Hydrogen: The Future of Energy

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Why is hydrogen so important?

- New, highly versatile energy carrier
- Cleaner, safer and cheaper fuel choice
- When combined with super-efficient fuel cell vehicles, enables a profitable transition from oil — profitable even for oil companies
- In a hydrogen economy, U.S. energy needs can be met from North American energy sources (including local ones), providing real security
- Hydrogen can accelerate renewable energy sources, which also have stable prices
- Hydrogen-ready vehicles can revitalize Detroit
The hydrogen cacophony (see “Twenty Hydrogen Myths,” www.rmi.org)

- Rapidly growing interest due to climate and security concerns
- Unfamiliar terms and concepts, many disciplines
- Speculation: winners, losers, hidden agendas?
  - Reinforce dominant incumbents, displace, or diversify?
  - Foolishness, panacea, or misleading and double-edged?
- Debate is overlaid on rancorous old debates
  - Oil, nuclear, renewables, climate, big business, right/left,...
- Unexpected realignments, strange bedfellows
  - Environmentalists: If President Bush, oil companies, and the nuclear industry like it, it must be bad
  - Wall St. J. editorial: If enviros like it, it must be bad
- Both advocates and opponents often poorly understand it!
We already have, invisibly, a partly hydrogen economy

- Two-thirds of the fossil-fuel atoms being burned today are hydrogen...as a part of hydrocarbons
- A large hydrogen industry exists today: it produces 1/4 the annual volume of the natural-gas industry worldwide
- The debate is about:
  - Whether we also need to combust the last third (carbon)
  - Whether it might be cheaper and more attractive not to burn the carbon, but to use only the hydrogen
  - To what degree and at what speed the fossil-fuel hydrogen should be replaced by renewable hydrogen
  - How renewable hydrogen will compete with hydrogen produced by nuclear fission (or eventually fusion?) power
  - At what scale
  - Who does it
  - Who decides and how
I’ll address pervasive myths with answers to eight questions:

◊ What is hydrogen?
◊ Is hydrogen safe?
◊ Why is hydrogen cheaper to use for vehicles?
◊ How is hydrogen now produced and used?
◊ What is the least-cost way to make and deliver hydrogen?
◊ What technologies are needed to enable a hydrogen transition?
◊ How can the U.S. profitably transition from oil to hydrogen?
◊ Are there enough North American primary energy sources for this transition?
What is it? Basic hydrogen facts

◊ Hydrogen is ~75% of the known universe

◊ On earth, it’s not an energy source like oil or coal
  ○ Only an energy carrier like electricity or gasoline — a form of energy, derived from a source, that can be moved around

◊ The most versatile energy carrier
  ○ Can be made from any source and used for any service
  ○ Readily stored in large amounts
  ○ Fungible with the other highest-quality carrier, electricity

◊ Almost never found by itself; must be liberated
  ○ “Reform” HCs or CHs with heat and catalysts
  ○ “Electrolyze” water (split H₂O with electricity)
  ○ Experimental methods: photolysis, plasma, microorganisms,...

◊ Can be made and used at any scale
Physical attributes of hydrogen

◊ Transparent, colorless, odorless, nontoxic
◊ Molecular hydrogen (H₂) is the lightest element and molecule
  ○ Per unit of energy contained, H₂ is 64% lighter than natural gas or 61% lighter than gasoline
◊ 1 kg of H₂ contains same energy as 1 U.S. gallon of gasoline, which weighs not 2.2 but 6.2 pounds
◊ The flip side of lightness is bulk
  ○ H₂ has 30% the energy of CH₄, both at atmospheric pressure
  ○ H₂ at 170 bar pressure has 6% the energy/volume of gasoline
◊ H₂ is advantaged if lightness is worth more than compactness
Is it safe?: A primer on Hydrogen safety

◊ All fuels are hazardous, but...
◊ Hydrogen is comparably or less so, but different
  o Buoyant (8× CH₄), diffusive (4×CH₄, 12× gasoline)
  o Clear flame can’t sear you at a distance; no smoke
  o Hard to make explode; can’t explode in free air; burns first
  o 4× gasoline-fume concentration required to burn; 22× less explosive power
  o Rises, doesn’t puddle
  o Hindenburg myth (1937) — nobody was killed by hydrogen fire
  o Completely unrelated to hydrogen bombs
Demonstrating hydrogen vs. gasoline safety


3 s: Ignition. $H_2$ @ 28 L/min, gasoline @ 0.68 L/min

60 s: $H_2$ flow subsiding; max 47°C on rear window, 19.4°C on tray behind rear seat. Zooming in on gasoline car…

90 s: $H_2$ plume nearly stopped.

140 s: Gasoline-car interior alight. Tires later burst.
Why is it cheaper? Basic hydrogen economics

- The most common fallacy is comparing hydrogen to other fuels in cost per unit of energy contained.
- What matters is cost per unit of service provided.
- E.g., a hydrogen fuel cell can propel a car 2–3× as efficiently as a gasoline engine car, so even if H₂ cost twice as much per unit of energy, it would cost the same or less per mile driven.
- Recovered heat from the fuel cell (and reformer), clean and silent operation, high-quality and ultra-reliable power supply, and many other “distributed benefits” may also have a big value.
Hydrogen cars will be cheaper per mile driven

◊ Gasoline

- Gasoline
- Diesel

![Diagram]

- Liquid fuel
- Retail site: $1.00/gallon (pretax)
- Vehicle: Avg. 20 mpg

= 5¢ per mile
Hydrogen cars will be cheaper per mile driven

◊ **Gasoline**

- Liquid fuel
  - Gasoline
  - Diesel

  Retail site: $1.00/gallon (pretax)

  Vehicle: Avg. 20 mpg

  = 5¢ per mile

◊ **Reformation**

- Liquid or gas fuel
  - Natural Gas
  - Biofuel

  Retail site reformer: 72% (LHV) conversion eff.

  Hydrogen:
  - $2.5/kg of H₂
  - ~$2.5/gallon gasoline

  Vehicle: 5× efficient

  100 mpg

  = 2½¢ per mile
Well-designed hydrogen cars will be cheaper per mile driven

**Gasoline**

- Liquid fuel
  - Gasoline
  - Diesel
- Retail site: $1.00/gallon (pretax)
- Vehicle: Avg. 20 mpg

**Reformation**

- Liquid or gas fuel
  - Natural Gas
  - Biofuel
  - $6/million Btu
- 72% (LHV) conversion eff.
- Retail site reformer
- Hydrogen
- Vehicle

**Electrolysis**

- Low cost power
- Retail site electrolysis
- Hydrogen
- Vehicle

- Hydro
- Offpeak wind
  - 3¢/kWh del.’d.
- 70% (LHV) conversion efficiency
- $3.2/kg of H₂
- 5x efficient
- 100 mpg

Gasoline: $1.00/gallon (pretax) Avg. 20 mpg = 5¢ per mile

Reformation: $2.5/kg of H₂ 5x efficient 100 mpg = 2½¢ per mile

Electrolysis: $3.2/kg of H₂ 5x efficient 100 mpg = 3¢ per mile

Costs:
- $3.2/kg of H₂ ~$3.2/gallon gasoline
- Offpeak wind: 3¢/kWh del.’d.
- 70% (LHV) conversion efficiency
- Natural Gas: 72% (LHV) conversion eff.
- Biofuel: ~$2.5/gallon gasoline
- Hydro: 70% (LHV) conversion efficiency

Conversion efficiencies:
- Gasoline: 5¢ per mile
- Reformation: 2½¢ per mile
- Electrolysis: 3¢ per mile
# Well-to-Wheels Efficiency

<table>
<thead>
<tr>
<th>Well to Tank (%)</th>
<th>Tank to Wheel (%)</th>
<th>Well to Wheel (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Gasoline Vehicle</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Prius</em> (Gasoline HV)</td>
<td>88</td>
<td>16</td>
</tr>
<tr>
<td><em>FCHV-4</em></td>
<td>88</td>
<td>30</td>
</tr>
<tr>
<td><em>FCHV</em> (Target)</td>
<td>58*¹</td>
<td>38*²</td>
</tr>
<tr>
<td><em>3 x Gasoline, 1.5 x HV</em></td>
<td>70</td>
<td>60</td>
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*With HV control*  

Source: Toyota Motor Corp. presentation at Shanghai Fuel Cell Vehicle Forum, 4–5 December 2002

*1 Natural gas base  *2 Measurement from the electric current
How is hydrogen now produced?

World

- Natural Gas
- Oil
- Coal
- Electricity

~50 million tonnes/y global H₂ output, growing ~6–7%/y

U.S.

8% of U.S. natural gas is used to make H₂
How is hydrogen now used?

World

- Ammonia fertilizer
- Oil refining
- Chemicals
- Food, microchips, metals, etc.

U.S.

~7 million tonnes/y used to make gasoline and diesel fuel
“Making hydrogen uses more energy than it yields”

◊ Of course! The laws of physics require that any conversion from one form of energy to another yield less useful energy than you start with — otherwise it’d be a perpetual-motion machine
  - Making gasoline from crude oil is ~73–91% efficient
  - Making coal into delivered electricity is ~29–35% efficient
  - We make these energy carriers because they’re worthwhile

◊ Hydrogen production is quite efficient
  - ~70–82% efficient from natural gas, 75–80+% from electricity (but ×1.15 to measure the same way as for fossil fuels)
  - The rest is heat that may also be recaptured and reused
  - Conversion efficiencies continue to rise; losses may be halved

◊ H₂’s 2–3× greater end-use efficiency in fuel cells richly justifies the costs and losses of producing it
How to make least-cost H\textsubscript{2}

- Proven, cost-effective, climate-safe methods already exist

1. Reform natural gas at the wellhead and reinject the CO\textsubscript{2}
   - Reforming (~8% of U.S. gas now) & reinjection (32 MT/y) are mature
     - Potentially three profit streams: H\textsubscript{2}, +CH\textsubscript{x}, –C

2. Electrolyze with climate-safe electricity (hydropower, offpeak windpower)
   - Greatly improves renewable economics if electricity is converted to H\textsubscript{2} and sold as motor fuel
     - U.S. gasoline at $1.25/gallon is equivalent at the wheels to $0.09–0.14/kWh electricity with a proton attached to each electron — so run dams in “Hydro-Gen” mode, shipping compressed hydrogen (a value-added product) instead of kWh (a raw commodity)
     - H\textsubscript{2} storage makes wind/PV power firm and dispatchable

3. In the future, hydrogen from coal, oil, and biomass (and perhaps experimental solar methods) will further hone competition...but we need only one solution and have at least two
“Hydrogen takes too much energy to deliver”

◊ The Myth: since H₂ is so light, “its physical properties are incompatible with the requirements of the energy market...because production, packaging, storage, transfer and delivery...are so energy consuming....” — Bossel & Eliasson

- They catalogued the delivery methods that the industry has already rejected for this reason (outside special niche markets) — very long pipelines, liquid H₂, steel tube trucks,...

- They considered only the costliest production method (electrolysis, which has 4% of the world market)

- They considered only centralized production, incurring its high distribution costs

- Their assessment is useful for helping others to understand (as hydrogen experts already do) how not to design a hydrogen economy, but gives no reasons not to design one correctly
How should we deliver hydrogen?

◊ Use the cheapest method by fully utilizing the existing, paid-for gas and electricity infrastructure

◊ Both centralized and distributed architectures
  o Centralized natural-gas reformers may or may not ultimately prove cheaper and more efficient than miniature ones
  o Distributed solution: small-scale reformers and electrolyzers
  o Cost <10% of a gas station’s capital cost, or ~2⅓% of the investment in the station plus its upstream oil supply
  o As with diesel fuel, fewer than one-third of filling stations need conversion
  o Deutsche Shell said it could install hydrogen in all German stations in two years
  o Integrate with deployment of fuel cells in buildings

◊ Central solution: merchant hydrogen production at refineries near urban centers with pipelines
Fuel cells — key to the hydrogen transition

- The most efficient way to make electricity; ~50–70% efficient (the rest is recoverable heat)
- Extremely reliable, virtually silent, few or no moving parts, no combustion
- Fully scaleable
Fuel cells are already viable

Fuel Cell Competitive Price Points

- Portable Electronics
- Portable
- Durable
- C&I Reliability/Power Quality
- Distributed Generation
- Cheap
- Ubiquitous?
- Transportation

The more “distributed benefits” you count, the higher fuel-cell price you can tolerate
The more efficient your vehicle, the higher fuel-cell price you can tolerate

5/03: 156 kinds of demonstration or concept fuel-cell cars, 68 hydrogen filling stations

We can make the price drop happen faster and more surely...
Making cars ready for hydrogen

- **Standard fuel-cell car:** insert fuel cell in near-normal, high-tractive-load platform
  - Fuel cell is too big and costly, so must sell many units at a loss (or wait a long time) to bring cost down
  - H₂ tanks are too big to package, so need onboard methanol or gasoline reformer
  - Reformers hell

- **Direct-hydrogen fuel-cell car:** ultralight, ultra-low-drag platform can use any driveline and fuel, but is peculiarly well suited to direct-hydrogen fuel cell
  - Fuel cell is small enough to afford, even at early prices
  - Now-commercial H₂-gas tanks for normal range are small enough to package — no storage problem
  - No reformer, high efficiency
  - Can produce cars as soon as fuel cells are ready
An uncompromised, same-cost, 5×-efficiency midsize SUV

- 5 adults in comfort, up to 69 ft³ of cargo
- hauls 1,012 lb up a 44% grade
- 1,889 lb (47% mass of Lexus RX300)
- sim. head-on wall crash @ 35 mph doesn’t damage passenger compartment
- sim. head-on collision with car 2× its mass, each @ 30 mph, prevents serious injury
- 0–60 mph in 8.2 seconds
- 99 mpg (2.38L/100 km, 42km/L, 5×RX300)
- 330 mi on 7.5 lb safely stored 5-kpsi H₂
- 55 mph on just normal a/c energy
- zero-emission (hot water)
- sporty, all-wheel digital traction
- ultra-reliable, software-rich, flexible
- wireless diagnostics/upgrades/tuneups
- 200k-mi warranty; no fatigue, dent, rust
- competitive manufacturing cost expected
- decisive mfg. advantages—≤90% less capital, space, assembly, parts count
- initial production could ramp up ~2007

An illustrative, production-costed, manufacturable concept car developed for a few million dollars in eight months in 2000 by Hypercar, Inc. (www.hypercar.com) — on time, on budget, with attributes never before combined in a single vehicle
55 mph on same power as normal a/c, so ready now for direct hydrogen fuel cells

- 35-kW load-leveling batteries
- 137-liter 5-ksi H₂ storage (small enough to package)
- 35-kW fuel cell (small enough to afford early)
The chairs of four major oil companies and several major car companies have said we’re entering the oil endgame and starting the hydrogen era.

Royal Dutch/Shell Group Planning scenario in 2001 envisaged a China-led hydrogen leapfrog:
- H₂ would fuel 1/4 of the industrialized world’s vehicles in 2025
- World oil remains stagnant to 2025, then falls
- China is already on this path, for compelling strategic reasons

U.S. & E.U. committed >$3b to H₂ R&D in 2003
Private sector has committed far more
“Insoluble chicken-and-egg problem” to get to $H_2$ cars

◊ Nobody would want a $H_2$ car with nowhere to fuel it, nor invest to make $H_2$ with nobody to buy it

◊ It’s normally assumed to be too costly to cover the country with $H_2$ infrastructure before selling $H_2$ cars — probably hundreds of billions of dollars

◊ This actually costs less than normal investments in oil-based infrastructure — and can be self-financing

◊ Key to transition: *integrate* deployment of fuel cells in buildings and in vehicles
How a rapid, profitable H₂ transition would work
How a Rapid Profitable H₂ Transition would work

Buildings use 2/3 of US electricity
How a rapid, profitable H₂ transition would work

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How a rapid, profitable H₂ transition would work

Buildings use 2/3 of US electricity

Marginal investment in H₂ compression, storage, and fueling, car-to-grid connection, and more durable fuel cell

US fleet has potential of 5–10 TW (6–12x US capacity)

First fleets, then drivers who work in or near buildings that have fuel cells

- gas or electricity
- fuel cell in building for co/trigen and UPS
- power & fueling center

Buildings use 2/3 of US electricity

Hydrogen appliance is sized for peak building loads that seldom occur
How a rapid, profitable H₂ transition would work

Buildings use 2/3 of US electricity

Marginal investment in H₂ compression, storage, and fueling, car-to-grid connection, and more durable fuel cell

US fleet has potential of 5–10 TW (6–12x US capacity)
How a rapid, profitable H₂ transition would work

Buildings use 2/3 of US electricity

Marginal investment in H₂ compression, H₂ fueling and grid connection
US fleet has potential of 5–10TW (6–12x US capacity)
As 

H₂ appliances get cheaper with mass production, put them elsewhere too, outside buildings… e.g., at filling stations
Hydrogen-ready cars + integrated with buildings = hydrogen transition

◊ No technological breakthroughs required (e.g., onboard reformers) — just durable and cheaper fuel cells
◊ Can market fuel-cell cars as soon as durable fuel cells become available, and can do so profitably many years earlier than inefficient vehicles would allow
◊ Meanwhile, engine or engine-hybrid Hypercar vehicles would impress (e.g., ~70+ mpg for a midsize SUV)
◊ No need for new liquid-fuel infrastructure (methanol, ultrapure gasoline,...) nor for liquid hydrogen
◊ Integrating mobile and stationary deployment makes the transition profitable at each step (>10%/y real return)
◊ It doesn’t matter whether durable stacks come first (favoring buildings) or cheap stacks (favoring cars); whichever comes first accelerates both markets
New supply strategy for B.C., California, and the Pacific NW?

- Import oil for transportation
- Heat with electricity and BC gas
- Electricity from hydro and thermal (coal being phased out, gas combined-cycle phased in)
- Minor renewables
- Key energy carrier is *grid* electricity
- Import no oil
- Fuel-cell vehicles, buildings, most industries
- Hydrogen as main energy carrier, from gas, “Hydro-Gen,” wind, and PVs
- Minor direct gas use for heat, mainly industrial
- Minor central hydroelectric supply; still onpeak el. sales; mostly onsite gen.; fish water

Intensive integrated superefficiency + distributed-generation experiments are emerging: Iceland, NZ, Yakushima, Vanuatu, Utsira,...Vancouver Island?
Do we have enough primary energy to make the hydrogen we need? 

(\eta \equiv \text{efficiency})

- If fueling $5\eta$ light and $2\eta$ heavy vehicles, \(\sim 50 \text{ MT/y } H_2\) could displace all U.S. highway-vehicle fuel.
- U.S. refineries use \(\sim 7 \text{ MT/y } H_2\) — enough to displace 1/4 of U.S. gasoline (2× Gulf share).
- \(\sim 10 \text{ MT/y } H_2\) could be made from 2.0 TCF of natural gas freed up by efficient end-use of gas and electricity and by electric load management.
- Alternatively, 50 MT/y \(H_2\) could be made by the Dakotas’ cost-effective windpower potential, with turbines on a few percent of the windiest available lands, leaving the rest for farming/ranching/wildlife.
“Won’t we just run out of natural gas even faster? Or of capital?”

◊ GM thinks U.S. use of natural gas would be lower with a miniature-gas-reformer H₂ transition

◊ RMI is checking, but can see how any net increase in natural-gas use could at worst be very small
  ○ Natural gas used to make H₂ could be approximately offset by gas saved in power plants, in boilers and furnaces, and in making H₂ for gasoline
  ○ Peak electricity demand is served by extremely inefficient gas-fired turbines...so shaving peak electric loads by 5% would save around 9% of the total U.S. use of natural gas

◊ Sandy Thomas ([www.h2gen.com](http://www.h2gen.com)) argues that global capital investment in a gas-based H₂ hydrogen fueling infrastructure over the next 40 y would be ~$1 trillion less than for gasoline, saving ~$600 of investment per car served; RMI is refining this estimate too
“Hydrogen is just a shill for nuclear power and fossil fuels”

◊ Even if electrolysis were a competitive way to make H₂, new nuclear plants are a hopelessly uncompetitive way to make electricity — forget it
  ○ Delivered cost of new nuclear el. would be \(\sim 2-3 \times\) new wind-power, \(5-10 \times\) gas cogen/trigen, \(10-30^+ \times\) end-use efficiency — so nuclear-el. H₂ would cost \(2-3 \times\) more/mi than record oil price
  ○ Far from saving nuclear power, H₂ will hasten its extinction

◊ It’s OK to use responsibly extracted fossil fuels to make hydrogen...
  ○ Temporarily to make H₂ from natural gas without carbon sequestration, because CO₂ released per mile would fall by \(\sim 2-5 \times\) (DOE: 2.5×)... 
  ○ And long-run to make H₂ with carbon sequestration (at large or probably, with emerging methods, small scale) — or its backstop technologies, which don’t require geological success
Renewables will compete well too — even better with hydrogen

- As already noted, H₂ boosts renewables’ economics
- Fuel cells’ distributed benefits are synergistic with those of renewables such as photovoltaics
- Reversible fuel cells go especially well with PVs
- DOE should fully fund both H₂ and renewables — not swipe H₂ funding from renewables as now
- Huge stranded renewables, such as Dakotas wind, will require substantial delivery investments (but will still be very worthwhile)
- Synergies from combining H₂ with renewables
  - All Danish energy — not just el. — could be cost-effectively, reliably obtained from windpower with two weeks’ H₂ storage
The Oil Endgame *Is Here*

- The chairs of 4 oil majors and 3 car majors have said so.

- The cost of securing and protecting oil supply lines raises national security concerns.

- Oil will probably become uncompetitive even at low prices before it becomes unavailable even at high prices.

- Like uranium already and coal increasingly, oil will become not worth extracting — good mainly for holding up the ground — because other ways to do the same tasks are better and cheaper.
More profitable for hydrocarbon owners too? Just try this quiz...

◊ \((H - C) > (H + C)\)?
◊ Is the hydrogen worth more without the carbon than with the carbon?
◊ Is hydrogen plus negacarbon (which someone may pay you *not* to put into the air) worth more than hydrocarbon? What if carbon is worth zero?
◊ Is a hydrocarbon worth more feeding a refinery or a reformer?
◊ Should refineries become merchant \(H_2\) plants? (Left as an exercise for the reader. Then run, do not walk, to the hydrogen economy.)
The dawn of the hydrogen era has begun

- Hydrogen-fueled superefficient vehicles will be safer and cleaner, cost less to drive, cost about the same to buy, and offer the potential to repay most or all of their cost from power sell-backs.
- Fuel cell and vehicle technology enablers are within reach.
- Enough hydrogen can be made cost-effectively from North American energy sources (even from just regional renewables) to eliminate gasoline and diesel use — creating real security.
- A fast transition to a hydrogen economy is already starting and can be profitable at each step.
It’s time — we just need leadership

“People and nations behave wisely — once they have exhausted all other alternatives.”
— Churchill

“Sometimes one must do what is necessary.”
— Churchill

“We are the people we have been waiting for.”
— Hopi Elders

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