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Coupling Hydrogen Fuel and Carbonless Utilities

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Executive Summary

A number of previous analyses have focused on comparisons of single hydrogen vehicles to petroleum and alternative fuel vehicles or of stationary hydrogen storage for utility or local power applications. LLNL's approach is to compare combined transportation/utility storage *systems* using hydrogen and fossil fuels. Computer models have been constructed to test the hypothesis that combining carbonless electricity sources and vehicles fueled by electrolytic hydrogen can reduce carbon emissions more cost effectively than either approach alone. Three scenarios have been developed and compared using computer simulations, hourly utility demand data, representative data for solar and wind energy sites, and the latest available EIA projections for transportation and energy demand in the U.S. in 2020. Cost projections were based on estimates from GRI, EIA, and a recent DOE/EPRI report on renewable energy technologies. Hydrogen technology costs were drawn from recent or ongoing analyses by Princeton University (Ogden 1995) and Directed Technologies Inc. (DTI) (Thomas 1998)for the Hydrogen Program.

The key question guiding this analysis was:

What can be gained by combining hydrogen fuel production and renewable electricity?

Bounding scenarios were chosen to analyze three "carbon conscious" options for the U.S. transportation fuel and electricity supply system beyond 2020:

Reference Case:	petroleum transportation & natural gas electric sector
Benchmark Case:	petroleum transportation & carbonless electric sector
Target Case:	hydrogen transportation & carbonless electric sector

A large number of assumptions were necessary to construct these scenarios, but preliminary model results indicate that if wind and solar electricity were massively deployed to replace fossil electric generation in 2020, and costs approached today's levels, a carbon tax of $86 billion/yr (applied over 0.49 GtC/yr or $175/tonneC) would be needed for solar and wind electricity to compare favorably to efficient combined cycle natural gas electric plants.

This picture becomes more favorable if electrolytically fueled hydrogen vehicles are also deployed. Coupling a hydrogen transportation sector to augmented solar and wind electricity sources improved flexiblity and utilization of renewables in a carbonless electricity system, reducing 75% more carbon emissions (0.86 GtC/yr) for only 10% greater system cost. The addition of hydrogen transportation fuel demand reduced carbon emissions further while lowering likely carbon tax rates ($/tonneC). Given future long-term petroleum fuel prices of $1.50-2.00/gal, carbon taxes of only $80-150/tonneC would be needed for solar and wind dominated carbonless electricity systems, combined with hydrogen production for vehicles, to compete with natural gas electric generation and petroleum vehicles.

Introduction

Conventional wisdom (e.g. Winter, 1988, Ogden 1989) has rationalized the pursuit of hydrogen energy systems as a solution to problems stemming from the use of fossil fuels: energy security, pollution, and greenhouse gas emissions. But advanced energy technologies using natural gas can be quite cost-effective albeit partial, solutions to these energy and environmental challenges. Cost-effective fossil energy technologies may seriously undercut the conventional rationale for widespread adoption of hydrogen energy systems.

The most notable example is probably natural gas vehicles which, while similar to hydrogen vehicles are likely to be more cost-effective at reducing air pollution, greenhouse gases, and oil imports. It is likely more cost-effective to begin reducing utility emissions through efficiency improvements, fuel switching to natural gas, and/or directly using relatively small amounts of solar and wind electricity (without energy storage), before producing hydrogen for transportation fuel or electricity load leveling (Thomas 1998).

It appears a strengthened rationale for hydrogen energy development can be constructed based on the need for deep greenhouse gas reductions - if significant synergies can be found between carbonless utilities and transportation coupled by hydrogen fuel (Berry 1996).

The largest benefit unique to hydrogen energy technology is the capacity for deep reductions in greenhouse gas emissions. The two largest greenhouse gas sources, utility electric generation and transportation fuel emissions, can be eliminated if electrolytic hydrogen and carbonless electric generation are sufficiently inexpensive. This analysis tests the hypothesis that carbon emission reductions can be more cost-effectively achieved if electrolytic hydrogen fuel production and electricity generation are closely coupled (see Figure 1). Our approach is to simulate transportation and utility sectors under a variety of cost, technology, and operational scenarios. The objective of this analysis is to determine the prerequisite economic and hydrogen technology developments for which this hypothesis can be relevant, and to identify corresponding hydrogen production, storage and utilization technology benchmarks.

Approach, Methodology, and Model Description

Approach: Aggressive Fossil, Renewable, and Hydrogen Scenarios

Three scenarios were constructed and used in our computer models of utility and transportation sectors, a reference, benchmark, and target case. These three scenarios were chosen as aggressive, mature, boundary cases. These scenarios test the widest range of possibilities that were most interesting, while maintaining a balanced basis for comparison, and keeping the analysis as simple as possible. If the results of these scenarios are sufficiently compelling then future analyses can explore more complex, detailed and perhaps more realistic transition scenarios. The year 2020 was chosen as the time period to analyze because of available EIA projections. 2020 also likely represents the fastest technically possible (and therefore most aggressive) transition to carbonless energy systems. It was felt that aggressive scenarios should be analyzed, since the a hydrogen transition will not be attractive unless technology development (.e.g. advanced electrolysis, low cost renewables, energy storage etc.) is successful. The fossil reference case used for coomparison was also aggressive for balance.

Each scenario had costs lower than today's energy systems. Aggressive technical and economic assumptions used in the benchmark renewable and target hydrogen scenarios included: high efficiency electrolysis, low cost renewable electricity and hydrogen storage, perfect demand and supply forecasting, etc. But the reference fossil energy case was equally aggressive, PNGV light-duty vehicle fleets are assumed, as well as very efficient use of natural gas to produce electricity. In line with EIA projections, no new capacity is assumed, in any scenario, for conventional carbonless electricity sources, such as nuclear or hydroelectric.

Methodology: Only the detail necessary to capture supply and demand patterns

Our computer models used only as much data as necessary to establish the rough magnitude of the benefits gained by coupling hydrogen fuel production with carbonless electrical sources. Real electricity demand and wind and solar supply data for an entire year, at hourly resolution, was necessary. Data representative of both a summer peaking (e.g. California) and winter peaking (e.g. Washington state) utility were gathered. Wind and solar data from "second tier" sites was chosen to approximate PV, solar thermal, and wind electricity sources based mostly in the West, Southwest, and Midwest. (Iannucci 1998) Detailed time zone and regional effects were neglected for simplicity. Transportation fuel use patterns were based on 12 hour resolution DOT data for passenger vehicles (Klinger 1984), and monthly EIA data for commercial vehicles (EIA 1998).

Model construction was kept as simple as possible. National aggregates for transportation and electricity demand were used. Single reservoirs of electricity and hydrogen production and storage capacity, scaled to the entire U.S., were used to represent thousands of solar thermal and wind farms, liquefaction facilities, and hydrogen filling stations used by millions of vehicles. Lumped national average costs for electricity transmission and distribution were used. Utility energy storage, when necessary was presumed to employ hydrogen storage and fuel cells. Decentralization of photovoltaics and hydrogen infrastructure was assumed to circumvent the complex issues of additional electricity transmission and distribution needs.

Financial calculations were kept as simple as possible. Operating costs were neglected where they were less than the resolution of capital cost or fuel estimates (typically ~10%). Capital investments were discounted at 6% over a cost-weighted average of ~25 years. Electricity prices reflected electricity transmission, distribution, conventional generation, and in the target scenario prorated electric and hydrogen generation and storage investments.

Model Description: Scenario simulation and optimization

LLNL used two computer modeling approaches in this analysis: simulation and multiperiod (e.g. 8760 hours) equilibrium optimization. Simulation provides faster but simpler results. Any given simulation model run simply provides the energy and economic performance of a given energy system configuration and operational rules. An optimization model run is slower and more complex, but can, in principle, determine the lowest cost configuration of technologies and operation of those technologies to meet given electricity and hydrogen demand time series. To date LLNL's network optimization code "METAnet" (Lamont 1994) is still being fine tuned for operational optimization of hydrogen electricity systems (A model schematic and typical optimization results are shown in figures 2-3). Optimal renewable energy system configuratios based on preliminary METAnet results appear capable of achieving costs 10-20% lower than simulation models, which may somewhat understate the attractiveness of intermittent electricity, and especially hydrogen fuel production, relative to conventional fossil fuel scenarios. Further development and analysis is needed. Consequently, the results generated from simulation models are used here.

The graphical interface simulation model software used for this study, STELLA, is commercially available (High Performance Systems Inc. of Hanover, NH). Visualization, conceptualization, and interconnection of technical, economic, or market variables is exceptionally easy. The value of each factor and its relationship to other factors are easily modified, allowing exploration of strategic parameter spaces such as production and storage scale, efficiency, discount rate, equipment lifetimes, fuel efficiency, and demand patterns. The model therefore allows dynamic analysis, and data can be easily updated.

Annual electricity flows from various sources (nuclear, hydroelectric, wind, solar thermal, and photovoltaic) to the electric grid and/or, stored as hydrogen (liquid, compressed, onboard, stationary etc.), and ultimately to transportation use in light-duty vehicles and commercial trucks, aircraft, and trains were modeled on an hour by hour basis. Supply and storage

Input Assumptions and Simulation Results

Preparation for a model run requires specification of equipment capacities, conversion efficiencies, and fuel use corresponding to a desired scenario. After each model run these paramaters were varied to explore the sensitivities of results to individual parameters and to achieve lower projected costs, more efficient operation etc. The final parameters chosen for each scenario and output results are given in Table 1. The data are discussed below.

Electricity Supply and Demand Assumptions

Solar and wind electricity generation patterns were based on annual data gathered at sites in California and Wyoming. as well as utility demand patterns from utilities in the Southwest and Northwest, provided by Distributed Utility Associates (DUA). These data were scaled up to meet the end-use electricity and hydrogen production needs based in EIA's reference case forecast for 2020. For example U.S. electric generation capacity is projected by EIA to be 993 GW in 2020 (up from ~700 GW today) (EIA 1998). This was rounded to 1 TW for simplicity and became thse scaling factor for both northern and southern utility demand pattern data from DUA. In the final results, southern utility demand data were used after model results were not strongly affected by which electricity demand pattern was used. Nuclear and hydroelectric capacity were taken from EIA data representing ~5% and ~10% of U.S. electric generating capacity in 2020 respectively.

During the simulation, in periods of insufficient renewable electricity, (windless nights, cloudy days etc.) electricity from fuel cells was produced using hydrogen in compressed (if available) or liquid stationary storage. In periods of excess electricity availability hydrogen was produced and stored.

Cost projections for renewable electric capacity were gathered by DUA using *Renewable Energy Technology Characterizations*(a joint project of EPRI and DOE). Natural gas fired electricity projections are from GRI. Transmission and generation electric costs were estimated by DUA, and scaled to meet a 1 TW peak demand (including coincident loads) (Iannucci 1998).

Hydrogen Transportation Fuel Demand and Use Assumptions

Transportation demand was modeled differently for different vehicle classes. Light-duty vehicle travel patterns (for days, nights, weekdays, and weekends) were taken from the 1983 Nationwide Personal Transportation Study (NPTS) completed for the National Highway Traffic Safety Administration (Klinger 1984). These patterns were then scaled to 12,000 miles/yr for a projected 270 million light-duty vehicles in 2020., equalliing the 3.24 trillion vmt projected y EIA for 2020. Drawing from the 1983 NPTS data, it was assumed that 15% (1800 miles/yr for an average driver)of vmt was due to long trips (<75 miles) and would require liquid hydrogen. PNGV fuel economy (~80 mpeg) was assumed for hydrogen vehicles.

Commercial vehicle fuel demand was approximated using monthly energy demand patterns from 1995-1997 for diesel (trucks and trains), and jet fuel (aircraft) using EIA data, and aggregate projections of fuel demand in 2020. Trucks and trains were are powered by compressed hydrogen, with the same fuel economy projected by EIA for diesel fueled vehicles.. Aircraft were fueled by liquid hydrogen, a 10% higher fuel economy than EIA projections due to hydrogen's low mass.

Hydrogen refueling patterns were identical to fuel use patterns (so that vehicles were essentially always full) except for light-duty vehicles which refueled less when station supplies were low for a few days, presuming a high fuel price sensitivity for drivers. Onboard hydrogen storage equipment costs for passenger vehicles and commercial trucks were included in the model.

Scenario Assumptions

Reference Scenario (natural gas electricity and petroleum transportation)

The reference scenario was the simplest because no intermittent resources were used. It was designed to be a strong competitor to carbonless electricity and hydrogen scenarios. In the reference scenario all transportation needs are met by petroleum. Light-duty transportation fleet efficiency has increased to PNGV levels (80 mpg or roughly 3 times greater than EIA projections for 2020). Petroleum demand for trucks, trains, and aircraft were taken directly from EIA projections. All electricity demand was met by natural gas combined cycle plants with an average 57% efficiency. Natural gas prices in 2020 were $3.05/GJ as per EIA projections. A key optimistic assumption was that greenhouse gas emissions from natural gas (methane)leakage would be negligible (methane is believed to be 10-20 times more potent than carbon dioxide as a greenhouse gas). In our aggressive reference scenario passenger vehicle efficiency and the efficient use of natural gas by utilities combine to reduce carbon emissions from transportation and utilities to only 870 mmtC/yr, compared to 1400 mmtC/yr projected by EIA for 2020 (EIA 1998).

Benchmark Scenario (solar, wind electricity and petroleum transportation)

The benchmark scenario assumes that all electricity demand is met by a mixture of solar thermal, wind, and photovoltaic (PV), instead of natural gas, as in the Reference Scenario. To meet a 1 TW capacity requirement, 0.85 TW of wind and 0.35 TW of solar thermal are assumed, as well as 0.15 TW (combined) of hydroelectric and nuclear. These capacities were chosen to match transmission and distribution capacity. A relatively small balance of electricity demand is supplied by distributed PV (0.05 TW). Utility energy storage is accomplished with steam electrolysis (Quandt 1986), and compressed or liquid hydrogen storage, as well as fuel cells.

Transportation demand was met by petroleum, exactly as in the reference scenario. Carbon emissions were 370 mmtc/yr.

Target Scenario (solar, wind electricity and hydrogen transportation)

The benchmark scenario assumes that all electricity demand is met by a mixture of solar thermal, wind, and photovoltaic (PV), instead of natural gas, as in the Reference Scenario. To meet a 1 TW capacity requirement, 0.85 TW of wind and 0.85 TW of solar thermal are assumed, as well as 0.15 TW (combined) of hydroelectric and nuclear. These capacities were chosen to match transmission and distribution capacity. A relatively small balance of electricity demand is supplied by distributed PV (1.8 TW). Utility energy storage, is accomplished with steam electrolysis, and compressed or liquid hydrogen storage, as well as fuel cells. Hydrogen not needed for electricity production is used as transportation fuel. Compressed hydrogen was used for 85% of light-duty vehicle fuel demand and all commercial trucking, while liquid hydrogen was used in aircraft and for long distance light-duty vehicle trips. As an efficiency measure liquid hydrogen was only converted from ortho to para phases when necessary for long-term storage. Carbon emissions from transportation and electricity production were, of course, zero for this scenario.

Scenario Results

Summary energy balances, costs and emissions results from each scenario's computer model runs are given below. Detailed assumptions and output parameters are given in Table 1.

Reference Scenario (natural gas electricity and petroleum transportation)

In the 2020 reference scenario, assuming utility natural gas prices are $ 3.05/GJ, the U.S. can meet its 5 trillion kWh/yr electric demand (1 TW peak) with efficient combined cycle natural gas turbines at a cost of $192 billion/yr, and utility carbon emissions of 490 mmtC/yr. Land and air transportation demands are all met with only 144 billion gallons of petroleum/yr (due to PNGV light-duty vehicles) with attendant with carbon emissions of 370 millon metric tonnes per year (mmtC/yr). Fuel costs @1.50/gallon would be another $216 billion/yr. The vast majority of petroleum demand is shared roughly equally between commercial trucks and aircraft. Passenger cars and trucks only account for <10% of petroleum use.

Total annual cost is ~$420 billion/yr with total carbon emissions of 0.86 GtC/yr.

Benchmark Scenario (solar, wind electricity and petroleum transportation)

In the 2020 benchmark scenario, U.S. electric generation is completely carbonlesss relying on small amounts of remaining hydroelectric and nuclear capacity, 850 GW of wind, 330 GW of solar thermal plants and 50 GW of photovoltaics to meet the same 5 trillion kWh/yr electric demand (1 TW peak). Daily and seasonal energy storage is accomplished using 1.5 billion kWh of compressed hydrogen and 275 billion kWh of liquid hydrogen storage. Roughly 7% of all electricity is lost in energy storage and reconversion. the capital investment for electric generation and hydrogen storage is estimated to be $ 3.2 trillion, resulting in annual electric costs of $290 billion. All land and air transportation fuel demands are met by petroleum, just as in the reference scenario, with petroleum costs of $216 billion/yr (@$1.50/gallon) emitting 370 million metric tonnes of carbon annually.

Total annual cost is therefore ~$506 billion/yr with carbon emissions of 0.37 GtC/yr.

Target Scenario (solar, wind electricity and hydrogen transportation)

In the 2020 target scenario, U.S. electric generation and transportation by car, truck and aircraft are completely carbonless. The electric generation system postulated in the benchmark scenario is augmented in the target scenario to provide electricity for additional hydrogen production, storage, and use. Solar thermal capacity is tripled to 0.85 TW, and photovoltaic capacity is expanded dramatically to 1.8 TW to meet additional electricity demands without transmission and distribution expansion. Two-thirds of electricity production is from solar thermal central receivers and distributed photovoltaics. Daily and seasonal energy storage is accomplished using 4 billion kWh of compressed hydrogen storage at refueling stations and 750 billion kWh of liquid hydrogen storage at stations and utilities. 11 trillion kWh of electricity is produced annually, of which 5 trillion kWh is used directly, less than 1% of end-use electricity is lost through storage and reconversion by fuel cells. The remaining 7 trillion kWh of electricity are used to produce 4.6 trillion kWh of hydrogen for transportation use, meeting transportation demands identical to the reference case. Roughly half of hydrogen is liquefied for aircraft and long car trips, while half is used in commercial trucks and for short distance urban trips (<75 miles one-way) in light-duty vehicles.

The estimated $6.6 trillion coupled carbonless electricity and transportation fuel system has levelized costs (combined for both electricity and hydrogen fuel supply) of ~$550 billion/yr and produces no carbon emissions (offsetting 860 million metric tonnes of carbon from the reference scenario).

Key Results, Conclusions, and Recommendations

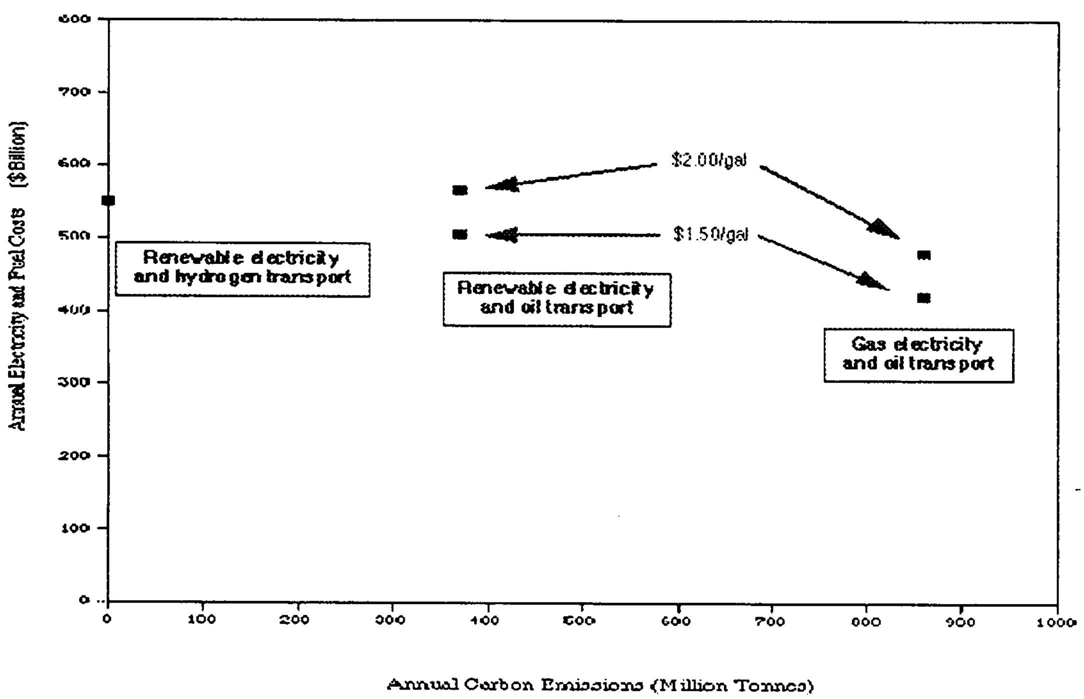
Key Results

The three scenario model runs summarized earlier, when taken and compared together, yield two key results:

1) It appears that, given inexpensive long-term oil and gas prices, improved natural gas electricity sources and very efficient (~80 mpg) passenger cars and trucks can be very competitive, producing lower carbon emissions in 2020 (0.86 GtC/yr than the same sectors do today (0.98 GtC/yr) in spite of 50% higher electricity and travel demand. However, even given this extremely aggressive fossil scenario, it will be difficult to reduce carbon emissions below 0.86 GtC/yr without sequestration (likely creating a hydrogen transportation sector), improved electric generation efficiency (likely requiring utility fuel cells), improved aircraft and freight transportation efficiency (reducing the fuel cost barrier to hydrogen use), and/or widespread use of renewable electricity sources (creating a surplus for hydrogen production)

2) If such deep carbon reductions are needed, it appears coupling electrolytic hydrogen fuel production to solar and wind electricity can achieve much greater carbon reductions more cost-effectively than solar and wind electricity alone. Given petroleum fuel prices of $1.50/gallon in 2020 the hydrogen-based target scenario reduced 75% more carbon emissions than the benchmark scenario for only ~10% higher cost. These results are more striking because they illustrate the potential advantages of hydrogen-fueled vehicles even in scenarios where most carbon reductions are made in the electric sector, and PNGV light-duty vehicles (the likeliest market for hydrogen fuel to penetrate) are only 1/3 of transportation carbon reductions.

These results are likely dependent upon solar, wind, and hydrogen cost assumptions as well as fossil fuel prices and carbon taxes or credits.. The figure below plots the estimated annual cost and carbon emissions of all three scenarios for petroleum fuel prices of $1.50-$2.00/gallon.



Annual cost vs. emissions for reference, benchmark, and target scenario model runs and long-term petroleum fuel prices ranging $1.50-2.00/gallon.

Key Results (Con't)

The previous plot shows that for long-term petroleum fuel prices comparable to $1.50/gal, renewable hydrogen and electricity is more cost-effective at carbon reduction than renewable electricity alone, even given optimistic renewable electricity costs and low discount rates (6%). If future petroleum fuel prices rise high enough (to ~$2.00/gal) using hydrogen vehicles could actually lower the effective cost of renewable electricity while reducing carbon emissions. The previous plot also indicates carbon reduction differences between scenarios are much greater than cost differences.

Cost differences are greatest between the fossil reference scenario and the others. These differences are principally dependent on fuel price assumptions ($3.05/GJ for natural gas and $1.50/gal for transportation petroleum) and efficiencies. It should be emphasized that no efficiency advantage was presumed for hydrogen vehicles (except for aircraft) in comparison to their petroleum-powered counterparts, and no upstrea,m carbon emissions or methane leakage were accounted for in the reference scenario.

Cost differences between the scenarios with hydrogen transportation (target scenario) and without it (benchmark)are again influenced somewhat by fuel prices, but this sensitivity is lessened due to the common technology assumptions employed in both (e.g. low-cost, efficient electrolyzers, advanced wind electricity etc.). Only under the unlikely conditions of simultaneously low oil prices and high interest (discount) rates, would the two cases compare substantially differently.

Interestingly, even though the renewable and hydrogen intensive target scenario has a greater proportion of high cost renewable electricity sources (e.g. solar) and greater energy storage rquirements than the benchmark scenario, it still had lower overall (combined transportation and electricity) costs. This supports the synergy hypothesis for the target scenario: that hydrogen fuel demand by vehicles can be a net benefit for renewable electricity systems. This also indicates that integrated hydrogen transportation/utility systems may be more attractive than stationary hydrogen utility storage alone.

Conclusions

High efficiency and coupling vehicles to utilities are most important

Although further sensitivity analyses and other refinements, such as new, nearer-term scenarios should provide an even clearer picture, two conclusions can be drawn from the results so far:

1) Super efficient hydrogen production and storage, and use are necessary for hydrogen to compete in both utility and transportation markets, even if optimistic renewable electricity targets are met. All of the efficiencies (liquefaction, electrolysis etc.) used in the hydrogen scenarios were best case. For reasons of end-use efficiency compressed hydrogen was used in the simulations wherever possible, as was only partially para converted liquid hydrogen.

2) Unless long term fossil fuel prices are very low *and* hydrogen vehicles have no efficiency advantage over fossil vehicles, coupling hydrogen fuel production to carbonless sources can be a substantial benefit. Carbon taxes would be reduced, and might even be eliminated depending upon relative hydrogen/fossil fuel prices and efficiencies.

Recommendations

Technology Development Needs

High efficiency, electrolysis, in some cases distributed on a small scale, is crucial. Cost targets for electrolysis of ~$500/kW and efficiencies of at least 90% are likely necessary. Hydrogen storage is secondary but still of significant importance. Light-duty vehicles and commercial trucks which could use compressed hydrogen as much as possible would be an important efficiency step. Bulk hydrogen storage cost targets (e.g. liquid hydrogen) for very large vessels, of ~$10/kg H2 stored are necessary, unless future demand and supply patterns can be better matched than in the scenarios used here. Compressed hydrogen storage costs projected by others (Thomas 1998) of $100-150/kg H2 were sufficient.

Systems Analysis Needs

This analysis has shown that significant environmental and economic advantages can exist for renewable electricity sources, when coupled with hydrogen fuel production for vehicles. The next step is a clearer understanding of these advantages, their requirements, and their limitations, under economic optimization conditions. A wide range of future analysis directions are possible. Hydrogen technology cost benchmarks can be determined as a function of fossil fuel prices and allowable carbon taxes. A determination of the importance of small amounts dispatchable carbonless electricity sources in the generation mix can be made. Transition scenarios for hydrogen vehicles and renewable electricity sources can be examined. LLNL plans to further develop its equilibrium optimization code to be able to answer these and similar questions.

Some new technical options could also be very important to examine in the future. One promising candidate would be a close-coupled steam electrolyzer/fuel cell using natural gas to produce electricity at night, storing waste heat to improve electrolysis efficiency during the day, when solar electricity is available, and in turn storing oxygen to improve fuel cell efficiency during the night. This could dramatically enhance the attractiveness of hydrogen production from renewable electricity, while providing a very efficient synergy with both fuel cells and natural gas utilities.

The most important market options to analyze will likely be the impact of small changes in seasonal demand patterns upon energy storage requirements, as well hydrogen fuel use in individual sectors of the transportation market.

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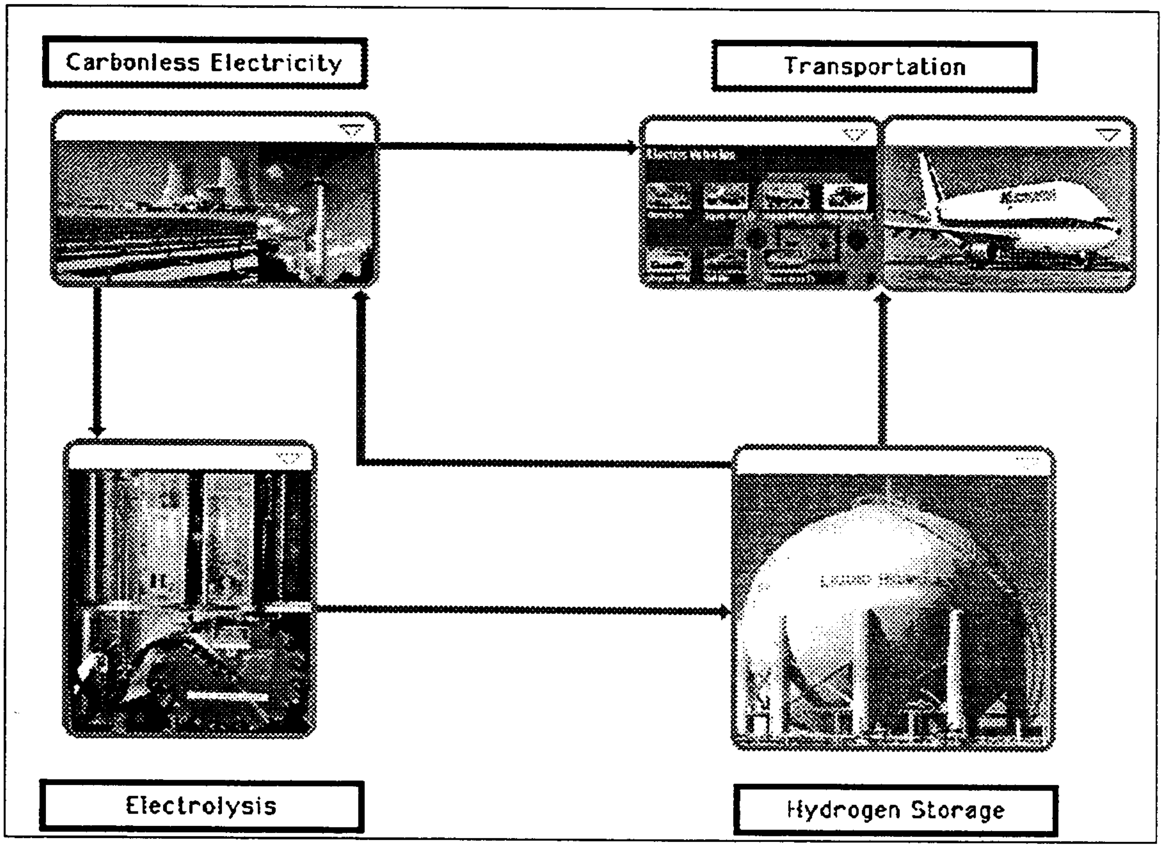

Figure 1. Conceptual representation of a coupled carbonless electricity and hydrogen transportation system and flows of electricity and hydrogen. Electricity generated from nuclear, solar, wind, or other carbonless electricity sources meets electricity grid needs first. Surplus electricity can either directly fuel batteries or other electric storage on vehicles or produces hydrogenfor ultiimate storage and use on vehicles. In periods of low solar and wind availability, stored hydrogen can be reconverted to electricity for use on conventional electricity grid.

Note: A number of additional options are not pictured. These include: hydroelectric and biomass generation, as well as mixed systems of compressed and liquid hydrogen storage, and hydrogen use by commercial trucks, in addition to aircraft and light duty vehicles.

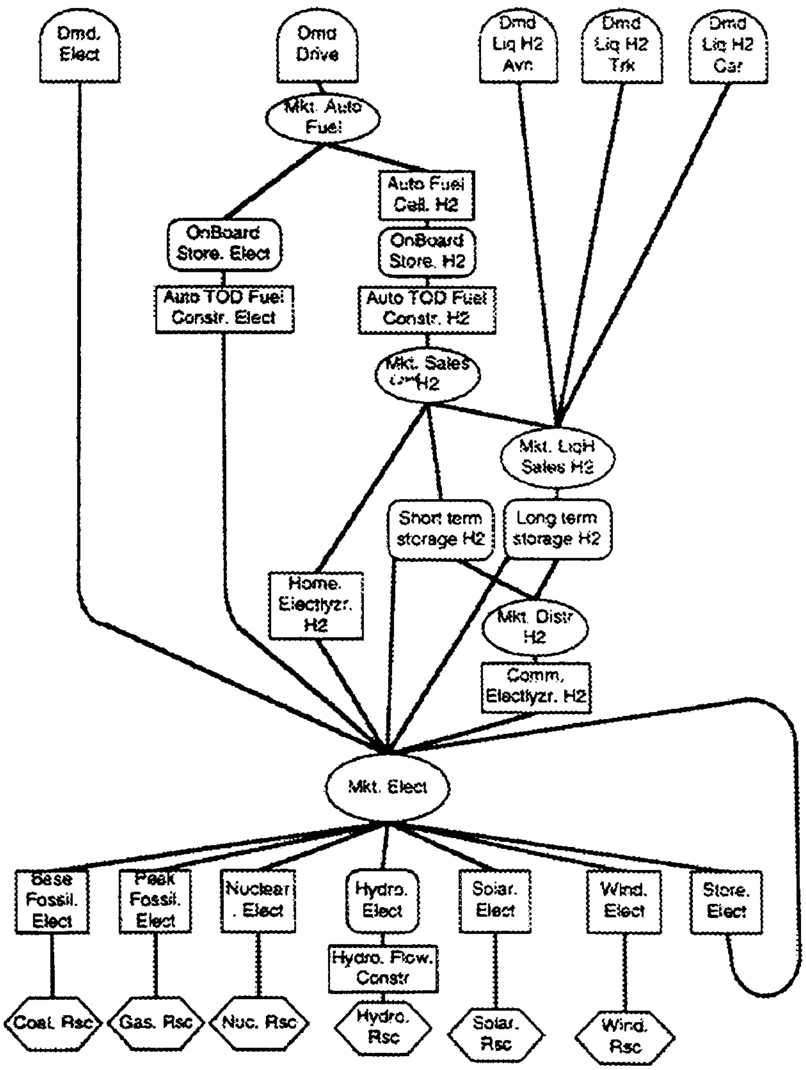

Figure 2. Conceptual schematic of a network optimization model approach to electricity and transportation systems. Electricity and hydrogen demand nodes (top) send demand quantities down through the network which are met from a number of sources supplying market nodes (e.g. Mkt. Elect.) these sources are technologies with costs and technical capabilities (capacity, efficiency etc.) of converting available resources (e.g. sun, wind, coal, gas etc. depicted as resource nodes at bottom) which are used according to resource prices and availability. These prices are then sent back up the network to the demand and storage nodes, which can adjust demand to repsond to availability and prices. This cycle is iterative, converging to a lowest cost equilibrium between supplies and demands.

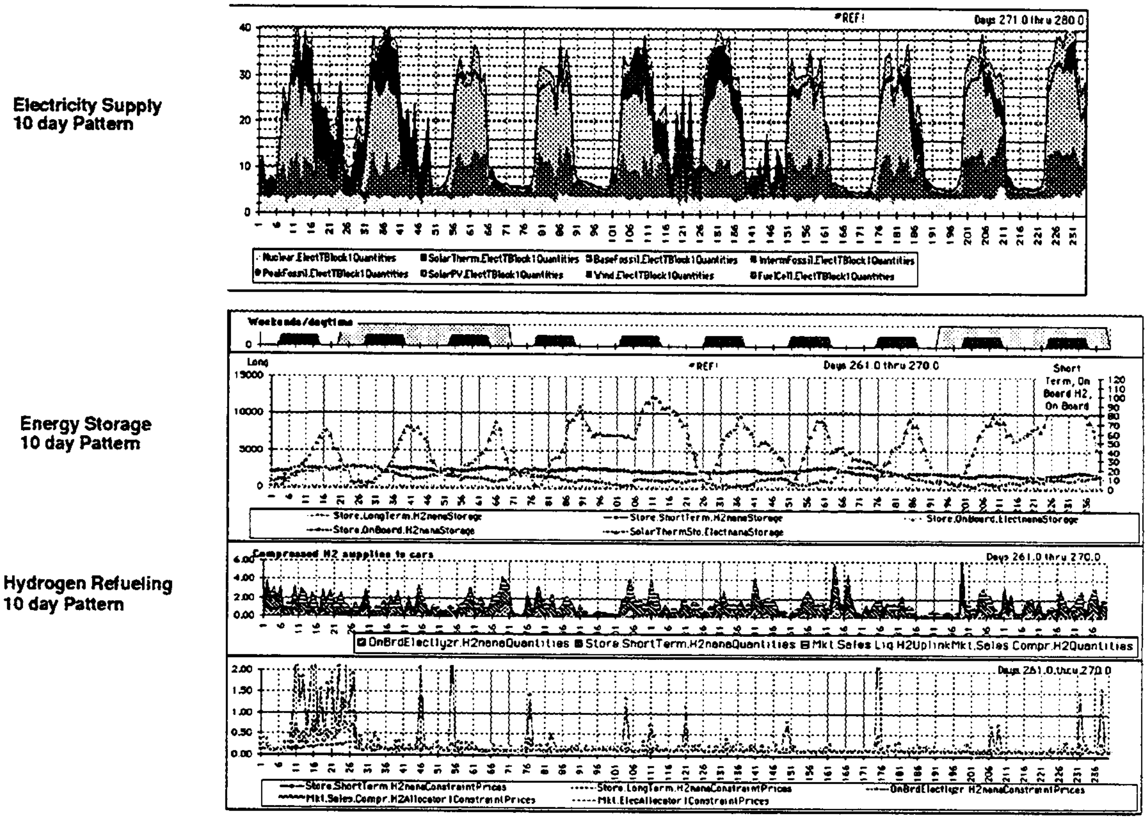

Figure 3. Typical output from LLNL's METAnet equilibrium network model. A 10 day period of hourly electric generation,, stationary and onboard energy storage, and refueling and prices are shown. A scenario run typically covers an entire year (36 of the above periods), Many runs are used to arrive at optimal capacities of electricity and hydrogen production and storage.

Table 1. System parameters used in computer model scenarios

Scenario		**Reference**		**Benchmark**		**Target**	
Electricity Demand (trillion kWh/yr)			5		5		5
Electric Supply (TW, trillion kWh/yr)			5		5.8		11
Natural Gas	($600/kW, $3.05/GJ)	1.0	5	-	-	-	-
Nuclear	($2000/kW)	-	-	0.05	0.44	0.05	.44
Hydroelectric	($2000/kW)	-	-	0.10	0.90	0.10	.90
Wind	($655/kW)	-	-	0.85	3.2	0.85	3.2
Solar Thermal	($2510/kW)	-	-	0.35	1.1	0.85	2.4
Solar Photovoltaic	($1110/kW)	-	-	0.05	0.12	1.8	4.3
Fuel Cells *	($200/kW)	-	-	1.0	(0.48)	1.0	(0.06)
Transportation Demand (trillion kWh/yr)		oil		oil		hydrogen	
Light-duty vehicles (urban)		1.16		1.16		1.16	
Light-duty vehicles (highway)		0.20		0.20		0.20	
Commercial trucks & rail		1.64		1.64		1.64	
Aircraft		1.45		1.45		1.63	
Hydrogen Supply (TW, kWh/yr)							
Electrolysis ($500/kW, 92% eff)		-	-		1.0		1.2
Compression ($100/kw 92%)		-	-		1.0		1.2
Liquefaction ($500/kW, 78 eff%)		-	-		1.0		1.0
Hydrogen Storage (kWh LHV H2)							
Onboard light-duty fleet ($150/kg H2)		-		-		15 billion	
Stationary Compressed ($150/kg H2		-		1.5 billion		4 billion	
Stationary liquid hydrogen ($10/kg H2)		-		275 billion		750 billion	
End-use Electricity Cost ($Billion/yr) (@6% discount rate)		192		290		225	
Transportation Fuel Cost (@$1.50/gal petroleum fuel)		216		216		225	
Electricity Carbon Emissions (GtC/yr)		.49		0		0	
Transportation Carbon Emissions (GtC/yr)		.37		.37		0	
Total Annual Carbon Emissions		.86		.37		0	
Total Cost ($Billion/year)		$420		$506		$550	
Breakeven Carbon Tax ($/tonneC)		-		$175		$150	