If a problem can’t be solved, enlarge it.

—Dwight David Eisenhower
“I can’t wait to see what happens when our industries merge.”

Henry Ford and Thomas Edison

188.5610 from https://www.thehenryford.org/exhibits/pic/2004/July.asp
The rise and fall of the U.S. whaling industry
The rise and fall of the U.S. whaling industry

Lamp retrofits from whale oil to coal oil gain market traction, become common

Drake strikes oil in Pennsylvania

annual-average real price of whale oil + sperm oil (2000 $/US gallon)

consumption of whale oil + sperm oil in American market (1,000 US gallons)
What if the biggest threats weren’t on the radar?
Heresy Happens
U.S. energy intensity, 1975–2017

Government and Industry Forecasts, ~1975
Lovins, *Foreign Affairs*, Fall 1976
Reinventing Fire, 2011

Actual
Geological reserves are a small part of resources

Schematic comparison of reserves and resources (by NERC for British Geological Survey)

One of many variants of the canonical McKelvey diagram used by the US Geological Survey and worldwide

Orebodies are limited. Energy efficiency isn’t (practically).

Increasing "accessibility" of reserves and resources.

Increasing geologic assurance.

Increasing economic feasibility.
How big is the energy efficiency resource?

Amory B Lovins

Rocky Mountain Institute, 22830 Two Rivers Road, Basalt CO 81621, United States of America

E-mail: abllovin@rmi.org
Lovins House, Old Snowmass, Colorado (1983)
US office buildings: 3–4× energy efficiency worth 4× its cost (site energy intensities in kWh/m²-y; US office median ~293)

Yet all the technologies in the 2015 example existed well before 2005!
5x-more-efficient new Indian commercial buildings

Infosys’s 1.5 million m² of 22k-m² office blocks (2009–14) in six cities:

- EPI fell 80%, to 66 kWh/m²-y
- with capex 10% to 20% lower than usual, and comfort better

Courtesy of Peter Rumsey PE FASHRAE (Senior Advisor, RMI) and Rohan Parikh (then at Infosys in Bengaluru, now at McBERL)
IPCC AR5 WG3 pp 702–704 (2014) reports that high-ambition European new (left) and retrofit (right) buildings show no significant increase in the cost of saved energy up to ≥90% savings. Some examples do show higher costs, but they needn’t: whatever exists is possible.
3-4x Energy Productivity in Buildings, 2x in Industry

Same or better services

Source: Reinventing Fire, RMI, 2011
Designing to save ~80–90% of pipe and duct friction—equivalent to about half the world’s coal-fired electricity

Typical paybacks ≤1 y retrofit, ≤0 new-build
But not yet in any textbook, official study, or industry forecast
Retrofitted Low-Friction Piping Layout

Images courtesy of Peter Rumsey, PE, FASHRAE, Senior Fellow, RMI
Which of these layouts uses less capital and energy?

- Less space, weight, friction, energy
- Fewer parts, smaller pumps and motors, less installation labor
- Less O&M, higher uptime
Start saving downstream

- Power Plant: -70%
- Power Grid: -9%
- Motor/Drivetrain: -12%
- Pump/Throttle: -55%
- Pipe: -20%

Delivered flow: 10%
-70% Power Plant
-9% Power Grid
-12% Motor/Drivetrain
-55% Pump/Throttle
-20% Pipe
5% Delivered flow
Conservatively, integrative design’s savings are not shown, yet total use falls 25% while light-duty vehicles are completely electrified and real GDP rises by 158%. Source: Lovins & RMI, Reinventing Fire (2011), p 204.
Hypercar Revolution midsize concept SUV (2000)
on-road 67 mpg (gasoline), 114 mpge (H₂)
carbon-fiber structure, ≤2-y retail payback

Toyota 1/X carbon-fiber concept PHEV sedan (2007)
Prius size, 1/2 fuel use, 1/3 weight

Bright IDEA 1-T 5-m³ aluminum fleet van (2009)
~100-mpge PHEV, 3–12×-efficiency, needs no subsidy

BMW i3 4-seat electric, carbon-fiber passenger cell
2013– mass-production, >150k sold @ $41–45k
111–124 mpg, MY2019 ≥200-mile range (≥300 w/REx)
Migrating advanced composites from military and aerospace to automobiles

95% carbon composite, 1/3 lighter, 2/3 cheaper (T100)
German Technology for Electrified Carbon-Fiber Cars

BMW’s sporty, 1250-kg 4x-efficiency i3 was profitable from the first unit, because it:
- pays for the carbon fiber by needing fewer batteries (which recharge faster)
- saves ~2.5–3.5 kg total for each kg of direct weight saved
- needs two-thirds less capital, ~70% less water, ~50% less energy, space, time
- requires no conventional body shop or paint shop
- provides clean, quiet, superior working conditions
- delivers 1.9 L-equivalent/100 km (124 mpge) on US or 1.7 on German test cycle
Tripled-Efficiency Trucks and Planes
Despite 90% more automobility, 118% more trucking, 61% more flying, US transportation without oil, for $17 per saved barrel.
LED and PV

Netherlands: trade electricity with fellow-customers
Utility revenues

Flexible demand

Customer preferences

Distributed renewables

No reactive power

Resilience imperative

Utility blockchain

Integrative design

Efficiency

Breakthrough batteries

Regulatory shifts

Storage (including EVs)

New financial & business models
Worldwide electricity generation by source, 1971–2017

Renewable energy’s costs continue to plummet

Wind and photovoltaics: U.S. generation-weighted-average Power Purchase Agreement prices, by year of signing

- **Utility-scale solar PPAs**
- **U.S. wholesale power price range**

**Levelized 2014 US$/MWh**
- Updated through Jun 2018; solar asterisks: Chile (2.91¢/kWh, Aug 2016) and Mexico (2.7 ¢/kWh, Feb 2017; $1.92¢, Nov 2017); wind asterisks: Morocco (Jan 2016), Mexico 1.7¢ (Nov 2017); Xcel Dec 2017 median levelized solar bids: 36 $/MWh and 30 $/MWh w/ and w/out storage; Xcel wind bids: $21/MWh and $16/MWh w/ and w/out storage

- Dec 2017 Xcel Colo. median bids
- * lowest unsubsidized world bids
- * lowest unsubsidized world bids

**Wind PPAs**

**U.S. wholesale power price range**

**Utility-scale solar PPAs**

**Levelized 2014 US$/MWh**
Wind and solar are increasingly competitive with just gas for a CCGT.
Renewables, efficiency, demand flexibility, and storage can provide all grid services traditionally provided by gas-fired power plants.

Source: RMI, *The Economics of Clean Energy Portfolios*, May 2018
More frontiers in beneficial electrification

9–20 kWt, 200 krpm DHW heat pump
>60% of Carnot efficiency
COP=6–15 for ΔT=13–31°C

Maravić stay-flat-bottom pots and conductive, smart-control hobs for 3–4× cooking efficiency

Masonry low-income houses’ integrated gut rehab + superinsulation retrofit, installable by residents or unskilled neighborhood youth, cut heating needs by >90% to $100/y, and cooling to a small window a/c. The $4,700 marginal cost paid back in a few years.

160–200+ °C process heat pumps emerging; Tesla Gigafactory saved 6–12 months and 98.5% of energy in a key process by eliminating gas
Best resources far away, or adequate resources nearby?