“Cathedral” Photovoltaics

Years

0 GW-y 1 GW-y 2 GW-y 3 GW-y 6 GW-y 10 GW-y 15 GW-y 21 GW-y 28 GW-y 36 GW-y 45 GW-y
International Energy Agency global wind and solar forecasts

Cumulative GW installed

Wind

Solar

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

6× upward revision since 2002

23× upward revision since 2002

Variable Renewables Can Be Forecasted At Least as Accurately as Electricity Demand

French windpower output, December 2011: forecasted one day ahead vs. actual

Source: Bernard Chabot, 10 April 2013, Fig. 7, www.renewablesinternational.net/wind-power-statistics-by-the-hour/150/505/61845/, data from French TSO RTE
Choreographing Variable Renewable Generation

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

Europe, 2015–17 renewable % of total electricity consumed

63%

Denmark 2015 (42% wind, 11% bio) (2013 windpower peak 136%—55% for all December)

60%

Scotland 2017 (53% without hydro)

36%

Germany 1H2018 (2016 peak 88%, 2018 ~90–100%)

63%

Portugal (2016, 29% without hydro) (2011 & 2016 peak 100%; 70% for 1H2013 incl. 26% wind & 34% hydro)

46%

Peninsular Spain (2016, 27% without hydro)
Transitioning to distributed renewables in Denmark

1980

- Central thermal
- Other generation
- Wind turbines

2012

Source: Risø
Grid flexibility resources

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

Ability to accommodate reliably a large share of variable renewable power

(All values shown are conceptual and illustrative)

Hydrogen storage not shown because its quantity is indeterminate.
Flexible loads: goodbye “duck curve”

These eight levers combine to make net load far smoother and lower (ERCOT, summer 2050)

Source: RMI analysis by Harry Masters, 2016, in course of publication
Cheaper renewables *and* batteries change the game

In Westchester, NY, 60% of residential consumption in the next decade could come more cheaply from PV

Source: RMI analysis “The Economics of Load Defection,” 2015
Load control + PVs = grid optional

Uncontrolled: ~50% of solar PV production is sent to the grid, but if the utility doesn’t pay for that energy, how could customers respond?

Controlled: flexible load enables customers to consume >80% of solar PV production onsite. The utility loses nearly all its windfall and most of its ordinary revenue.

Source: RMI analysis “The Economics of Load Flexibility,” 2015
Accelerating plug-in auto growth and falling battery price

Global Plug In vehicles, now 4 million, are growing ~50% per year, with battery pack price now below $200/kWh and falling fast


Plug-In Vehicle sales, 2011–2017

Battery pack price, 2011–2017 (nominal $)
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
Tripled US end-use efficiency and quintupled renewables by 2050

IRRs: 33% buildings, 21% industry, 17% mobility, 14% all those plus a resilient, 80%-renewable, 50%-distributed electricity system.
Real hurdle rates for efficiency investments, based on 2011 sectoral risk/reward tolerances: autos 3%-y retail payback, heavy trucks 15%-y, buildings 7%-y, industry 12%-y, electricity generation 5.7%-y (based on investor-owned utilities’ weighted-average cost of capital).
Analysis in constant 2009 $; discounting to 2010 present value is at OMB’s 3%-y prescribed for federal energy-efficiency investments.
Activity levels and energy prices from USEIA’s 2010 Annual Energy Outlook Reference Case, extrapolated to 2050.
Sectoral adoption rates based on stock-and-flow or consumer-choice models consistent with observed market behavior.
2010–2017 U.S. progress toward Reinventing Fire’s 2050 goals

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

- **GDP**
- **Primary energy intensity**
- **Renewable electricity generation**
- **Electric intensity**

- **Trillion 2009 chained $**
- **2010–2017 TWh/y**
- **kBTU / 2009 $ chained GDP**
- **kWh / 2009 $ chained GDP**

- RF
- Actual
Solutions to:
REINVENTING FIRE: CHINA
A ROADMAP FOR CHINA'S REVOLUTION IN ENERGY CONSUMPTION AND PRODUCTION TO 2050

EXECUTIVE SUMMARY
AUGUST 2016

ENERGY RESEARCH INSTITUTE OF THE NATIONAL DEVELOPMENT AND REFORM COMMISSION,
THE CHEMICAL GROUP OF LAWRENCE BERKELEY NATIONAL LABORATORY AND
SCHOOL OF MANAGEMENT, GS

SUPPORTING PARTNER: ENERGY FOUNDATION CHINA.
RMB 21T 2010 NPV +587% 42%

- in savings
- bigger GDP
- 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 2C°

Worldwide annual CO₂ emissions under Reinventing Fire scenario

Business-as-usual

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

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

Assumptions:
• CO₂ emissions are calculated using Reinventing Fire for U.S., Roadmap 2050 for EU, Reinventing Fire: China for China. Other OECD is calculated using the Reinventing Fire 2010–2050 trajectory; Other Non-OECD using the Reinventing Fire: China 2010–2050 trajectory.
• CO₂ budget is calculated by ETH Zürich from IPCC data and assumptions for non-CO₂ emissions to define an energy-related CO₂ budget.
• Cumulative CO₂ emissions for 2010–2050 under the Reinventing Fire scenario are 1121 Gt by 2050, 79 Gt below the 1200 Gt 2010–2050 carbon budget for 50% probability of ≤2C˚ average temperature change, but 331 Gt above the carbon budget for ≤1.5C˚ average temperature change.

...and with conservatively assessed natural-systems carbon removal...
Detecting an early signal of the energy transition

Annual percent change in global non-carbon share of total final energy consumption, 1975–2016, and primary energy intensity, 1975–2017

Sources: TFEC (IEA), renewables (BP, except IEA for renewable heat only); synthetic primary energy intensity (BP, World Bank); no adjustments for weather, economic cycles, or other fluctuations.
Global total final commercial energy consumption from non-fossil-fuel sources, 1975–2017 (21% of 2016 total)

Sources: TFEC (IEA Energy Balances for renewable heat, BP for all others)
Global energy savings are accelerating like renewables

Annual changes in global primary energy intensity, 1981–2017

Average change 1981–2010: 1.2%/y
Average change 2011–17p: 2.1%/y

IEA's 450-ppm CO₂ scenario calls for 2.6%/y intensity drop to 2030

#1 threat to gas: methane “slip” (vents, flares, leaks, other uncombusted)

CH$_4$ emissions ×2.5, 60% human, 25% of warming 100- vs 20-y CO$_2$ “equivalence” hides the opportunity ~78% is lost upstream, of which ~60–80% is intentional

But CH$_4$ lasts only 9±2 y, so cutting just 10–25 MT/y could rebalance the global CH$_4$ cycle. Why stop there?

Abating even more (the profitable half of O&G industry emissions) could profitably displace 160 GTCO$_2$—fastest way to turn down the thermostat, buying more time to decarbonize

Just closing flares and fixing vents in a few thousand places could do this profitably! What are entrepreneurs waiting for?
Value > Price > Cost
Easter Parades on Fifth Avenue, New York, 13 years apart

1900: where’s the first car?

1913: where’s the last horse?

Renewables replacing $38b/y kerosene market
From the Age of Carbon to the Age of Silicon
Profitable Climate Protection with Development and Security

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