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

Henry Ford and Thomas Edison
Reduced energy intensity has had 30× the impact of renewable growth
(United States, 1965–2018p, not weather-normalized, EIA data)

- Primary energy use if at 1975 efficiency and structure
- Energy saved by reduced intensity
- Actual primary energy use
- Growth in renewable energy use

1975–2018p savings from intensity reduction: 2,589 qBTU
1975–2018p growth in total renewable output: 87 qBTU
Heresy Happens

US primary energy intensity, 1975–2017

Index of U.S. Primary Energy Per Dollar of Real GDP

Government and Industry Forecasts, ~1975

Lovins, Foreign Affairs, Fall 1976

Reinventing Fire, 2011
How big is the energy efficiency resource?
Lovins House, Old Snowmass, Colorado (1983)
US office buildings: >5–10× best-efficiency gains in 5 years
(site energy intensities in kWh/m²-y; US office median ~293)

2010 retrofit
- 277 → 173 (~38%)

2010–11 new
- 284 → 85 (~70%)

2013 retrofit
- ... → 108 (~63%)

2015 new
- ... → 51 (~83%)

... and in Germany, 2013 new
- ... → 21 (~93%)

Yet all these technologies existed well before 2005!
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)
Cooling midrise apartment buildings in India

5–10% urban window a/cs could reach 50–60% by 2030, adding 150 GW peak load
Requiring efficient a/c ([superefficient.org](http://superefficient.org)) could save ≥40 GW
Requiring/incentivizing smart a/c could add ≤110 more GW of demand response
Could use on-bill financing, as India did for 75M LED lamps
Could meanwhile adopt/encourage efficient building envelopes needing little/no a/c
“Energiesprong” unsubsidized mass retrofit of public housing

Before: 6 Dutch units, each with annual energy bills ~€1.5–2k

After: net-zero-energy, expected soon to be financed just from energy savings; made affordable by industrializing the manufacturing: retrofit originally cost €150k/unit, now €75k (15% subsidized), self-financing target ~€65k, long-term goal €40k
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
RMI’s latest >$40b worth of integrative design in diverse industrial projects—retrofits and newbuilds (solid = built, shaded = incomplete data, circle = not yet built)
20 paths to decarbonizing process heat (e.g. for cement)

**Eliminate need:** onsite building services vs remote infrastructure, 3D printing/local mfg., chemical microreactors, telecoms vs roads, shared & connected mobility vs parking, urban form vs automobility (⅓ less concrete)

**Service, not stuff:** Solutions-economy business models (structural services not tons of cement, mobility services,...)

**Productive use:** Elegantly frugal structural design with appropriate safety margins, rewarding civil engineers for quality
- Use other materials: e.g., ultralight carbon-fiber cars for heavy metal cars, timber for concrete, adobe/caliche,...
- Increase substituents: fly-ash, ground glass, rice-hull derivatives, nano or fume silica,... for clinker, bamboo for rebar
- Improve materials-quality uniformity (3x in cement by eliminating Chinese shaft kilns)

**Materials efficiency:** e.g., fabric concrete forms (≥2x), tension not compression structures (~8x), Girshenfeld, Miralon
- Close materials loops: longevity, dematerialization, reuse, remanufacturing, recycling, downcycling,...
- Less onsite waste via ontime delivery (Cemex), tighter specs, Smart crushing/unhydrated cement recovery
- Capture significant knock-on effects such as reduced energy to transport cement, build roads & factories,...

**Cleaner stuff:** Substitute carbon-free or -positive chemistries (Solidia, Calera, Novacem,...)
- Processes requiring less or no heat or (biomimetically—abalone shell)
- Processes requiring lower temperatures: olivine+steam, ecocement, Bang bacterial cement, geopolymers,...

**Make better:** More-efficient processes, equipment, and controls
- Heat recovery and cascading, cogeneration: e.g., McKay’s Hong Kong dioxin-free municipal-solid-waste cogen

**Make cleanly:** Fuel-switching: biofuels, bioprocessing byproducts, waste solvents, old tires, crop wastes,...
- Solar process heat (logical evolution for solar concentrators; can include cogen; feasible even with cloud)
- Renewable electricity for heat pumps—now 160°C, soon >200°C
- Renewable electric process heat or plasma
- Renewable hydrogen process heat or reductant
Designing to save \( \sim 80-90\% \) of pipe and duct friction—equivalent to about half the world’s coal-fired electricity.

Typical paybacks \( \leq 1 \) y retrofit, \( \leq 0 \) new-build
But not yet in any textbook, official study, or industry forecast.
Designing to save ~80–90% of pipe and duct friction—by making them fat, short, and straight

Big pipes, small pumps

Nonorthogonal layout, 3D diagonals, few & sweet bends
Retrofitted Low-Friction Piping Layout

Images courtesy of Peter Rumsey, PE, FASHRAE
Start saving downstream

Energy units

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

10% Delivered flow
160 Energy units

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

5% Delivered flow
For best ultralighting, migrate advanced composites from military & aerospace to automobiles

95% carbon composite, 1/3 lighter, 2/3 cheaper
Reinventing the Wheels

Hypercar *Revolution* midsize concept SUV (2000)
on-road 3.6 L/100 km (gasoline) or 2.1 (H₂)
carbon-fiber structure, ≤2-y retail payback

Toyota 1/X carbon-fiber concept PHEV sedan (2007)
*Prius* size, 1/2 fuel use (1.8 L/100 km), 1/3 weight

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

BMW *i3* 4-seat electric, carbon-fiber passenger cell
2013– mass-production, >150k sold @ $41–45k
1.9 L/100 km (124 mpg), 247-km range (≥370 w/REx)
A competitive carbon-fiber electric car, 2013–

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 mass saved (Detroit says <1.3–1.5)
• needs two-thirds less capital, ~70% less water, ~50% less energy, space, time
• requires no conventional body shop or paint shop
• provides safe, clean, quiet, superior working conditions
• delivers 1.9 L\text{equiv}/100 \text{ km} (124 \text{ mpge}) on US 5-cycle test, 1.7 Ger., ~1.6 old US cycle
• provides exceptional visibility, agility, traction, and crash safety
Tripled-Efficiency Trucks and Planes
What if oil owners’ biggest threats weren’t on the radar?
Powering a home with just 27 watts of solar PV

~25-watt DC superefficient appliance package (LBNL), shown with 40 W PV panel

- 1 x 400 lm LED bulb (5 W)
- 1 x 300 lm LED tube (3 W)
- 1 x 23-inch / 56-cm LED-backlit LCD TV (12-13 W)
- 1 x 10-inch / 25-cm table fan (5 W)
- 1 x clock radio
- 1 x mobile phone charger (~2 W)

25 W incandescent lamp (~210–250 lm) shown for comparison, not PV-powered

Photo courtesy of Lawrence Berkeley National Laboratory
LED and PV

Netherlands: trade electricity with fellow-customers
Storage (including EVs)  
Regulatory shifts  
System re-engineering  
Flexible loads  
End-use efficiency  
Customer preferences including resilience  
Distributed renewables  
New financial + business models, including utility blockchain and transactive energy  
Utility revenues
Worldwide electricity generation by source, 1971–2017

International Energy Agency global wind and solar forecasts

Cumulative GW installed

Wind

- WEO 2002
- WEO 2004
- WEO 2006
- WEO 2008
- WEO 2010
- WEO 2012
- WEO 2014
- WEO 2015
- WEO 2016
- WEO 2017

6x upward revision since 2002

Solar

- 23x upward revision since 2002

Actual
BNEF forecast

Renewable energy’s costs continue to plummet

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

Levelized 2014 US$/MWh

Dec 2017 Xcel Colo. median bids

U.S. wholesale power price range

Utility-scale solar PPAs

Wind PPAs

Updated through Jun 2018; solar diamonds: Chile (2.91¢/kWh, Aug 2016) and Mexico (2.7 ¢/kWh, Feb 2017; 1.7¢/kWh, Nov 2017); wind diamonds: 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 $18/MWh w/ and w/out storage


North America’s lowest unsubsidized world bids

“Cathedral”

Photovoltaics

0 GW-y

3 GW-y

1 GW-y

2 GW-y

Years
Choreographing Variable Renewable Generation

ERCOT power pool, Texas summer week, 2050 (RMI hourly simulation, 2004 renewables data)
Choreographing Variable Renewable Generation

Europe, 2015–18 renewable % of total electricity consumed

74%
Denmark 2017 (2013 windpower peak 136%—55% for all December)

71%
Scotland 2018

38%
Germany 2018 (2016 peak 88%, 2018 ~90–100%)

66%
Portugal (2018, 42% without hydro) (2011 & 2016 peak 100%)

46%
Peninsular Spain (2016, 27% without hydro)
Grid flexibility resources

(All values shown are conceptual and illustrative)

- Efficient use
- Demand response
- Accurate forecasting of wind + PV
- Diversify renewables by type and location
- Dispatchable renewables and cogeneration
- Distributed electricity storage incl. EVs
- Thermal storage
- Fossil-fueled backup
- Bulk storage

Ability to accommodate reliably a large share of variable renewable power

(Hydrogen storage not shown because its quantity is indeterminate)
Accelerating EV growth and falling battery price

Global EV sales are growing at a ~65% CAGR, with battery pack price already averaging below $200/kWh.

Sources: BNEF; Tesla Model S: https://www.greencarreports.com/news/1103667_electric-car-battery-costs-tesla-190-per-kwh-for-pack-gm-145-for-cells
Quattro: https://electrek.co/2017/06/28/audi-electric-car-battery-cost-for-2016-145kwh-cell-cost-volt-margin-improves-35%

Battery pack price, 2010–2018 (2018 $/kWh)

BEV and PHEV annual sales, 2011–2018

Sources: BNEF; Tesla Model S: https://www.greencarreports.com/news/1103667_electric-car-battery-costs-tesla-190-per-kwh-for-pack-gm-145-for-cells
Quattro: https://electrek.co/2017/06/28/audi-electric-car-battery-cost-for-2016-145kwh-cell-cost-volt-margin-improves-35%
From PIGS to SEALS

Personal Internal-combustion Gasoline Steel

Shareable Electric Autonomous Lightweight [mobility-as-a-]Service
中华人民共和国
国民经济和社会发展第
十三个五年规划纲要
2016年03月17日
Transportation problems in China
From disorganized chaos to smooth travel experience
From superblock to walking distance

Graphics courtesy of Peter Calthorpe
“A wise, detailed, and comprehensive blueprint” — President Bill Clinton

REINVENTING FIRE

BOLD BUSINESS SOLUTIONS FOR THE NEW ENERGY ERA

AMORY B. LOVINS AND ROCKY MOUNTAIN INSTITUTE

PREFACE BY MARTIN ODON, PRESIDENT, REVOLV COMPANY

JOHN W. ROWE, CHAIRMAN AND CEO, EXELIN CORPORATION
$5T$ in savings (net present value, private internal cost) +158% bigger economy 0 oil, coal, nuclear
2010–2018p U.S. progress toward *Reinventing Fire’s* 2050 goals

Actuals (USEIA) are not weather-adjusted. *Reinventing Fire* progression based on constant exponential growth rate.

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**GDP**

- **Trillion 2009 chained $**
  - RF
  - Actual

**Primary energy intensity**

- **kBTU / 2009 $ chained GDP**
  - RF
  - Actual

**Renewable electricity generation**

- **TWh/y**
  - RF
  - Actual

**Electric intensity**

- **KWh / 2009 $ chained GDP**
  - RF
  - Actual
Solutions to:
21T RMB 2010 NPV

+587% in savings

bigger GDP

42% less carbon

经济节约

经济规模

碳排放减少
*Reinventing Fire* applied worldwide will keep within the 2010–2050 carbon budget for 50% probability of 2°C.

Worldwide annual CO₂ emissions under *Reinventing Fire* scenario

2034: cumulative post-2010 emissions exceed 1.5°C budget

Business-as-usual
- USA
- EU
- China
- Other OECD
- Other Non-OECD
- Worldwide RF
- IEA 450 scenario

...and with conservatively assessed natural-systems carbon removal...
Easter Parades on Fifth Avenue, New York, 13 years apart

1900: where’s the first car?

1913: where’s the last horse?

From the Age of Carbon to the Age of Silicon
Profitable Climate Protection with Development and Security