Rocky Mountain Institute Quest for Solutions (RMIQ) Public Lecture
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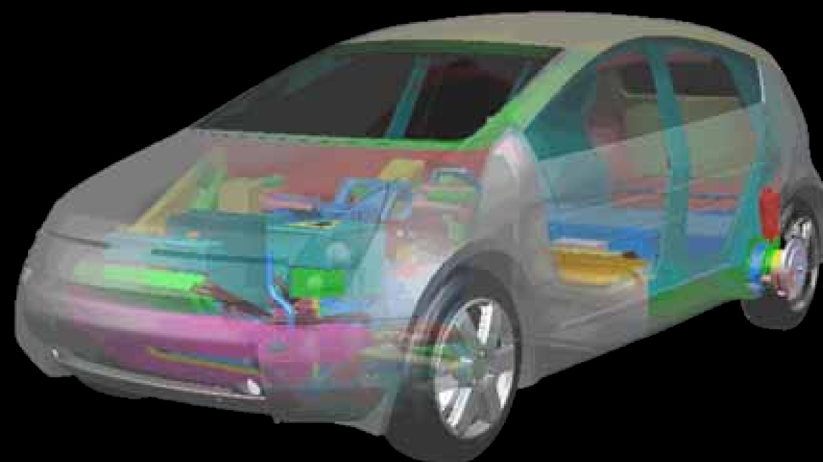
Hydrogen: The Future of Energy



Amory B. Lovins

Chief Executive Officer
Rocky Mountain Institute
www.rmi.org

Chairman of the Board
Hypercar, Inc.
www.hypercar.com

ablovins@rmi.org

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 H_2O 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 (H_2) is the lightest element and molecule
  - Per unit of energy contained, H_2 is 64% lighter than natural gas or 61% lighter than gasoline
- 1 kg of H_2 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
  - H_2 has 30% the energy of CH_4, both at atmospheric pressure
  - H_2 at 170 bar pressure has *6%* the energy/volume of gasoline
- **H_2 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
  - Buoyant (8× CH_4), diffusive (4×CH_4, 12× gasoline)
  - Clear flame can't sear you at a distance; no smoke
  - Hard to make explode; can't explode in free air; burns first
  - 4× gasoline-fume concentration required to burn; 22× less explosive power
  - Rises, doesn't puddle
  - *Hindenburg* myth (1937) — *nobody* was killed by hydrogen fire
  - Completely unrelated to hydrogen bombs

Demonstrating hydrogen *vs.* gasoline safety

M.R. Swain, "Fuel Leak Simulation," www.eren.doe.gov, 2002.

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 H_2 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

liquid fuel → retail site → vehicle **= 5¢ per mile**

liquid fuel	retail site	vehicle
• Gasoline • Diesel	$1.00/gallon (pretax)	Avg. 20 mpg

Hydrogen cars will be cheaper per mile driven

◇ Gasoline

liquid fuel → retail site → vehicle = 5¢ per mile

- Gasoline
- Diesel

$1.00/gallon (pretax)

Avg. 20 mpg

◇ Reformation

liquid or gas fuel → retail site reformer → hydrogen → vehicle = 2½¢ per mile

- Natural Gas
- Biofuel

72% (LHV) conversion eff.

$2.5/kg of H_2 ~$2.5/gallon gasoline

5× efficient 100 mpg

Well-designed hydrogen cars will be cheaper per mile driven

◇ Gasoline

liquid fuel → retail site → vehicle = 5¢ per mile

- Gasoline
- Diesel

$1.00/gallon (pretax)

Avg. 20 mpg

◇ Reformation

liquid or gas fuel → retail site reformer → hydrogen → vehicle = 2½¢ per mile

- Natural Gas
- Biofuel
- $6/million Btu

72% (LHV) conversion eff.

$2.5/kg of H_2 ~$2.5/gallon gasoline

5× efficient 100 mpg

◇ Electrolysis

low cost power → retail site electrolysis → hydrogen → vehicle = 3¢ per mile

- Hydro
- Offpeak wind 3¢/kWh del.'d.

70% (LHV) conversion efficiency

$3.2/kg of H_2 ~$3.2/gallon gasoline

5× efficient 100 mpg

Well-to-Wheels Efficiency

	Well to Tank (%)	Tank to Wheel (%)	Well to Wheel (%)
Gasoline Vehicle	88	16	14%
Prius (Gasoline HV)	88	30	26%
Hydrogen FCV	58*1	38*2	22%
FCHV-4	58*1	50*2	29% With HV control
FCHV (Target)	70	60	42% 3 x Gasoline, 1.5 x HV

Japanese 10-15 Mode

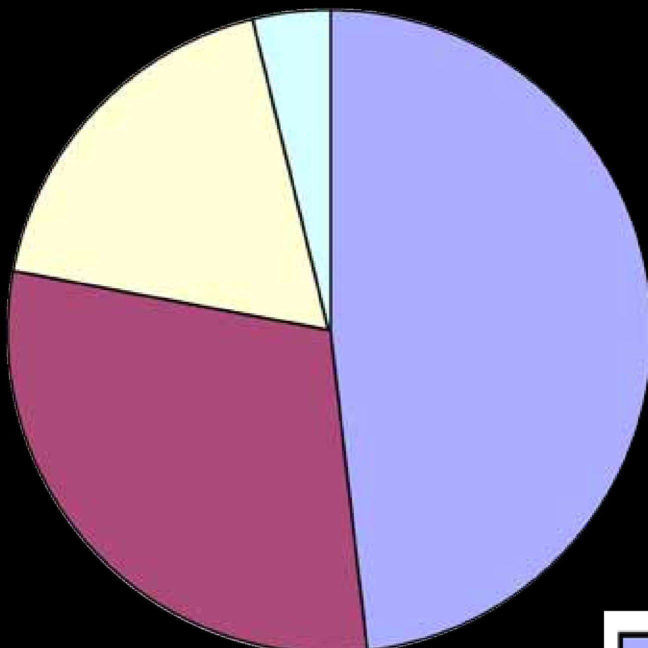
Toyota's estimation

*1 Natural gas base *2 Measurement from the electric current

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

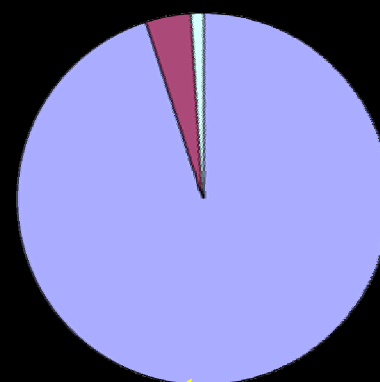
How is hydrogen now produced?

World



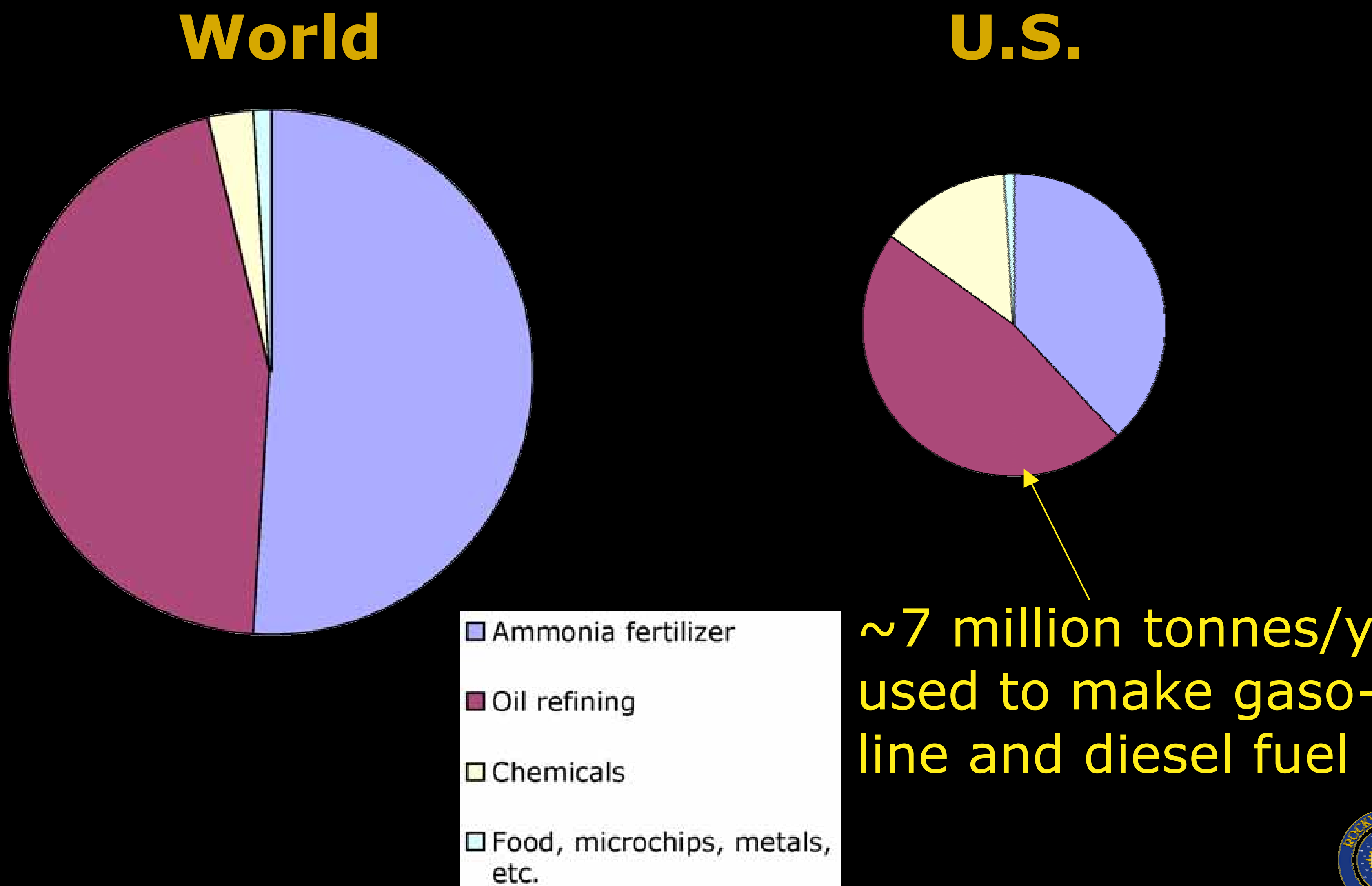
~50 million tonnes/y global H_2 output, growing ~6–7%/y

U.S.



8% of U.S. natural gas is used to make H_2

How is hydrogen now used?



"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
- H_2'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_2

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

1. Reform natural gas at the wellhead and reinject the CO_2
   - Reforming (~8% of U.S. gas now) & reinjection (32 MT/y) are mature
     - Potentially three profit streams: H_2, $+CH_x$, –C
2. Electrolyze with climate-safe electricity (hydropower, offpeak windpower)
   - Greatly improves renewable economics if electricity is converted to H_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_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 H_2 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 H_2, 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?

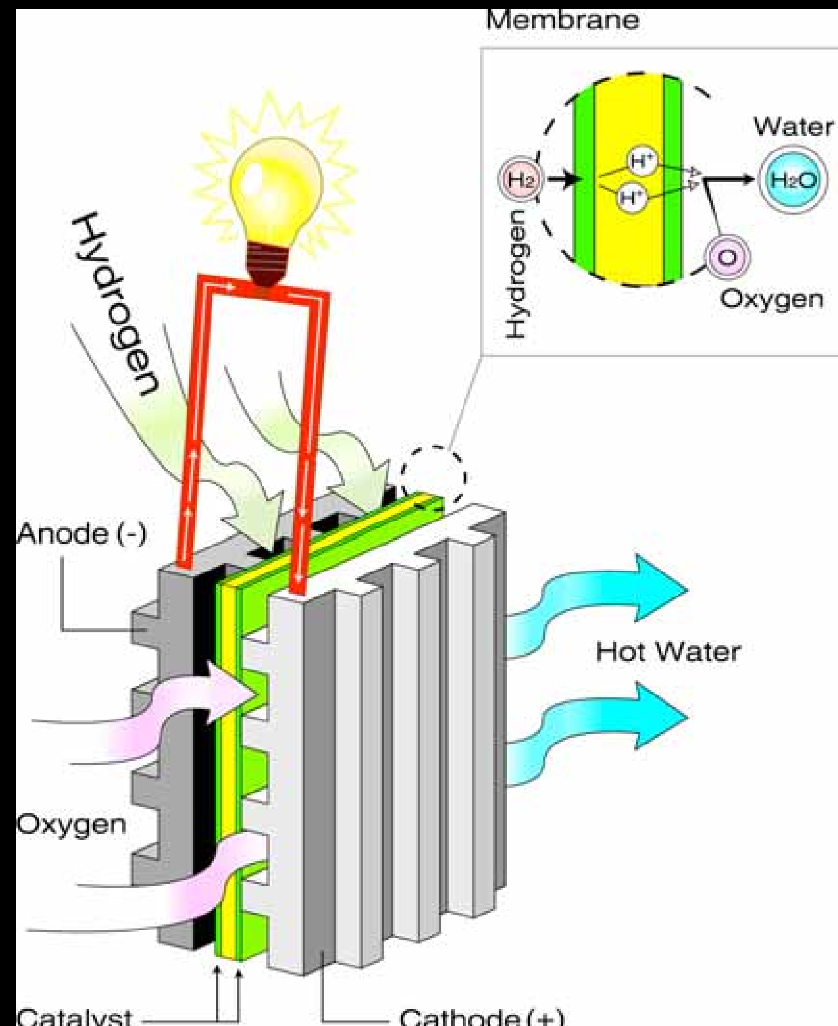
- Use the cheapest method by fully utilizing the existing, paid-for gas and electricity infrastructure
- Both centralized and distributed architectures
  - Centralized natural-gas reformers may or may not ultimately prove cheaper and more efficient than miniature ones
  - Distributed solution: small-scale reformers and electrolyzers
  - Cost <10% of a gas station’s capital cost, or ~$2\frac{1}{2}$% of the investment in the station *plus* its upstream oil supply
  - As with diesel fuel, fewer than one-third of filling stations need conversion
  - Deutsche Shell said it could install hydrogen in all German stations in two years
  - 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

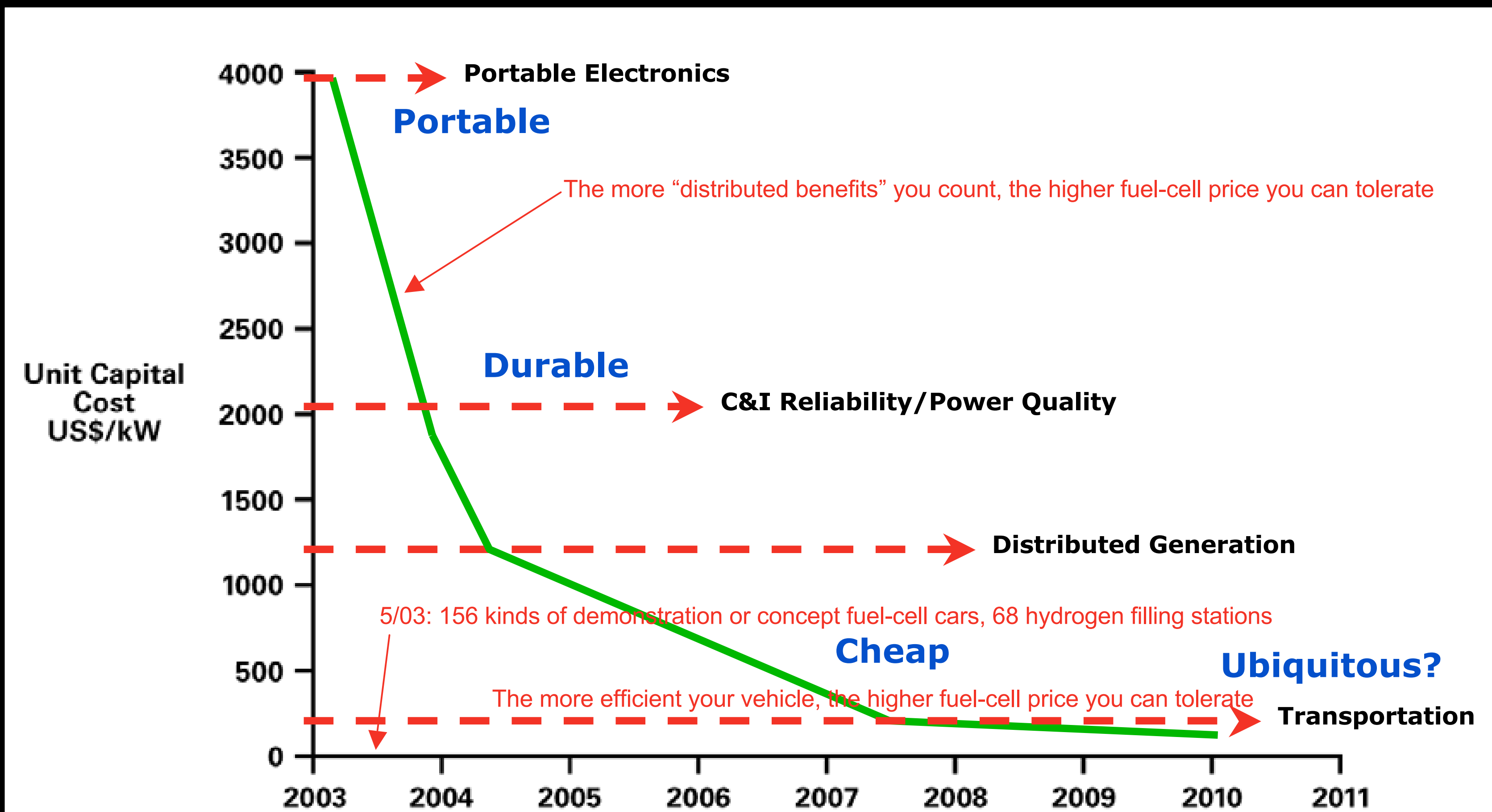
- Fully scaleable



Fuel cells are already viable

Fuel Cell Competitive Price Points

(1993–2003 Cost Reduction: % catalyst÷20, cost ÷10, vol./kW ÷10)



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
- H_2 tanks are too big to package, so need onboard methanol or gasoline reformer
- Reformer hell

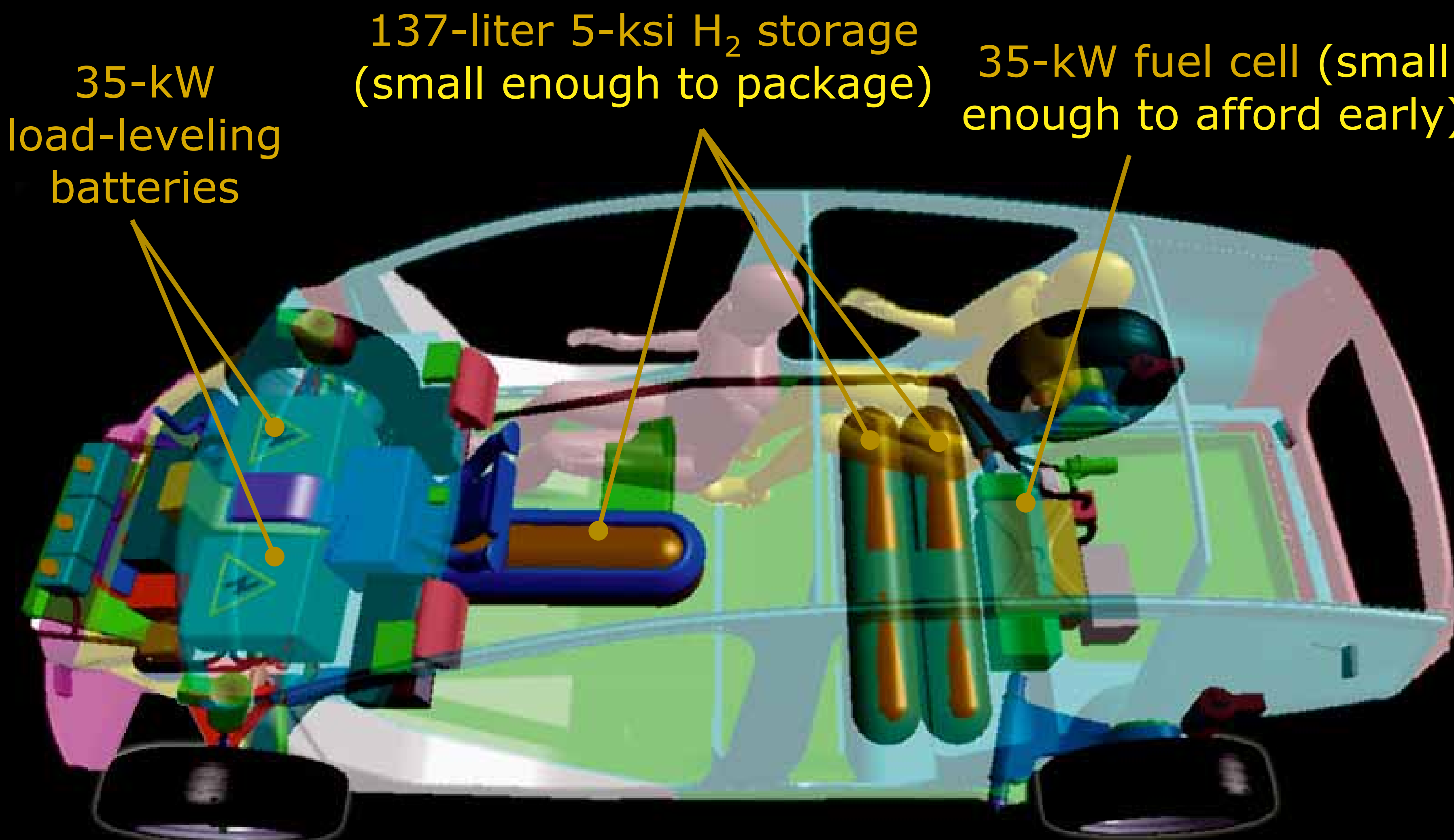
- **Direct-hydrogen fuel-cell car:** ultralight, ultra-low-drag platform can use any driveline and fuel, but is peculiarly well suited to direct-hydrogen fuel cell
- Fuel cell is small enough to afford, even at early prices
- Now-commercial H_2-gas tanks for normal range are small enough to package — **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

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***

- 5 adults in comfort, up to 69 ft^3 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 (2.38 L/100 km, 42 km/L, 5×*RX300*)
- 330 mi on 7.5 lb safely stored 5-kpsi H_2
- 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

55 mph on same power as normal a/c, so ready now for direct hydrogen fuel cells



Ready or not, here it comes

- 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
  - H_2 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 H_2 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 H_2 transition would work

gas or electricity

How a Rapid Profitable H_2 Transition would work

gas or electricity → fuel cell in building for co/trigen and UPS

Buildings use 2/3 of US electricity

How a rapid, profitable H_2 transition would work

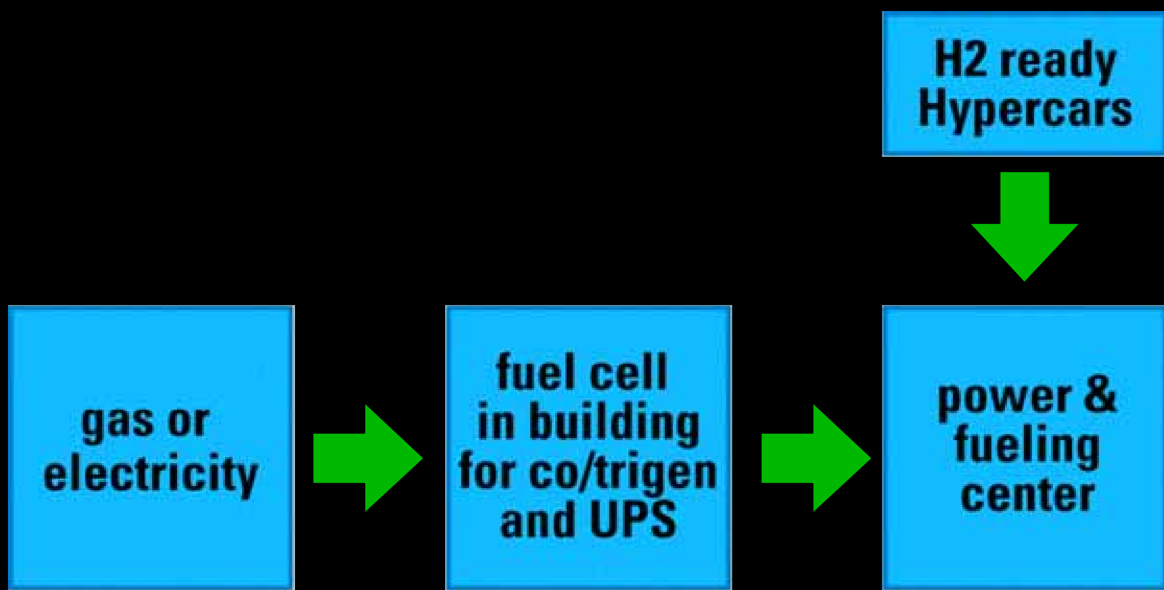
H2 ready Hypercars

gas or electricity

fuel cell in building for co/trigen and UPS

Buildings use 2/3 of US electricity

How a rapid, profitable H_2 transition would work



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

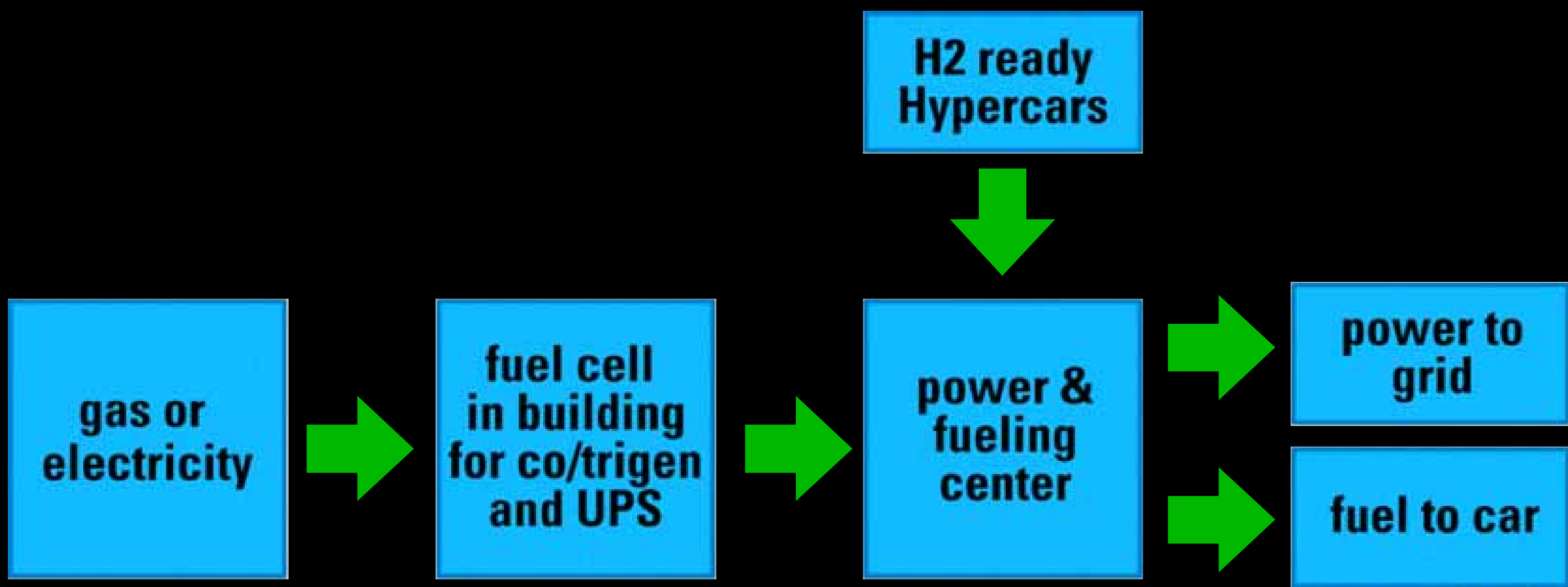
Buildings use 2/3 of US electricity

Hydrogen appliance is sized for peak building loads that seldom occur

Marginal investment in H_2 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 H_2 transition would work



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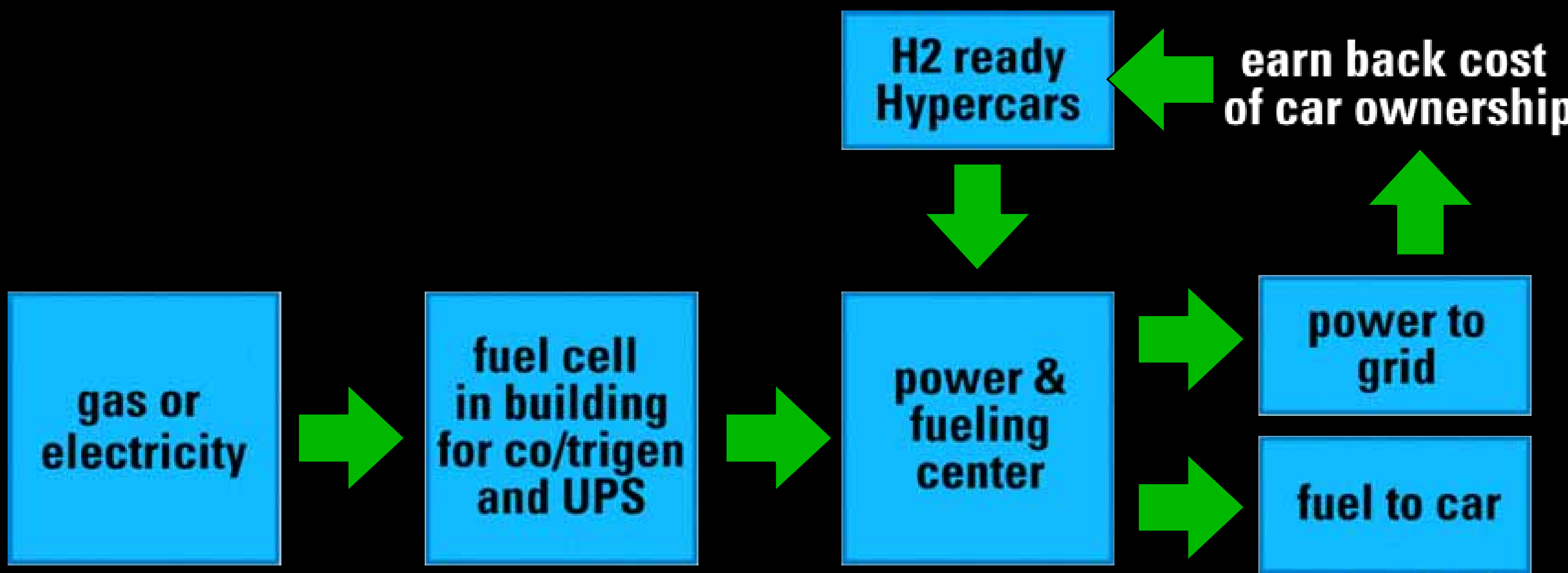

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Marginal investment
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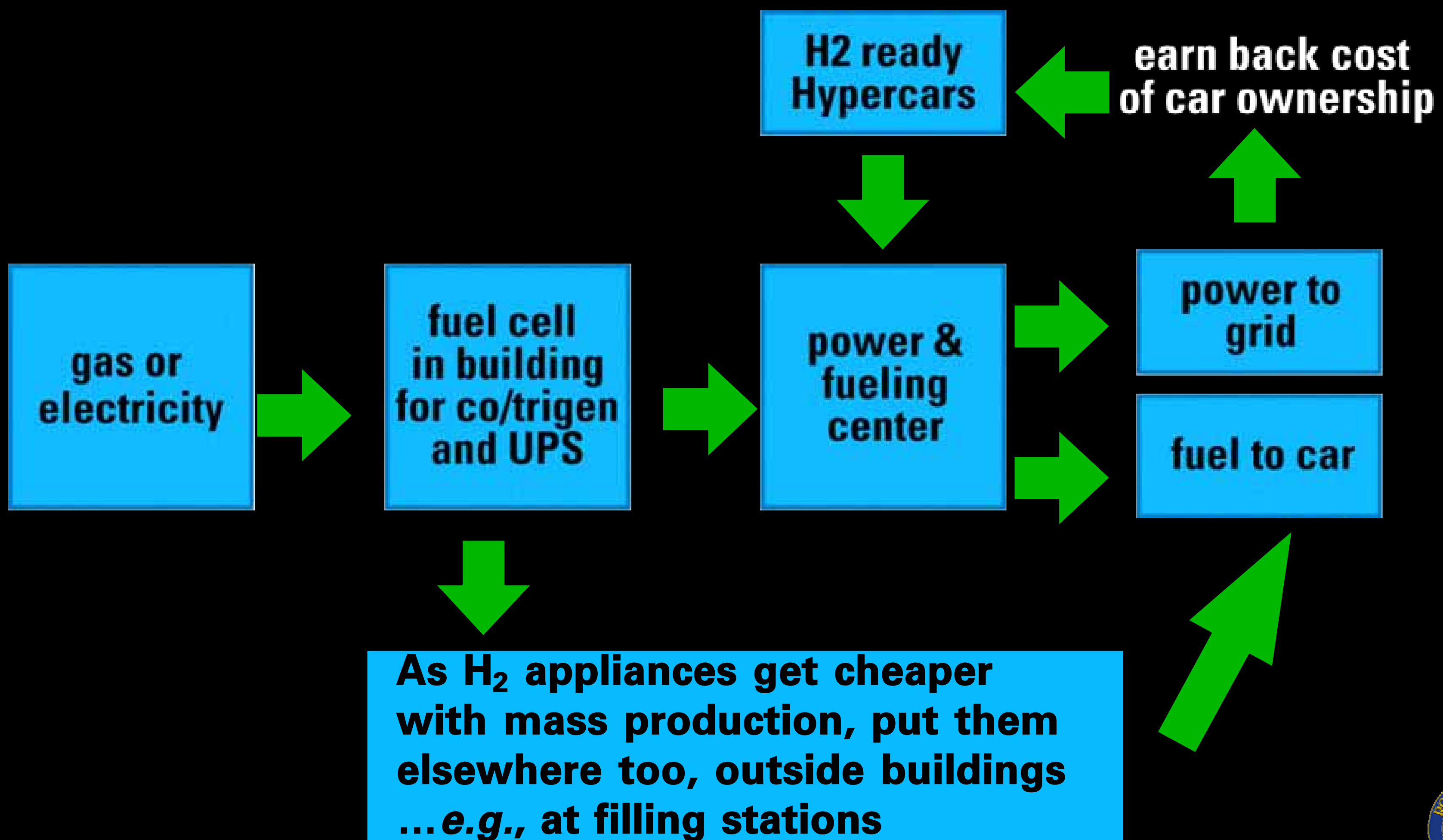
How a rapid, profitable H_2 transition would work



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 com-bined-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 hydro*electric* 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?

($\eta \equiv$ efficiency)

- If fueling 5η light and 2η heavy vehicles, ~50 MT/y H_2 could displace all U.S. highway-vehicle fuel
- U.S. refineries use ~7 MT/y H_2 — enough to displace 1/4 of U.S. gasoline ($2\times$ Gulf share)
- ~10 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 H_2 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 H_2 could be approximately offset by gas saved in power plants, in boilers and furnaces, and in making H_2 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) argues that global capital investment in a gas-based H_2 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 H_2, new nuclear plants are a hopelessly uncompetitive way to make electricity — forget it
  - Delivered cost of new nuclear el. would be ~2–3× new wind-power, 5–10× gas cogen/trigen, 10–30⁺× end-use efficiency — so nuclear-el. H_2 would cost 2–3× more/mi than record oil price
  - Far from saving nuclear power, H_2 will hasten its extinction
- It's OK to use responsibly extracted fossil fuels to make hydrogen…
  - Temporarily to make H_2 from natural gas without carbon sequestration, because CO_2 released per mile would fall by ~2–5× (DOE: 2.5×)…
  - And long-run to make H_2 *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, H_2 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 H_2 *and* renewables — not swipe H_2 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 H_2 with renewables
  - *All* Danish *energy* — not just el. — could be cost-effectively, reliably obtained from windpower with two weeks' H_2 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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