Technology Integration for Radical and Profitable Transport Efficiency

Amory B. Lovins

Chief Executive Officer
Rocky Mountain Institute
www.rmi.org

Chairman of the Board
www.fiberforge.com

ablovins@rmi.org

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Peer-reviewed
DoD-cosponsored
Integrative
Comprehensive
Fully documented
Transparent
For business/military leaders
Built around competitive-strategy business cases
Base case: EIA 1/04 Ref Case 2000 $, 5% real discount rate

Book, technical annex, and related materials are all free downloads at:

www.oilendgame.com

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Over the next few decades, the United States can get completely off oil and revitalize its economy—led by business for profit, and technologically catalyzed by the military for mission effectiveness.
Unlikely Allies Fight U.S. Oil Dependence

Bipartisan Network to Press for Reduced Consumption, Quicker Development of New Fuels
Whalers ran out of customers... before they ran out of whales... even before Drake struck oil in 1859!

Rise and fall of the U.S. whaling fleet, 1821–1884

- Sperm oil production (100,000 gal/y)
- Whale oil production (100,000 gal/y)
- Sperm oil price (2000 $/gal)
- Whale oil price (2000 $/gal)
- Whaling-fleet displacement (10,000 tons)
- Crude-oil wellhead price (2000 $/gal)
- Crude-oil production (100,000 gal/y)
Winning the Game: restoring competitiveness \textit{and} eliminating oil dependence

- National security \textit{and} national competitiveness at risk

Why should we care?

- Oil insecurity, geopolitical rivalry, price volatility, perhaps depletion, climatic stability, ...
- Japan, EU, China will eat Detroit for lunch; Airbus is challenging Boeing; core sectors are at risk; the U.S. choice

How do we win?

1. Efficient end-use can save half the oil @ $12/bbl (2000 $)
2. Biofuels can replace another fifth
3. Saved gas can displace the rest \{ av. cost $18/bbl \}

Vs. EIA’s forecast $26/bbl in 2025, save net $70 billion a year
How do we capture this prize?

- Invest $90 billion in transportation equipment industries, plus...
  - $90 billion to build an advanced biofuels industry

- Business should lead, but...
  - ...needs acceleration, while...
  - ...expanding customer choice and reducing business risks

- Federal government: lead, follow, or get out of the way

- Creates 1 million good new American jobs (3/4 rural)
  - Preserves 1 million jobs
  - Returns >$150 billion/year
  - CO₂ 26% lower, for free

- Support, not distort, business logic with new policies...
  - Market-oriented without taxes
  - Innovation-driven without mandates
  - Reduce federal deficit
  - Broad political appeal

- Needs little or no Congressional action
  - Can be administrative, or done by the states
The energy future is choice, not fate

U.S. petroleum product consumption and net petroleum imports, 1950–2025

24% of U.S. oil imports coming from Persian Gulf

Practice run 1977–85: GDP +27%, oil use –17%, oil imports –50%, Gulf imports –87%

You are here

24% of U.S. oil imports coming from Persian Gulf

Equivalent of 2025 Persian Gulf imports displaced

Alternative supply exceeds this

Total Petroleum Use

Conventional Wisdom + Drift

Conventional Wisdom + Coherent Engagement

State of the Art + Coherent Engagement

Net Imports

Conventional Wisdom + Drift

Conventional Wisdom + Coherent Engagement

Plus Biofuels and Biomaterials

Plus Saved Natural Gas Substitution

State of the Art + Coherent Engagement

Plus Biofuels and Biomaterials

Plus Saved Natural Gas Substitution

Equivalent of 2025 Persian Gulf imports displaced

Alternative supply exceeds this

You are here
Cars and light trucks: save 69% of 2025 fuel @ 57¢/gallon

Ultralight (e.g. carbon composites), low drag, hybrid

GM *Ultralite* 1991, 5 seats, 0–60mph/7.3s, 84 mpg, nonhybrid

Opel *Eco-Speedster* 2002, 2 seats, 155 mph, 94 mpg, diesel hybrid

Toyota *Allesandro Volta* 2004, 3 seats abreast, 408 hp, 0–60/<4 s, 32 mpg

Hypercar *Revolution* 2000 virtual design, 5 seats, midsize SUV, 66 mpg gasoline hybrid w/3-y payback, 0–60/7.1 s), 114 mpg w/H₂

Surprise: 2x-mpg ultralighting is free, because the costlier materials are offset by cheaper automaking and smaller propulsion system.
Heavy trucks: save 25% free, 65% @ 25¢/gallon

Better aero & tires, better engines etc., less weight

PACCAR high-eff. concept truck
Colani/Spitzer tanker (Europe), reportedly 11.25 mpg

6.2 to 11.8 mpg with 60% IRR by improving aero drag, tires, engines, mass, driveline, acces. loads & APU; then ~16 mpg via operational improve-ments; being built 2005

Big haulers’ margins double from 3% to 6–7%...so create demand pull — currently underway, led by major customers
Planes: cost-effectively double or triple efficiency

Save 20% ~ free (787, 2007)

...then, ~2015–20, save 45% @ 46¢/gal; with blended-wing-body & internal engines, ~65% at comparable or lower cost, via lighter weight, better engines & aerodynamics
Platform physics is about to transform powertrain choices

◊ **Halved curb mass**, with very low $C_{DA}$ and $r_0$, in highly integrative and radically simplified designs

◊ Result: meet all conflicting requirements at once
  - Safety (despite mass dispersion of vehicles on the road)
  - Fuel economy ($2 \times \sim$free, $\geq 3 \times w/2-y$ U.S. payback), CO$_2$
  - Performance, packaging, styling, marketability, flexibility
  - Manufacturability, cost, durability, reparability, recyclablility
  - Suitability for alternative fuels, clear path to affordable H$_2$

◊ **Big strategic advantages in manufacturing**

◊ **Powertrains get smaller, lighter, simpler, cheaper**
  - Less cost, lower emissions, better vehicle dynamics & NVH
  - Uncompromised or better performance and reliability
  - Better packaging, nonlinear mass decompounding...
Decompounding mass and complexity also decompounds cost

- Reduce mass & drag
- Less power needed
- $H_2$
  - Smaller drivetrain
  - New technology
- Smaller, lighter chassis parts
- Better packaging
  - More crush space

New design strategy, materials, and technologies

Only ~40–80 kg C, 20–45 kW, no paint?
Critical insight: light weight before aerodynamics and powertrain creates 68% of SUV fuel savings (hybrid: 16%)

U.S. gallons per year in typical U.S. driving pattern

Means: light metals, composites, ultralight steels

Issues: crashworthiness and manufacturing cost
Light vehicles: challenging a basic Detroit and Washington assumption

- Efficiency assumed to be a tradeoff against price, size, performance, safety, ...
- Hence policy intervention needed to induce customers to buy the compromised vehicles; but Congress has gridlocked on that for >20 years
- But what if superefficiency were a byproduct of breakthrough engineering, so people would buy the cars because they’re better—like buying digital media instead of vinyl phonograph records?
- An engineering end-run around tax/CAFE gridlock
- Robust business model based solely on value to customer and competitive advantage to maker
Where does a car’s gasoline go?

- 6% accelerates the car, <1% moves the driver
- Three-fourths of the fuel use is weight-related
- Each unit of energy saved at the wheels saves ~7–8 units of gasoline in the tank (or ~3–4 with a hybrid)
- **So first make the car radically lighter!**
Three technology paths: aluminum, light steels, carbon composites (the strongest & lightest)

- Carbon-composite crush structures can absorb 6–12× as much energy per pound as steel
- This can make cars lighter but bigger and safer... and simpler and potentially cheaper to manufacture

• Immaterial damage when T-boned by Golf
• 15 lb of carbon crush cones (0.4% of car’s weight) can absorb all crash energy @ 66 mph
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 an halved-weight SUV with two Tier Ones, *Intl. J. Veh. Design* 35(1/2):50–85 (2004), with a 2-y payback at today’s gasoline price
Midsize 5-seat Revolution SUV
Ultralight (1,889 lb) but ultrasafe
0–60 mph in 8.2 s (later 7.1)
66 mpg w/gasoline hybrid
114 mpg w/H₂ fuel cell

Show car and a complete virtual design (2000),
uncompromised, production-costed,
manufacturable at competitive cost

“We’ll take two.”
— Automobile magazine
World Technology Award, 2003
Ultralight autobody materials

- aluminum front subframe
- advanced-composite passenger safety cell
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 ~10³)
  ♦ Self-fixturing, detoleranced in 2 dim.
  ♦ No body shop, optional paint shop
  ♦ Plant gets 2/5 cheaper, 2/3 smaller
Rapid progress with midvolume cost-competitive advanced composites

◊ BMW: 60 specialists at Landshut, world’s biggest RTM press, series production ASAP
  o Already making >1k/y carbon roofs, hoods,…
  o Website strongly praises carbon composites

◊ Honda and Toyota: carbon-fiber airplanes

◊ Fiberforge®: 1999 RMI spinoff (W. Colo.)
  o Patented digital automated fiber placement process
  o Thermoform to net shape, cycle times→1–2 minutes
  o ≥80% of hand-layup aerospace performance @ 20% of cost
  o Mature process should beat Al in $/part, steel in $/body at midvolume, and steel in $/car at any volume
  o Selling samples to automaker/Tier 1 customers, e.g. JCI Genus seat (Detroit Auto Show Jan 05)
  o World Technology Award, 2003
Automated volume mfg. of continuous-fiber-reinforced thermoplastic structures
See www.fiberforge.com for technical details and papers

1. Digitally controlled automated fiber placement to create a flat preform (tailored blank™)
   ◊ Designed for high throughput with precise fiber alignment
   ◊ Can vary in thickness, fiber mix/alignment/location, shape
   ◊ Thus ideal for anisotropic parts optimized to load paths
   ◊ Computed from CAD drawing; layup at 1350 mm/s and rising

Carbon/PEEK 200-mm hemisphere

SOME DIVERSE MATERIALS
SYSTEMS & APPLICATIONS

Carbon/nylon-6 seat-back frame
Automated volume mfg. of continuous-fiber-reinforced thermoplastic structures

2. Thermoform on hot die to net shape, cool, trim

High material efficiency, low cost (can start with creel fiber and thermoplastic pellets), very low scrap

Fast processing, exceptional performance & lightness
This means that ultralight hybrid midsize SUVs fueled with gasoline could achieve 66 mpg for 57¢/gal.

<table>
<thead>
<tr>
<th>Pretax Retail Price of Selected Crossover Vehicles (2000 $)</th>
<th>USEPA city/hwy mi/gal</th>
<th>Cost of Saved Energy ($/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 Audi Allroad 2.7T</td>
<td>18.5</td>
<td>–</td>
</tr>
<tr>
<td>Gasoline ICE Ultralight</td>
<td>44.6</td>
<td>0.15</td>
</tr>
<tr>
<td>Gasoline Hybrid Ultralight</td>
<td>66.0</td>
<td>0.56</td>
</tr>
<tr>
<td>H₂ Fuel Cell Ultralight</td>
<td>107.8</td>
<td>2.11</td>
</tr>
</tbody>
</table>

...based on a concept-SUV virtual design with two Tier Ones, production-costed mainly by bids (the rest by independent consultants and 9% by in-house models).
Ultralight-but-safe light vehicles open a new, vast, roughly free ultralight-hybrid design space.

All Vehicles Shown in Green are Adjusted to EIA’s 2025 Acceleration Capability for That Class of Vehicle
RMI’s 2004 Average Vehicles are for EIA’s 2025 Sales Mix

<table>
<thead>
<tr>
<th>Price Increase (MSRP 2000 $)</th>
<th>Absolute Miles per U.S. Gallon (EPA Adjusted, Combined City/Highway)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20 30 40 50 60 70 80 90</td>
</tr>
<tr>
<td>500</td>
<td>2,000 2,500 3,000 3,500 4,000 4,500 5,000</td>
</tr>
</tbody>
</table>

- **2004 Prius** (2004 Actual to ~2007 Goal)
- **2004 RMI Conventional Wisdom Average Car**
- **2004 RMI Conventional Wisdom Light Truck**
- **DeCicco & Ross 1995 Full Avg.**
- **DeCicco, An & Ross 2001 Mod & Adv Cars**
- **NRC 2001 Light Trucks**
- **NRC Low 2001 Light Trucks**
- **NRC Low 2001 Cars**
- **NRC High 2001 Cars**
- **2002 ULSAB-AVC Hybrid** (Rough RMI Estimate of Initial and More Mature Cost)
- **2002 ULSAB-AVC**
- **2004 RMI State of the Art Average Car**
Where a long-haul Class 8 truck’s diesel fuel goes

Focus: End of Chain [Fuel] → [Engine] → [Drivetrain] → [Tractive Loads]

- ~38% efficient today: Engine & drivetrain
- Represents >100 years’ R&D: Engine efficiency is more difficult to improve further than is end-use efficiency

End-use: Consider what would happen if we halved aerodynamic drag and mass

* Assuming driver utilizes engine at 95% of max efficiency due to driving habits (it’s probably much less in reality)

Source: Technology Roadmap for the 21st Century Truck Program (DOE 2000), RMI analysis
Focus on fuel end-use: Reducing air drag + rolling resistance by 50%, and idling by 80%, saves ~50% of fuel—without engine improvements.

- Eliminate >50% of fuel use
- No change in engine & drivetrain: same 38% efficiency

* Assume no change in driver behavior from previous slide

Source: Technology Roadmap for the 21st Century Truck Program (DOE 2000), RMI analysis
Heavy trucks use 12% of all U.S. oil in 2025; the same technologies could save 65% of that use at 25¢/gal diesel.

Start: 6.2 mpg

End: 11.8 mpg, then ~16-equivalent w/further improvements

Cost of Saved Energy (2000$/Gal Diesel)

- $0.50
- $1.00
- $1.50
- $2.00
- $2.50

Diesel Fuel Saved (Mbbl/d) in 2025 (vs. EIA Jan. 2004 Reference Case)

Conventional Wisdom: Average CSE = $0.13/gal

State of the Art: Average CSE = $0.25/gal

EIA 2025 Pre Tax Diesel Price (1.04/gal)

EIA 2025 Post Tax Diesel Price (1.34/gal)

Main sources: MIT, ANL, industry tests
Airplanes: industry agrees fleet can get 2–3× more efficient

- Keys: advanced composites, new engines, aerodynamics
- Could save 45% of EIA 2025 fuel @ av. 46¢/gal Jet-A
Hypothetically assuming full deployment in 2025; actually we realize half the savings by then.

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.

No further invention is assumed during 2005–2025
New biofuel technologies could provide 3.7 Mbbl/d cheaper than oil—without subsidies or crop/land/water problems

- Brazil has replaced >1/4 of its gasoline with sugar-cane ethanol, competitive without subsidy; oil savings so far are 50× the startup subsidy; exporting 2007–08 to Japan and China
- Europe in 2003 made 17× as much biodiesel as U.S.: oil companies distribute it; shifts farmers from subsidy to revenue
Over 12 TCF/y of natural gas could be saved by lucrative energy efficiency.

Over 12 TCF/y can be used either to substitute for oil or to power the H₂ transition.
Great flexibility of ways and timing to eliminate oil in next few decades
- Buy more efficiency (it’s costing only half as much as the oil it replaces)
- Efficiency is only half captured by 2025—7 Mbbl/d still in process
- “Balance” can import crude oil/product (can be all N. Amer.) or biofuels
- Or saved U.S. natural gas @ $0.9/MBTU can fill the “balance”...or
- H₂ from saved U.S. natural gas can displace “balance” plus domestic oil
- Not counting other options, e.g., Dakotas windpower—huge H₂ resource
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

- 137-L, 3.4-kg, 345-bar H₂ storage (small enough to package) for 330-mile range
- 35-kW fuel cell (small enough to afford early: ~32x less cumulative production needed to reach needed price)
- 35-kW load-leveling batteries
So the first automaker to go ultralight wins the fuel-cell race

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Power (kW)</th>
<th>Type</th>
<th>Cost @ $100/kW</th>
<th>Range (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypercar Revolution</td>
<td>35</td>
<td>hybrid</td>
<td>$3,500</td>
<td>531</td>
</tr>
<tr>
<td>Jeep Commander 2</td>
<td>50</td>
<td>hybrid</td>
<td>$5,000</td>
<td>190</td>
</tr>
<tr>
<td>Hyundai Santa Fe FCV</td>
<td>75</td>
<td>fuel cell</td>
<td>$7,500</td>
<td>402</td>
</tr>
<tr>
<td>Honda FCX-V4</td>
<td>85</td>
<td>fuel cell</td>
<td>$8,500</td>
<td>298</td>
</tr>
<tr>
<td>Ford Focus FCV</td>
<td>85</td>
<td>hybrid</td>
<td>$8,500</td>
<td>322</td>
</tr>
<tr>
<td>Toyota FCHV-4</td>
<td>90</td>
<td>hybrid</td>
<td>$9,000</td>
<td>249</td>
</tr>
<tr>
<td>GM HydroGen III</td>
<td>94</td>
<td>fuel cell</td>
<td>$9,400</td>
<td>402</td>
</tr>
<tr>
<td>GM Hy-Wire</td>
<td>94</td>
<td>fuel cell</td>
<td>$9,400</td>
<td>129</td>
</tr>
</tbody>
</table>
Five hydrogen surprises (see “20 Hydrogen Myths,” www.rmi.org)

◊ >2/3 of fossil-fuel atoms burned today are H₂ — we only need to get rid of the last 1/3 (carbon)
◊ Natural gas use won’t go up much, may go down — and the U.S. can save half its natural gas for <$1/GJ via well-known gas & electric efficiency
◊ Hydrogen will need less capital than gasoline does—plausibly by several hundred $/car
◊ Hydrogen would reduce drivers’ fuel cost per km
◊ Hydrogen is more profitable for HC companies: even if nobody pays to keep carbon out of the air, hydrogen is worth more without than with carbon, so extracting H₂ in a reformer tends to be more profitable than adding H₂ in a refinery
Platform physics is more important than powertrain—and is vital to its economics

- Cars can run clean IC engines on gasoline or NG ($\equiv 1\eta$)
- Better ones using hydrogen in IC engines ($\leq 1.5\eta$)
- Still better ones using H₂ in IC-engine hybrids ($\sim 2.5\eta$)
  - Ford “Model U” concept car...but tanks $\times 4\times$ bigger (niche market)
- Better still: ultralight autobodies, low $C_D A$ & $r_0$ ($\geq 3\eta$)
- Power those platforms with IC-engine hybrids ($3.5-4\eta$)
  - Hypercar 5-seat carbon Revolution has the same $m_c$ & $C_D$ as 2-seat aluminum Honda Insight...Insight-engine hybrid version 3.6L/100km
- Best: put fuel cells in such superefficient bodies ($5-6\eta$)
- **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,...
- H₂ needs $5\eta$ vehicles far more than vice versa
- $5\eta$ vehicles make robust the business case for providing the H₂ that their fuel cells would need
The creative-destruction challenge for oil companies

- The Oil Endgame is starting: the chairs of 4 oil majors and 3 car majors have said so
- Oil will probably become uncompetitive even at low prices before it becomes unavailable even at high prices
- Biofuels can be the transitional product line, as oil companies are exploiting in Europe
- Compelling arguments for changing business model to provide mobility and access, not gallons
- In the future, H₂ in hydrocarbons will be worth more without C than with C (even if nobody pays to protect the climate), so it’s better to take H₂ out of HCs (reform) than to put more in (refine); oil asset values may be sustained or increased
What if DoD investment in advanced light materials could transform the U.S. economy as profoundly as Internet, GPS, and chips?

- Advanced materials & propulsion systems can find a Saudi Arabia (>9 Mbbl/d) of saved oil under Detroit & Seattle...
- ...and help DoD transform its forces, strengthen warfighting capability, and cut fuel cost by billions of $/y and logistics cost by tens of billions of $/y
- The U.S. could cut oil use by 50% by 2025, imports by 75%
- The key DoD action needed is S&T investment in advanced materials, especially high-volume/low-cost manufacturing

The prize:
- A nega-Gulf every 7 y
- Vastly less world dependence on oil and conflict over oil
- A competitive Big 3
- Cheaper oil; more balanced U.S. trade, global development, and diplomacy
- More capable and confident warfighting
- Less need for it
- A safer world
Implementation recommendations for advanced-technology light vehicles

- **Size- and revenue-neutral “feebates”**
  - Fees on inefficient models, rebates on efficient models to widen the price spread within each size class
  - No incentive to change size; more choice & OEM profit
  - $1,000 per 0.01 gpm shows *lifecycle* fuel saving, not 2 y
  - $2,000 per 0.01 gpm equivalent to $3.50/bbl extern’y

- Create a new million-car-a-year market by financing very efficient new cars for low-income citizens...and scrapping clunkers

- **Smart military/government fleet procurement**

- “Golden & Platinum Carrots” to speed innovation

- **Loan guarantees to retool/retrain U.S. OEMs & Tier 1–2 suppliers (offset by equity warrants)**

- **NHTSA switches CAFE to size basis, not weight**
Mobilization: Accelerating Change

4.5 Mbbl/d saved, $391 billion in retail fuel savings

90–100% State of the Art vehicles by 2040

- **Average Vehicles** (rather like today’s cars)
- **Conventional Wisdom** (27% more efficient, 1-y payback)
- **State of the Art** (ultralight hybrids)
Big, fast changes have happened

- U.S. 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, U.S. 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
A profitable U.S. transition beyond oil

U.S. oil use and imports, 1950–2035

- government projection (extrapolated after 2025)
- end-use efficiency @ $12/bbl
- plus supply substitution @<$26/bbl (av. <$18/bbl)
- plus optional hydrogen from leftover saved natural gas and/or renewables (illustrating 10% substitution; 100%+ is feasible)

Petroleum use

Petroleum imports
So before you design a powertrain, or even choose which kind you want, or select a fuel and its infrastructure...

- Design the whole vehicle as a system
- Optimize physics *first*—especially mass
- Watch the powertrain become smaller, easier, simpler, cheaper, and better
- Watch your fuel choices become easier, simpler, faster, and cheaper
What are we waiting for?
Let’s play the Oil Endgame to win.

Free download from
www.oilendgame.com
The U.S. oil problem

- Americans use 26%, produce 9%, and own 2–3% of the world’s oil, so we can’t drill our way out
- Fungible in world market; issue is use, not imports
- The next barrel is cheaper abroad than at home
- Only three solutions in a market economy
  - Protectionism
  - Trade
  - Substitution

- Three basic approaches to oil strategy
  - Ostrich
  - Drill and kill
  - Innovate and revitalize—cheaper, safer, surer; our focus
The wider context: eight keys to energy security

- Remove climate change’s risks and costs
- Make electric blackouts impossible by design
  - Efficiency & load response, distributed generation, renewables
  - More and bigger powerlines are part of the problem
- Continue the market’s phaseout of nuclear power
  - Removing ambiguity unmasks proliferators
- Apply to natural gas what we’ve learned about el.
  - Efficiency & load response; avoid overshoot into costly LNG
- Evolve the whole energy system toward resilience
  - Efficient, dispersed, diverse, renewable (*Brittle Power* thesis)
- Get off oil—systematically, rapidly, and profitably
- Same for DoD, now the world’s largest oil buyer
- Change the energy policy process so it works (*NEPI*)
Our economic framework (2000 $)

- EIA 2025 Refiner’s Acquisition Cost (RAC) is $26/bbl
- We compare all costs w/ RAC on the short-run margin
- We omit all externalities; many are important
  - The market values oil-price volatility at ~$3.5/bbl over next 5 y
  - Some upstream and downstream capex to 2025+ is avoidable
  - Military: U.S. pays ~2–3× as much for peacetime readiness costs of forces whose main mission is Gulf intervention as for Gulf oil; could cost ~$10/bbl (econometric) or several times that much; even so, the market currently attaches a ~$5-12/bbl security-risk premium
  - Nonmilitary federal budget net subsidies: ~$2–3/bbl and rising
  - Environmental and climatic: NAS/NRC ~$11/bbl but very uncertain
  - Major costs to foreign relations, peace, development,...

- We count rebound for light vehicle VMT, but net the effect of sustaining gasoline tax revenues & of IHS
- Transparent: all #s from hand calculator/spreadsheets
- All discounting is at 5%/y real (OMB uses 3.2%/y)
No general-equilibrium calc, but if savings drop RAC far below EIA’s $26/bbl...

- Since we save half the oil, the value of that saving will drop by the same amount as the cost of the other half—a wash (assuming no change in energy taxation)

- Our savings might decrease at low oil prices, but there are important countervailing effects:
  - Half our SOA savings cost <$12/bbl on the short-run margin; the average of all SOA savings costs <76¢/gal retail gasoline
  - Our SOA savings are conservatively calculated, assume only technologies being commercialized now, and omit many options
  - Once installed, efficiency techniques don’t get uninstalled—our savings are technological/permanent, not behavioral/temporary
  - If the U.S. fully adopts our recommendations, that’s only 1/4 of the world market, diluting 4:1 the effect on world market price
  - While the U.S. & others save, low- & mid-cost reserves outside the Gulf are being depleted, increasing OPEC’s market power
  - EIA may understate demand growth in China, India, etc.

- So we don’t think lower oil prices (resulting from the wild success and fast, wide adoption of our recommendations) are likely to change our results significantly... though that’d be a nice problem for the world to have
How to return U.S. gas prices to ~$2–3 for ~3–5 y: ~5% electric load management/demand response

Natural Gas Oil Savings Resulting From Reducing 2000 U.S. Electric Peak Load

Percent Reduction in 2000 U.S. Electric Peak Load

- 100,000 bbl/d Oil Saved (L Axis)
- TCF/y Natural Gas Saved (L Axis)
- Gas Savings as % of Total 2000 U.S. Gas Consumption (R Axis)

Note: This August 2003 analysis by Kyle Datta and his colleagues at Rocky Mountain Institute uses the entire published plant-by-plant inventory, and assumes economic dispatch. There are unresolved minor uncertainties associated with dual-fueled peaking plants, interregional power flows, and transmission constraints. Copyright © Rocky Mountain Institute 2003. All rights reserved.
Saving U.S. natural gas

Potential Savings of U.S. Natural Gas (TCF/y) via End-Use Efficiency (Five-Labs Study data)

Average CSE
State of the Art = –$0.53/10^6BTU

Not shown: ~0.06 TCF/y of gas saved by CSU compressor improvements @ ~$0.16/MBTU; ~0.21 TCF/y avoided by not compressing gas that’s been saved, if and only if it’s not promptly reused;

...or feedstock savings: biomaterials-for-gas substitutions (~0.9 Mbbl/d), end-use savings such as plastics recycling, or using organic & precision farming to displace the ~0.5 TCF/y for N fertilizer

Five-Labs (CEF) Study’s conservative costs of saving electricity, less avoided onpeak gen. cap. & deferred grid cap., saves electricity at −1.6¢/kWh. Converted at the appropriate heat rates, that can save 25% of total 2025 gas use at –$1.5/10^6BTU.
Substituting saved gas for oil if relative burner-tip prices unknown

Potential 2025 Substitution of Saved Natural Gas for Suitable Uses of Oil (Mbbl/d)

- Average CSE Conventional Wisdom = $-4.2/bbl
- Average CSE State of the Art = $2.4/bbl

Potential 2025 Substitution of Saved Natural Gas for Suitable Uses of Oil (Mbbl/d)

- Residential Buildings
- Industrial Fuel
- Commercial Buildings
- Buses
$180 billion total investment for
>$150 billion annual return

- The $180 billion investment over 10 years is small compared to our other choices: $18 billion a year vs.:
  - Oil imports (largely wasted, money lost)—$18 billion every 5–6 weeks
  - $40 billion a year for Homeland Security, some oil-related
  - $50+ billion a year in peacetime military readiness for Gulf intervention (~2–3× what we pay to buy oil from the Gulf); increasing oil-protection burdens on all Commands

- >$150 billion a year in societal value by 2025
  - $133 billion a year in lower oil consumption (@ USEIA’s $26 a barrel)
  - $10–30+ billion a year in military fuel logistics costs saved
  - $0.5 billion a year in unnecessary agricultural subsidies
  - $11 billion a year in carbon credit value

- What’s it worth to eliminate worries about oil’s insecurity, volatility, and depletion? To regain the moral high ground? To have a safer world?
Today’s concept vehicles will go mainstream, integrating ultralight, ultra-low-drag, and advanced-propulsion.

**CARS:** save 69% at 57¢/gal

**TRUCKS:** save 25% free, or 65% @ 25¢/gal

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

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

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

Surprise: ultralighting is **free** — offset by simpler automaking and the 2×smaller powertrain!
The future is already here: today’s concept vehicle approaches will be tomorrow’s mainstream ...

CARS: save 69% at 57¢/gal

PLANES: save 20% free (787), 45% @ 46¢/gal

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

TRUCKS: save 65% @ 25¢/gal

Technology is improving faster for efficient end-use than for energy supply
Two ways to drive 12 km in the city

“Avcar” production platform (U.S. 1994 average)

Near-term Hypercar with interior space equivalent to 1994 Avcar

One Liter Fuel

15% Efficient Conventional Engine & Driveline (fuel to wheels)

2–4% used for Accessories

12% gets to wheels

Aero Drag $C_{DA} = 0.76 \text{ m}^2$

Rolling Drag $r_0M + f = 200 \text{ N}$

Braking $M = 1443 \text{ kg}$ 0% Recovered

Aero Drag $C_{DA} = 0.42 \text{ m}^2$

Rolling Drag $r_0M + f = 69 \text{ N}$

Net Braking $M = 600 \text{ kg}$ 48% Recovered

0.33 L Fuel

24% Efficient Complete Hybrid Driveline (fuel to wheels)

0.5–1% used for Accessories

23% gets to wheels

76% lost as heat and emissions

In highway driving, efficiency *falls* because there is far more irrecoverable loss to air drag (which rises as $v^3$) and less recoverable loss to braking.
Designing backwards

- Conventional design: from fuel to wheels
  - ~7 units of fuel are used to deliver 1 unit of energy to the wheels (“compounding losses”)
  - Since ~85% of the fuel energy is lost in the engine, en route to the wheels, and in accessories, focus on incremental reductions in those losses

- Hypercar® design: from wheels back to fuel
  - Radically cut the car’s mass and drag first
  - Each unit of energy saved at the wheels saves ~7 units of fuel up front (“compounding savings”)
  - This makes tripled efficiency straightforward with a conventional engine-driven hybrid, ≥5× with fuel cells
Saving >80% of fuel...incidentally

◊ Conventional design: save fuel as specific goal
◊ Trade off and compromise other design goals (size, cost, performance, perhaps safety)
◊ Rely on government intervention—efficiency standards, gasoline taxes, subsidies, mandates—to induce people to buy those less attractive cars

◊ Hypercar design: make the car superior, yet comparably priced, so people will want to buy it (like buying digital media instead of vinyl phonograph records)
◊ This also happens to save even more fuel
◊ Ultralight, ultra-low-drag triggers a long series of “virtuous circles”; then hybrid drive can make the car lighter, simpler, cheaper
◊ Mass savings snowball... nonlinearly
Decompounding mass and complexity also decompounds cost.

- Reduce mass & drag
- Less power needed
- H₂, smaller drivetrain, new technology
- Smaller, lighter chassis parts
- Better packaging, more crush space

New design strategy, materials, and technologies.
Affordable cars via costly materials

- Conventional design: stamped/welded steel
- Cheap material/kg, but costly to manufacture
- Two years to design & make ~1,000 steel dies
- High capital intensity, breakeven volume, and financial risk per model
- Long product cycle time increases risk
- Uninviting risk/reward profile

- Hypercar design: molded/glued advanced composites
- Costly material/kg, but we all buy cars by the car, not by the kg; offset by mfg.
- <20 dies, can be soft tooling
- Self-fixturing assembly
- Many-fold less capital, assembly, parts, time
- Small propulsion system
- Very low breakeven volume and risk per model
- Not sumo but aikido
Current and projected new-car eff. stds. (in US CAFE g CO$_2$/km-NEDC)

Detroit must act to avoid the “Creative Destruction” fate

- U.S. share for light vehicles steadily declining; SUVs last profit bastion; Big 3 mkt. capitalization < Toyota
- Consumers want provide comfort and safety without guilt—but won’t pay much more
- Breakthrough vehicles will be a disruptive product. Do we have the management vision this shift requires?...
- ...or will we fall short, and succumb to Schumpeter’s “creative destruction”?
- The question is who will make them: the U.S. or Japan (or possibly Europe and China and India)?
- If we fail to act, our car companies, and the industrial cluster that depends on them, could fade away
- We can import efficient cars to replace foreign oil...or make the cars ourselves and import neither
Analogy: did anyone notice the U.S. water-efficiency revolution?
U.S. energy/GDP already cut 43%,
to very nearly the 1976 “soft path”

...but that just scratches the surface, especially for oil
Seattle/Chicago has already bet on efficiency: Boeing vs. Airbus

- The competitive battle for the next generation of commercial aircraft features the efficient 787 (~20% less fuel, ~same price) vs. A380
- Disruptive change is more than technology, it’s also new business models
- Boeing is betting on a change in the airline business model to point-to-point (discounters) vs. fortress hubs (legacy airlines)
- Since the market cap of U.S. discount airlines is already 4× that of the 6 U.S. legacy airlines, Boeing may have made a good bet
Demonstrating hydrogen vs. gasoline safety

Side-by-side worst-case test of deliberate leakage of hydrogen (left: 1.54 kg = entire tank volume in ~100 s, 185 MJ) compared with a rather small leak of gasoline (right: 1.6-mm hole, 2.37 L, 74 MJ). The hydrogen flame is visible because sodium in particulates naturally present in the air. This test assumed a leak at the tank’s Pressure Relief Device (yielding the fastest possible loss) and failure of the standard H₂ sensor, pressure-drop, and flow-comparator shutoff devices. A hydrogen leak under a fuel-cell vehicle designed to standard protocols would require failure of those three safety devices and of the fuel line.


3 s: Ignition. H₂ @ 28 L/min, gasoline @ 0.68 L/min

60 s: H₂ flow subsiding; max 47°C on rear window, 19.4°C on tray behind rear seat. Zooming in on gasoline car…

90 s: H₂ plume nearly stopped.

140 s: Gasoline-car interior alight. Tires later burst.
Rapid, profitable H$_2$ transition
(RMI for National Hydrogen Assn., April 1999)

◊ Put fuel cells first in buildings for co-/trigen + UPS
  o Fuel with natural-gas reformers (or off-peak electrolyzers)
  o Big market—buildings use 2/3 of U.S. electricity

◊ Meanwhile introduce H$_2$-ready Hypercar® vehicles
  o Fleets (return nightly to the depot for refueling)
  o 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
    › First ~2M earn back much/most of cost of car ownership
      - U.S. full-fleet potential ~5–10 TW, ~6–12× grid capacity
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
    - $\sim 10^3$ reformers @ $6$/GJ gas beat $0.24$/L in $/km$
- Scaleable, modular, big economies of mass-production; carbon sequestration may scale down to the forecourt
- 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 $\text{H}_2$ transition (3)

◊ ≥2 proven, cost-effective, climate-safe methods
  o Reform natural gas at the wellhead and reinject the CO$_2$
    ‣ Reforming (6–8% of U.S. gas now) & reinjection are mature
    ‣ Potentially three profit streams: $\text{H}_2$, $+\text{CH}_x$, $-\text{C}$
    ‣ Strong industry interest (BP, Shell, Statoil), 200-y resource
  o Electolyze with climate-safe electricity
    ‣ Greatly improves ecs. of renewable electricity, bec. $\text{H}_2$-to-wheels is $\sim2–3\times$ more efficient than gasoline-to-wheels
      − Even U.S. old gasoline ($0.33$/L) 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 instead of kWh (a value-added product instead of the electron commodity)
      − $\text{H}_2$ storage makes wind/PV power firm and dispatchable

◊ Probably more: coal, oil, various renewables,...
Hydrogen-ready cars + integration with buildings = fast, profitable H₂ transition

◊ No technological breakthroughs required (new storage tech or onboard reformers); as soon as durable and cheaper fuel cells arrive, fuel-cell cars can be marketed profitably, many years earlier than would be possible with inefficient vehicles

◊ Staged deployment based on building & gas-station reformers

◊ Meanwhile, engine or engine-hybrid Hypercar® vehicles can save most of the oil & CO₂ (3.5 L/100 km midsize SUV, vs 2.1 with H₂ FC)

◊ It doesn’t matter whether stacks first become durable (favoring buildings) or cheap (favoring cars); whichever happens first will accelerate both markets

◊ No need for new liquid-fuel infrastructure (methanol, ultrapure gasoline,…), liquid H₂, or costly central H₂ production/distribution

◊ Integrating mobile and stationary deployment makes the transition profitable at each step (>10%/y real return)
California’s 2000–01 electricity crisis: media myths vs. realities

- Demand didn’t soar — normal, CEC correctly forecast
- California didn’t stop building capacity in the ’90s
  - CA added 4–5 GW of distributed generation (> nuclear capacity)
- There was not a physical shortage of capacity
- Nutty restructuring (disaster designed by committee)
  - Sold utilities’ fossil-fuel plants to a small number of buyers
  - Seven firms controlled 2/3 of bidding space; each could move mkt.
  - Each made more profit selling less electricity at a higher price
  - ≥10 GW called in sick; efficient use defunded and disincentivized
  - So a system that had met a 53-GW load in summer 1999 crashed on a 29-GW load in January 2001 (but munis were generally OK!)
- ~20 other linked causes, many linked to natural gas
- Customers undid 5–10 y demand growth in 1–2Q01
- That plus long-term contracts put out the fire
- Supply then overshot, as regionally and nationally
State/regional policy opportunities

◊ Electric and natural-gas distribution utilities
  o Efficient use, aligned incentives; distrib. bens. (www.smallisprofitable.org)

◊ Light vehicles
  o Revenue- and size-neutral feebates; shift registration/excise?
  o Smart procurement (aggregating state and local?)
  o Pay-at-the-pump insurance; shift tax from fuels to roads & driving
  o Fund initial dealer carrying charges/bonuses for superefficient cars

◊ Heavy trucks
  o Allow extra axle, 2-/3-trailer combos w/better brakes, 60 mph
  o Raise GVWR to EU norm (110klb), 14’H, 59’L
  o Require fuel-economy driver’s ed

◊ Biofuels (integrate with general farm/ranch reform)
  o Procurement, labeling, detaxation?, ?bonds, totalflex vehicles
Bringing affordable, ultralight, advanced-composite vehicles to market starting 2010

- Insider view of industry programs and state of mfg. process development supports this timeline
- Some OEMs may be faster: BMW 2005?; Honda & Toyota entering the carbon-fiber aircraft business
Absent demand-driving policies and *Conventional Wisdom* and *State of the Art* technologies

"EIA-mobiles" include only 5% [poor] hybrids by 2025; 2025 av. new LV is only **0.5 mpg better than in 1987**
Drift scenario

Absent demand-driving policies, Conventional Wisdom vehicles capture half the market in 2020
Let’s Get Started scenario

Feebates at the $1,000/0.01 gpm rate allow buyers to see 14, not 3, years of fuel savings

27%-less-fuel-consumptive light vehicles pay back in a few years
Let’s Get Started scenario

Low-income scrap-and-replace program is not a big oil saver, but it’s vital for equitable social development

Reality check: a 2025 fleet as efficient as 2004 hybrid cars & SUVs would save 1/6 of all 2025 oil use (2 Gulfs’ worth), costing ~$45b/y
Increasing the feebate rate to $2,000/0.01 gpm starts to count public goods.

- **State of the Art**
- **Conventional Wisdom**
- **Average Vehicle**
Mobilization: Accelerating Change

Adding smart government procurement and Golden and Platinum Carrot competitions increases market capture pulls *State of the Art* vehicles to an earlier starting date.