over various output measures, including the net benefits of whatever portfolio is being analyzed.

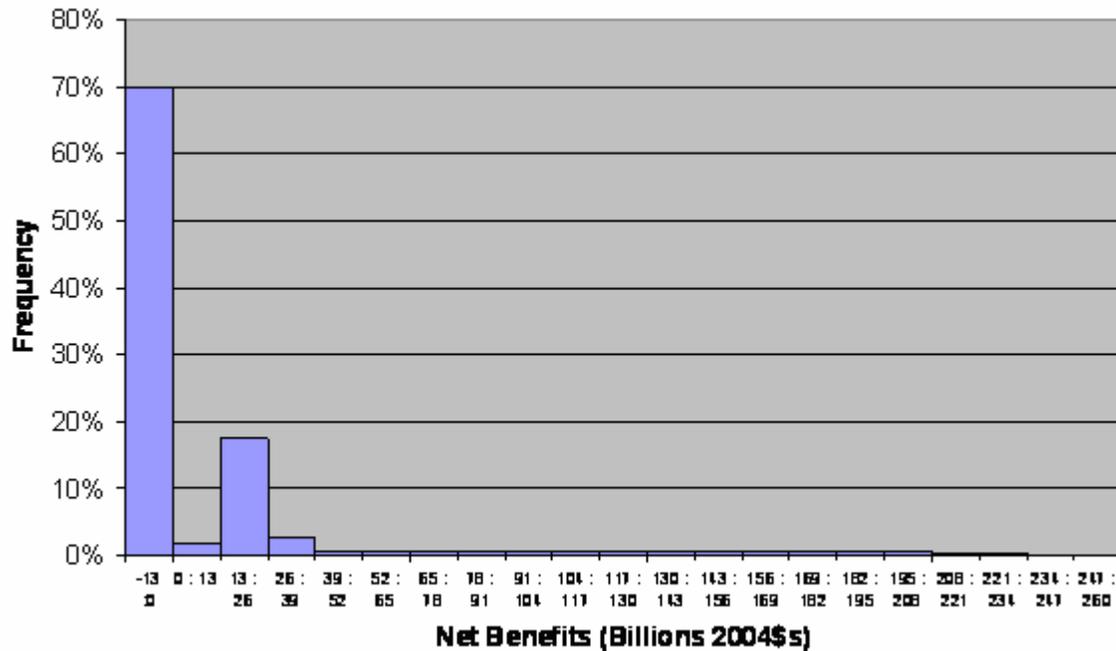


**Figure 4.** GCEP Technology Assessment A Simplified Example

As a simple example of this methodology consider the case where world energy demand is aggregated and there are only four technology areas in the GCEP portfolio – solar, wind, biomass and carbon sequestration. The distribution of benefits for the solar technology alone is shown in Figure 5.

Although the most likely level of benefits for this technology is slightly negative (i.e., R&D expenditures and no benefits) reflecting an assumed probability of technical success of .3, there is a substantial probability of annual benefits of \$20 Billion per year and relatively small probabilities (tenths of a percent) for benefits all the way up to about \$250 Billion per year. These very large benefits occur when the cost of the new technology is very low and the demand for it very high because of, e.g., high baseline carbon emissions, high fossil fuel prices, poor success in the develop of other alternative sources of energy by GCEP or anybody else, and a high policy induced financial penalty on carbon emissions.

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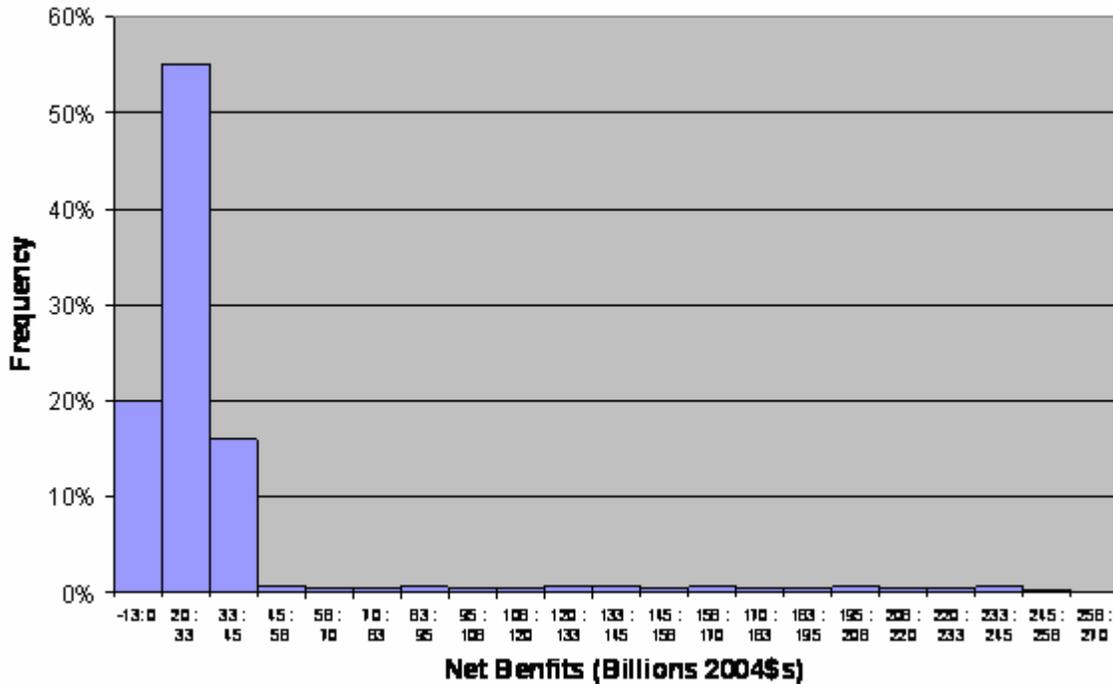


**Figure 5.** Net Annual Benefits of GCEP Solar Technology R&D Program, Circa 2040

Figure 6 shows results for another example portfolio consisting of solar, wind, biomass, and carbon sequestration technology research programs. This collection of technology programs is referred to as a “mini” portfolio because although it includes 4 technology programs they are drawn from only 2 of the 11 GCEP areas. Here the payoff is higher but not dramatically higher because this is substitution between the payoffs of the different elements of the portfolio. There is also much less chance of a negative payoff which results from diversification: that is, the probability of all four technologies proving to be technically infeasible (about .2) is much less than any individual technology program proving to be infeasible. Finally the probability of very large benefits is larger (about .5 to 1.0% for annual benefits \$240 Billion or more) as it is better to have two or more chances at a technically feasible and relatively low cost carbon free technology than only one when the demand for carbon free energy is high due to fuel market conditions and public policies.

#### A More Realistic Prototype Framework

Although useful for illustrating the basic concepts of the technology evaluation framework, the highly aggregated system described above, it is not very realistic because it ignores important regional and sectoral characteristics as well as the dynamics of new technology introduction and diffusion that can have significant impacts on the value of the GCEP portfolio. However, detail needs to be added to the system carefully and only in ways that focus it better on the assessment objective.



**Figure 6.** Net Annual Benefits from GCEP Mini-Portfolio

The current prototype divides the demand and supply of non-carbon energy into two sectors – electricity generation and transportation and five regions – US, Europe, Japan, China and India. We may include “other sectors” and “rest of the world” categories, but even that may not be necessary to pick up most of the portfolio benefits. In this implementation we also able to incorporate more realistic representations of technology dynamics and resource supply effects.

**Results: Modeling the Transition to a Hydrogen Economy**

This year’s work in micro level analysis of technologies focused entirely on models designed to examine implications of a possible transition to a hydrogen economy, or more precisely, of a transition to using hydrogen in place of gasoline as fuel for light duty vehicles. This modeling and analysis was developed jointly for GCEP and for the National Research Council (NRC) “Committee on Alternatives and Strategies for Future Hydrogen Production and Use”. This work was incorporated in the National Academies’ recently published study: *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*.

A complete draft of the National Academies’ study is currently available online at [www.nap.edu](http://www.nap.edu). A final version of the report will be published and available at that site once the line editing has been completed and the document has been typeset. In this technical report we summarize some of the modeling and analysis developed jointly for

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GCEP and the National Academies' study. It should be noted that this modeling and analysis included intellectual contributions by all members of the NRC committee and by its consultants, in addition to the contributions by James Sweeney.

#### The Modeling and Analysis: Summary of Methods

The goal of the modeling and analysis was to develop insights into the implications of moving to hydrogen as fuel for light duty vehicles. But there are still many technical, institutional, regulatory, and economic barriers to the use of hydrogen as an automotive fuel. This modeling and analysis is based on explicit assumptions that an aggressive research and development effort is successful in reducing the costs of proton exchange membrane (PEM) fuel cells, is successful in solving the challenge of on-board storage of sufficient quantities of hydrogen, is successful in developing safety and other regulatory standards. The analysis is based on the assumption that, as a result of the R&D and of the regulatory progress, the total production and maintenance costs of fuel cell vehicles becomes equivalent to that of hybrid vehicles fueled by gasoline, or that any additional costs of such vehicles is matched by increased functionality that vehicle purchasers would find attractive enough to compensate for the additional production and maintenance costs. The work conducted for GCEP does not make a judgment about whether the R&D will be so successful, but rather provides analysis of the implications of such successful R&D.

The modeling and analysis started with mathematical models which build up estimates of the unit costs (costs per kilogram of hydrogen) that could be expected for the various hydrogen-supply technologies. These models are designed to estimate unit costs of the production, transportation, and dispensing of hydrogen for use in automobiles. These models incorporate estimates of the major components of cost, including the capital depreciation and amortization, feedstock costs, costs of electricity or other energy inputs, costs of separating carbon dioxide from the gas stream, costs of sequestering carbon dioxide, and operations and maintenance costs. Consistent assumptions about economic conditions, interest rates, electricity costs, and carbon prices (if any) are used across the various technology estimates. These models were first developed by SFA Pacific to be used by the NRC committee. They were subsequently modified as a result of deliberations by the NRC committee members.

The unit cost models are available in two versions. The first includes estimates of costs that would be incurred if current technologies were utilized. The second version includes estimates of unit costs, conditional upon technological advances. The latter version depends on the technological judgments of the members of the NRC "Committee on Alternatives and Strategies for Future Hydrogen Production and Use".

Linked to this the first group of unit cost models are models designed to examine the quantitative impacts of various technologies if successful. Currently the primary such model is a relatively simple vintage capital representation of automobile use of fuels. The model uses as inputs the assumed fractions of new vehicles in any future year which would be fueled by hydrogen and the assumed fractions of new gasoline-powered vehicles that are hybrid vehicles or conventional vehicles. This model then keeps track of

the projected number of vehicles produced in any year, the capital stock of automobiles from the various vintages, the average fuel efficiency of each vintage, the fraction of vehicles from each vintage that would be fueled by hydrogen as opposed to gasoline, the assumed differential fuel efficiency of new hydrogen vehicles, the growth of vehicle miles traveled, and the resulting consumption of hydrogen and gasoline.

In addition, these consumption estimates have been combined with estimates of carbon dioxide emissions from gasoline-based consumption and the carbon dioxide emissions from the various hydrogen-producing technologies in order to estimate how implementation of various hydrogen production technologies might decrease or increase the emissions of carbon dioxide into the atmosphere and the quantities out of carbon dioxide sequestered.

Similarly, based on estimates of the unit cost of producing hydrogen from various technologies, the model are used to provide quantitative estimates of changes in the total cost of fuel for vehicles, conditional on implementation of the various hydrogen-production technologies. For the NRC study, these unit costs are based on the unit cost models described above.

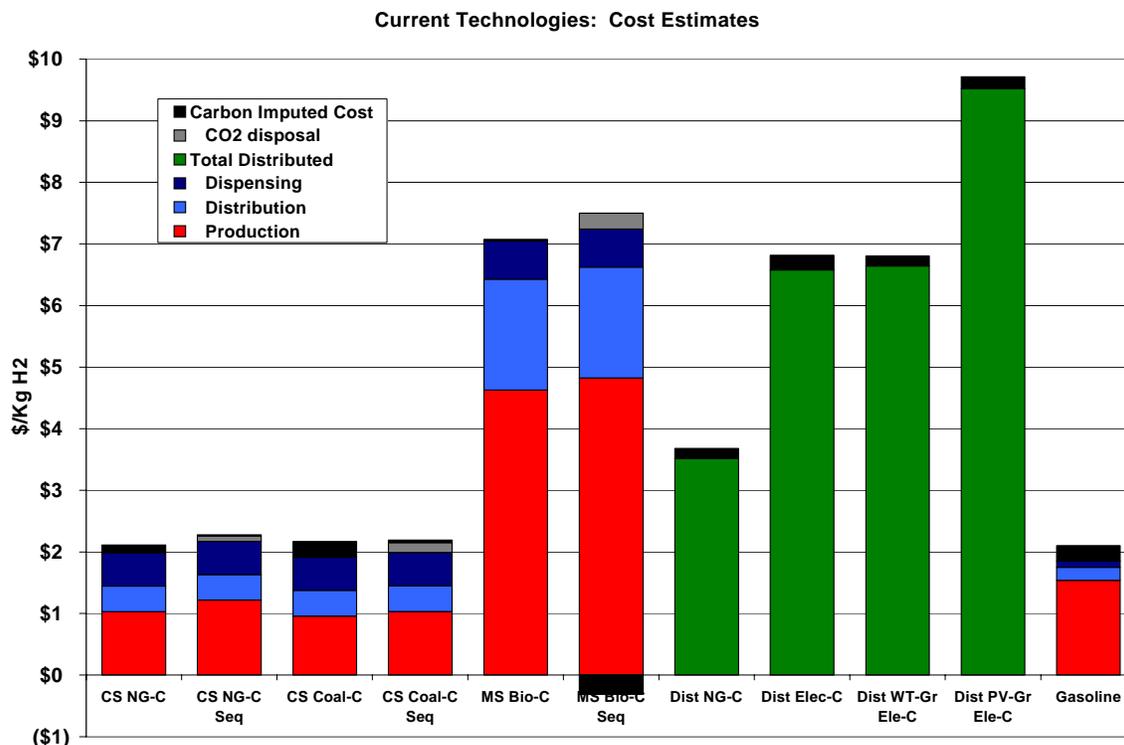
Finally, these models are used to estimate quantities of other resources that would be used to produce the hydrogen. Estimates currently have been developed for use of natural gas, coal, and land, conditional on various technological pathways for hydrogen production. In addition, for scenarios in which carbon dioxide is separated and sequestered, the annual quantities and cumulative quantities of sequestered carbon are estimated.

#### Results Included in the National Academies' Hydrogen Study

In what follows are graphical summaries of results of the modeling and analysis, as included in the National Academies' recently published study: *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. The interested reader can read more detailed discussions of these results in that study, currently available online at [www.nap.edu](http://www.nap.edu).

Figure 7 shows the estimated unit costs of the various technologies, based on currently available state of technology. The heights of the bars represent the unit costs, expressed as dollars per Kg of hydrogen. The four bars on the left are all central station technologies (CS), large enough to produce 1.2 million Kg of hydrogen per day, roughly enough to fuel 2 million light duty vehicles from each such plant. Two use coal as a feedstock (Coal) and two use natural gas (NG). For one coal and one natural gas technology carbon dioxide is separated and sequestered (Seq); for the other two technologies carbon dioxide generated during the production process is vented into the atmosphere (No label). The two bars in the center are all mid-size (MS) technologies, large enough to produce 24,000 Kg of hydrogen per day, roughly enough to fuel 40 thousand light duty vehicles from each such plant. They use biomass (Bio) as a feedstock, which is gasified for producing hydrogen.

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**Figure 7.** Unit Cost Estimates for Currently Available Technologies

The next four bars are distributed (Dist) technologies, large enough to produce 480 Kg of hydrogen per day, roughly enough to fuel one thousand light duty vehicles from each such station. The first of these distributed technologies is a small reformer, using natural gas as a feedstock. The other three use electrolyzers, in which electricity is used to dissociate water, producing hydrogen and oxygen. One of these three is based on electricity taken from the grid; such electricity is represented as being generated by mix of primary energy sources typical of the U.S. grid. The second is based on two sources of electricity: electricity is generated from wind turbines (WT) during the time sufficient electricity is available from these turbines; electricity is taken from the grid at all other times. The third is also based on two sources of electricity: electricity is generated from photovoltaic (PV) cells during the time sufficient electricity is available from these PVs; electricity is taken from the grid at all other times<sup>1</sup>.

The final bar represents gasoline, expressed in a per-mile hydrogen-equivalent basis. This bar represents the cost to produce enough gasoline to drive one hybrid vehicle the same number of miles as a fuel cell vehicle can be driven using one Kg of hydrogen. In this discussion, that will be referred to as the “per-mile hydrogen equivalent” gasoline cost. This gasoline cost is based on nation-wide U.S. estimates, for crude oil prices of

<sup>1</sup> We also examined electricity derived entirely from wind turbines or from photovoltaic cells, not using grid electricity as a backup. However, these would require substantially larger electrolyzers, since the electrolyzer would be operating only a small fraction of the time. The increased capital cost of the larger electrolyzer leads to significantly greater unit costs than those pictured in this graph.

\$30 per barrel. This estimate is very sensitive to the assumptions about the future price of crude oil.

In Figure 7, five different components of costs are presented for the central station and the mid-size technologies: production, distribution by pipeline or truck, dispensing, CO<sub>2</sub> disposal (sequestration), and “carbon imputed cost”. The “carbon imputed cost” is an estimate of environmental cost of carbon dioxide release, based on an assumed environmental cost of \$50 per tonne of carbon. However, for the distributed station, the production and dispensing cost are modeled as being part of one integrated operation; there is no distribution cost because the hydrogen is produced on site. Thus only the total distributed cost and the “carbon imputed cost” are included for these technologies.

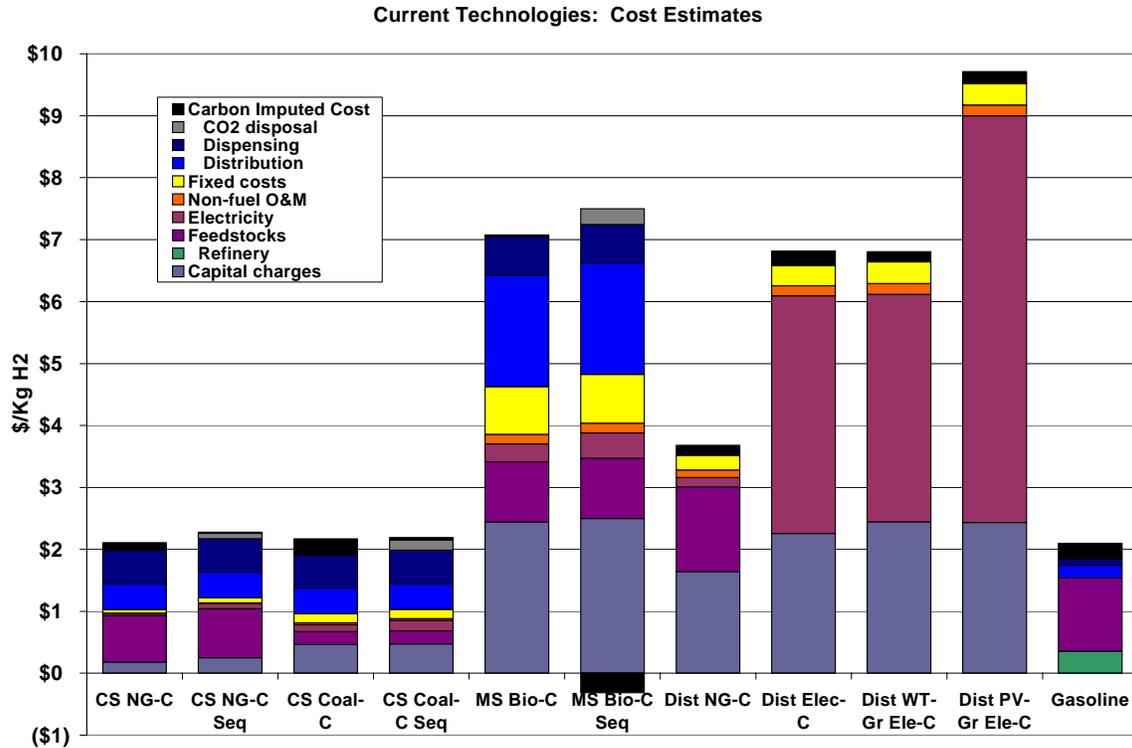
Figure 7 indicates that even with current technologies, if the U.S. were to have large enough hydrogen production plants, it would be possible to produce hydrogen using either coal or natural gas as a feedstock, at delivered unit costs that would be very similar to unit costs (on a per-mile hydrogen equivalent basis) of using gasoline in hybrid vehicles. This implies that if the challenges of producing fuel cell vehicles were solved, so that these vehicles had production and maintenance costs equivalent to these costs for hybrid vehicles, then at a large scale of hydrogen production the fuel costs for fuel cell vehicles would also be very similar to fuel costs for hybrid vehicles. Thus such vehicles could be competitive with hybrid vehicles.

Figure 7 also indicates that unless technologies are improved from the current technologies, hydrogen produced from renewable energy or by electrolyzing water would be substantially more expensive than hydrogen produced from fossil fuels.

More detailed cost estimates are shown in Figure 8 for the same current technologies. In this figure, the production costs are further broken down into several cost components: capital charges, feedstock costs, electricity cost, non-fuel operations and maintenance (O&M) and fixed costs. These categories are also shown for the distributed hydrogen production technologies.

Figure 8 shows that for hydrogen generated using electrolysis, the cost of electricity is the most important cost element, followed by capital costs, primarily capital costs of electrolyzers and of storage facilities. Capital costs are large components of the cost of biomass. In addition, distribution costs of these mid-size facilities are large, since distribution by pipeline increases sharply on a per-unit basis for these smaller facilities. Distribution by truck seems to be the lowest cost option.

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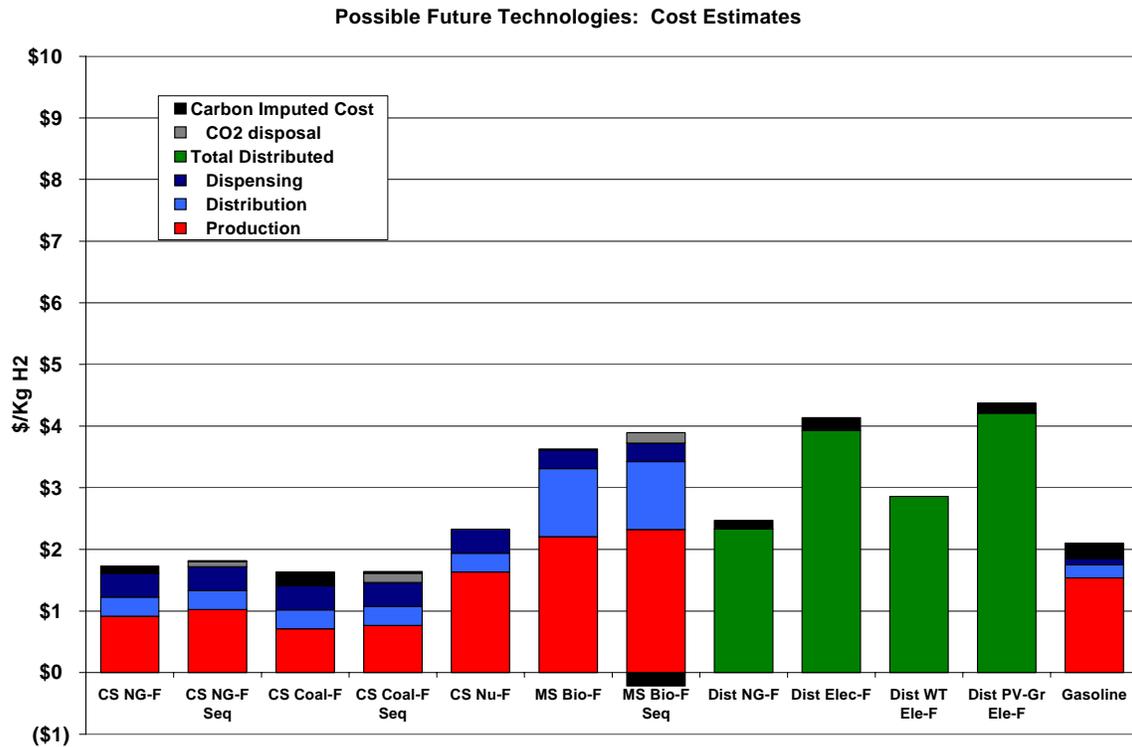


**Figure 8.** Details of Unit Cost Estimates for Currently Available Technologies

We have developed similar cost estimates for potential future technologies. These estimates were based on the technical judgments by the members of the NRC “Committee on Alternatives and Strategies for Future Hydrogen Production and Use”. They are meant to represent moderately optimistic judgments about the improvements in these technologies, if an aggressive R&D program is directed toward the technologies and is successful. Figure 9 presents these cost estimates, using the same scale as used in Figure 7. Only one new technology is introduced: nuclear energy (Nu) in a reactor run at high enough temperatures to cause direct dissociation of hydrogen from oxygen in water.

Figure 9 shows that with technological advances, hydrogen could be generated from fossil fuels, distributed, and dispensed to the consumers at costs lower than the costs of gasoline (with \$30 per barrel crude oil prices.) Cost of hydrogen from wind-turbines, from distributed natural gas reforming, and from nuclear power would be more expensive than gasoline costs, but not very much more expensive.

The potential future generation of hydrogen by electrolysis, using wind turbines for the electricity is based on the wind turbines being used to provide all of the electricity. If the cost of fuel cell stacks drop sharply, then costs of electrolyzers are likely to drop sharply as well. Such a change would make low quality, intermittent electricity economically attractive for electrolysis: it would be more economical to invest in large electrolyzers and to use them only when the wind turbines are generating electricity.



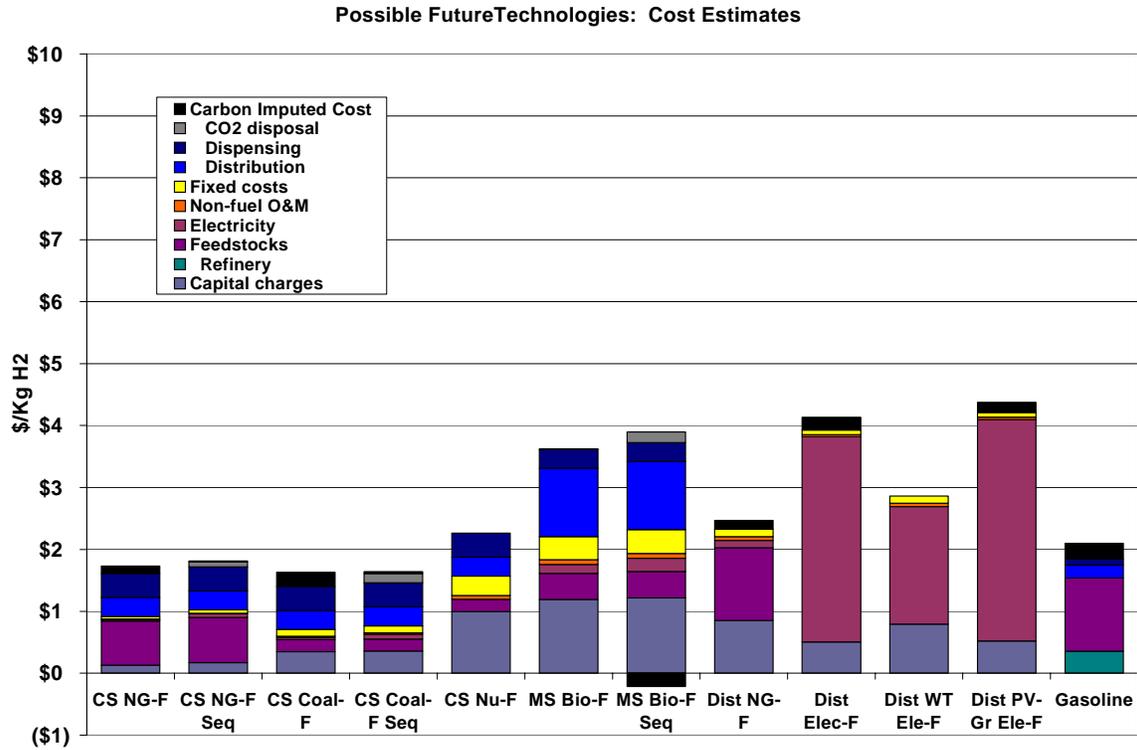
**Figure 9.** Unit Cost Estimates for Possible Future Technologies

Gasification of biomass and electrolysis from grid-derived electricity or from photovoltaics is expected to be substantially more expensive, even with the technology advances we have postulated.

More detail on these cost estimates is provided in Figure 10. This figure shows that the high cost of electricity is expected to be the dominant factor in the unit costs of electrolysis-based hydrogen production. It shows that the high costs of distribution of hydrogen from mid-sized plants is a key factor, but not the only factor, in the high unit costs of biomass gasification. This suggests that methods of reducing this cost, say through a network of pipelines that could connect mid-sized plants could significantly reduce these cost estimates.

Additional discussion of these cost estimates is provided in the National Academies' recently published study: *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*.

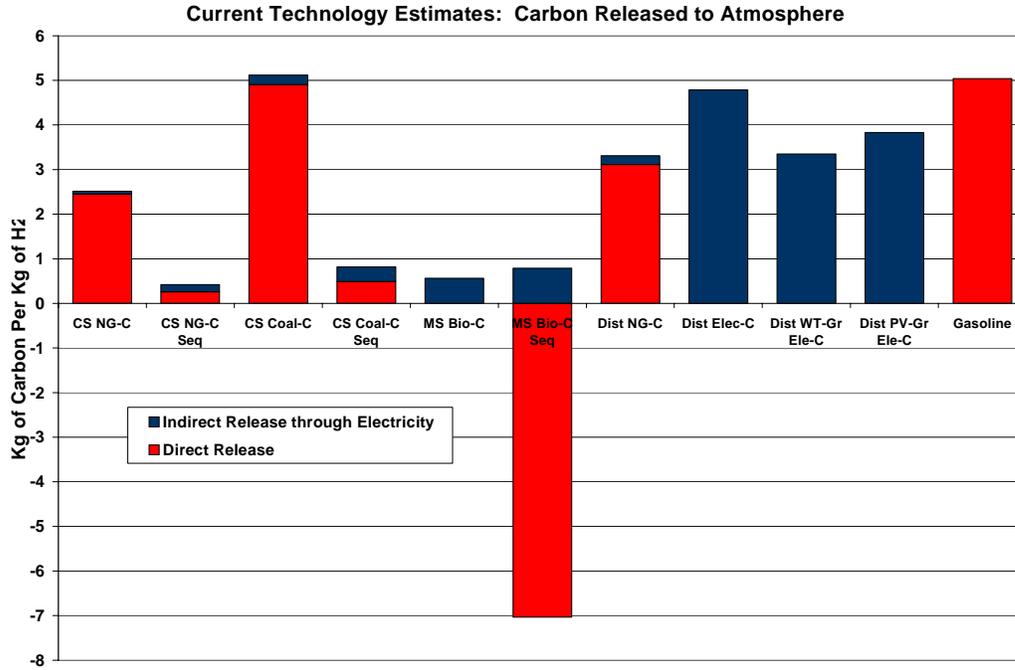
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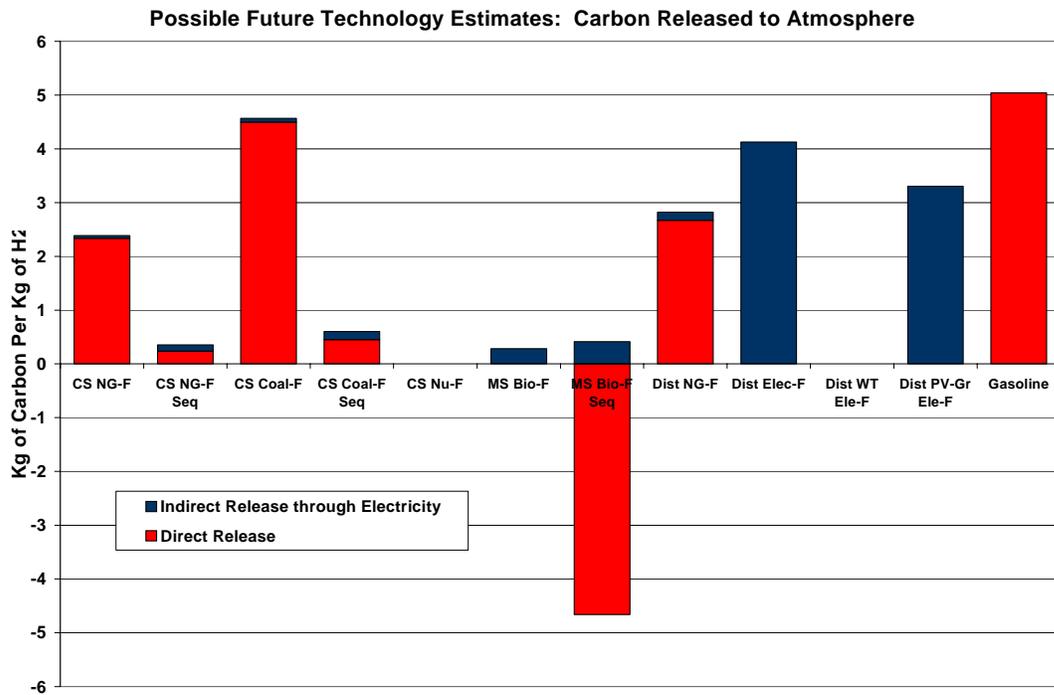
**Figure 10.** Details of Unit Cost Estimates for Possible Future Technologies

Unit estimates of carbon releases into the atmosphere from light duty vehicles are provided in Figure 11 for currently available technologies and in Figure 12 for possible future technologies.

These graphs suggest none of the technologies would increase the unit emissions of carbon dioxide into the atmosphere above the amounts that would be associated with use of gasoline in hybrid vehicles. Technologies involving capture and sequestration of the carbon dioxide could sharply reduce the unit releases of carbon dioxide. Generation of hydrogen through electrolysis could reduce unit emissions, but for current technologies the reduction would not be very large. However, with potential future technologies, use of wind turbines could reduce emissions to zero, since in this case no grid-based electricity would be used. Use of natural gas could reduce emissions, but again, not by large amounts, absent carbon dioxide sequestration.



**Figure 11.** Unit Estimates of Carbon Releases for Currently Available Technologies



**Figure 12.** Unit Estimates of Carbon Releases for Possible Future Technologies

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Biomass technology is particularly interesting from a carbon management perspective, if the carbon dioxide is separated and sequestered when the biomass is gasified. In that case, only a very little carbon dioxide would be released into the atmosphere at the point of gasification. None would be released at the point of use. However, growing of the biomass would take carbon dioxide out of the atmosphere. Most of this carbon dioxide would be sequestered. Thus, on net, use of biomass could reduce the amount of carbon dioxide: on net it could lead to negative emissions of carbon dioxide, if the carbon dioxide were separated and sequestered.

The unit estimates discussed above were incorporated into a vintage capital model of the light-duty vehicle evolution over time in order to create several quantitative scenarios of the introduction and growth of hydrogen use in light duty vehicles. We turn now that that discussion.

As discussed above, the analysis assumes that the maintenance and production costs of fuel cell vehicles can be made equivalent to the costs of hybrid vehicles. In order to meet this end, fuel cells would need very large improvement from their current state. In particular, it would be necessary to meet cost targets for the fuel cell stack of about \$50 per KW. The stacks would need much longer lives than is now the case, on the order of 4,000 to 5,000 hours of operation over the normal lifetime of a passenger car. On board storage of hydrogen must be improved in order to provide an adequate range between refuelings, on the order of 300 miles. In what follows, in some scenarios we assume all these goals have been met.

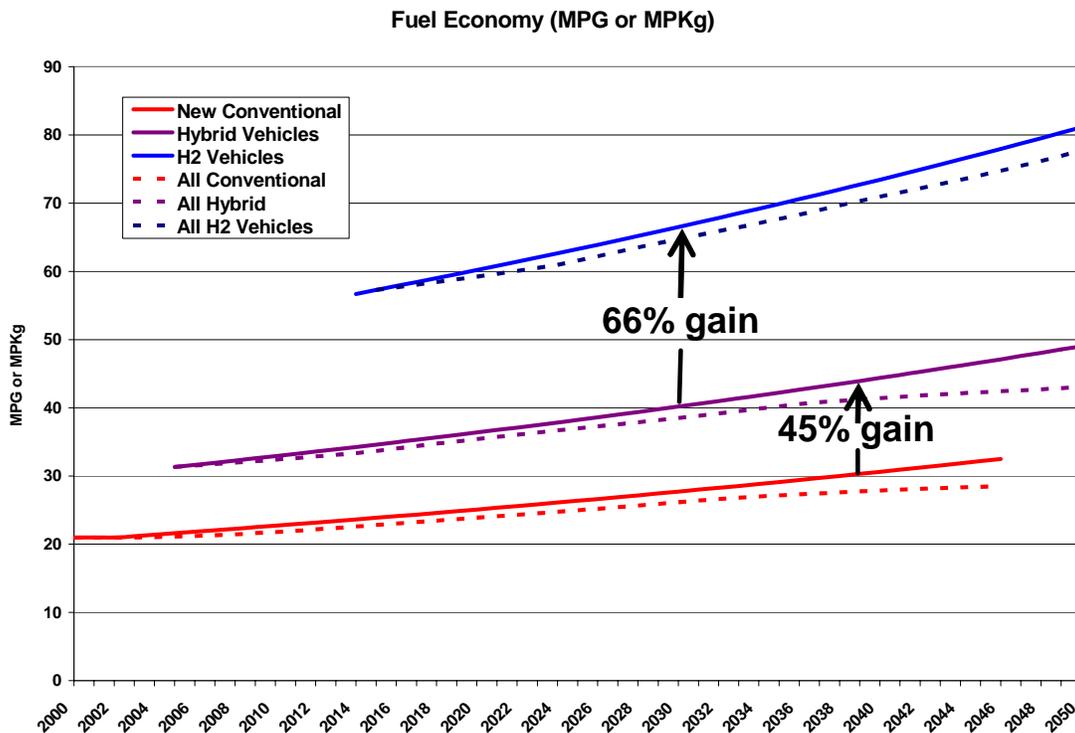
We have developed three scenarios in order to estimate quantitatively the impacts of fuel-cell vehicles. The first scenario, perhaps the most unlikely, is one in which the goals are not met, so that hydrogen vehicles are never introduced in large scales. In addition, in this scenario hybrid vehicles never command a large market share, so that almost all of the vehicles remain conventional gasoline-fueled light duty vehicles.

The second scenario is also one in which the goals are not met, so that hydrogen vehicles are never introduced in large scales. But in this scenario hybrid vehicles grow steadily in market share, ultimately replacing all conventional vehicles.

The third scenario is one in which the fuel-cell vehicle goals are met and hydrogen progressively becomes the dominant fuel for light duty vehicles. In this scenario, hybrid vehicles first replace conventional vehicles over time; then H<sub>2</sub> vehicles replace hybrid vehicles. The number of conventional vehicles follows same time trajectory whether or not hydrogen vehicles are successfully introduced.

The second and third scenarios allow the comparison between a successful introduction of hydrogen fuel cell vehicles and no successful such introduction. The first scenario provides a baseline for projections of the current system.

The analysis depends on assumptions about the changes over time in the fuel efficiency of the three types of vehicles. We assume that in each scenario the fuel efficiency of conventional vehicles again begins grow. We assume that hybrid vehicles have a 45% gain in fuel efficiency over conventional vehicles and that fuel cell vehicles have a 66% gain over hybrids. Figure 13 shows the assumed fuel efficiencies over time, measured in miles per Kg of hydrogen or miles per gallon of gasoline, of the fleet of new light duty vehicles. Note that these estimates include not just small vehicles, but a mix of differing weights and sizes of light duty vehicles.

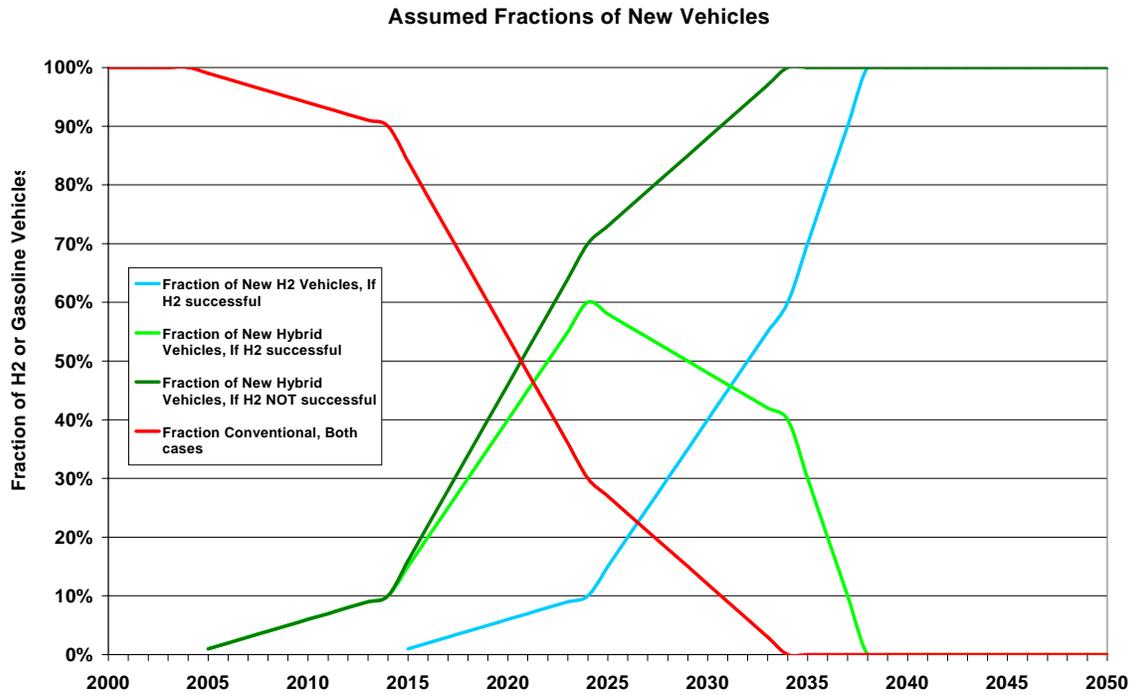


**Figure 13.** Fuel Economy Over Time Assumed for Three Vehicle Technologies

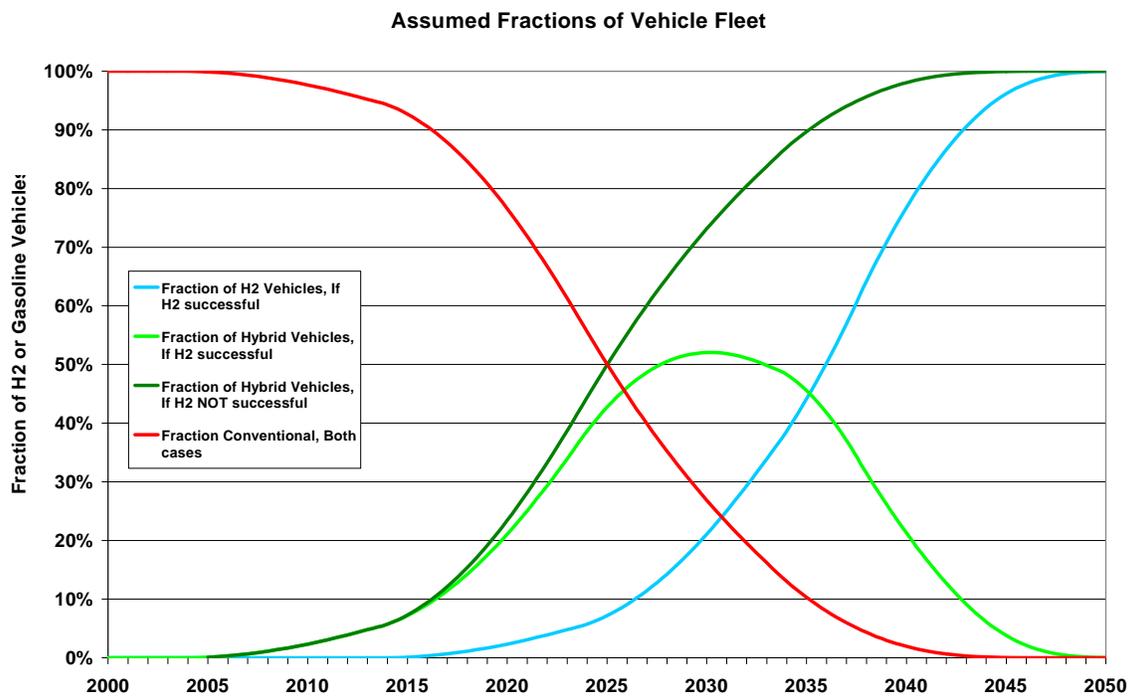
Figure 14 shows the assumed penetration rates of the new vehicles in the second and third scenario. (In the first scenario there is no penetration of either hybrid or fuel cell vehicles.) In the second scenario, hybrid vehicles increase to 100% market share of new vehicles and conventional vehicles decrease to zero market share by 2035. In the third scenario, the growth of hybrids is interrupted by the rapid growth of hydrogen fuel cell vehicles, which increase to 100% market share before 2040.

The entire inventory of vehicles on the road adjusts only with a lag to the adjustments in new vehicle sales, since in any year, the inventory is dominated by previous vintages of vehicles. Figure 15 provides estimates of the on-the-road inventory of vehicles, using a very simple vintage capital model of the vehicle fleet.

### III. Analysis Activities



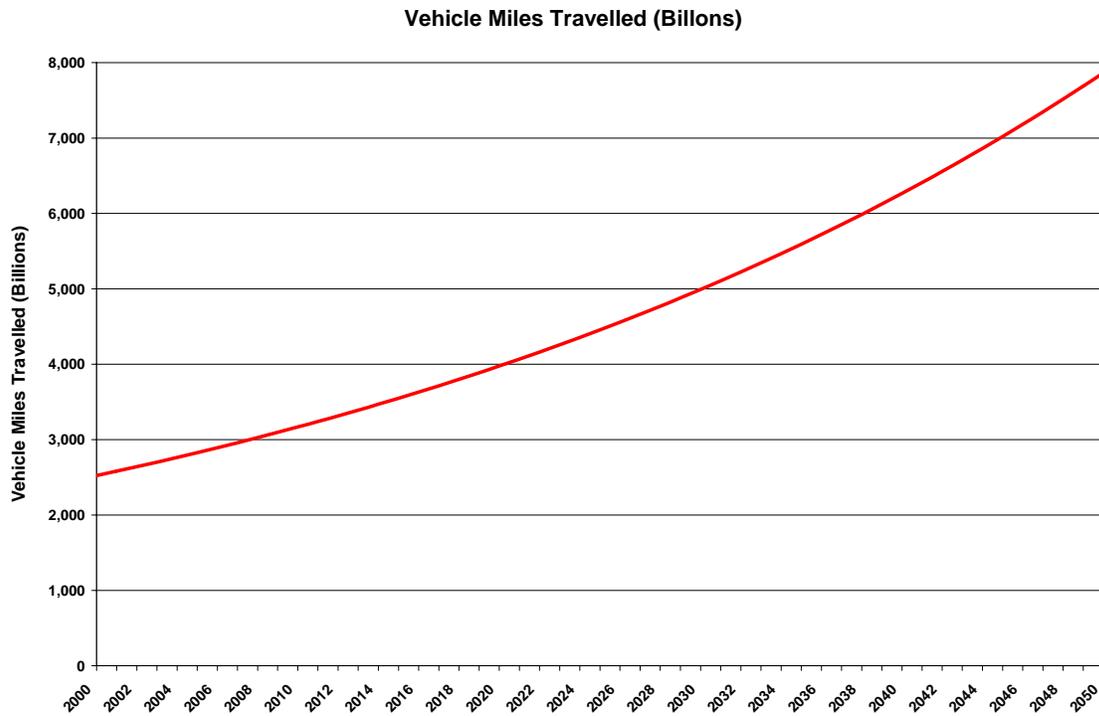
**Figure 14.** Assumed Fractions of New Vehicle Types: Three Scenarios



**Figure 15.** Estimated On-the-Road Fractions of Vehicle Technologies

Figure 14 and Figure 15 represent an optimistic assessment of the rate at which new fuel cell vehicles can penetrate into the market and the rate at which the fleet of vehicles would evolve. They show that if hydrogen technologies are successful, the evolution of the system would occur only over many decades, converging to 100% market share of hydrogen vehicles no earlier than about 2050.

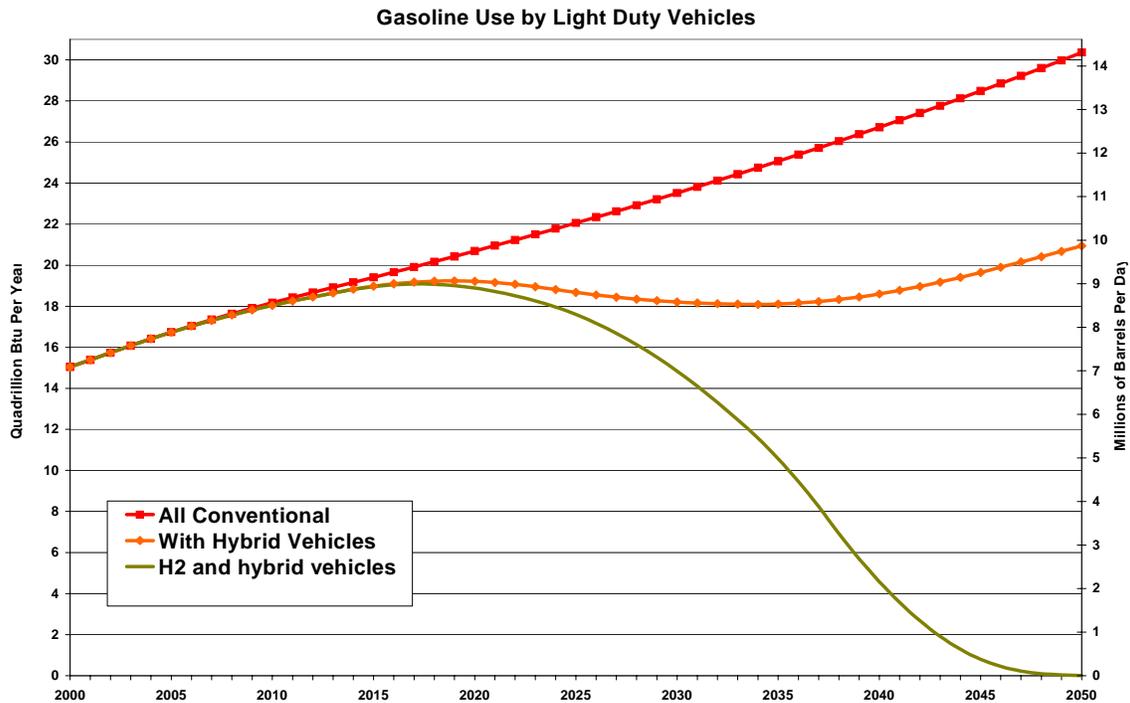
In order to determine the consumption of gasoline and of hydrogen in the various scenarios, it is also necessary to estimate how much vehicles would be driven, the vehicles miles of travel. We assumed that the total vehicle miles would increase by 2.3% per year over the time horizon. The assumed trajectory of vehicle miles traveled is shown in Figure 16.



**Figure 16.** Assumed vehicle miles of travel (Growing 2.3% per year)

The assumptions described above lead to projections of gasoline use over time in the three scenarios. These estimates are shown in Figure 17. This figure shows that absent either hybrid vehicles or hydrogen fuel cell vehicles gasoline consumption would steadily increase over time. The second scenario shows that a market shift toward hybrid vehicles could stop the growth of gasoline consumption, at least temporarily. However, if hydrogen fuel cell vehicles were to follow the diffusion pattern of scenario three, then by 2050 consumption of gasoline would be completely phased out.

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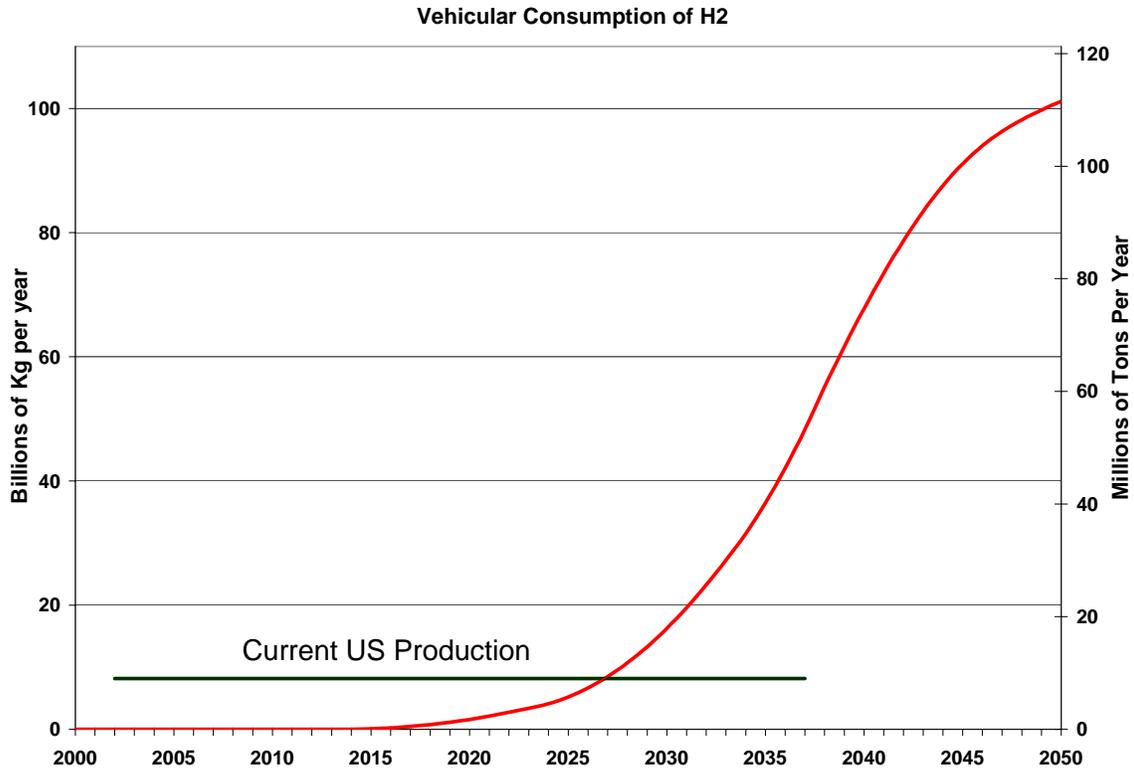
**Figure 17.** Gasoline Use by Light Duty Vehicles: Three Scenarios

As gasoline consumption is decreased in the third scenario, hydrogen consumption would be increased over time. Figure 18 shows the projected increase in hydrogen consumption over time, if hydrogen fuel cell vehicles penetrate the market consistently with the third scenario.

Figure 18 shows that it would be not until about 2027 that hydrogen use for light duty vehicles would be as large as the current U.S. production of hydrogen. However, by 2050, the use of hydrogen for vehicles could increase to over 100 billion Kg per year, or over 100 billion tons of Kg per year.

In what follows, it will be assumed that the hydrogen production and use for light duty vehicles follows the growth path of Figure 18.

However, various pathways are possible for producing the hydrogen, including each of the technologies shown in Figure 7 and Figure 8. In order to examine the implications of the various technologies, impacts of moving to a hydrogen economy are examined under the assumption that all of the hydrogen is produced using a single technology. The graphs in the subsequent portion of this report are based on 100% of the hydrogen being generated from a single technology.



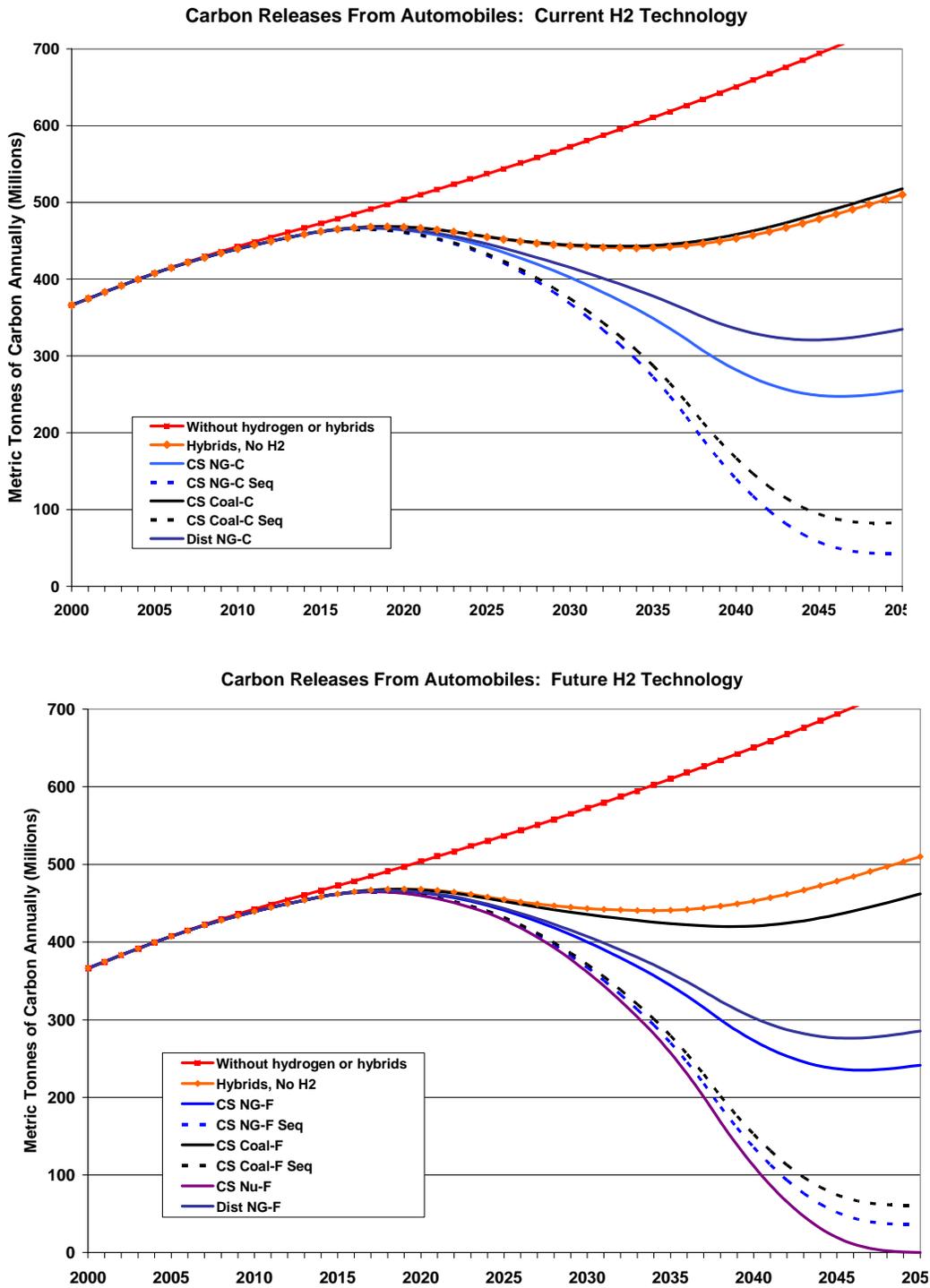
**Figure 18.** Light Duty Vehicle Use of Hydrogen, If Hydrogen is Adopted

In fact, moving toward a hydrogen economy would not lead to all hydrogen production being based on a single technology. It is more likely that a mix of technologies would be utilized. In that case, the various impacts would be based on a weighted average of the impacts estimated for the various single technology scenarios.

We turn now to an examination of the impacts of hydrogen technologies on carbon dioxide released into the atmosphere.

Under these assumptions, the transition to hydrogen could greatly influence the emissions of carbon dioxide into the atmosphere. If no hydrogen were introduced into the system, but hybrid vehicles grew in market share consistently with scenario two, the emissions of carbon dioxide into the atmosphere would increase until the year 2010 and would then remain roughly constant through the year 2040. This is shown by the orange curves in Figure 19 below.

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**Figure 19.** Carbon Releases into the Atmosphere from Light Duty Vehicles: Hydrogen Produced from Fossil Fuels

Figure 19 shows carbon dioxide releases for the current technologies and the possible future technologies, (upper panel and lower panel, respectively), for fossil-fuel based production of hydrogen plus hydrogen generated from direct thermal dissociation of hydrogen in a nuclear plant.

For both the current technologies and the possible future technologies, generation of hydrogen using natural gas can significantly reduce the carbon dioxide emissions. Emissions could be sharply reduced by capturing and sequestering the carbon dioxide. Generation of hydrogen from nuclear facilities would even further reduce the emissions.

Figure 20 shows emissions of carbon dioxide for hydrogen made with renewable energy – biomass, photovoltaics, wind turbines – and hydrogen electrolyzed using grid-based electricity. Carbon dioxide releases would be reduced if hydrogen were generated using photovoltaics, wind turbines, nuclear power, or biomass. However, using grid-based electricity to when the wind turbine or photovoltaics was not producing electricity would reduce the degree to which these technologies reduce the carbon dioxide releases.

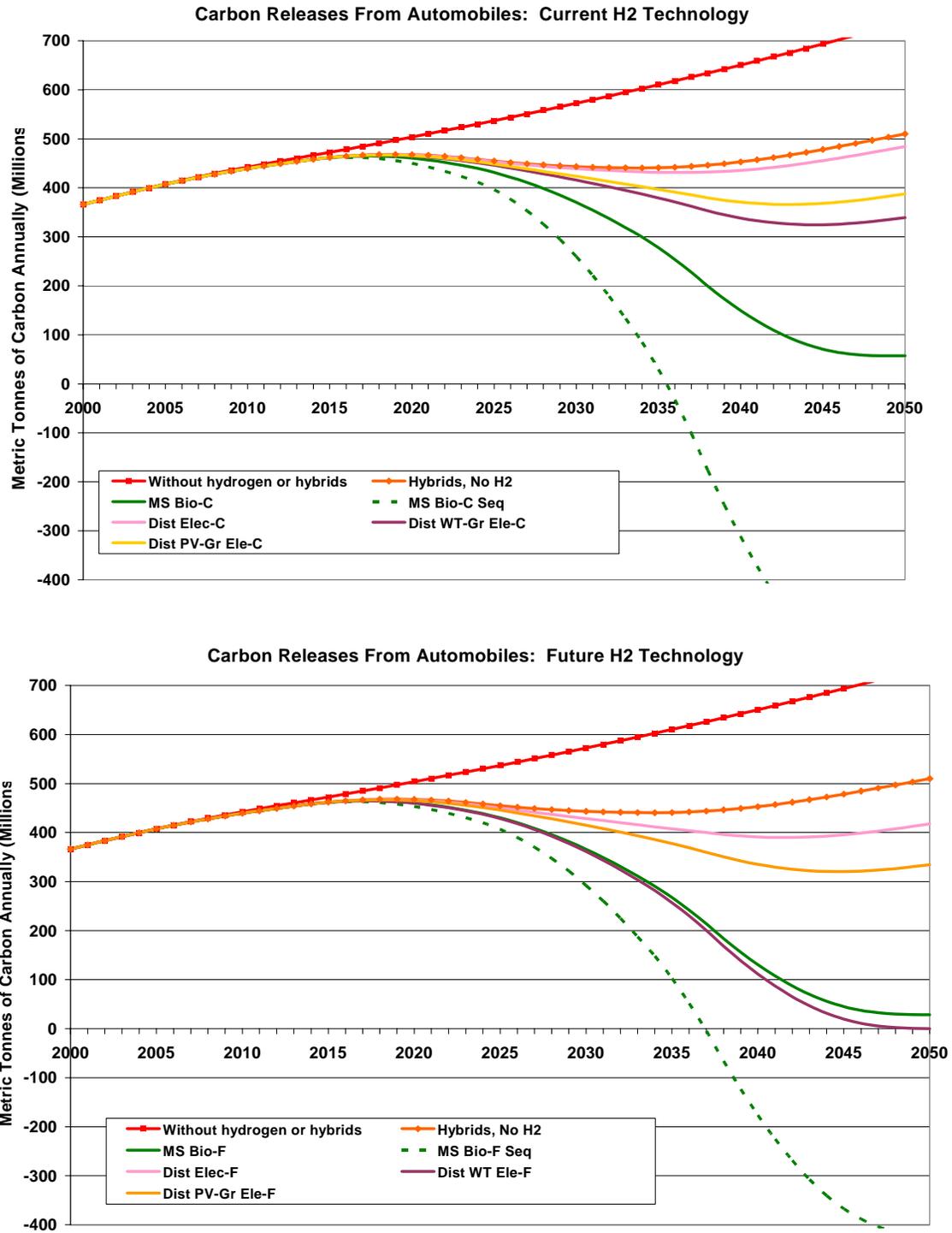
This graphs show the dramatically negative releases of carbon dioxide from use of biomass when, after the biomass is gasified, the carbon dioxide is separated and sequestered.

We have also examined the impacts of the various hydrogen pathways on the use of other natural resources.

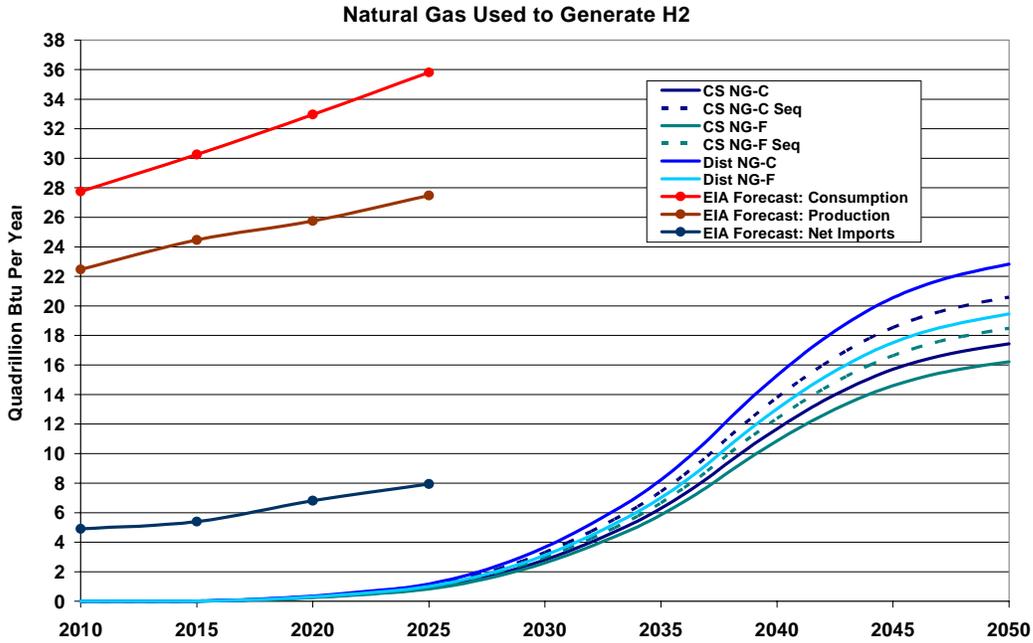
Figure 21 shows the amounts of natural gas that would be used by the various technologies that use natural gas as a feedstock. This graph also plots the projections, to the year 2025, from the Energy Information Administration, of natural gas production, consumption, and exports, not counting use for hydrogen production. The large amount of natural gas that would be needed for hydrogen production could not be supplied from domestic resources. These quantities would likely lead to increased imports of natural gas.

This impact can be quantified by comparing the reductions in oil use – and hence oil imports – with the increase in natural gas consumptions – and hence imports. These comparisons are shown in Figure 22, for potential new technologies. A graph based on potential future technologies would look very similar. This graph shows that, on an energy equivalent value, the increases in natural gas imports would be very similar in magnitude to the reductions in oil imports. Such a shift cannot be expected to contribute to energy security.

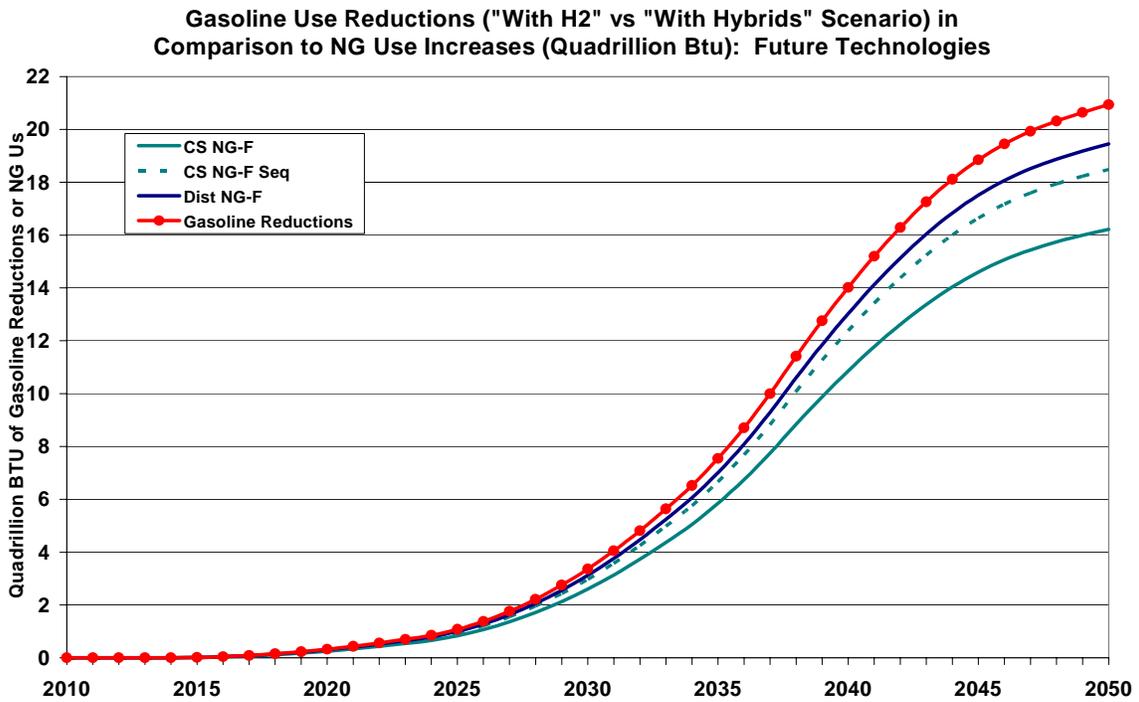
### III. Analysis Activities



**Figure 20.** Carbon Releases into the Atmosphere from Light Duty Vehicles: Hydrogen Produced Using Current Non-Fossil Fuel Technologies



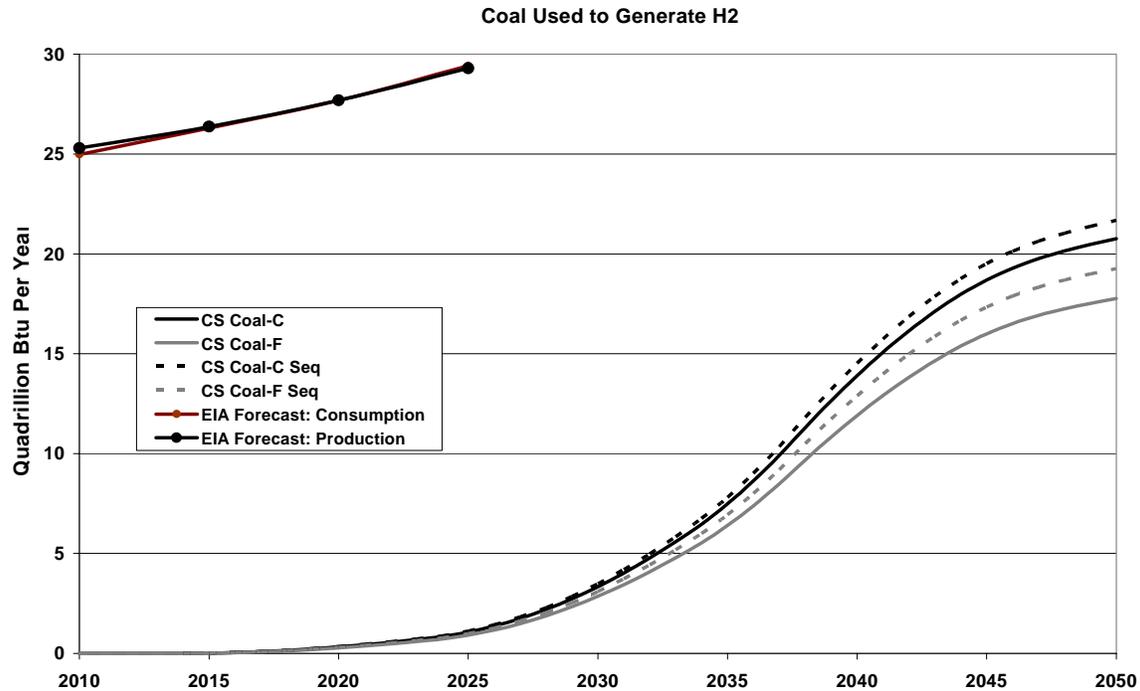
**Figure 21.** Natural Gas Used to Generate Hydrogen: Current and Future Natural-Gas-Based Technologies



**Figure 22.** Impacts on Gasoline Use vs Natural Gas Use: Possible Future Technologies

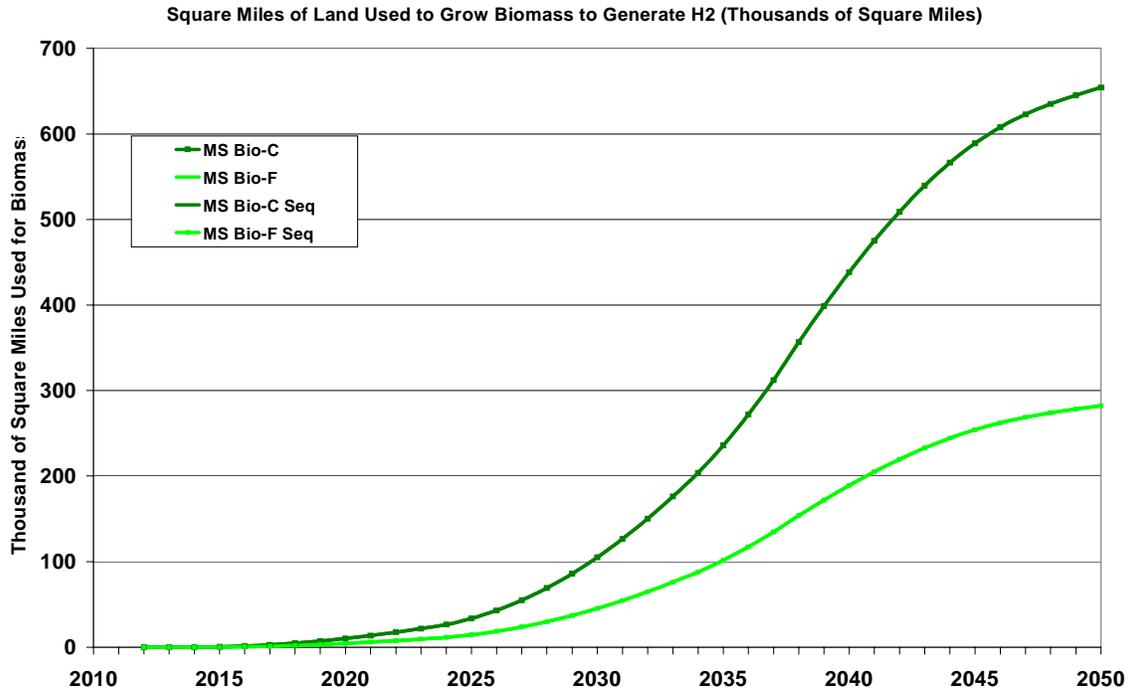
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For hydrogen generation using coal, however, the results are quite different. Figure 23 shows the amount of coal that would be used if all of the hydrogen were produced from coal. The EIA projections of U.S. coal production and use are also plotted on the same graph. Although coal used for hydrogen production could be a significant fraction of the projected use of domestic coal, this increase in production could be satisfied from domestic coal production.



**Figure 23. Impacts on Coal Use: Current and Future Technologies**

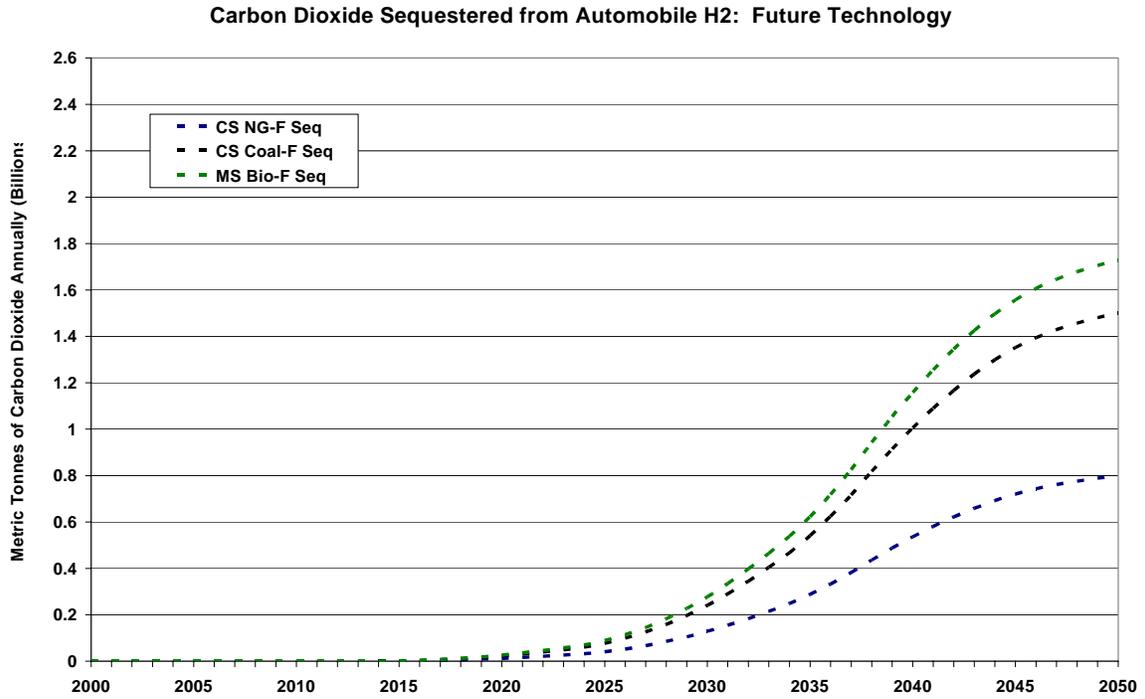
If biomass were used as the feedstock, then it would be necessary to grow the biomass. Figure 24 provides estimates of the amount of land that would be required if all of the hydrogen were produced using biomass. This suggests that 300,000 to 600,000 square miles of land would be needed to produce all the hydrogen from biomass. In order to put this in perspective, it can be noted that the U.S. currently uses 700,000 square miles of land as crop land and 900,000 square miles of pasture land. This suggests that, although one could use biomass to produce some hydrogen, it would not be viable to use it as the primary source of hydrogen.



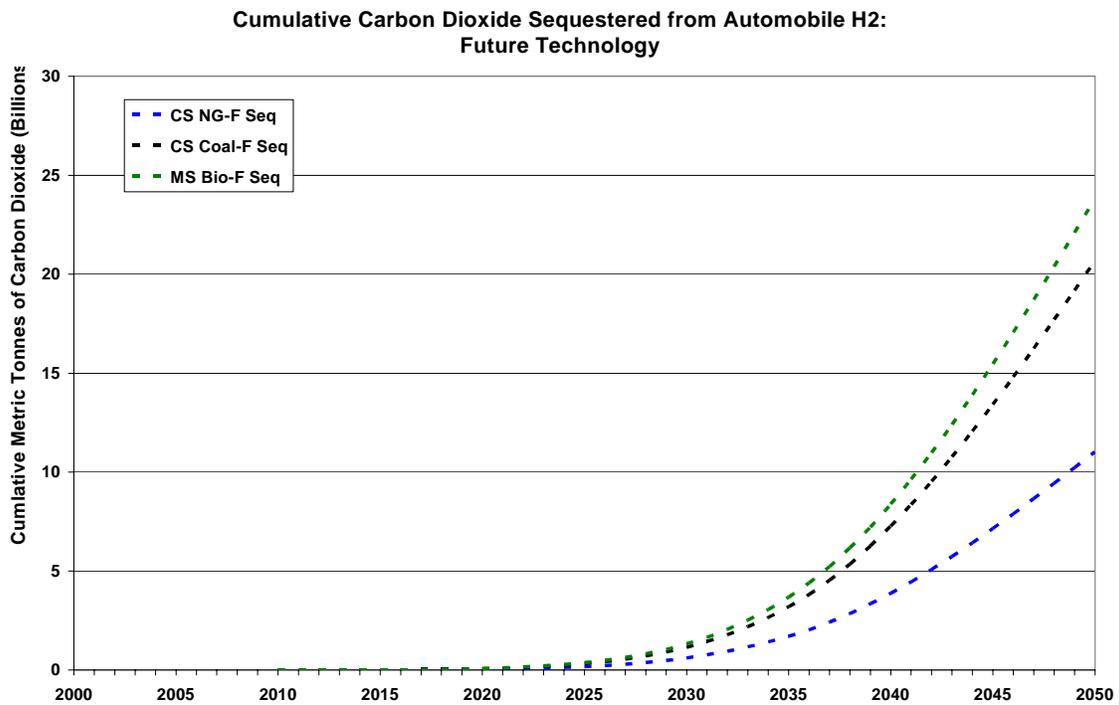
**Figure 24. Land Use of Hydrogen Based on Biomass Technology**

The final natural resource examined is sites for sequestration of carbon dioxide. Figure 25 shows the annual amount of carbon dioxide that would be sequestered for those technology pathways that involve sequestration. shows the cumulative amount of carbon dioxide that would be sequestered. These suggest that between 0.8 and 1.6 billion metric tonnes would be sequestered annually, leading to a cumulative amount sequestered by 2050 of between 10 and 20 billion metric tons. Much research is still needed to ascertain the amount of carbon dioxide that could be safely sequestered. However, for perspective, it can be noted that the estimated capacity of depleted U.S. oil and gas reservoirs is between 25 and 50 billion metric tonnes. In unminable U.S. coal seams there is an estimated capacity to sequester carbon dioxide of 15 billion metric tonnes.

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**Figure 25.** Annual Amount of Carbon Dioxide Sequestered: Future Technologies



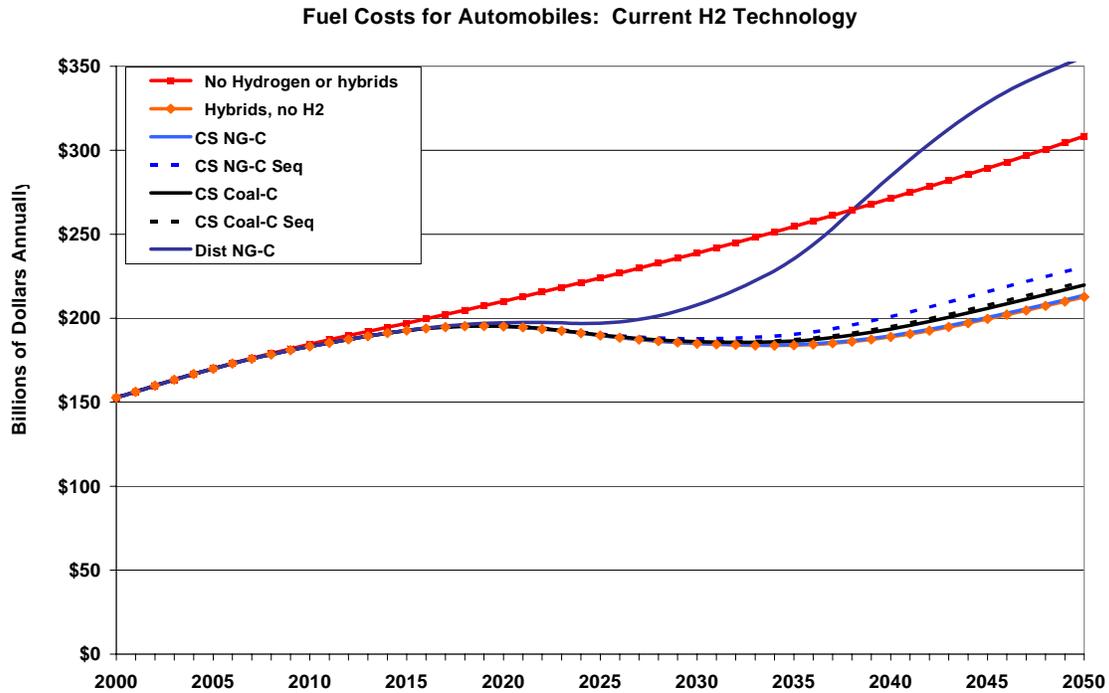
**Figure 26.** Cumulative Amount of Carbon Dioxide Sequestered: Future Technologies

Finally is the issue of cost for the supply of fuel for the nation's fleet of light duty vehicles. Using the unit cost estimate in combination with estimates of the rate of introduction of hydrogen vehicles allows estimation of the total costs to the fuel system. These estimates appear in Figure 27 through Figure . Figure 27 and Figure 28 provide estimates for hydrogen produced from fossil fuels, while Figure 29 and Figure provide estimates for hydrogen produced with renewables.

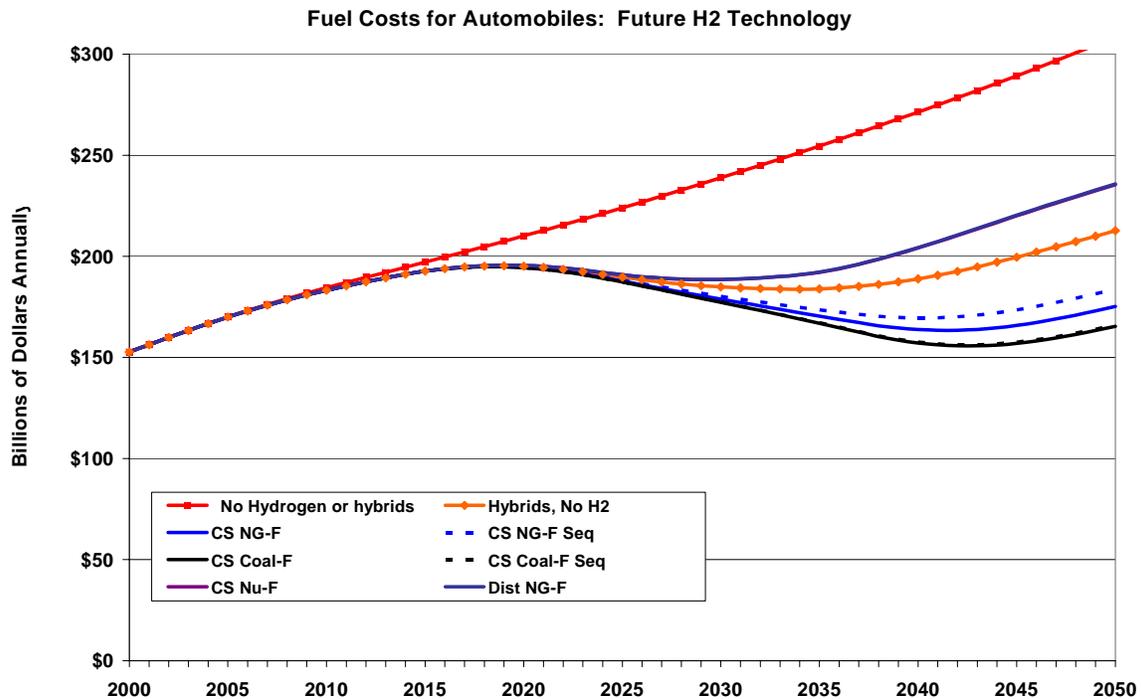
With current technologies, distributed generation of hydrogen from natural gas would remain less costly than use of gasoline in conventional vehicles until the late 2030s. By 2030, without new technologies, the size of the hydrogen market would have increased enough that the cost of distributed generation of hydrogen using natural gas would exceed even the cost of gasoline in conventional vehicles. However, with the potential new technologies, all of the fossil fuel sources of hydrogen would result in a total fuel system cost less than would be the cost of gasoline used in conventional vehicles. Total costs would be similar to costs of the system if hybrid vehicles came to dominate the market.

On the other hand, hydrogen from electrolysis based on renewables or grid-based electricity, or hydrogen from biomass, would lead to sharp increases in the entire fuel system cost with current technologies. (See Figure 29) Even with the potential new technologies (Figure ) most hydrogen production using renewables would be more expensive than the use of gasoline in conventional vehicles and substantially more costly than the use of gasoline in hybrid vehicles.

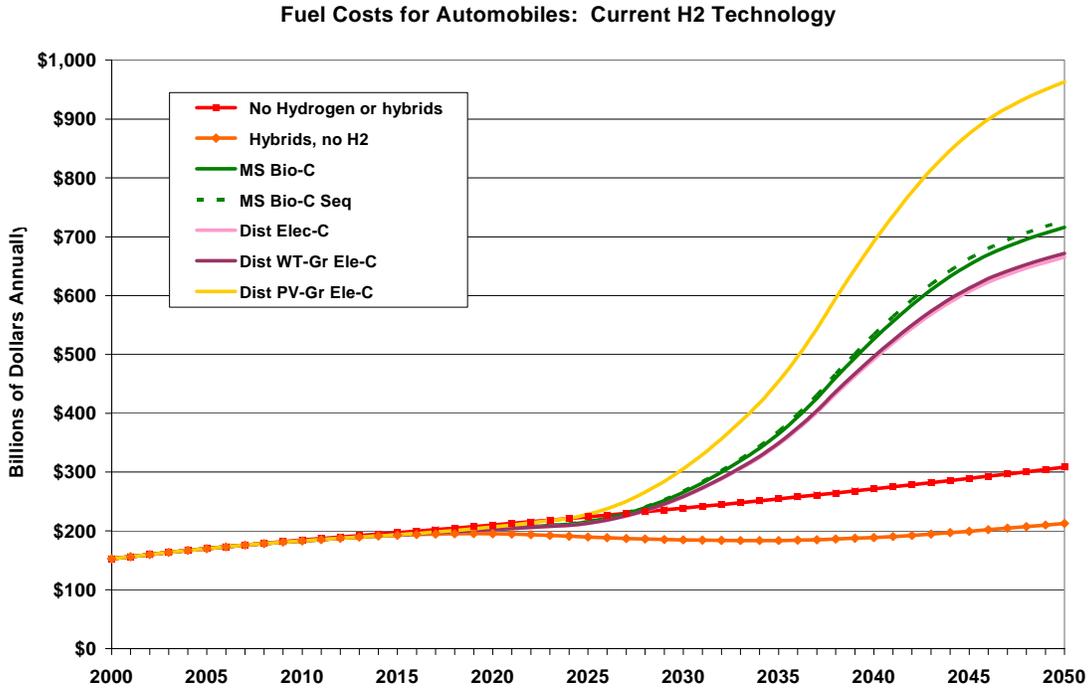
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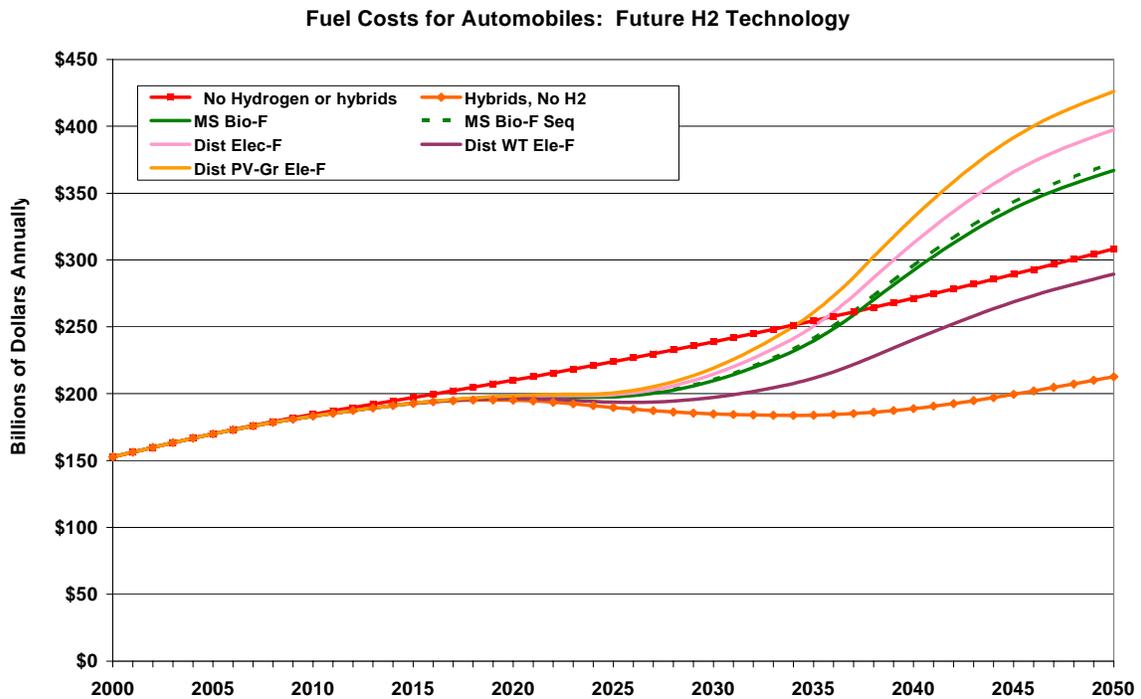
**Figure 27.** Fuel Costs for Light Duty Vehicles: Current Fossil-Fuel-Based Technologies



**Figure 28.** Fuel Costs for Light Duty Vehicles: Possible Future Fossil-Fuel-Based Technologies



**Figure 29.** Fuel Costs for Light Duty Vehicles: Current Non-Fossil-Fuel-Based Technologies



**Figure 30.** Fuel Costs for Light Duty Vehicles: Potential Future Non-Fossil-Fuel-Based Technologies

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#### **Publications**

1. Weyant, John P. "Public and Private Sector Roles in Fostering Technological Change in Global Climate Change Policy Development", Annual Meeting of the American Economics Association, San Diego, California, January 4, 2004.
2. Sweeney, James L., "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs", keynote address, National Hydrogen Association, Annual U.S. Hydrogen Conference, April 27, 2004.
3. Sweeney, James L., "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs", seminar at ExxonMobil, March 9, 2004.
4. Sweeney, James L., National Renewable Energy Lab, National Advisory Council meeting. May 18 and 19, 2002. Council meeting to discuss NREL role in the DOE hydrogen program.
5. Sweeney, James L., "Energy Policy Issues" Briefing of President George Bush, Richard Cheney, John Snow, Don Evans, the White House, January 30, 2004.
6. Sweeney, James L., "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs", Energy Modeling Forum Affiliates Conference, January 28, 2004.

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1. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, National Research Council, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council, Forthcoming, 2004.

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