Use of Hydrogen for the Light Duty Transportation Fleet: Technology and Economic Analysis

Comparative Energy Security and Environmental Implications of Chemical and Gaseous Hydrogen Economies

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In this work we present results of techno-economic modeling and scenario analysis for attaining the environmental and energy security goals, articulated by President Bush in February, 2003, of reducing petroleum consumption by 11 million barrels per day and carbon emissions by 500 million metric tons, C equivalent, per year, by the year 2040. While much attention has centered on the development of the "hydrogen economy" and the potential of H_2-fuel cell vehicles (FCVs) to achieve these goals, we develop an additional scenario that focuses on the use of hybrid-electric vehicles (HEVs), and the expansion of gasification and Fischer-Tropsch synthesis plants at refineries. The FCV-based scenario may be thought of as a "gaseous" hydrogen economy whereas the HEV-based scenario, a "chemical" one, in which H_2 is used to enhance fuel quality and to produce clean synthetic liquid fuels. The Presidential goals are interpreted as reductions from reference case levels. Under both gaseous and chemical hydrogen economy scenarios, energy security and carbon emissions charges are used by the model to drive the economy to the stated goals. We highlight plausible technological pathways and potential least-cost solutions that enable this achievemen, including coal-to-liquids technology. However, needed policy drivers, investment decisions, resource use, and environmental performance differ across the scenarios and over the study period (2010-2040). The scenarios include detailed characterizations of energy conversion processes and integrate the petroleum, natural gas, transportation, and electricity generation markets and show important potential interactions among these markets.

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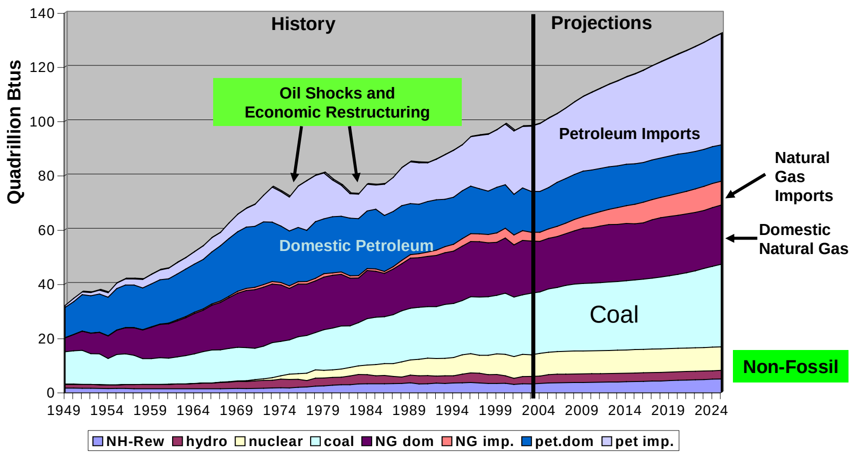
INTRODUCTION

In February, 2003, President George W. Bush described a vision of energy independence and environmental progress, based on the use of hydrogen. Entitled "Hydrogen Fuel: a Clean and Secure Energy Future," this initiative seeks to reduce both the dependence of the United States upon sources of fuel supply located in volatile regions of the world and also emissions of pollutants and greenhouse gases. President Bush stated that the "full" development of hydrogen power, mediated through hydrogen fuel cell vehicles, would, by 2040, reduce oil demand by 11 million barrels per day, emissions of carbon equivalent by 500 million metric tons per year, and reduce air pollution.[1]

Figure 1: US Energy Consumption by Fuel
1949-2025



Source: **EIA**; 1948-2003: ***Annual Energy Review 2003***, Table 1.3; 2004-2025: ***Annual Energy Outlook 2005***, Tables 1,2, and 17

To appreciate the ambitious nature of these goals, one must consider current trends in petroleum use and carbon emissions. Fossil fuels account for over 85% of energy consumption in the United States,[2] or approximately 86 of the 100 quadrillion (10^{15}) British thermal units (Btus) (hereinafter "quads") consumed in 2004 (Figure 1). In 2004, the US consumed over 40 quads of energy from petroleum, 22 quads from coal, 23 quads from natural gas, about 8 quads of nuclear power, and about 6 quads of hydro and other renewable energy. The post-WWII trend of ever-increasing energy consumption dipped twice in the 1970s. The 1979 peak of 80.9 quads was not surpassed until 1988. Similarly for petroleum, consumption peaked in 1978 at 37.97 quads, a level not matched for 21 years, until 1999. Since the mid-1980s, petroleum and energy consumption have resumed their growth paths, with brief pauses for economic slowdowns in 1991 and 2001-2002. Energy consumption in 2004 surpassed its most recent earlier peak in 2000, although energy consumption from natural gas seems to have flattened in the current period.[3]

Since the February 2003 Presidential announcement, numerous analyses have been issued examining various issues surrounding the "hydrogen economy." The Department of Energy's research and development goals aim to commence the commercialization of hydrogen fuel cell vehicles after a commercialization decision point in 2015.[4] The National Research Council issued an authoritative report describing the immense tasks necessary for a hydrogen economy to take hold by 2050. Hydrogen production, transportation, storage, and use are scrutinized, at length.[5] Critics of a potential hydrogen economy have focused on issues ranging from infrastructure costs to major technical hurdles. These include infrastructure for delivery, storage, and dispensing hydrogen, technology required for safety considerations, and technology required to improve the competitiveness of FCVs and to reduce hydrogen production cost (especially for renewable-based hydrogen). Also, the appeal of more near-term, advancing and competing transport technologies represents an ongoing hurdle for FCVs.[6] Occasionally lost in this debate concerning the hydrogen fuel initiative are the dual quantitative goals set by the President. These two goals spring from parallel desires: to improve energy security, and to reduce the probability and extent of dramatic climate change. This pair of goals fundamentally drive this scenario study.

Energy Security

The most recent forecast from the Energy Information Administration (EIA)sees continued growth in energy consumption from fossil fuel sources. Due to projected declines in domestic supply amidst continued growth in demand for petroleum and natural gas, imports of each are expected to increase dramatically, meeting all incremental demand for these fuels, whereas almost all coal will continue to be produced domestically.

With respect to petroleum, in 2004, the United States consumed 20.5 million barrels per day (mmb/d), of which almost 11.9 mmb/d were imported. Since the peak of US crude oil production in 1970, imported crude oil and petroleum products define the growth profile of petroleum consumption. EIA expects that crude oil imports from OPEC nations will account for 95% of incremental US supply between 2002 and 2025.[7]

Table 1:Reserves/Production, Year-end 2004, US v. World

Fuel/years left	oil	gas	coal
Non-US	44	81	177
US	11	10	245

Source: *BP Statistical Review of Energy 2005*

The United States enjoys a strategic advantage in the use of coal, possessing 25% of the world's reserves of coal, but only 3% of reserves of oil and natural gas each. Coal is the only fossil fuel for which the US ratio exceeds that of the rest of the world (Table 1).[8]

Table 2: US Greenhouse Gas Emissions, 1990-2002 (Teragrams)

Year	CO_2	CH_4	N_2O	HFC,PFC,SF_6	Total
1990	5002	643	393	91	6129
2002	5782	598	416	138	6935

Source: EPA, *2004 Greenhouse Gas Inventory*, National Inventory Tables, Table ES-2. 1Tg=10^6 metric tons

Greenhouse Gases

However, coal is both pollution- and CO_2-intensive when burned. Because carbon dioxide is the most pervasive greenhouse gas, the Presidential Initiative focuses on carbon reductions as a means to mitigate the risk of climate change. The Environmental Protection Agency has developed inventories of four categories of greenhouse gases: carbon dioxide, nitrogen dioxide, methane, and fluorocarbons and fluorides. According to the *2004 National Inventory* tables, between 1990 and 2002, overall GHG emissions in the United States rose from 6129 teragrams (Tg) of CO_2 equivalent to 6930 Tg,CO_2 eq., an increase of more than 13% (Table 2). CO_2 itself, which comprises over 83% of US GHG emissions, grew over 15% during the same time, reaching 5782 Tg. A teragram is a million metric tons. Multiplying the CO_2 emission figure by a factor of 12/44 converts the mass to its carbon equivalence, yielding 1577 million metric tons of carbon equivalent emissions in 2002. The primary source for CO_2 emissions listed in the *National Inventory* are fossil fuel combustion and cement manufacture.

Table 3: US CO_2 Emissions from Fossil Fuel Combustion, by Sector, 2002, Tg CO_2

Sector/Fuel	Residential	Commercial	Industrial	Transportation	Electricity	Total
Petroleum	105	53	406	**1708**	72	2365
Natural Gas	267	169	424	35	299	1195
Coal	1	9	126	0	**1868**	2005
Total	373	231	956	1764	2240	5564

Source: EPA, *2004 Greenhouse Gas Inventory*, National Inventory Tables, Table 3.3

Table 3 demonstrates that the largest contributions to national CO_2 emission result from the combustion of coal in the electricity sector, and the burning of petroleum for transportation uses. These sectors provide services to all other components of the economy. The combustion of coal accounts for over 83% of CO_2 emissions from electricity generation, while that of petroleum emits 98% of the transportation total. Given the dominant positions of coal- and petroleum-based emissions, the most cost-effective strategies for reducing emissions must address the use of these fuels in their primary sectors. Indeed, coal-based R&D addressing the hydrogen economy not only targets energy security but also addresses the two largest components of CO_2 emissions (65%) in the Nation's economy. This study therefore targets the transportation and electricity generation sectors for the reductions in petroleum use and carbon emissions.

The scale of the challenge in reducing petroleum consumption is immense. Of the current 20mmb/d of petroleum consumption, over 13mmb/d is used by the transportation sector, and of the 13 million, almost 9mmb/d is consumed as motor gasoline. Further, consumption will certainly grow if unconstrained. For instance, the EIA projects that vehicle miles traveled will increase from its current level of 2.6 trillion miles to 4 trillion miles by 2025, a growth rate of 2.0% per year. Meanwhile, fuel economy is only projected to grow for light-duty vehicles (LDVs) by 0.3% per year.[9]

2. The Scenarios

This study develops scenarios that offer possible pathways to achieve the twin goals of improving energy security and mitigating climate change. This study interprets the numerical presidential goals as reductions from expected future levels (in 2040), rather than from current levels, in contradistinction to the DOE *Posture Plan* and the NRC study. Note that enough technological uncertainty exists in the development of fuel cells and the related hydrogen system to propel the Department of Energy to pursue varied technologies that may serve in a transition to a hydrogen economy, or as ends in their own right.[10]

Therefore, this study constructs three scenarios: a reference case, a transition or evolutionary case that centers on internal combustion engine and electric motor vehicle hybrids, and a revolutionary case that imagines the emergence of a hydrogen economy based on the proliferation of hydrogen fuel cell vehicles. In the reference case no special effort is made to reduce either petroleum consumption or GHG emissions. The two alternative scenarios both incorporate initiatives aimed at reducing petroleum consumption by 11mmb/d by 2040, but each employing a different technical pathway.

In a competitive free market economy, the dominant systems of production deploy least-cost technology for satisfying societal demands within the existing structure of prices and regulations. To move the energy system to a new equilibrium with different least-cost technology-- in this case, a much reduced petroleum and carbon intensity-- it is necessary to impose a new set of prices and/or regulations. Policy initiatives can change both prices and regulations, and the present study generates for each alternative scenario the effective energy security and carbon charges necessary to lead to the desired result of technology development and subsequent deployment. However, the specific form or set of policy initiatives is left to policy makers and the political process.

Each of the scenarios is briefly described below.

Reference Case: "Business as usual"	**Extended Transition ($Chemical\ H_2$)** Hybrid-electric vehicles and Clean Hydrocarbons	**Hydrogen Achievement ($Gaseous\ H_2$)** Hydrogen Production for Fuel Cell Vehicles
Oil Prices From $37/bbl in 2010; Gas Prices from $6/mmBtu	Coal Power/Fischer-Tropsch Co-Production Plants	DOE H2 Posture Plan guidelines
"Clear Skies"-Like Emissions Targets	Energy Security Charges on premium fuels from 2010	H2A program (DOE EE) H2 cost data
Hydrotreating and Clean Fuels Refining	Carbon Charges on Electricity generation from 2015	More stringent clean air regulations begin in California
Nuclear Generating Capacity Constant	Four size categories of Hybrids; eventual Plug-Ins	Technological "breakthroughs" assumed

Common Assumptions and Modeling

The scenarios are run using Argonne's AMIGA model, a dynamic, computable general equilibrium model.[11] The three scenarios share common assumptions regarding oil and gas prices, air pollution targets, motor vehicle fuels specifications, and projected vehicle miles traveled. We abstract from issues concerning the energy intensities of commercial and residential buildings, adopting the conventions of the *Annual Energy Outlook 2005*. The scenarios assume oil and gas prices that, while considerably higher than prices projected in the *AEO 2005* reference case ($25/b in 2010), remain below several industry estimates.[12] In the case of such analyst's estimates proving more accurate, the alternative scenarios discussed herein would become competitive more quickly with a corresponding, higher cost reference case. Air pollution targets follow the administration's "Clear Skies" initiative.[13] Nuclear capacity is assumed to be constant. Refineries adjust to stringent sulfur restrictions for gasoline and diesel fuel.[14]

Currently, oil refineries are the largest users of hydrogen, which is most commonly produced by steam methane reforming of natural gas. In almost all U.S. refineries, hydrogen is used hydrotreating processes to remove impurities, such as sulfur, nitrogen, and heavy metals, from petroleum streams. Use of hydrotreating is increasing due to more stringent fuel sulfur regulations. With this subsequent increase in demand for hydrogen at refineries, gasification may become an attractive source of hydrogen. In the short term, refinery-based gasifiers will likely be fed by petroleum coke or other petroleum residuals. In the longer term domestic coal could become a feedstock, and liquid fuels in addition to hydrogen could be produced; thus reducing the amount of crude oil needed to produce transportation fuels. Co-production of power and Fischer-Tropsch liquid fuels may be economic at a $40/MWh price of electricity and $60/b for FT fuels.[15] The fuels, however, require upgrading or blending before use in vehicles. Further modeling will integrate clean fuels production, including FT liquids and upgrading into the refinery complex, based on a variety of feedstock (petroleum coke, residual oil or coal).

Costs and performance detail for advanced hybrid-electric vehicles emanate from an EPRI (2001) study for HEVs, including "plug-ins".[16] Additional support for the spectrum of advanced vehicle technologies can by found in an NRC study of fuel economy.[17] The economic model, AMIGA, then applies learning curves to the EPRI figures to represent progress over the study period. Hydrogen FCV mileage and cost estimates were based on the NRC H2 study, and DOE metrics.[18]

The scenarios, then, can also be referred to as the *Reference*, an *Extended Transition to Future Energy (Chemical H_2)*, and the *Hydrogen Transformation Achievement (Gaseous H_2.)* Both *Extended Transition* and *Hydrogen Achievement* differ from the *Reference* because an energy security charge, modeled as a Btu tax on premium fuels (gasoline, diesel, jet fuel.) and a carbon charge, modeled as a simple tax, are imposed upon producers. In the *Hydrogen Achievement*, the research and development goals of the DOE are met, with industry embarking upon commercialization of FCVs after 2015. At historic rates of technology deployment, commercial introduction should occur around 2025 with significant impact upon transportation sector by 2035. [19] In the *Extended Transition* case, the DOE hydrogen research goals are not met, requiring the central role of HEVs after 2015. Technologies, such as advanced conventional and hybrid vehicles, greater use of refinery hydrogen to produce super-clean petroleum-based fuels, and coal-based production of synthesis gas for supplementing petroleum fuels, have near-term availability and could successfully be used over a possible transition period. The transition period would, if necessary, allow adequate time to develop a foundation upon which to build commercial hydrogen production, distribution, storage, retailing, and end-use capabilities. The transition technologies would achieve large reductions in petroleum consumption by using hydrogen in applications with relatively small technical risk, providing additional time for development of highly innovative hydrogen technologies, such as the hydrogen FCV. The *Extended Transition* case offers a parallel technology path representing a valuable insurance policy for the nation should the *Hydrogen Achievement* case proves technically or competitively unattainable. Moreover, in the *Hydrogen Achievement* case, even if the research goals are met, an additional policy driver is necessary for the FCVs to overcome the cost advantage of HEVs. This driver could be very strict anti-smog regulations, in the form of incentives for "zero-emission" vehicles. This is modeled as beginning in California, before spreading to the East Coast and the larger US cities.

Interim Scenario Results

1. Targets

Targeted reductions are from levels listed in the table below. Extrapolations from AEO2005 (using average annual growth figures) are listed for comparison.

Table 4: Scenario Targets

Model/year/reduction	**2005**	**2025**	**2040**
Petroleum consumption (mmb/d)			
AEO2005	21	28	35
AMIGA	21	27	31
Target (AMIGA – 11mmb/d)			**20**
Carbon equivalent (mmt/yr)			
AEO2005	1171	1645	2151
AMIGA	1169	1562	1751
Target (AMIGA – 500 mmt/yr)			**1251**

Source EIA *AEO2005* Yearly Tables 11 and 18 (transport petroleum; electric power); AMIGA reference run

Reductions from future levels depend upon modeling assumptions. With the assumptions at work in the AMIGA reference case, the presidential goals translate into reductions that return future petroleum consumption and emission levels to approximately current levels.

Given conditions of increasing miles driven, vehicles in stock, and electricity demand, petroleum consumption must be limited and generation patterns altered. These are hard constraints. For increasing energy security premiums to drive change with minimal economic displacement, technologies must be in development to facilitate the reductions in consumption and emissions.

2. Externality Charges

Table 5: Externality Charges

Year	2010	2015	2020	2025	2030	2035	2040
Carbon Charges ($/ton C)							
Extended Transition	0	$17.51	$23.43	$31.35	$41.96	$56.15	$75.14
Hydrogen Achievement	0	$13.22	$17.69	$23.68	$31.68	$42.4	$56.74
Energy Security Premia ($/barrel)							
Extended Transition	$6.23	$7.08	$8.05	$9.16	$10.41	$11.84	$13.46
Hydrogen Achievement	$6.12	$6.96	$7.91	$8.99	$10.23	$11.63	$13.22

Source: AMIGA Scenario Runs

Both alternative scenarios include externality charges given in Table 5. AMIGA optimizes the imposition of charges. While the energy security premia are essentially equivalent between the scenarios, carbon charges differ. Because of the assumed more stringent anti-smog regulations in the *Hydrogen Achievement*, and the greater efficiency of the FCV, the derived carbon charge is lower in *Hydrogen Achievement* than in the *Extended Transition.*

Table 6: Effective Oil Prices

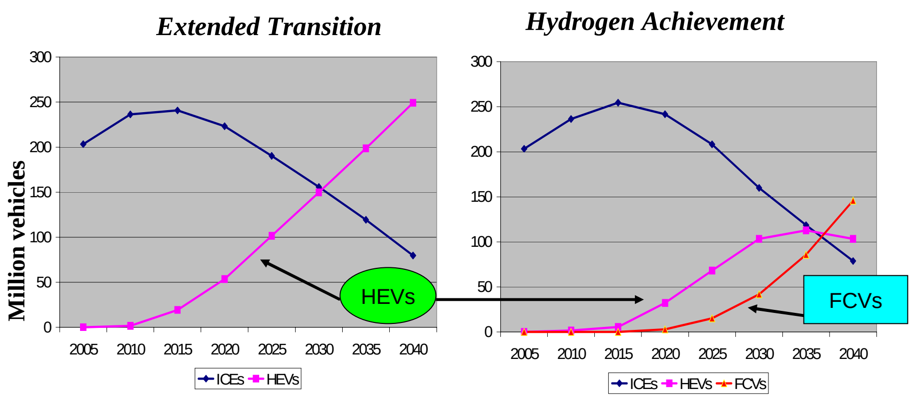
	2010	2015	2020	2025	2030	2035	2040
(1)World Oil Price	$37.06	$37.64	$37.87	$38.11	$38.34	$38.58	$38.82
(2)Energy Security charge per bbl – *Ext. Trans.*	$6.23	$7.08	$8.05	$9.16	$10.41	$11.84	$13.46
(3)Energy Security charge per bbl – *Hyd. Achv.*	$6.12	$6.96	$7.91	$8.99	$10.23	$11.63	$13.22
(4)Carbon Charge per bbl – *Ext. Trans.*	$0	$2.07	$2.76	$3.7	$4.95	$6.63	$8.87
(5)Carbon Charge per bbl – *Hyd. Achv.*.	$0	$1.56	$2.09	$2.79	$3.74	$5	$6.7
Effective Oil Prices							
***Extended Transition* =(1)+(2)+(4)**	**$43.29**	**$46.79**	**$48.68**	**$50.97**	**$53.7**	**$57.05**	**$61.15**
***Hydrogen Achievement* =(1)+(3)+(5)**	**$43.18**	**$46.16**	**$47.87**	**$49.89**	**$52.31**	**$55.21**	**$58.74**

While the electricity sector bears only the carbon charge, liquid fuels face both the carbon charge and an energy security premium, in both scenarios, raising effective oil prices, as seen in Table 6. Of course, in *Hydrogen Achievement*, vehicles face three constraints. Note that the scenarios project effective oil prices at the end of the period equivalent to levels prevailing today (year 2005), suggesting that a transition towards advanced vehicles is likely to occur if these prices are sustained, albeit in a manner that “shocks” the economy instead of one that fosters a smooth transition.

3. Advanced Vehicle Penetration and Goals Achievement

Under the charges above and, in the *Hydrogen Achievement*, additional anti-smog regulations, consumers choose across vehicle size classes amongst conventional ICEs, HEVs, and FCVs in a manner that yields the following aggregate distributions (Figure 2):

Figure 2: Vehicle Stocks

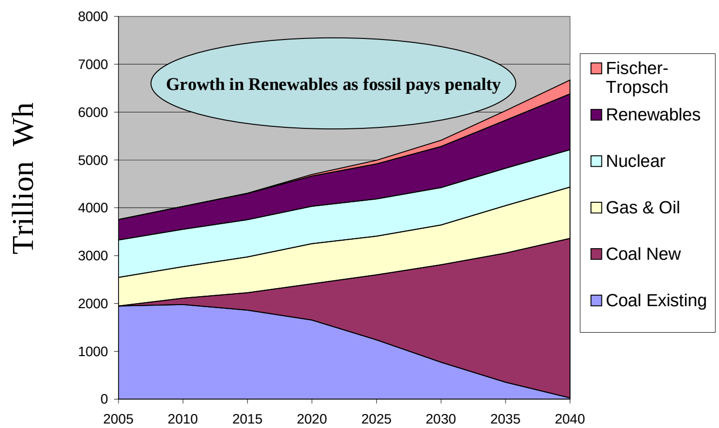


Source: AMIGA Presidential Goals Scenario Runs

Note that in the *Hydrogen Achievement*, FCVs compete with HEVs to displace ICEs, highlighting the insurance role of hybrid technology. Note as well that in both cases, ICEs remain in circulation and thus the fuel supply infrastructure must as well. This provides and incentive to integrate hydrogen-intensive clean fuels production and carbon sequestration, to the extent made necessary under the goals. That is, while most of the low cost potential to simultaneously reduce carbon and oil consumption comes from more efficient transportation,[20] additional petroleum consumption is offset by coal-based Fischer-Tropsch fuels production. Capture and sequestration of carbon is practiced at these facilities in order to avoid adding carbon to the atmosphere.[21] In extended Transition, 85%of the petroleum goal is met through vehicle efficiency, and 15% by coal-FT substitution. Under the constraints, approximately 10% of the new coal fleet (IGCC units) need to capture and sequester carbon. Improved vehicle efficiency meets 80% of the emissions reductions goals, the power sector, 20%, in Extended Transition. Slightly more reduction occurs in Hydrogen Achievement due to the higher efficiency of FCVs, and consequently less FT fuels production is required. Also, the bulk of the hydrogen produced for FCvs comes from steam methane reforming.

4. Generation Mix and Integration with Transport

Figure 3: Electricity Generation by Fuel Type, *Extended Transition*



Source: AMIGA *Extended Transition* Run

The carbon charge induces investment in both advanced coal technologies that allow for carbon capture and sequestration, and also generation from renewable sources (Figure 3). Under both alternative scenarios energy consumption by the transport sector levels off. In *Extended Transition*, more of the motive power in the transportation sector is supplied by the electricity grid through plug-in HEVs (Table 7). After 2030, petroleum consumption by the HEV fleet falls as plug-ins become more prevalent.

Table 7: Energy Source for HEV fleet (Trillion Btus)

Source	2005	2010	2015	2020	2025	2030	2035	2040
Petroleum	3	77	842	2121	3372	3858	3777	2832
Grid	0	0	0	34	212	594	1215	2034

Source: AMIGA *Extended Transition* Run

5. Concluding Observations

The key innovation of these scenarios is the reconciliation of energy security and climate change mitigation goals. While the optimization puts the focus on vehicles, coal gasification plays an important role in each alternative scenario, in a co-production mode: power and hydrogen in the FCV-based scenario, and power and Fischer-Tropsch fuels in the HEV scenario. Thus coal-based R&D effectively supports the primary drivers of the hydrogen economy under either alternative scenario. Through the imposition of premium fuels and carbon charges, the scenarios balance the energy security and carbon reduction objectives.

Notes

[1] President George W. Bush, February 6, 2003, in a speech at the National Building Museum. Text at http://www.whitehouse.gov/news/releases/2003/02/20030206-12.html.

[2] Energy Information Administration, online *Annual Energy Review 2003*, Table 1.3 Energy Consumption by Source, 1949-2003; http://www.eia.doe.gov/emeu/aer/txt/ptb0103.html; For 2004 figures, EIA, Monthly Energy Review July 2005, Table 1.3.

[3] See EIA, *Monthly Energy Review*, "Table 1.3: Energy Consumption by Source," http://www.eia.doe.gov/emeu/mer/pdf/pages/sec1_7.pdf. Note other fuel sources have rebounded while gas consumption has moderated.

[4] United States Department of Energy, *Hydrogen Posture Plan*, "An Integrated Research, Development, and Demonstration Plan," February, 2004, pp. 19-21. The commercialization would take 10 years to achieve significant penetration of H2 FCVs (from 2025).

[5] National Research Council, *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs*, February 2004.

[6] Examples are B. Eliasson & U. Bossel, "The Future of the Hydrogen Economy: Bright or Bleak?" Fuel Cell World Proceedings (Luzern), 1–5 July 2002, pp. 367–382, European Fuel Cell Forum (Morgenacherstr. 2F, CH-5452 Oberrohrdorf, Switzerland), posted at: www.methanol.org/pdfFrame.cfm?pdf=HydrogenEconomyFinalReport.pdf;. Joseph Romm, Testimony to Committee on Science, U.S. House of Representatives, March 3, 2004 http://www.house.gov/science/hearings/full04/mar03/romm.pdf; Shinnar, The Hydrogen Economy, Fuel Cells and Electric Cars, *Technology in Society*, 25 (2003), pages 455-476; Nurettin Demirdoven and John Deutch, "Hybrid Cars Now, Fuel Cell Cars Later," *Science*, vol. 305, 13 August 2004, pp. 974-976

[7] EIA, AEO2005, Supplemental Tables, Table 117. http://www.eia.doe.gov/oiaf/aeo/supplement/supref.html.

[8] The US possesses approximately 3% of the world's reserves of oil and natural gas each, but 25% of the world's reserves of coal. See *BP Statistical Review of Energy 2004*.

[9] EIA, *Annual Energy Outlook 2005*, Table A7.

[10] US DOE, *Strategic Plan*, p. 21.

[11] D.A. Hanson, *A Framework for Economic Impact Analysis and Industry Growth Assessment: Description of the AMIGA System*, Argonne National Laboratory, April 1999.

[12] J. Marshall Adkins, Wayne Andrews, and Jeffrey L Mobley, *Raymond James Energy Monthly – February 2005*, p. 4. See also Paul Sankey, "A Scratched Record…" Deutsche Bank: *Integrated Oil*, 10 July 2005.Both reports are available upon request. For comparison, the *Hydrogen Posture Plan* milestones are predicated on a natural gas price $4.00/mmBtu.

[13] See http://www.whitehouse.gov/news/releases/2002/02/20020214.html. Clear Skies cuts sulfur dioxide (SO2) emissions by 73 percent, to 3 million tons in 2018. Emissions of nitrogen oxides (NOx) by 67 percent, to 1.7 million tons in 2018, and Mercury (Hg) emissions by 69 percent, to15 tons in 2018. The scope of the initiative makes these targets more restrictive than EPA's current Clean Air Interstate Rule and Clean Air Mercury Rule

[14] US EPA, **EPA420-F-99-051**,*EPA's Program for Cleaner Vehicles and Cleaner Gasoline,* December 1999; **EPA420-F-00-057**, *Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*, December 2000, and EPA, **40 CFR Parts 9, 69, et al.** *Control of Emissions of Air Pollution from Nonroad Diesel Engines and Fuel; Final Rule*. **Federal Register** , Vol. 69, No. 124 , Tuesday, June 29, 2004 / Rules and Regulations. For gasoline, the sulfur limitations are an average of 30 parts per million (ppm) by 2006/7; for highway diesel, 15ppm by 2006, and for off-road diesel, 15ppm by 2010..

[15] Dale Keairns and Richard Newby, 2005, "Fuels and Electric Co-Production Plant Cost and Performance Projections," NETL working paper, available upon request

[16] *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options,* EPRI (Electric Power Research Institute) Palo Alto, California. 1000349. See Figure 2-1, p. 2-5.

[17] National Academy Of Sciences, 2002, *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards,* (Washington, DC: National Research Council, National Academy Press, 2002).

[18] US DOE, Office of Energy Efficiency and Renewable Energy, Office of Transportation Technologies, "Quality Metrics Report."

[19] US DOE, *Hydrogen Posture Plan,* pp. 19-21.

[20] Note this contradicts in some ways the assertions in Keith and Farrell, 2003, "Rethinking Hydrogen Cars" *Science*, Vol. 301, 18 July 2003, pp. 315-316. Of course, they were not considering optimizing under concomitant constraints.

[21] Keairns and Newby. Capture and sequestration is indeed less expensive at these facilities than at power-only IGCC plants. This is because the off-gas from the FT reactor has a very high CO2 content (>60 vol%) and relatively low CO content (< 10 vol%). Thus, little shift is needed to maximize the CO2 content in the gas. 95% of this off-gas can be captured.