Electric Energy Systems Transformation

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National Science Foundation

Columbia University
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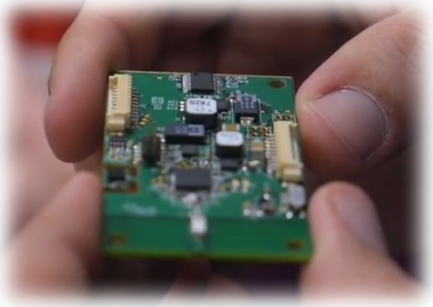
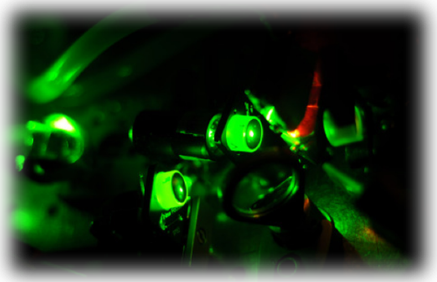
NSF ENG

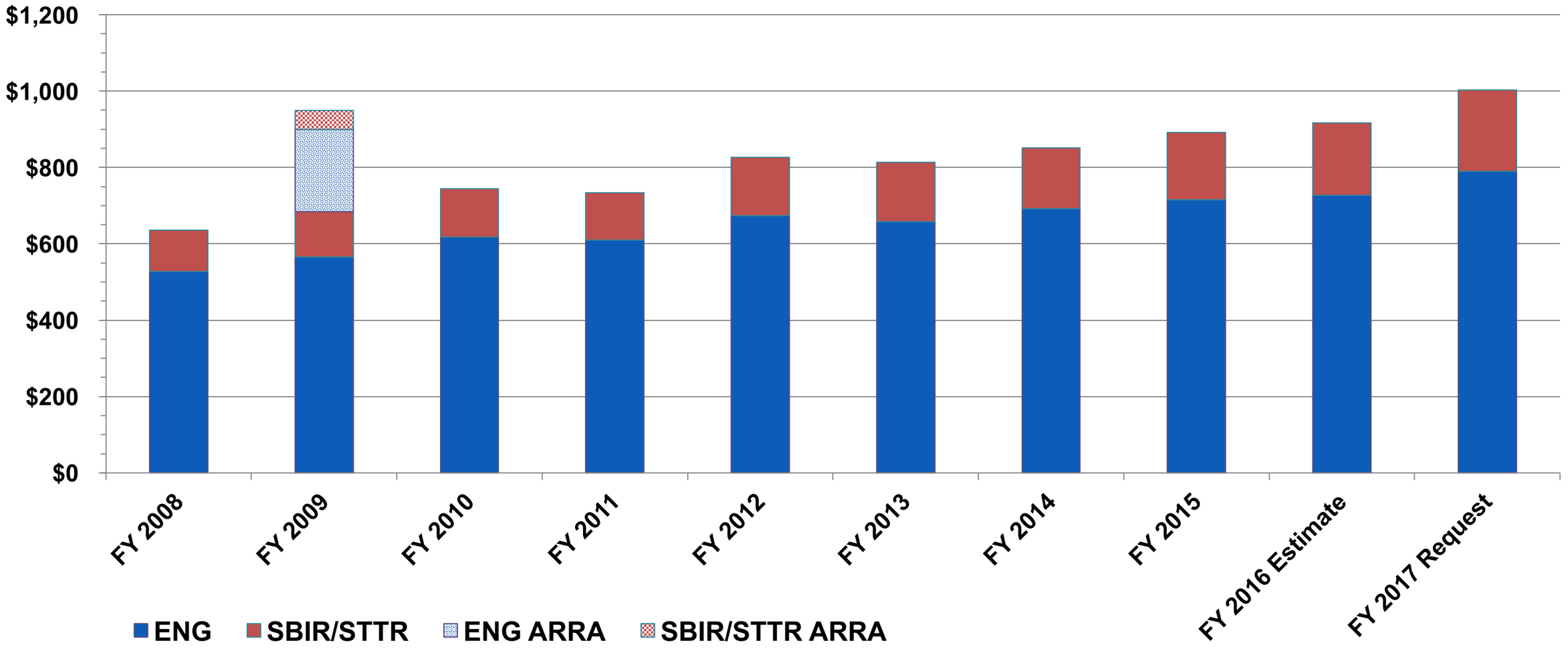
Investing in engineering research and education and fostering innovations to benefit society



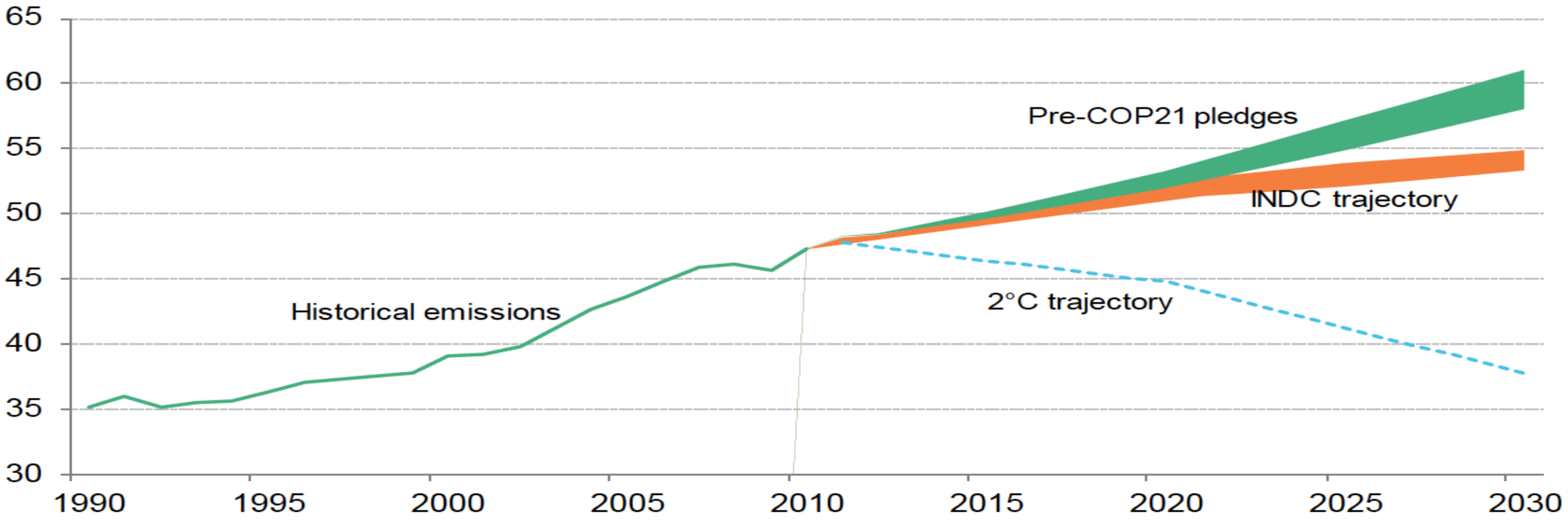


Credits, left to right: Google; Shanti Hamburg, MAE, West Virginia University; NSF; NSF; Franz X. Kärtner and Greg Hren, MIT.

ENG and SBIR/STTR R&RA Budgets ($M)

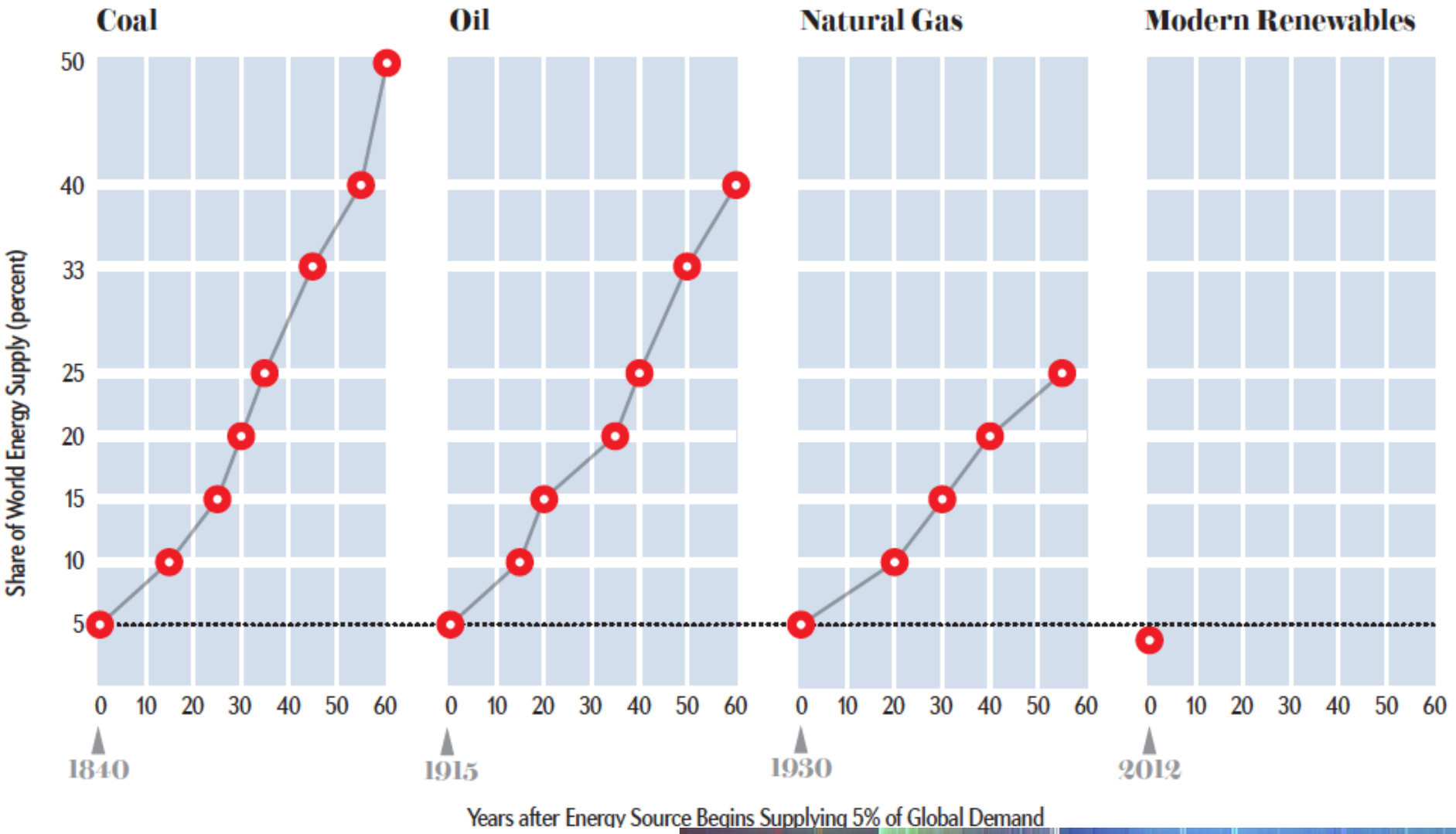


Global CO2 Emissions



Source: UNFCCC, UNEP, Climate Action Tracker, Bloomberg New Energy Finance

Major Energy Transitions are Slow!



Credit: V. Smil, Scientific American, January 2014

Carbon Budget for 2 Degree

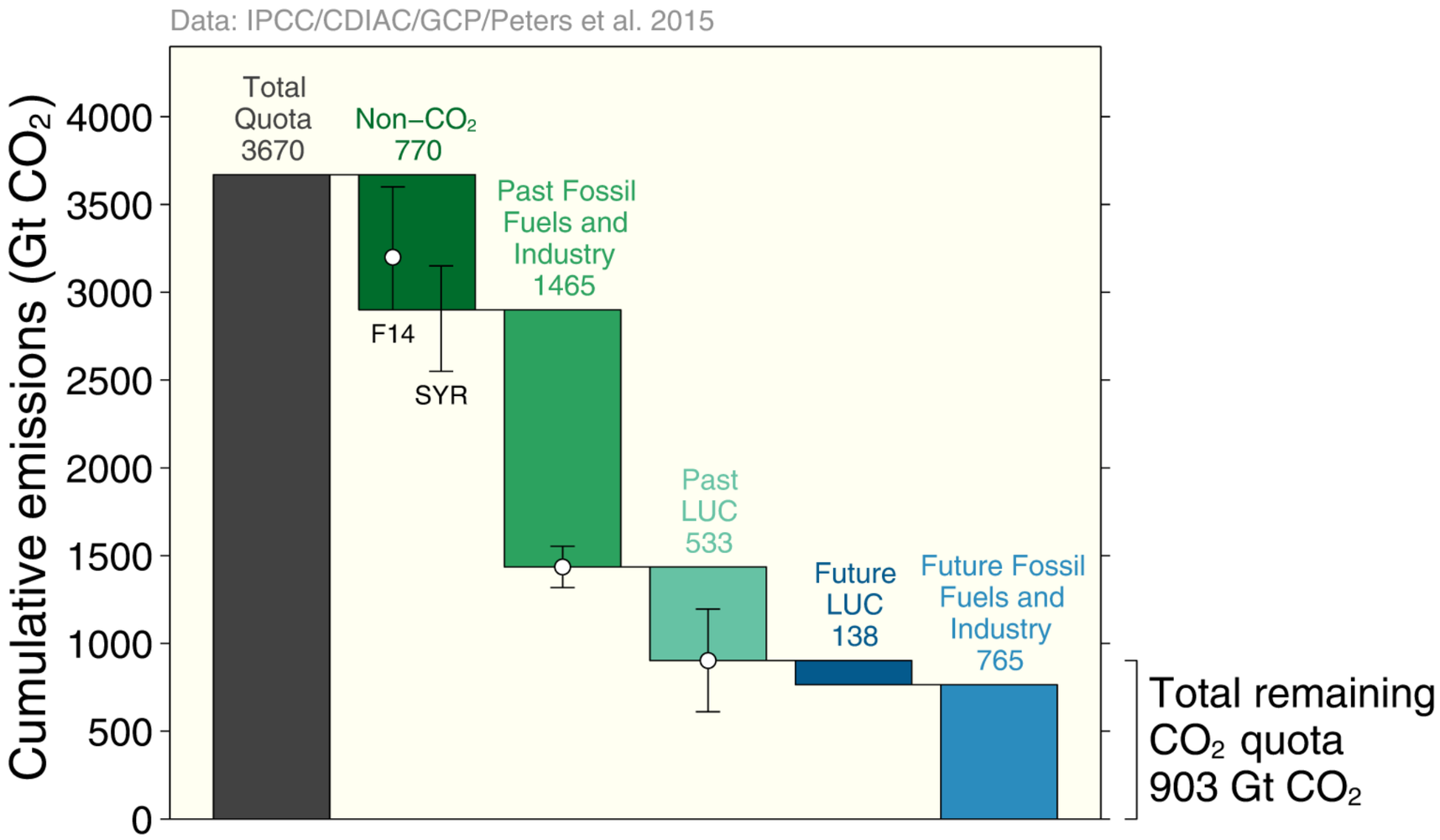
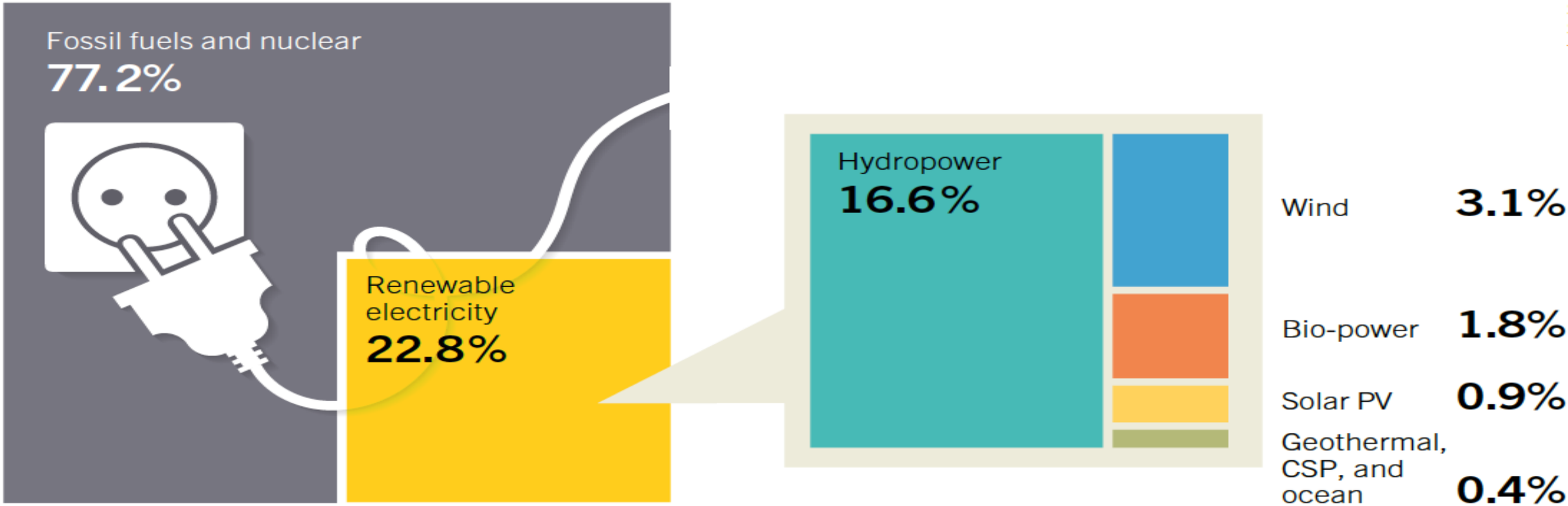


Figure 3. Estimated Renewable Energy Share of Global Electricity Production, End-2014



Based on renewable generating capacity in operation at year-end 2014.

REN21 Renewable Energy Policy Network for the 21st Century

Figure 4. Renewable Power Capacities* in World, EU-28, BRICS, and Top Seven Countries, 2014

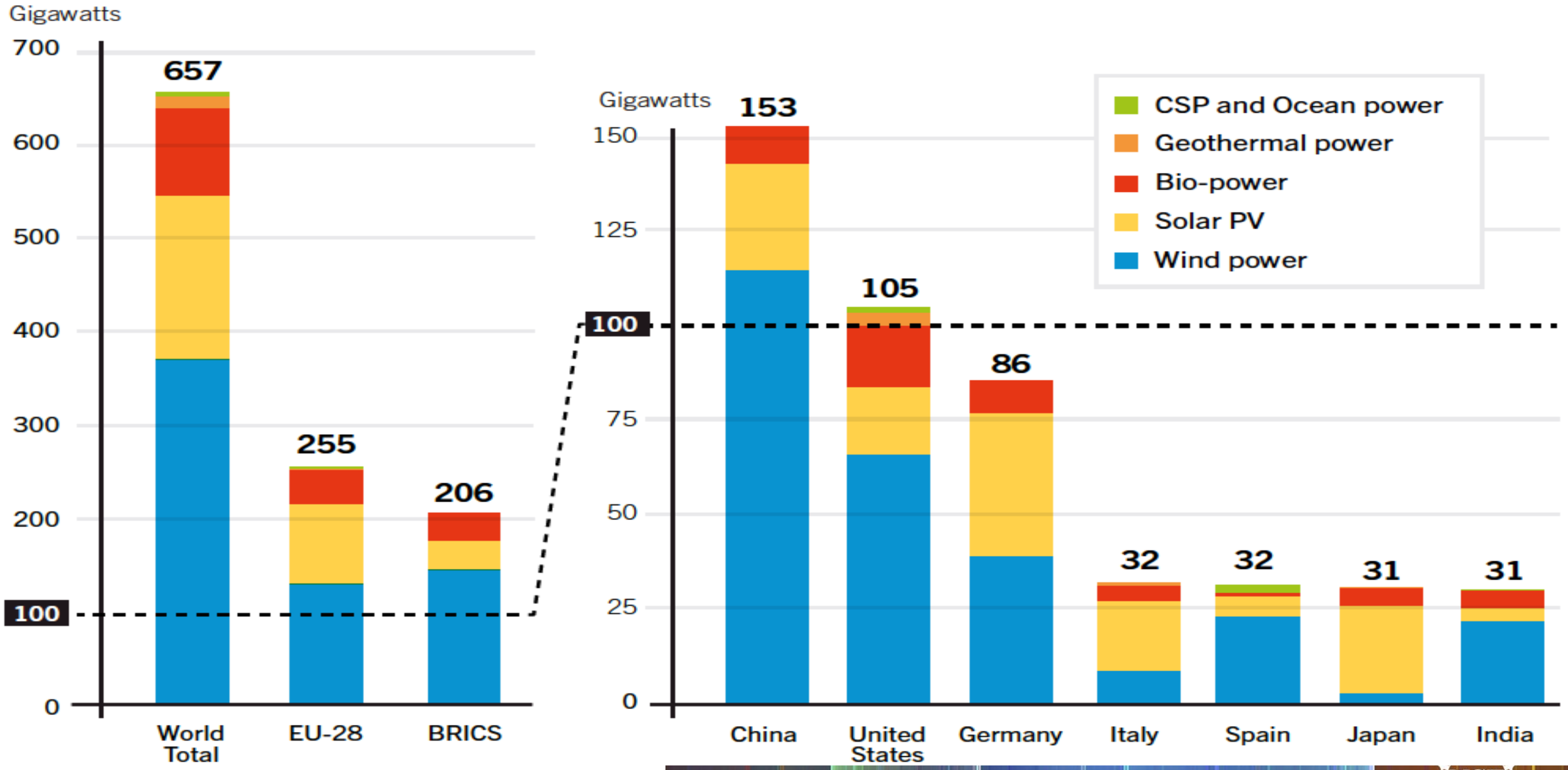


Figure 14. Hydropower Global Capacity, Shares of Top Six Countries and Rest of World, 2014

Total Hydro
1055 GW

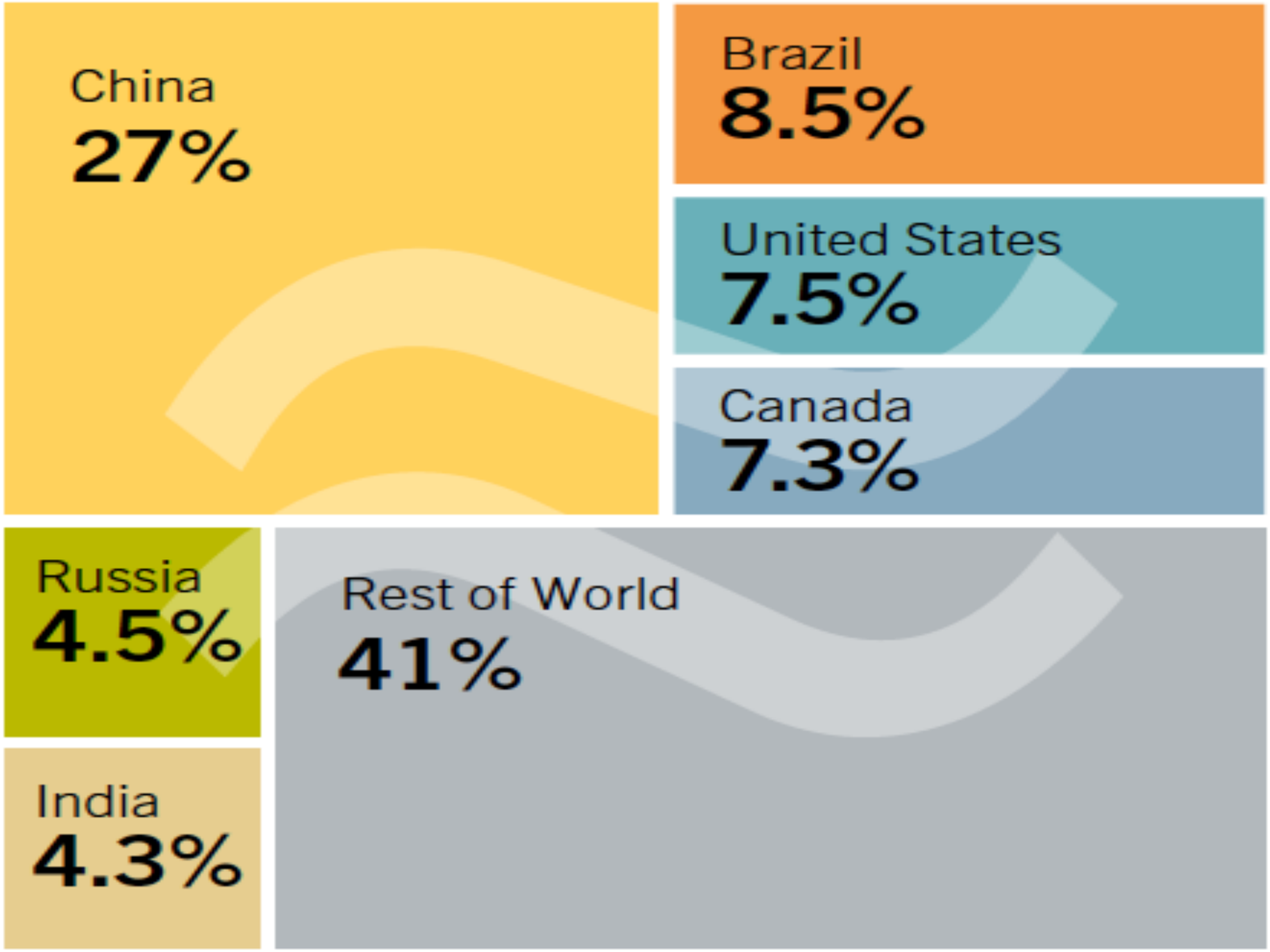


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Figure 16. Solar PV Global Capacity, 2004–2014

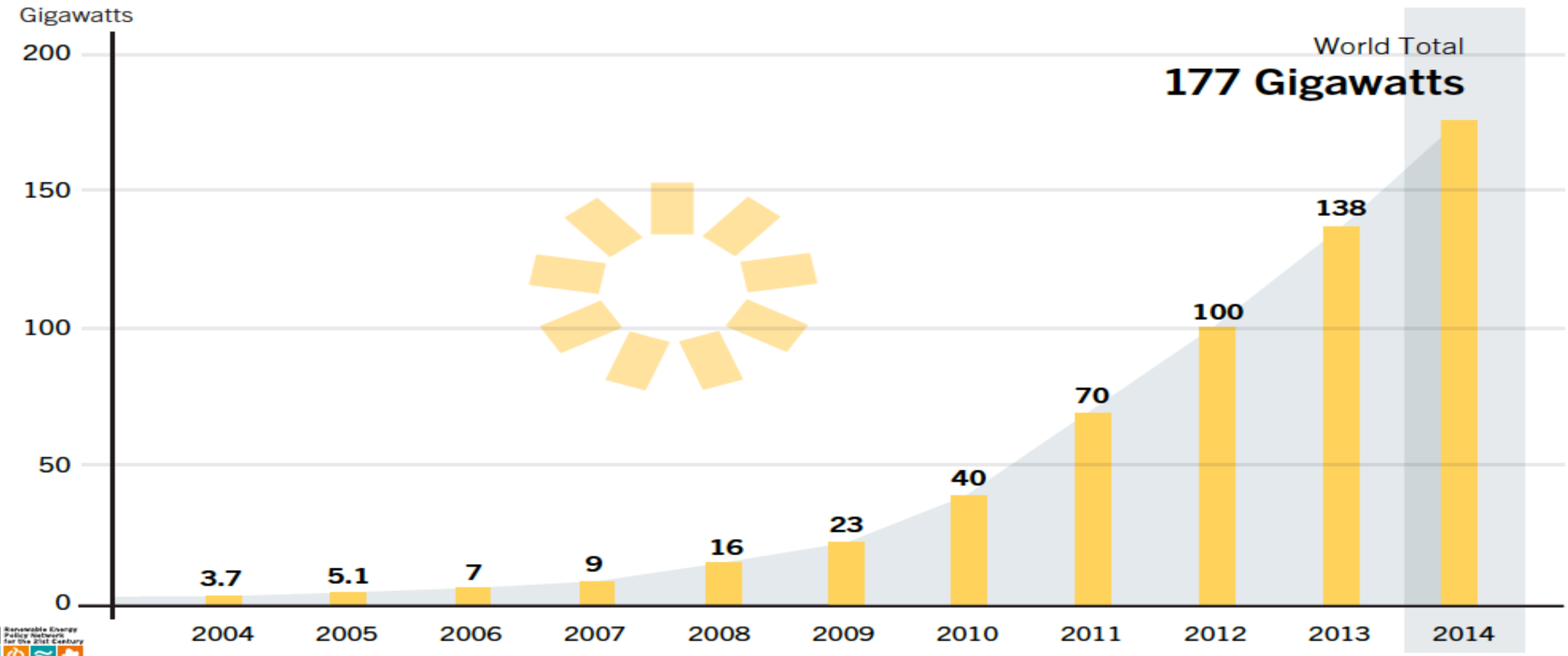

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Figure 17. Solar PV Capacity and Additions, Top 10 Countries, 2014

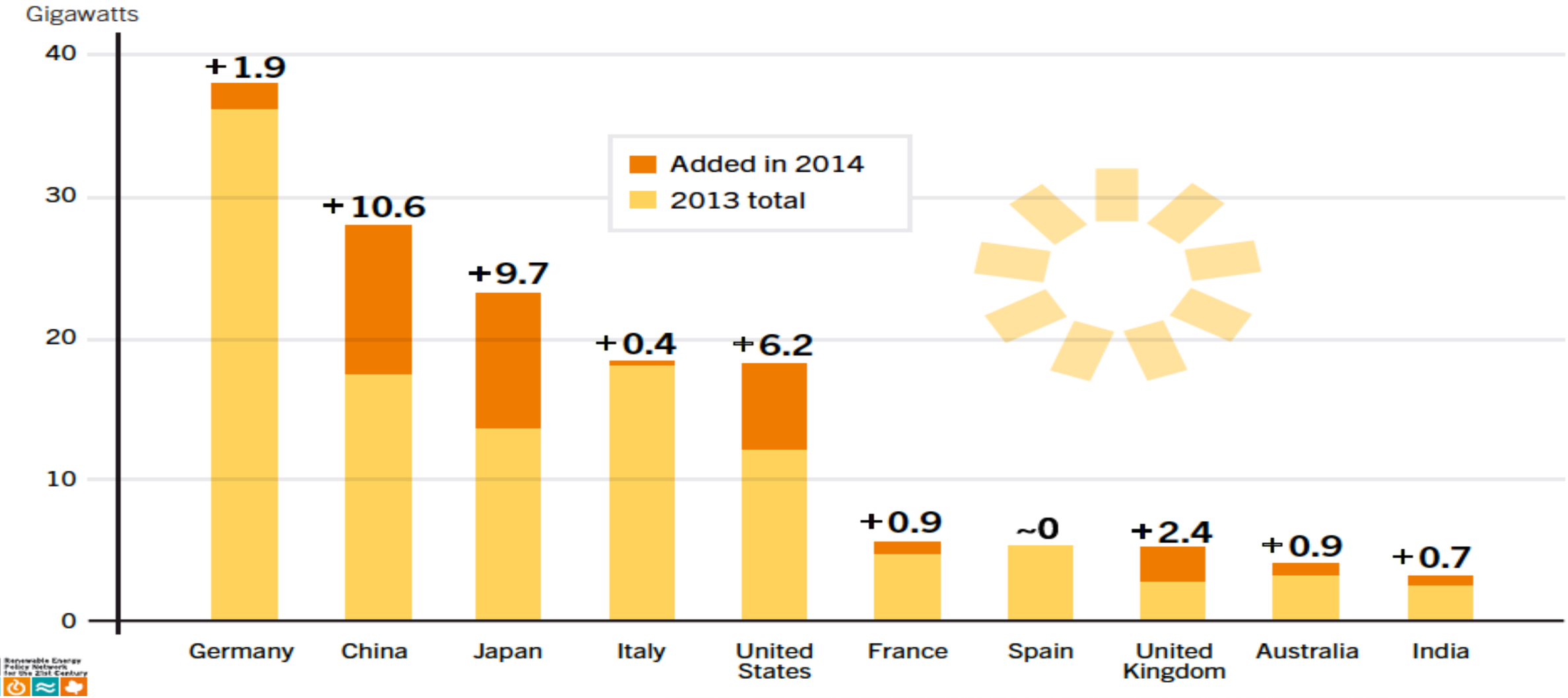

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Figure 22. Wind Power Global Capacity, 2004–2014

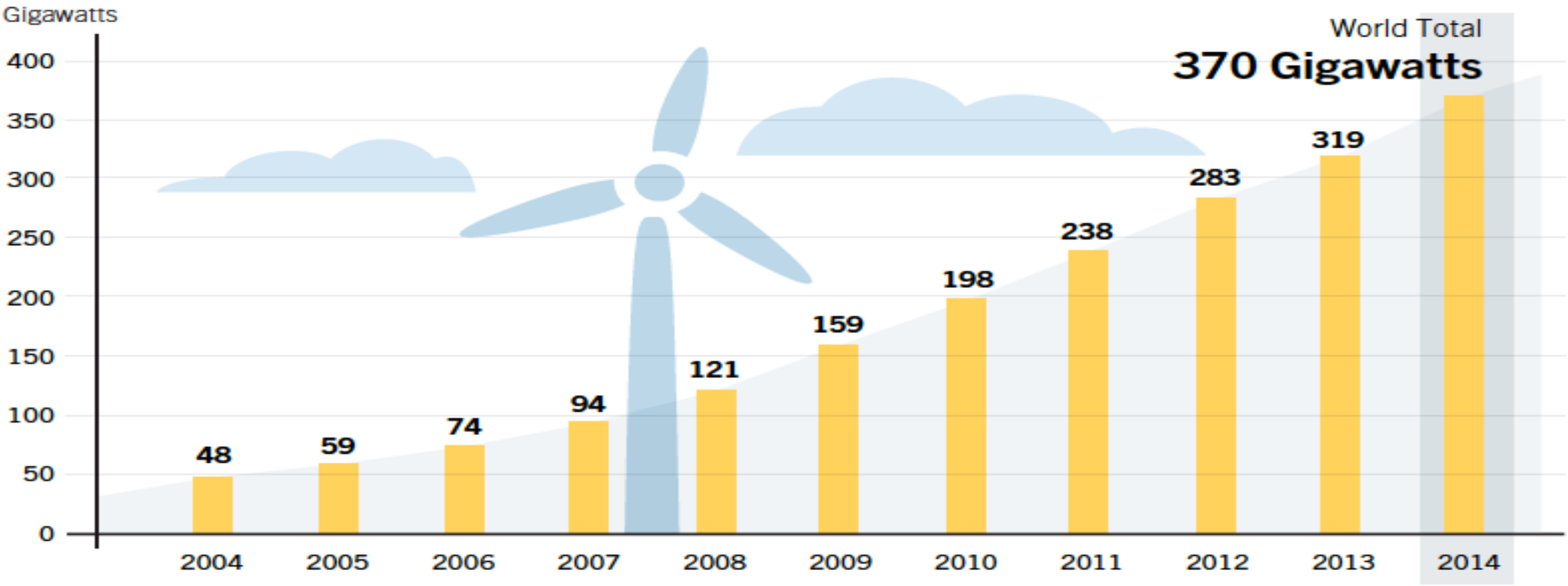
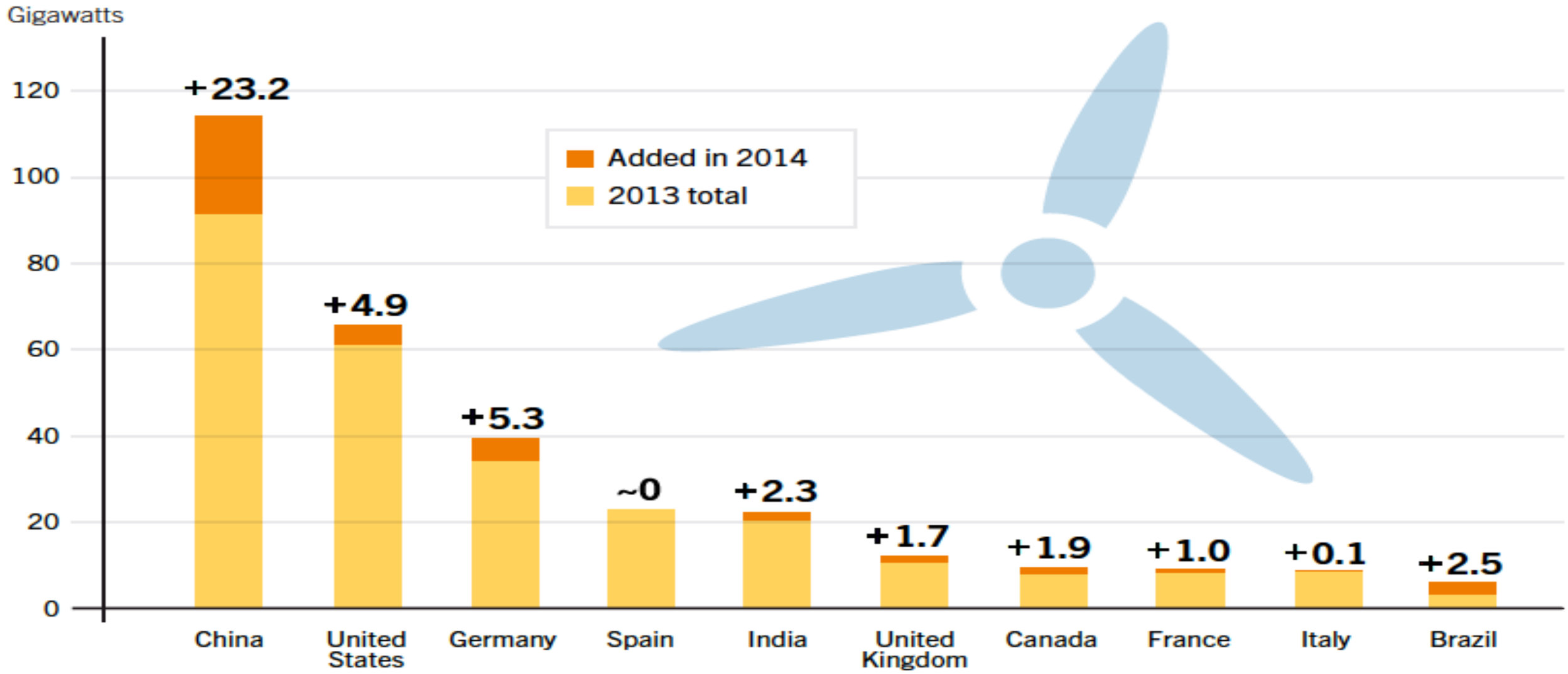
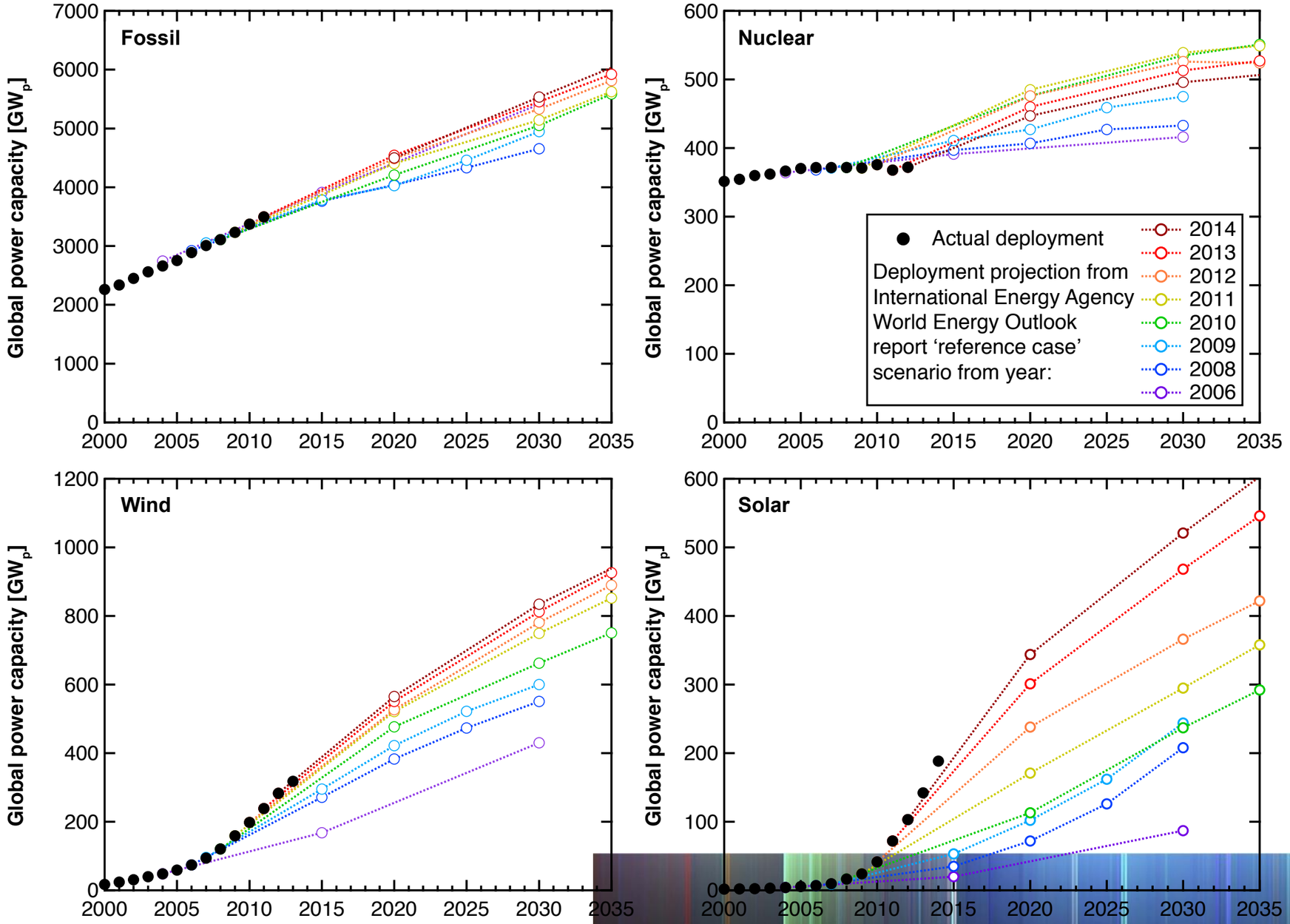


Figure 23. Wind Power Capacity and Additions, Top 10 Countries, 2014



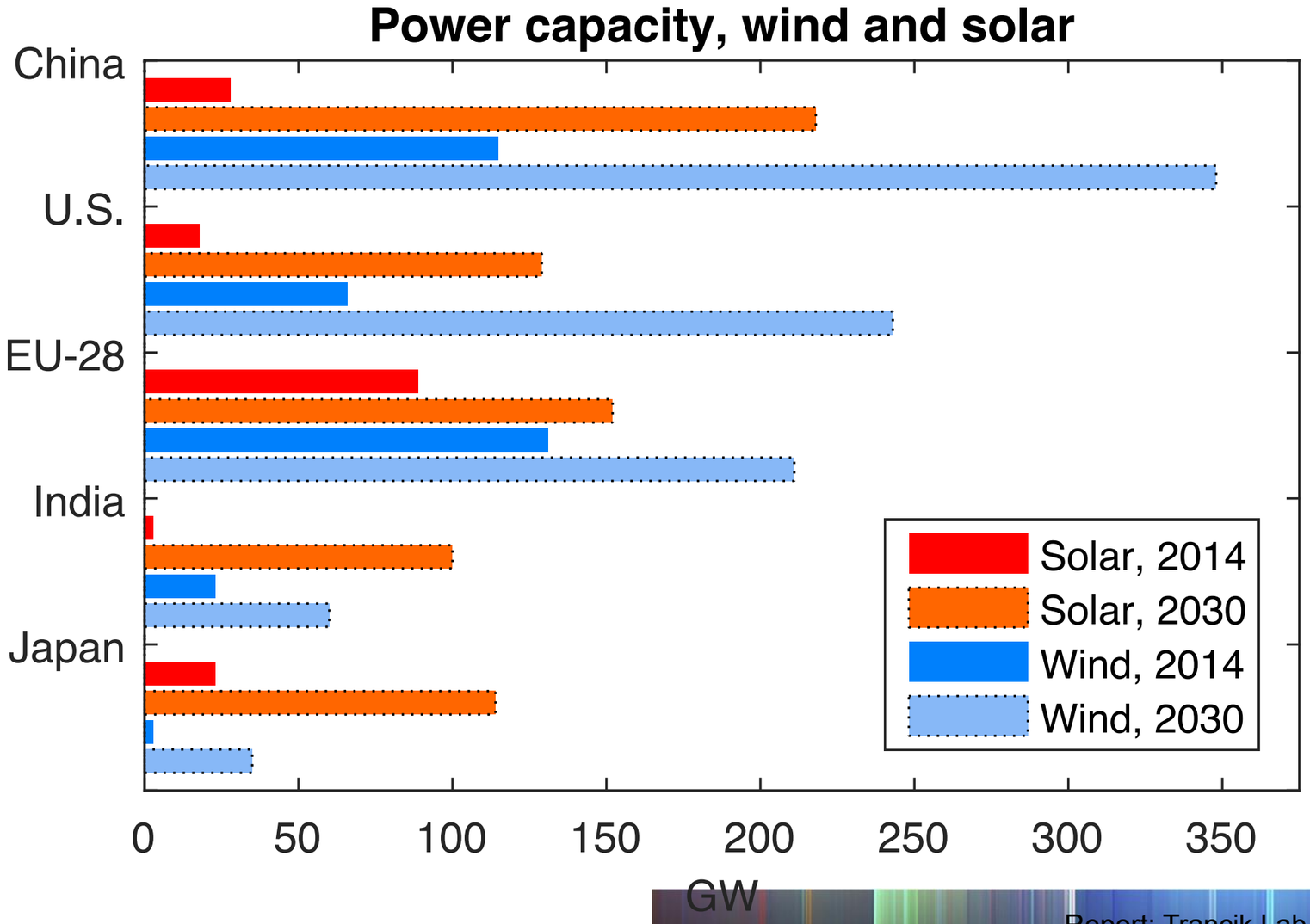
Wind and solar energy have grown faster than expected



Source; Trancik, MIT, 2015

Report: Trancik Lab, MIT, 2015

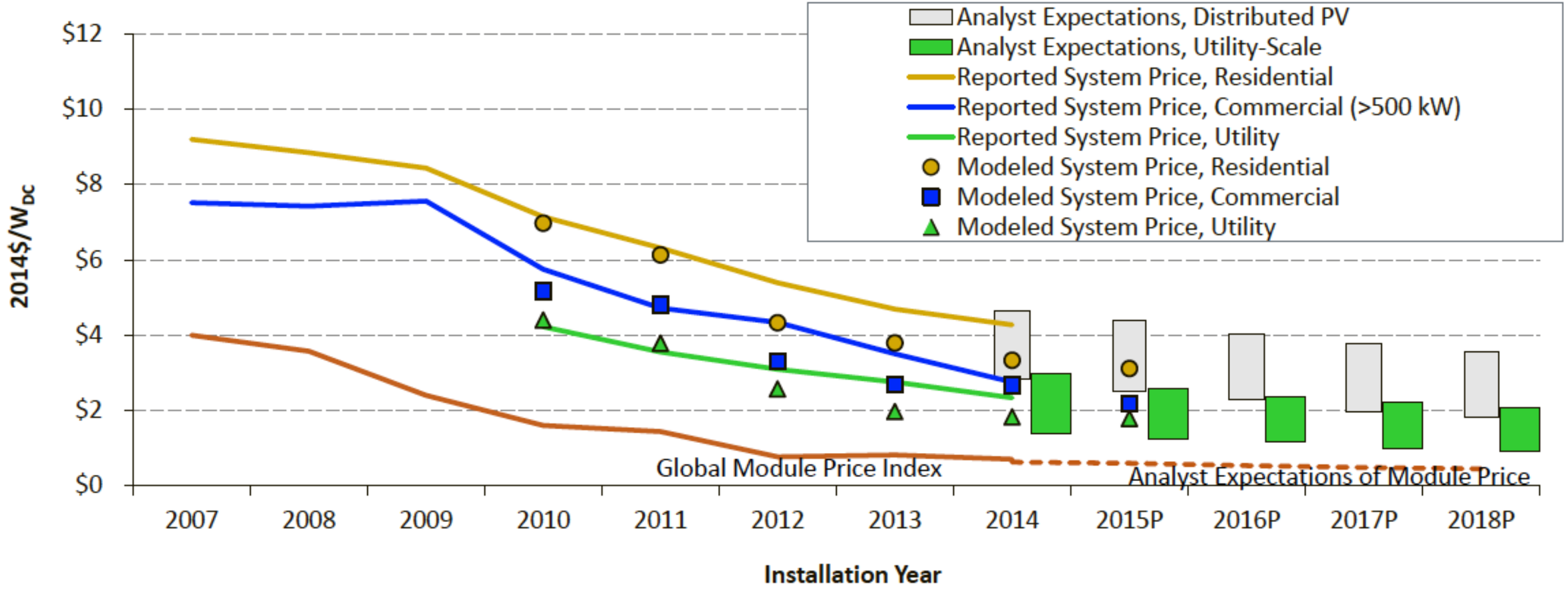
Renewables growth under countries' climate pledges (INDCs)



Source; Trancik, MIT, 2015

Report: Trancik Lab, MIT, 2015

Reported, Bottom-up, and Analyst-Projected Average U.S. PV System Prices over Time

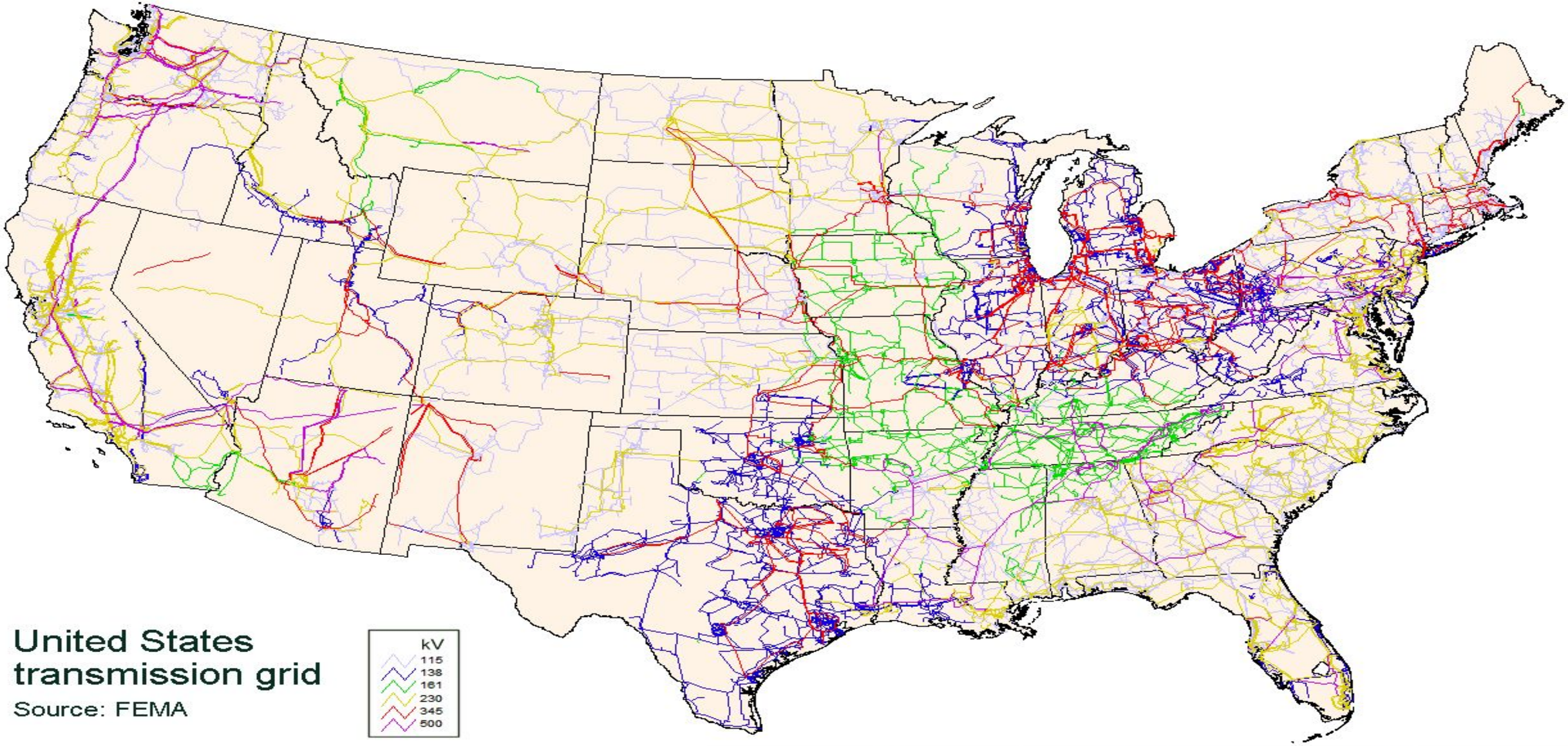


Source: DOE

- All methodologies show a downward trend in PV system pricing
- Reported pricing and modeled benchmarks historically had similar results; however, they have recently diverged in estimated pricing.

PV: Utility Scale vs Residential

- PV Generation costs:
  - residential-scale systems: 16.7¢/kWh
  - utility-scale PV systems: 8.3¢/kWh
- Reasons for this gap:
  - lower total plant costs per installed kilowatt for larger facilitie
  - greater solar electricity due to optimized panel orientation and tracking;
  - other economies of scale and efficiencies
- Avoided transmission and distribution costs by residential-scale systems are not large enough to significantly impact this gap in generation costs.



See also: http://www.npr.org/templates/story/story.php?storyId=110997398

Competing Requirements for the Electric Grid

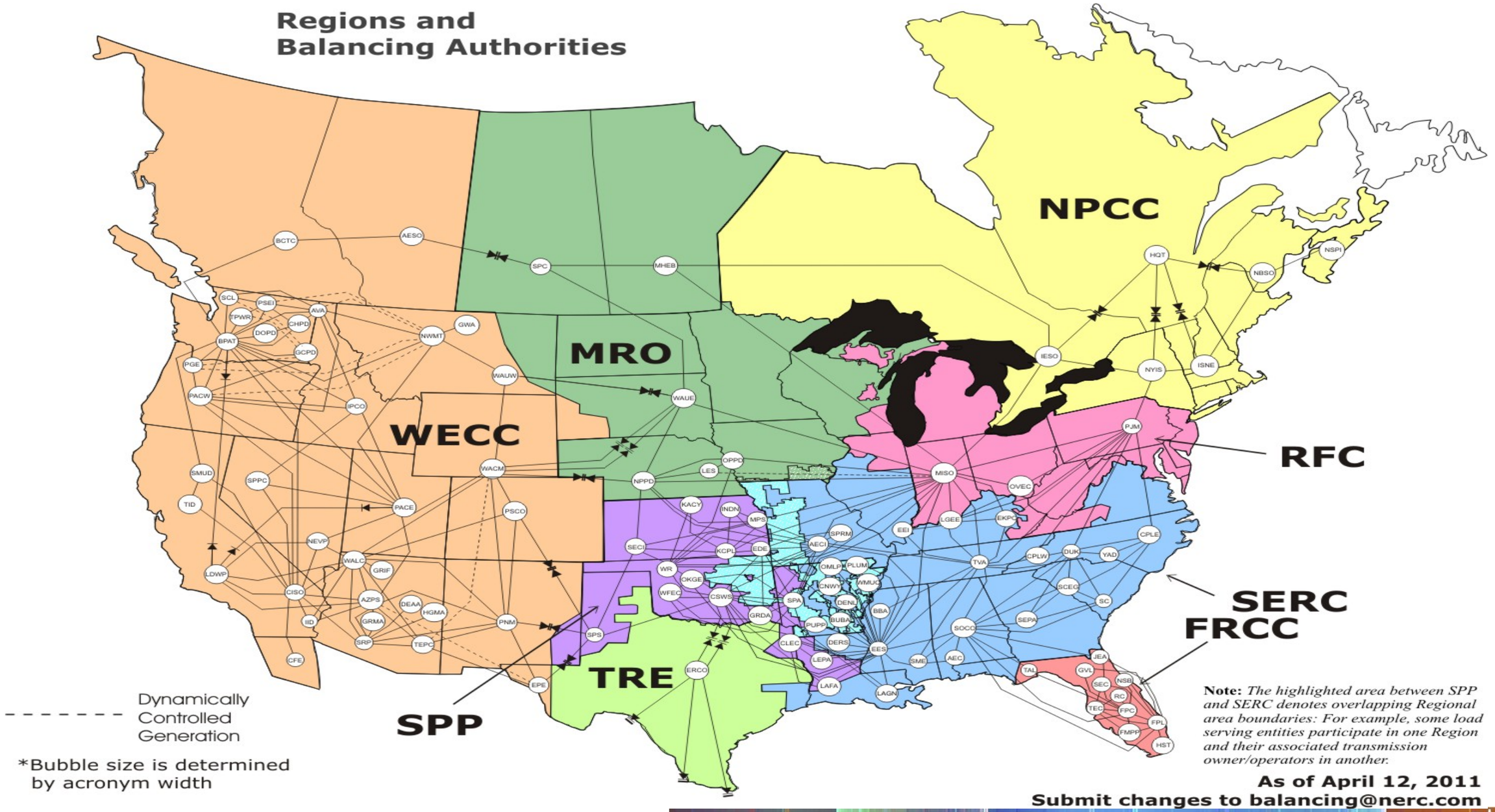
- Reliability
  - Capacity adequacy, fuel security, system operations and control, cybersecurity, resilience to extreme events, variability of renewable generation, leveraging demand flexibility
- Sustainability
  - Renewable generation, energy efficiency
- Cost
  - Economic growth, quality of life, low income consumers, developing nations,

Electric Grid Characteristics

- High voltage transmission network - a *mesh* network
- Distribution networks - largely *radial* networks
- *Dynamic system* with multiple time scales
- Milliseconds, seconds, minutes, hours, days, months, and years
- Electric energy storage - very expensive
- Energy produced must equal energy consumed on a second-by-second basis – *power balance*
  - *A complex hierarchical control system to ensure stability and performance of the large scale networked power system*

Power Balance

- *Power balance* – balance power generation and consumption on a second-by-second basis
- Traditional Approach: *adjust supply to meet demand with reliability*
- Natural uncertainty in consumption [load]
- Use of reserve capacity to manage uncertainty and contingencies
- Day-ahead – hourly schedules, one day ahead
- Real-time – 5 minute schedules, 15 minutes ahead
- Automatic generation control using system frequency
- Deregulation of the electricity sector – *unique mix of engineering and economics*

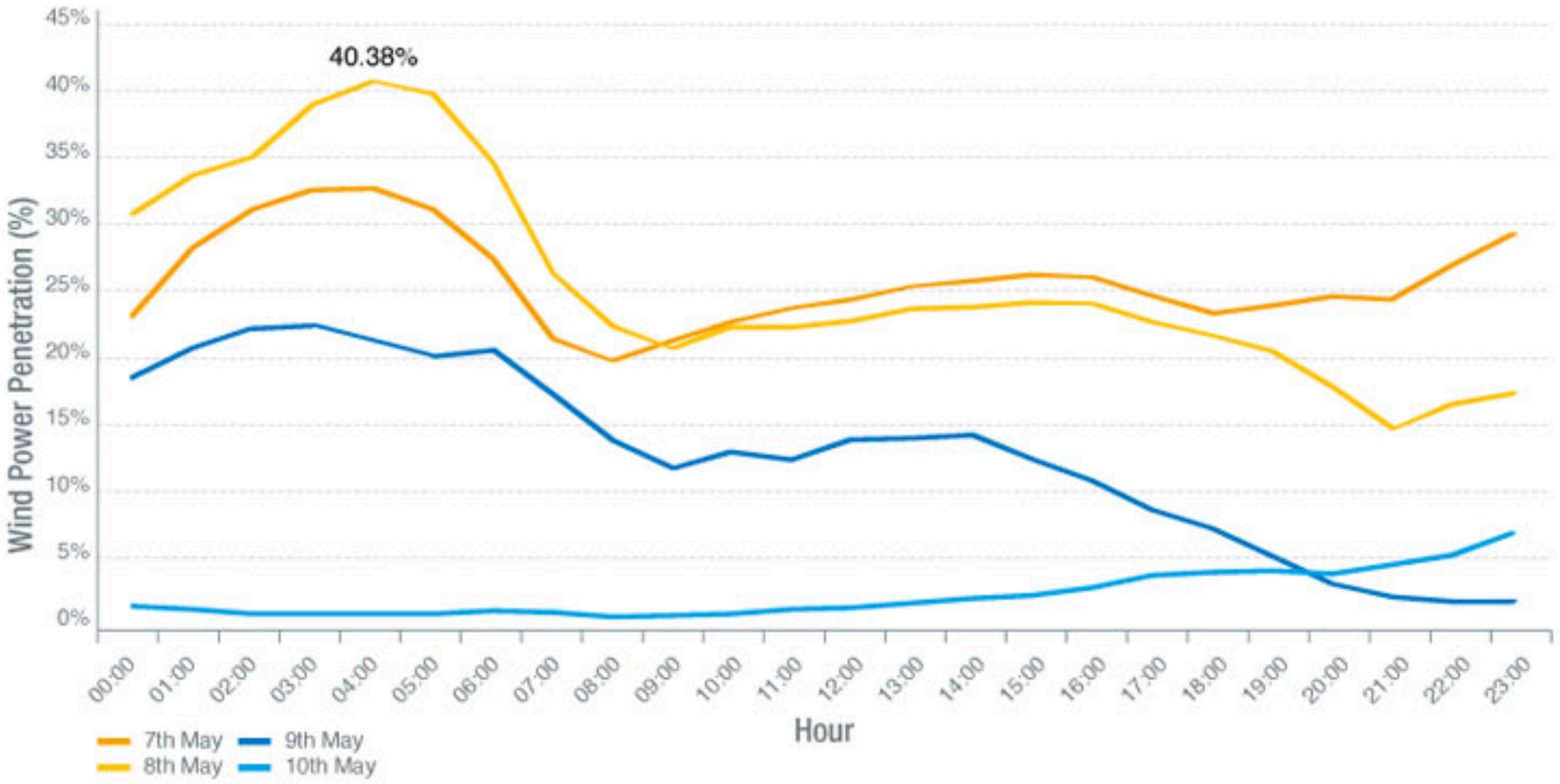

Regions and
Balancing Authorities
NPCC
MRO
WECC
RFC
SERC
FRCC
TRE
SPP
Dynamically
Controlled
Generation
*Bubble size is determined
by acronym width
Note: The highlighted area between SPP and SERC denotes overlapping Regional area boundaries: For example, some load serving entities participate in one Region and their associated transmission owner/operators in another.
As of April 12, 2011
Submit changes to balancing@nerc.com

Source: NERC

Variability of Wind and Solar

- Power output varies in all time frames:
  - Annual
  - Seasonal
  - Daily
  - Hours
  - Minutes
  - Seconds

Hourly wind penetration in Ireland May 7–10, 2009



Source: NREL

Intermittency, uncontrollability, and uncertainty - principal causes of difficulty at the operational level in integration of wind and solar into the grid.

California Duck Curve

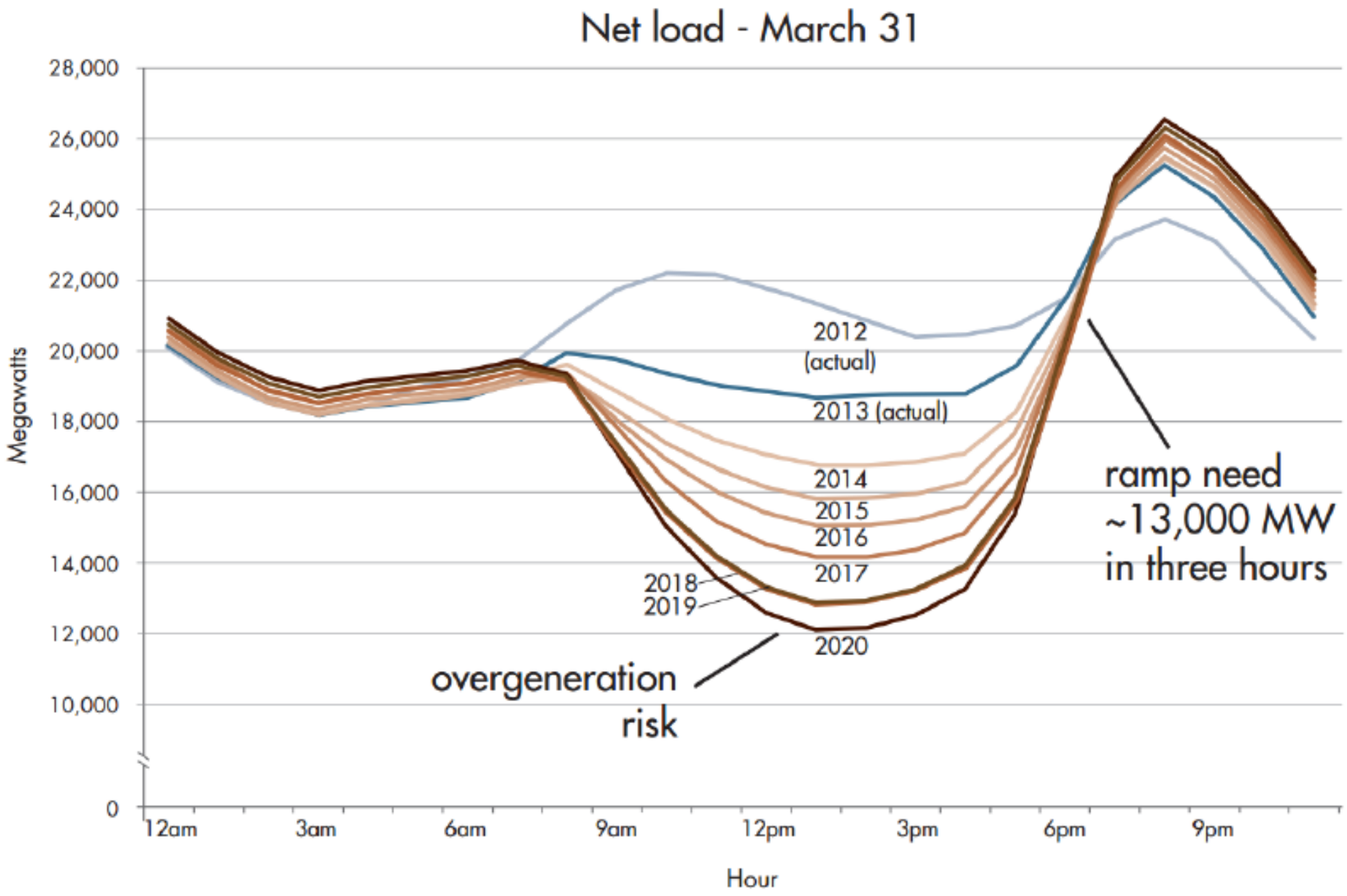


Figure 1. The CAISO duck chart

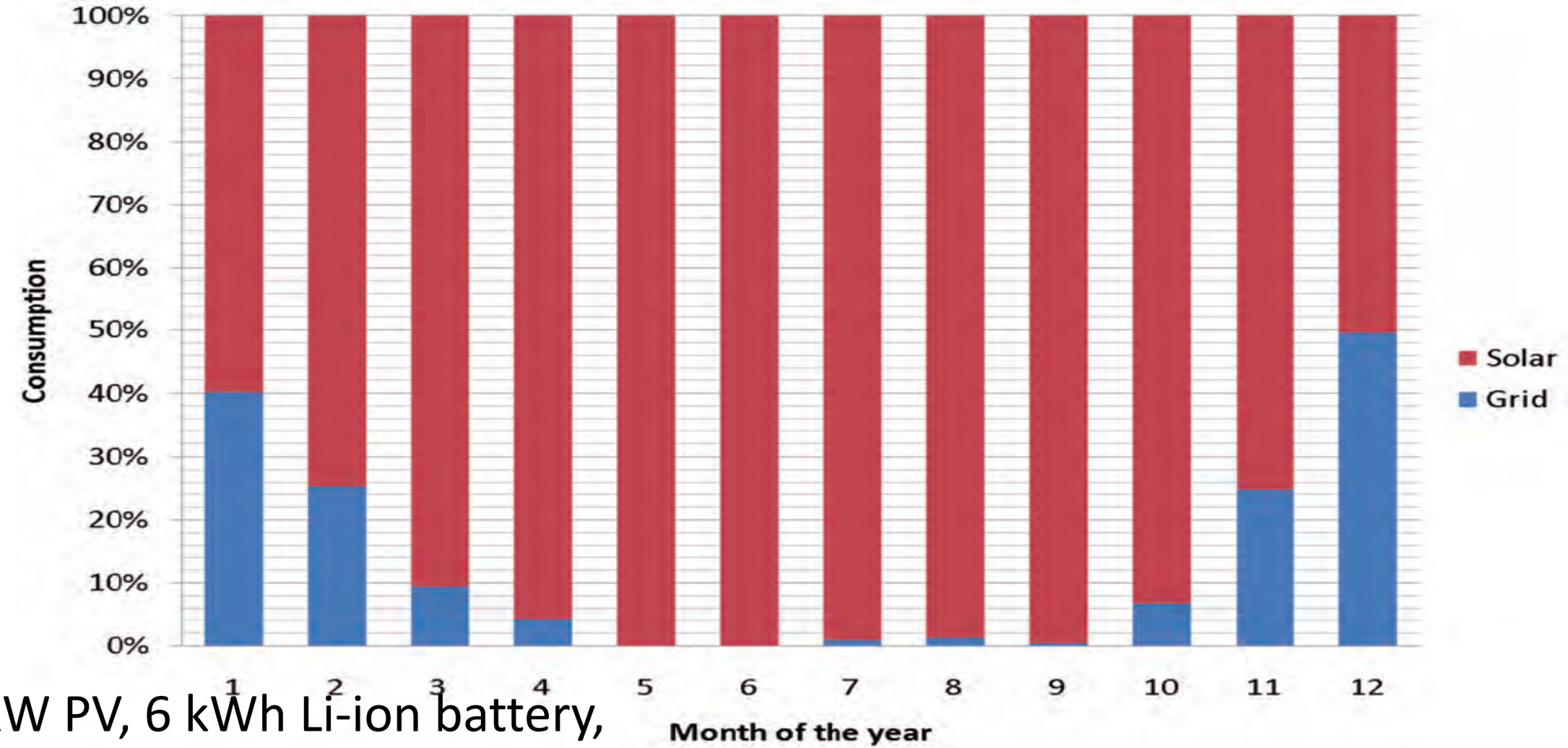
Source: CAISO 2013

Enablers of Renewables Integration

- New transmission infrastructure including DC
- Larger balancing areas and geographic aggregation
- Improved forecasting
- Stochastic optimization for smart operations
- Demand side control
- Distributed deployment and control
- More frequent intra-day markets
- Storage
- Electric transportation
- Conversion to transportation fuels

Imagine if we had Cost Effective Storage and PV

Madrid, Spain



10.7 kW PV, 6 kWh Li-ion battery, electronics/controls

Source: Schwunk, Fraunhoffer

ECCS: Renewables DCL

- NSF 15-082: “Dear Colleague Letter: Research on Theory and Analytical Tools for Power Networks with High Levels of Renewable Generation”

- Purpose: support creative ideas addressing the continuing rise of renewable electric power generation.

ECCS: Renewables DCL

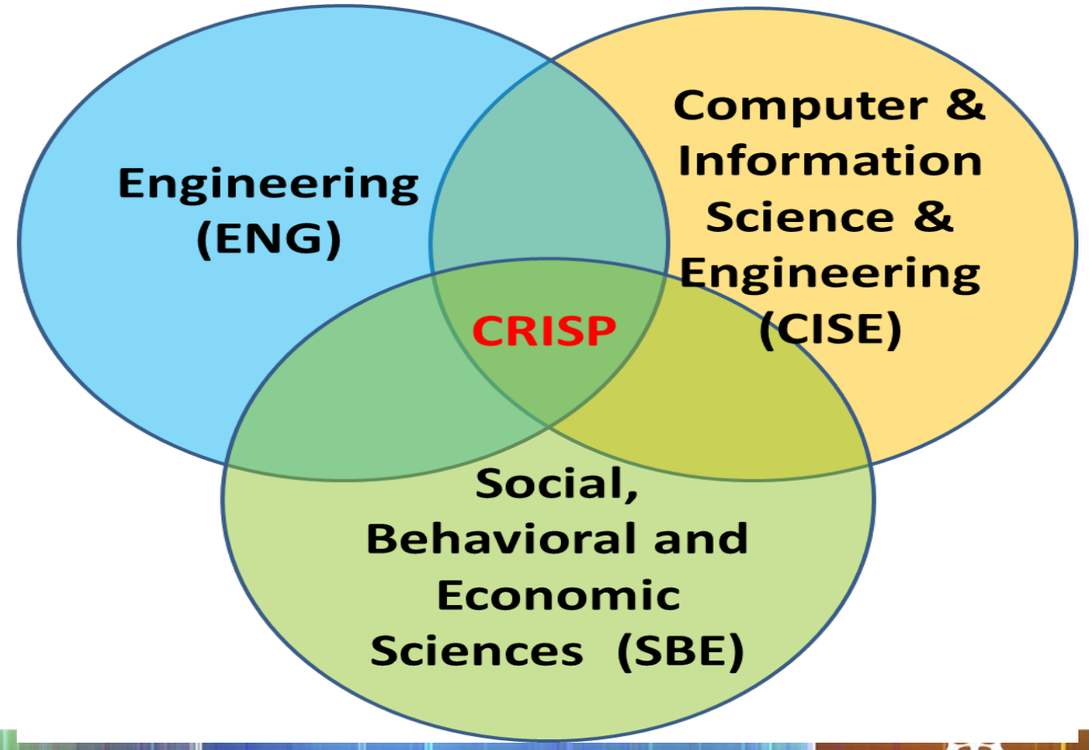
- Does large penetration of renewables affect power quality & grid stability? If so, what needs to be done? New policy? New automation?
- Are current market mechanisms appropriate going forward?
  - What policies should be in place to avoid undesired economic consequences of the evolution to the next generation grid?
- Do protection systems need redesign as the penetration of renewables increases?

Funded Proposal Topics (14 Grants)

- Grid stability analysis techniques with stochastic renewables (Mathieu; Chow).
- Policy issues for long term planning of the transition from thermal-dominated electric energy systems to a renewable-dominated design (Conejo; Tong).
- Stochastic optimization/mixed-integer programming for topology control of future grid (Oren/Sen)
- Design of new market mechanisms (Gupta/Turitsyn; Li; Poolla; Parvania/Scaglione; Zhu)
- Prosumer-centric energy management incorporating behavior modeling (Xie; Saad/Poor/Mandayam) – including use of Nobel prize winning “prospect theory” methodology by the latter team.
- Applying allometry (development of biological shapes) to understanding of power distribution network structure (Dobson).
- New framework for power system protection (Santoso).

CRISP: Critical Resilient Interdependent Infrastructure Systems & Processes

- FY15 funding for CRISP: $20 million
  - *Type 1 Awards*: 3-year projects, $500k max
  - *Type 2 Awards*: 3-4 year projects, $1M-$2.5M



CRISP Program Goals

1. Create new approaches/solutions for design/operation of infrastructures as processes/services
2. Enhance understanding/design of ICIs and processes under disruptions from any cause
   - natural, technological, organizational or malicious
   - various timescales and intensities
3. Create knowledge for innovation in ICIs to safely, securely, and effectively expand range of goods and services they enable
4. Improve ICI's effectiveness, efficiency, dependability

Engineering Research Centers

- Future Renewable Electric Energy Delivery and Management Systems Center (FREEDM)
- Center for Ultra-Wide Resilient Electric Energy Transmission Networks (CURENT) – joint with DoE
- Quantum Energy and Sustainable Solar Technologies (QUEST)- joint with DoE
- Smart Lighting
- New ERC Competition *underway*

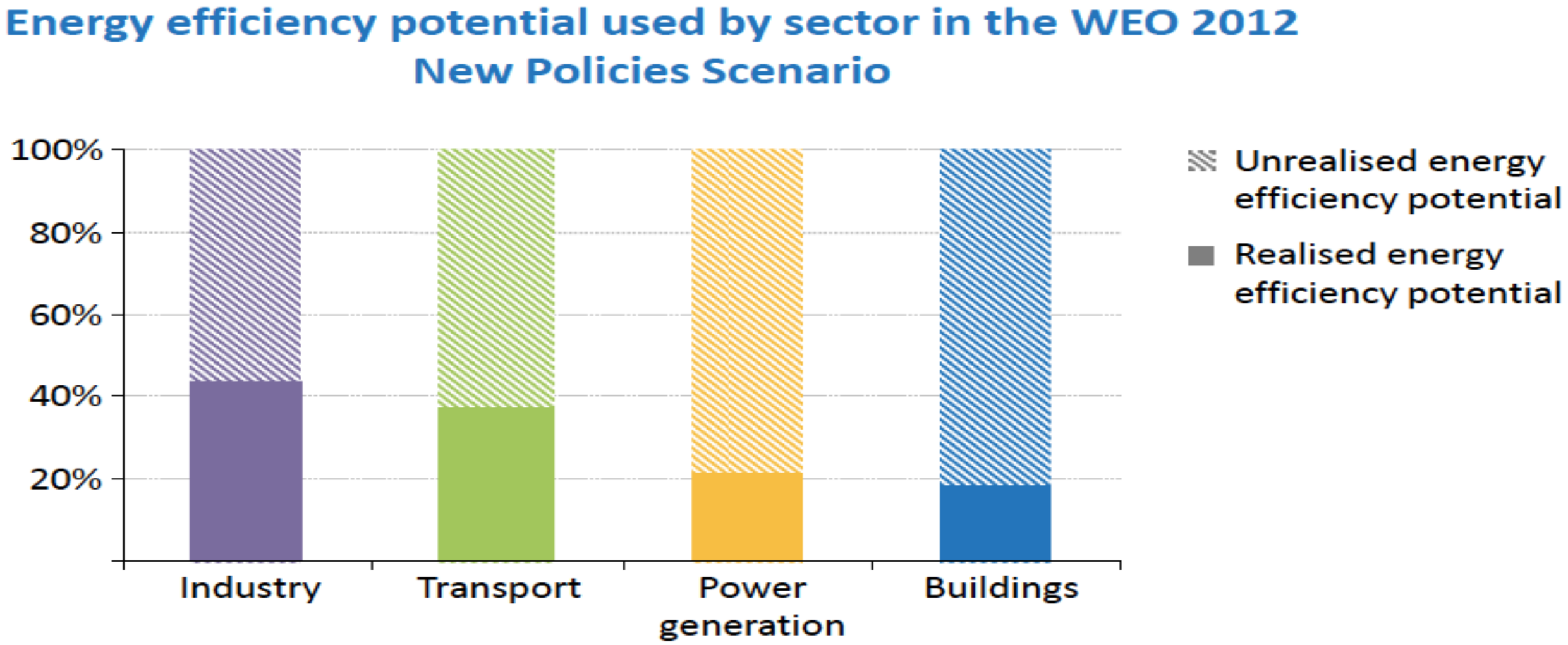
Industry-University Cooperative Research Centers

- Power Systems Engineering Research Center (PSERC)
- Energy-Smart Electronic Systems (ES2)
- Energy Harvesting Materials and Systems (CEHMS)
- Grid-Connected Advanced Power Electronic Systems (GRAPES)
- Advanced Vehicle and Extreme Environment Electronics (CAVE3)
- Novel High-V/T Materials and Structures (HVT)
- Next Generation Photovoltaic
- Silicon Solar Consortium
- Wind Energy Science, Technology and Research (WindSTAR)

The most important way to speed up the gradual transition to renewables is to lower overall energy use through efficiency gains. The faster global demand rises, the more difficult it is to supply a large fraction of it.

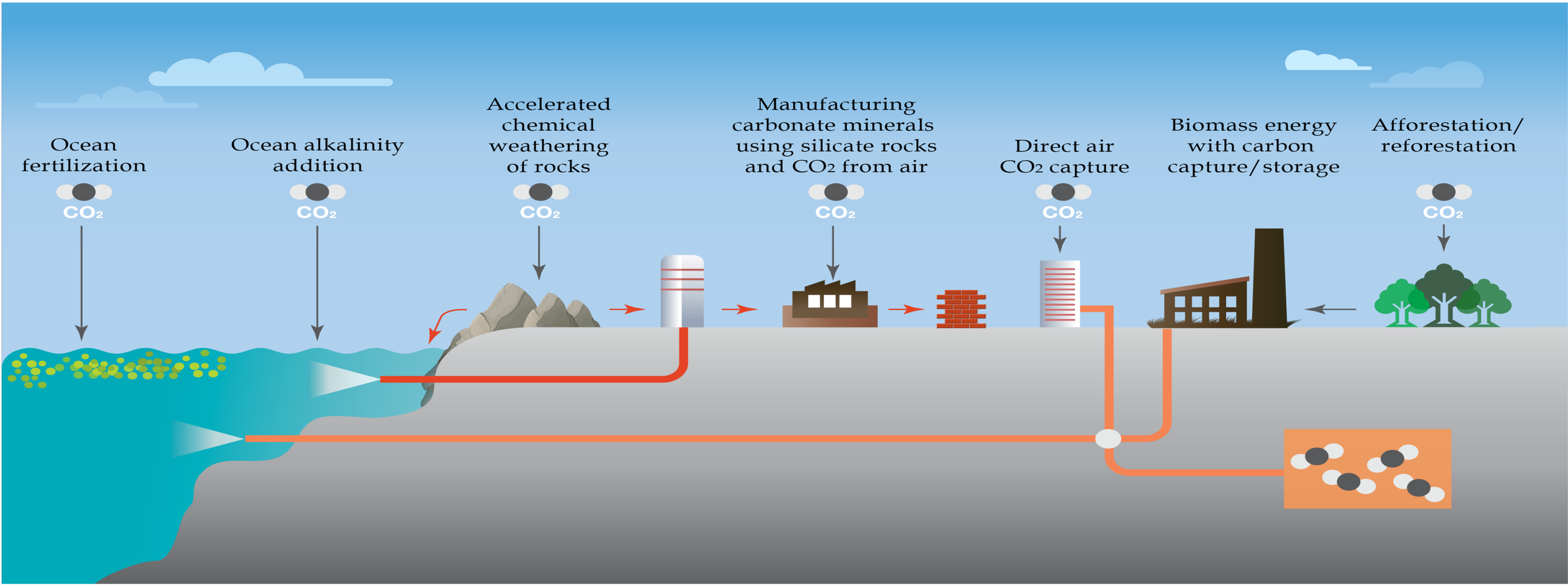
Vaclav Smil, Scientific American, January 2014

IEA on Energy Efficiency



Source: IEA, WEO 2012

Negative Emissions Technologies



Source: Caldeira, K., Bala, G., Cao, L., 2013.
The Science of Geoengineering.
Annu. Rev. Earth Planet. Sci. 41, 231–256.

… the CO2 trend “is perfectly in line with a temperature increase of 6 degrees Celsius, which would have devastating consequences for the planet.”

Fatih Birol

IEA chief economist

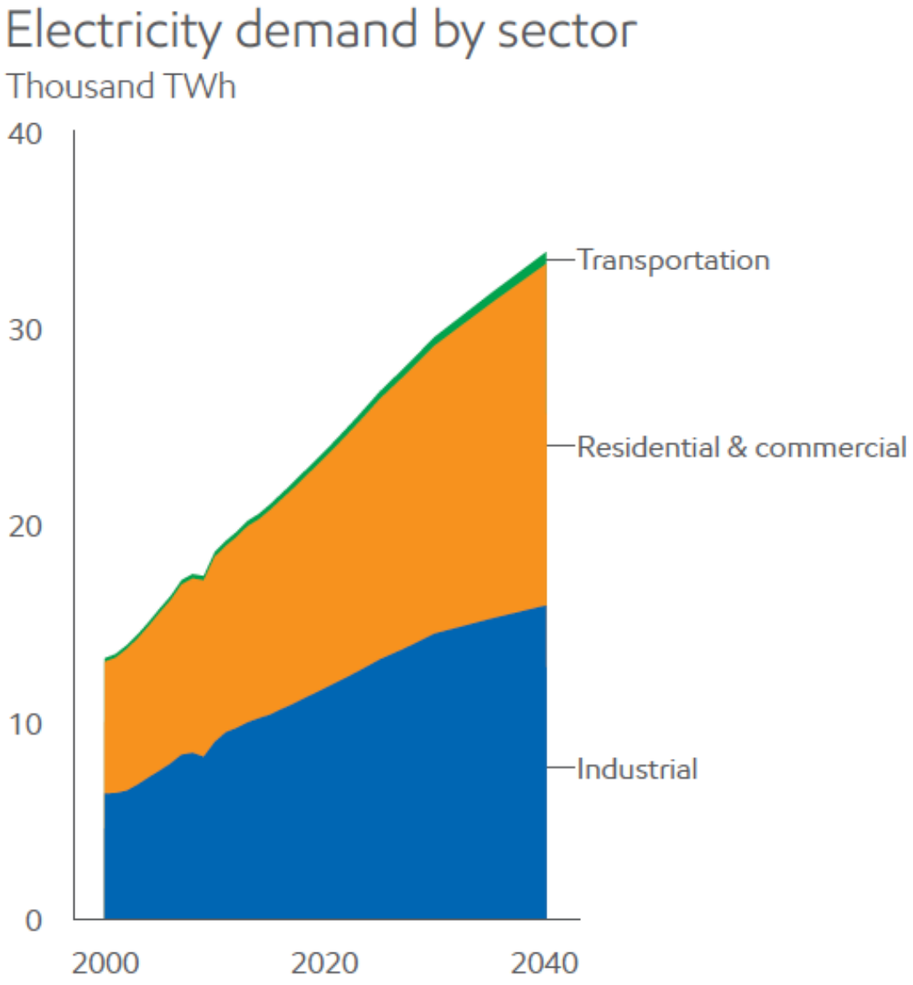
QUESTIONS?

IDEAS, SUGGESTIONS!

pkhargon@nsf.gov

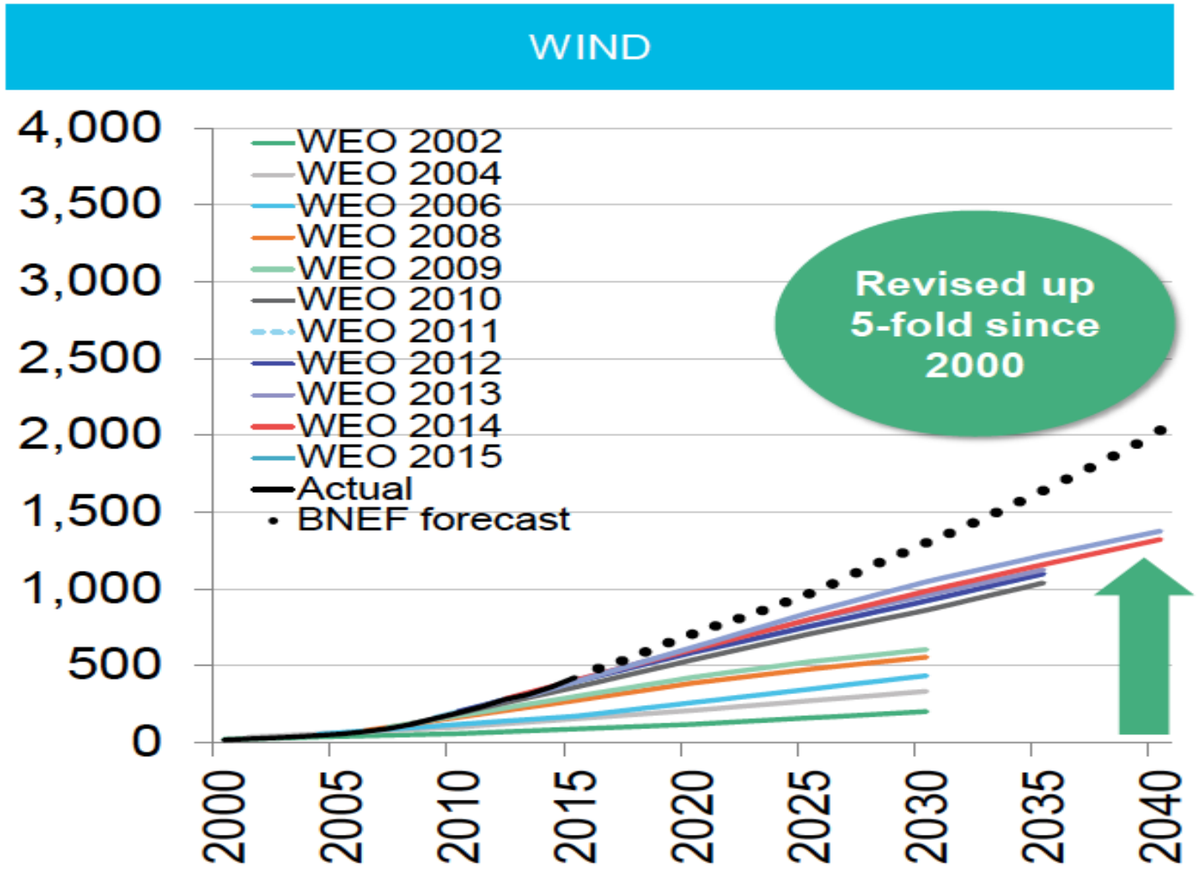
Electric Energy Projections

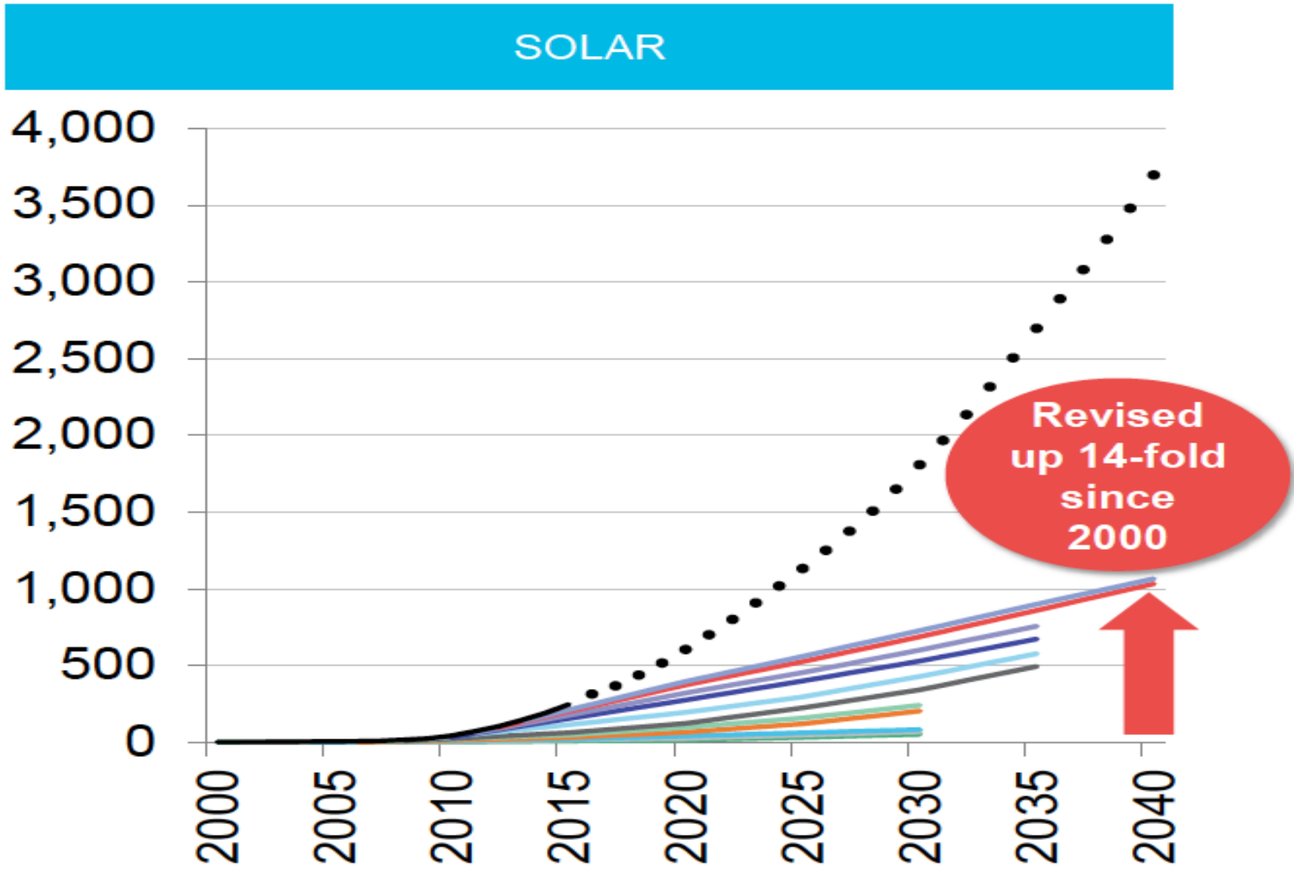
- Global electricity demand rising by 65 percent 2014-2040
- Residential and commercial electricity demand rises by 70 percent 2014-2040; industry up 55 percent
- Industrial growth eases post-2030 as China's economy shifts from manufacturing
- Transportation electricity demand doubles 2014-2040, but only 2 percent of total use



Source: Exxon Annual Energy Outlook

Wind and Solar Capacity Projections





Source: IEA, Bloomberg New Energy Finance,

Electricity System R&D Needs

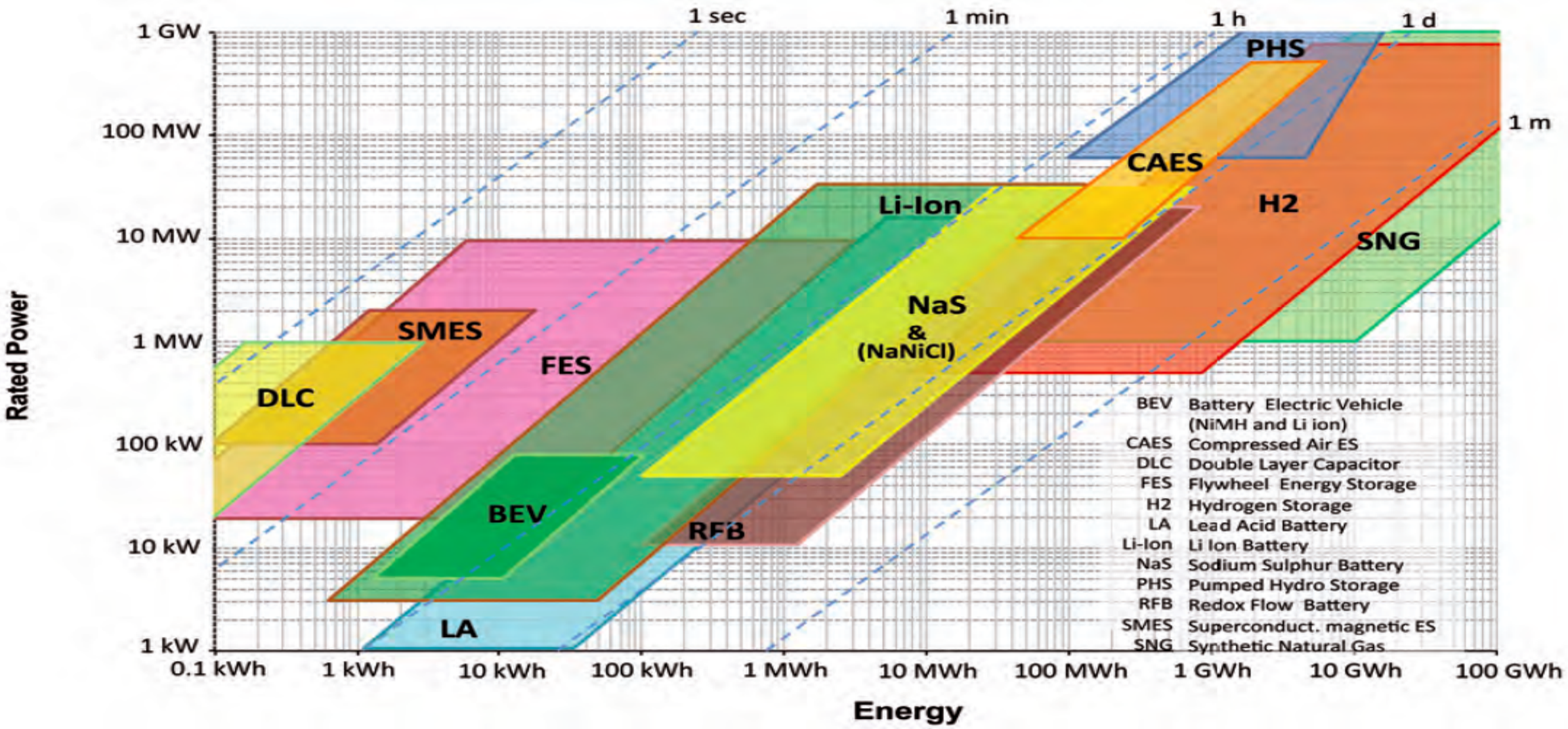
- Develop and refine interoperable grid architectures and new system designs
- Develop software and visualization tools that use new data from transmission and distribution system devices for enhanced, real-time operations and control
- Research material innovations and develop transmission and distribution component designs for higher performance, reliability, and resilience
- Embed intelligence, communication, and control capabilities into distributed energy resources and systems such as microgrids to support grid operations

Electricity System R&D Needs

- Improve energy storage capabilities and systems designs that lower costs while increasing capacity and performance, and facilitating integration
- Develop high-fidelity planning models, tools, and simulators and a common framework for modeling, including databases
- Design innovative technologies and resilient and adaptive control systems to improve physical- and cyber-security of the grid

Key Challenges to Deep Renewable Integration

- New transmission infrastructure
- Larger geographic balancing areas
- Greater flexibility in all aspects of power system operations
- Cost-effective energy storage
- Provision of reserves
- Grid management and control



Source: Fraunhoffer

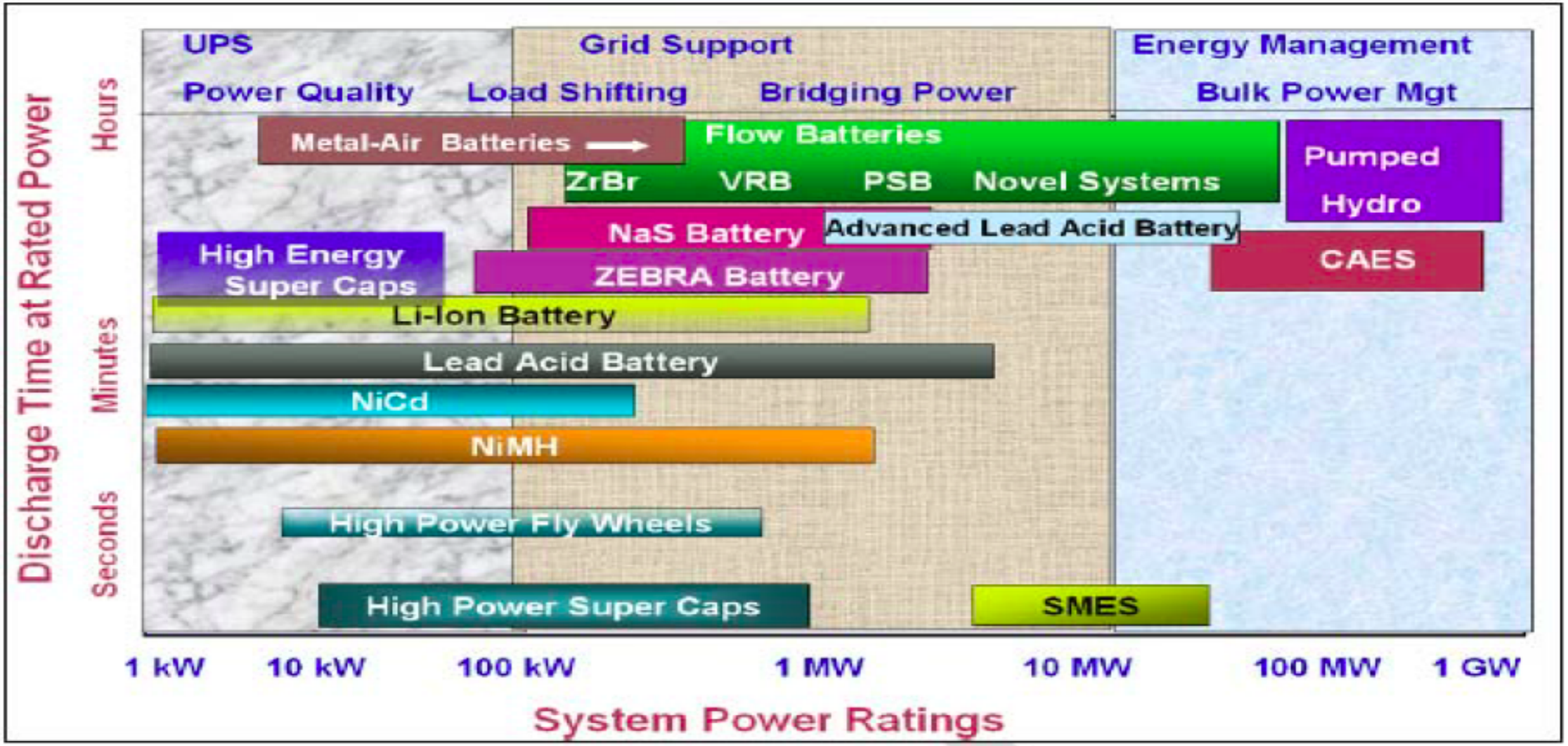


Figure 4: Energy Storage Options: Discharge Time vs. Capacity Ratings[20]

NET	2050 Potential (per year)	Key constraints	Notes
Afforestation and Other Forestry	1-3 $GtCO_2$, 0.13-0.38 ppm	Conservative estimates of available land area and carbon yields	Higher estimates for afforestation may conflict with land used for food production or energy crops
Agricultural Soil Carbon	1.4-3.9 $GtCO_2$, 0.18-0.50 ppm	Suitable land areas and attainable annual sequestration rates	Fewer trade-offs with other land uses; saturation and risk of impermanence limit cumulative potential
Biochar	~2.2 $GtCO_2$, ~0.28 ppm	Pyrolysis of 60 EJ per year (3 Gt per year) bioenergy residues and wastes	May conflict with other demands for residues and wastes; assumes 80% stability over century timescales
BECCS	~1.5 $GtCO_2$, ~0.19 ppm	Constrained by CCS roll-out and integration with bioenergy, using IEA projections for 2050	Bioenergy supply is a less limiting constraint than CCS development to 2050.
Direct Air Capture	~0.25 $GtCO_2$, ~0.03 ppm	This figure assumes use for EOR at a scale equivalent to the current US market	High costs give it very little role pre-2050 in 'optimal' mitigation models
Ocean Liming	~0.25 $GtCO_2$, ~0.03 ppm	This figure assumes all existing lime wastes from cement production are used for carbon capture	No detailed projections / models available, but similar challenges to DAC
TOTAL	6.6-11.1 $GtCO_2$, 0.85-1.42 ppm		

Carbon Budgets

Table 1: 2011 and 2014 remaining cumulative carbon budgets for different peak warming and probability thresholds. Data and information are taken from table 2.2 of IPCC Syn, 2014 with cumulative emissions between 2011-2013 calculated from Le Quéré, 2014.

	Warming*	Likelihood**	Budget (CCE)*** in 2011	Emitted (CCE) 2011-2013	Budget (CCE)*** in 2014
[GtCO2]	< 1.5°	66%	400	116	284
		50%	550	116	434
		33%	850	116	734
	< 2.0°	66%	1000	116	884
		50%	1300	116	1184
		33%	1500	116	1384
	< 3.0°	66%	2400	116	2284
		50%	2800	116	2684
		33%	3250	116	3134
[GtC]^	< 1.5°	66%	109	32	77
		50%	150	32	118
		33%	231	32	200
	< 2.0°	66%	272	32	241
		50%	354	32	322
		33%	408	32	377
	< 3.0°	66%	653	32	622
		50%	762	32	731
		33%	885	32	853

^Conversion factor: 1 GtC = 3.664 GtCO2

Source: Pfeiffer et al 2016, Oxford University