
ROCKY MOUNTAIN
INSTITUTE

Disruptive Energy Futures

Amory B. Lovins エイモリー B. ロビンス
Cofounder and Chief Scientist

F20, Tōkyō, 13 June 2019

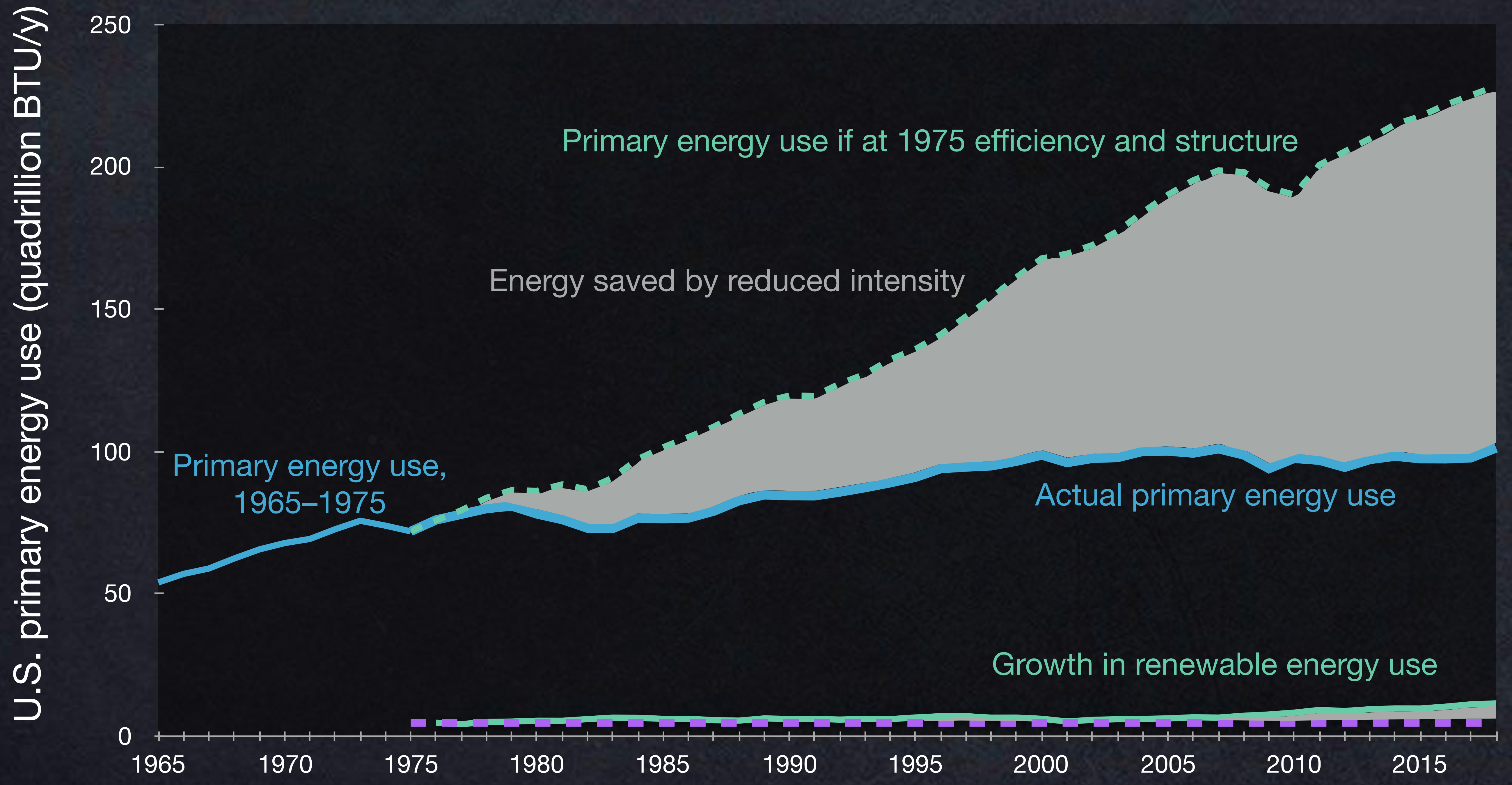
Henry Ford and Thomas Edison

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

188.5610 from https://www.thehenryford.org/exhibits/pic/2004/July.asp

Reduced energy intensity has had 30× the impact of renewable growth

(United States, 1965–2018p, not weather-normalized, EIA data)

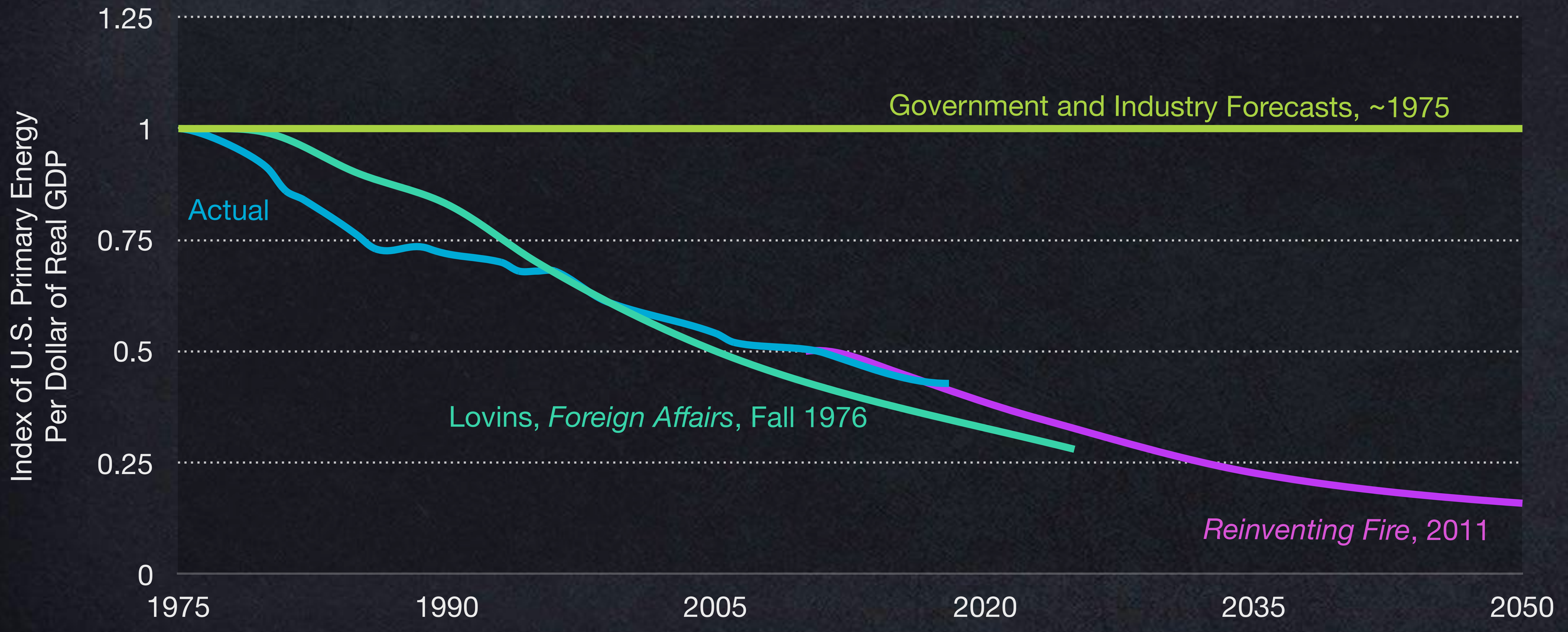


1975–2018p savings from intensity reduction: 2,589 qBTU

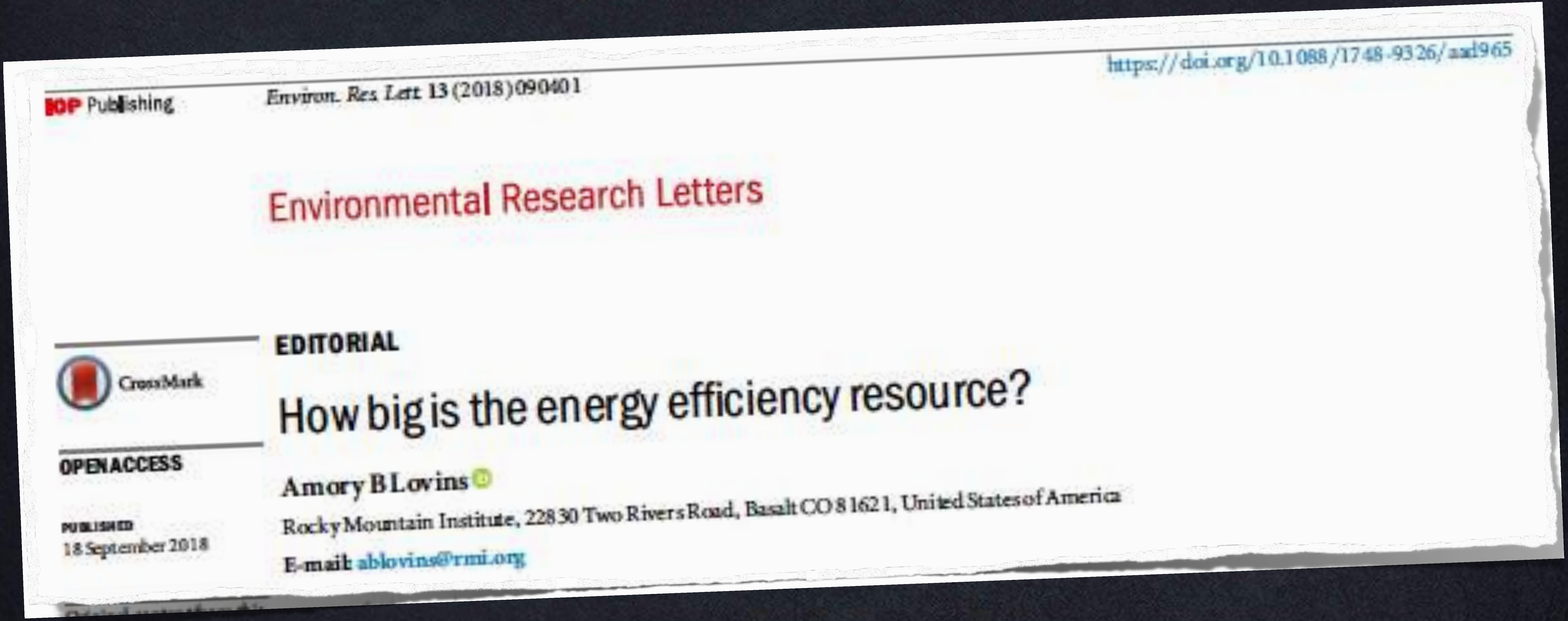
1975–2018p growth in total renewable output: 87 qBTU

Heresy Happens

US primary energy intensity, 1975–2017



A new technical paper on integrative design


IOP Publishing Environ. Res. Lett. 13 (2018) 090401 https://doi.org/10.1088/1748-9326/aad965

Environmental Research Letters

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EDITORIAL

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: ablovins@rmi.org

Lovins House, Old Snowmass, Colorado (1983)

US office buildings: >5–10× best-efficiency gains in 5 years

(site energy intensities in kWh/m^2-y; US office median ~293)

~277➞173 (–38%)
2010 retrofit

284➞85 (–70%)
2013 retrofit

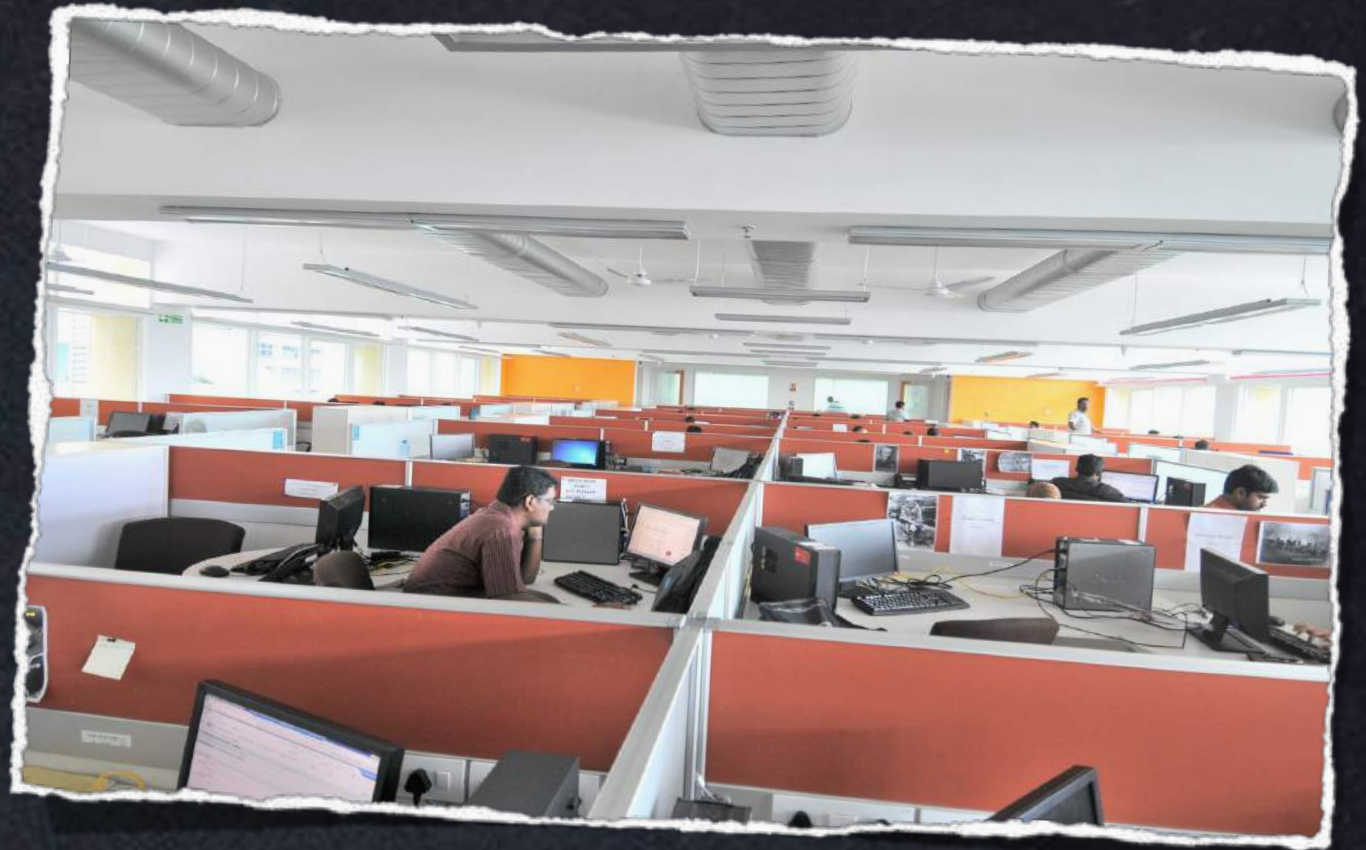
...➞108 (–63%)
2010–11 new

...51 (–83%)
2015 new

...21 (–93%)
…and in Germany,
2013 new
(office and flat)

Yet all these technologies existed well before 2005!

5x-more-efficient new Indian commercial buildings



Infosys's 1.5 million m^2 of 22k-m^2 office blocks (2009–14) in six cities:

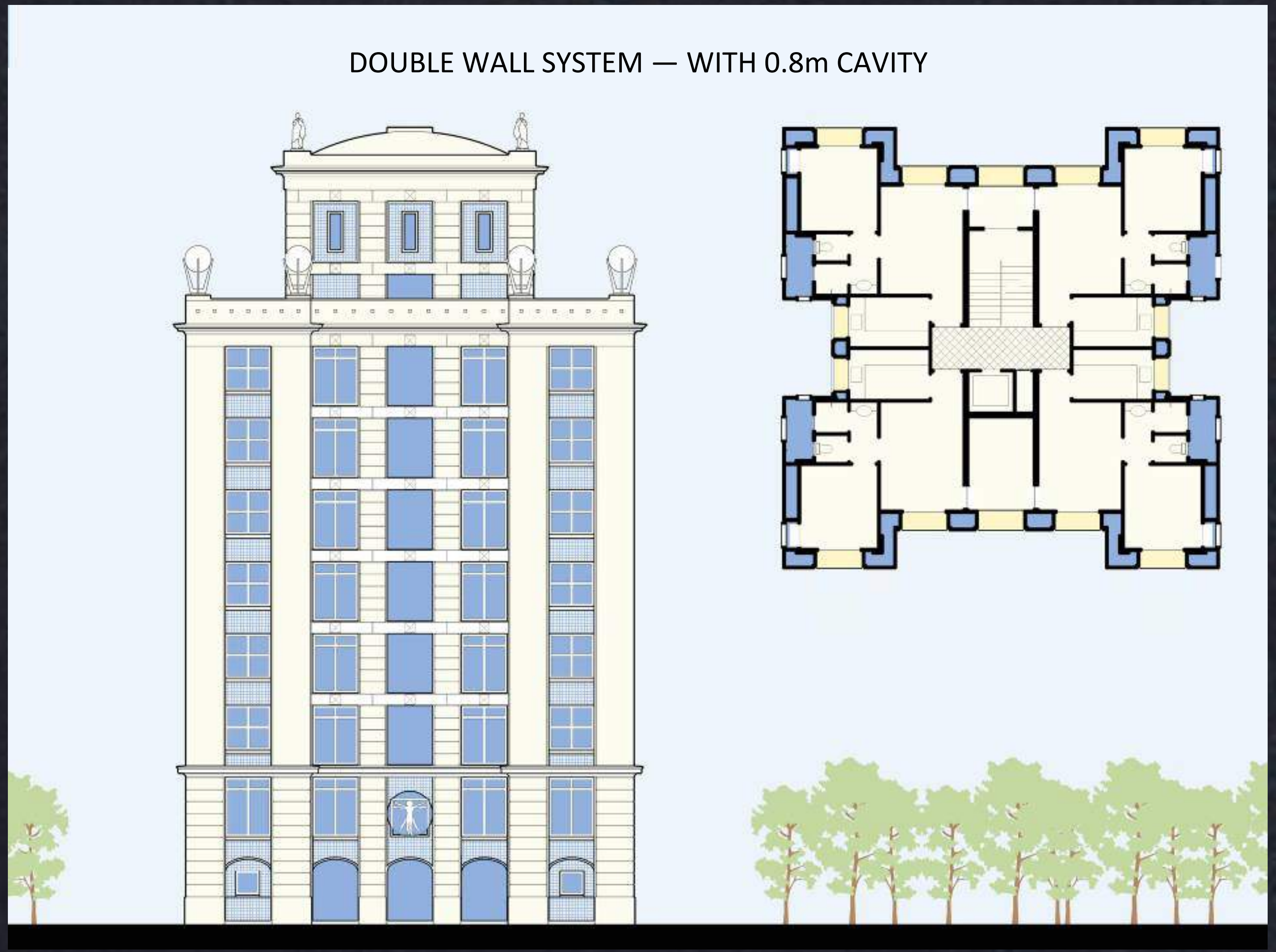
EPI fell 80%, to 66 kWh/m^2-y

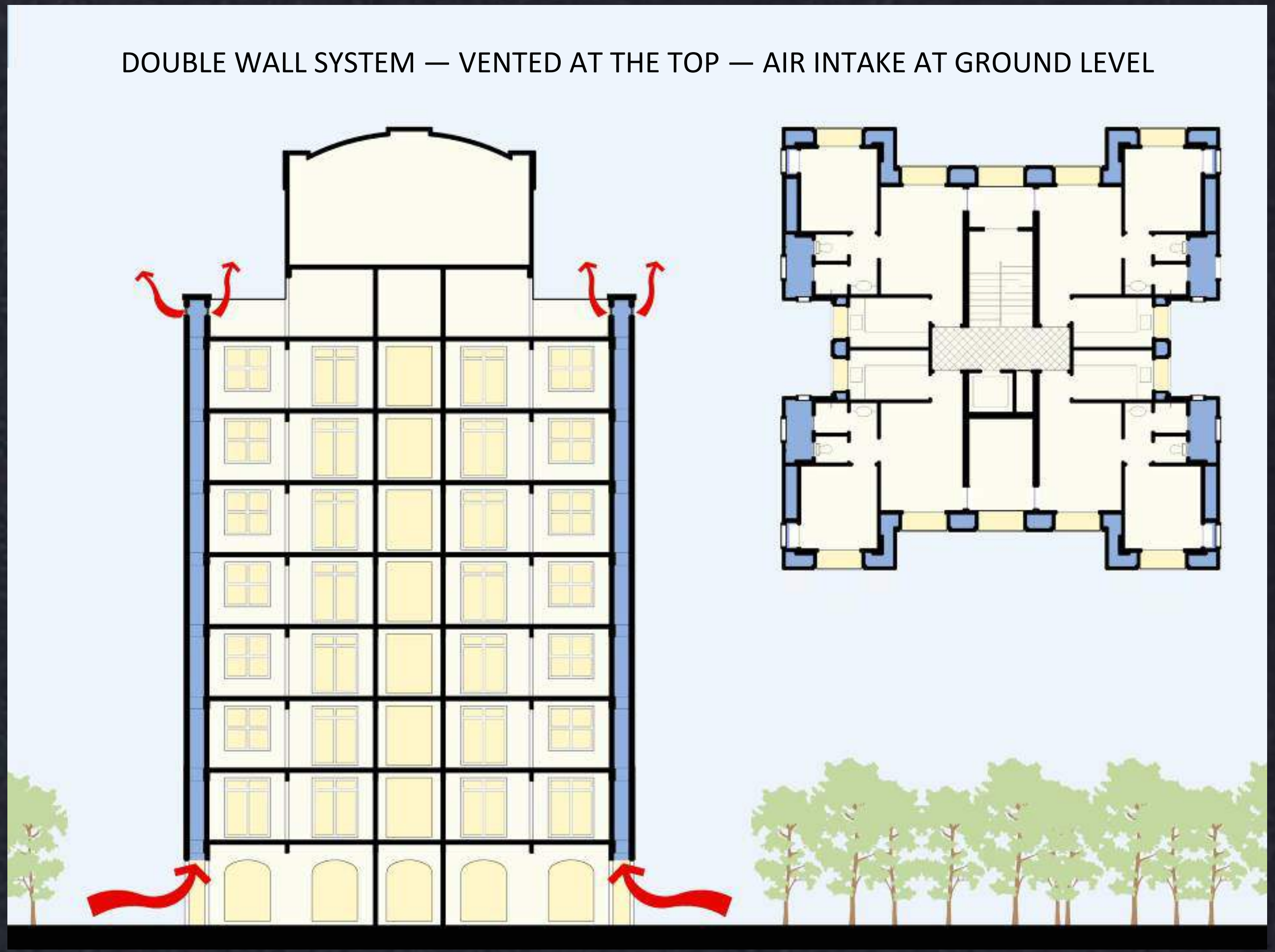
with capex 10% to 20% *lower* than usual, and comfort better

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

Design courtesy of Dhiru Thandani AIA





5–10% urban window a/cs could reach 50–60% by 2030, adding 150 GW peak load

Requiring efficient a/c (superefficient.org) could save ≥40 GW

Requiring/incentivizing smart a/c could add ≤110 more GW of demand response

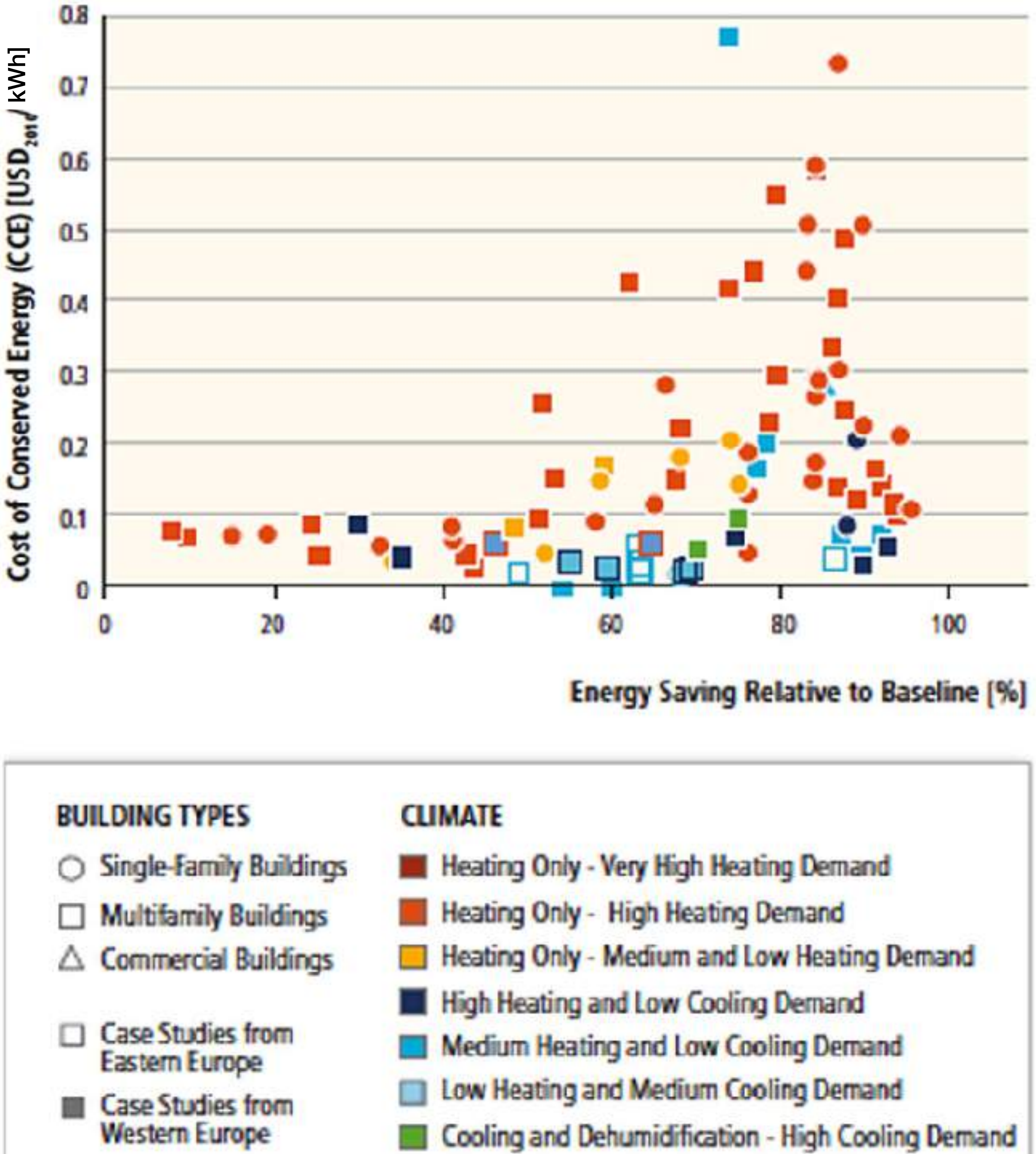
Could use on-bill financing, as India did for 75M LED lamps

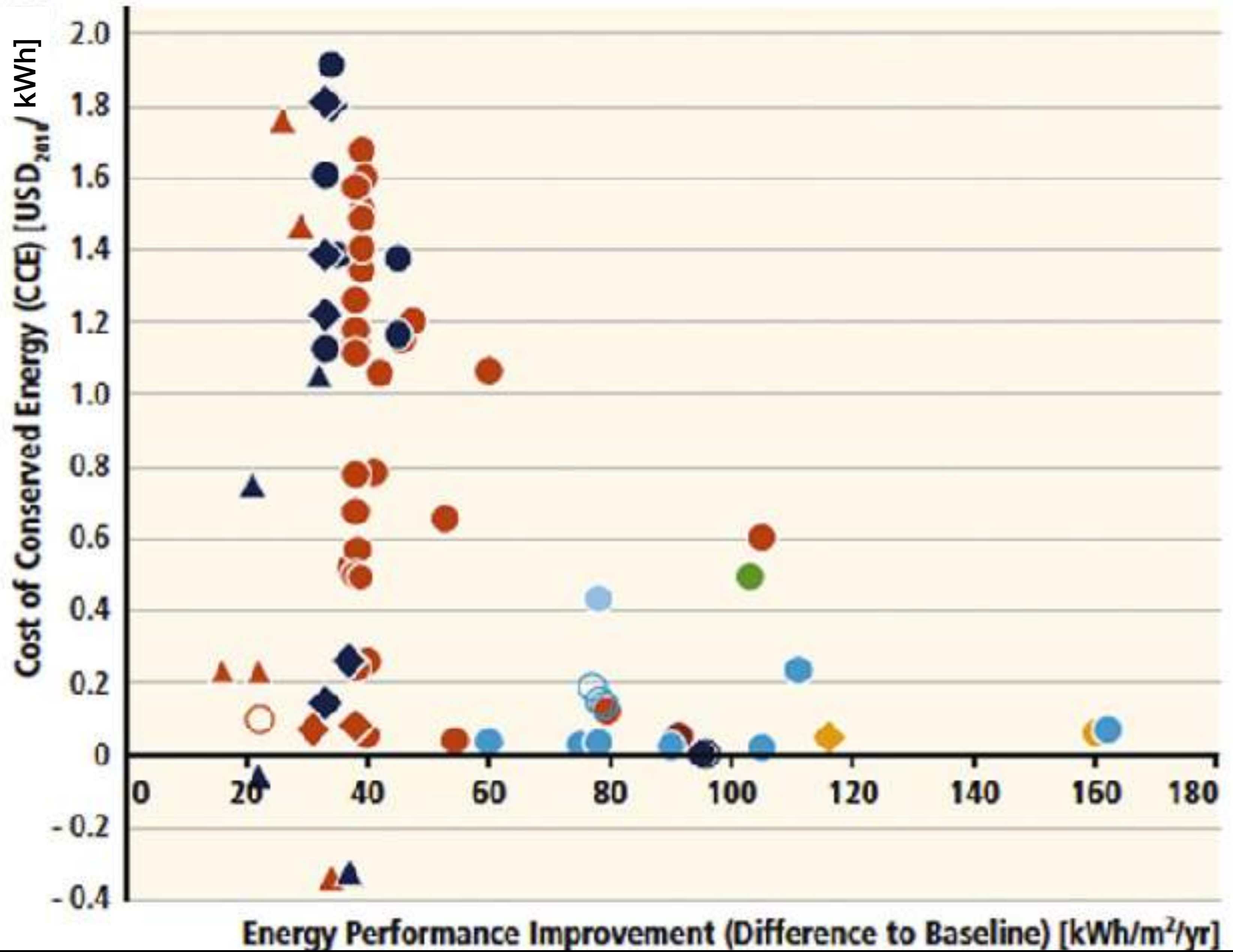
Could meanwhile adopt/encourage efficient building envelopes needing little/no a/c

“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.

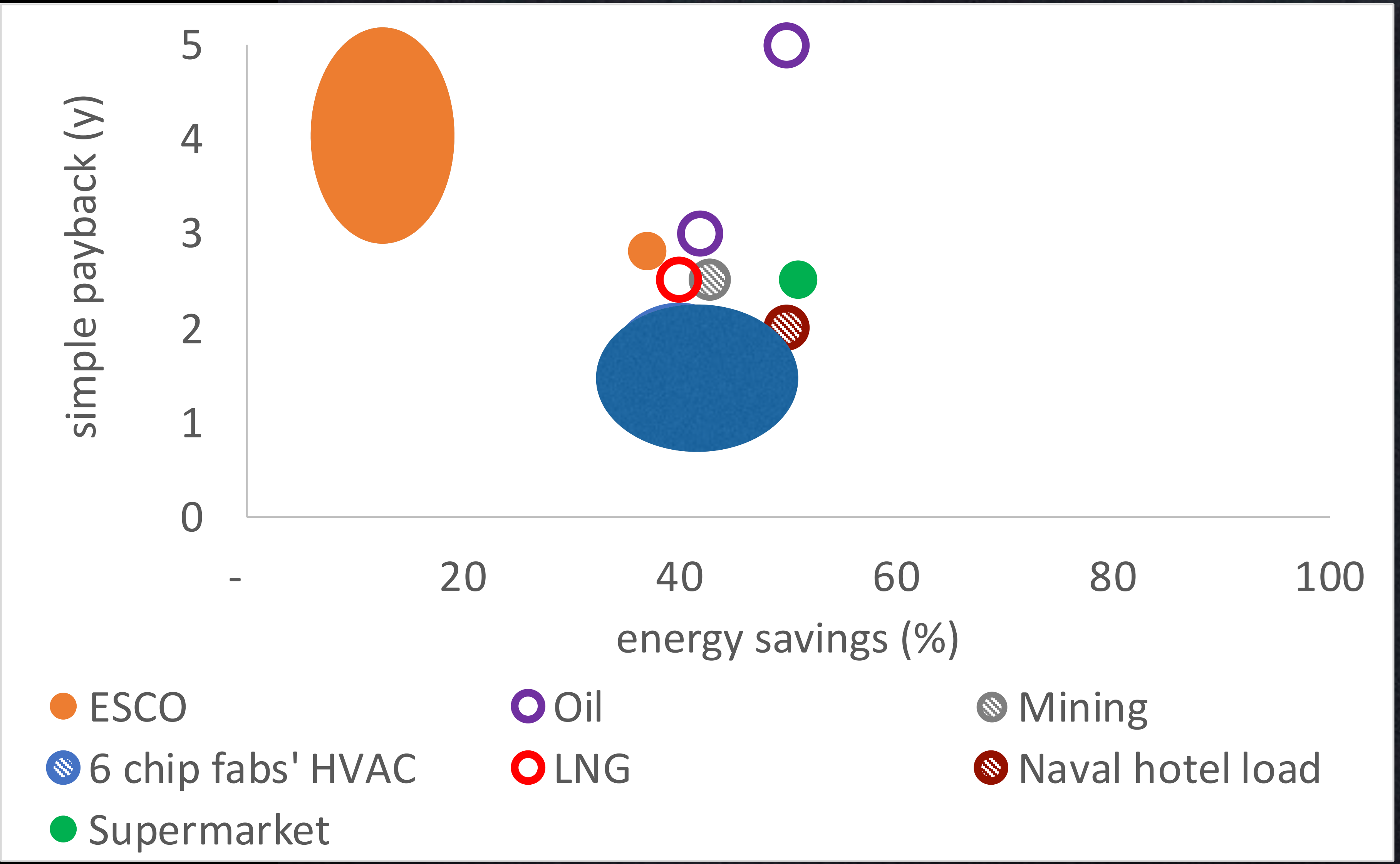
3-4x Energy Productivity in Buildings, 2x in Industry

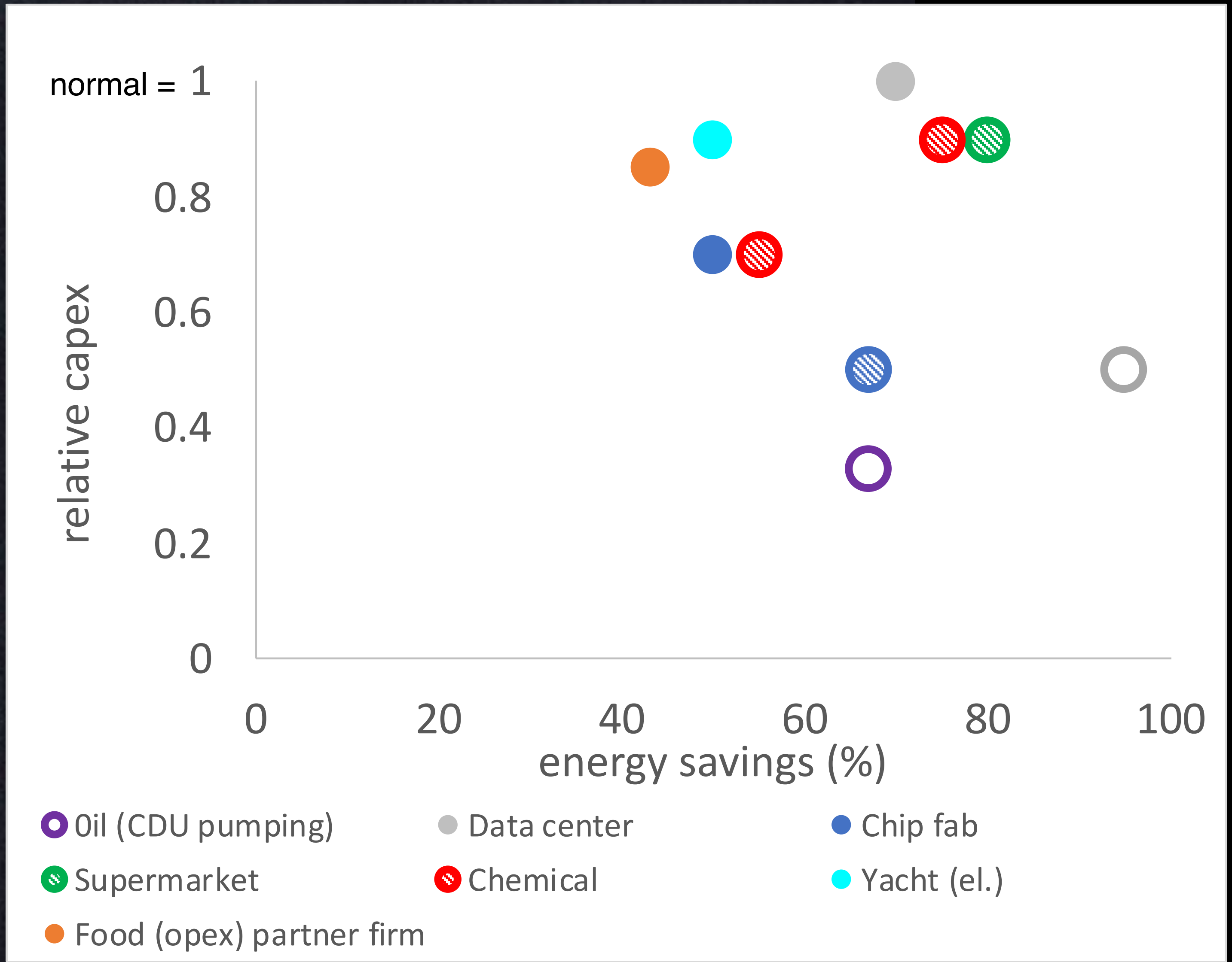
Same or better services

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)





Retrofits **Newbuilds**

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 (3× in cement by eliminating Chinese shaft kilns)

Materials efficiency: *e.g.*, fabric concrete forms (≥2×), tension not compression structures (~8×), 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 ~80–90% of pipe and duct friction—equivalent to about half the world's coal-fired electricity

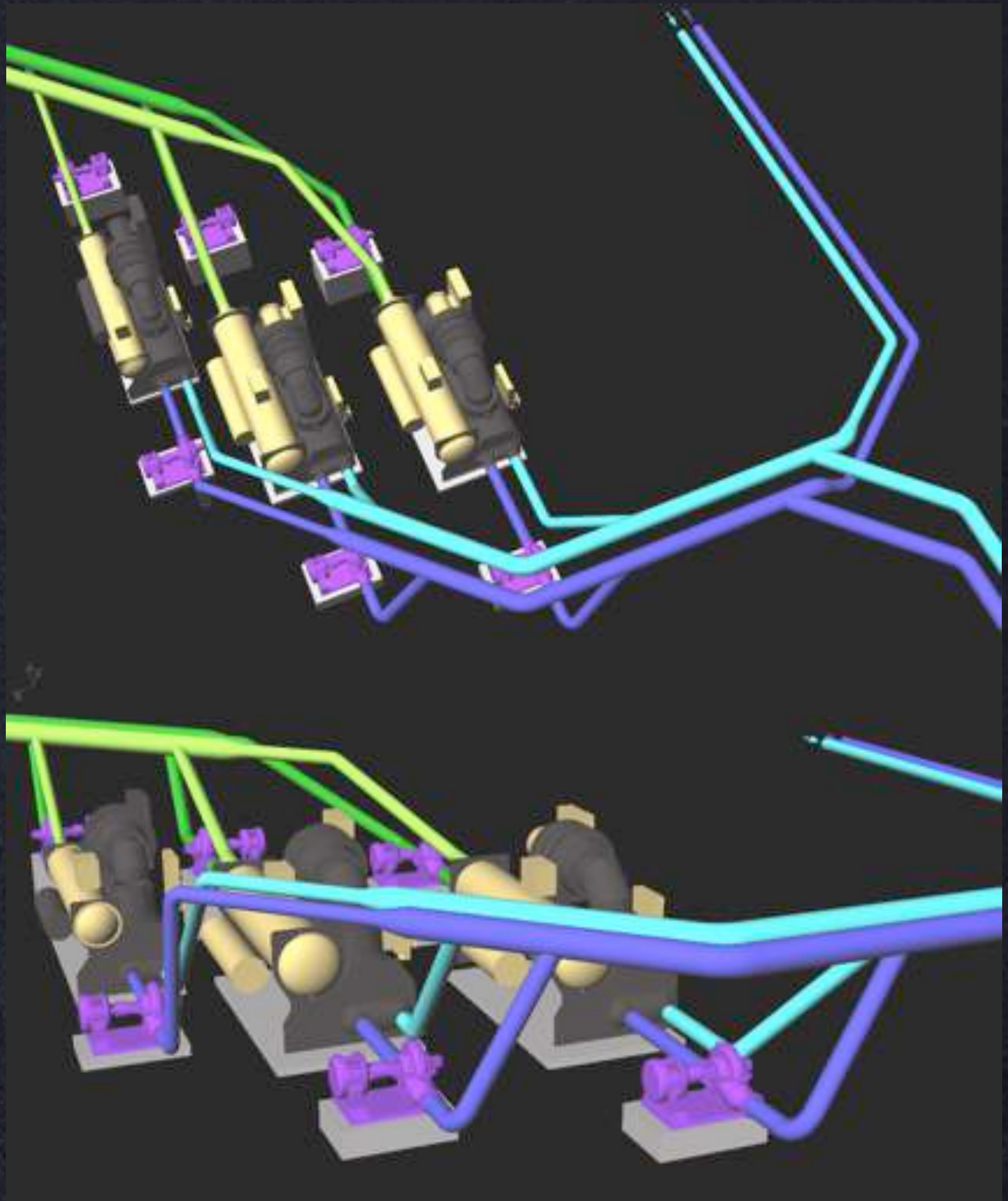
thin, long, crooked

fat, short, straight

Typical paybacks ≤1 y retrofit, ≤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

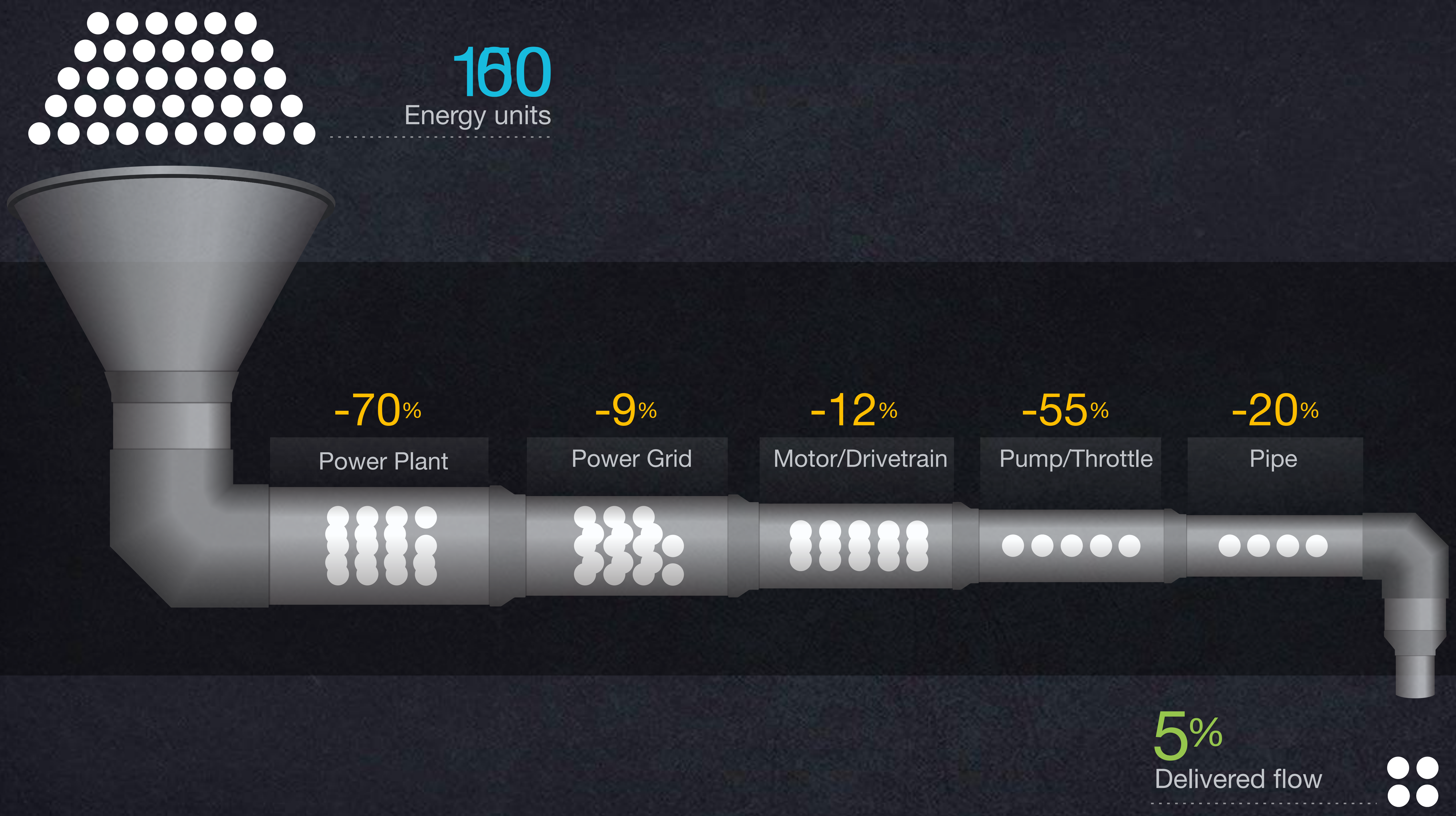


Nonorthogonal layout, 3D diagonals, few & sweet bends

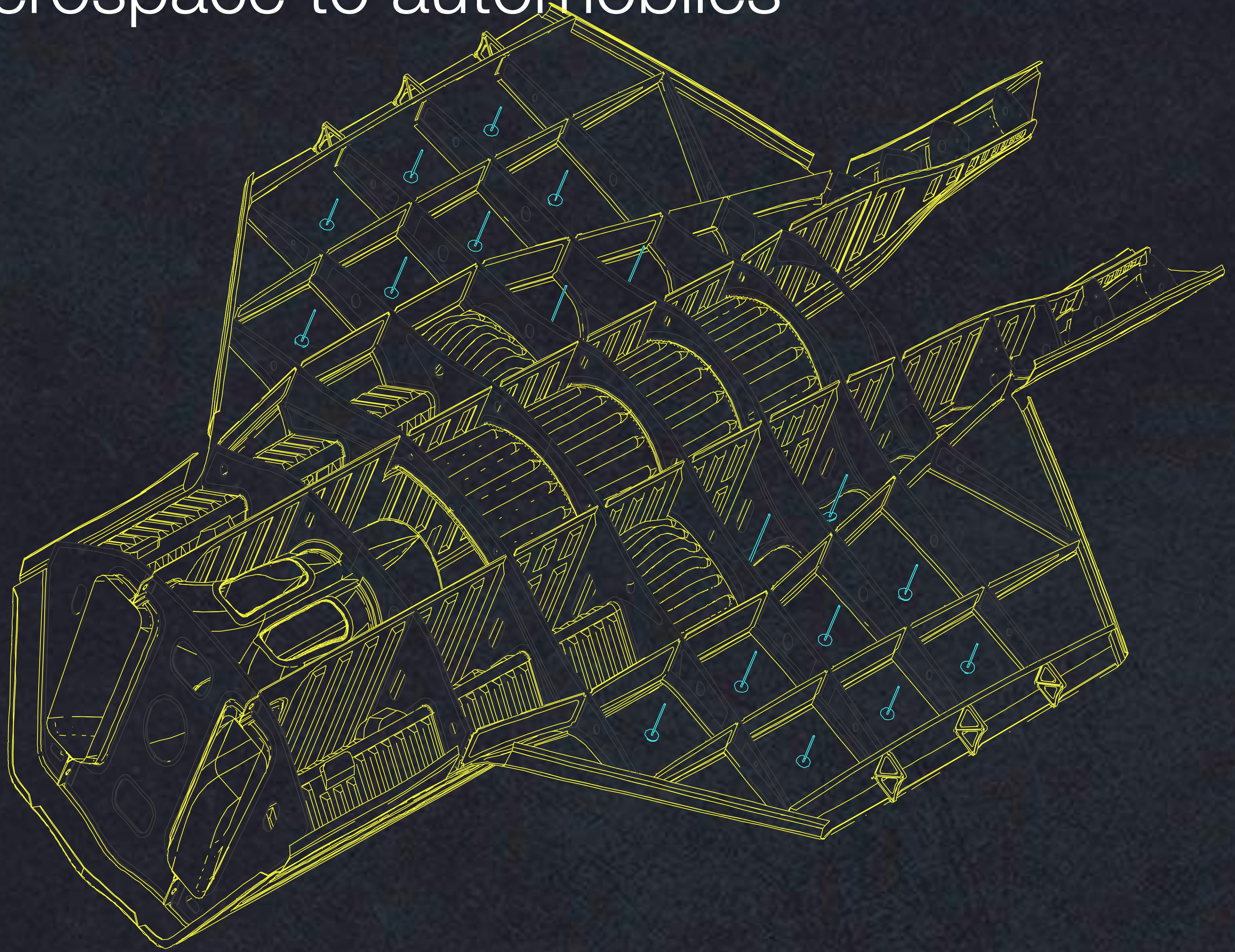
Retrofitted Low-Friction Piping Layout

Images courtesy of
Peter Rumsey, PE, FASHRAE

Start saving *downstream*


100
Energy units
-70%
Power Plant
-9%
Power Grid
-12%
Motor/Drivetrain
-55%
Pump/Throttle
-20%
Pipe
5%
Delivered flow

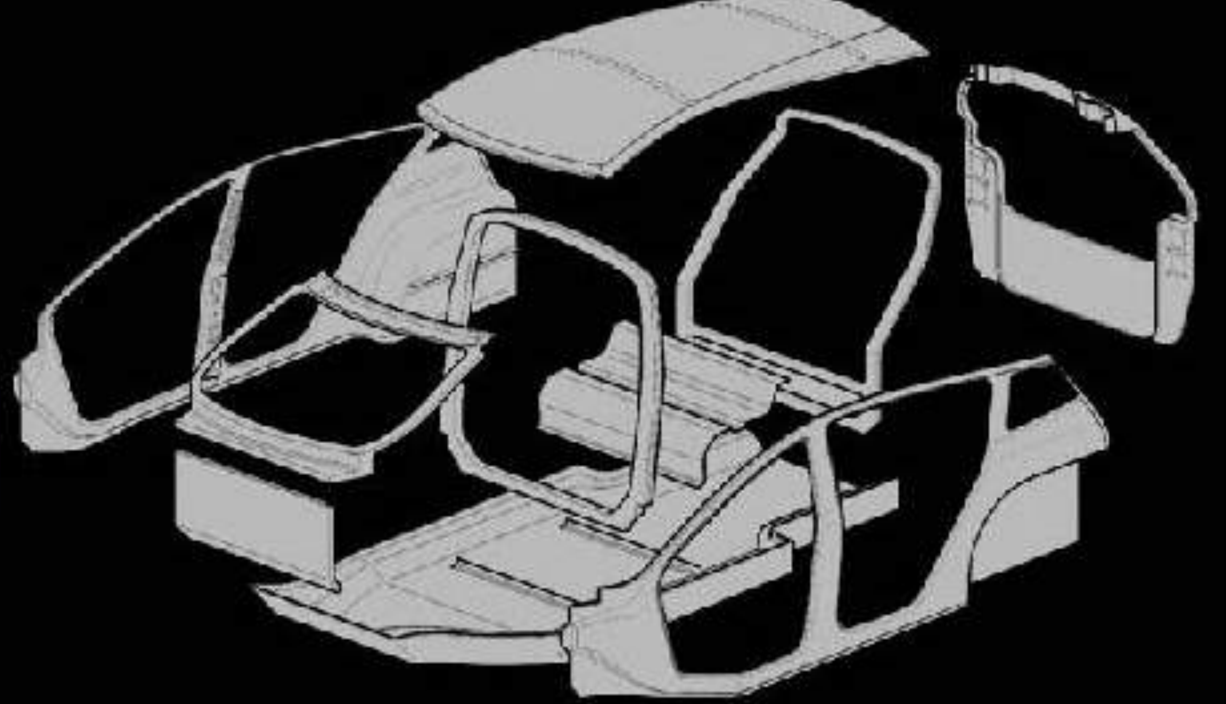
For best ultralighting, migrate advanced composites from military & aerospace to automobiles



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 (H_2)
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-m^3 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 mpge), 247-km range (≥370 w/REx)

A competitive carbon-fiber electric car, 2013–

sglcarbon.com

2013 BMW *i3*, http://www.superstreetonline.com/features/news/epcp-1303-bmw-i3-concept-coupe/

BMW MY2013's ~120–150-kg carbon-fiber-composite passenger cell; m_c 1,250 kg

https://www.autocar.co.uk/car-news/industry/bmw-set-make-more-extensive-use-carbon-fibre

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_{equiv}/100 km (124 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

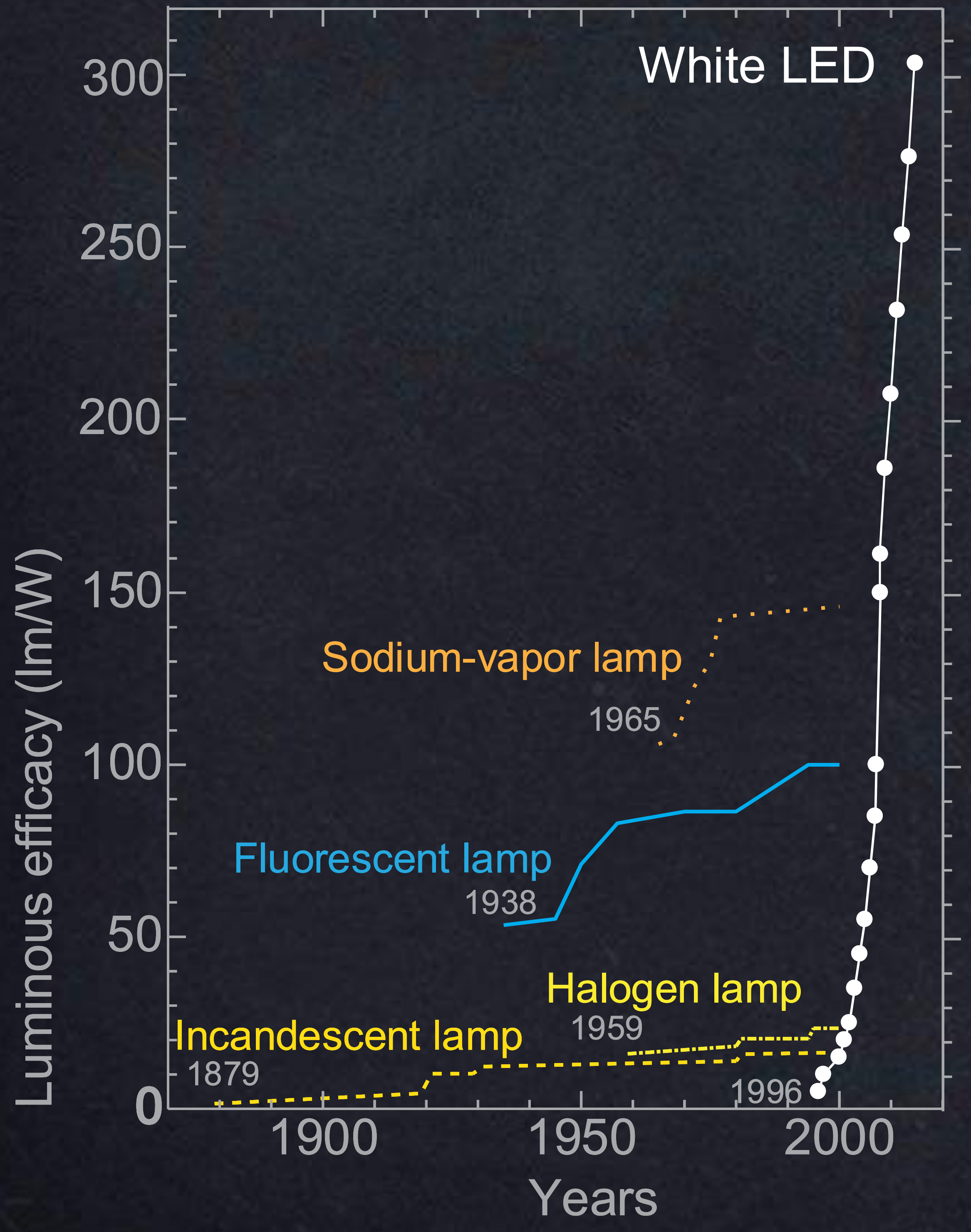
25 W incandescent lamp (~210–250 lm) shown for comparison, not PV-powered

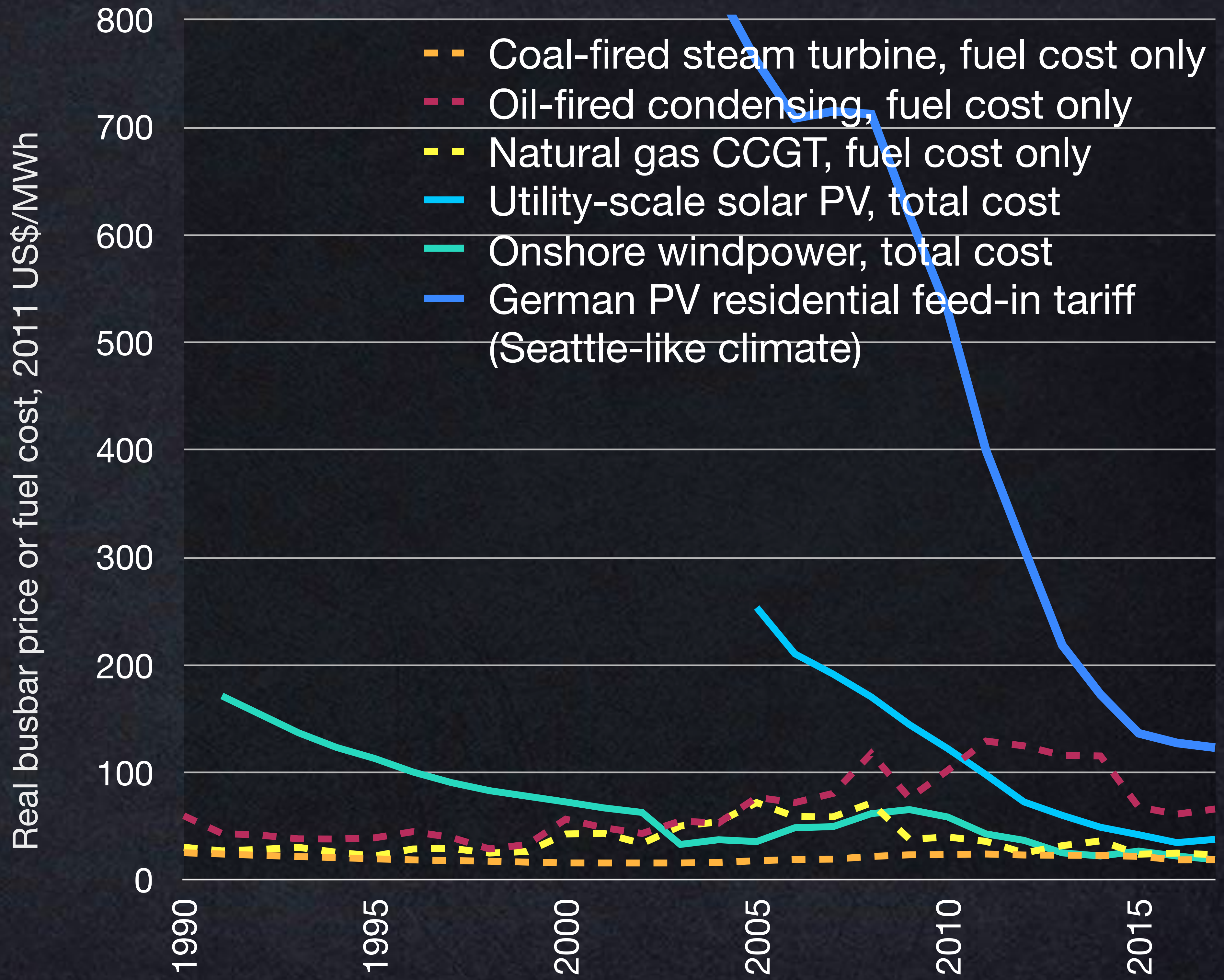
Photo courtesy of Lawrence Berkeley National Laboratory

~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)

LED and PV





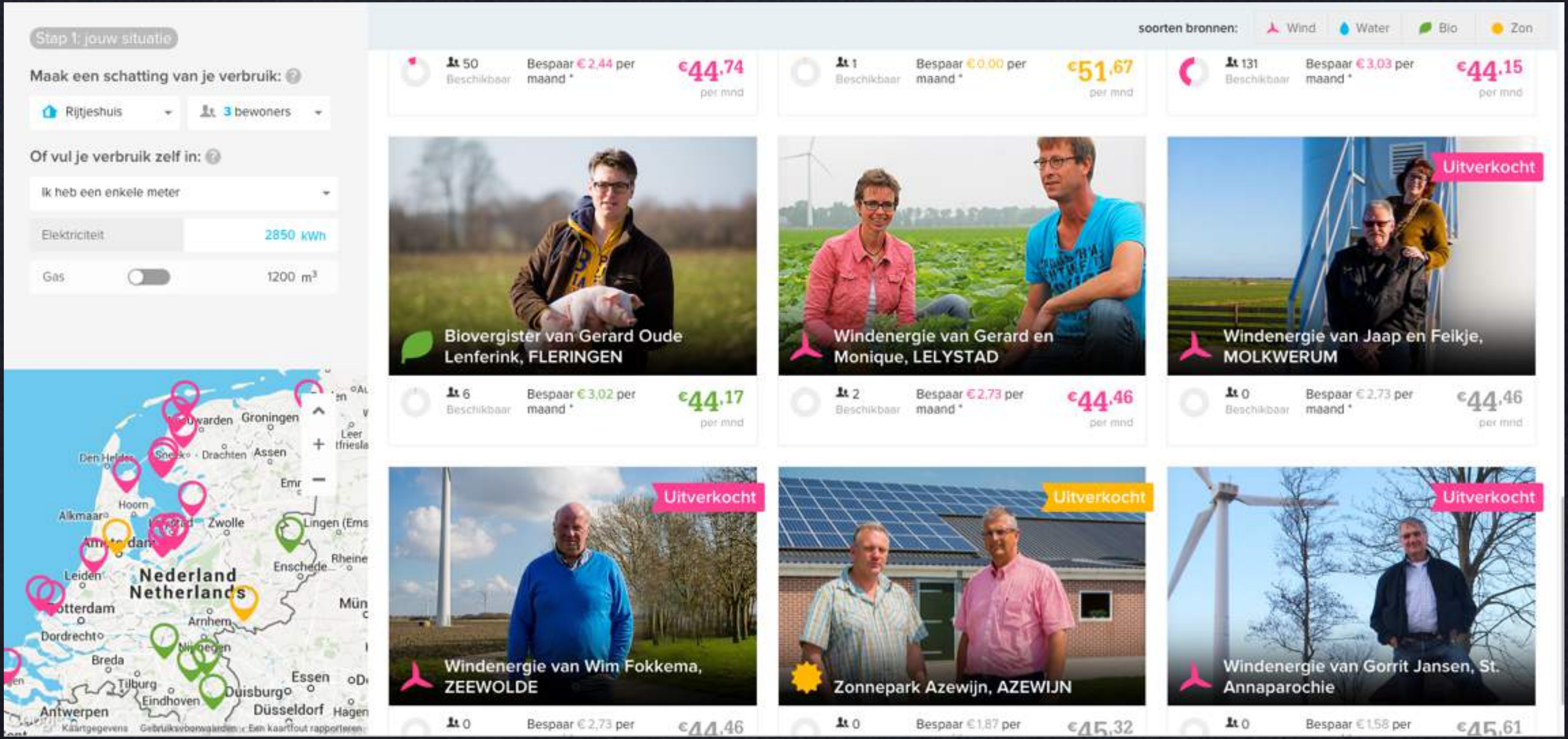
Sources: L: courtesy of Dr. Yukio Narukawa (Nichia Corp., Tokushima, Japan) from *J. Physics. D: Appl. Phys.* ***43***(2010) 354002, doi:10.1088/0022-3727/43/35/354002, updated by RMI with CREE lm/W data, 2015, www.cree.com/News-and-Events/Cree-News/Press-Releases/2014/March/300LPW-LED-barrier;. R: RMI analysis, at average 2013 USEIA fossil-fueled generation efficiencies and each year's real fuel costs (no O&M); utility-scale PV: LBNL, *Utility-Scale Solar* and USDOE, *Wind Technologies Market Report*s, "Windbelt" (Interior zone) windfarms' average PPA; German feed-in tariff (falls with cost to yield ~6%/y real return): Fraunhofer ISE, *Cost Perspective, Grid and Market Integration of Renewable Energies*, p 6 (Jan 2014); all sources net of subsidies; graph inspired by 2014 "Terrordome" slide by Michael Parker at Bernstein Alliance

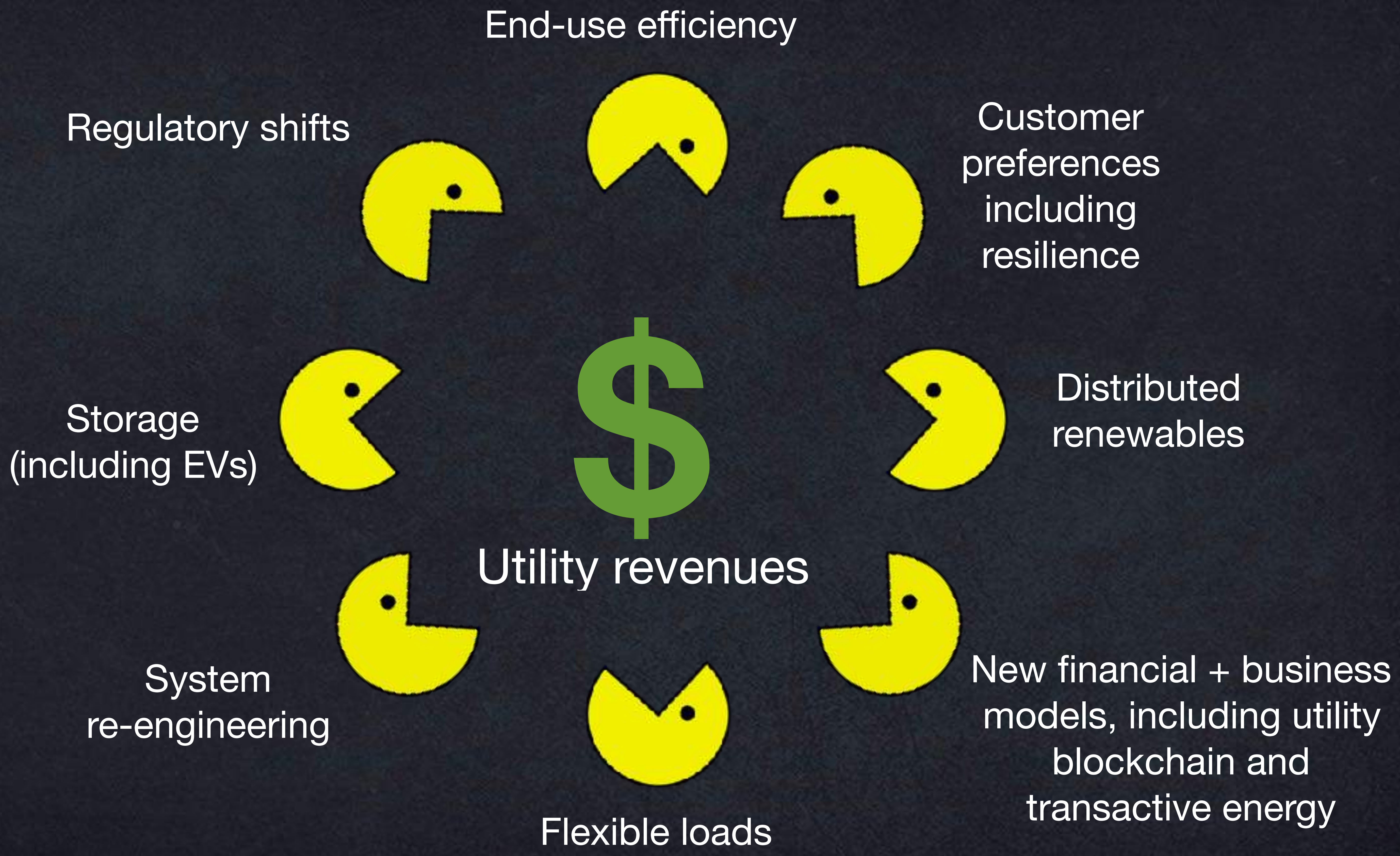




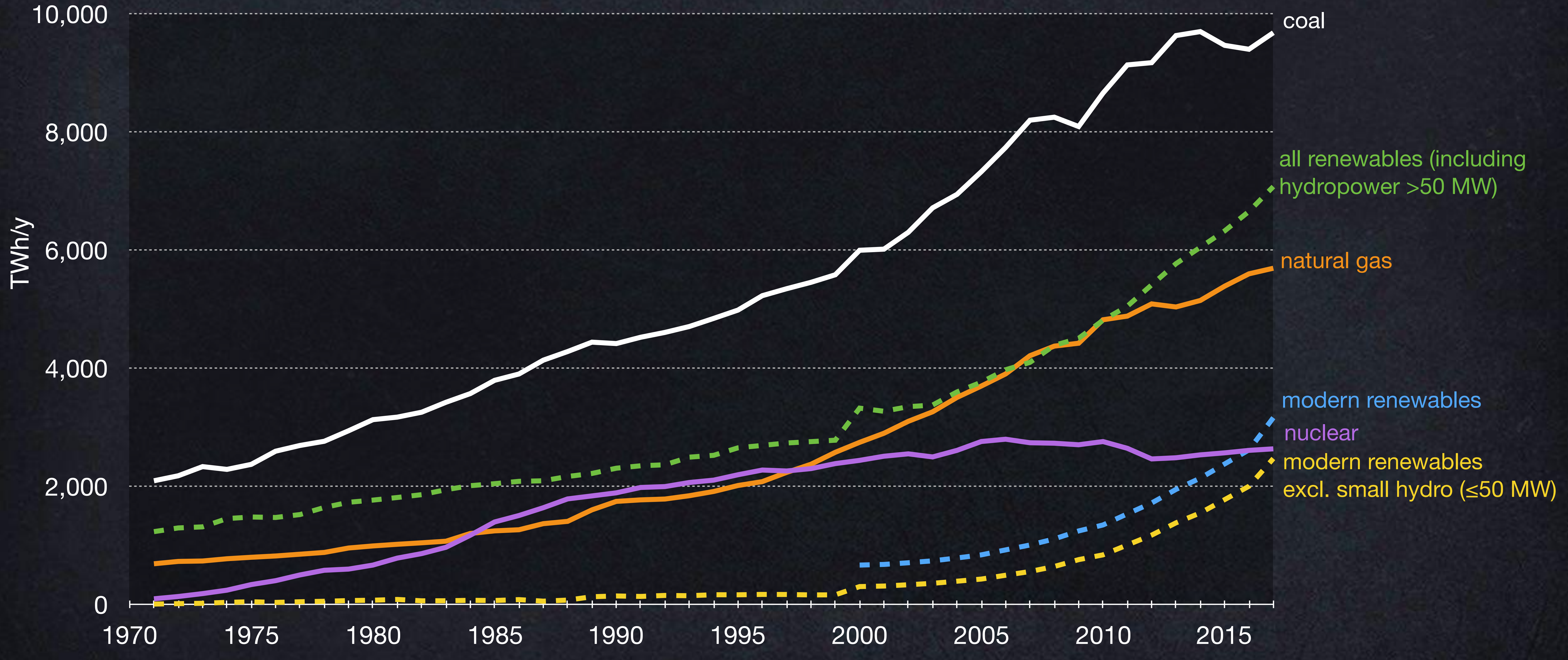
76

Netherlands: trade electricity with fellow-customers



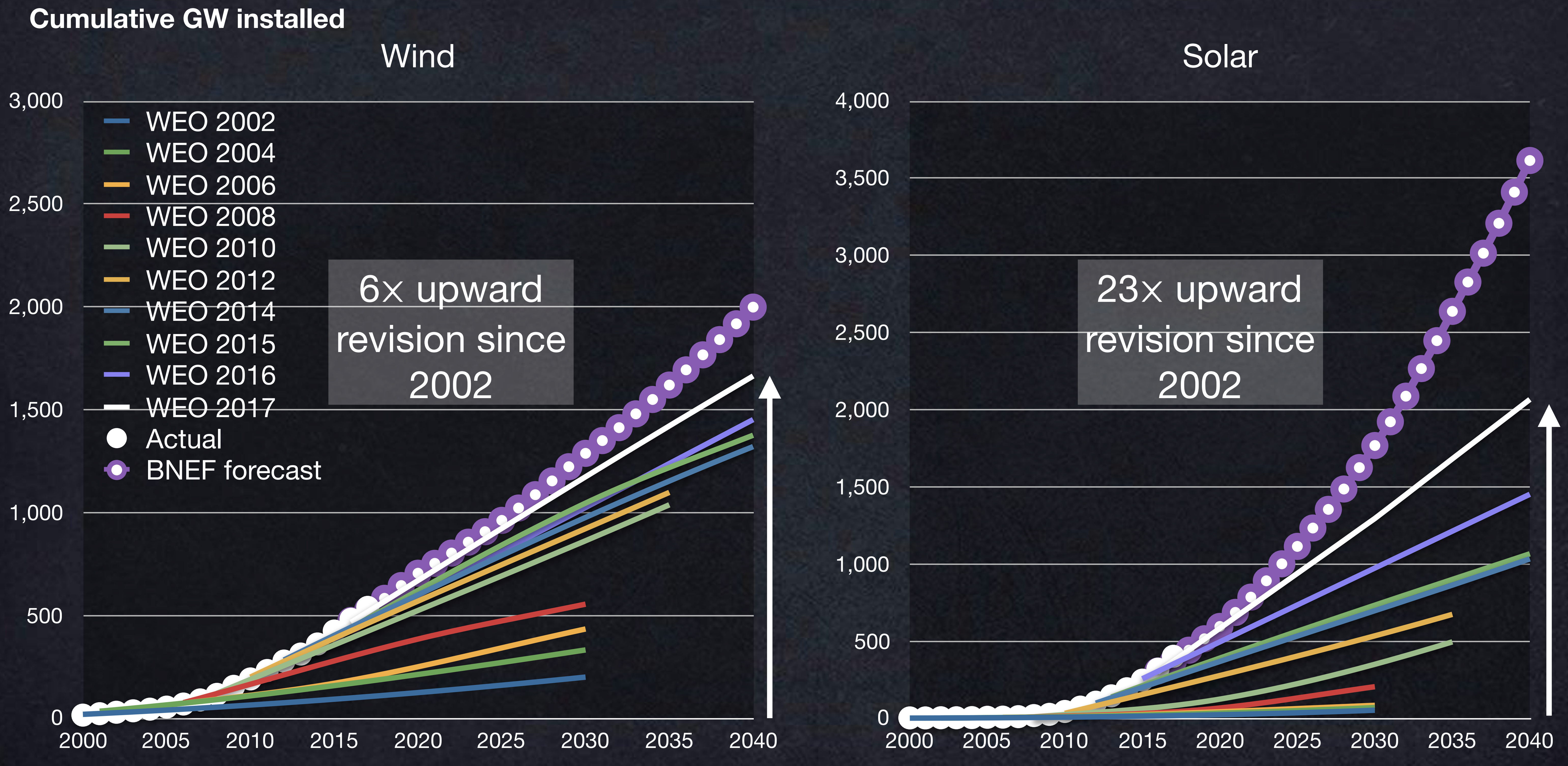

End-use efficiency
Customer preferences including resilience
Distributed renewables
New financial + business models, including utility blockchain and transactive energy
Flexible loads
System re-engineering
Storage (including EVs)
Regulatory shifts
$
Utility revenues

Worldwide electricity generation by source, 1971–2017p



A B Lovins *et al.*, "Relative deployment rates of renewable and nuclear power: a cautionary tale of two metrics," *El. Res. & Soc. Sci.* **38**:188–192 (2018), doi:10.1016/j.erss.2018.01.05.
Preliminary 2017 data from IEA, "Global Energy & CO_2 Status Report 2017," 22 Mar 2017, http://www.iea.org/publications/freepublications/publication/GECO2017.pdf,

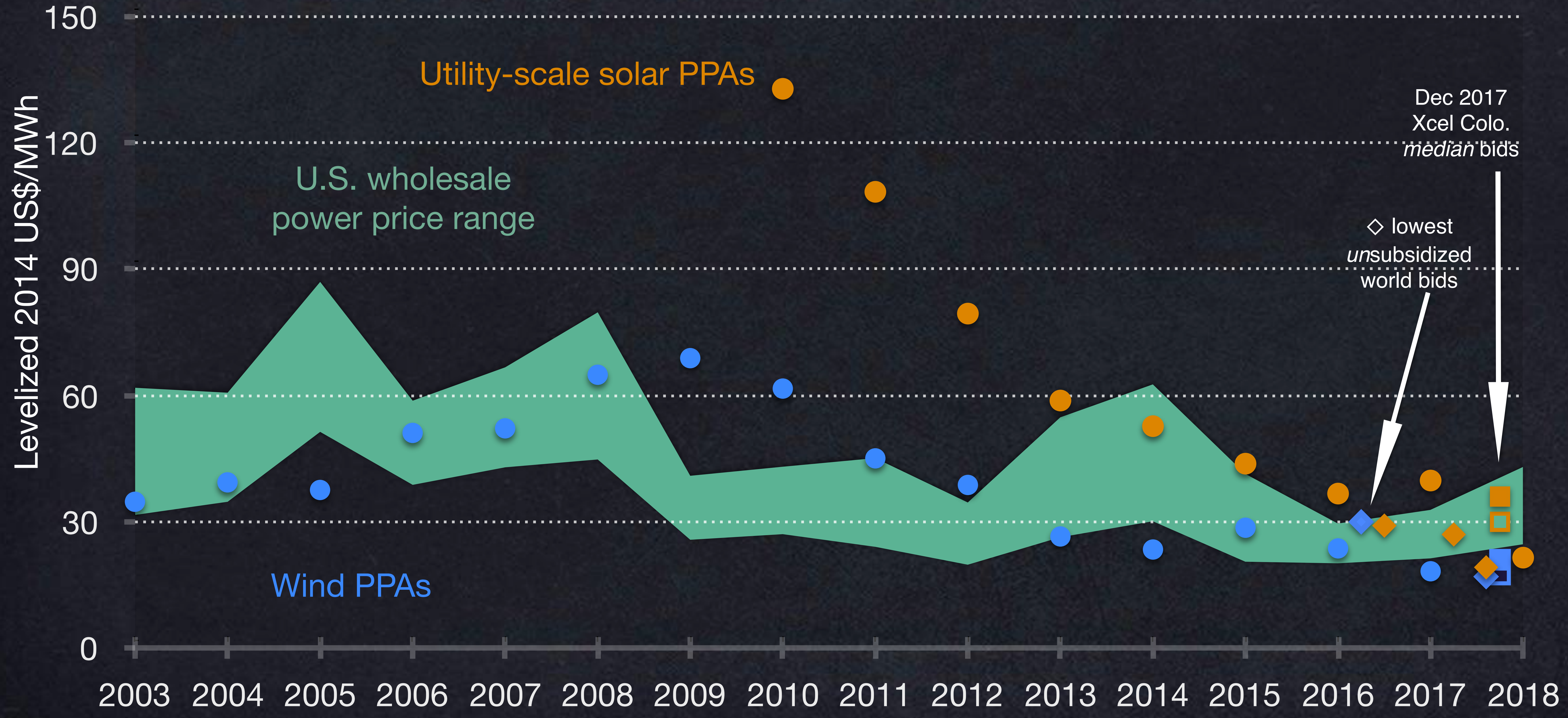
International Energy Agency global wind and solar forecasts



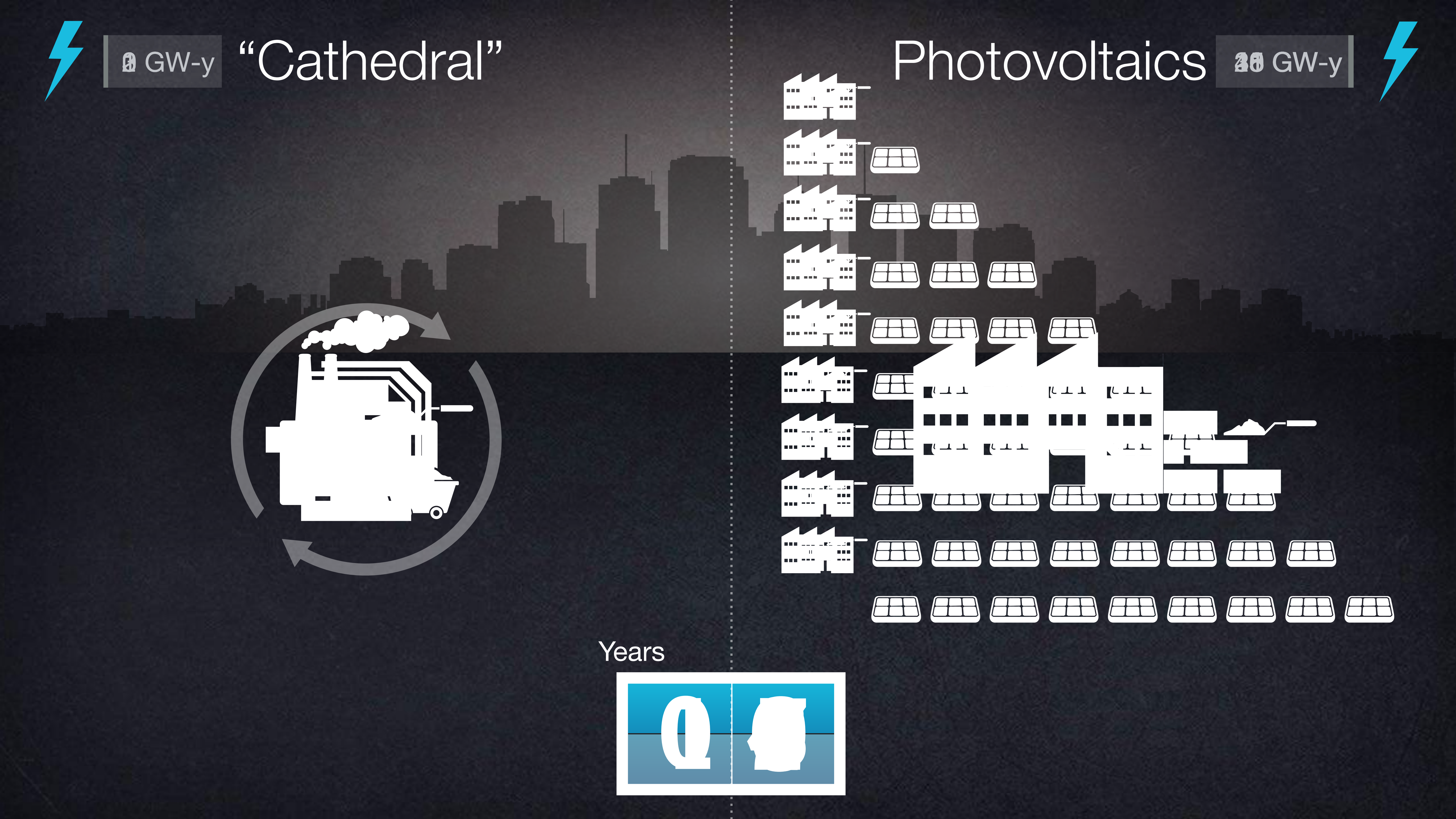
Source: IEA *World Energy Outlook* series, Bloomberg New Energy Finance June 2017 forecast. Slide inspired by Michael Liebreich's 2016 BNEF Summit keynote

Renewable energy's costs continue to plummet

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

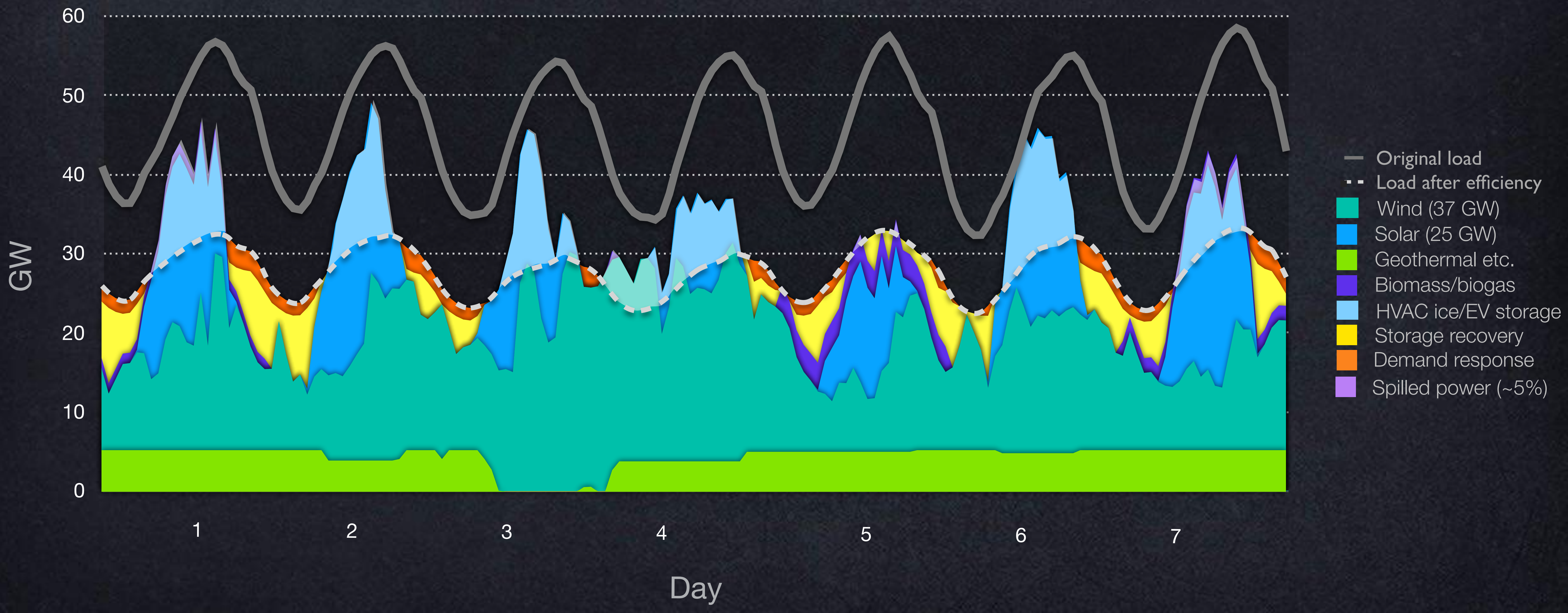


Updated through Jun 2018; solar diamonds: Chile (2.91¢/kWh, Aug 2016) and Mexico (2.7 ¢/kWh, Feb 2017; $1.92¢, Nov 2017); wind diamonds: Morocco (Jan 2016), Mexico 1.7¢ (Nov 2017); Xcel Dec 2017 median levelized solar bids: 36 $/MWh and 30 $/MWh w/ and w/out storage; Xcel wind bids: $21/MWh and $18/MWh w/ and w/out storage
Wholesale price range: RMI Analysis of BloombergNEF, Prices, Tariffs & Auctions, US Power & Fuel: https://www.bnef.com/core/data-hubs/5/83?tab=Prices


GW-y
"Cathedral"
Photovoltaics
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%

Scotland, 2018

71%

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

38%

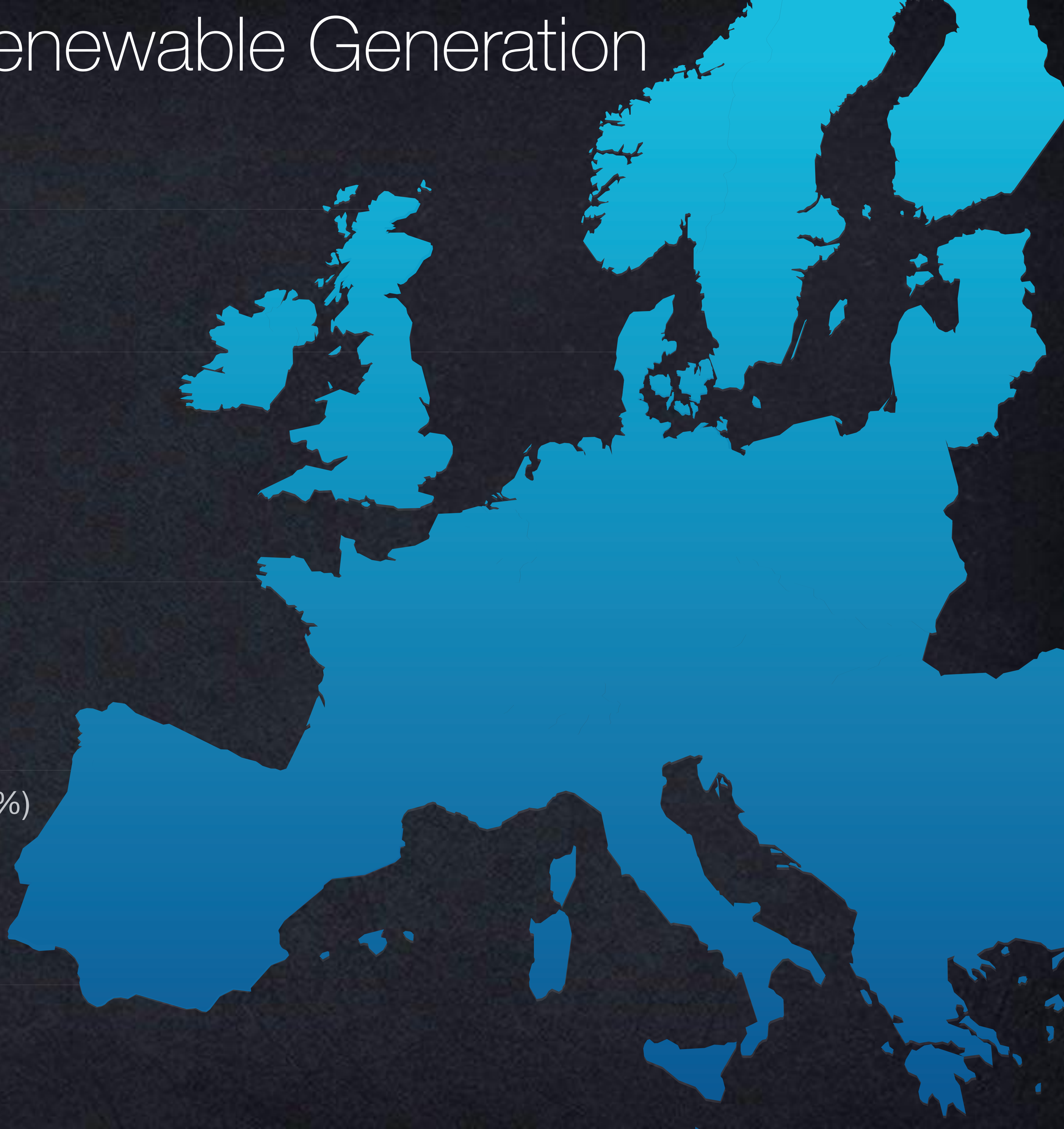
Germany 2018 (2016 peak 88%, 2018 ~90–100%)

66%

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

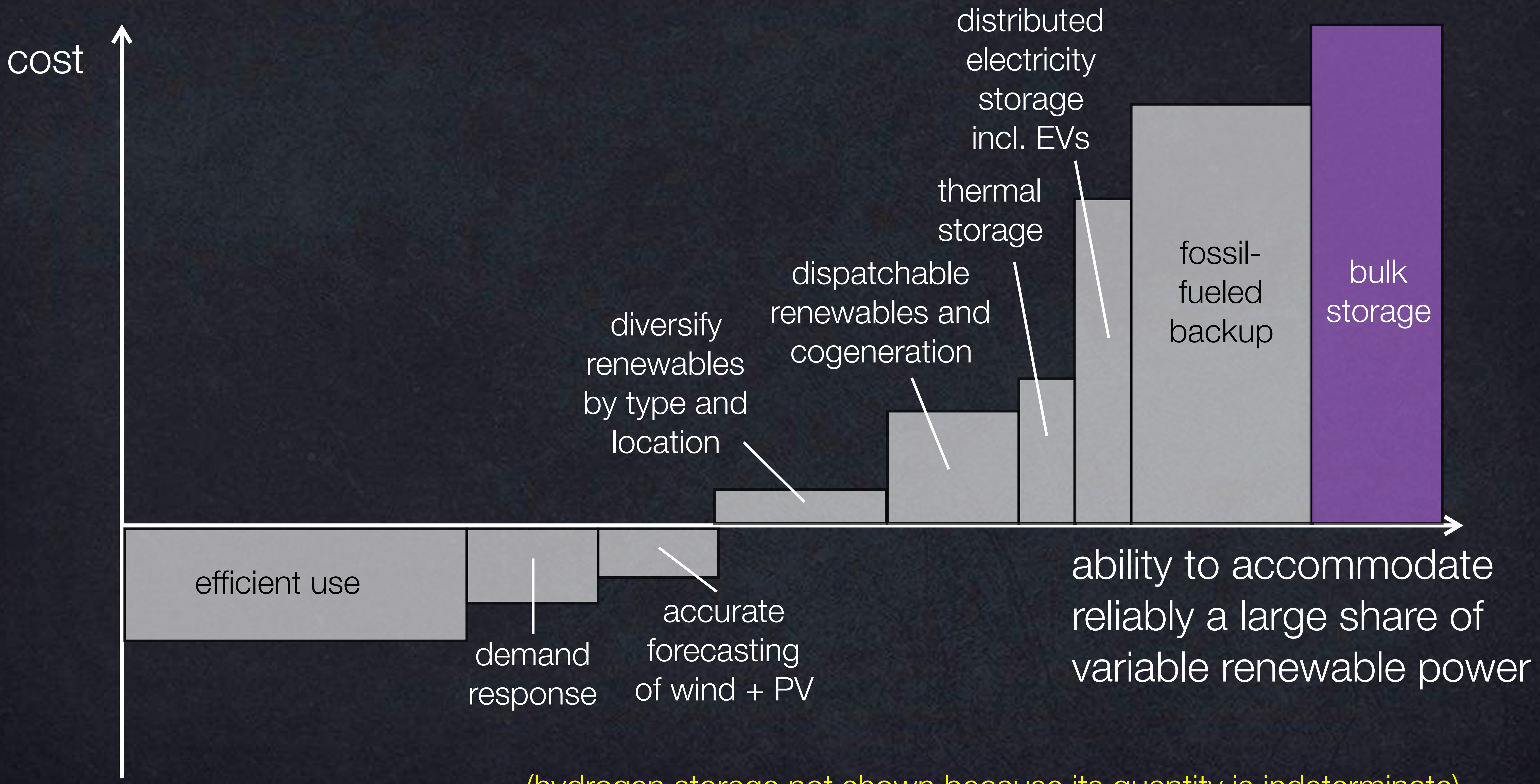
46%

Peninsular Spain (2016, 27% without hydro)



Grid flexibility resources

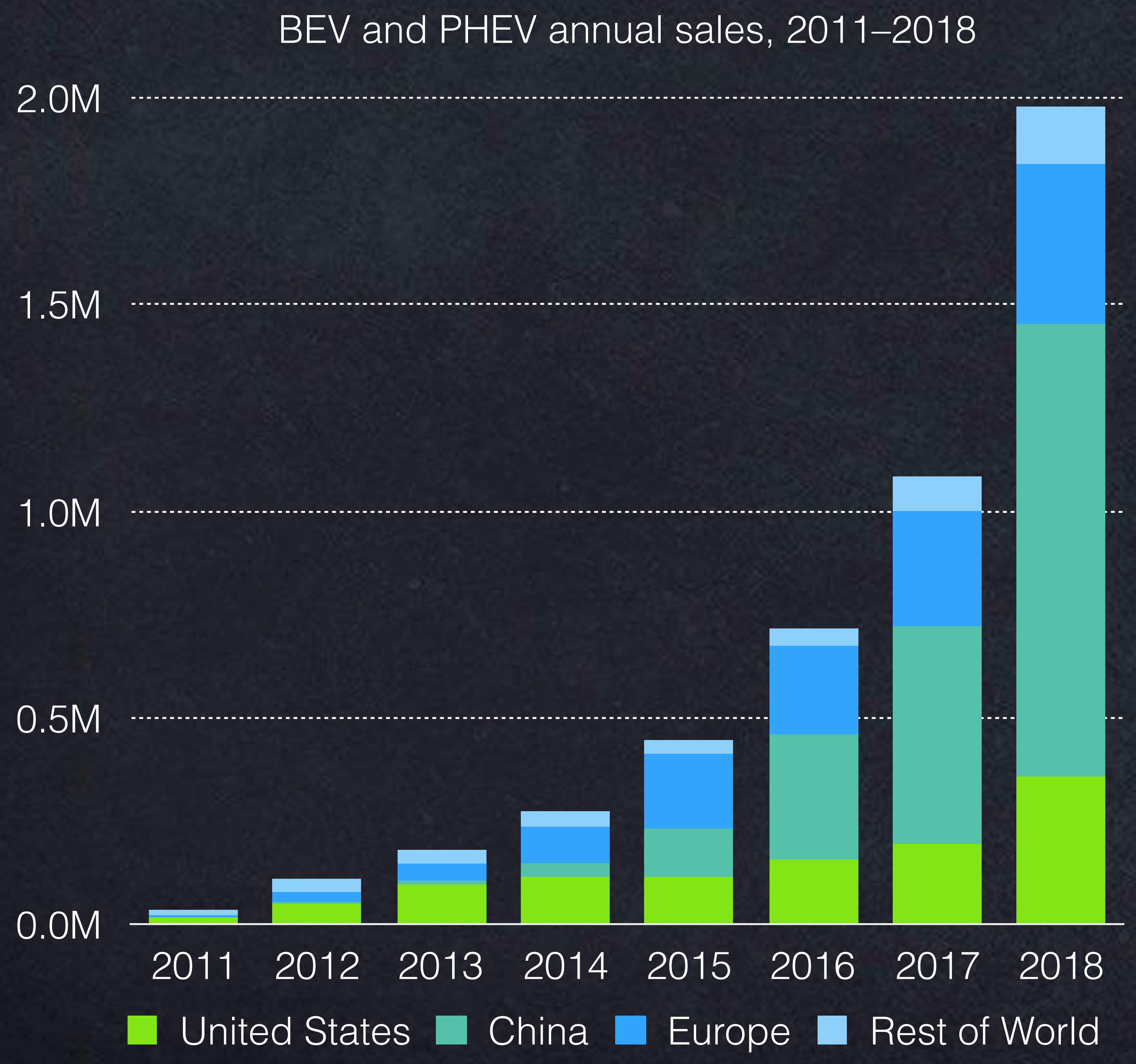
(all values shown are conceptual and illustrative)

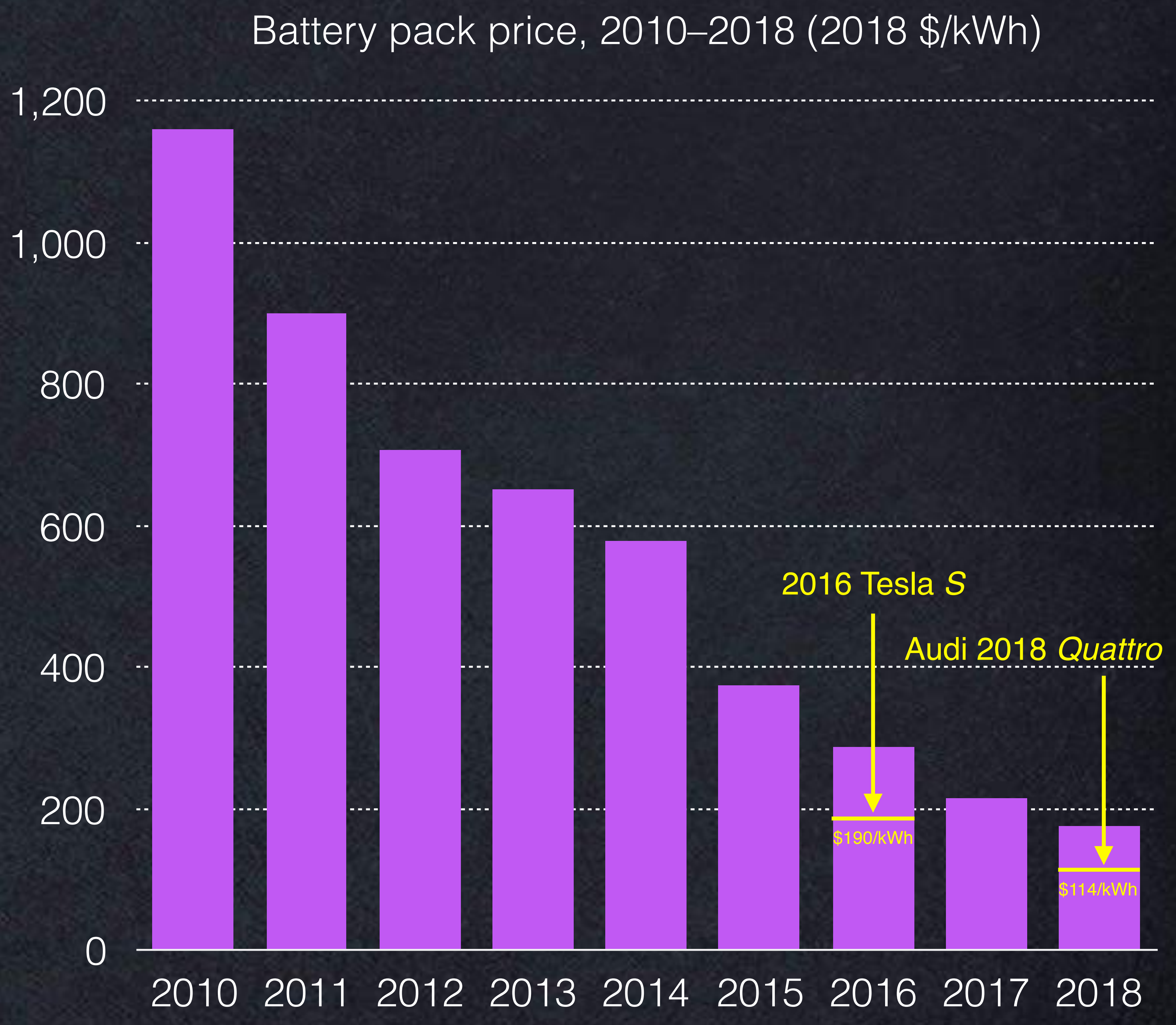


(hydrogen storage not shown because its quantity is indeterminate)

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



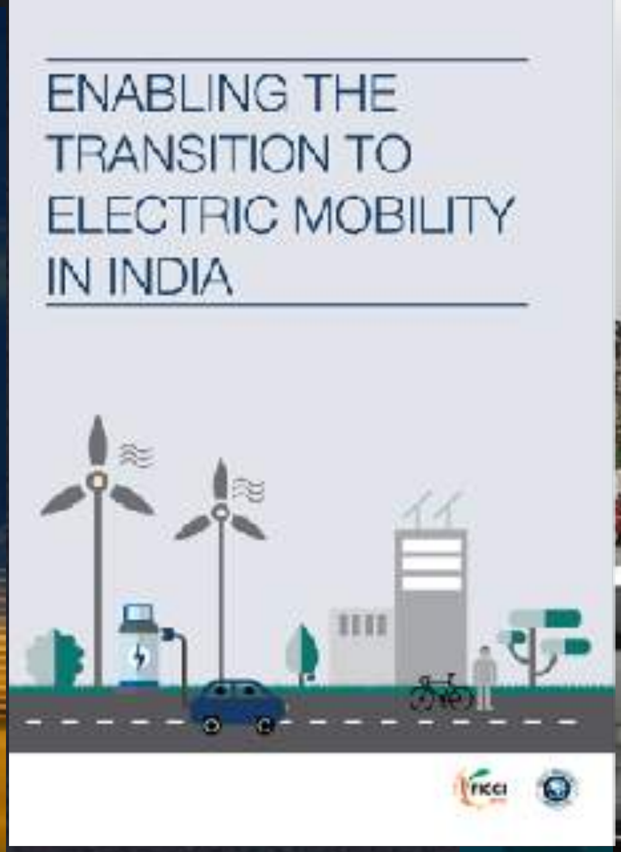


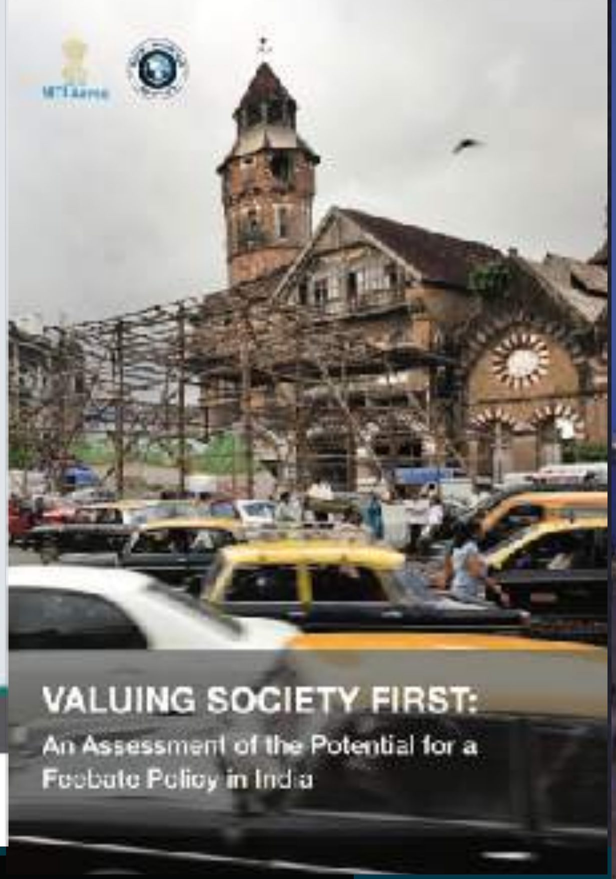
Sources: BNEF; Tesla Model *S*: https://www.greencarreports.com/news/1103667_electric-car-battery-costs-tesla-190-per-kwh-for-pack-gm-145-for-cells
Quattro: https://electrek.co/2017/06/28/audi-electric-car-battery-cost/for-2016-145kwh-cell-cost-volt-margin-improves-3500/

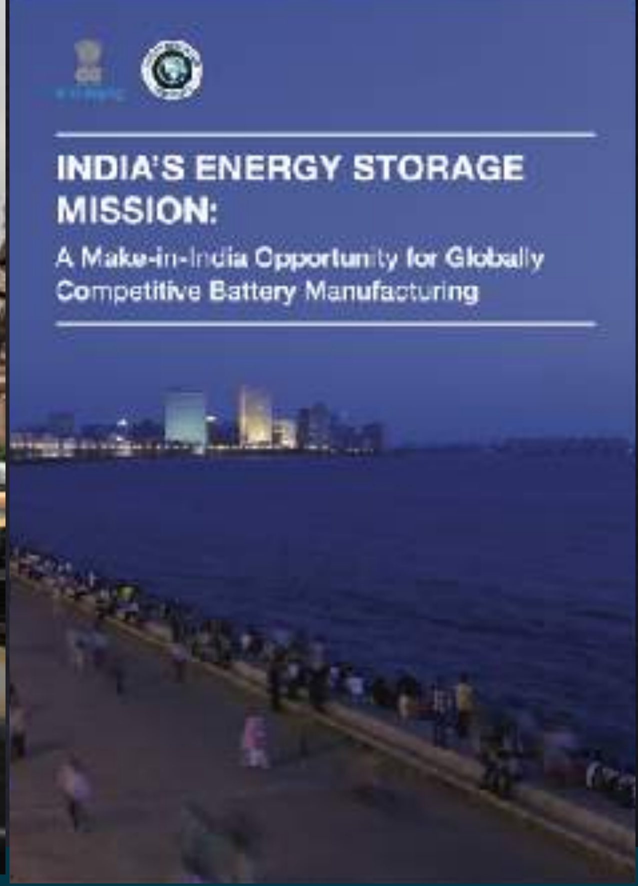
From PIGS to SEALS

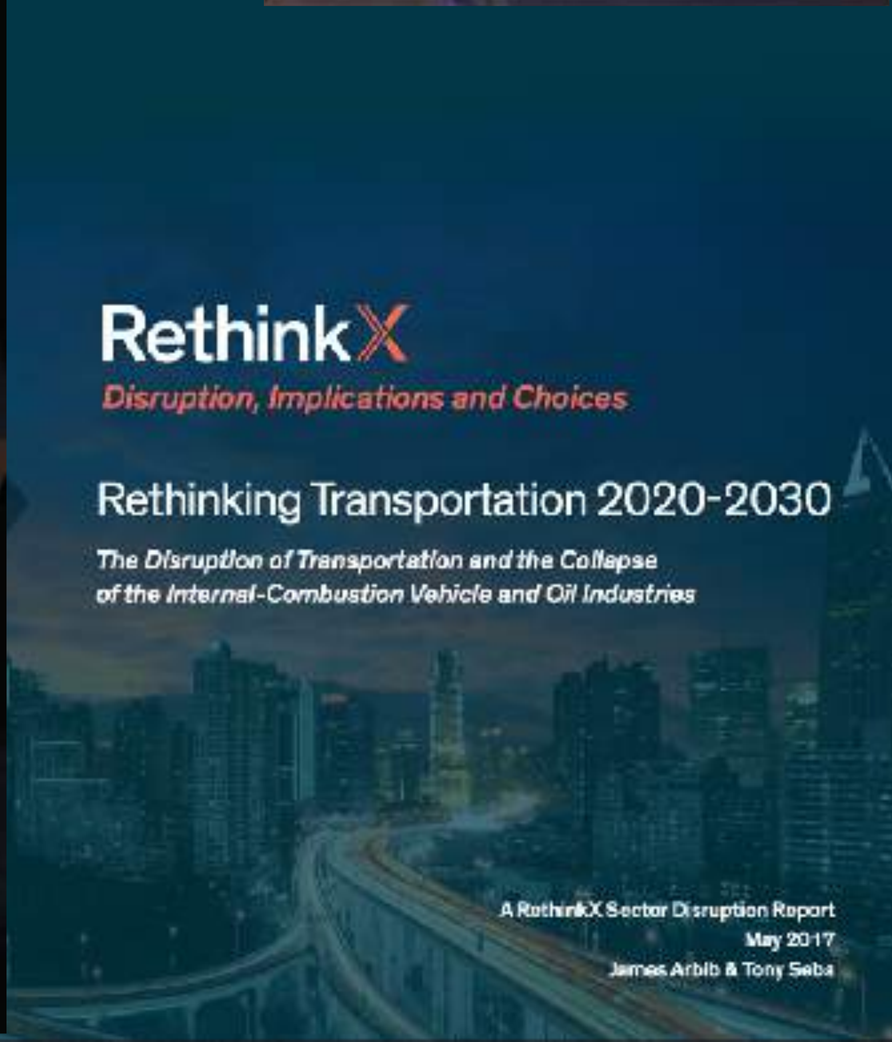
Personal **I**nternal-combustion **G**asoline **S**teel

Shareable **E**lectric **A**utonomous **L**ightweight [mobility-as-a-]**S**ervice



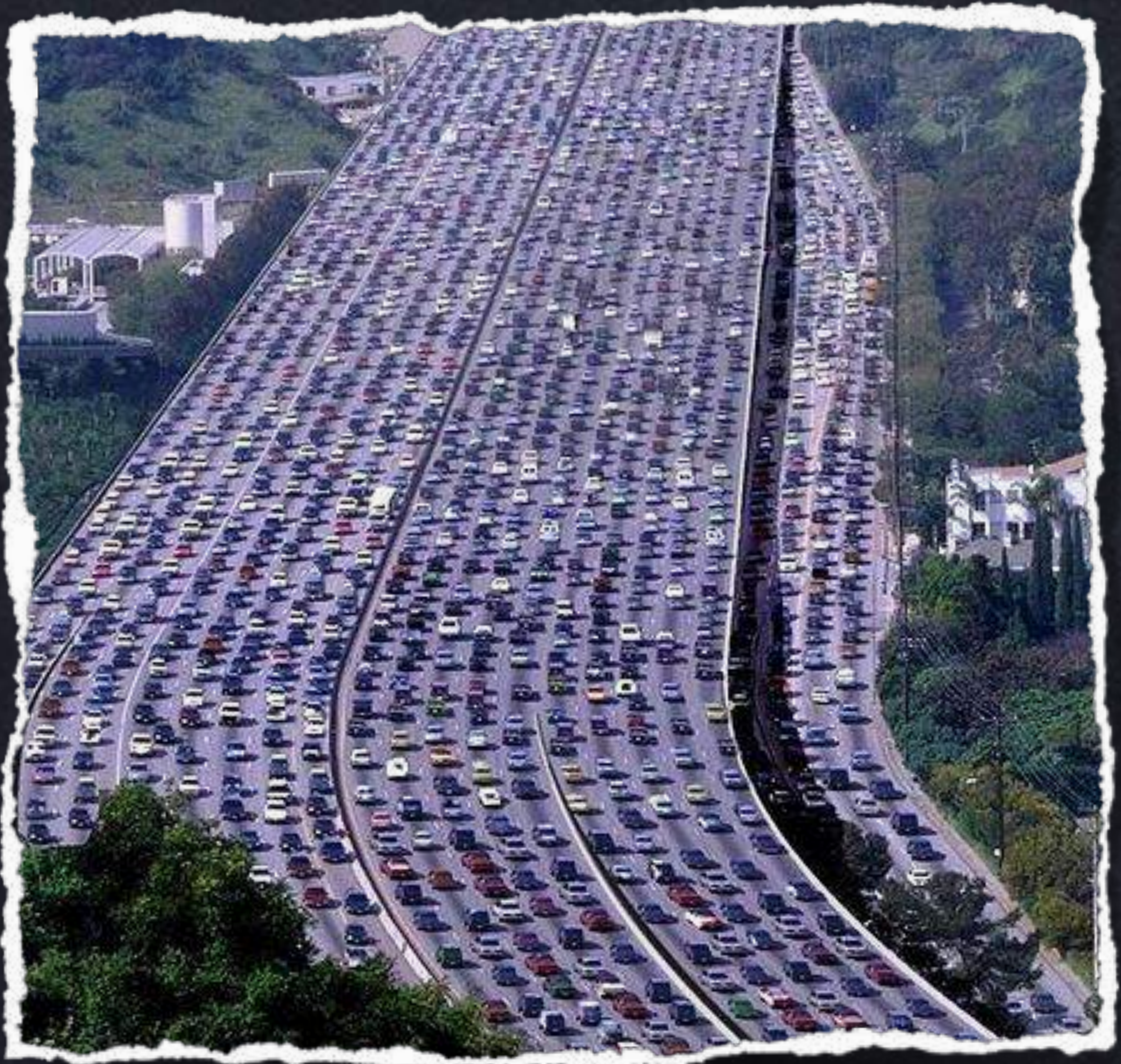






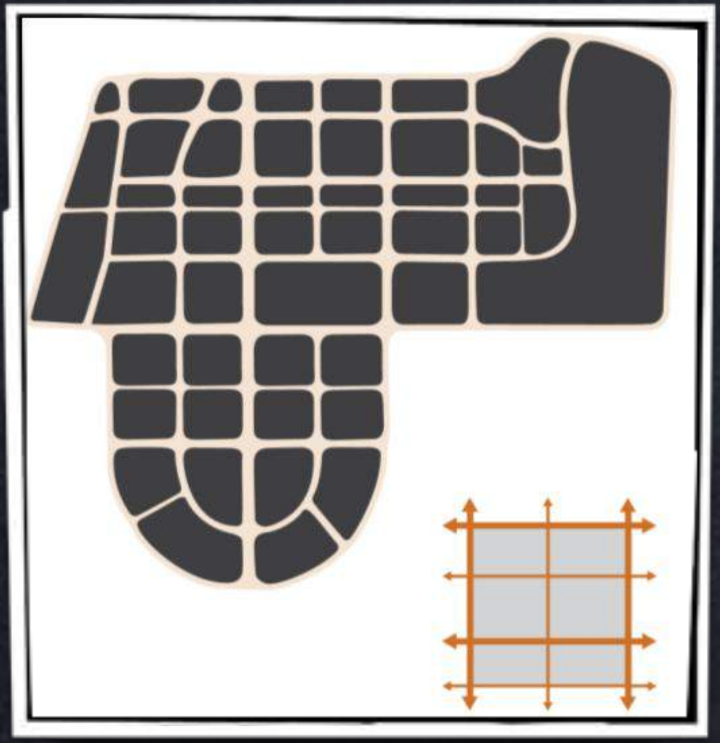
中华人民共和国
国民经济和社会发展第
十三个五年规划纲要
2016年03月17日

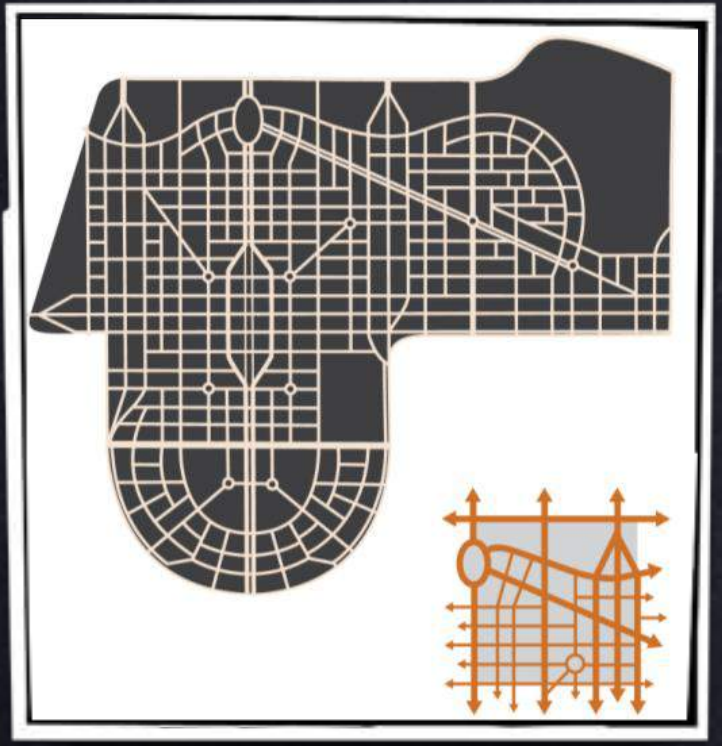
Transportation problems in China



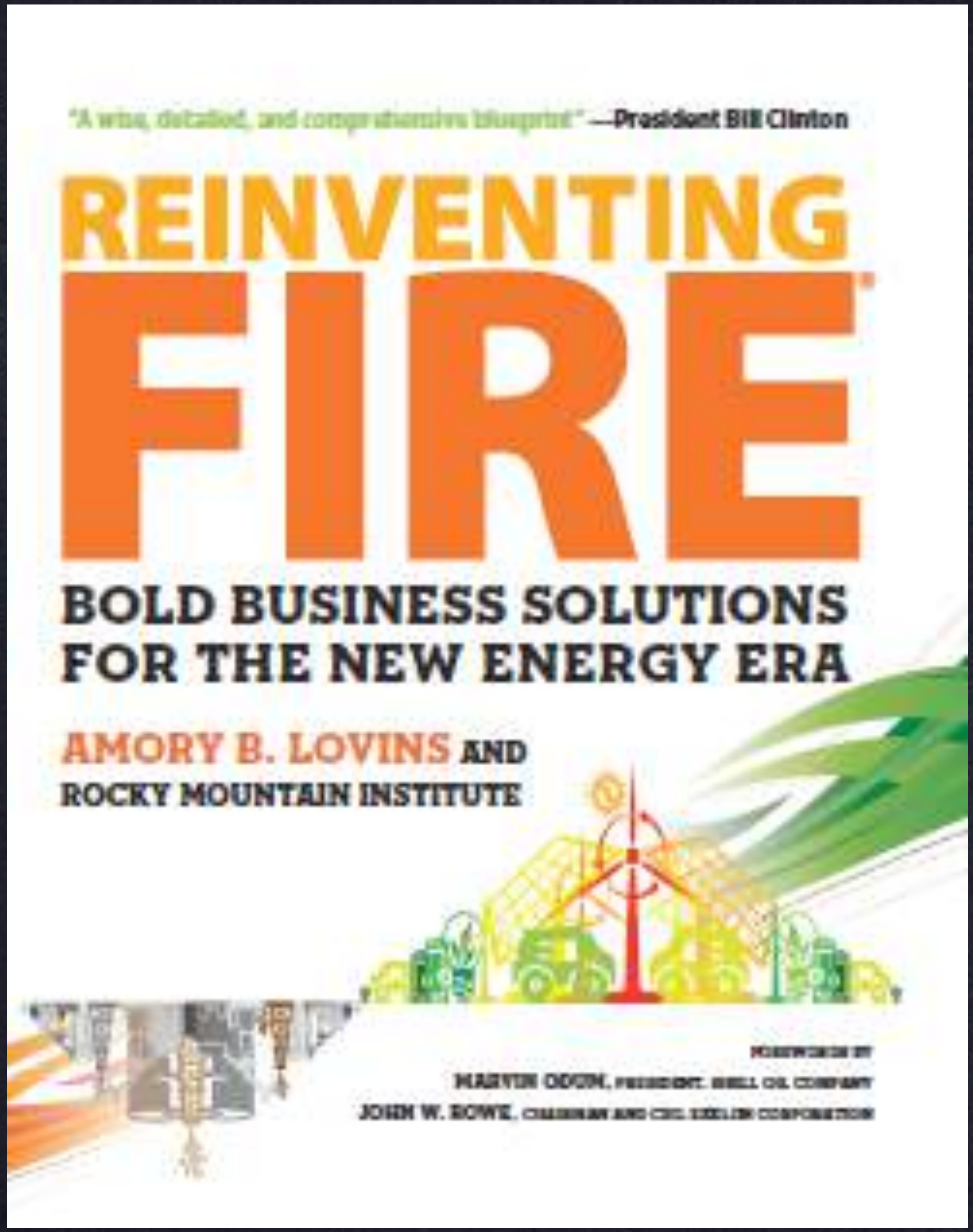
From disorganized chaos to smooth travel experience

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
MARVIN ODUM
JOHN W. ROWE


REINVENTING FIRE
重塑能源
新能源世纪的商业解决方案

$5T

in savings (net present value, private internal cost)

+158%

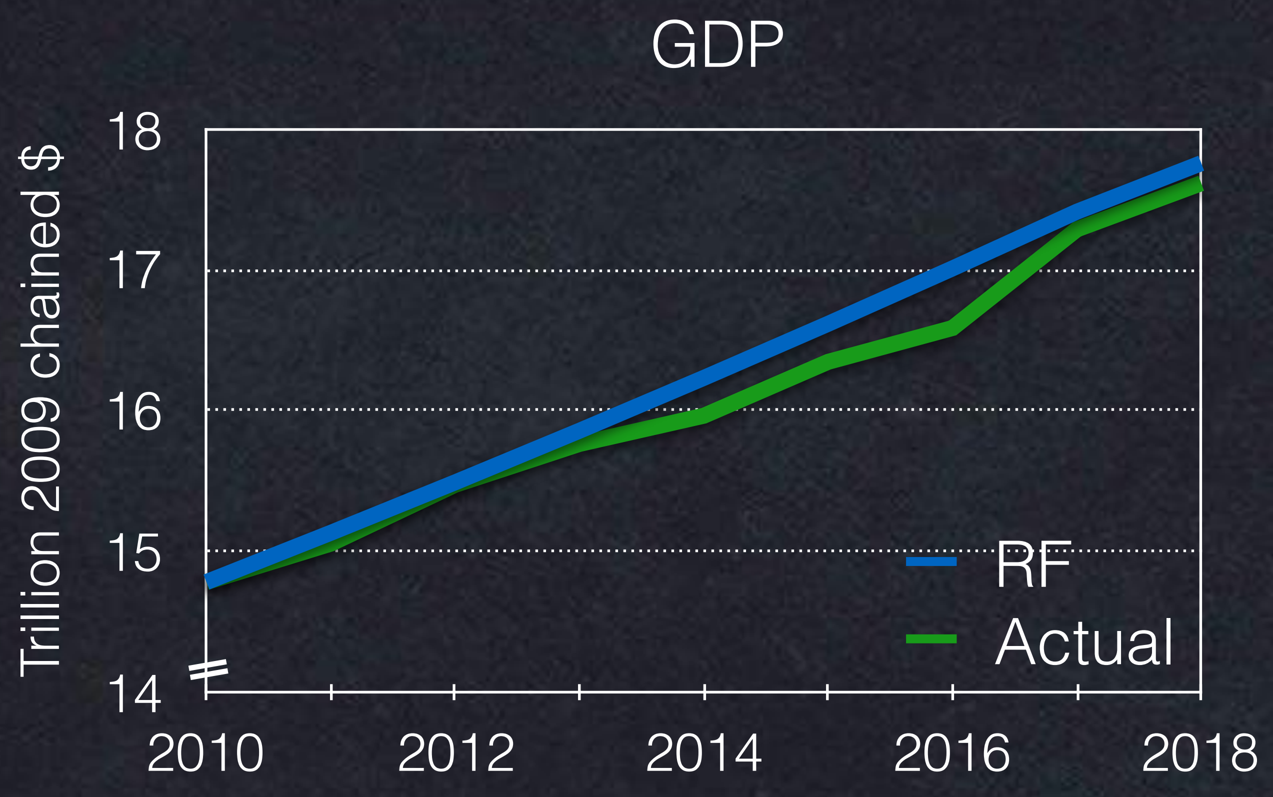
bigger economy

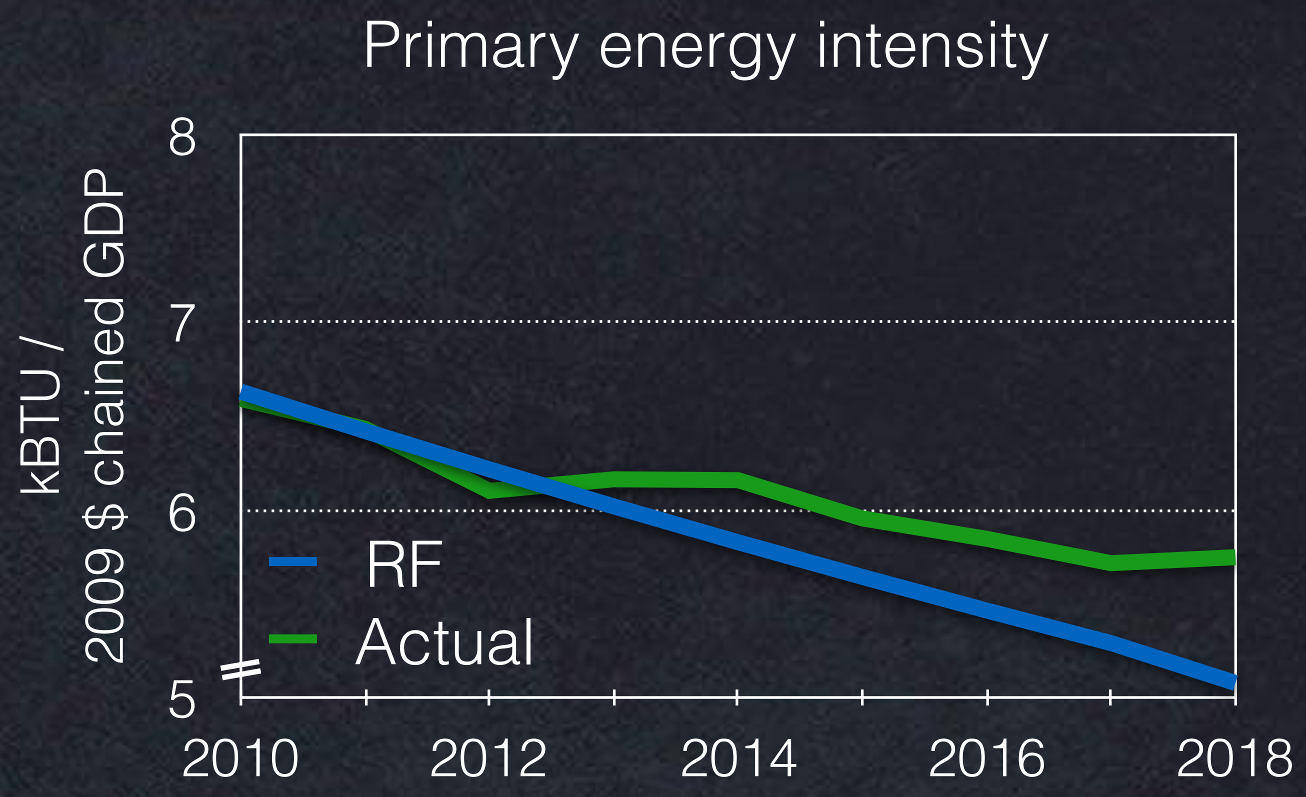
0

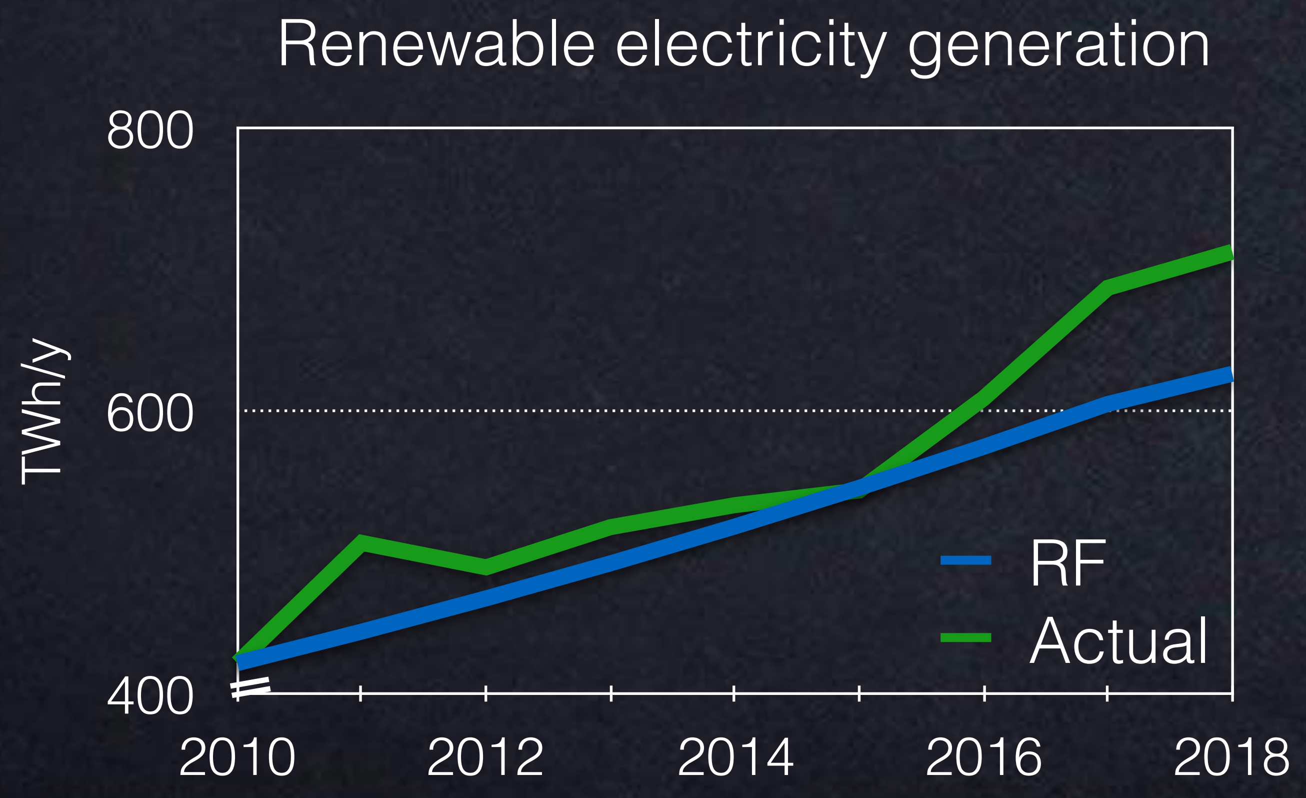
oil, coal, nuclear

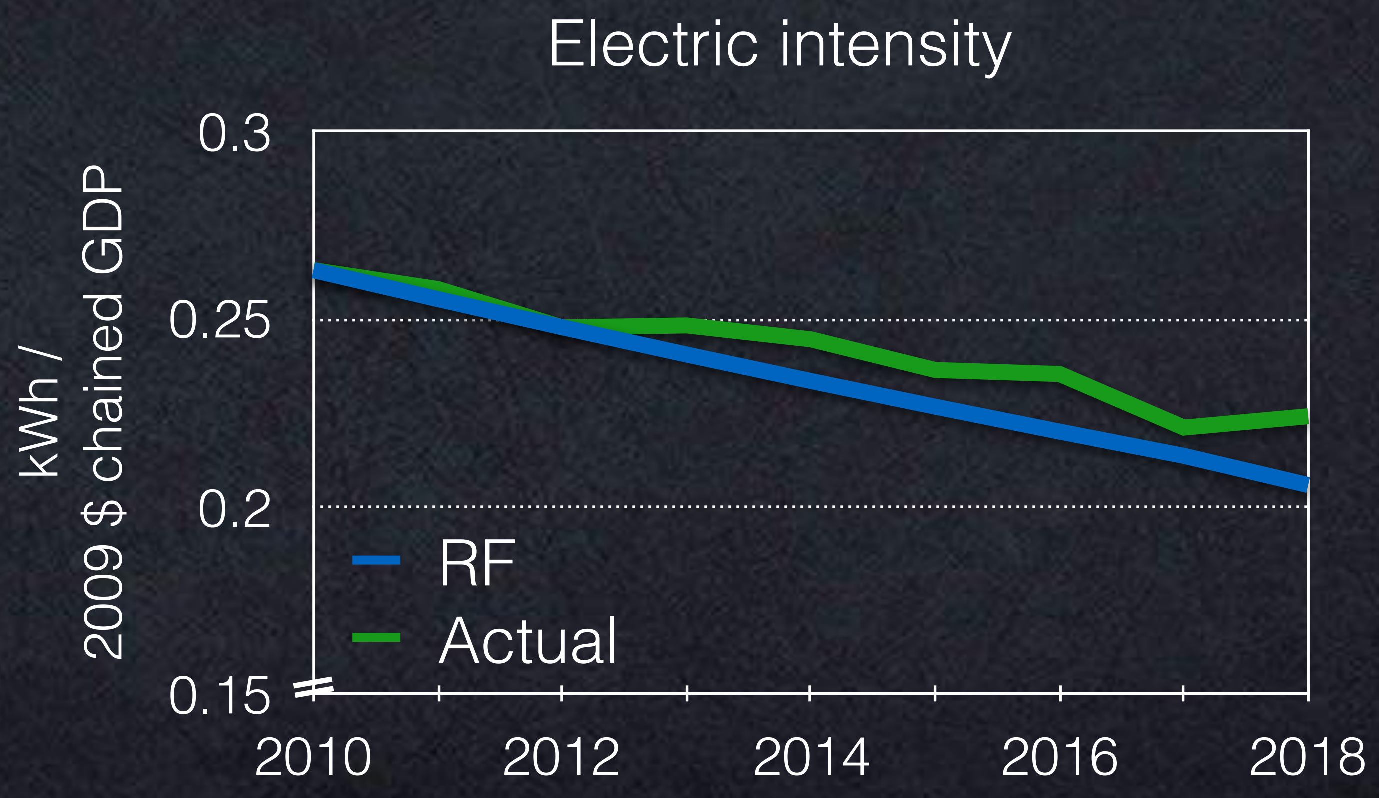
2010–2018p U.S. progress toward *Reinventing Fire's* 2050 goals

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

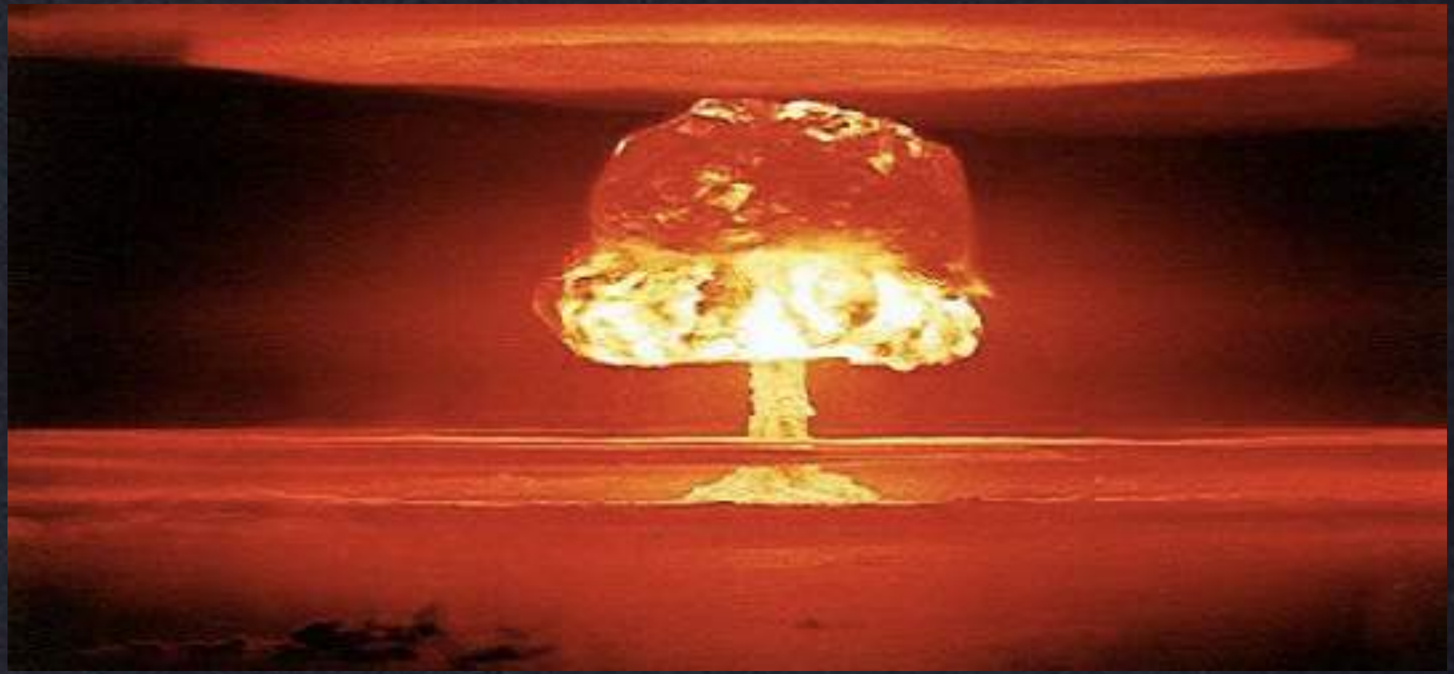


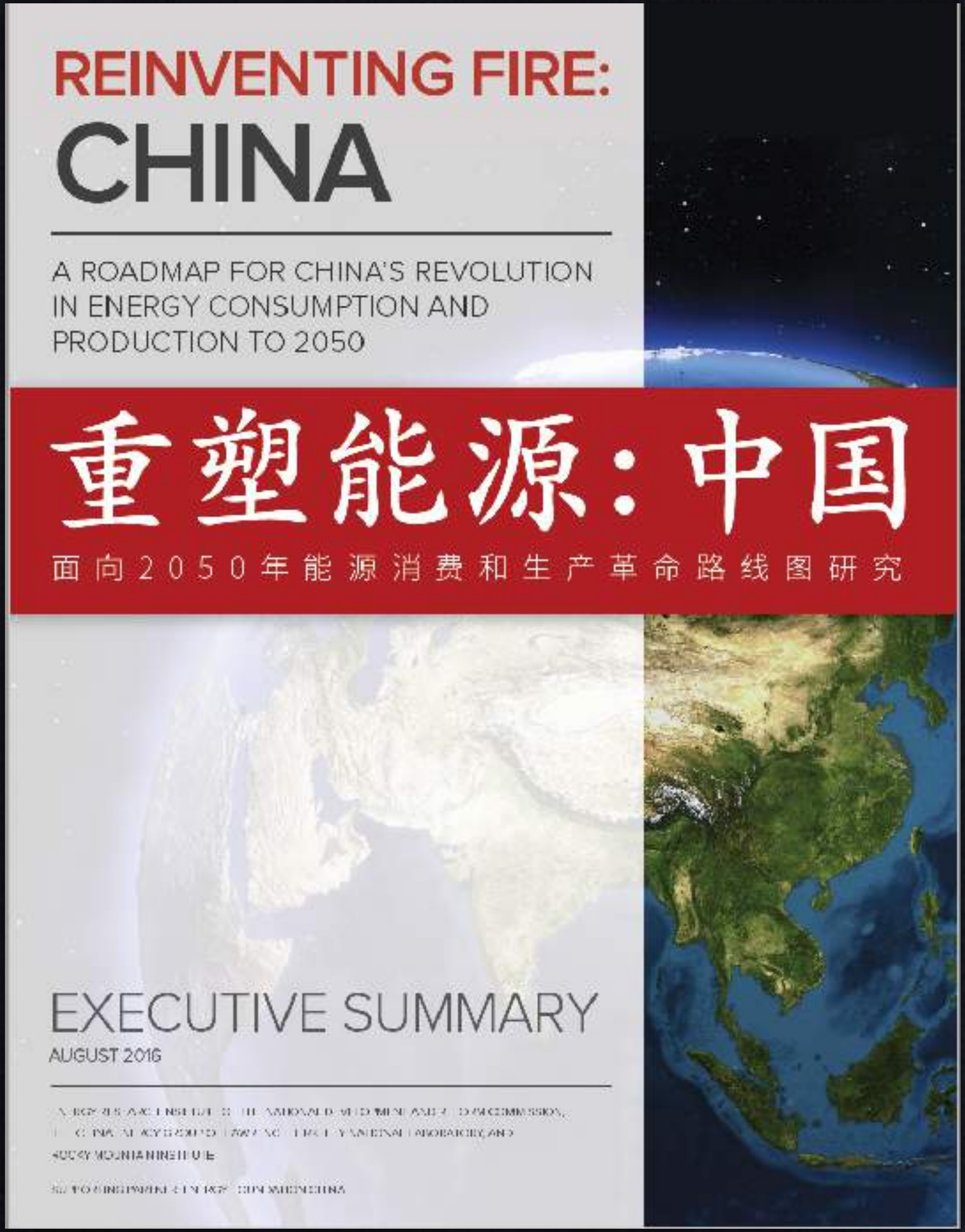






Solutions to:




REINVENTING FIRE:
CHINA
A ROADMAP FOR CHINA'S REVOLUTION IN ENERGY CONSUMPTION AND PRODUCTION TO 2050
重塑能源：中国
面向2050年能源消费和生产革命路线图研究
EXECUTIVE SUMMARY
AUGUST 2016


国家发展和改革委员会能源研究所
Energy Research Institute National Development And Reform Commission
BERKELEY LAB
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RMB 21T
2010 NPV

in savings
经济节约

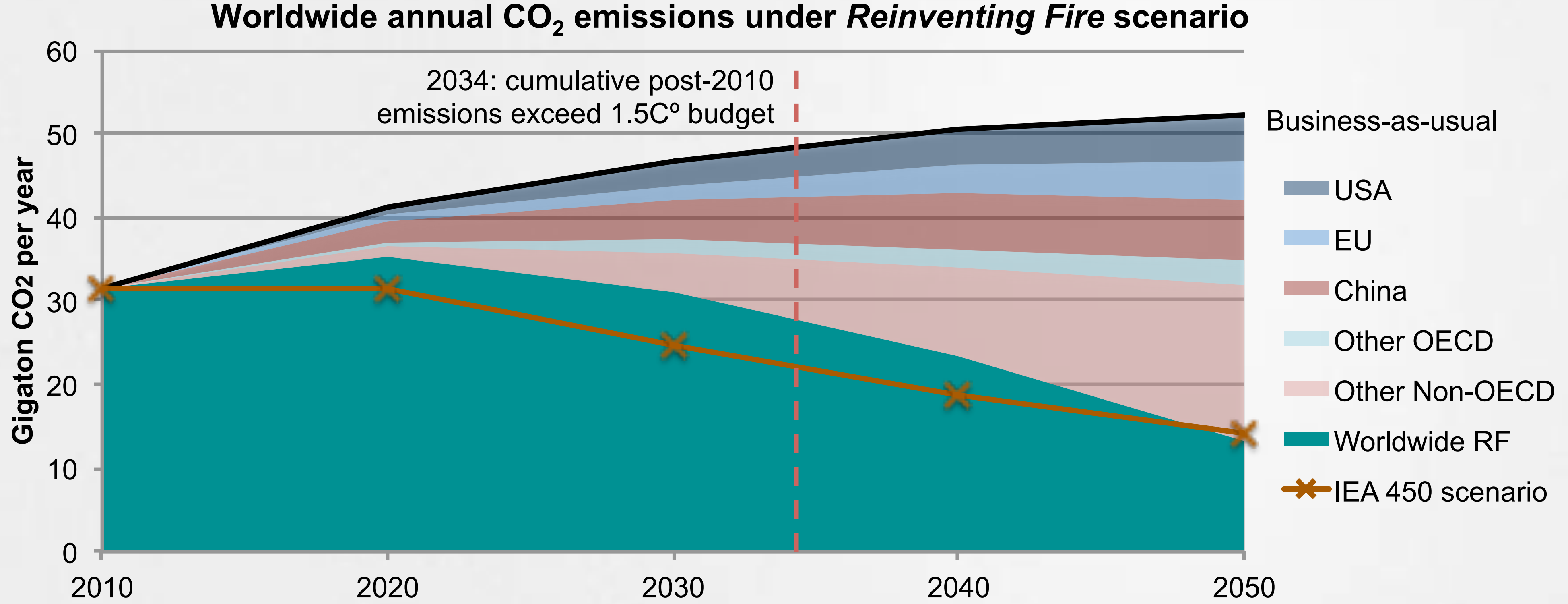
+587%

bigger GDP
经济规模

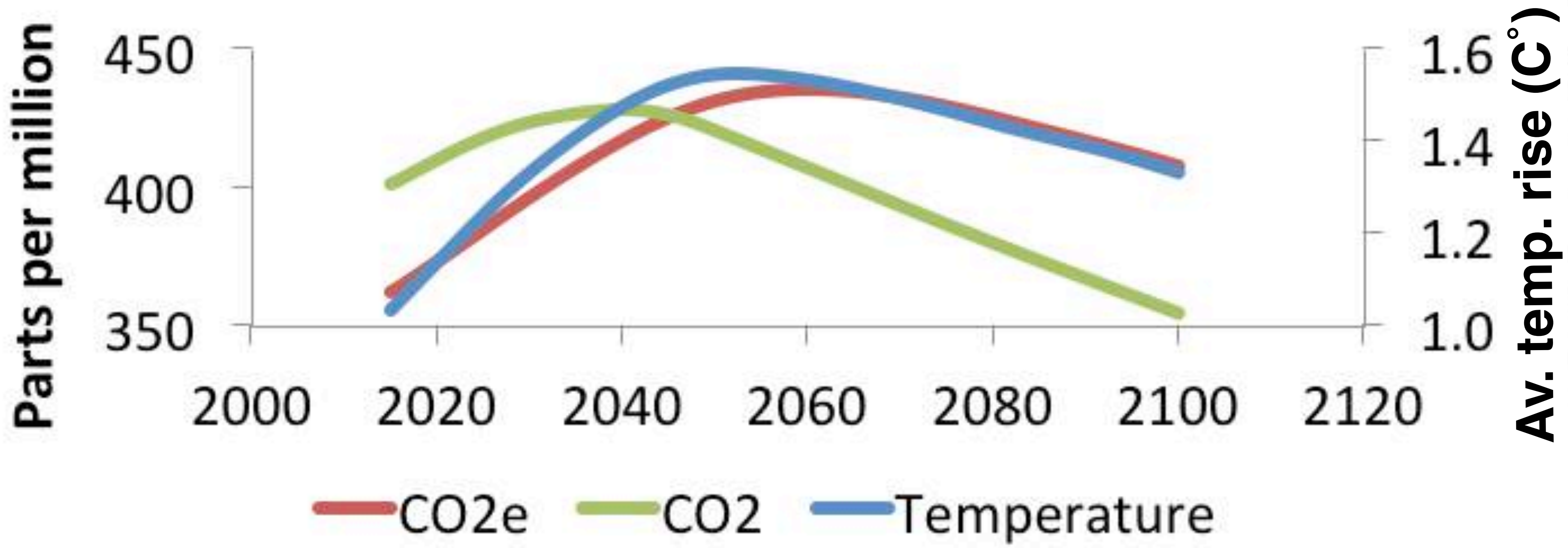
42%

less carbon
碳排放减少

Reinventing Fire applied worldwide will keep within the 2010–2050 carbon budget for 50% probability of 2Cº



…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?

Images: L, National Archive, www.archives.gov/research/american-cities/images/american-cities-101.jpg; R, shorpy.com/node/204.
Inspiration: Tona Seba's keynote lecture at AltCar, Santa Monica CA, 28 Oct 2014, http://tonyseba.com/keynote-at-altcar-expo-100-electric-transportation-100-solar-by-2030/

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