Mitigating & Adapting to Climate change: Extreme Weather Events, a Worldwide Energy Revolution and Geoengineering options

Week 5: April 24th, 2017
Wind and Solar

Paul Belanger, Ph.D.

Announcements

12A» NEWS MONDAY, APRIL 24, 2017 • DENVERPOST.COM

SCIENCE

Message to world leaders: Ignore

Bloomberg says not to follow Trump's lead on climate change.

By Steve Peoples
The Associated Press

NEW YORK» New York billionaire Michael Bloomberg urged world leaders not to follow President Donald Trump's lead on climate change and declared his intention to help save an international agreement to reduce carbon emissions.

Michael Bloomberg

- new book, "Climate of Hope: How Cities, Businesses, and Citizens Can Save the Planet," co-authored by former Sierra Club executive director Carl Pope.
- specific policy objective: to help save an international agreement, negotiated in Paris, to reduce global carbon emissions
- believed the U.S. would hit that goal regardless of what Trump does because of leadership at the state level and market forces already at play in the private sector.

Thursday April 27th , 7 p.m.
HERE at JUC

- **Colorado Renewable Energy Society:**
  - Jeffco chapter presents:

KK DuVivier: Deep Decarbonization - It's the Rules, Stupid!

  - https://www.cres-energy.org/

NREL TOUR MAY 8TH

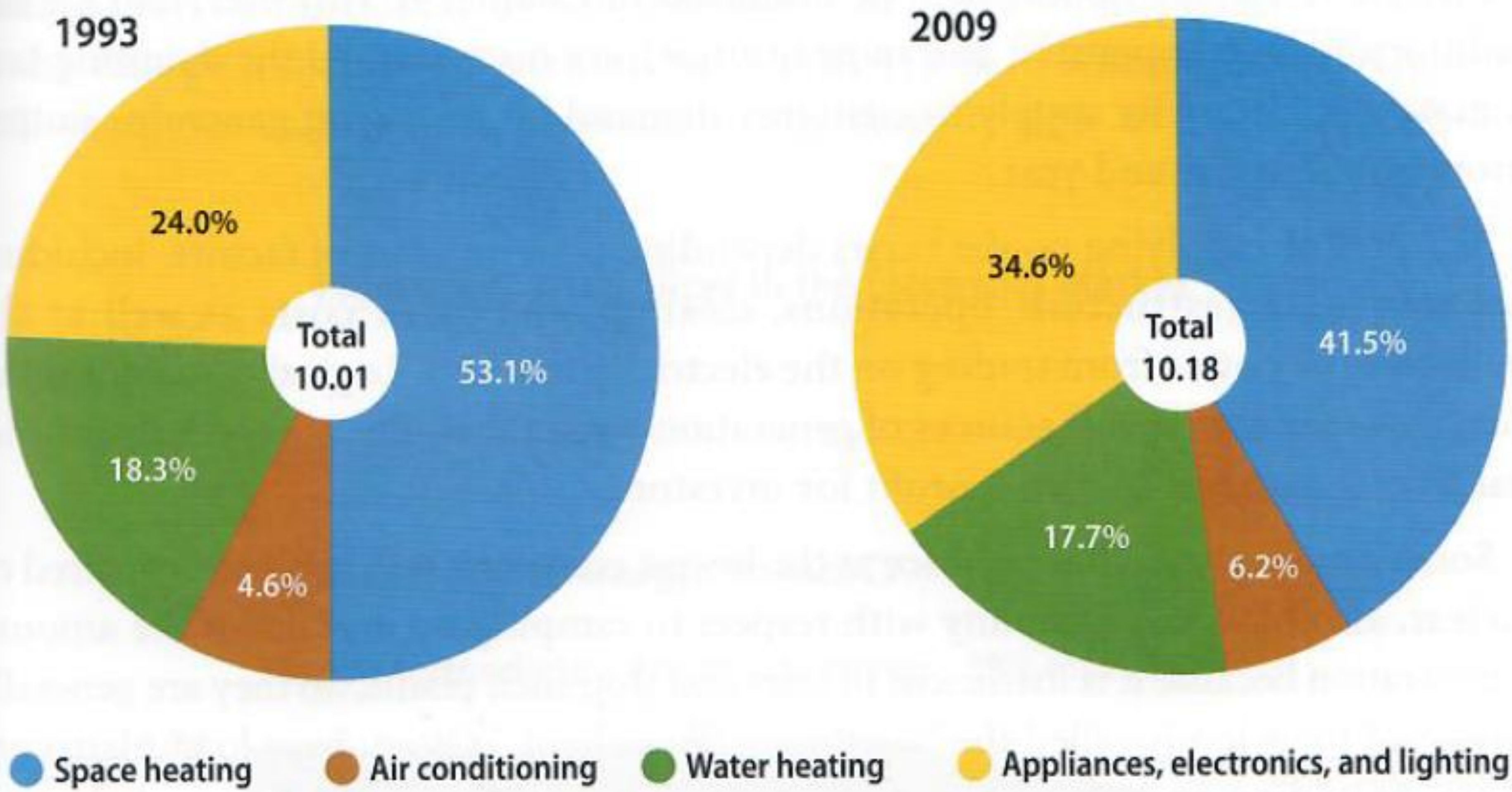
- Energy Systems Integration Lab
- 1:30-3:00 p.m.; please aim to be there ~1 p.m.
- GOVERNMENT ID: CDL / passport
- Read attachments I sent

- Paul Belanger:

  - PEBelanger@glassdesignresources.com
  - c. 303-249-7966; h 303-526-7996

Figure 5.3. Energy Consumption in Homes by End Uses

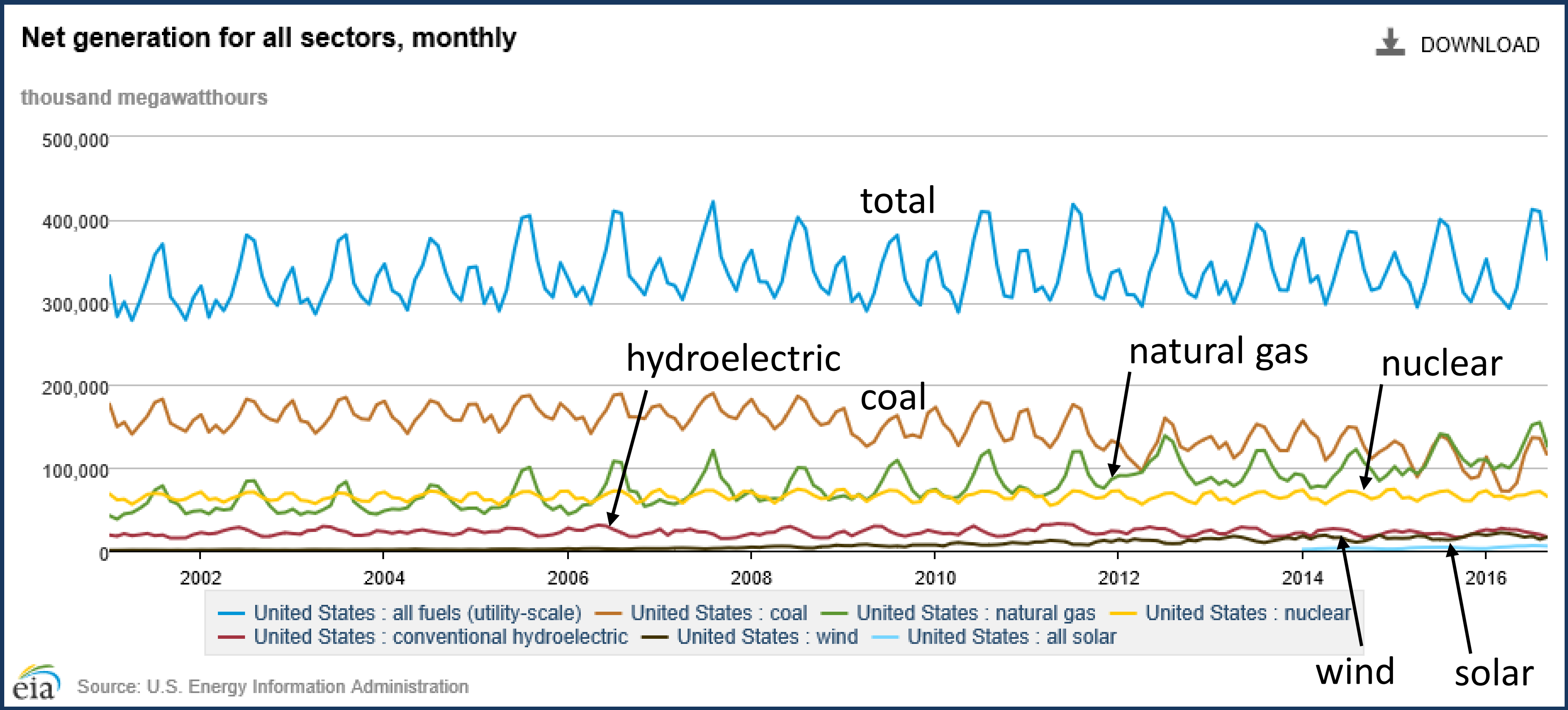
quadrillion Btu and percent



Source: U.S. Energy Information Administration, http://www.eia.gov/todayinenergy/detail.cfm?id=10271.

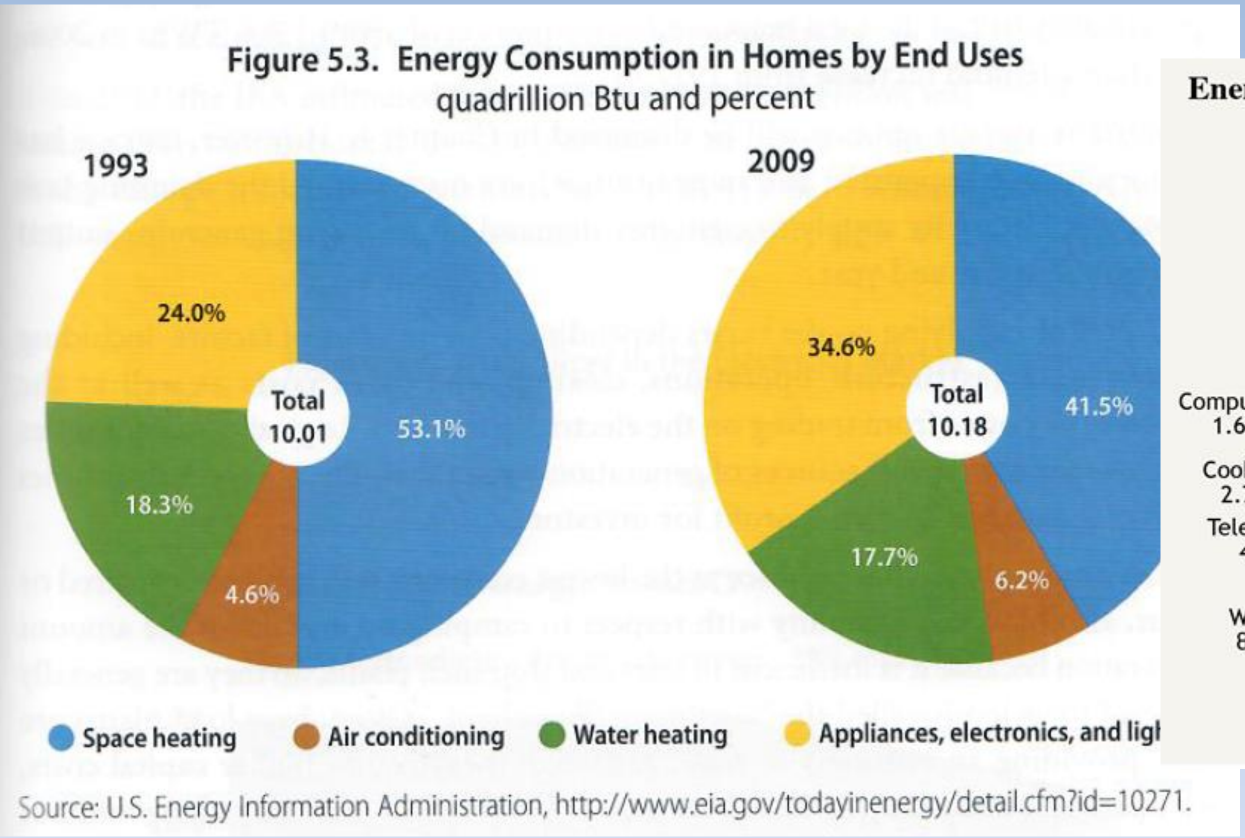
Electricity Generation in the U.S. by Source

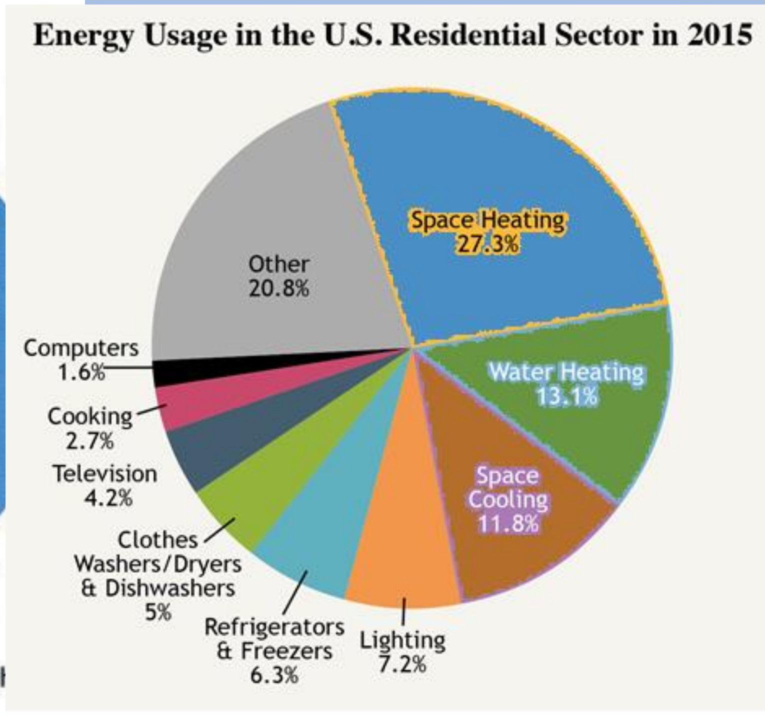
U.S. Energy Information Administration, Nov 2016



Overall electrical generation in the United States is roughly flat for 2006-2016.
Coal-fired generation has been dropping since 2009.
Summer usage causes annual fluctuations of about one-third.
Wind is 5.1% and solar is 1.4% of all electrical generation as of October 2016.

1993 vs. 2009 vs. 2015





http://needtoknow.nas.edu/energy/energy-use/home-work/

LAST WEEK - SOLUTIONS TAKE AWAY (modified):

ELECTRIFY EVERYTHING BY NON-CARBON SOURCED ELECTRICAL GENERATION!

SOLAR THERMAL

BIOCHAR/BIOFUELS

To Do that (i.e. non-Carbon Energy), in addition to efficiency improvements:

Might need to subsidize nuclear

Storage: battery, thermal, other

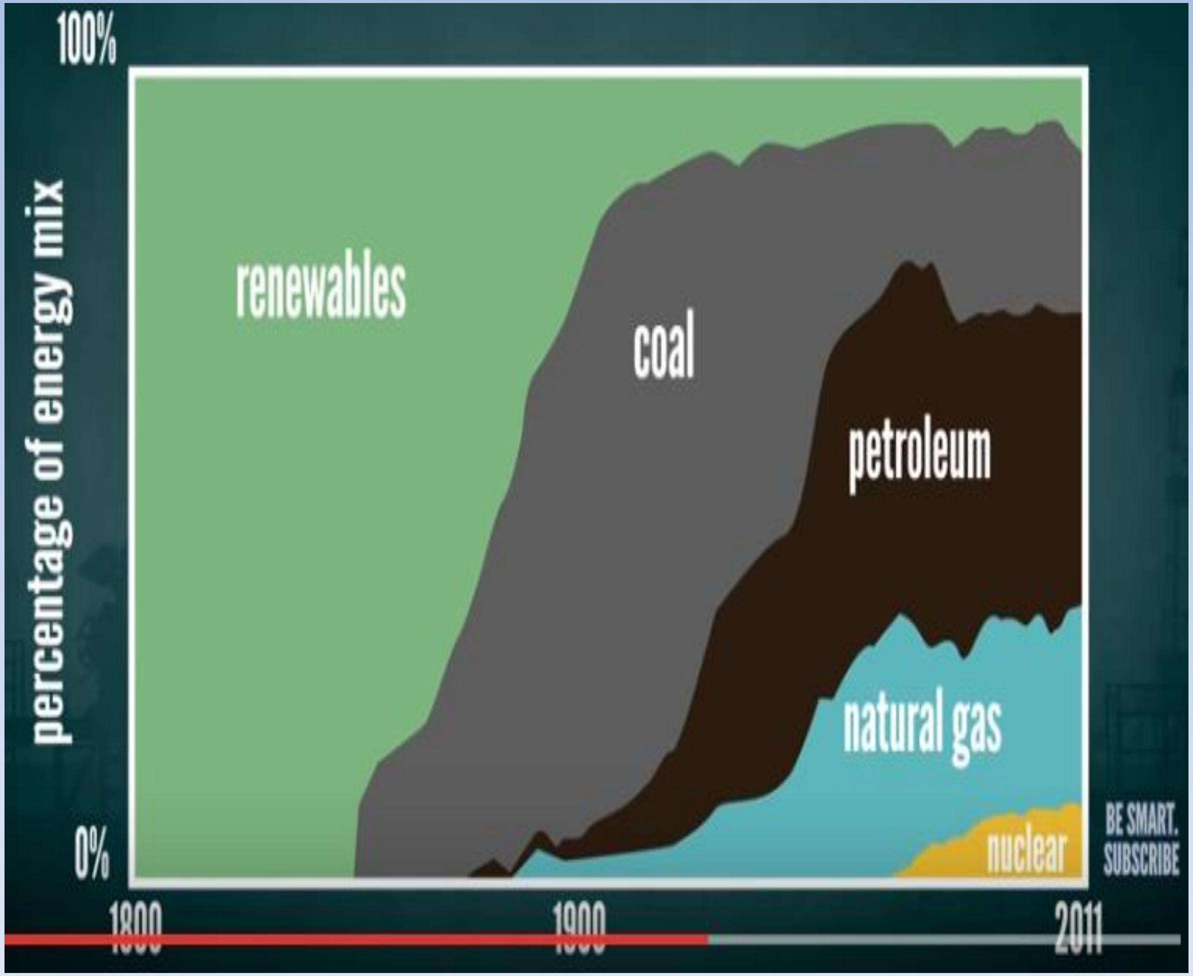
Grid conversion / infrastructure

Decisions

- David Grinspoon:

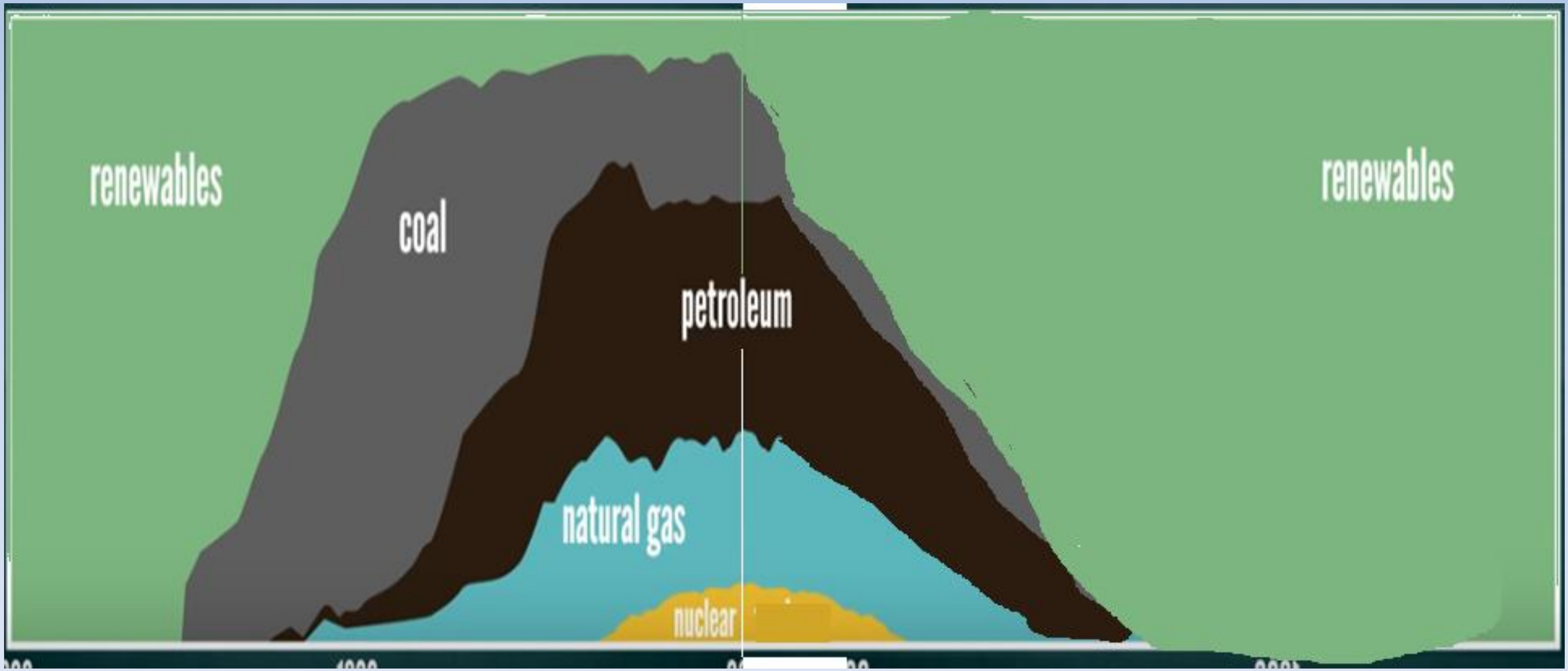
“The decisions we make today will have an impact not only on this 21st century but on the 22nd and 23rd centuries and beyond”

HISTORICAL
Renewables to Coal-Petroleum-Natural Gas-Nuclear



https://www.youtube.com/watch?v=Fjbx5Xq_ULc&t=10s

PROJECTIONS:
Renewables to Coal-Petroleum-Natural Gas-Nuclear --
Back to Renewables



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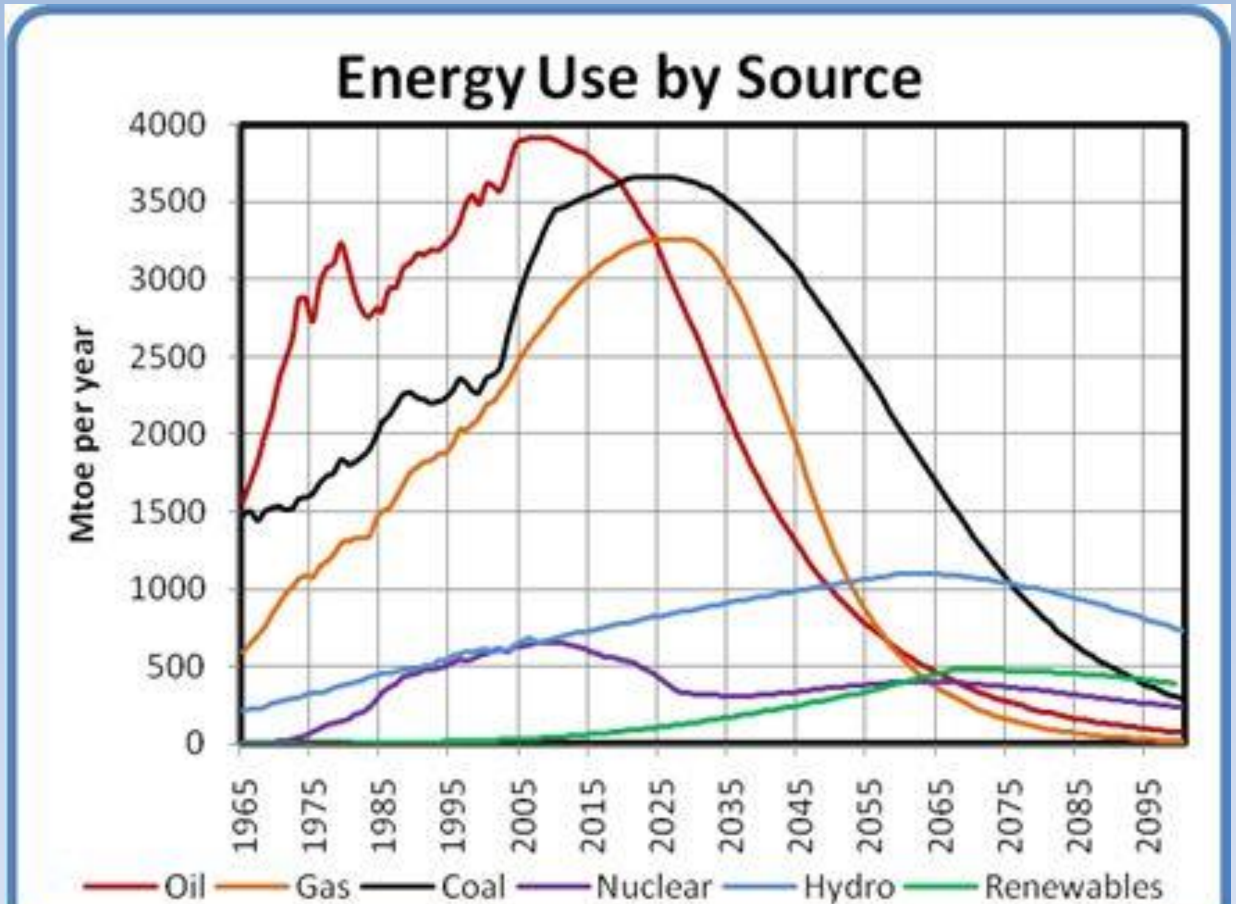
AND the figures for renewables are LAUGHABLE!



http://www.greatchange.org/ov-cherfuka,WEAP.html

http://www.economywatch.com/economy-business-and-finance-news/how-energy-consumption-employment-and-recessions-are-interlinked.26-09.html

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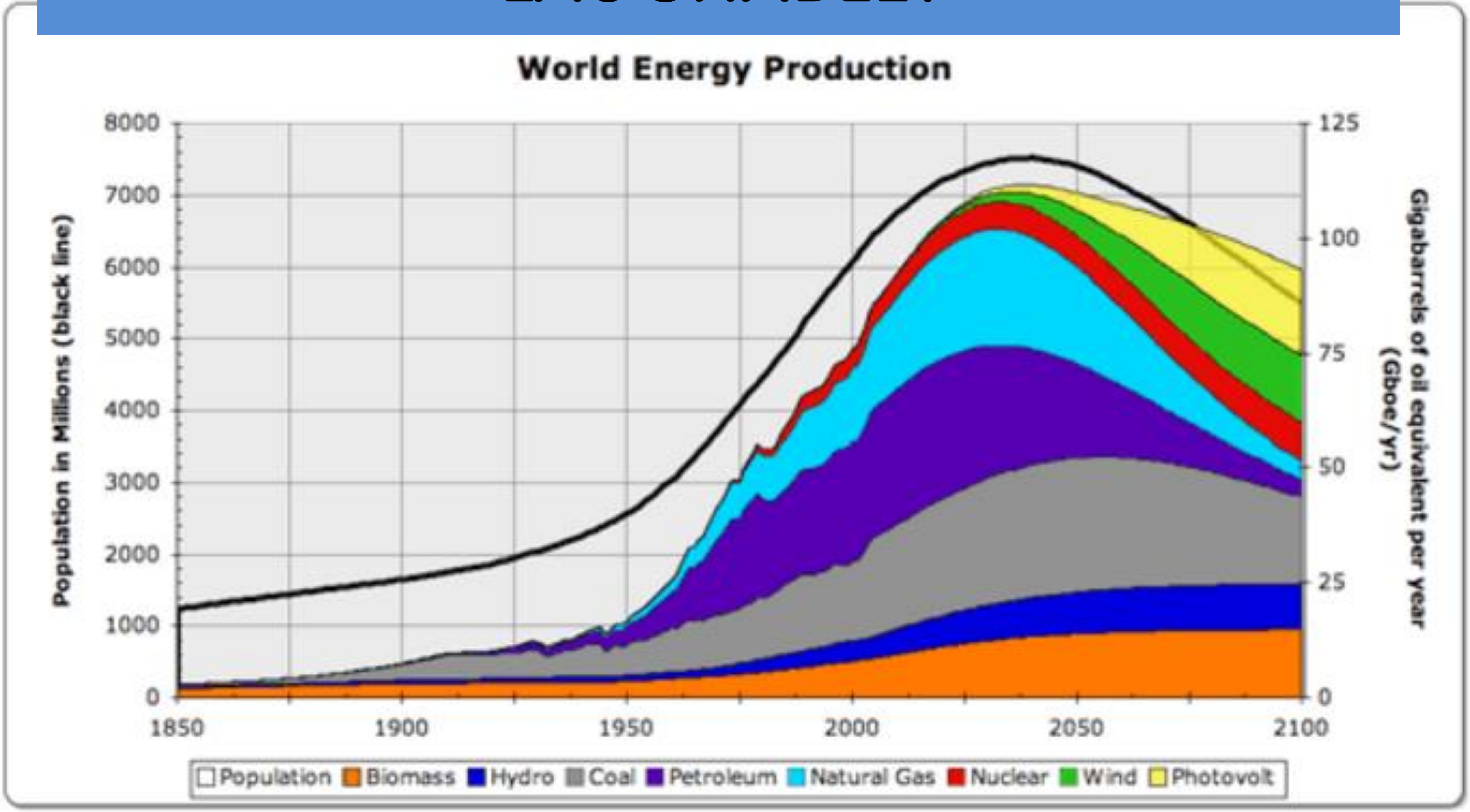

LINK to click on picture for your own assumptions:

http://tqe.quaker.org/2007/TQE155-EN-WorldEnergy-1.html

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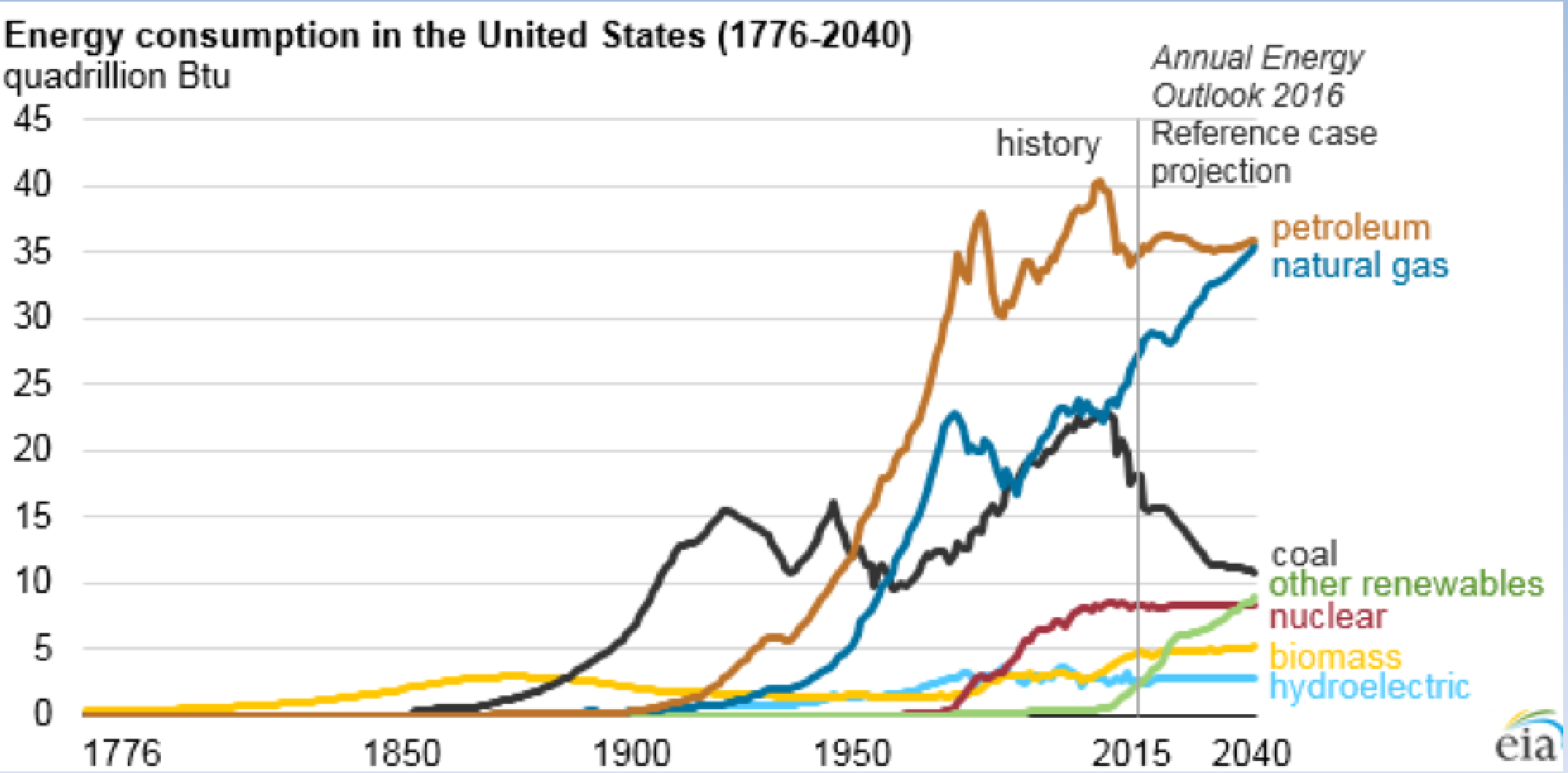
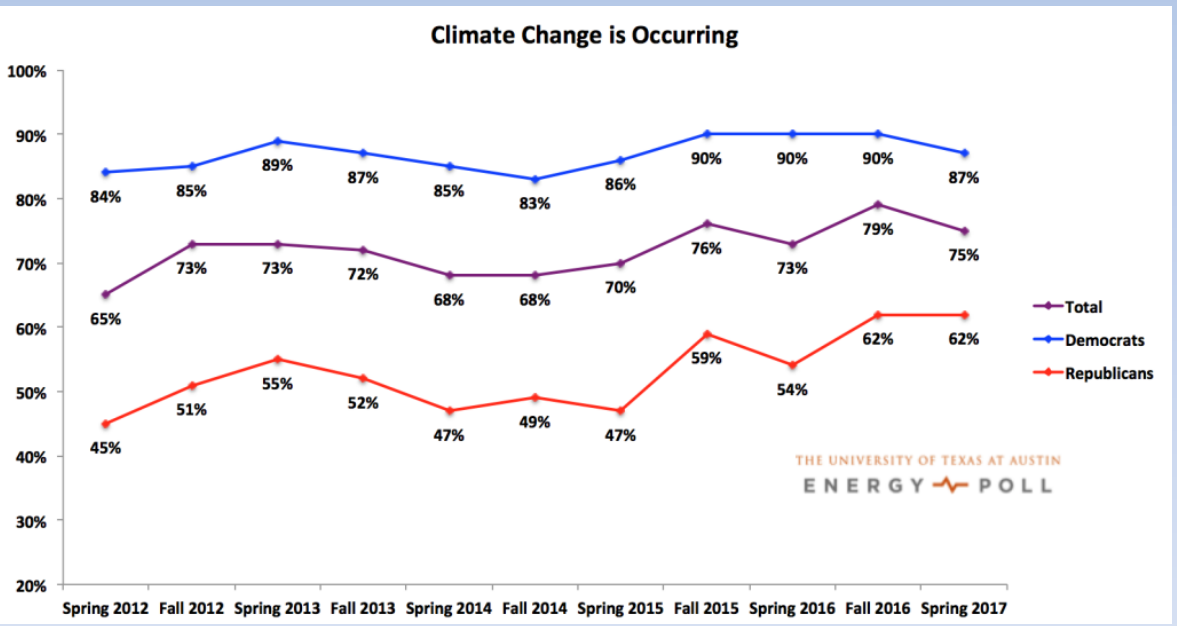


THIS WEEK – SOLAR AND WIND

- SOLAR
  - PV – PhotoVoltaics
    - Monocrystalline, Multi, thin-film
    - Road, sidewalk, rooftop, tracking 1-axis/2-axis, etc.
  - CSP – Concentrated Solar Power
- Wind
  - Turbines
  - Vertical, etc.

RENEWABLES / NON-CARBON SOURCES OF ENERGY:

- THE ENERGY TRANSITION THAT NEEDS TO HAPPEN
  - BUT REMEMBER – THE CHALLENGE:



- 70% believe global warming is occurring
- 55% understand it is caused by human activity
- Only 5% believe anything can or will be done

http://www.utenergypoll.com/

http://climatecommunication.yale.edu/

BEFORE WE GO ON: UNITS

POWER

SI = Watt = J/s

Other units – see white board:

kW, GW, TW

(for Kilo- 10^3,

giga- 10^9,

tera- 10^{12})

BTU

QUADS (10^{15} BTUs)

ENERGY

SI = J = power-time

Or Watt-s

Or what you are used to getting billed for:

kWh @ ~0.11/kWh

CARBON

Gt C = Gt CO2/3.67
(mass 44/mass 12 C)
32.7/3.67 = 8.91 Gt C

Images of change— The Energy Transition

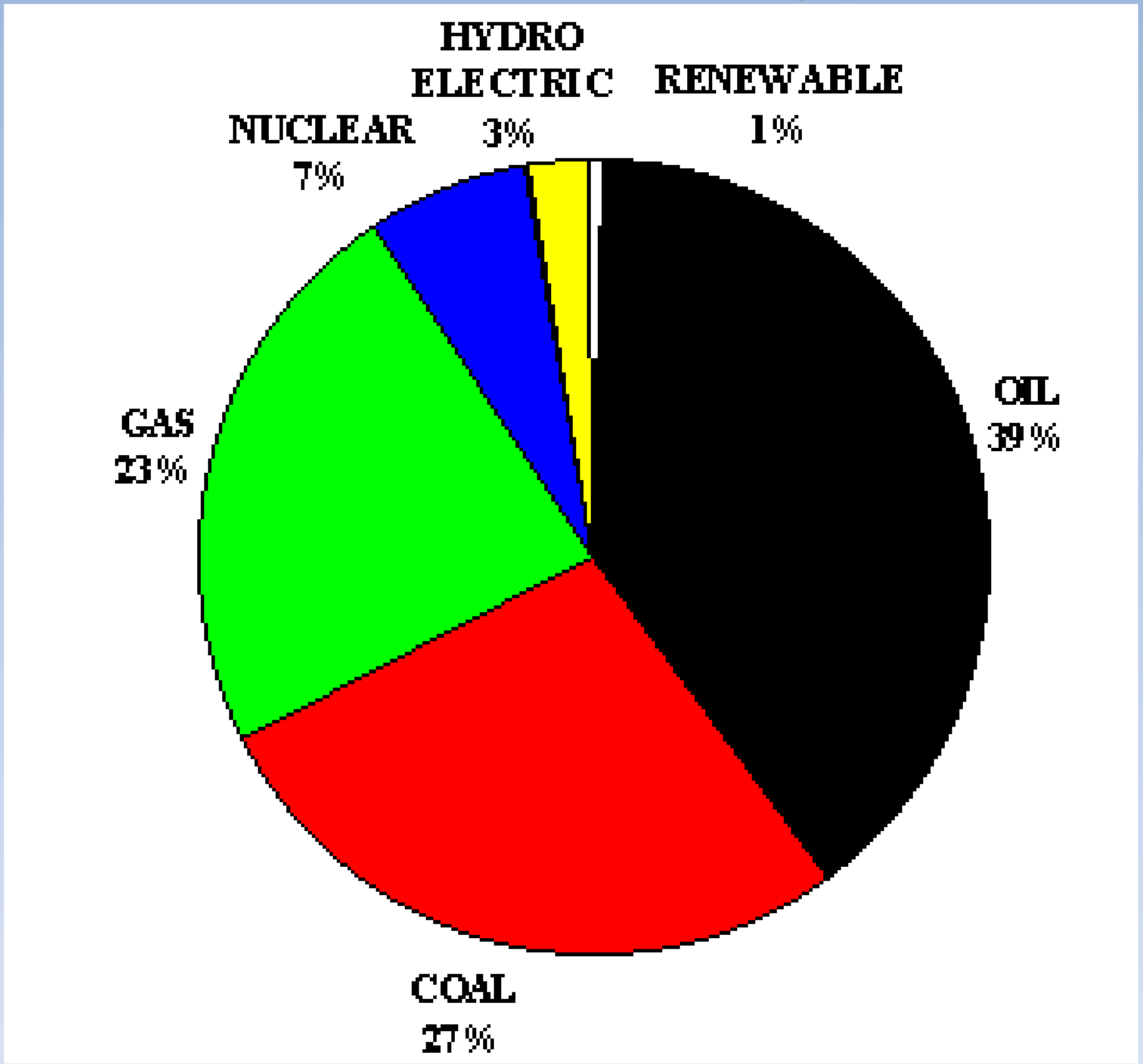
Some Compiled by Phil Nelson, 2017

Earth

Human Population = 7.3 B
Annual Electricity Demand = 23,300 TWh
Annual CO2 Emissions = 32.2 Gt
Fraction of GHG Emissions from Energy Use ≈ 68%

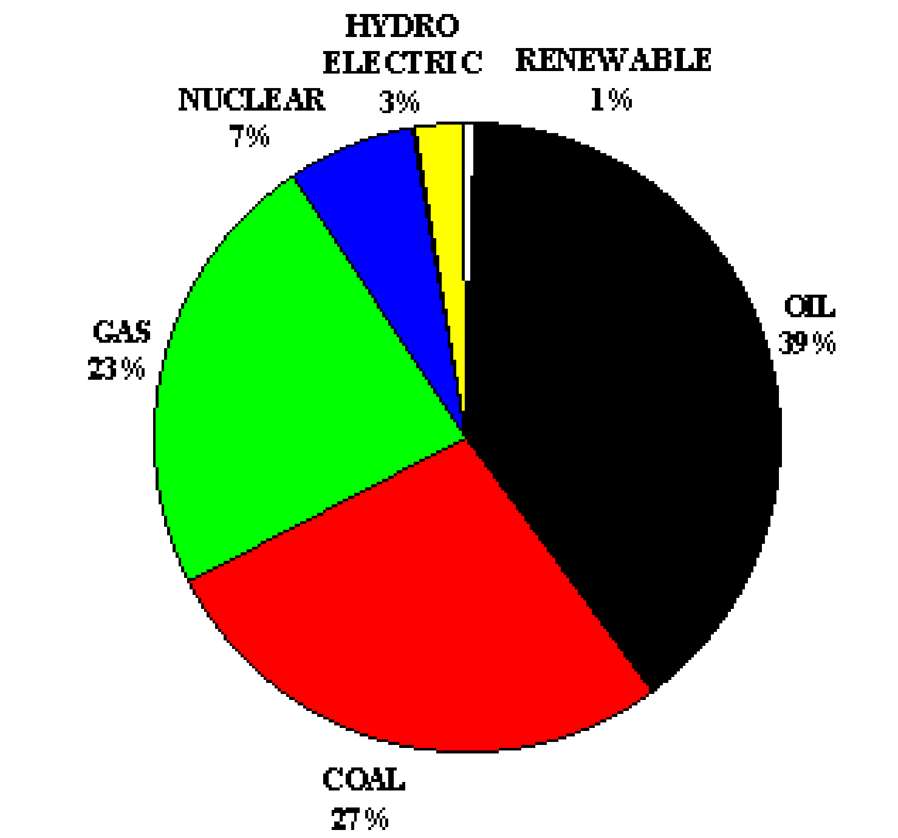
Gt C = Gt CO2/3.67
(mass 44/mass 12 C)
32.7/3.67 = 8.91 Gt C

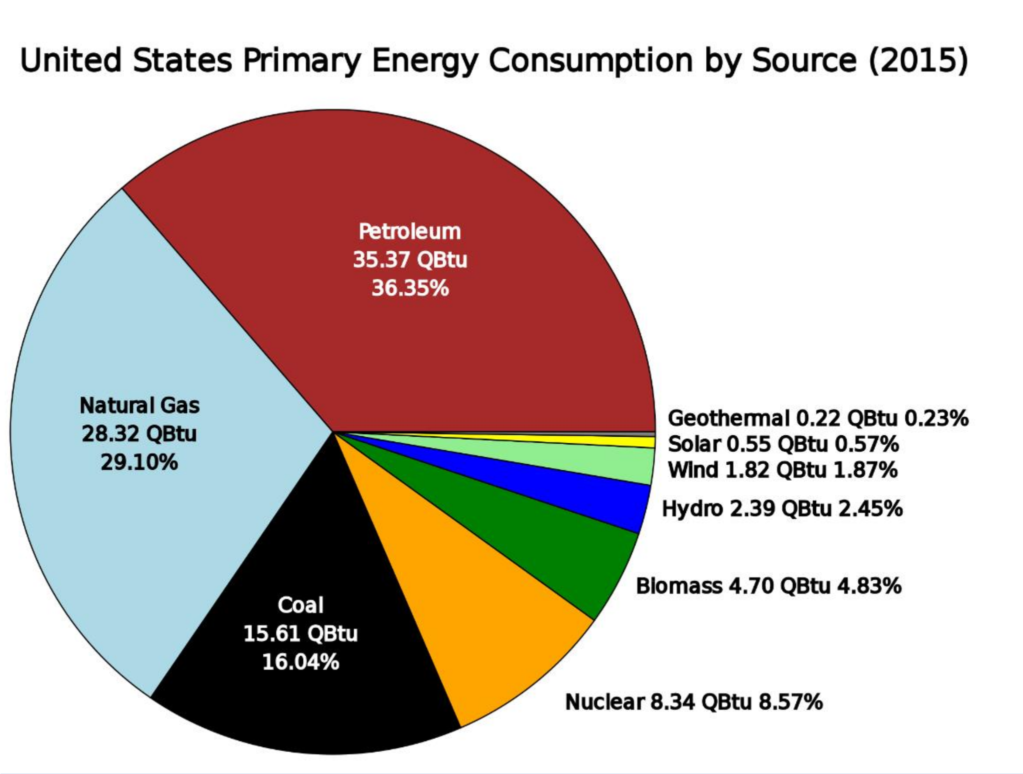
Total Worldwide Energy Production



http://www.worldfuturefund.org/wffmaster/Charts-HTML/Energy/wff-energy.htm

Total Worldwide vs. U.S. Energy Production

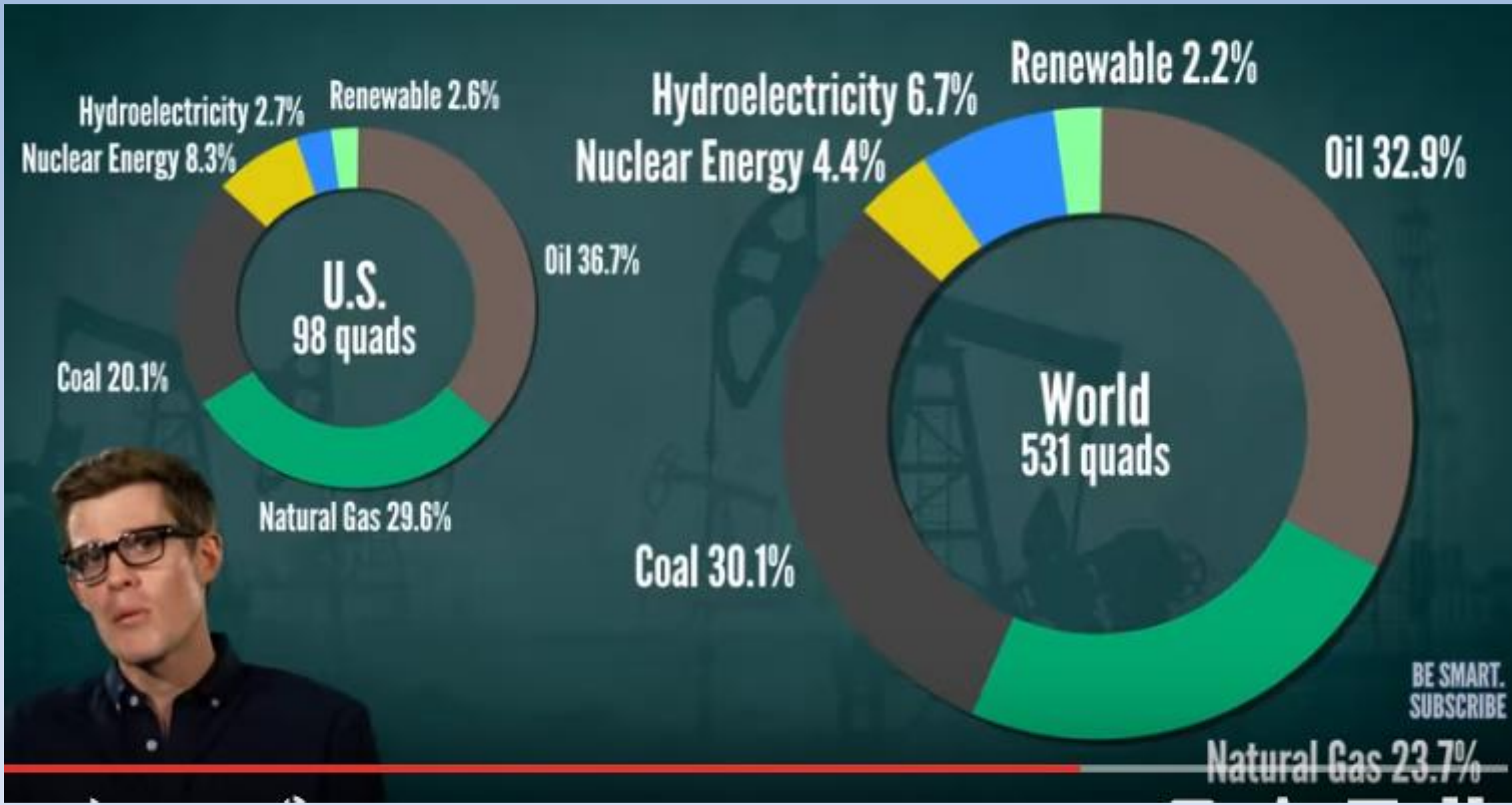




http://www.worldfuturefund.org/wffmaster/Charts-HTML/Energy/wff-energy.htm

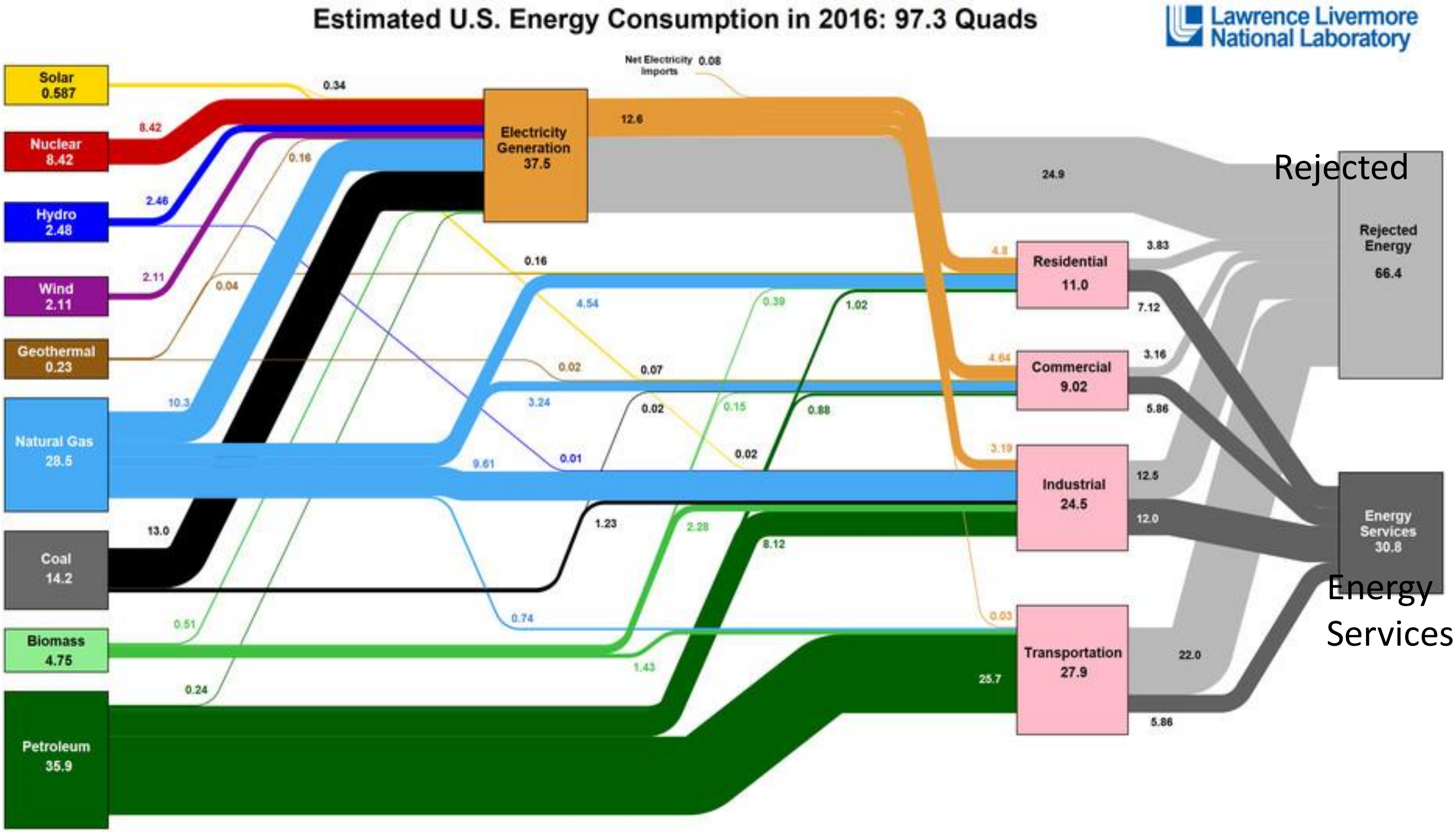
https://en.wikipedia.org/wiki/Energy_policy_of_the_United_States

U.S. Use Matches World in Proportion



Energy in the U.S. in 2016 – Sources, What it is used for, and how much of it is wasted – a bit of a mind-blower Vox.com April 2017

Estimated U.S. Energy Consumption in 2016: 97.3 Quads



Source: LLNL March, 2017. Data is based on DOE/EIA MER (2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Concentrated Solar Power – (CSP)

NREL's PV Research Portfolio

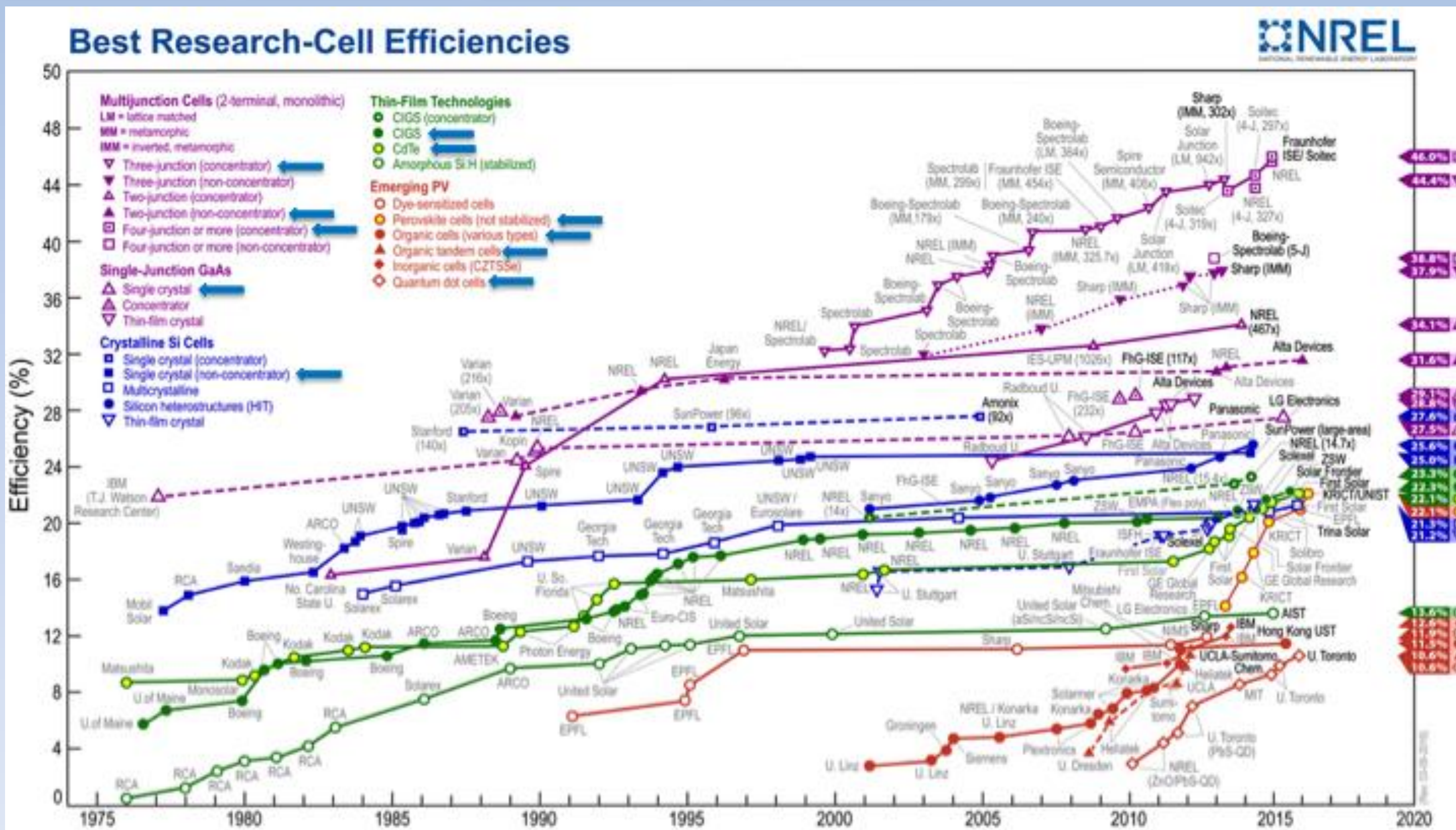
PV Research at NREL

PV Technologies

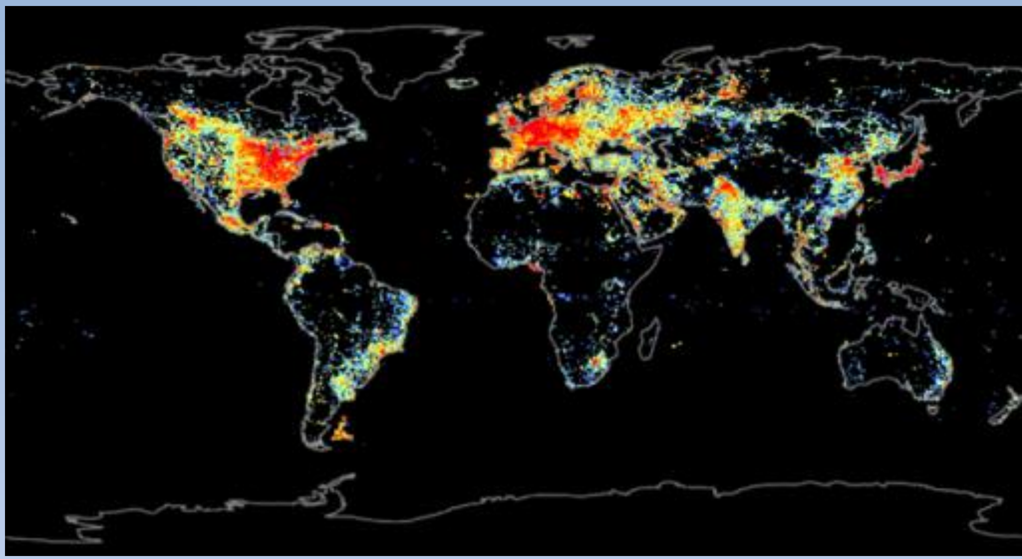
- **Thin Film PV** — CIGS / CdTe / Novel
- **III-V** — MJ & 1J
- **Silicon** — cSi 1J & Tandems
- **Perovskites** & OPV

PV Cross-Cutting R&D

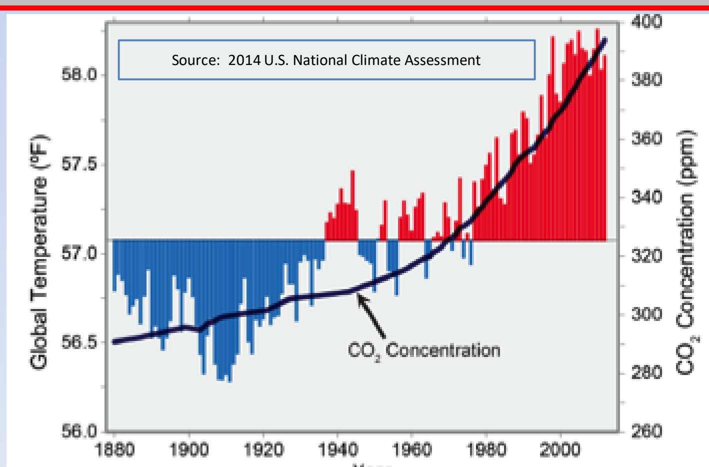
- **Measurements & Characterization**
- **Module Reliability & Systems Engineering**

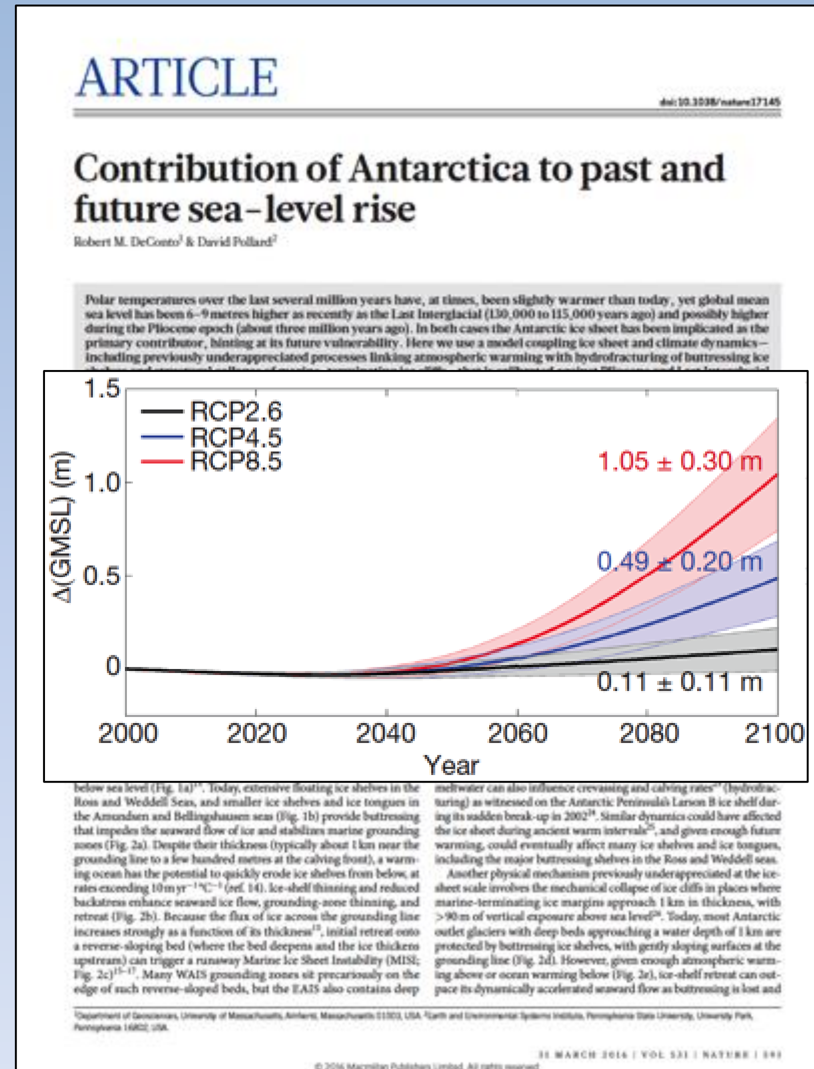


Motivation is Clear – Energy Needs vs. CO_2



- **Humanity requires ~6 TW of electrical generating capacity, ~2/3 from fossil fuels.**
- **$[CO_2]$ ~402 ppm and rising.**

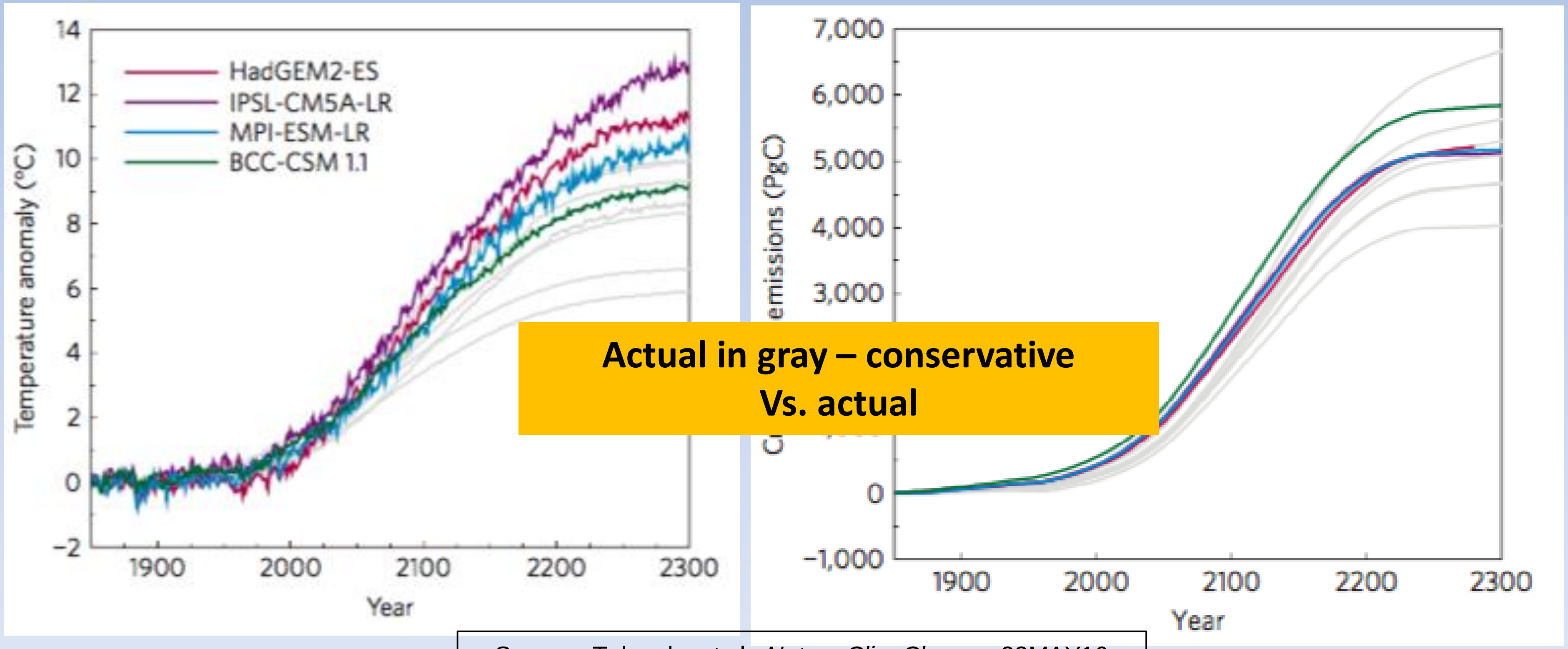




Nature - 31 March, 2016

Latest Earth System Model Results

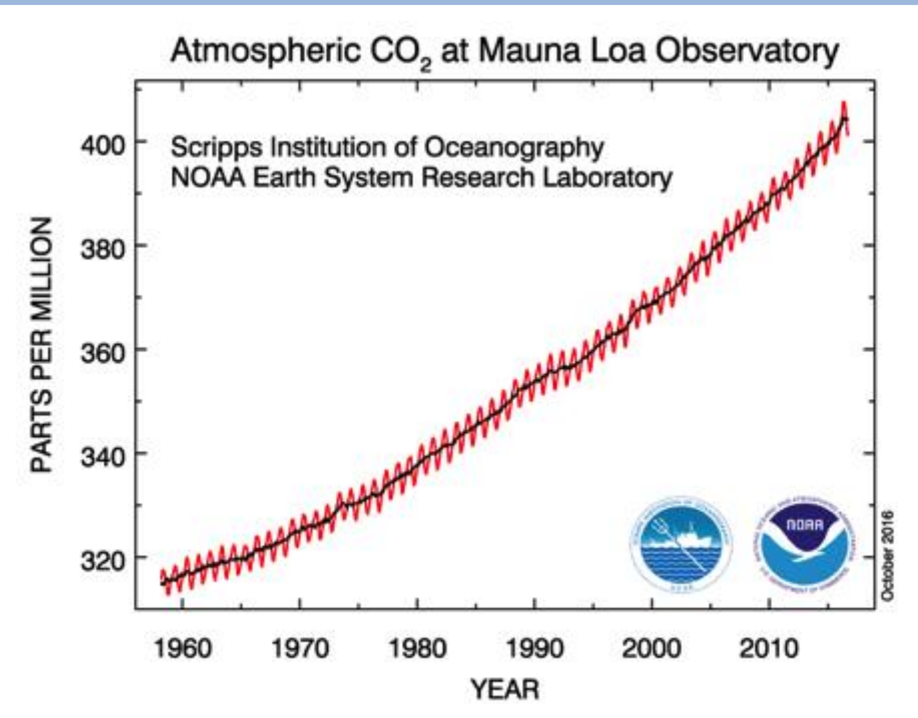
- Predicted global average surface temperature has gone up, not down, with increasingly sophisticated earth system models.
- Warming and CO2 emissions are in fact roughly linear.
- Burning all of earth's fossil fuel resources, projected by ~2200 given current trends, would result in global average warming of 6.4–9.5° C, **mean Arctic warming of 14.7–19.5° C.**

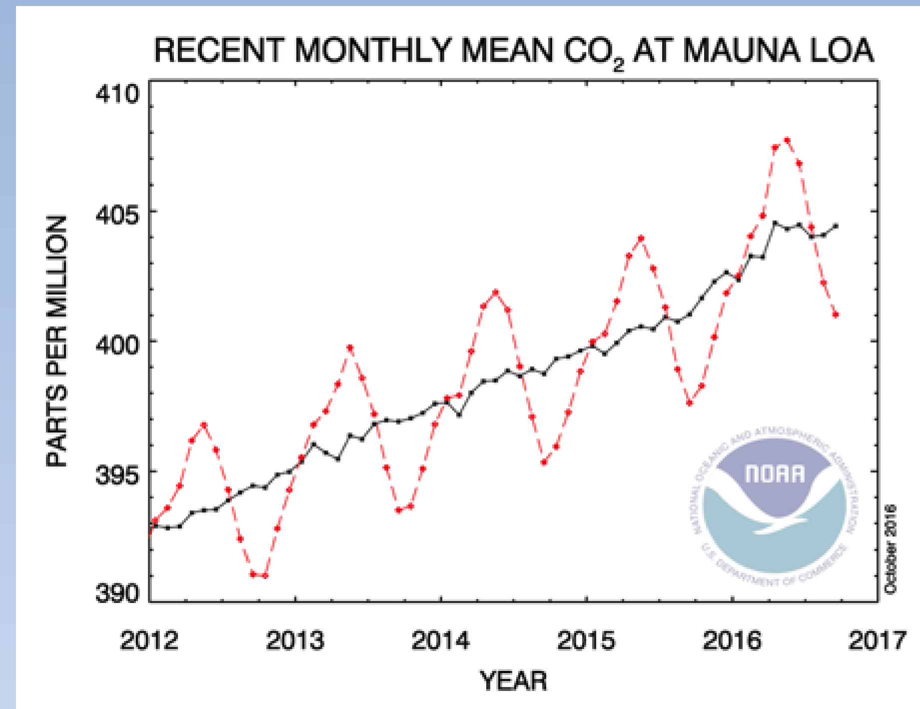


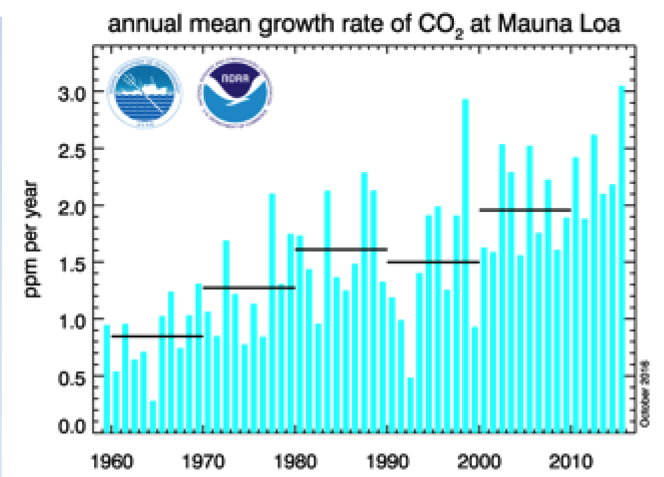
Actual in gray – conservative
Vs. actual

Source: Tokarska et al., *Nature Clim Change*, 23MAY16

450ppm Goal: Dramatic Change Needed

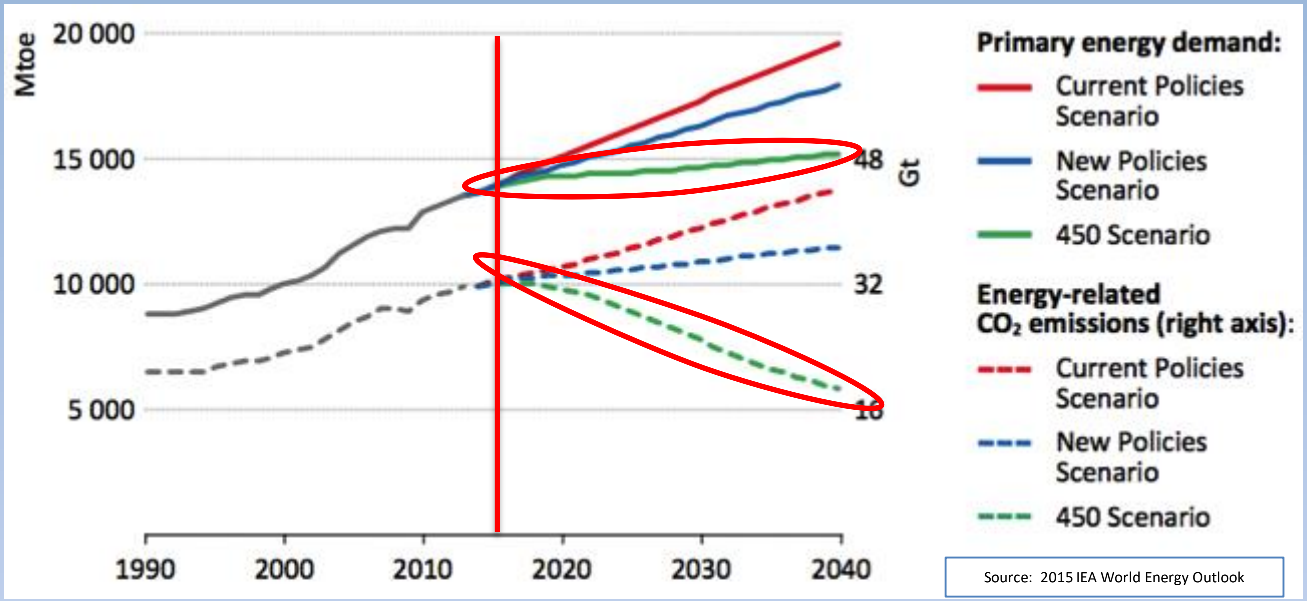






- Average rate of CO_2 increase for last decade was 2 ppm/year.
- Average global CO_2 concentration is now approaching 402 ppm so even with last decade's rate of increase, we'll hit 450 ppm by 2040!

450ppm Goal: Dramatic Change Needed

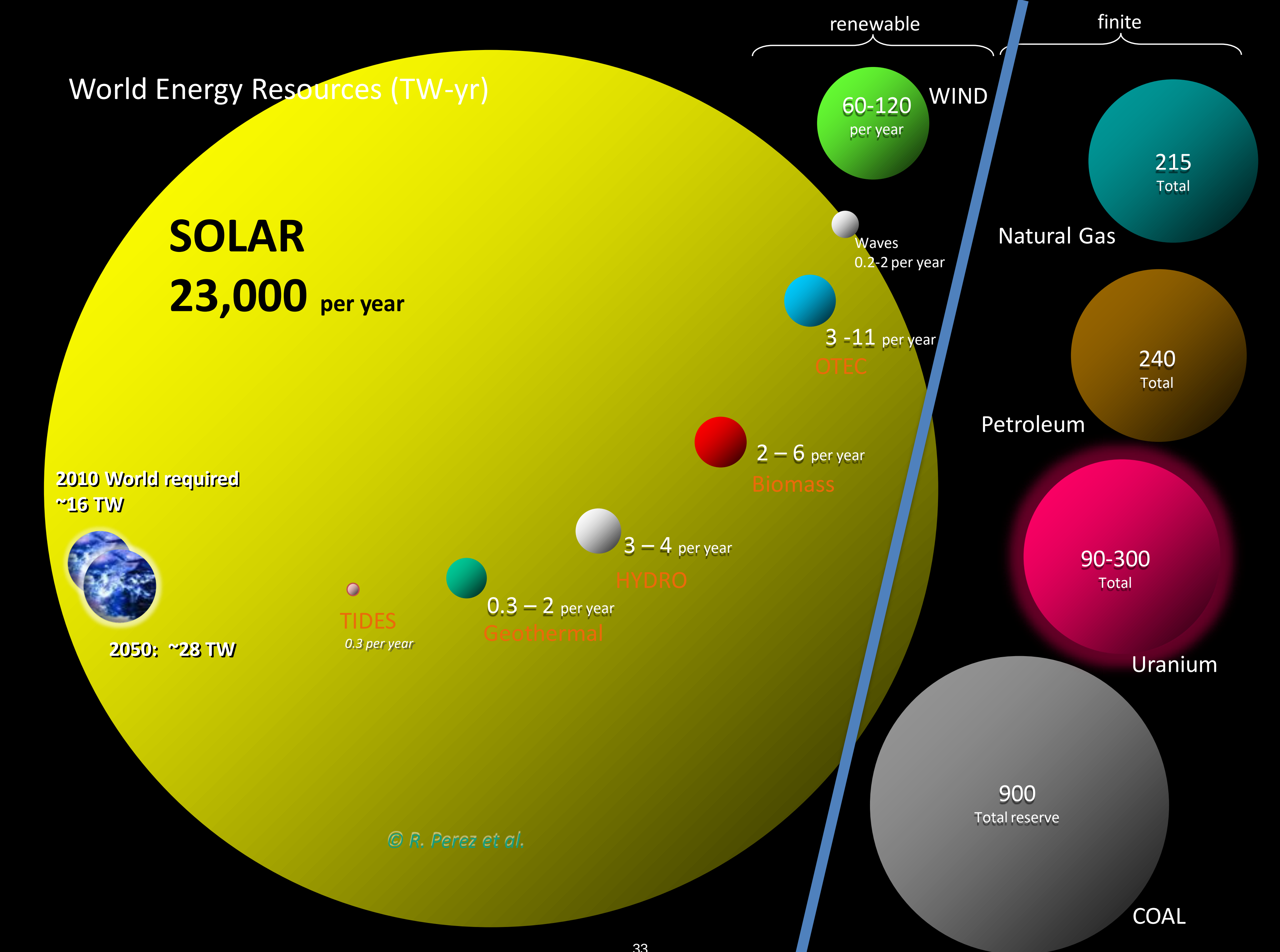


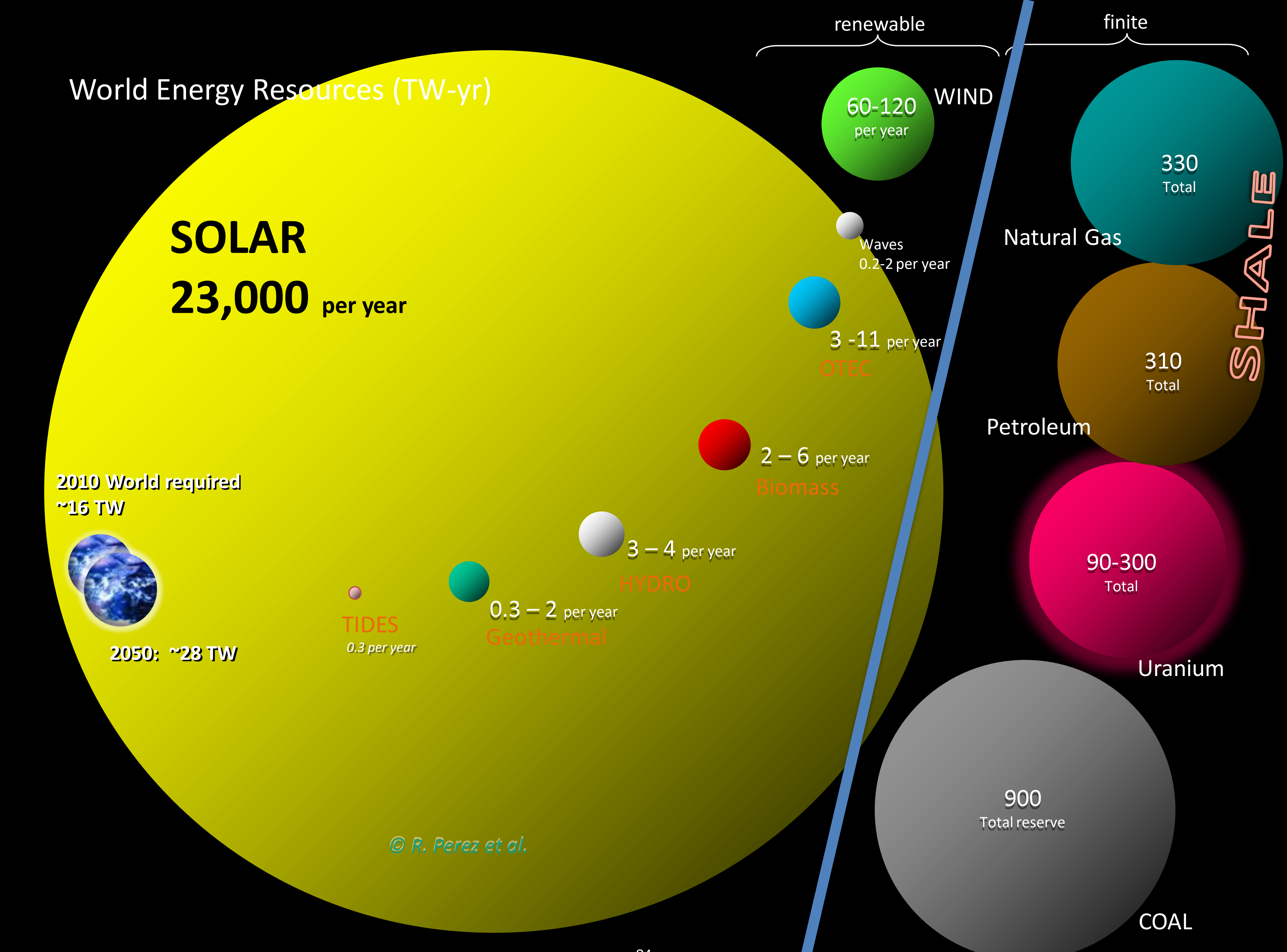
- Must hold overall energy consumption essentially flat for the next 25 years through major gains in energy efficiency.
- Must begin a major shift to zero carbon generation immediately, with measurable reductions by 2020.




HOW IS THE WORLD RESPONDING?

<u>THE WORLDWIDE ENERGY REVOLUTION!</u>


World Energy Resources (TW-yr)
renewable
finite
SOLAR
23,000 per year
60-120 per year
WIND
Waves
0.2-2 per year
3 -11 per year
OTEC
2 – 6 per year
Biomass
3 – 4 per year
HYDRO
0.3 – 2 per year
Geothermal
TIDES
0.3 per year
2010 World required
~16 TW
2050: ~28 TW
215
Total
Natural Gas
240
Total
Petroleum
90-300
Total
Uranium
900
Total reserve
COAL
© R. Perez et al.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HYDRO
2 – 6 per year
Biomass
3 -11 per year
OTEC
Waves
0.2-2 per year
60-120
per year
WIND
330
Total
Natural Gas
310
Total
Petroleum
SHALE
90-300
Total
Uranium
900
Total reserve
COAL
© R. Perez et al.

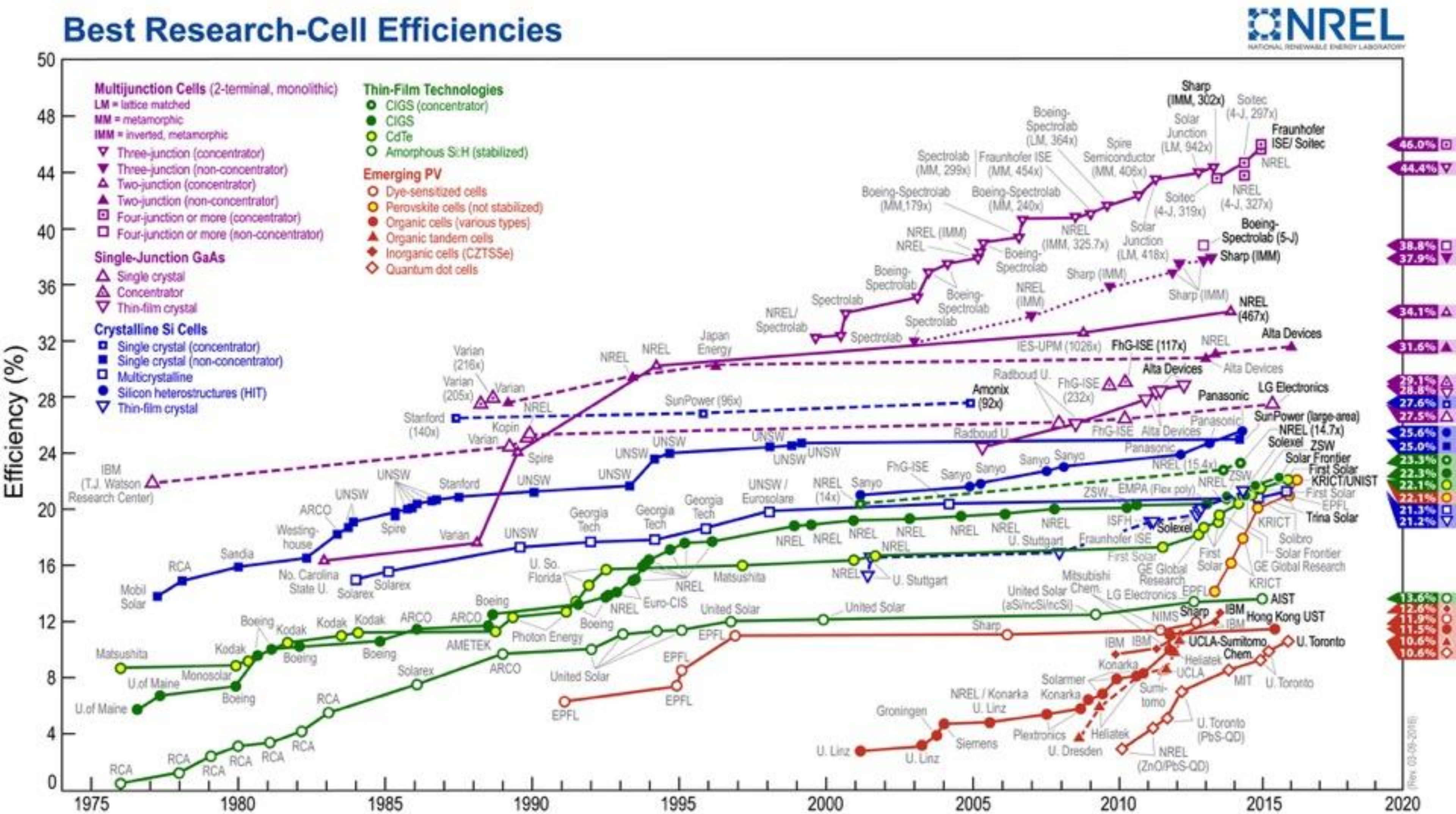
HOW IS THE WORLD RESPONDING?

<u>THE WORLDWIDE ENERGY REVOLUTION!</u>

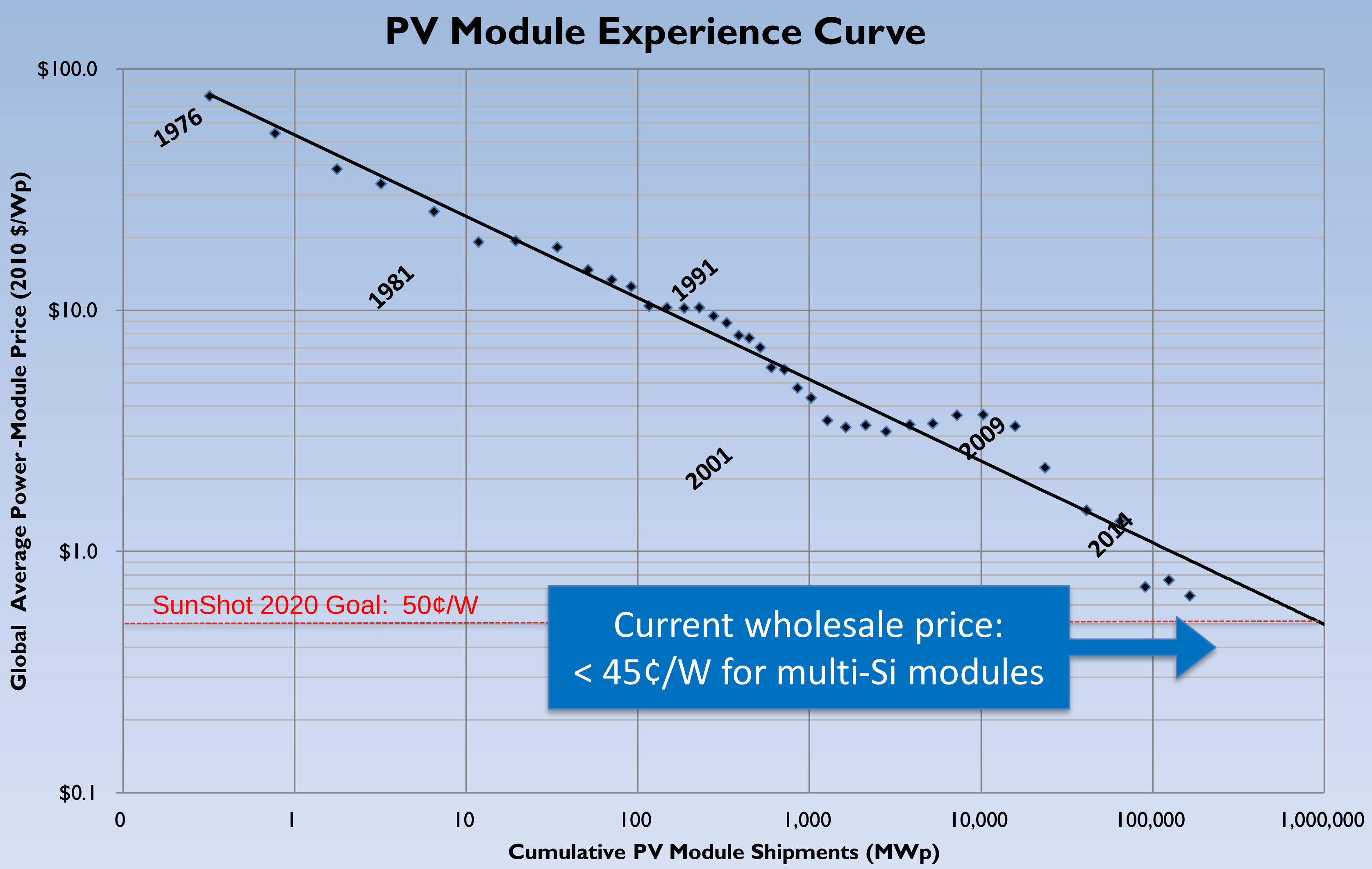
Overview

1. Brief introduction of NREL, the MCST Directorate and NREL's PV Program.
2. Energy and climate change.
3. Cell efficiency and module cost - 39 years of progress.
4. Enabling PV as a global carbon emissions reduction tool.
5. 10TW by 2030.

PV Research – Dramatic Progress

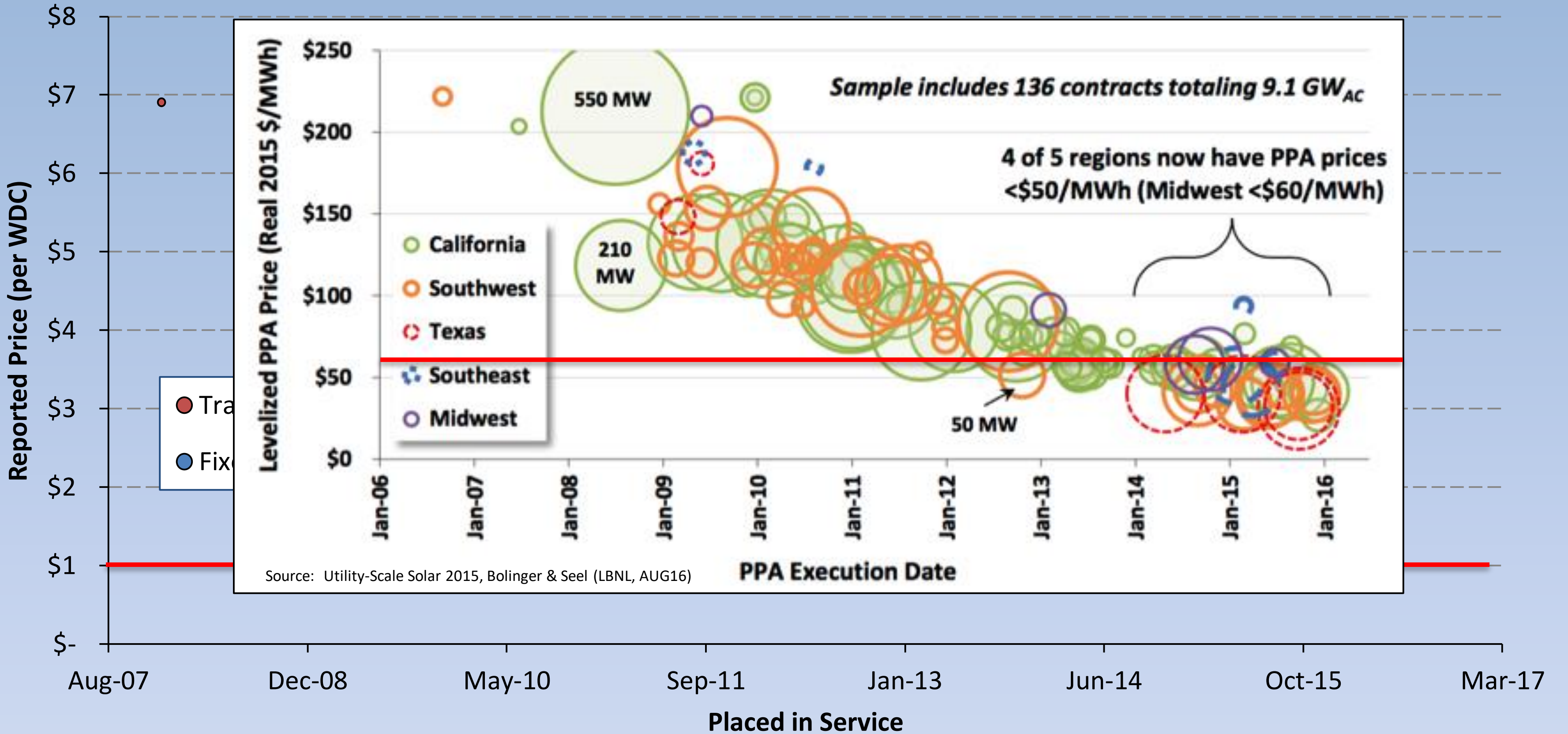


Silicon PV Module Cost Decline



Sources: Strategies Unlimited, Navigant Consulting & Paula Mints

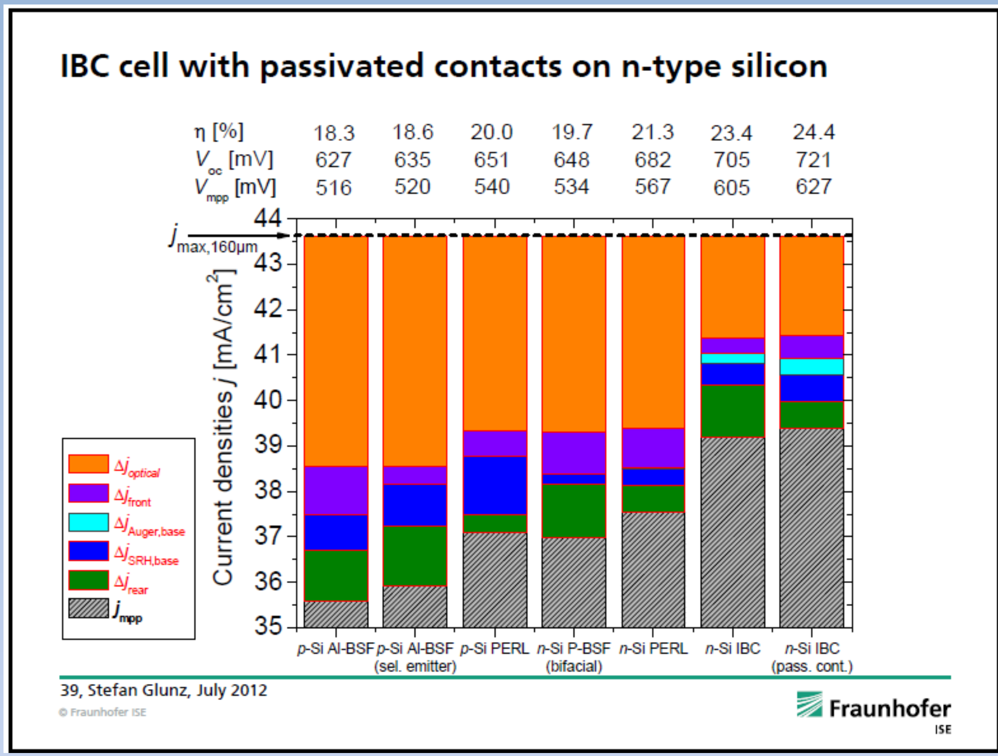
US System Pricing – Utility Scale >5 MW



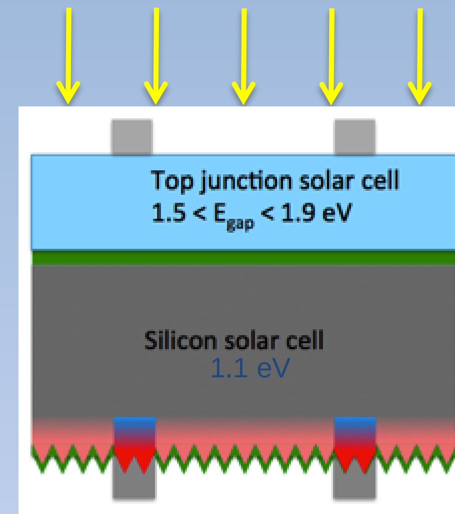
- PV system costs at all scales declining rapidly.
- SunShot goal of $1/W corresponds to LCOE of 6 ¢/kWh.

Original Source: NREL 3Q15 Solar Update, Feldman et al., 19JAN16

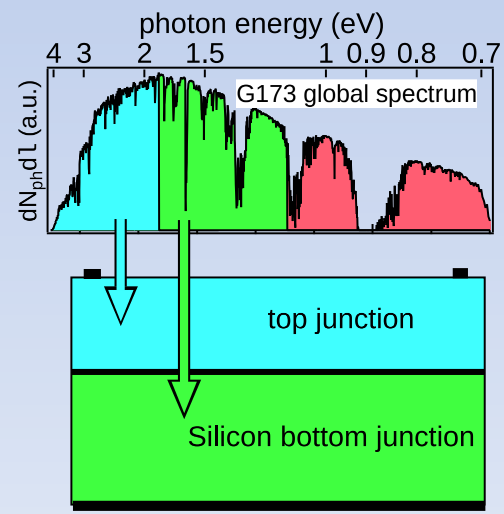
Si Tandem Cells



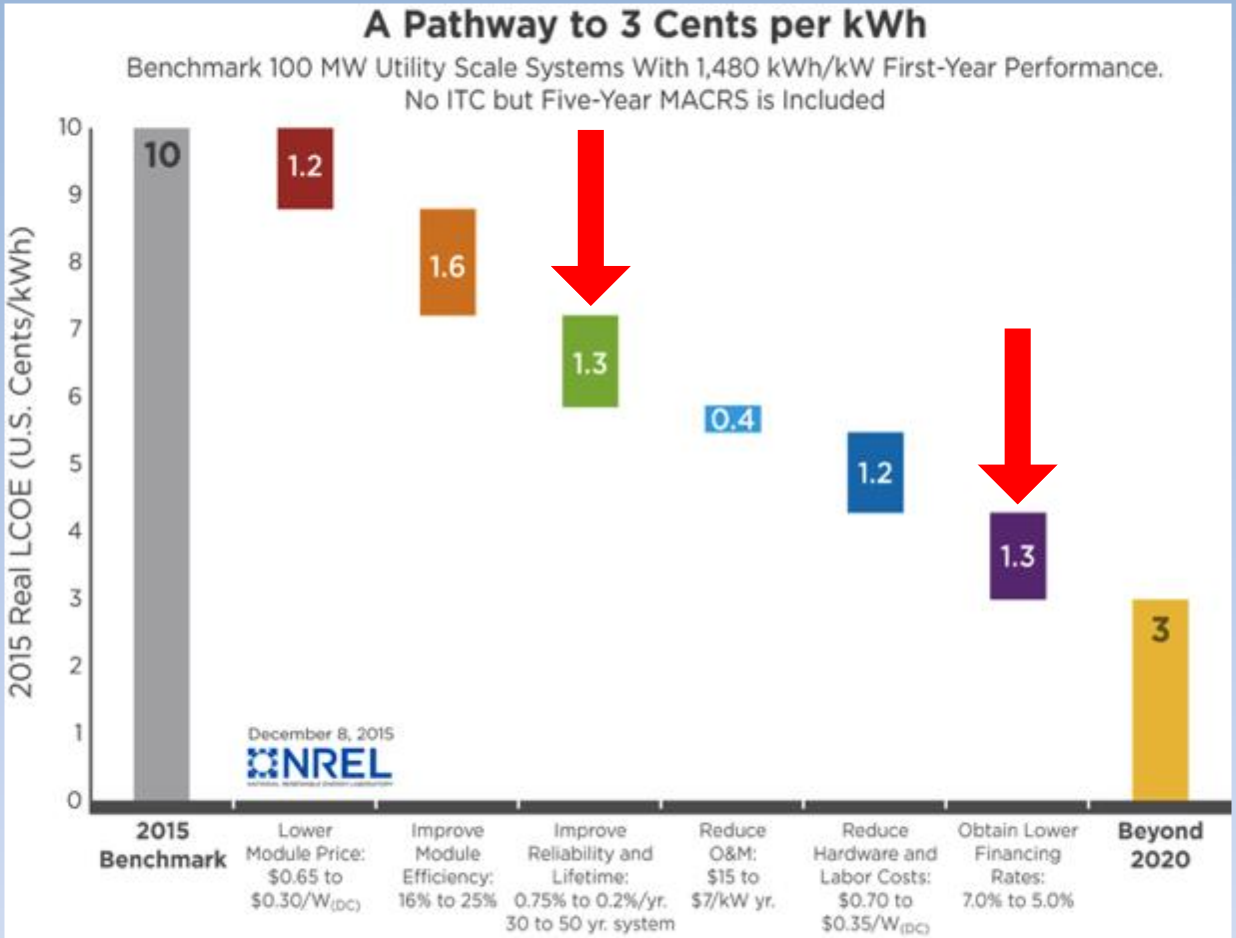
Source: Stefan Glunz presentation, NREL Si Workshop in Vail, CO, July, 2012



- Path to > 30% efficiency for Si wafer based cells.
- Top cell requirements:
  - Lattice & CTE match to Si if epitaxially grown
  - ~1.7 eV band gap
- Perovskites may evolve into good polycrystalline choice.

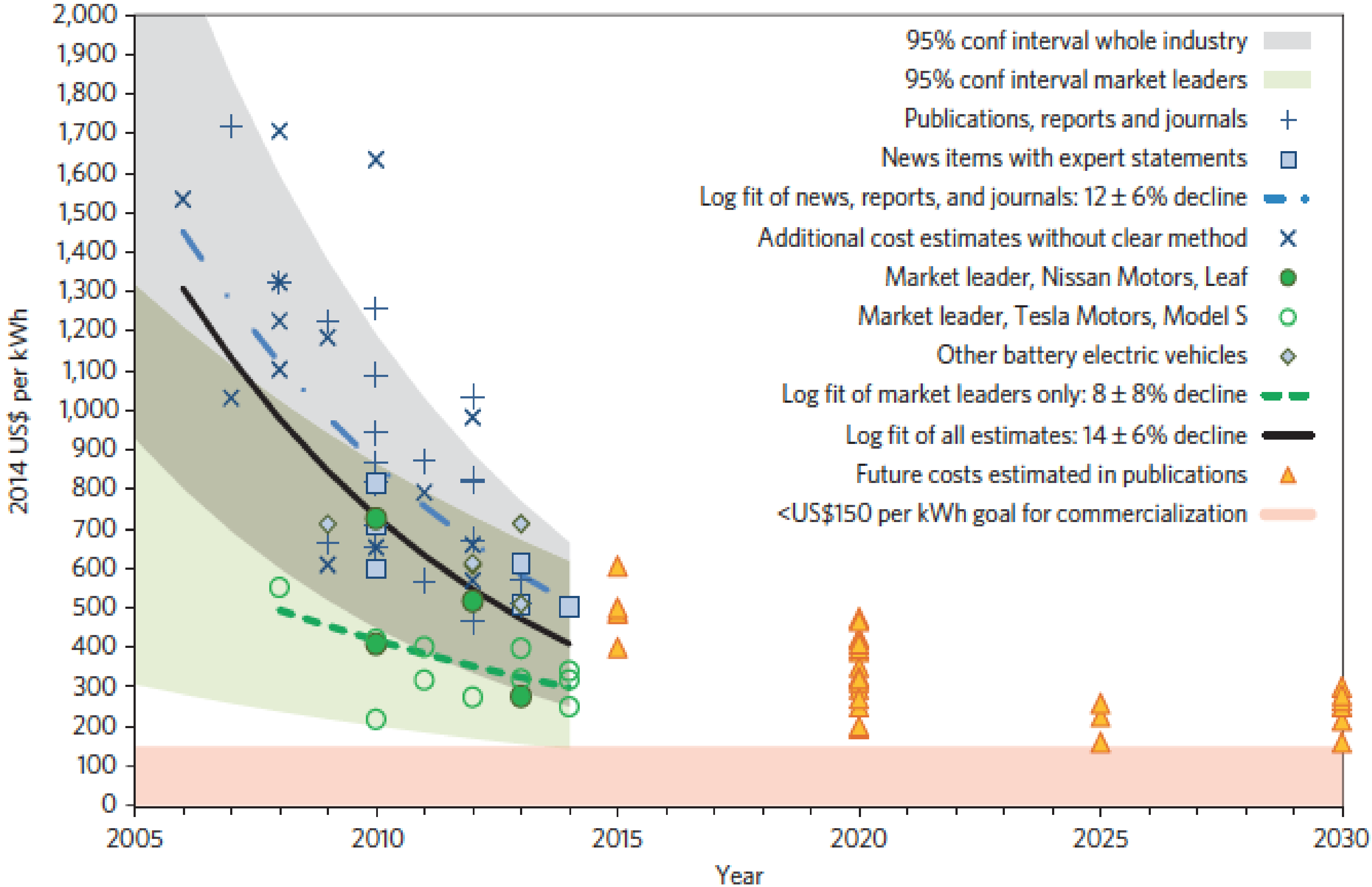


Example – Path to 3¢/kWh LCOE Target



Module cost, efficiency and **reliability** will be the focus of major new R&D efforts.

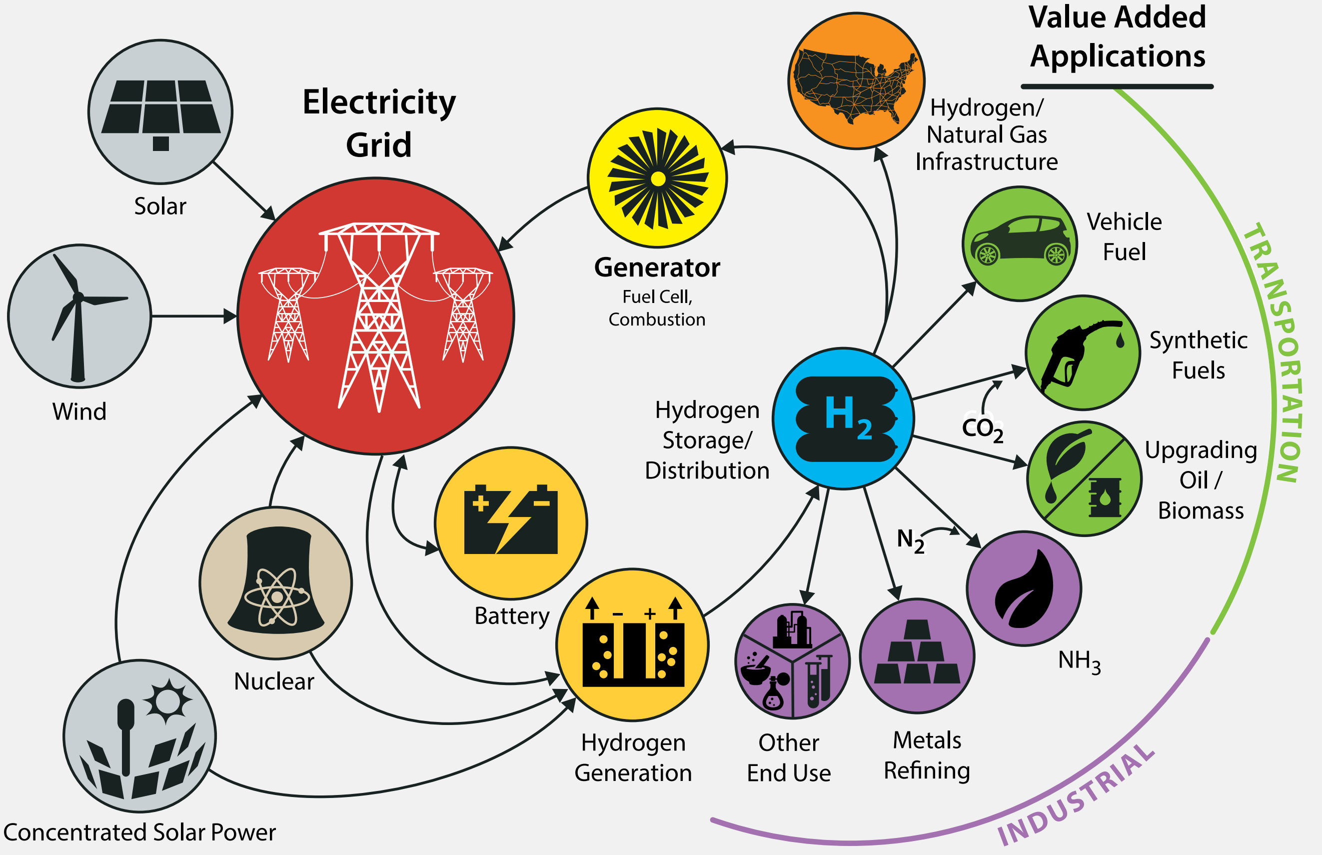
Li Ion Batteries - Cost Declines



Source: Nykvist & Nilsson, *Nature Climate Change*, 23MAR15

Future Energy System – Commodity H_2

Future H_2 at Scale Energy System



WHY HYDROGEN?

- Hydrogen is an ideal clean energy carrier—connecting diverse energy sources to diverse applications
- It can play a unique and critical role in addressing many of the energy sector's greatest challenges

TODAY'S ENERGY SYSTEM

- Renewable energy—particularly wind and solar—offer great promise but have challenges associated with variable and concurrent generation
- Options to achieve deep decarbonization while meeting society's multi-sector energy demands are limited, particularly in the industrial and transportation sectors

FUTURE H_2 AT SCALE ENERGY SYSTEM

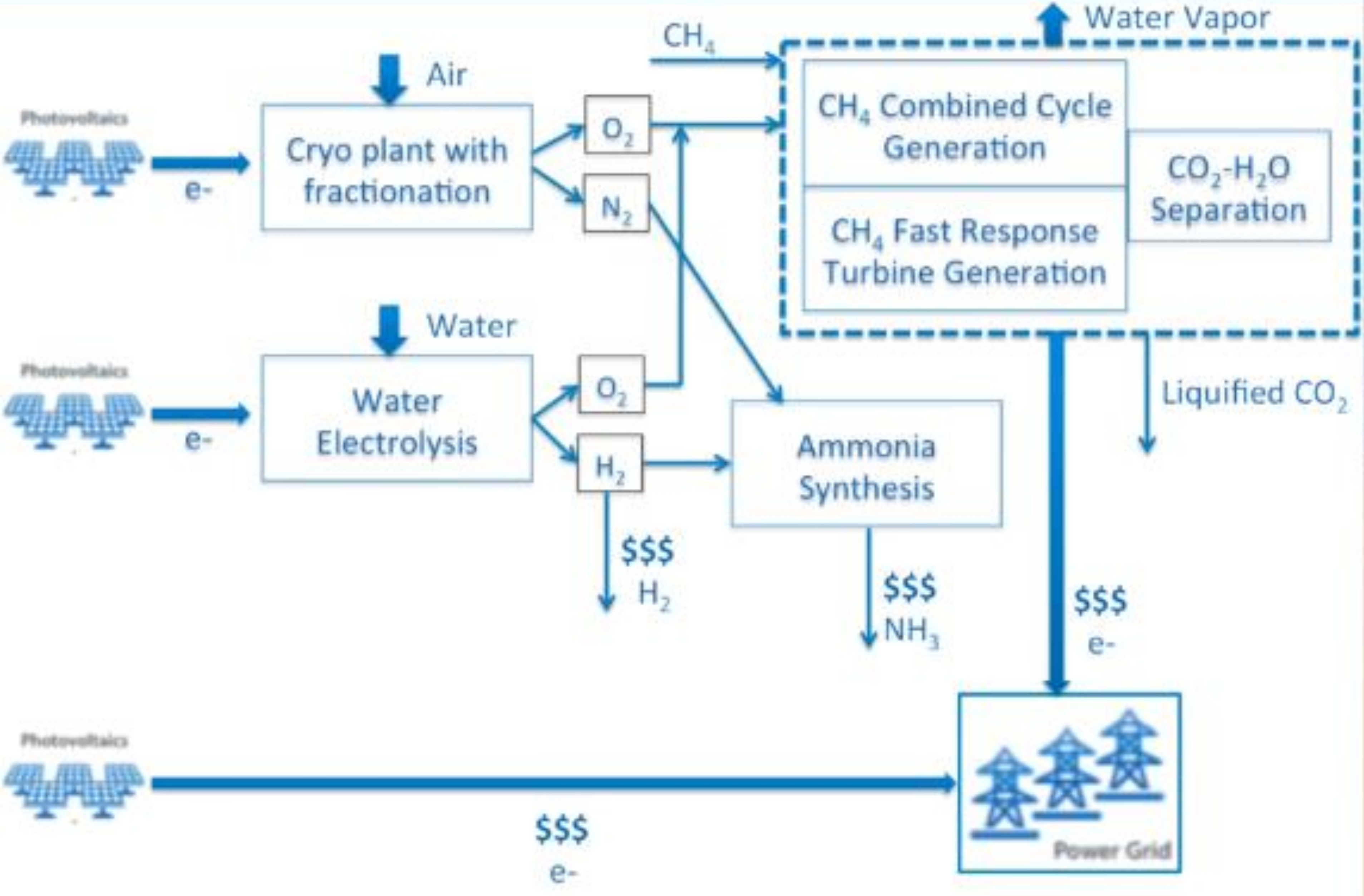
- Connects low-carbon energy sources to all of the energy sectors
- Uses carbon-free, renewable inputs to service all of society's energy needs, in particular the difficult to decarbonize sectors of industry and transportation
- Does not compete with other options—rather, it enables increased renewable penetration
- Can decrease 45% of all U.S. carbon emissions by 2050

NREL NATIONAL RENEWABLE ENERGY LABORATORY | ENERGY SYSTEMS INTEGRATION FACILITY

U.S. DEPARTMENT OF ENERGY

The ESIF helps NREL contribute to the U.S. Department of Energy's and our nation's energy goals by providing the R&D capabilities needed to collaborate with private industry, academia, government, and public entities on utility-scale projects focused on solving issues in relation to grid integration of renewable energy and other efficiency technologies.

Hybrid Systems – CCS with PV and H2/NH3 Production



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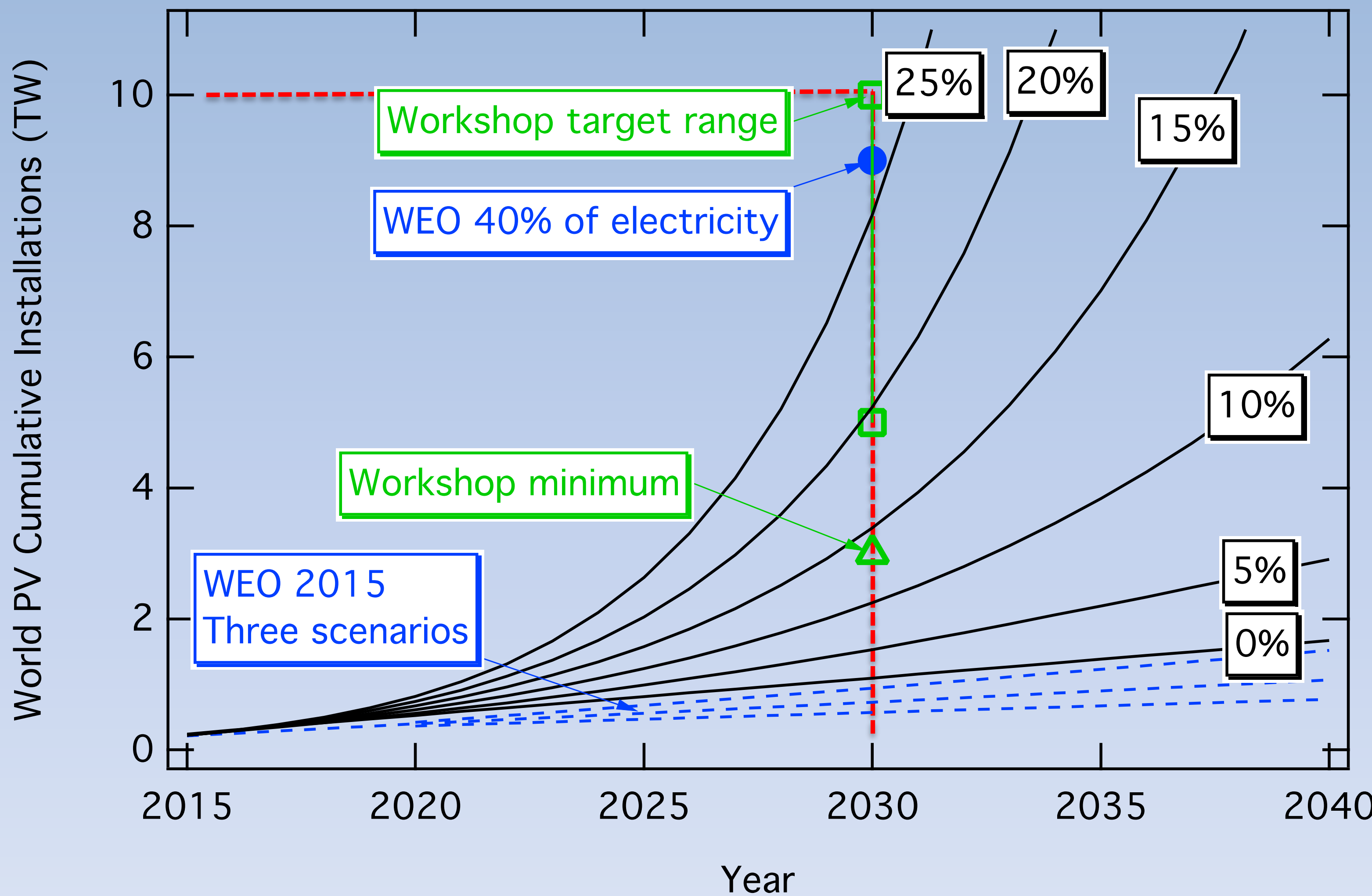
10TW by 2030



World PV Cumulative Installations (TW)
0
2
4
6
8
10
2015
2020
2025
2030
2035
2040
Year
25%
20%
15%
10%
5%
0%
Workshop target range
WEO 40% of electricity
Workshop minimum
WEO 2015
Three scenarios

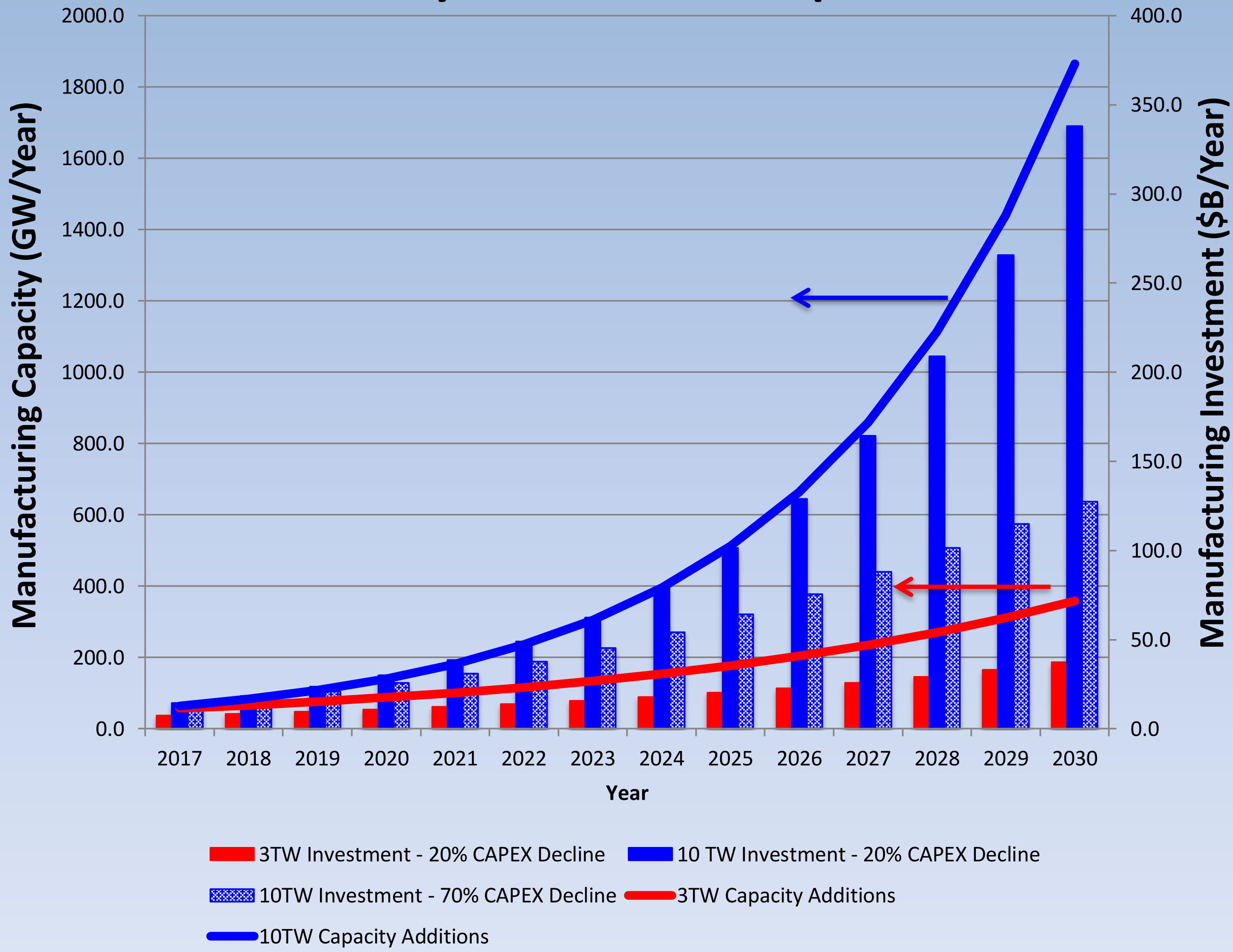
Pathway to 10TW of PV in 2030

Case (All Cases Based on 2015 WEO, "450 Scenario")	**PV Generating Capacity (TW)**	**PV Energy Produced (TWh)**	**Fraction of World Electricity Generation**
WEO Projection for PV in 2030	1.0	1,297	4%
PV at 15% of World Electricity in 2030	3.4	4,452	15%
PV at 20% of World Electricity in 2030	4.5	5,936	20%
10TW of PV in 2030	**10.0**	**13,179**	**44%**
PV at 50% of World Electricity in 2030	11.3	14,841	50%
PV at 15% of World Energy in 2030	14.9	19,575	66%
PV at 20% of World Energy in 2030	19.9	26,100	88%
PV at 30% of World Energy in 2030	29.8	39,150	132%

- 10TW of cumulative PV generating capacity by 2030 is needed to meet atmospheric CO2 targets.
- How will we get there?

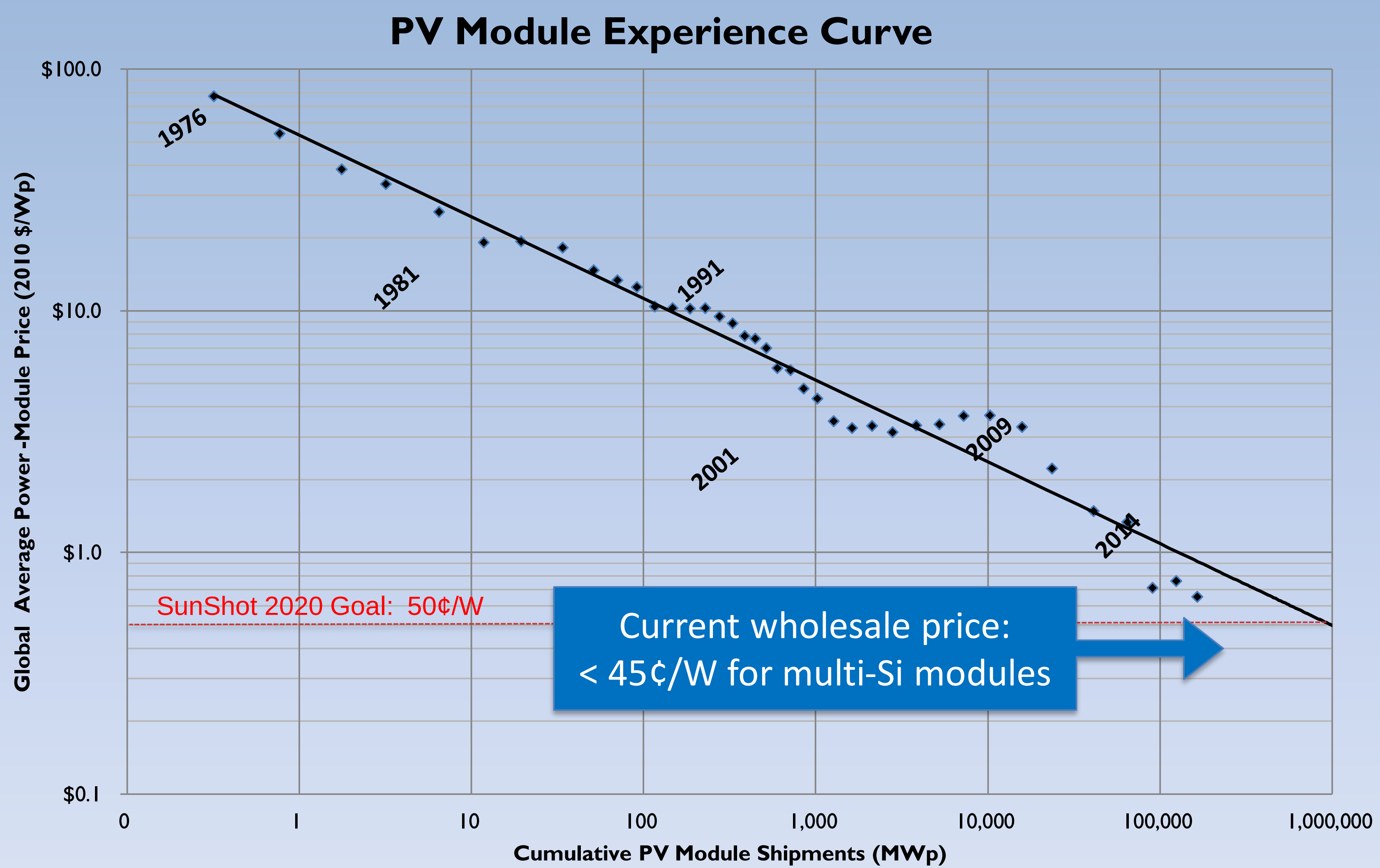
⇒Cheap PV generated electricity will create new demand.

10TW by 2030 – Capital Intensity Role

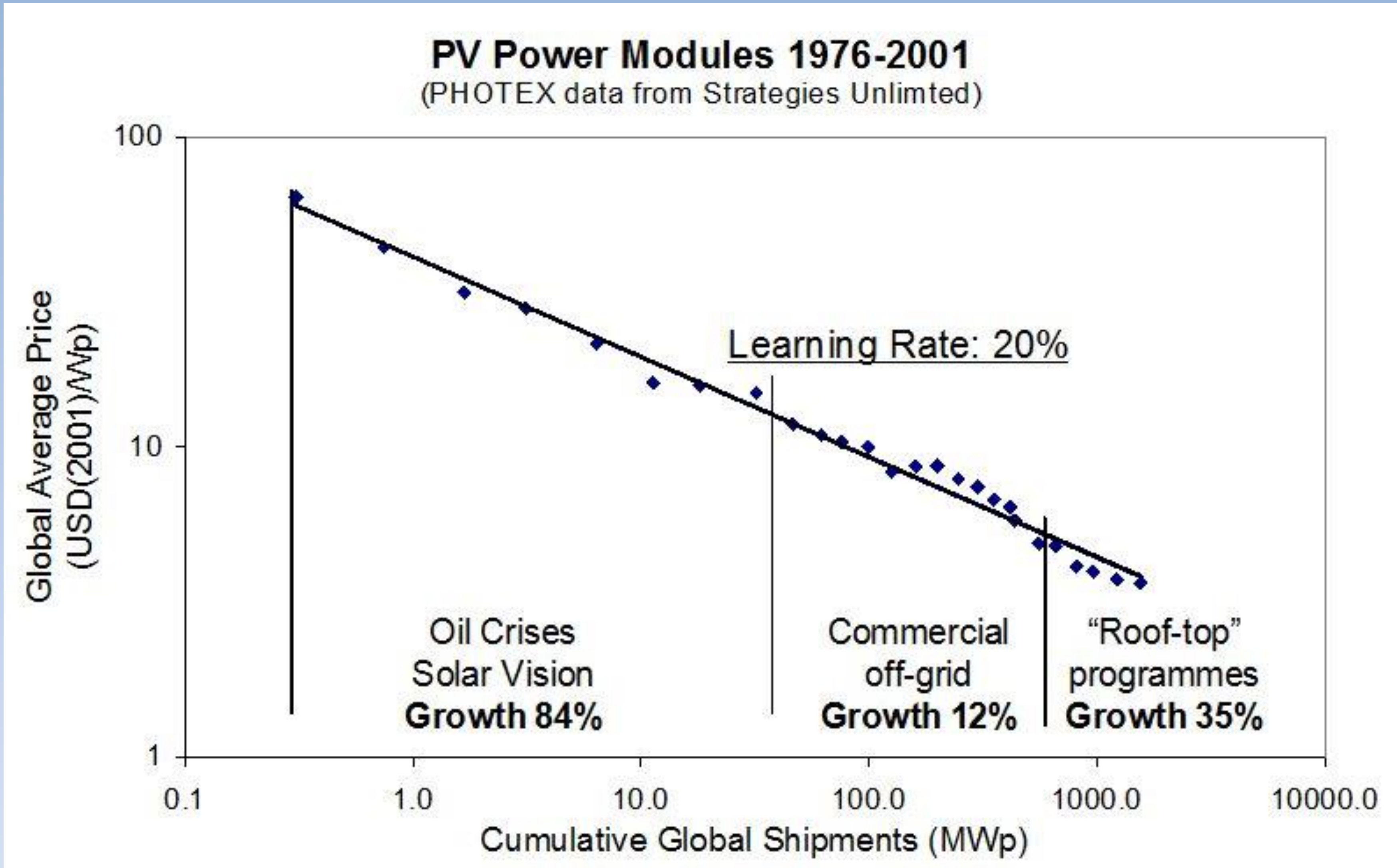


- Left axis shows annual production capacity required in GW/year.
- Right axis shows annual mfg. investments required in $B/year.
- Red line and bars shows the case for 3TW by 2030 assuming only a 20% decline in capital intensity.
- Blue line and bars shows the case for 10TW by 2030 comparing both a 20% and 70% decline in capital intensity.

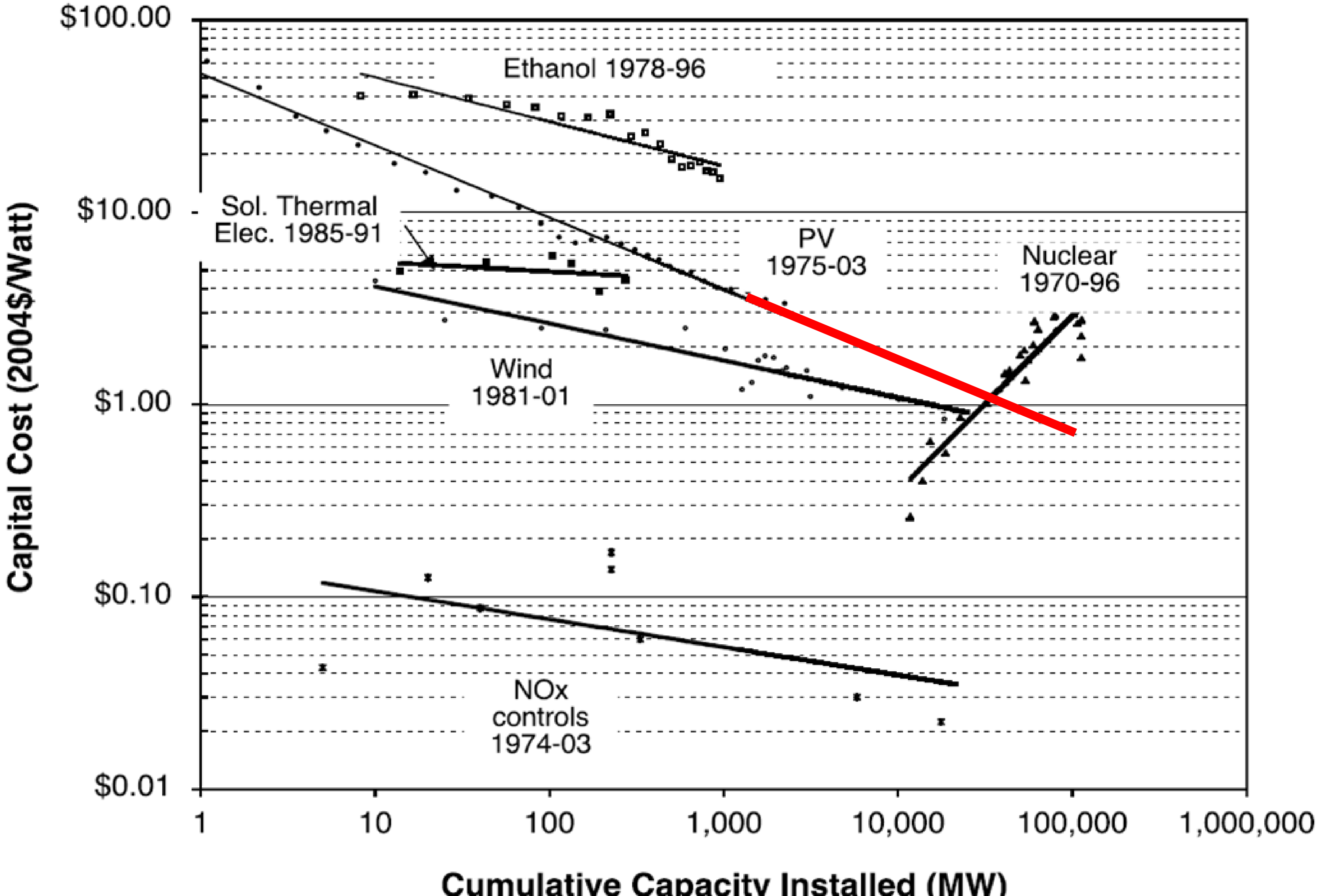
Silicon PV Module Cost Decline



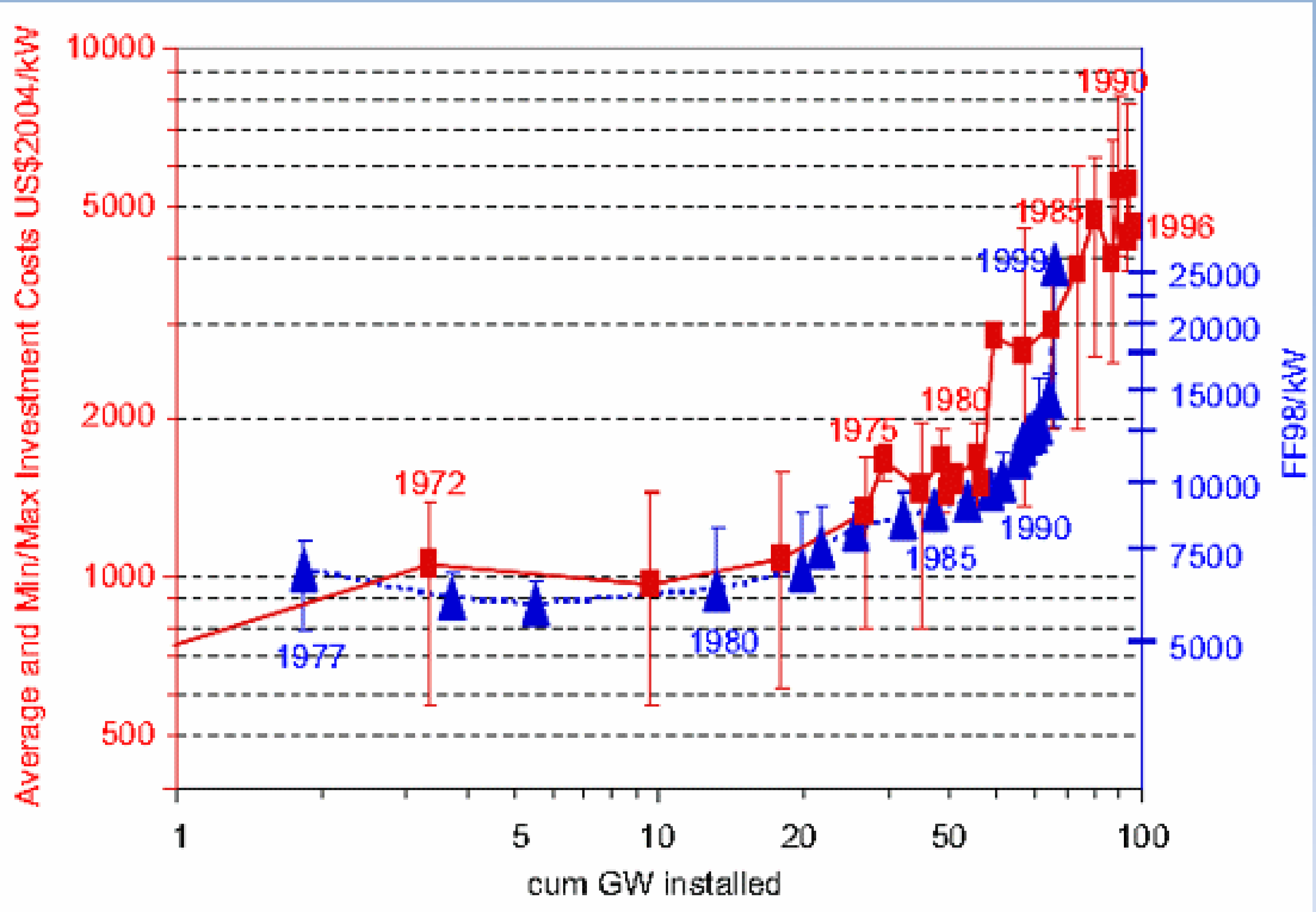
Sources: Strategies Unlimited, Navigant Consulting & Paula Mints



https://www.intechopen.com/books/climate-change-research-and-technology-for-adaptation-and-mitigation/energy-technology-learning-key-to-transform-into-a-low-carbon-society



https://carbonremoval.files.wordpress.com/2014/12/energy-learning-curves.png



https://thinkprogress.org/does-nuclear-power-have-a-negative-learning-curve-b389ef2de998

PV

Solar Energy

Golmud Solar Park, Western China – 200 MW

PV Markets – Residential

PV Markets – Commercial

Credit: IKEA

PV Markets – Utility

PV Markets – Utility

Solar Star

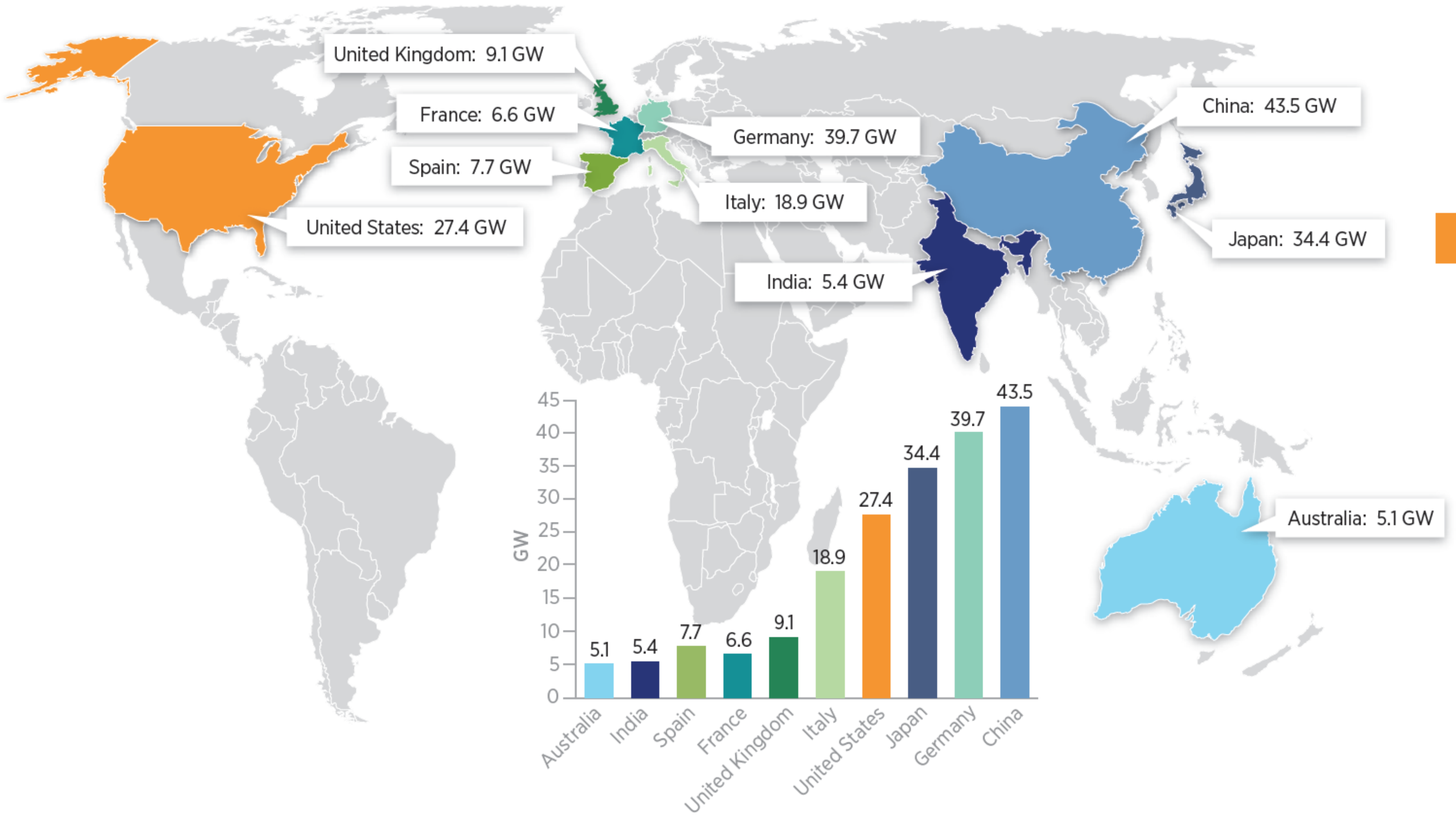
- BHE Renewables
- 1.7 million SunPower c-Si panels
- 579 MWac
- Power for 255,000 homes
- 300,000 tons CO_2 displaced
- 5 square miles

PV Markets – Utility

Desert Sunlight Solar Farm

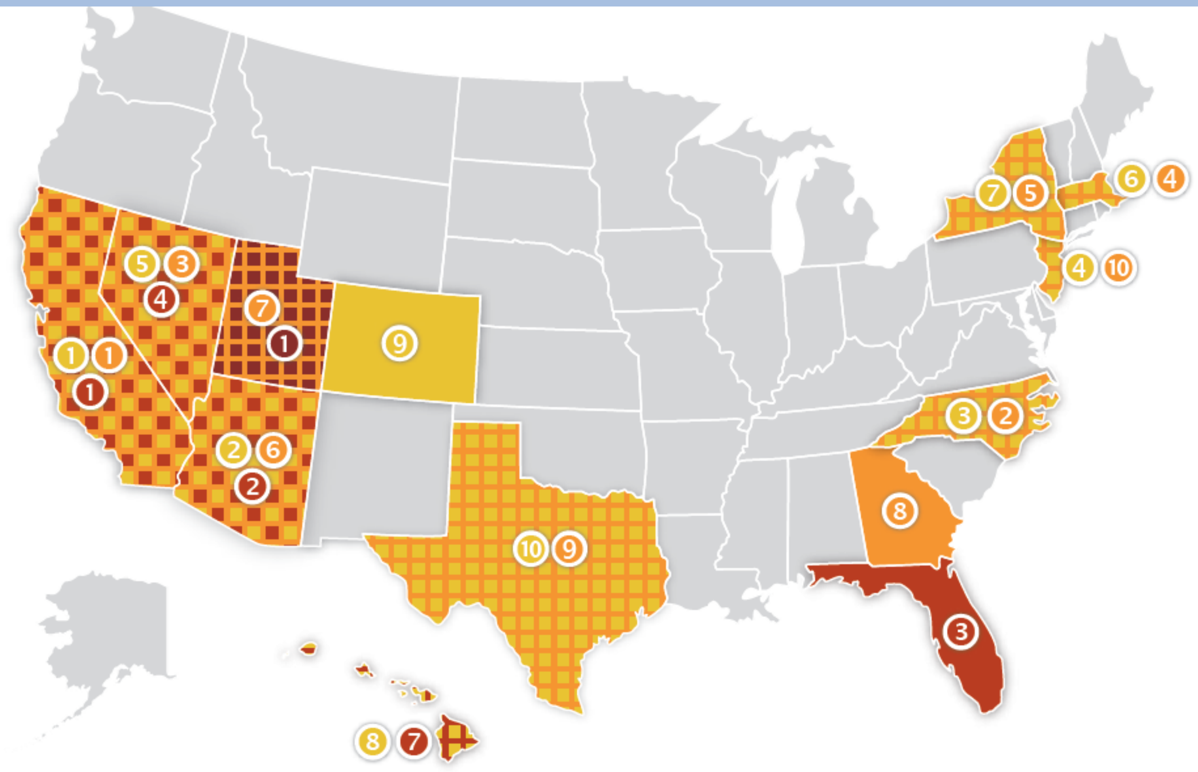
- NextEra Energy
- 8.8 million First Solar CdTe panels
- 550 MWac
- Power for 160,000 homes
- 300,000 tons CO_2 displaced
- 6.2 square miles

Global Solar Energy Markets - 2015



Sources: REN21, SEIA/GTM
Includes CSP and grid-connected PV; capacity is reported in MWac.

U.S. Solar Deployment



PV Cumulative Capacity[1] (MW)	
❶ California	11,987
❷ Arizona	2,020
❸ North Carolina	2,087
❹ New Jersey	1,632
❺ Nevada	1,042
❻ Massachusetts	1,037
❼ New York	638
❽ Hawaii	557
❾ Colorado	542
❿ Texas	537

PV Annual Capacity[1] Additions (MW)	
❶ California	3,266
❷ North Carolina	1,160
❸ Nevada	307
❹ Massachusetts	286
❺ New York	241
❻ Arizona	234
❼ Utah	231
❽ Georgia	209
❾ Texas	207
❿ New Jersey	181

CSP Cumulative Capacity[2] (MW)	
❶ California	1,256
❷ Arizona	283
❸ Florida	75
❹ Nevada	174
❼ Hawaii	7

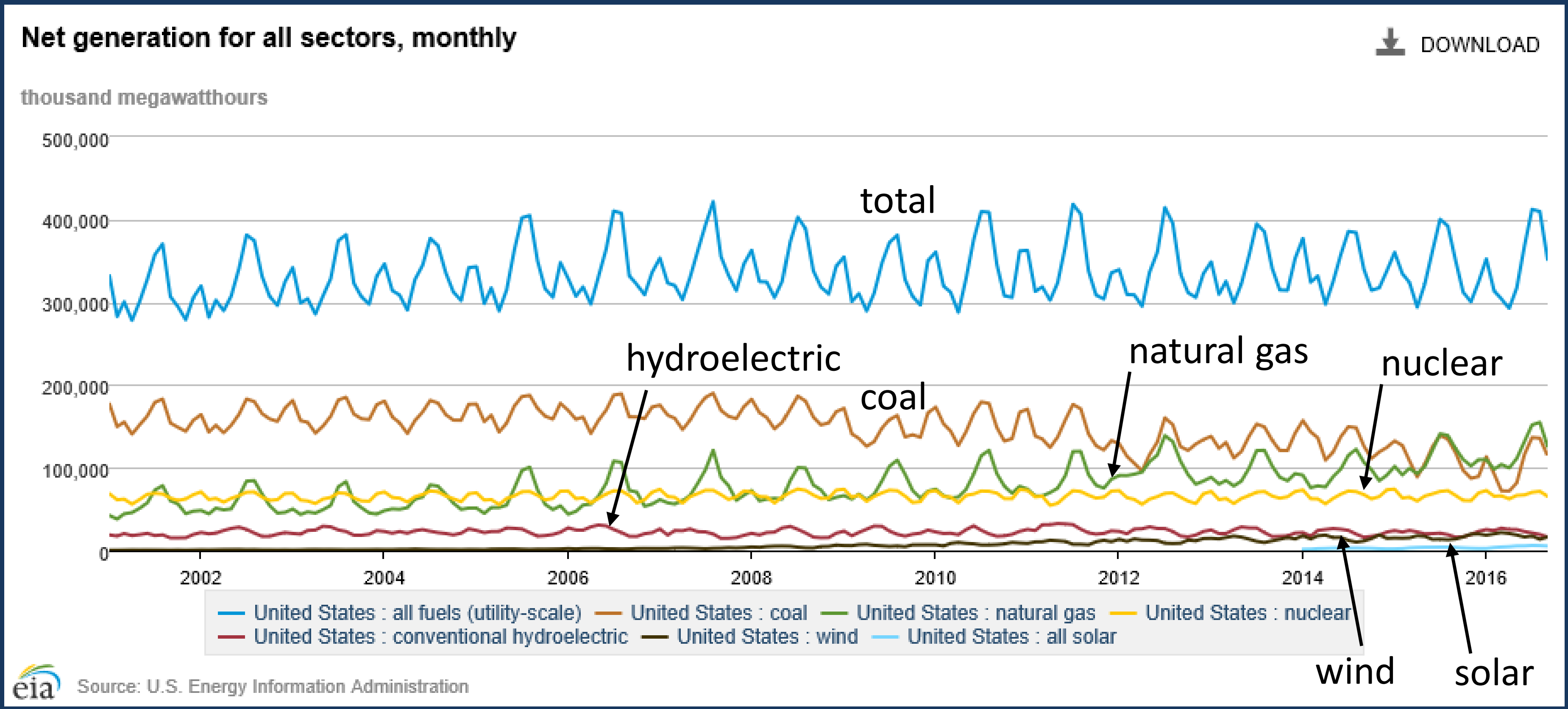
CSP Annual Capacity Additions (MW)	
Nevada	110

Sources: GTM/SEIA and IREC

The Energy Transition—
Trends

Electricity Generation in the U.S. by Source

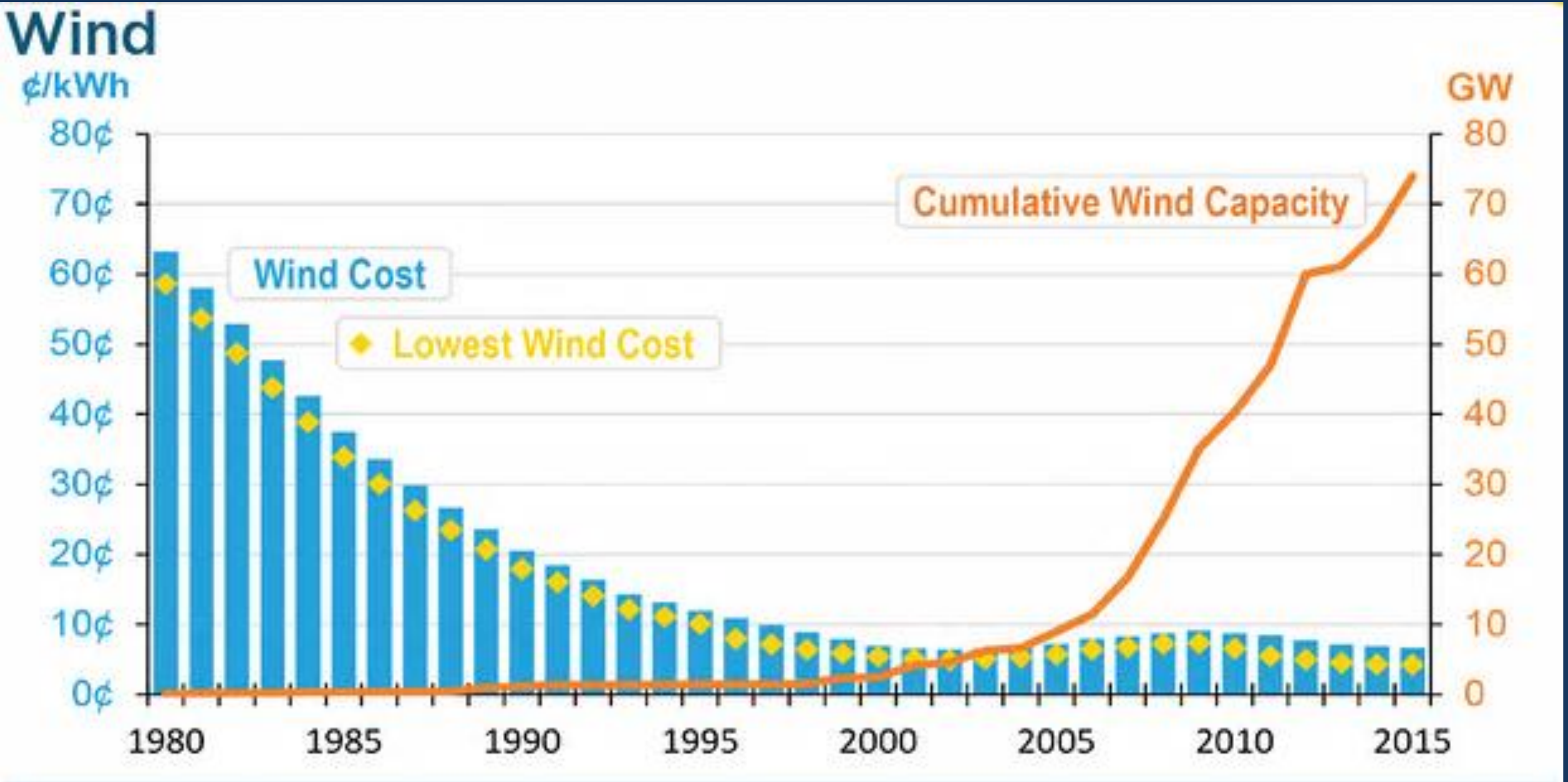
U.S. Energy Information Administration, Nov 2016



Overall electrical generation in the United States is roughly flat for 2006-2016.
Coal-fired generation has been dropping since 2009.
Summer usage causes annual fluctuations of about one-third.
Wind is 5.1% and solar is 1.4% of all electrical generation as of October 2016.

Wind energy is blowing away expectations

…due to its low cost, US wind energy has tripled since 2008. Wind now supplies 5% of total US electricity generation. *DOE 2016 report, via The Guardian, 3 Oct 2016.*

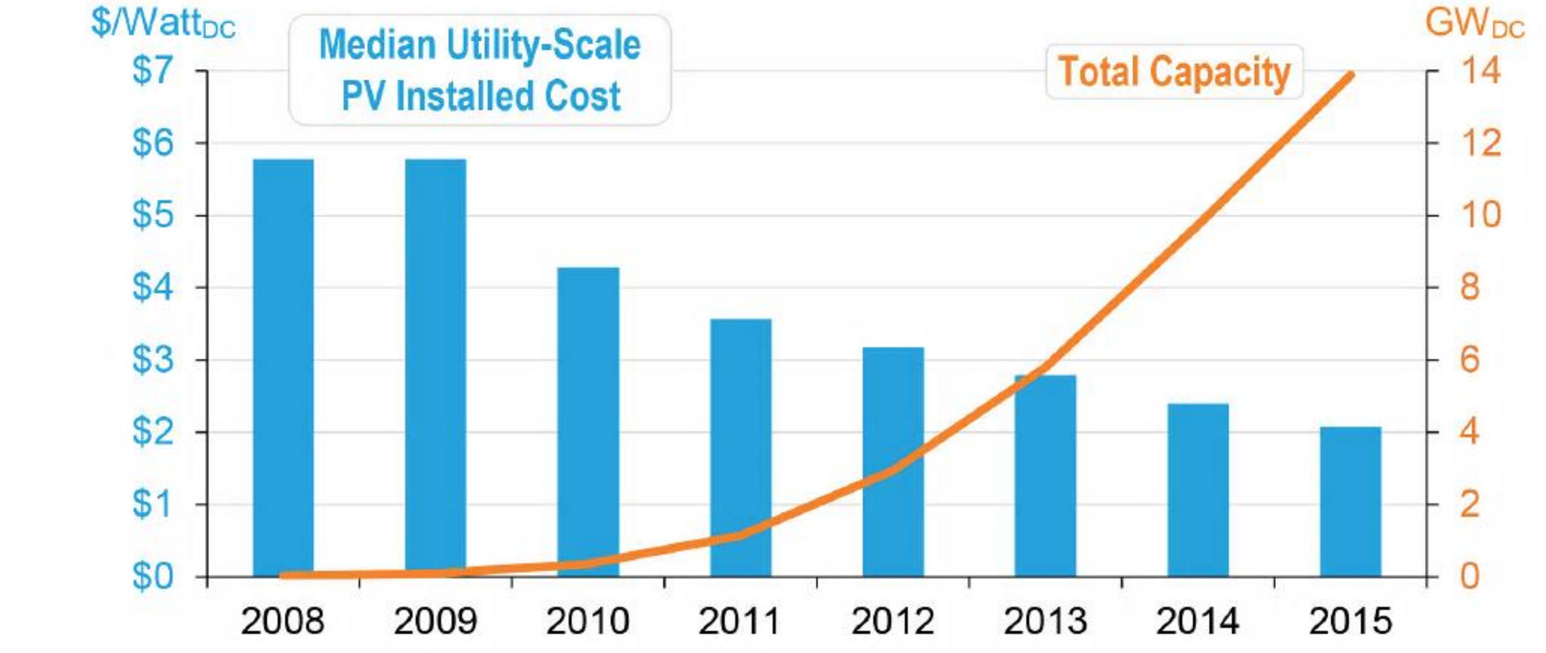


Cost data from references are inflation adjusted to dollar year 2015, and exclude the production tax credit. "Wind Cost" data estimates the levelized cost of energy from a representative wind site from references [1] and [2] and "Lowest Wind Cost" represents costs derived from power purchase agreements from good to excellent wind resource sites in the interior of the country as reported in reference [9]. [1] Deployment data also from reference [9]. 1 gigawatt (GW) = 1,000 megawatts (MW).

Solar energy's bright future

Utility-scale solar farm costs have fallen 64% since 2008, and distributed solar costs have fallen by 54%. *DOE 2016 report, via The Guardian, 3 Oct 2016.*

Solar PV: Utility-Scale



Costs from reference [4]; Deployment from reference [16]. Costs shown are the median costs and exclude the effect of the Investment Tax Credit. 1 gigawatt (GW) = 1,000 megawatts (MW). Costs and capacity are reported as DC power.

The World's First Solar Road Opens in France

Justin Worland, Time, 22 Dec 2016

The French Ministry of the Environment funded the 1-km (0.6 mile) project to test whether solar panels can be implemented effectively at a large scale. The project is intended to power the streetlights in the French town of Tourouvre-au-Perche in Normandy.

French Minister for Ecology, Sustainable Development and Energy, Segolene Royal walks on a solar panel road during its inauguration in Tourouvre, France

The Largest Solar Farm In Alabama Is Now Online

Steve Hanley, ClearTechnica, March 19, 2017

The largest solar farm in Alabama history is now online and contributing about 75 megawatts of clean renewable energy.

Jay Stowe, vice president of distributed energy resources for the Tennessee Valley Authority, says, "It is a 640-acre solar energy center. There's about 300,000 solar panels that will be able to produce enough power to supply about 15,000 homes with carbon-free electricity." The River Bend solar farm cost $150 million and is the largest in the TVA system or the state of Alabama

U.S Solar Jobs Boom While Oil, Coal Coal Struggle **Fortune, 12 Jan 2016**

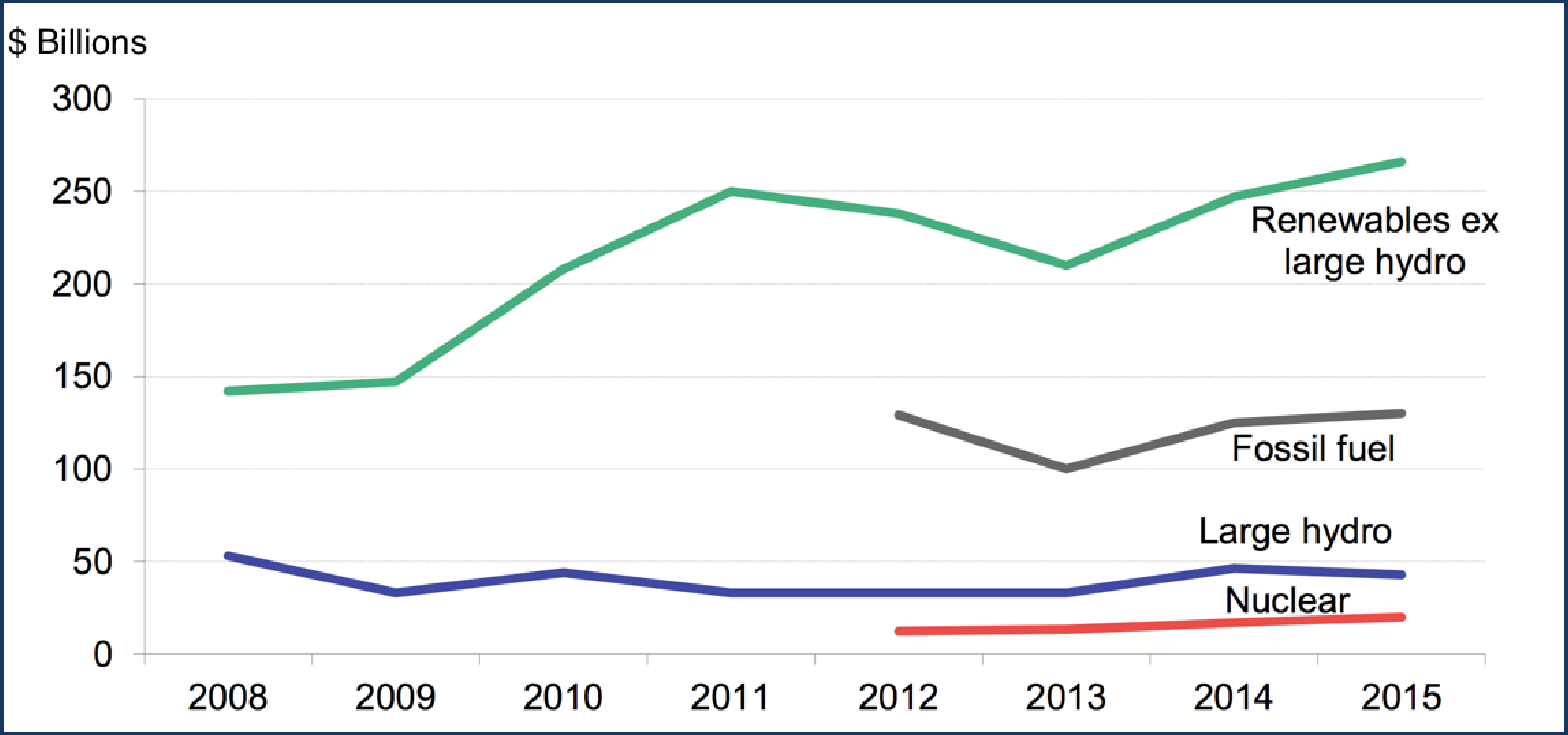
More Americans are now installing solar panels on building rooftops than mining coal or extracting oil and gas, according to a report released Tuesday by the non-profit solar advocacy group The Solar Foundation.

The U.S. solar industry grew dramatically in 2015, and is expected to continue to do so this year. The industry now employs 209,000 workers after adding over 35,000 jobs last year. By the end of this year, its ranks are expected to grow to 240,000 workers.

An installer for Stellar Solar carries a solar panel during installation at a home in Encinitas in San Diego, California, U.S. Photograph by Sam Hodgson — Bloomberg via Getty Images

Renewables are beating fossil fuels 2 to 1

Bloomberg News, by Tom Randall



Investment in World Power Capacity, 2008-2015

Bloomberg New Energy Finance, UNEP 6 Apr 2016.

We’re adding record amounts of wind and solar — and we’re still not moving fast enough

Washington Post, 25 Oct 2016

Renewable energy projects surpassed all other sources of new electricity added to the global supply last year, says a new report released this week by the International Energy Agency. In 2015, renewables made up more than half of all new installed capacity, with the greatest gains seen in onshore wind and solar.

That said, renewable energy sources still only account for about 23 percent of the electricity actually produced worldwide, the report notes. The agency predicts that this share will increase to 28 percent by the year 2021, making renewables the fastest-growing source of electricity generation in the world.

The report predicts that the U.S. will commission 107 gigawatts of new renewable additions — mostly wind and solar — by 2021, a 50 percent increase from 2015. The report attributes the U.S. success to a long-term extension of federal tax credits for renewables…

A general view shows solar panels used to produce renewable energy at the photovoltaic park during its official 2015 inauguration in Cestas, southwestern France. (Reuters/Regis Duvignau)

The Energy Transition—
Wind Power

Wind Energy

Wind Energy - Offshore

Westermeerwind Wind Farm

- Noordoostpolder, Netherlands
- 144 MW

Horn Rev Wind Farm

- West coast of Denmark
- 160 MW

Wind Energy - Onshore

Peetz Table Wind Energy Center

- Peetz, Colorado
- 575 MW

Cedar Creek Wind Farm

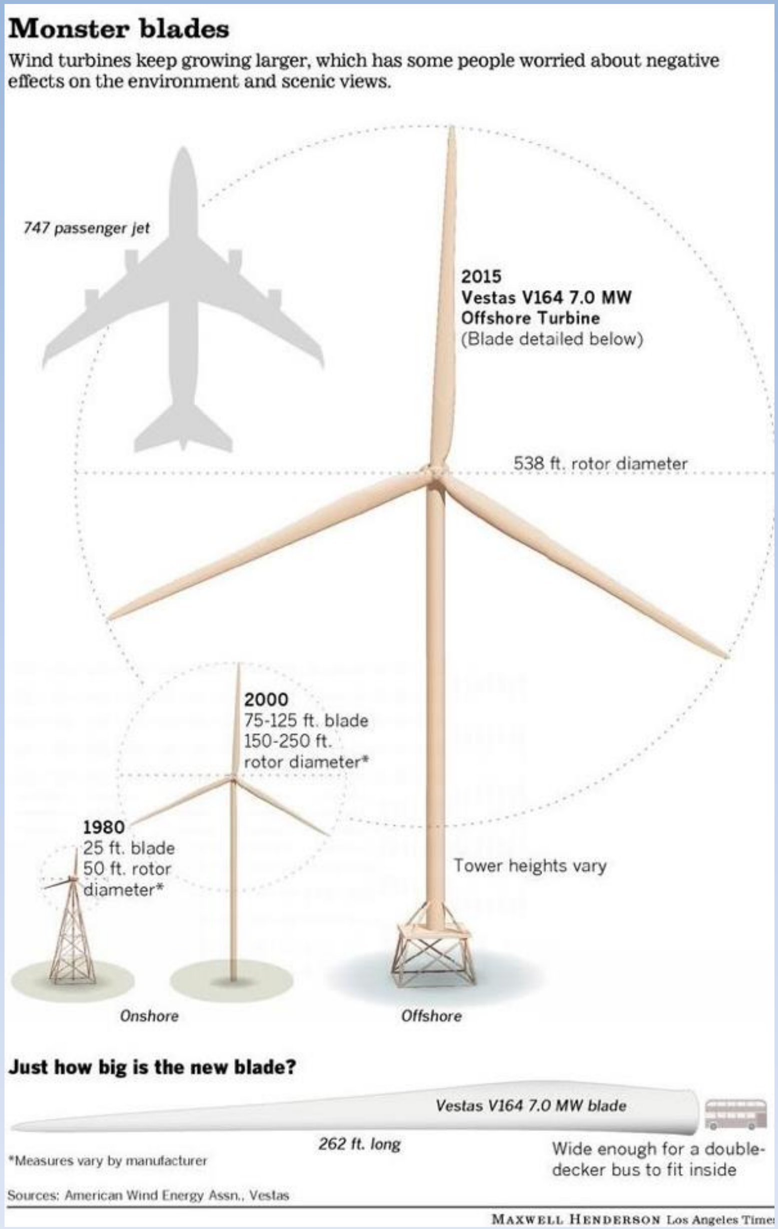
- Grover, Colorado
- 550 MW

Wind Machines - Scale

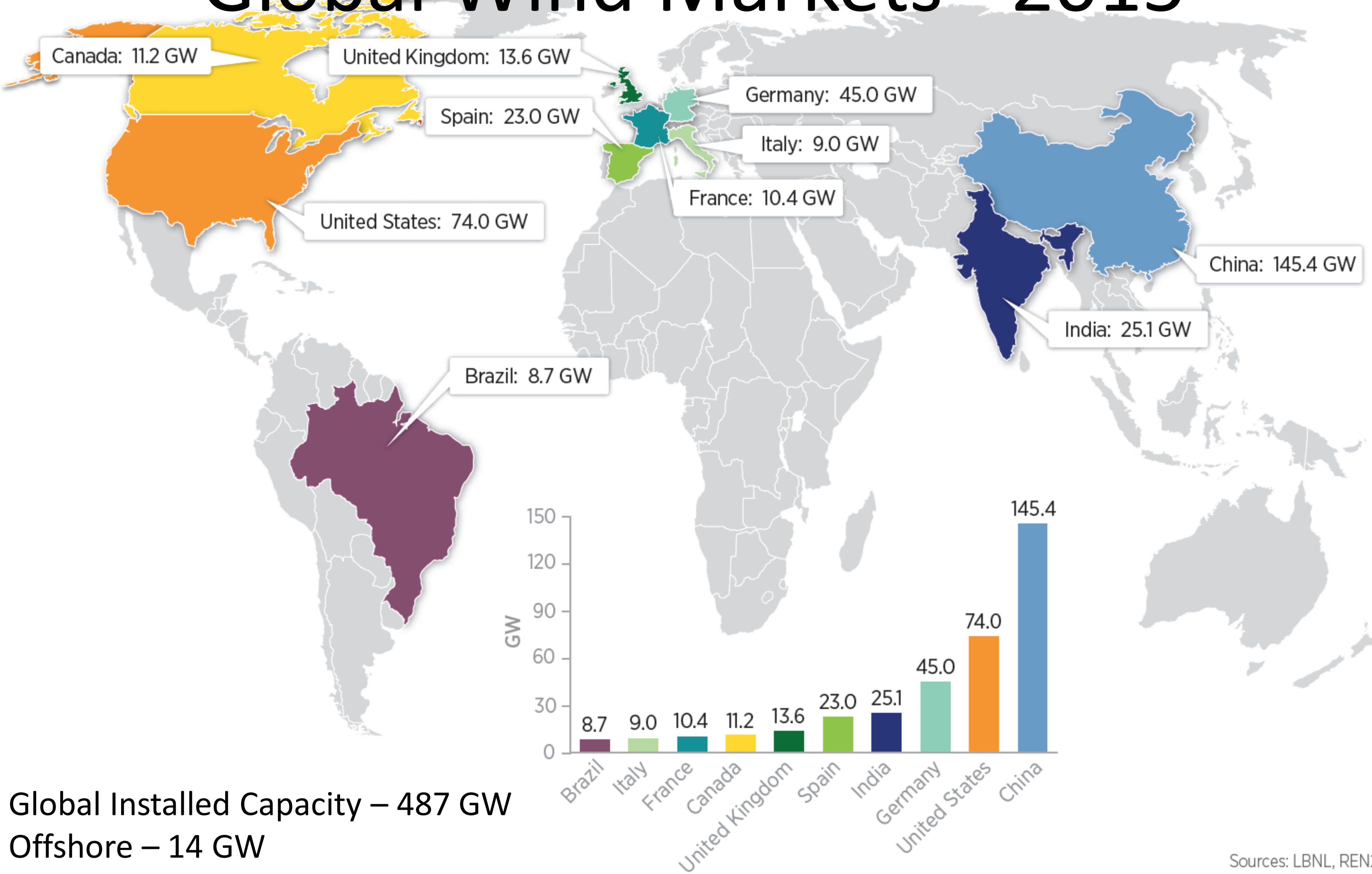
National Wind Technology Center
Boulder, Colorado

GE – 1.5 MW
Alstom – 3 MW
Siemens – 2.3 MW

Wind Machines - Scale



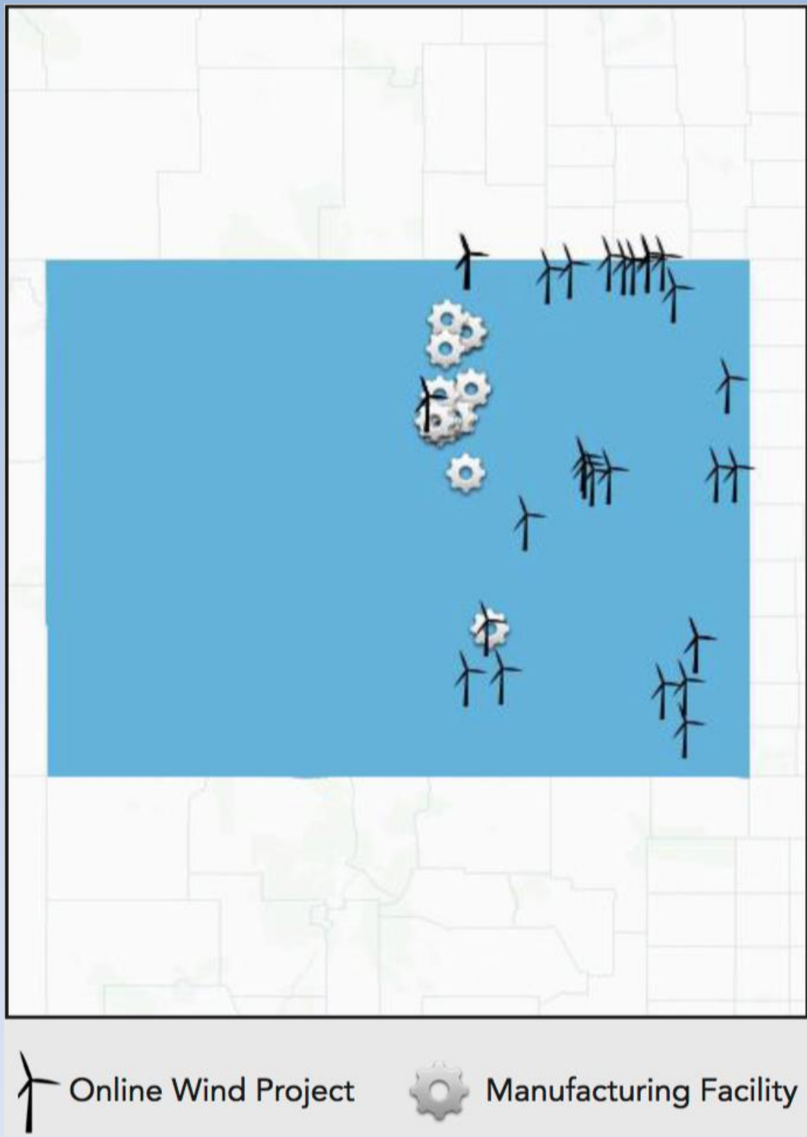
Global Wind Markets - 2015

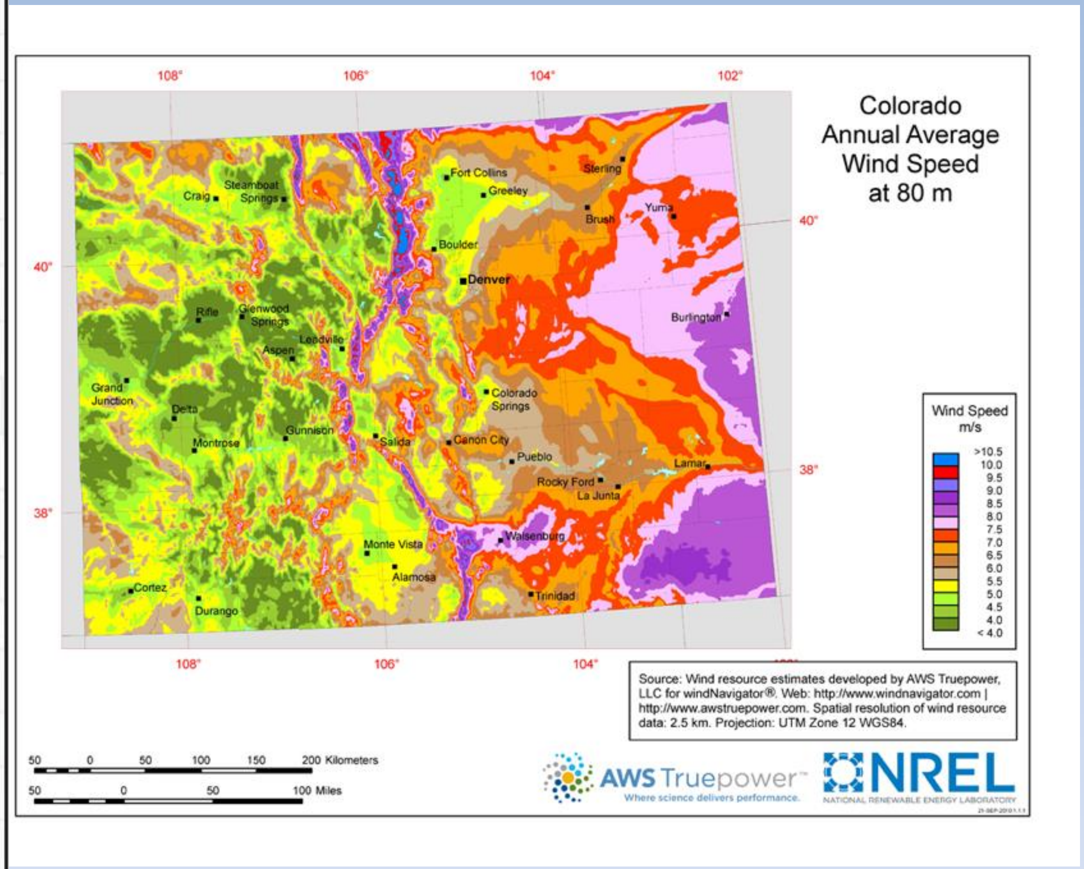


Global Installed Capacity – 487 GW
Offshore – 14 GW

Sources: LBNL, REN21

Colorado Wind Development

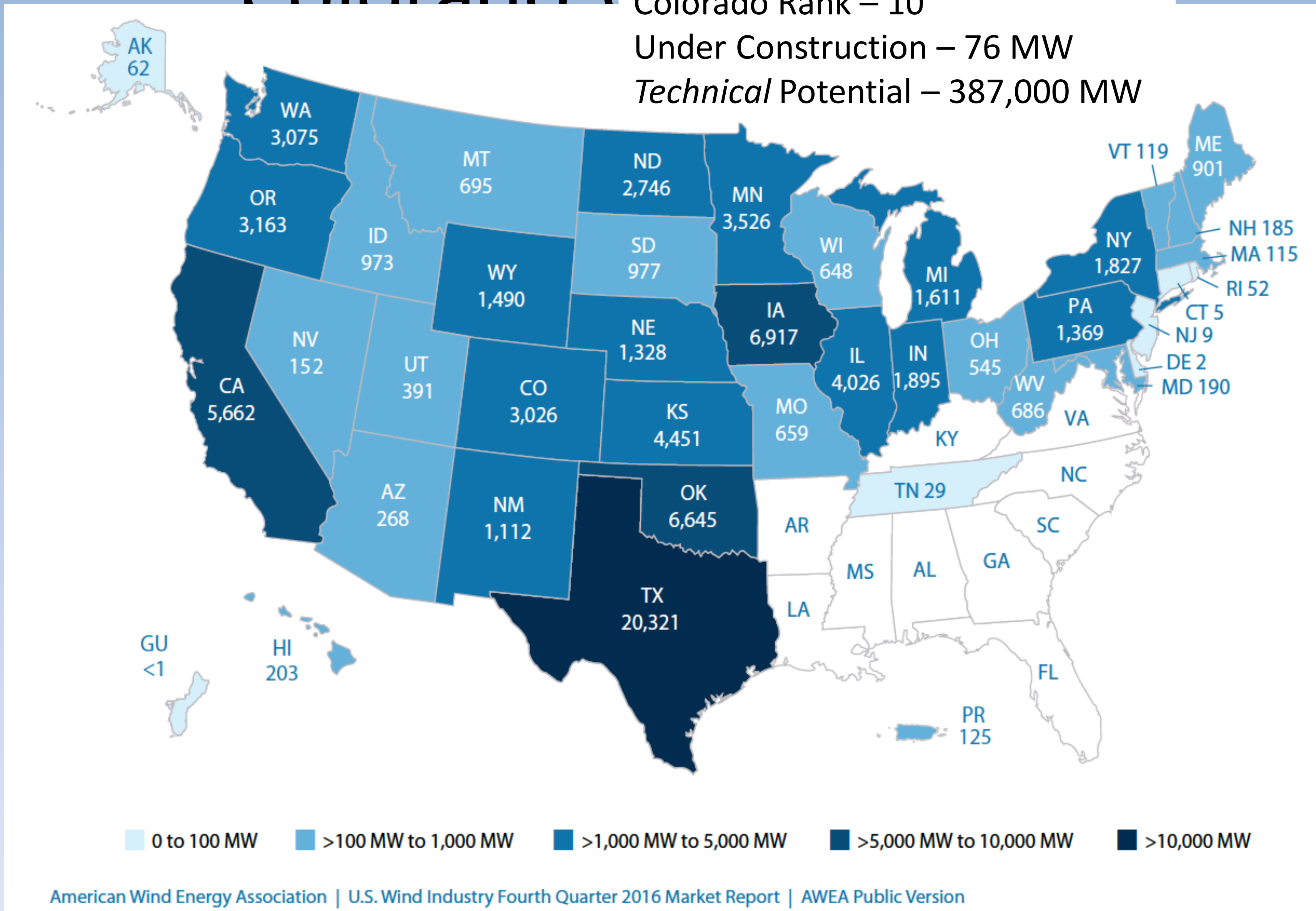




Sources: NREL and AWEA

Colorado

Colorado Rank – 10
Under Construction – 76 MW
Technical Potential – 387,000 MW



Colorado Wind Development

STATE WIND FACTS

Wind Projects

- **Installed wind capacity:** 3,026 MW
- **State rank for installed wind capacity:** 10th
- **Number of wind turbines:** 1,913
- **State rank for number of wind turbines:** 8th
- **Wind projects online:** 25 (Projects over 10 MW: 17)
- **Wind capacity under construction:** 76 MW
- **Wind capacity in advanced development:** 600 MW

Current Wind Generation

For the 12 month period ending October 2016, wind energy provided 16.87% of all in-state electricity production.

- **Equivalent number of homes powered by wind:** 846,000

Wind Generation Potential

The DOE Wind Vision Scenario projects that Colorado could produce enough wind energy by 2030 to power the equivalent of average American homes.

- **Land based technical wind potential at 80 m hub height:** 274,353 MW
- **Land based technical wind potential at 110 m hub height:** 262,878 MW (Source: NREL)

Environmental Benefits

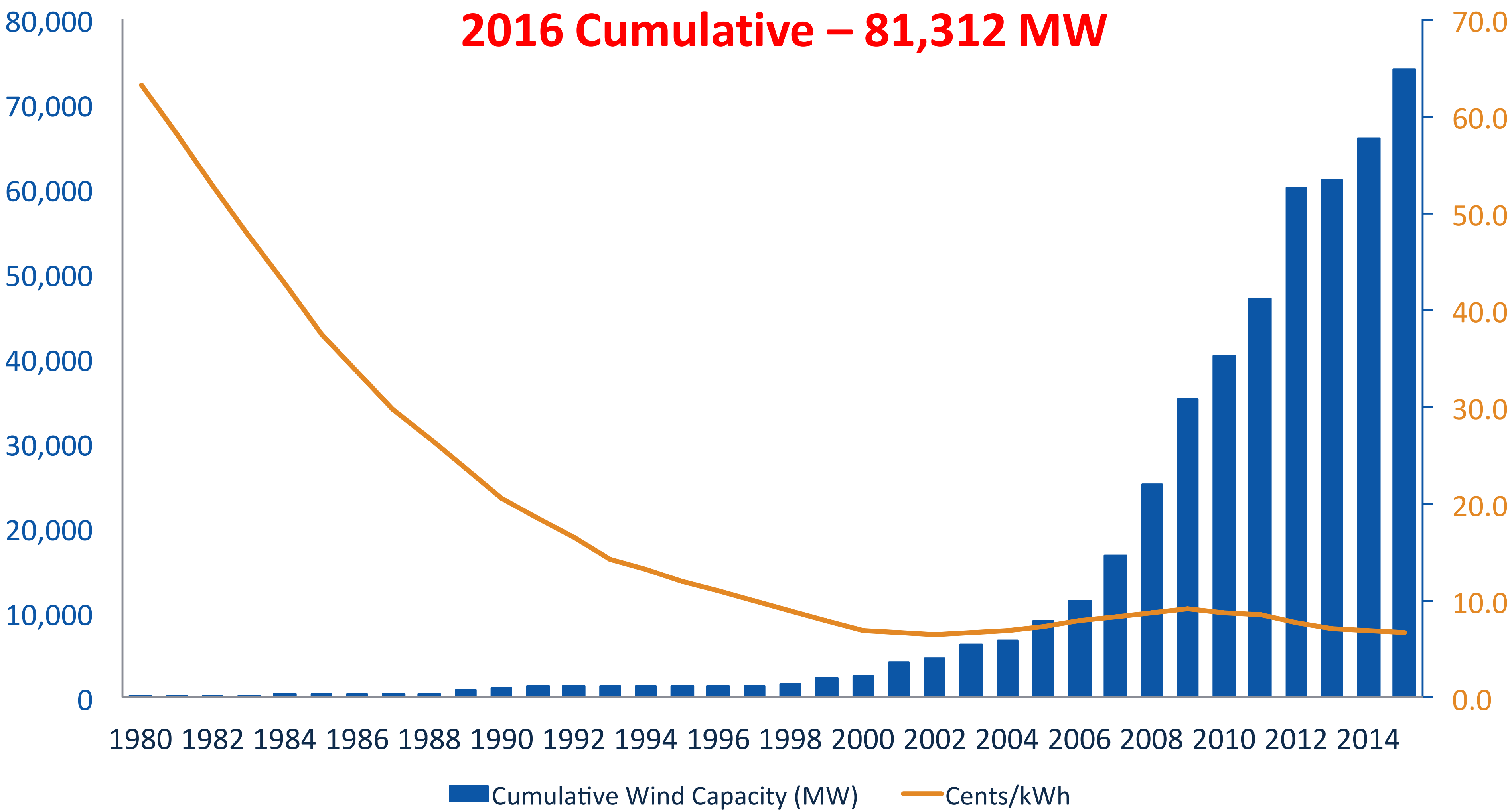
Generating wind power creates no emissions and uses virtually no water.

- **2015 annual state water consumption savings*:** 4.4 billion gallons
- **2015 equivalent number of water bottles saved:** 33.1 billion
- **2015 annual state carbon dioxide (CO_2) emissions avoided:** 8.0 million metric tons
- **2015 equivalent cars worth of emissions avoided:** 1.7 million

*Based on national average water consumption factors for coal and gas plants

Source: AWEA

U.S. Wind Market Growth



2016 – 8,727 MW
(EIA)

Source: DOE 2016: Revolution…now, the future arrives for five clean energy technologies

AND I'LL CONTINUE FROM HERE NEXT WEEK

- FINISH WIND
- COVER NUCLEAR
- COVER STORAGE
- COVER GRID OPTIONS
- DISCUSS NREL VISIT NEXT WEEK
- PERSONAL SOLUTIONS INVIDIDUALS CAN MAKE

LINKS

- Greg Wilson: Ramping Up Solar to Power the World https://www.youtube.com/watch?v=7CDPHxcnq4c
- David Mooney Energy In Transition. NREL's David Mooney on Renewables https://www.youtube.com/watch?v=zYKrXVgmqW4
- Stanford http://thesolutionsproject.org/infographic/

- Other videos: https://www.youtube.com/channel/UCr81EUb2qVJVfmmlJMxEHVw/videos

OTHER LINKS

- https://www.eia.gov/
- https://www.eia.gov/totalenergy/
- https://www.eia.gov/energyexplained/
- https://www.eia.gov/tools/faqs/
- https://www.eia.gov/environment/

https://i.kinja-img.com/gawker-media/image/upload/t_original/ihsllhptnnm4vb7wuvgq.jpg