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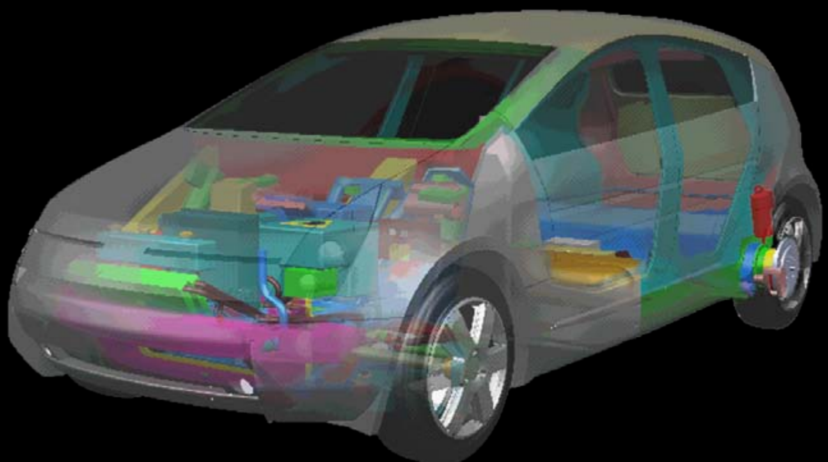
INSTITUTE

Hydrogen, Fuel Cells, and Infrastructure Technologies Program, USDOE
HTAC Annual Meeting, Crystal City VA, 5 Nov 09

A Practical and Profitable Hydrogen Transition

Integrating Hypercars®, Buildings, Hydrogen, and Distributed Generation



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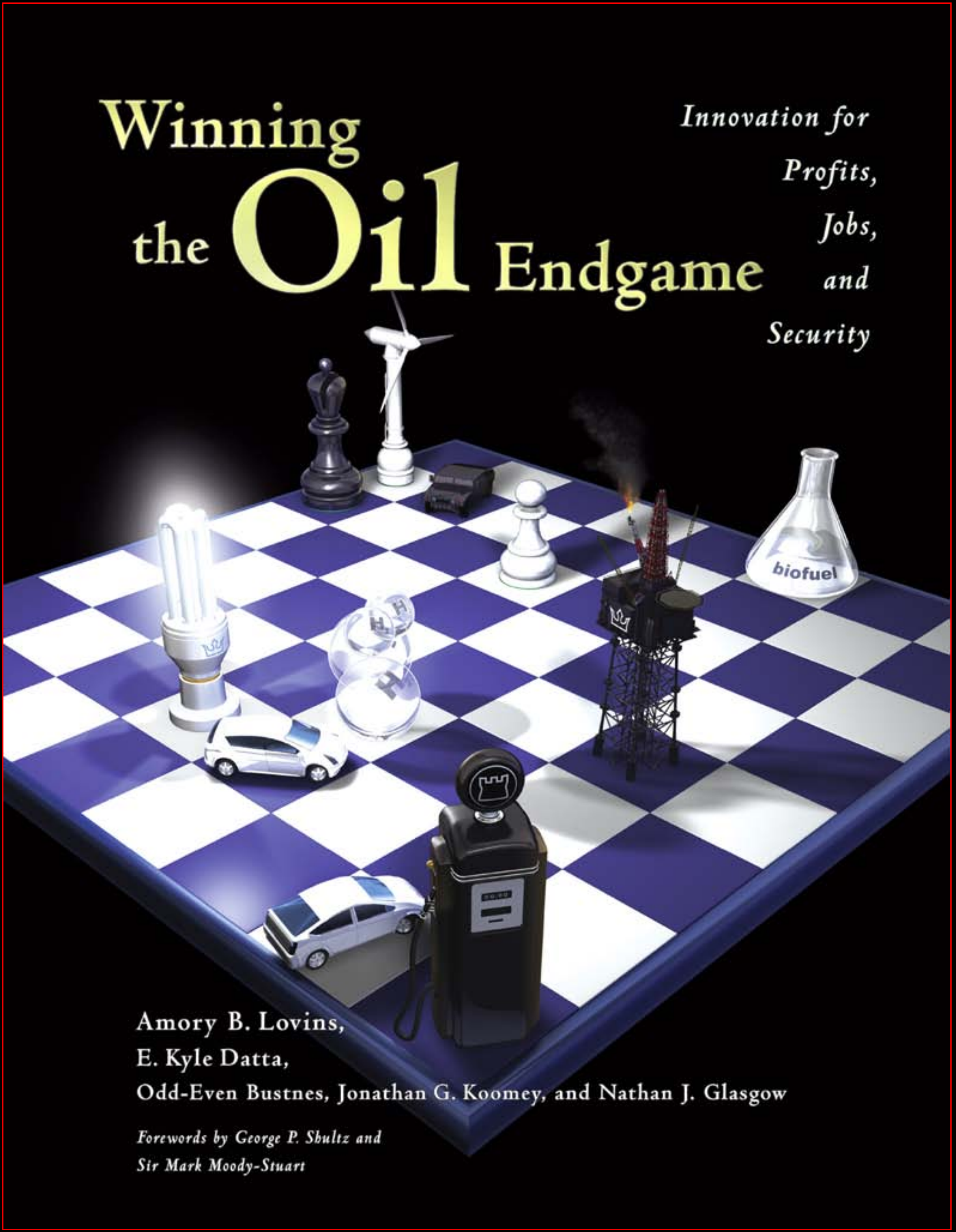
Based on competitive strategy cases for cars, trucks, planes, oil, military

Book and Technical Annexes are free at:

www.oilendgame.com

Over the next few decades, the US can eliminate its use of oil and revitalize its economy, led by business for profit. (So can others.)



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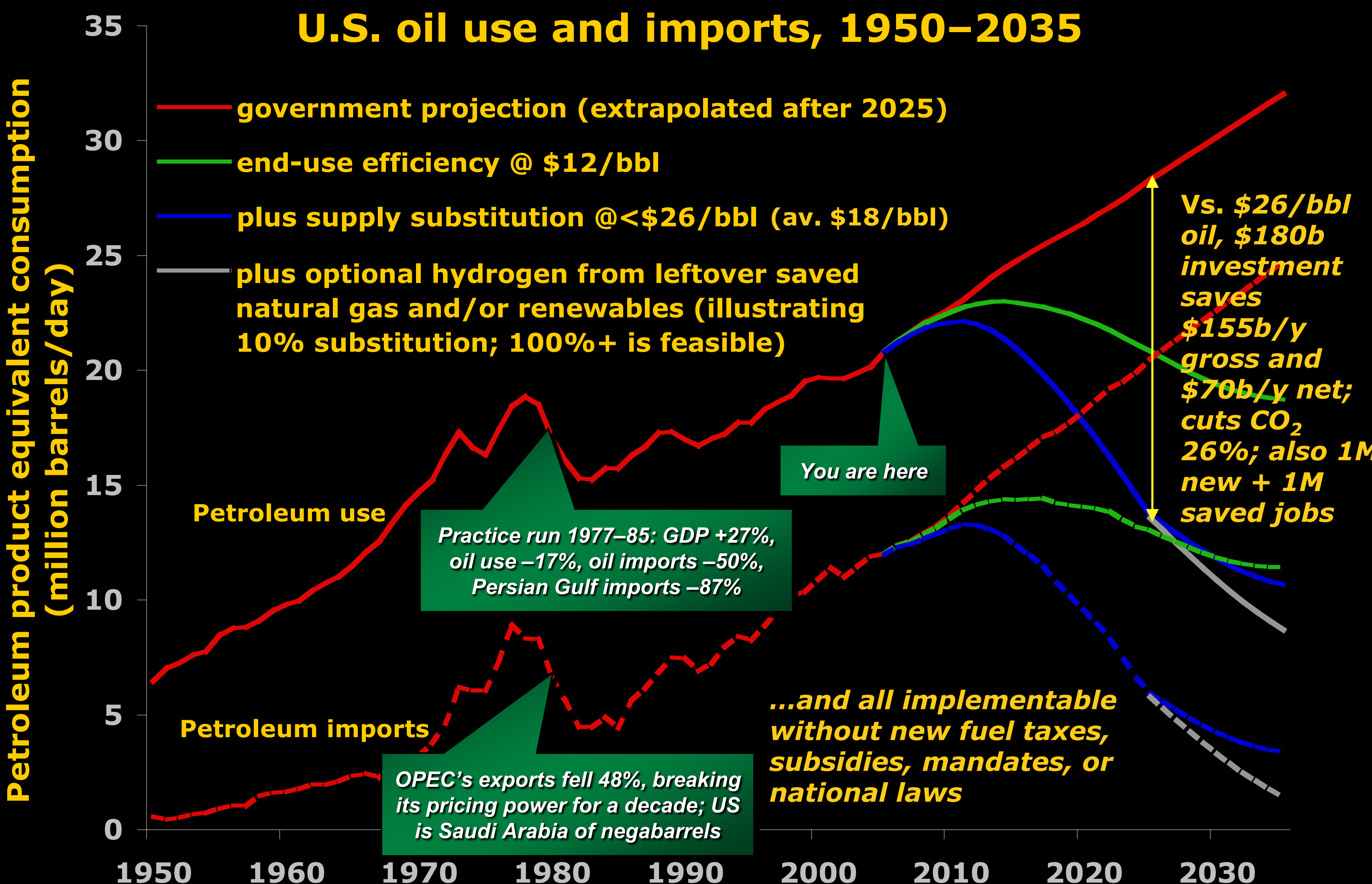
A profitable US transition beyond oil (with best 2004 technologies)



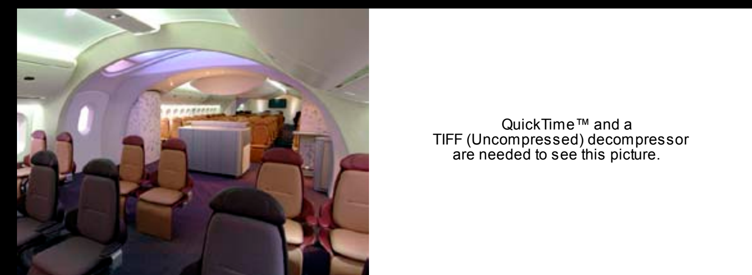
Vehicles use 70% of US oil, but integ-rating low mass & drag with advanced propulsion saves ~2/3 very cheaply

CARS: save 69% at 57¢/gal

Surprise: ultralighting is ***free* —** offset by simpler automaking and the 2–3× smaller powertrain

155 mph, 94 mpg

PLANES: save 20% free, 45–65% @ ≤46¢/gal

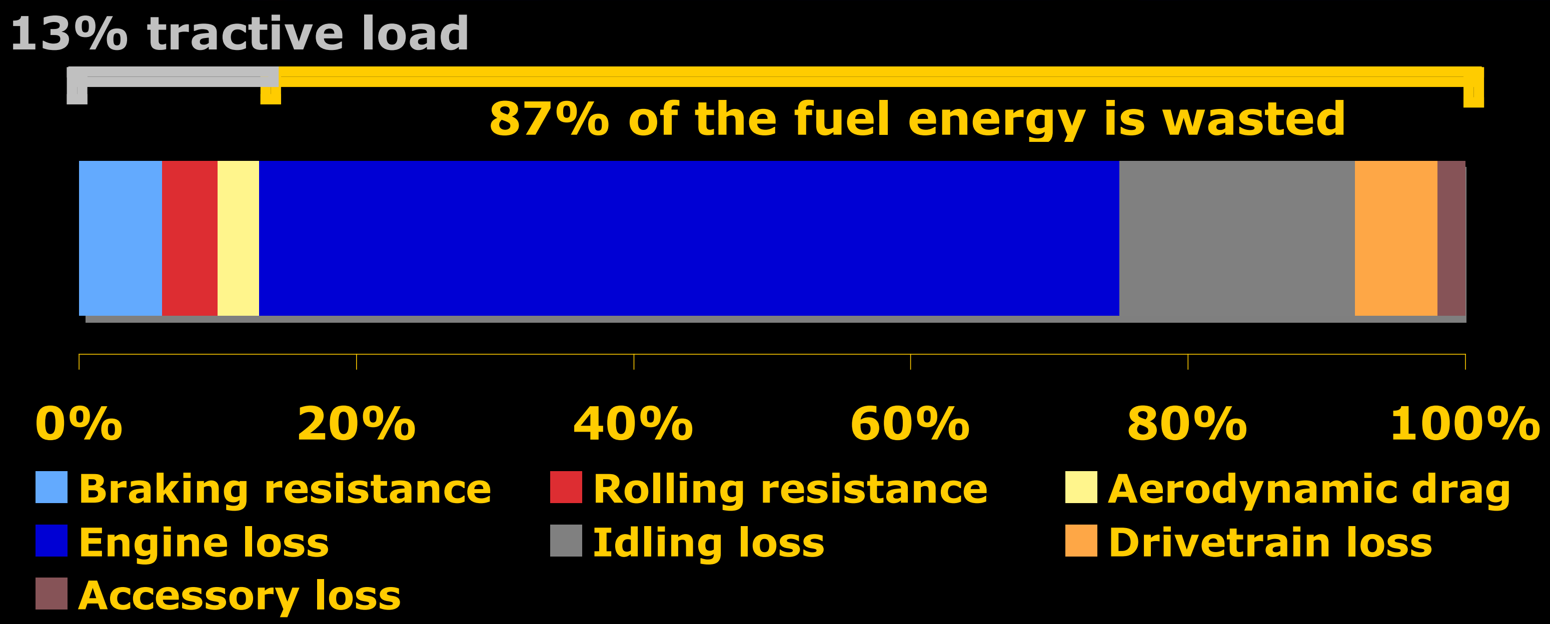


BLDGS/IND.: big, cheap savings; often *lower* capex

TRUCKS: save 25% free, 65% @ 25¢/gal

Technology is improving faster for efficient end-use than for energy supply

Where does a car’s gasoline go?



- 6% accelerates the car, <1% moves the driver
- Over 2/3 of the fuel use is caused by the car’s mass
- Each unit of energy saved at the wheels saves ~7–8 units of fuel in the tank (or ~3–4 with a hybrid)
- **So first make the car radically lighter-weight!**

Migrating innovation from military aerospace to civilian cars

◇ At the Lockheed Martin Skunk Works®, engineer David Taggart led a ’94–96 team* that designed an advanced tactical fighter-plane airframe…

- made 95% of carbon-fiber composites
- 1/3 lighter than its 72%-metal predecessor
- *but 2/3 cheaper*…
- because it was designed for optimal manufacturing from composites, not from metal

*Integrated Technology for Affordability (IATA)

◇ Finding no military customer for something so radical, he left. I soon hired him to lead the 2000 design of a halved-weight SUV with two Tier Ones — *Intl. J. Veh. Design* **35**(1/2):50–85 (2004)…

Midsize 5-seat Revolution concept SUV (2000)
Ultralight (857 kg) but ultrasafe
0–100 km/h in 8.3 s: 2.06 L/100 km (114 mi/USgal) w/fuel cell
0–100/7.2 s: 3.56 L/100 km (67 mi/USgal) w/gasoline hybrid

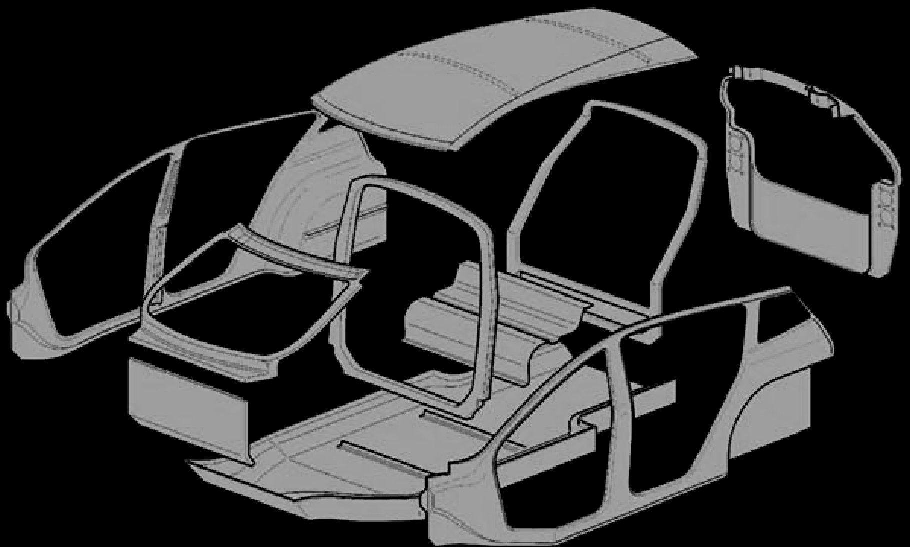
"We'll take two."
— *Automobile* magazine

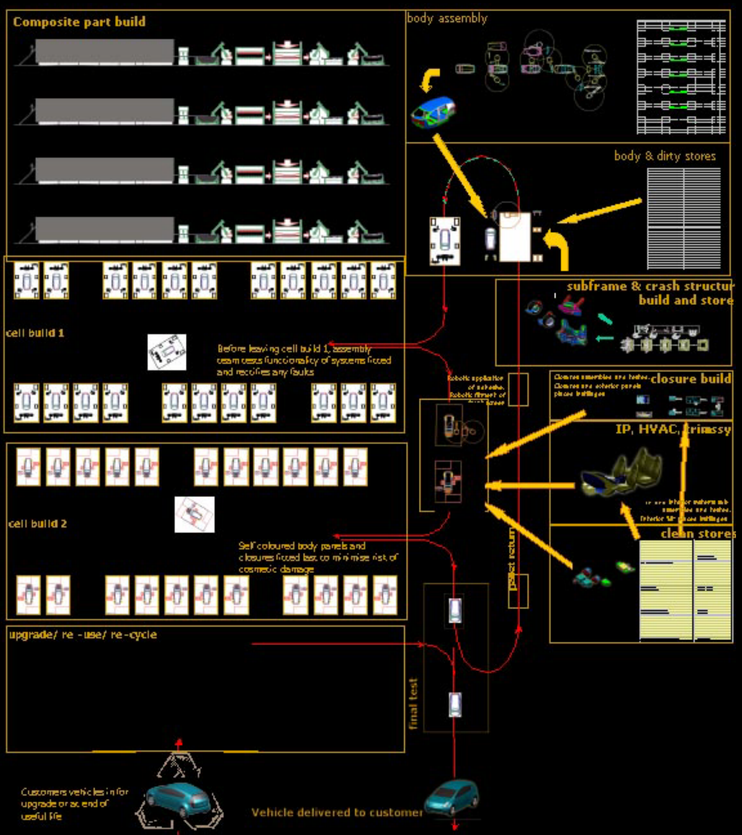
World Technology Award, 2003

Show car and a complete virtual design, safer, uncompromised; hybrid is manufacturable at 50,000/y with a $2,511 higher retail price

Radically simplified manufacturing

- Mass customization
  - *Revolution* designed for 50k/year production volume
  - Integration, modular design, and low-cost assembly
  - Low tooling and equipment cost





- 14 major structural parts, no hoists
- 14 low-pressure diesets (not ~10^3)
- Self-fixturing, detoleranced in 2 dim.
- No body shop, optional paint shop
- 2/5 less capital/car·y, 2/3 smaller plant

Toyota's Hypercar®-class *1/X* concept car (Tokyo Motor Show, 26 Oct 2007)

- 1/2 *Prius* fuel use, similar interior vol. (4 seats)
- 1/3 the weight (420 kg)
- carbon-fiber structure
- 0.5-L flex-fuel engine under rear seat, RWD
- plug-in hybrid-electric (if plain hybrid, 400 kg)

• One day earlier, Toray announced a ¥30b plant to mass-produce carbon-fiber autobody panels and other parts for Toyota, Nissan, …; in July 2008, similar Honda/Nissan/Toray deal announced too

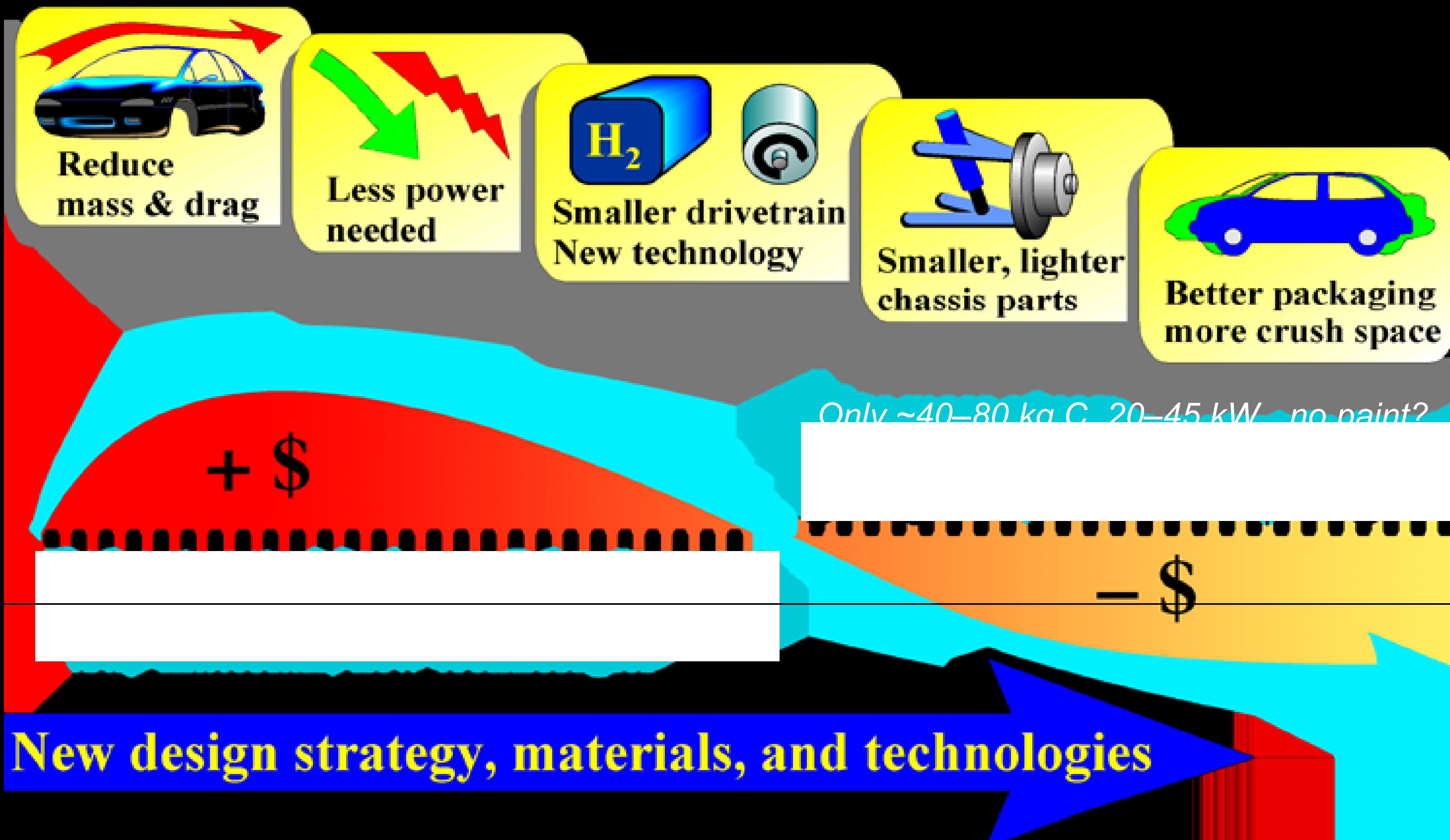
• Nov 2007: Ford announced 113–340-kg weight cuts MY2012–20

• Dec 2007: 15% av. weight cut in all Nissan vehicles by 2015; China formed auto lightweighting alliance targeting –200 kg 20*10*

Bright Automotive's 2009 *IDEA*

- Commercial 1-ton fleet van with in-cab office, 5 m^3 cargo, quiet and comfortable
- **160**-mpg-equivalent (LA90, 50 mi/day urban route, *vs.* US norm 12–14 mpg); on 80 mi/day, **70–75** mpg
- m_c 3,200 lb, target C_d 0.30
- PHEV (50-mi electric range, 400-mi total range)
- Needs no subsidy: low tractive load makes the batteries small enough to yield a compelling business case for fleets
- NAFTA & EU market each 1M/y

Decompounding mass and com–plexity also decompounds cost



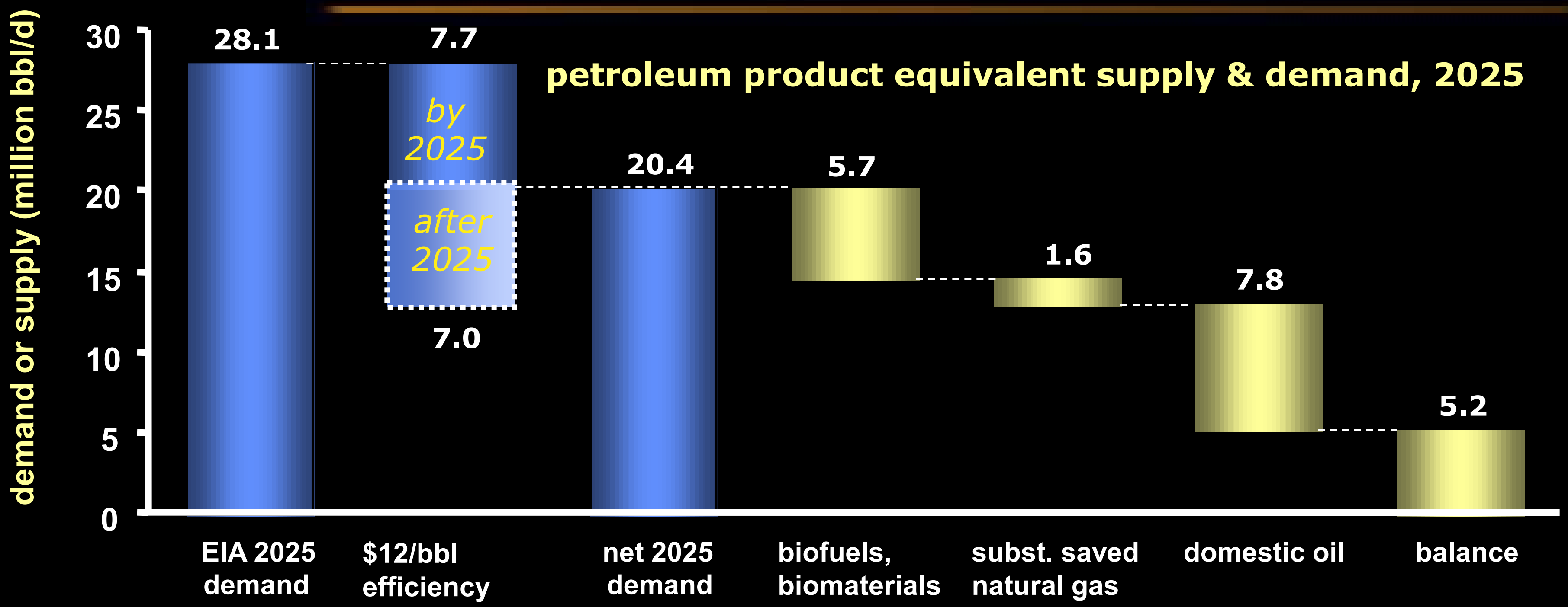
Stages of the emerging automotive [r]evolution

Oil use per mile

100%

- An excellent hybrid, properly driven, doubles efficiency
  - Considerably more if new diesels can meet ever tighter clean-air regulations
- Ultralighting (+ better aero and tires) redoubles efficiency
- Cellulosic-ethanol E85 quadruples oil efficiency again
  - Biofuels can make driving a way to protect, not harm, the climate
- A good plug-in hybrid (entering the market 2010–11) redoubles fuel efficiency again, and could be lucrative if the power grid buys its electric storage (“Smart Garage”)—could even displace all coal and nuclear plants
  - Precursor of "vehicle-to-grid" fuel-cell play—power plant on wheels
  - So far, these stages can save 97% of the oil/mile used today
- Hydrogen fuel cells also compete, *iff efficient vehicle*, via lower ¢/mile and 2–6× less CO_2/mile (or zero CO_2 if renewable)

2025 demand-supply integration



Great flexibility of ways and timing to *eliminate* oil in next few decades

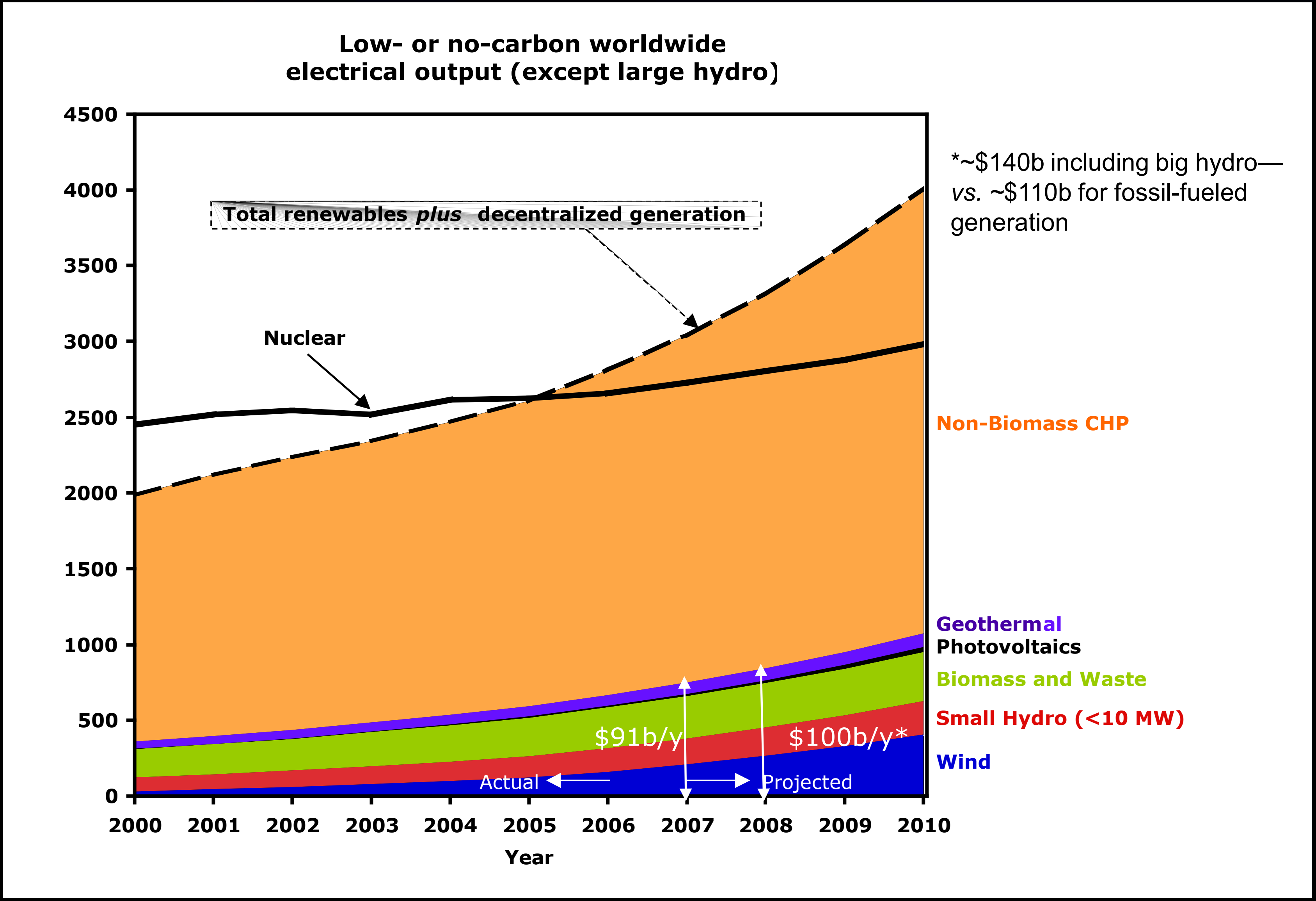
- **Buy more efficiency (it's so cheap)**
- **Wait for the other half of the efficiency—7 Mbbl/d still in process in 2025**
- **"Balance" can import crude oil/product (can be all N. Amer.) or biofuels**
- **Or saved U.S. natural gas @ $0.9/MCF can fill the "balance"…or**
- **H_2 from saved U.S. natural gas can displace "balance" *plus* domestic oil**
- **Not counting other options, *e.g*. Dakotas windpower—50 MT/y H_2 source**

Implementation is underway via "institutional acupuncture"

- RMI's 3-year, $4-million effort has led & consolidated shifts
- Need to shift strategy & investment in six sectors
  - Aviation: Boeing did it (*787 Dreamliner*)…and beat Airbus
  - Heavy trucks: Wal-Mart led it (with other buyers being added)
  - Military: emerged Feb 08 as the federal leader in getting U.S. off oil
  - Fuels: strong investor interest and industrial activity
  - Finance: rapidly growing interest/realignment will drive others
- Cars and light trucks: slowest, hardest, but now changing
  - Alan Mulally's move from Boeing to Ford with transformational intent
  - Union and dealers not blocking but eager for fundamental innovation
  - Tsunami of Schumpeterian "creative destruction" is causing top executives to be far more open to previously unthinkable change
  - Emerging leapfrogs by China, India, new market entrants
  - Competition, at a fundamental level and at a pace last seen in the 1920s, is changing automakers' managers or their minds, whichever comes first—sped by RMI's transformational projects, X Prize, feebates

Electric shock: low-/no-carbon decentralized sources are eclipsing central stations

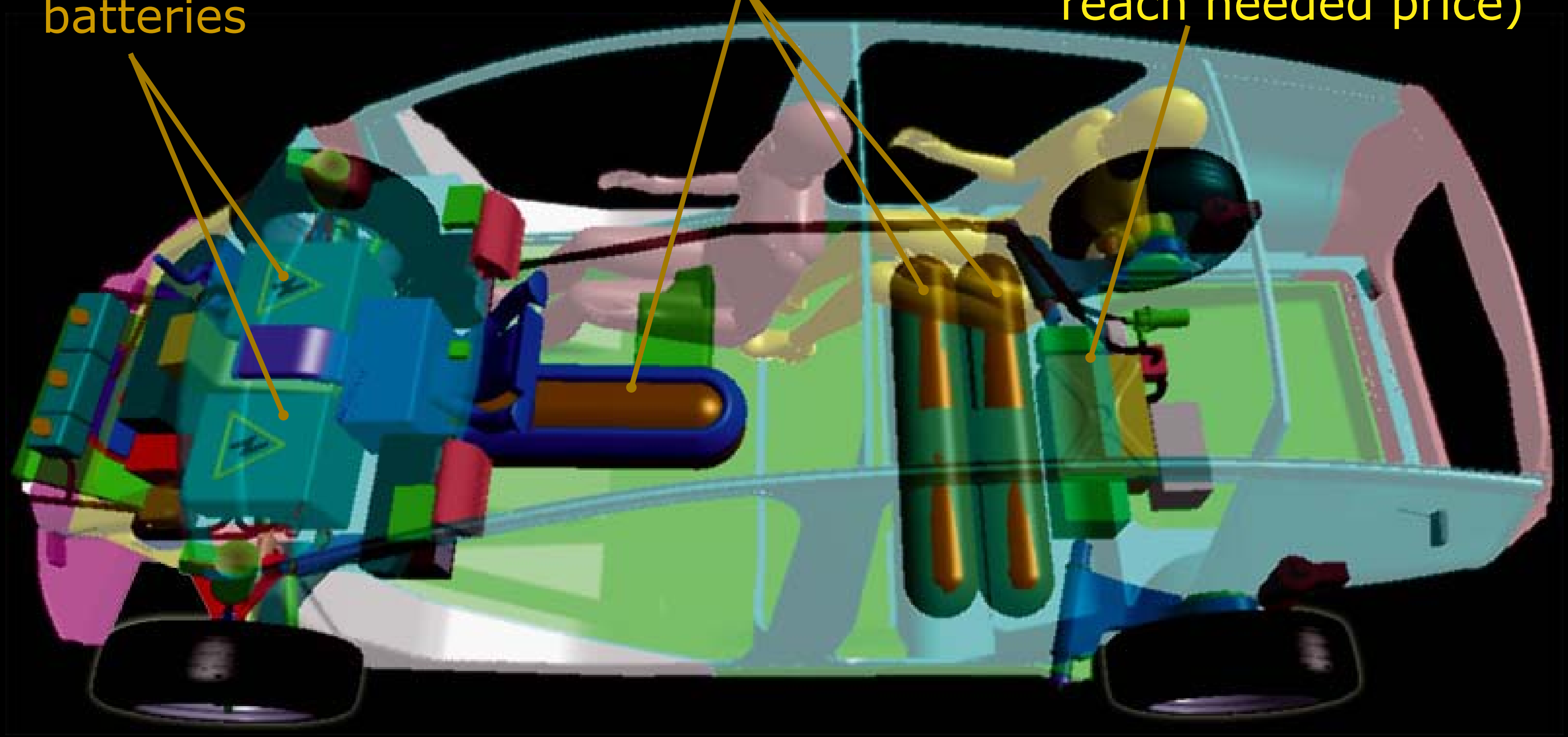
RMI analysis: www.rmi.org/sitepages/pid171.php#E05-04



Global new grid connections (GW/y) by year, 1995–2008

QuickTime™ and a
decompressor
are needed to see this picture.

1,889-lb curb mass (÷2), low drag, load ÷3, so 55 mph on same power as normal a/c, so ready now for direct hydrogen fuel cells



The first automaker to go ultra-light also wins the fuel-cell race

Vehicle	Power (kW)	Type	Cost @ $100/kW	Range (km)
Hypercar *Revolution*	35	hybrid	**$3,500**	531
Jeep *Commander 2*	50	hybrid	**$ 5,000**	190
Hyundai *Santa Fe FCV*	75	fuel cell	**$ 7,500**	402
Honda *FCX-V4*	85	fuel cell	**$ 8,500**	298
Ford *Focus FCV*	85	hybrid	**$ 8,500**	322
Toyota *FCHV-4*	90	hybrid	**$ 9,000**	249
GM *HydroGen III*	94	fuel cell	**$ 9,400**	402
GM Hy-Wire	94	fuel cell	**$ 9,400**	129

Platform physics is more important than powertrain—and is vital to its economics

- Cars can run clean IC engines on gasoline or NG (≡1η)
- Better ones using hydrogen in IC engines (≤1.5 η)
- Still better ones using H_2 in IC-engine hybrids (~2.5η)
  - Ford "Model U" concept car…but tanks >4× bigger (niche market)
- Better still: ultralight autobodies, low drag, Otto (3η)
- Power those platforms with IC-engine hybrids (4η)
  - Hypercar 5-seat carbon *Revolution SUV* has the same m_c & C_D as 2-seat aluminum Honda *Insight*…hybrid SUV gets 67 mpg, *Insight* 64
- Best: put fuel cells in such superefficient bodies (5–6η)
- **The aim isn't *just* saving fuel and pollution**
  - Also strategic goals in automaking, plug-in power-plants-on-wheels, off-oil, primary fuel flexibility, accelerated transition to renewables,…
- **H_2 needs 3–4η vehicles far more than vice versa**
- **3–4η vehicles make robust the business case for providing the H_2 that their fuel cells would need**

"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 — allegedly costing hundreds of billions of dollars
  - For comparison, though: US spent $2.2 trillion ('00$) on oil imports 1975–2003, incurring a ~$4–14 trillion economic cost from OPEC's pricing power; *2008* US net oil imports cost $351b
- Actual infrastructure investment, intelligently done, is *less* than normal investments in *oil*-based infra-structure — and can be self-financing
- Key to transition: *integrate* deployment of fuel cells in buildings and in vehicles (RMI's 1999 synthesis)

Rapid, profitable H_2 transition
(RMI, NHA paper, April 1999, www.rmi.org)

- Put fuel cells first in buildings for co-/trigen + UPS
  - Fuel with natural-gas reformers (or off-peak electrolyzers)
  - Big market — buildings use 70% of US electricity
- Meanwhile introduce H_2-ready Hypercars®
  - Fleets (return nightly to the depot for refueling)
  - General market: start with customers who work in or near the buildings that by then have fuel cells
    - Use buildings' hydrogen appliances for refueling
      - Sized for peak building loads that seldom occur
    - Sell kWh and ancillary services to grid when parked
      - Marginal investment in H_2 compression/fueling, grid connection, & more durable fuel-cell stack is modest
    - Earn back much/most of cost of car (for first ~2 million)
      - US full-fleet potential ~5–10 TW — ~6–12× grid cap.

Rapid, profitable **H_2 transition (2)**

- Meanwhile, hydrogen appliances get cheaper, so put them outside buildings too
  - At filling stations — a much better business than gasoline
    - Use two ubiquitous, competitive retail commodities — CH_4 and el. — and play them off against each other
    - Use just the offpeak distribution capacity for gas and electricity that is already built and paid for
    - Mainly reformers: electrolyzers favored only at high volume, small unit scale, and cheap offpeak kWh
    - ~10^3 reformers + $6/MCF gas beat $0.91/gal gasoline in $/mile and emit (uncontrolled) 2–5× less CO_2/mi than today's cars—a good transitional step toward no-carbon
  - Scaleable, modular, big economies of mass-production
  - As both hydrogen and direct-hydrogen fuel-cell vehicles become widespread, bulk production and central distribution of hydrogen becomes practical and may be justified

Rapid, profitable **H_2 transition (3)**

- ≥2 proven, cost-effective, climate-safe methods
  - Reform natural gas at the wellhead and reinject the CO_2
    - Reforming (≥6% of U.S. gas now) & reinjection are mature
    - Potentially three profit streams: H_2, $+CH_x$, $-C$
    - Strong industry interest (BP, Shell, Statoil), 200-y resource
  - Electrolyze with climate-safe electricity
    - Greatly improves ecs. of renewable electricity, bec. H_2-to-wheels is ~2–3× more efficient than gasoline-to-wheels
      - Even 2002 US gasoline ($1.25/gal) was 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 instead of kWh (a value-added product instead of the electron commodity)
      - H_2 storage makes wind/PV power firm and dispatchable
- Probably more: coal, oil, various renewables,...

Hydrogen-ready cars + integration 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 achieve most of the oil savings
- 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)
- In this integrated strategy, it doesn't matter whether stacks first become durable (favoring buildings) or cheap (favoring cars); whichever happens first will accelerate both markets

Five hydrogen surprises (see "20 Hydrogen Myths," www.rmi.org)

- >2/3 of fossil-fuel atoms burned today are H_2—we only need to get rid of the last 1/3 (the carbon)
- Making hydrogen from natural gas wouldn't significantly raise natural gas demand & might lower it (GM)
  - 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; even if this weren't true, shaving 15% of US electric peak loads + saving 9–17% of direct gas fuels 90% of highway vehicles
- Hydrogen will need less capital than gasoline does
  - By ~$600/car, says Sandy Thomas (www.h2gen.com)…basically because gas is less capital-intensive upstream than is oil
- Hydrogen would reduce drivers' fuel cost per km
  - This metric, taking account of hydrogen's superior end-use efficiency, is valid; common $/GJ comparisons are not!
- Hydrogen is more profitable for hydrocarbon owners

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…even if carbon is worth zero?
- Can you make more money removing hydrogen in a reformer than adding it in a refinery?
- Generally yes…so oil owners can make more money even in a world that buys no oil!
- Similar logic applies to coal, whose highest-value use is making hydrogen

Delivering hydrogen at least cost: use paid-for gas & el. infrastructure

- Distributed architectures are probably cheaper/faster
  - Mass-produced miniature reformers appear cheaper and slightly more efficient (tighter thermal integration)than centralized ones
  - S. Thomas: adding H_2 adds <10% of a gas station's capex — or ~2¹/₂% of investment in the station *plus* its upstream oil supply
  - As with diesel fuel, <1/3 of filling stations need conversion; S. Thomas says converting 10–20% in US would cost only ~$2–4b
  - GM says for $12b, 11,700 [costly] forecourt reformers could put one ≤2 miles from 70% of US drivers, plus every 25 mi of NHS
  - Less conversion is needed with GPS-rich vehicles & GIS siting
  - ~70% of US filling stations serving ~90% of gasoline demand have natural gas service; for the rest, use LPG or hydrous ethanol
  - Deutsche Shell said H_2 in German filling stations could take 2 y
  - Sweden has a clever low-cost transition roadmap (baff.info)
  - Integrate with deployment of fuel cells in buildings
- Central solution: near-urban refineries sell merchant hydrogen from surplus reformers via short pipelines

Five steps to a hydrogen future

- Make the cars ready for the hydrogen
  - Gasoline & biofuel hybrids, then ultralights, then fuel cells
  - Ultralight, ultra-low-drag hybrids make conventional H_2 tanks packageable and fuel-stacks quickly affordable
  - Automakers' R&D investment will do best if targeted to make cars lighter, not tanks smaller and stacks cheaper
- Integrate fuel-cell deployment in stationary and mobile applications so they reinforce each other
- Get serious about efficient use of natural gas
  - Reward utilities for cutting bills, not selling more energy
- Embrace decentralized electricity and gas systems
  - Bigger may well not be cheaper — no evidence yet that it is
  - Distributed benefits are enormously valuable; count & capture!
- Evolve H_2 toward renewables, but meanwhile don't let the perfect prevent the good ($CH_4 \rightarrow H_2 + CO_2\uparrow$)

"Those who think it can't be done shouldn't interrupt those doing it."

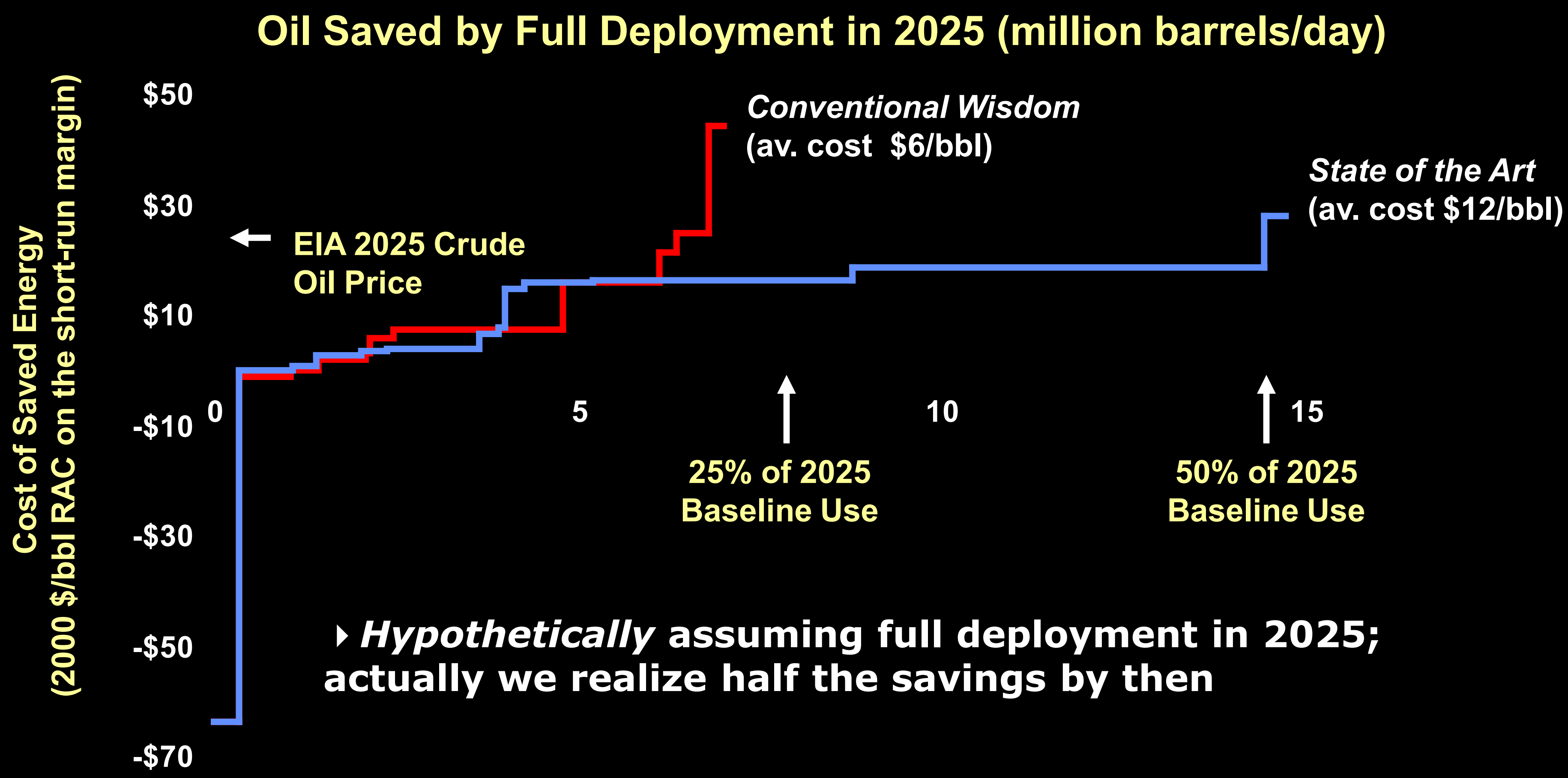
—Robert W. Shaw, Jr.

"Only puny secrets need protection. Big discoveries are protected by public incredulity."

—Marshall McLuhan

www.oilendgame.com

It pays to be bold: saving half the oil for $12/bbl is better than saving a fourth at $6/bbl — else alt. supplies cost too much



- *Hypothetically* assuming full deployment in 2025; actually we realize half the savings by then

No further invention is assumed during 2005–2025

Five ways government can help

1) **Stimulate demand for very efficient vehicles**
   - Feebates—revenue- and size-neutral, more automaker profit
   - Create a new million-car-a-year US market through leasing to low-income customers (and scrapping inefficient/dirty cars)
   - Smart military and government fleet procurement; 'Golden Carrot' and 'Platinum Carrot' to speed innovation
   - Heavy-lorry-buyer info/leadership, airline loan guarantees
2) **Build vibrant 21st Century industries by sharing R&D risk and deploying faster than the private market**
   - Military R&D should finance advanced materials development
3) **Lower risk of investment for new manufacturing plants through loan guarantees to automakers**
4) **Support development of domestic energy supply infrastructure (hydrocarbons → carbohydrates)**
5) **Remove barriers to efficiency through coherent policies and purging perverse incentives**

Big, fast changes have happened

- US automakers switched in **SIX YEARS** from 85% open wood bodies to 70% closed steel bodies—and in **SIX MONTHS** from making four million light vehicles per year to making the tanks and planes that won World War II
- Major technological transformations take **12–15 years** to go from 10% to 90% adoption
- The key is to get to the first 10% much faster!
- In 1977–85, US cut oil intensity 5.2%/y—equivalent, at a given GDP, to a Gulf every 2.5 years
- If every 2025 light vehicle were as efficient as the best 2004 cars & SUVs, they'd save 2 Gulfs' worth

Global industry already makes as much H_2 as efficient road vehicles would need

- ~50 MT/y H_2 (2003) is ~1/4 as many Nm^3/y as CH_4
- At 120 MJ/kg LHV, 50 MT/y H_2 (~37–45% used by refineries) — *if* it all directly fueled 5η* light vehicles instead — could displace two-thirds of all U.S. gasoline (or all by ~2010 at 6%/y H_2 growth)

  *Hypercar®-class platform physics mean nominally "3η" if Otto, "4η" hybrid or Diesel, "5η" (at least) if fuel-cell

- If fueling 5η light and 2η heavy vehicles, 50 MT/y H_2 could displace all U.S. highway-vehicle fuel (and, with *WTOE*'s 3η heavy vehs. & planes, planes too)
- U.S. refineries alone use ~7 MT/y H_2 — enough, if so used, to displace 1/4 of U.S. gasoline (2× Gulf share) or 1/7 of U.S. highway-vehicle fuel

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, making fuel cells cost-effective *today* in certain building and industrial applications, even at handmade prices — see Joel Swisher's *Cleaner Energy, Greener Profits*

Well-designed hydrogen cars will be cheaper per mile driven

◇ Gasoline

= 5¢ per mile

- Gasoline
- Diesel

$1.00/gallon (pretax)

Avg. 20 mpg

Well-designed hydrogen cars will be cheaper per mile driven

- Gasoline

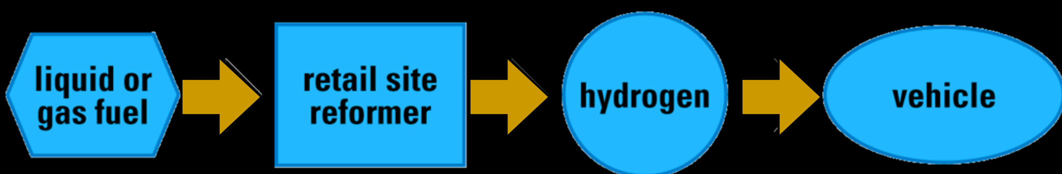
= 5¢ per mile

- Gasoline
- Diesel

$1.00/gallon (pretax)

Avg. 20 mpg

- Reformation



= $2^{1}/_{2}$¢ 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

Qualitatively consistent w/ Ford & Accenture findings. Carbon sequestration has little effect on these results.

◇ Reformation

liquid or gas fuel → retail site reformer → hydrogen → vehicle = $2^1/_2$¢ per mile (or at Toyota's 3.75× efficiency target, 3.3¢/mi)

- 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

Nuclear H_2 can't make money or sense, but reforming H_2 from HCs can

- Even if electrolysis were a competitive way to make H_2, new nuclear plants are a hopelessly uncompetitive way to make electricity — forget it
  - Nuclear-el. H_2 would cost 2–3× more/km than oil at an all-time record price (5/06 reactor price implies delivered H_2 parity with reforming ~$40/GJ gas); nuclear-thermolytic H_2 looks little better (?500–>700 °C, unimpressive η, significant capital cost)
  - 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 km would fall by ~2–5× (USDOE says 2.5×)…
  - And long-run to make H_2 *with* carbon sequestration (at large or probably, with emerging methods, small scale: several firms think they'll be able cheaply to sequester forecourt-reformer CO_2 or even turn it into a useful product) — or its backstop technologies, which don't require geological success

Making cars ready for hydrogen

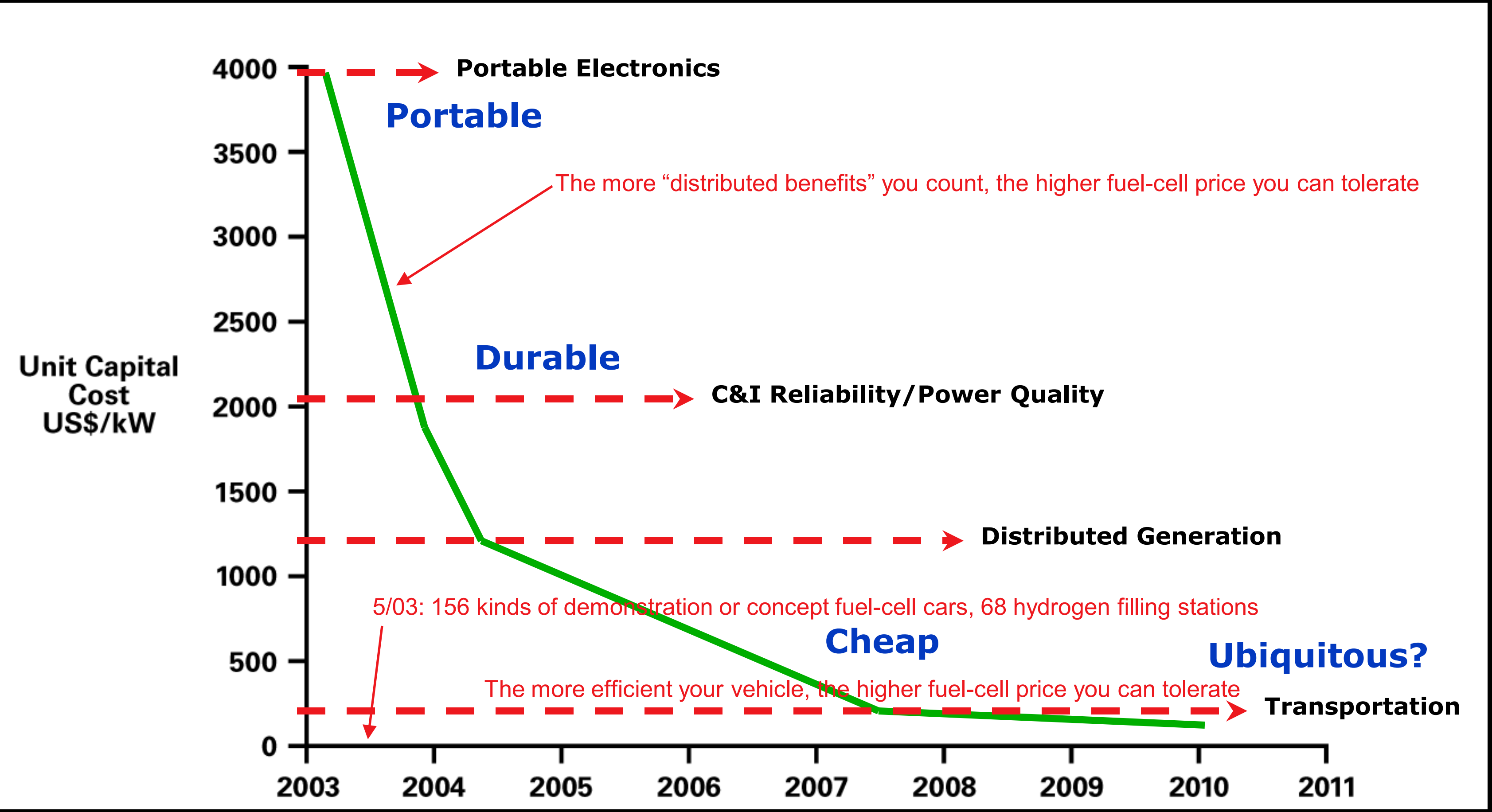
- **Standard fuel-cell car:** insert fuel cell in near-normal, high-tractive-load platform
- Stack is too big and costly, so must sell many units at a loss (or wait a long time) to bring cost down
- H_2 tanks are too big to package, so need onboard methanol or gasoline reformer
- Reformer hell

- **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
- Stack is small enough to afford, even at early prices
- Now-commercial H_2-gas tanks for normal range are small enough to package
- No reformer, high efficiency
- Can produce cars as soon as fuel cells are ready

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…