Renewing Our Energy Future

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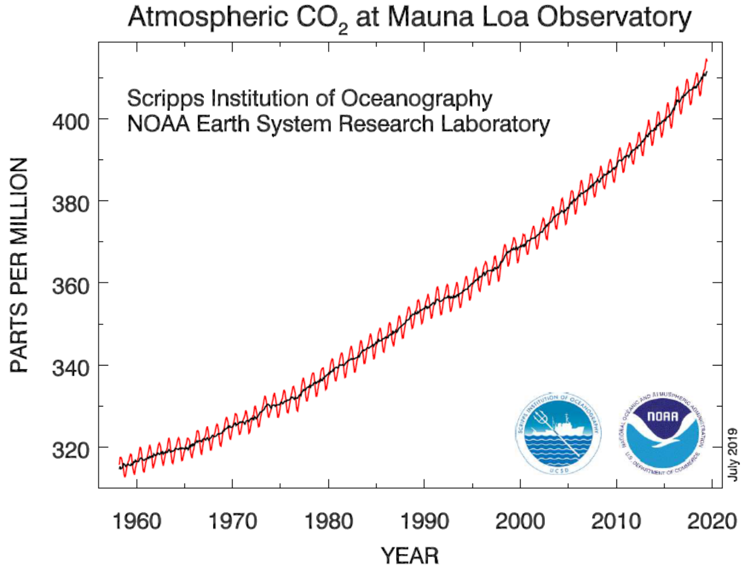
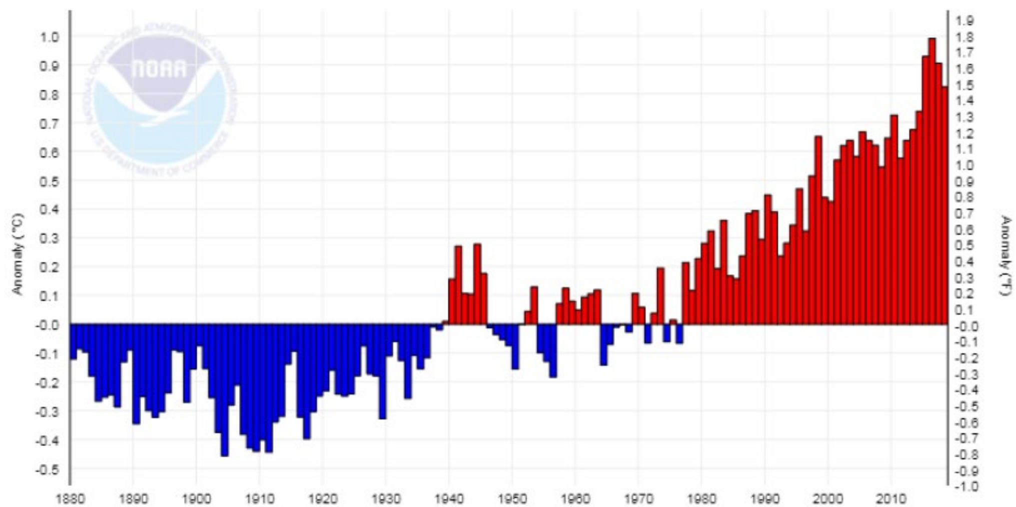
Observed Atmospheric CO_2 and Temperatures

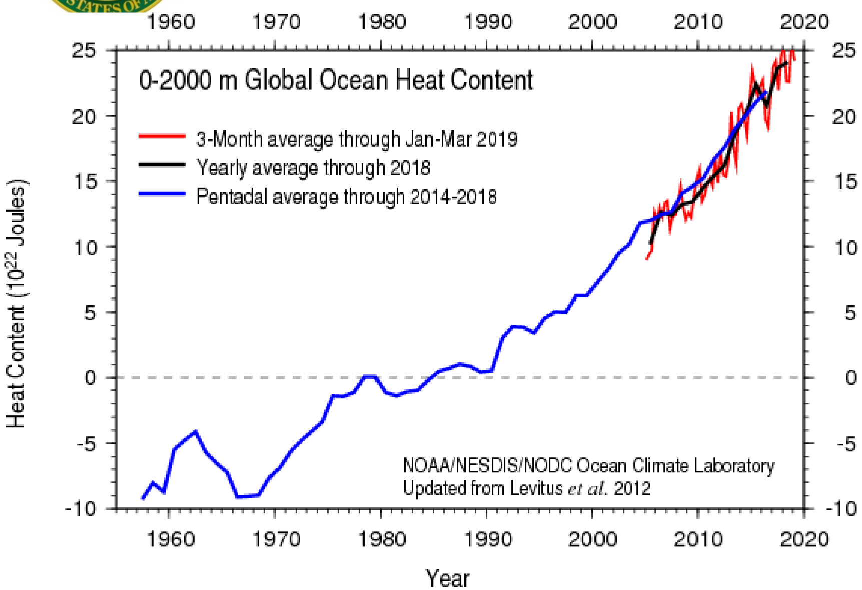


https://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/co2_data_mlo.pdf



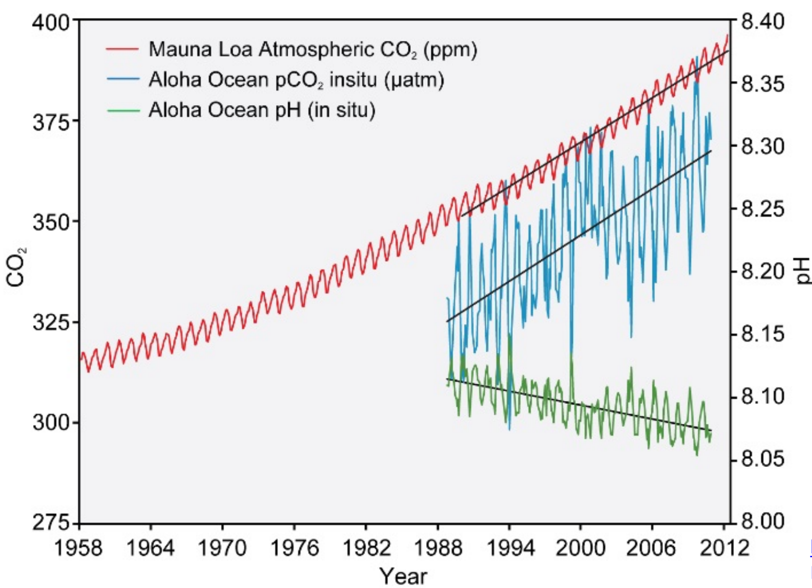
NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published July 2019, retrieved on July 25, 2019 from https://www.ncdc.noaa.gov/cag/

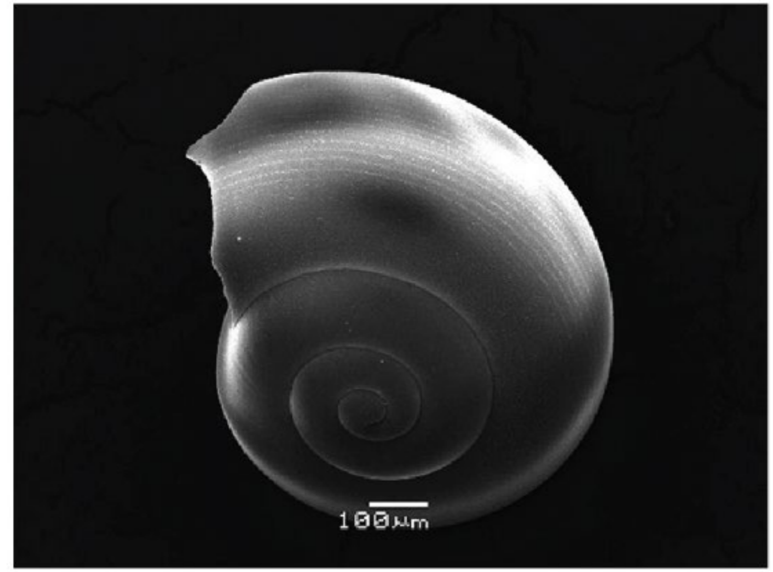
Observed Oceanic Temperatures and CO_2

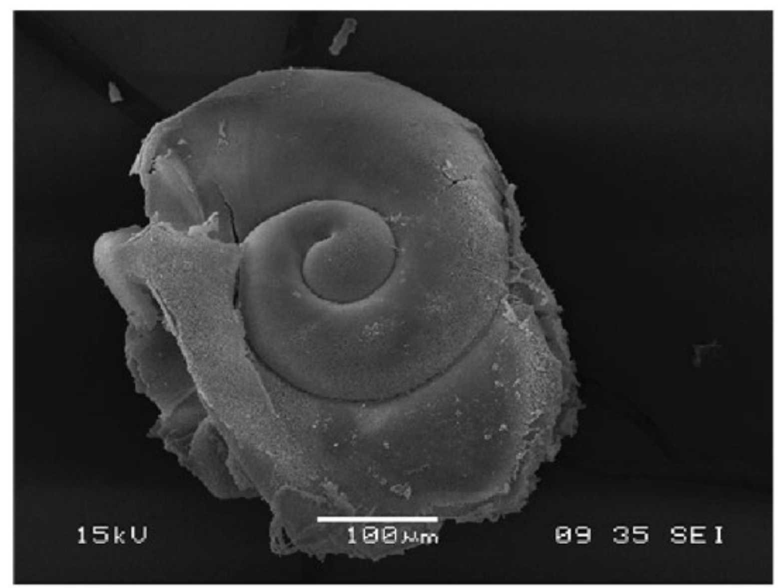


NOAA Ocean Heat and Salt Content, https://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/

As Oceans Absorb CO_2, They Become More Acidic



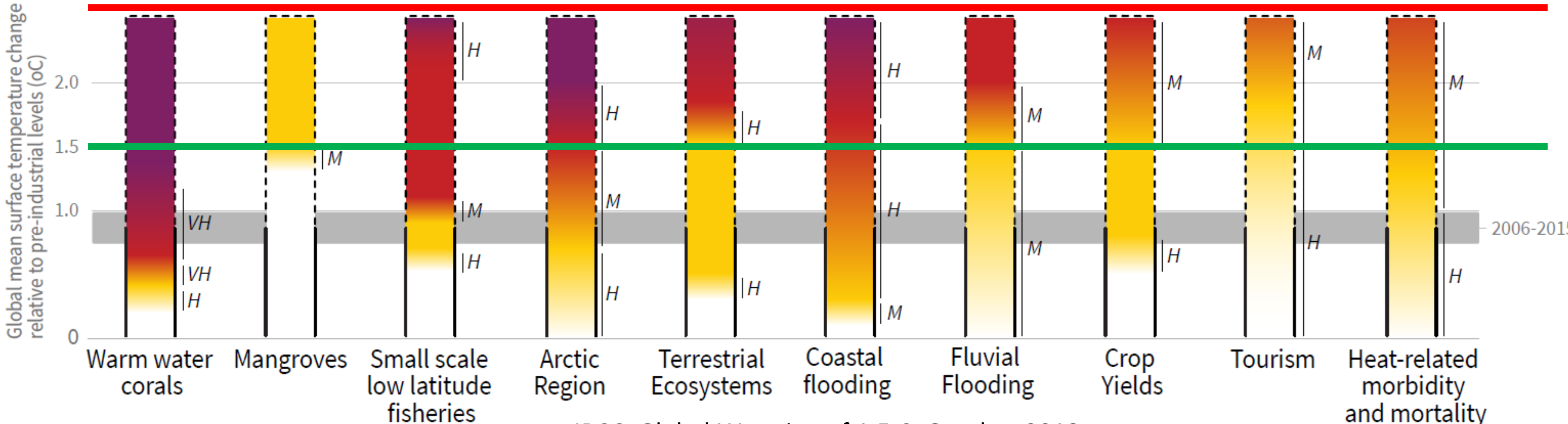




https://nca2014.globalchange.gov/report/our-changing-climate/ocean-acidification#intro-section-2

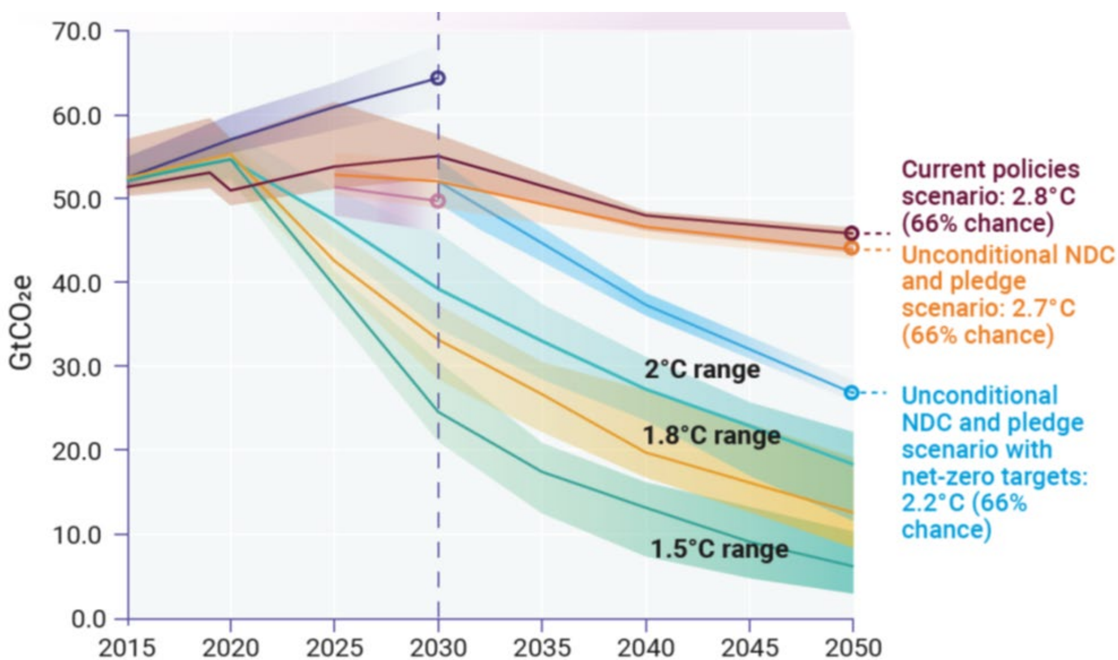
Photos: Bednarsek, et al, “Extensive Dissolution Of Live Pteropods In Southern Ocean”, Nature Geoscience, 2012, p.881

Impacts & Risks for Selected Natural, Managed, & Human Systems



IPCC, Global Warming of 1.5 C, October 2018

UNEP, Emissions Gap Report 2021



Energy and Efficiency Challenges

- **Security**
  - **Physical security**, e.g., energy infrastructure
  - **Availability of energy supplies, critical materials, equipment**
  - **Conflict-related security** impacting global energy commodities or equipment

- **Economic**
  - **Energy prices, price volatility, import costs**
  - **Energy system investments—capital intensive, long lifetime, subject to fuel price volatility**
  - **Costs of Energy Disruptions**

- **Environmental**
  - **Atmosphere:**
    - **Pollutants** (e.g., SOx, NOx, PM [$PM_{2.5}$], Hg, Pb, …)
    - **GHGs** (e.g., CO_2, CH_4, BC, N_2O, …)
  - **Water: Pollutants** (e.g., acids, toxics), thermal discharges, water withdrawals, physical disruption, …
  - **Land: Pollutants** (e.g., acids, toxics), physical disruption, ….
  - **Habitat; Biological Diversity**

How Can We Meet Our Energy Challenges?

- **End Use: Efficiency; Electrification**
  - Buildings
  - Industry
  - Transportation

- **Power:**
  - Renewable Energy; Fossil/CCS; Nuclear
  - Energy Storage: Batteries; PHS; CAES; H_2; Thermal; …
  - Energy Infrastructure (T&D; EV Recharging; Pipelines)
  - Negative-Emissions Technologies (ReForestation; Soil Restoration; BECCS; DAC; etc.)

- **Fuels**
  - Hydrogen, NH3, others
  - Biofuels

- **Science: Discovery Science; Directed Science**

Much can be done with existing technologies, but further Research, Development, Demonstration, and Deployment (RDD&D) can accelerate, broaden, deepen, and strengthen needed changes.

HOW DO WE MASSIVELY ACCELERATE DEPLOYMENT?

Time Frames

RDD&D

- Political decisions ~ 2-30+ years
- Technology R&D ~ 5-10+
- Production model ~ 2-4+
- Financial ~ 2-4++
- Market penetration ~10++

Speed and Scale

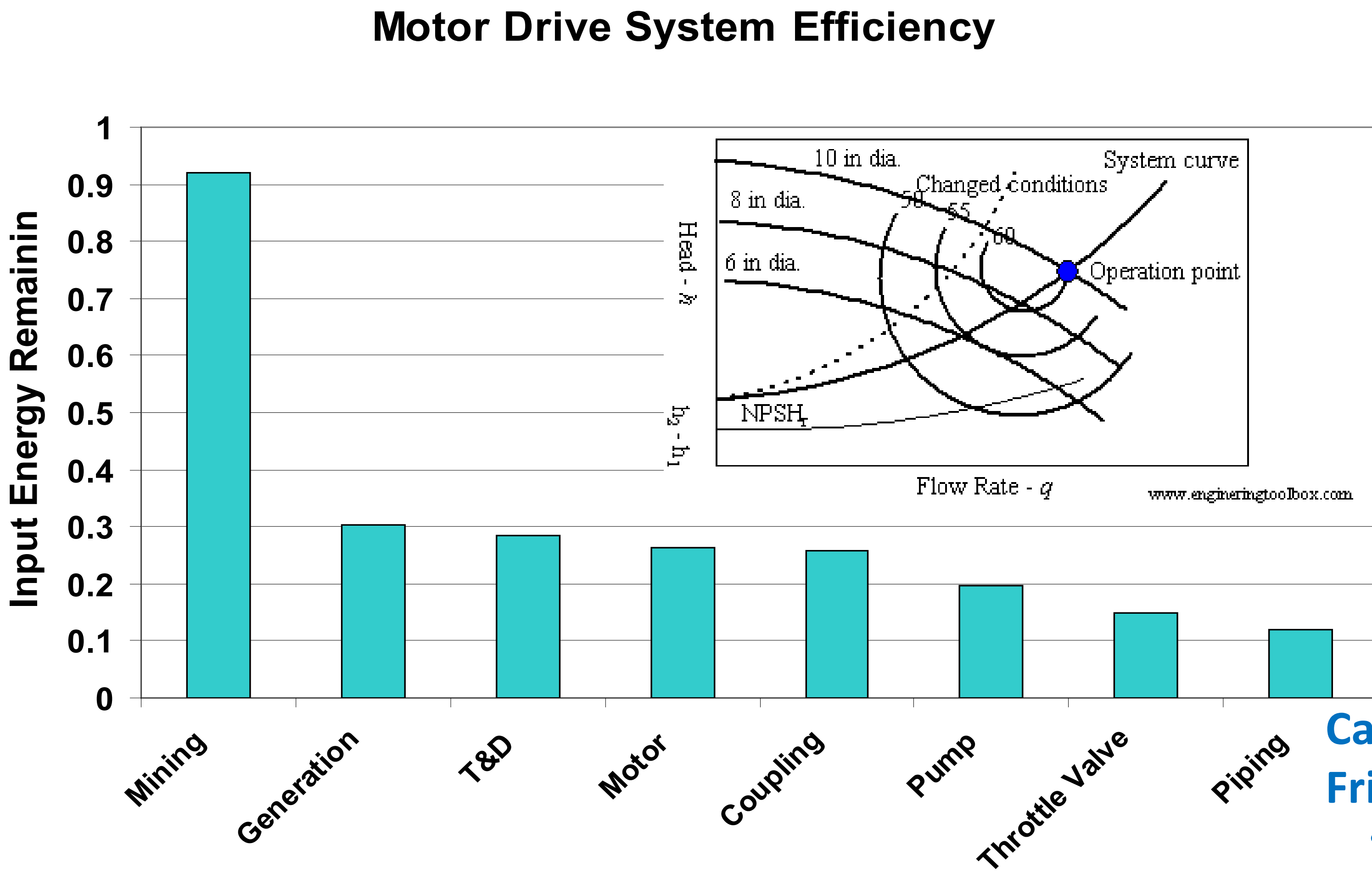
Capital stock turnover

- Cars ~ 15 years
- Appliances ~ 10-20
- Industrial Equip. ~ 10-30+
- Power plants ~ 40+
- Buildings ~ 60-80+
- Urban form ~100s

Reversals?

- Land Use Change ~ 100s++
- Extinctions ~ Never

End-Use Efficiency



Capital ~D

Friction ~1/D^5

- **GHGs**
- **Air Toxics**

Reducing energy loss in end-use systems has large leverage upstream!

Think Systems: Full System Energy Use; Material Supply/Use/End-Of-Life/; Full System Emissions/Land Use/Water Impacts/Habitat/etc.

Power Sector Pathways and Challenges

- **Efficiency Everywhere**

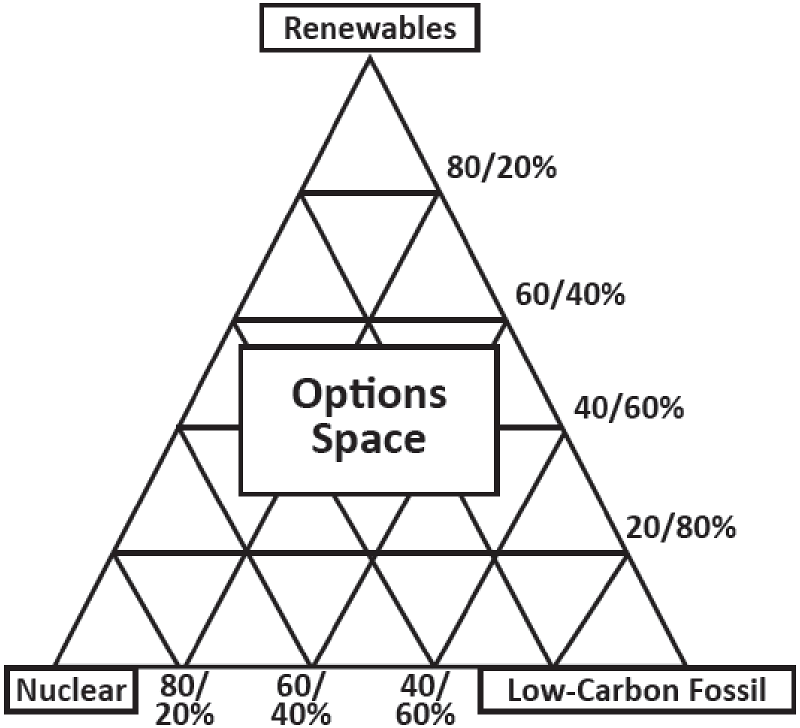
- **Clean Electricity**:
  - **Renewable Energy**
    - **Solar**
    - **Wind**
    - **Biomass Power**
    - **Geothermal**
    - **Hydropower**
    - **Ocean**
  - Fossil Energy with CCS
  - Nuclear Energy

  - **Storage**
    - **Diurnal**
    - **Long Duration**

  - **Transmission Infrastructure**

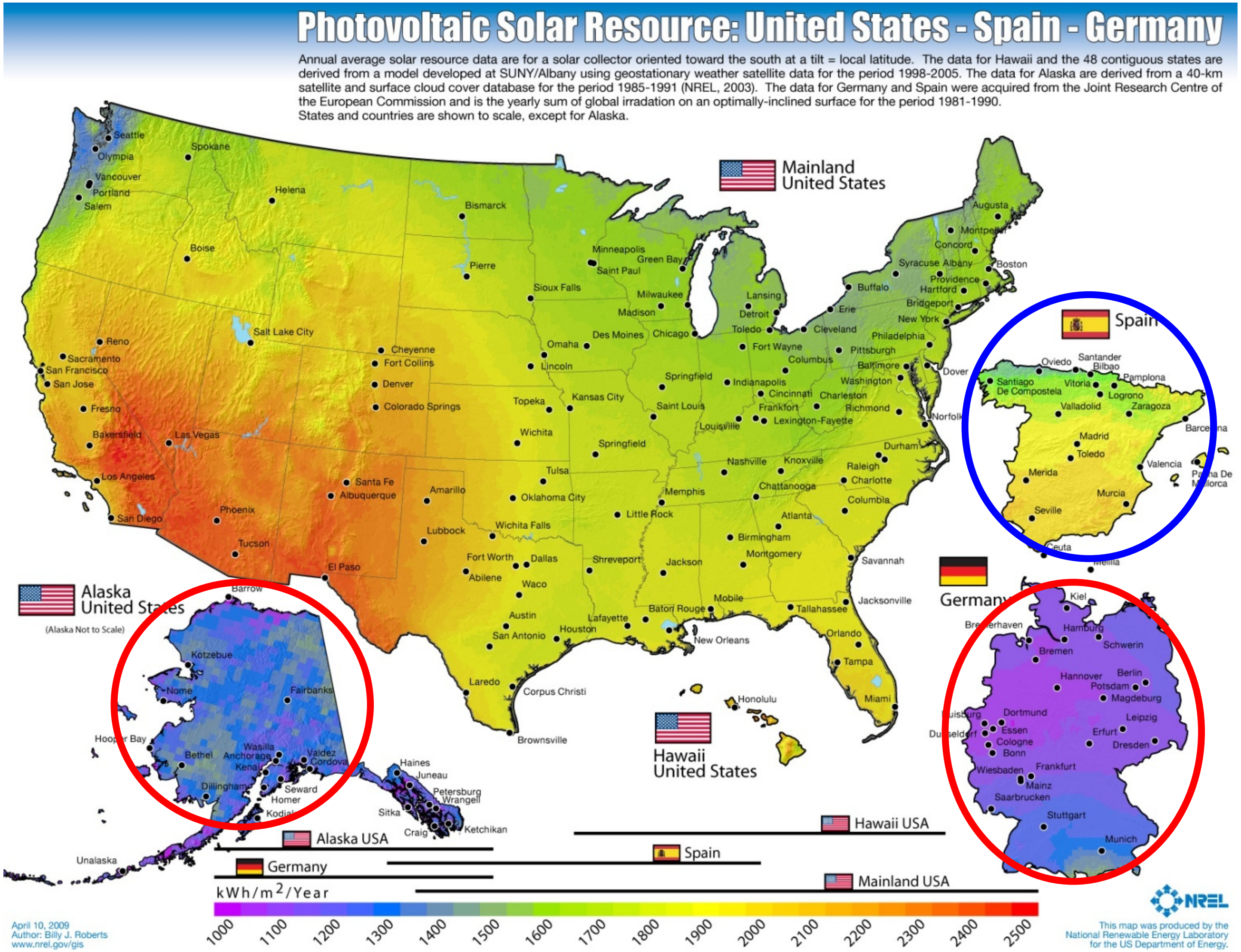
All will likely contribute to clean electricity needs for the foreseeable future.

All face challenges: technical, economic, siting, variability, land use, environmental, policy, etc.



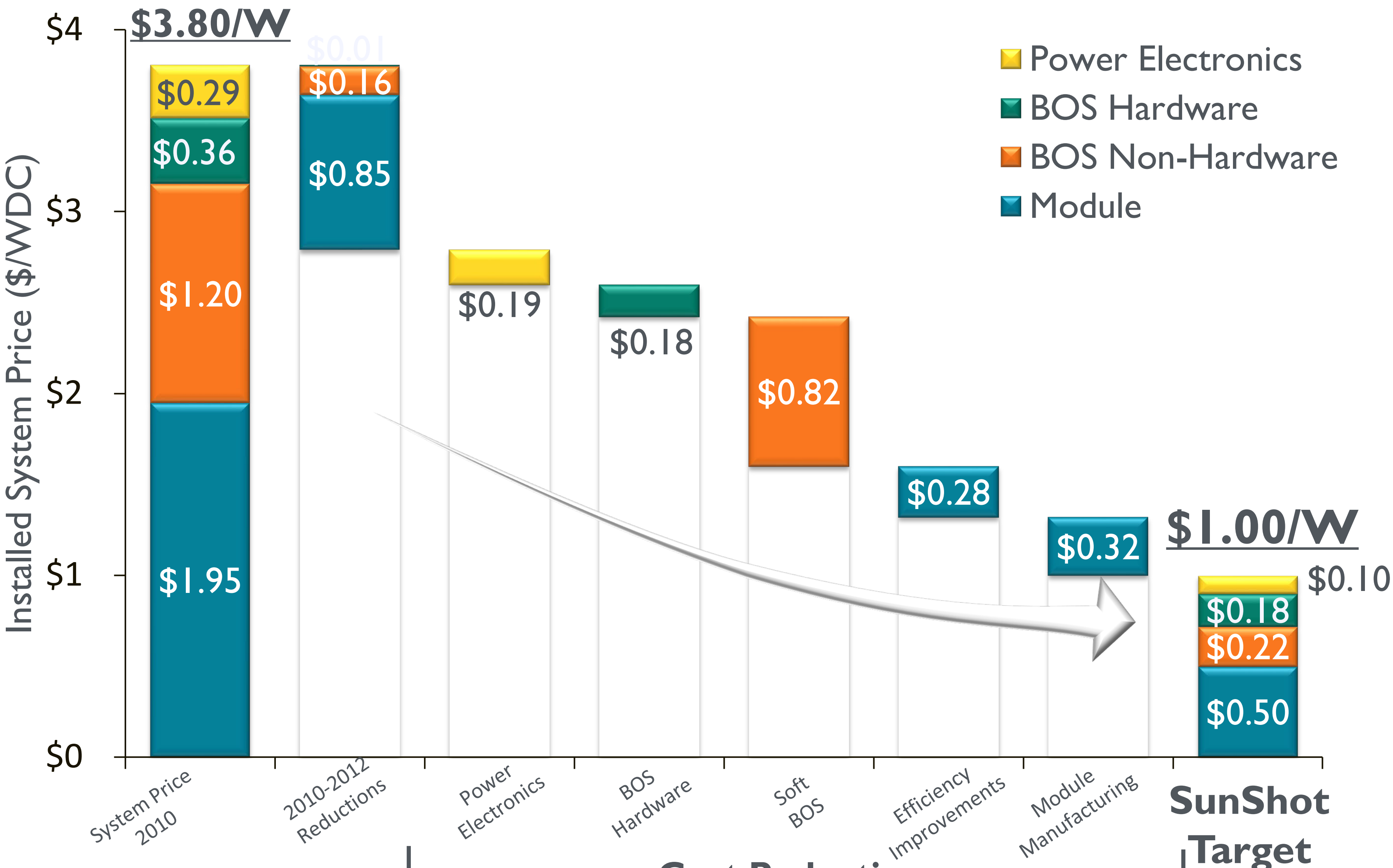
HOW FAR?
HOW FAST?
HOW WELL?
AT WHAT COST?
BEST PATHWAYS?

Solar Energy Resources



- **Solar technologies have enormous resource potential: >100X current energy use**

SunShot-2011: Directly Cost Competitive Solar by 2020
(Utility Goal Achieved in 2017)



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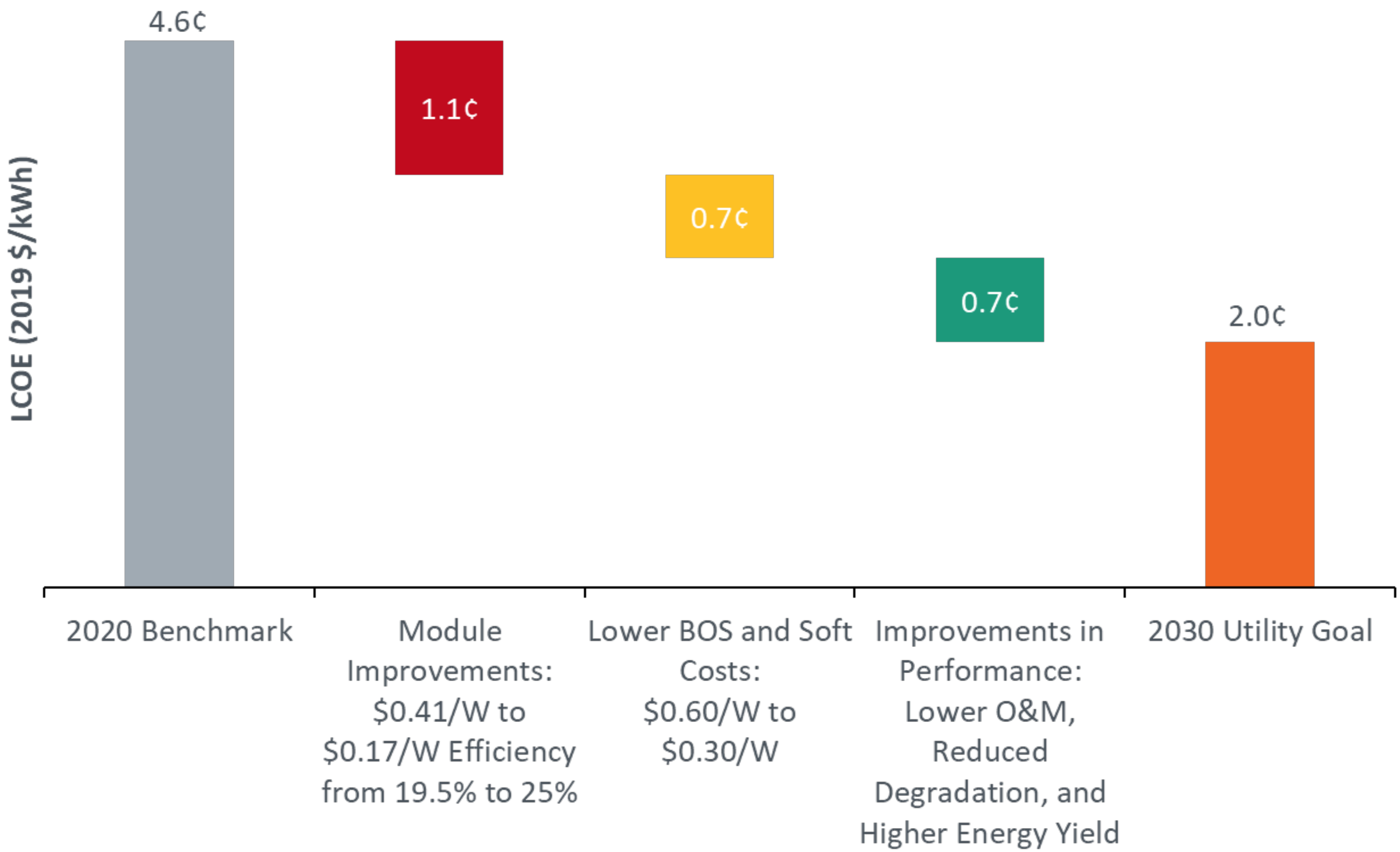
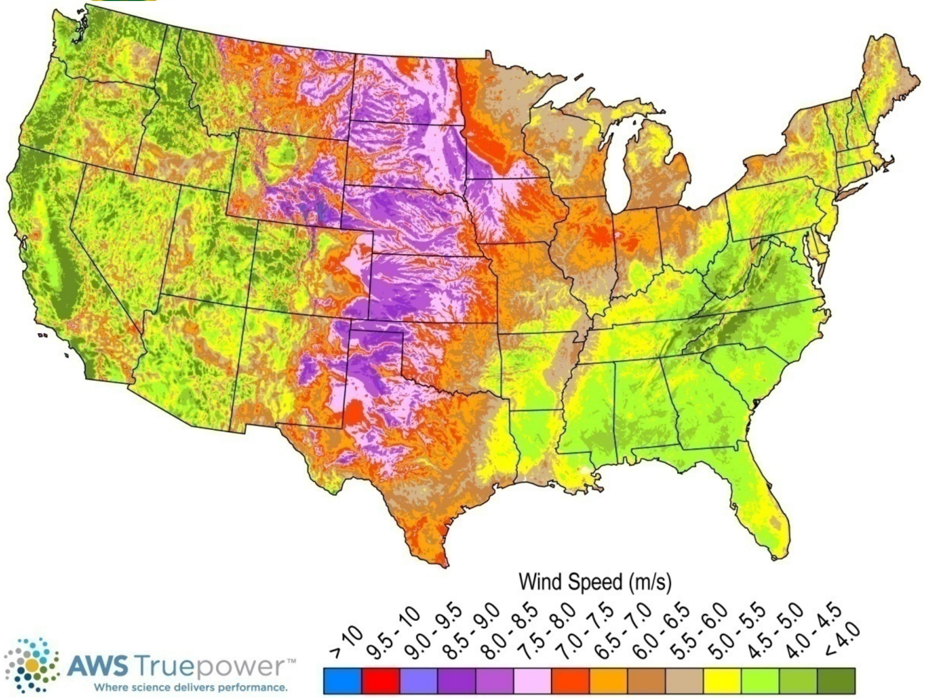
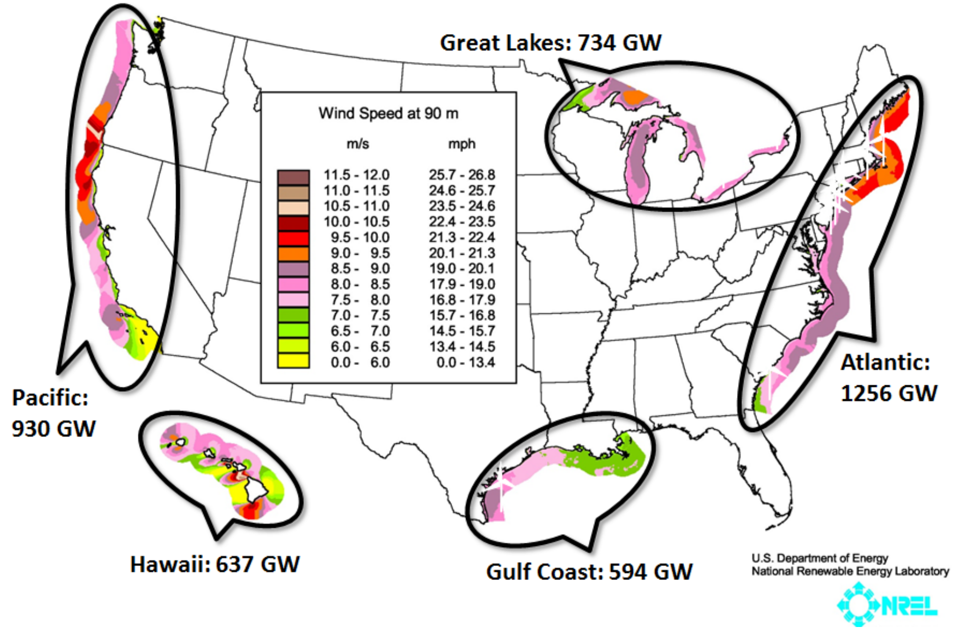
A Solar PV Pathway To 2 cents by 2030



Source: Robert Margolis, David Feldman, NREL

Wind Resources





- Highest quality wind resources are located in the Central states and offshore
- Combined onshore and offshore (fixed-bottom) resource is ~10,000 GW

Wind Power

GE Wind 1.5 MW

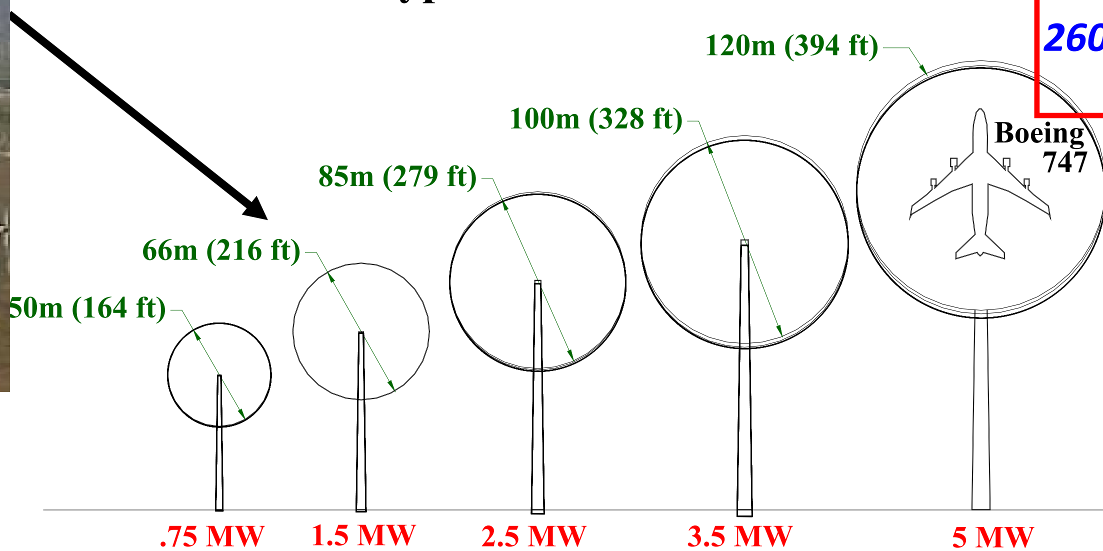
The total economic benefits:

For R&D investments in:

- Turbulence models;
- Wind tunnel experiments of turbine aerodynamics;
- Blade materials;
- Airfoil design codes;
- Demonstration and testing.

GE Haliade-X, offshore wind turbine: 12 MW; 260m height; 220m rotor diameter

Typical Rotor Diameters



Source: EERE/WTP

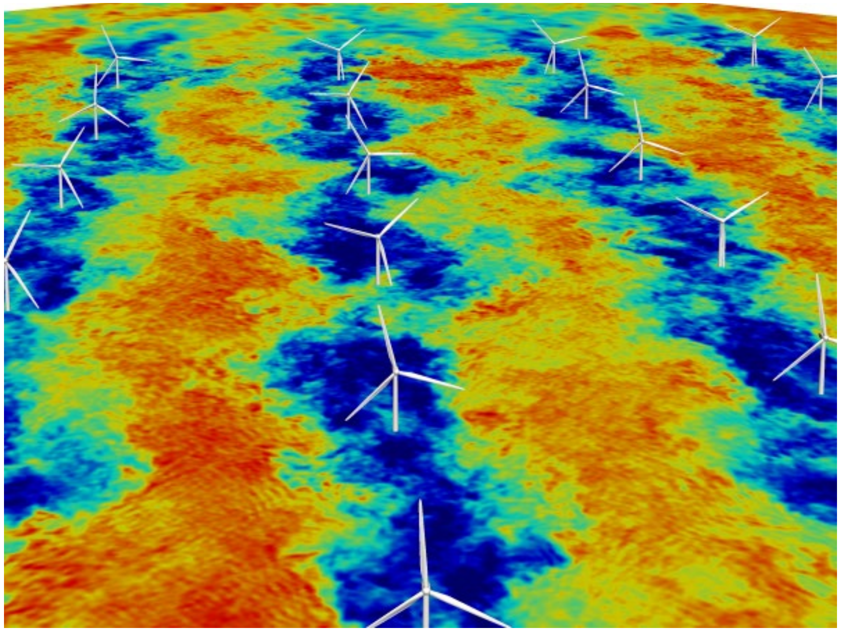
Onshore Turbine Scaling Challenges

Transport of an 80-meter blade to a 7-MW test turbine in Scotland illustrates logistics challenges.
Source: USDOE, "Wind Vision: A New Era for Wind Power in the United States." March 2015, see Chapter 2. https://energy.gov/eere/wind/wind-vision

Manufacturing in the Field?

Wind Advancing

- **Atmosphere to Electrons (A2e)**:
  - Plant-level losses of up to 20% and higher due to turbine-wake interactions, turbulence, blade boundary layer dynamics, terrain, etc.
  - Develop new, *predictive* high-fidelity modeling capability to study fundamental flow physics of whole wind plants to understand turbine-turbine & complex-terrain interactions and reduce costs.



Source: NREL

Wind Advancing

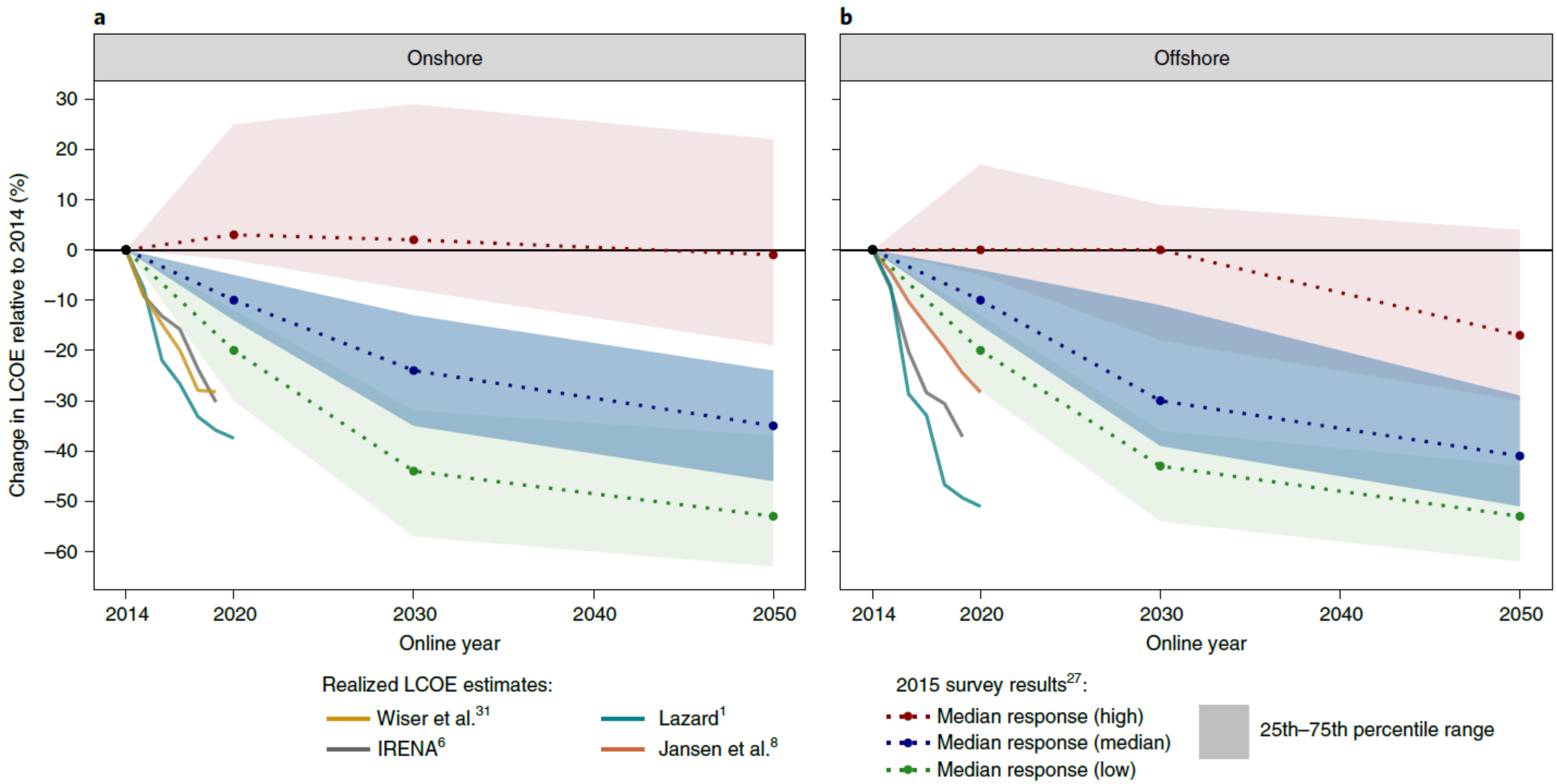


Fig. 1 | Results from the 2015 expert elicitation compared with recent published estimates of realized LCOE. a,b, Dotted lines with shaded areas extending to 2050 reflect the 2015 survey response median and the 25th–75th percentile range for the high-, median- and low-cost scenarios for onshore (**a**) and offshore (**b**) wind[27]. These are compared with a number of recent published estimates of the actual (realized) LCOE for onshore and offshore wind from 2014 to 2019–2020 (solid lines)[1,6,8,31]. The 2020 survey results are not plotted in this figure.

Source: Ryan Wiser, et al, "Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050", Nature Energy, 2021, https://doi.org/10.1038/s41560-021-00810-z

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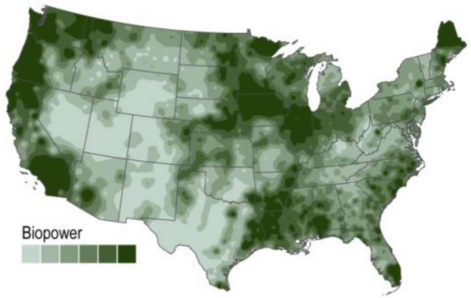
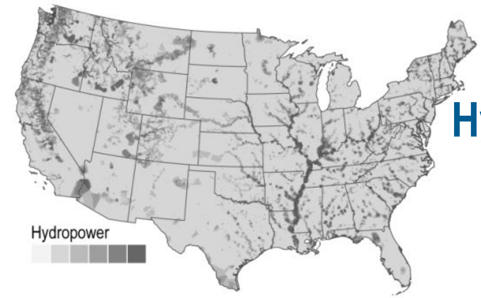
Renewable Resources and Technologies

Biopower ~100 GW

- Stand-alone
- Cofired with coal





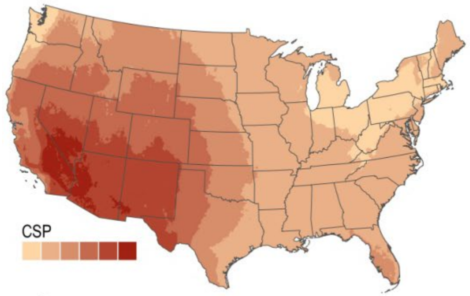
Hydropower ~200 GW

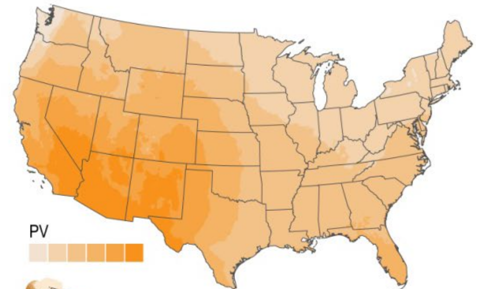
- Run-of-river

CSP ~37,000 GW

- Trough
- Tower

With thermal storage





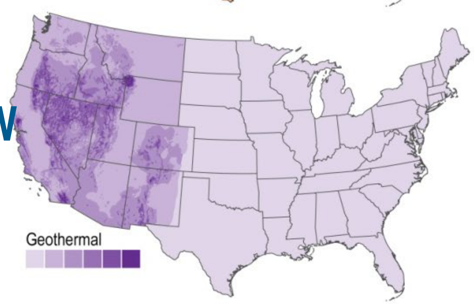
PV ~80,000 GW (rooftop ~700 GW)

- Residential
- Commercial
- Utility-scale

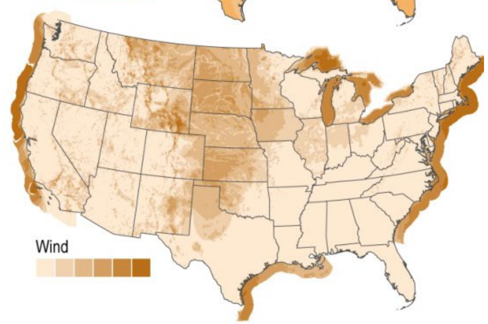
Geothermal ~36 GW

- Hydrothermal

-EGS ~100 GW?



Resource
Dark = Higher
Light = Lower



Wind ~10,000 GW

- Onshore
- Offshore fixed-bottom

Current U.S. Generating Capacity ~ 1200 GW producing ~4100 TWh/y

- **RE characteristics, including location (exclusions), technical resource potential, and grid output (dispatchability), were considered**
- **Technical resource potential shown, not economic potential**

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Electric Power Systems

Hydropower

BioPower

Photovoltaics

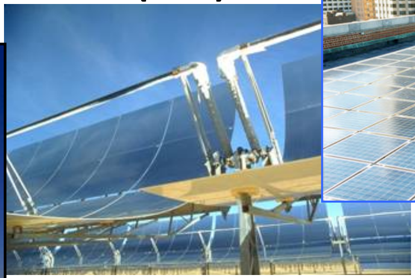
Geothermal

Wind

Distributed Generation
Demand Response
Distributed Storage
Smart Grid

Electric Vehicles

Concentrating Solar Power (CSP)



Photovoltaics

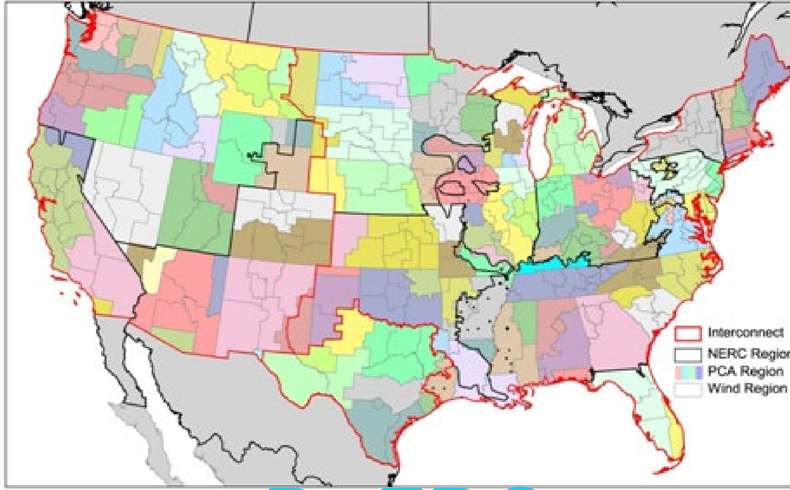
Variable Renewables

- **Site Specific**
- **Variable & Uncertain**

System Integration

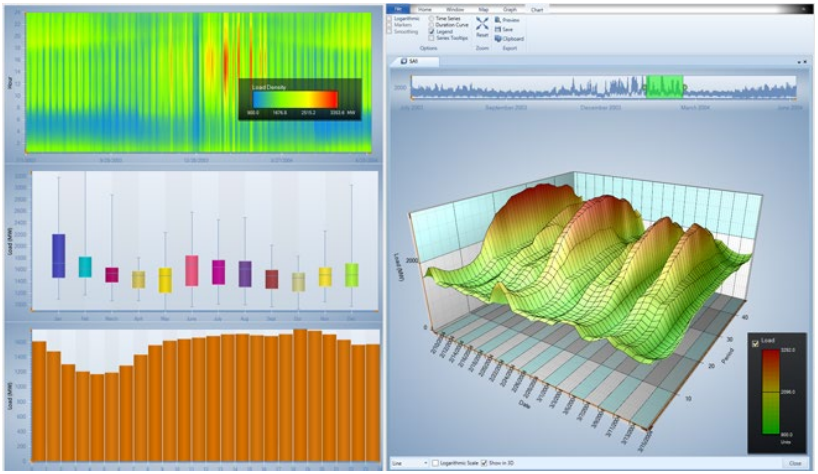
System Modeling

- **NREL ReEDS:**
  - **Capacity Expansion Model**
  - 356 regions in continental US; 134 power control areas; RTOs; States; NERC areas; Interconnects.
  - **Temporal Resolution**: 17 time slices in each year: 4 daily x 4 seasons, 1 super-peak



ReEDS
(capacity expansion)

- **Plexos**
  - **Commercial chronological unit commitment model** for short term; load duration curve analysis for medium term; long term optimization model for new builds and retirements; etc.
  - **5-minute dispatch/8760 hours**, high penetration studies, and other current work.
  - ERGIS: 5,600 Generators; 60,000+ transmission nodes; all transmission 69+ kV

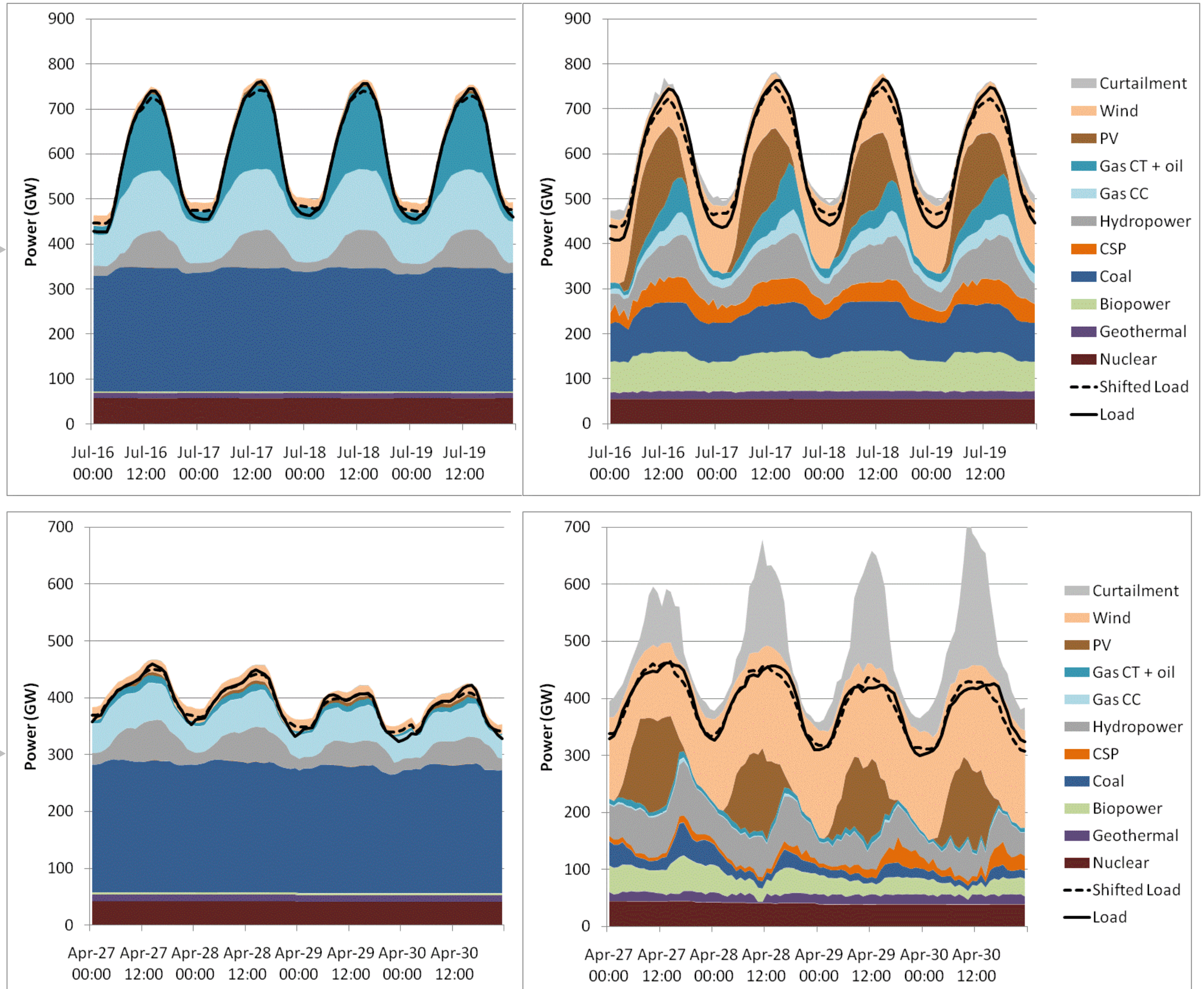


PLEXOS
Energy Exemplar

Electricity supply and demand can be balanced in every hour of the year in each region with 80% electricity from renewables*

Summer Peak

Spring Off-Peak



Baseline

80% RE-ITI 2010 Case

*Full reliability analysis not conducted in RE Futures

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Seasonal Challenge

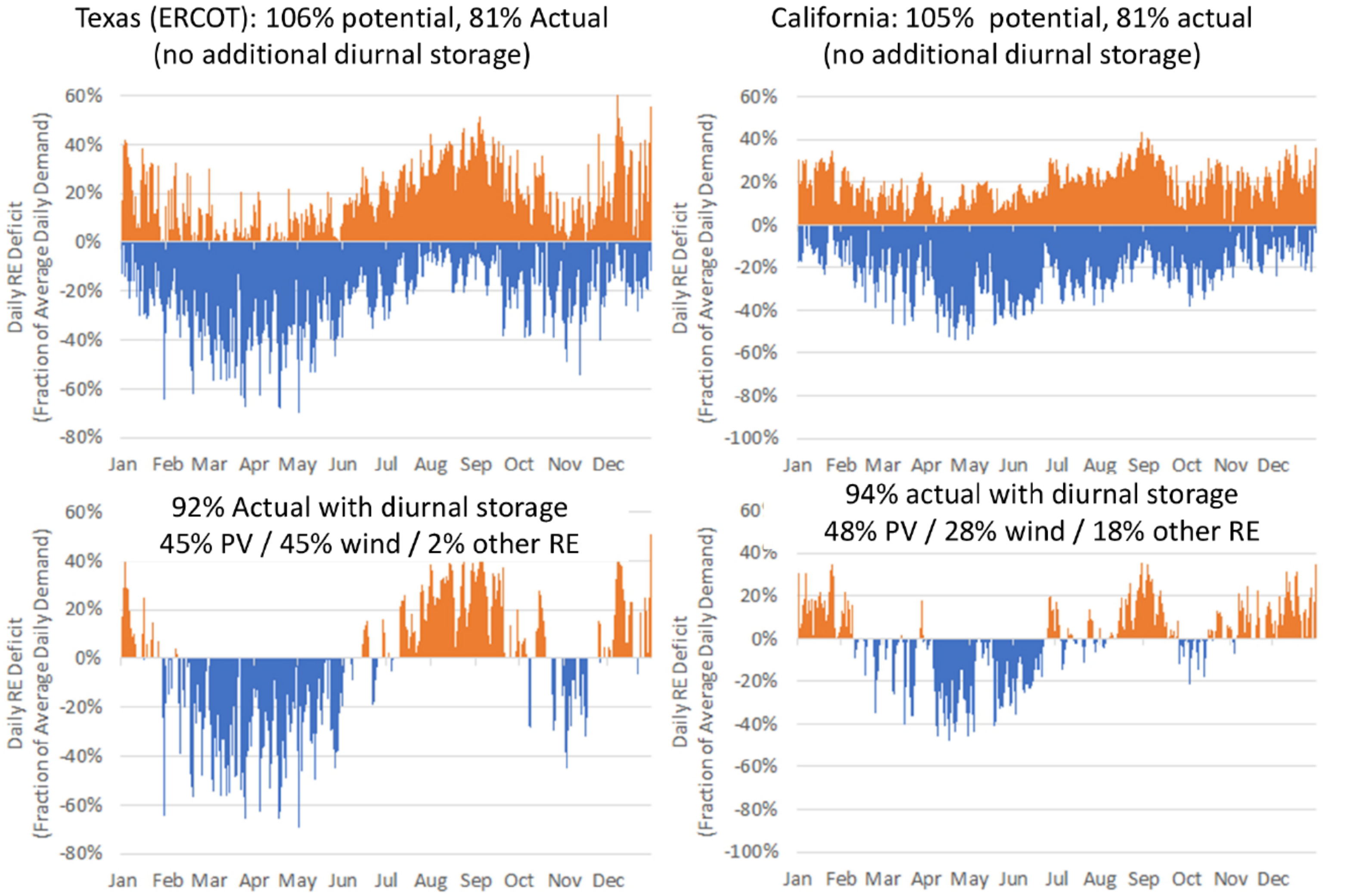
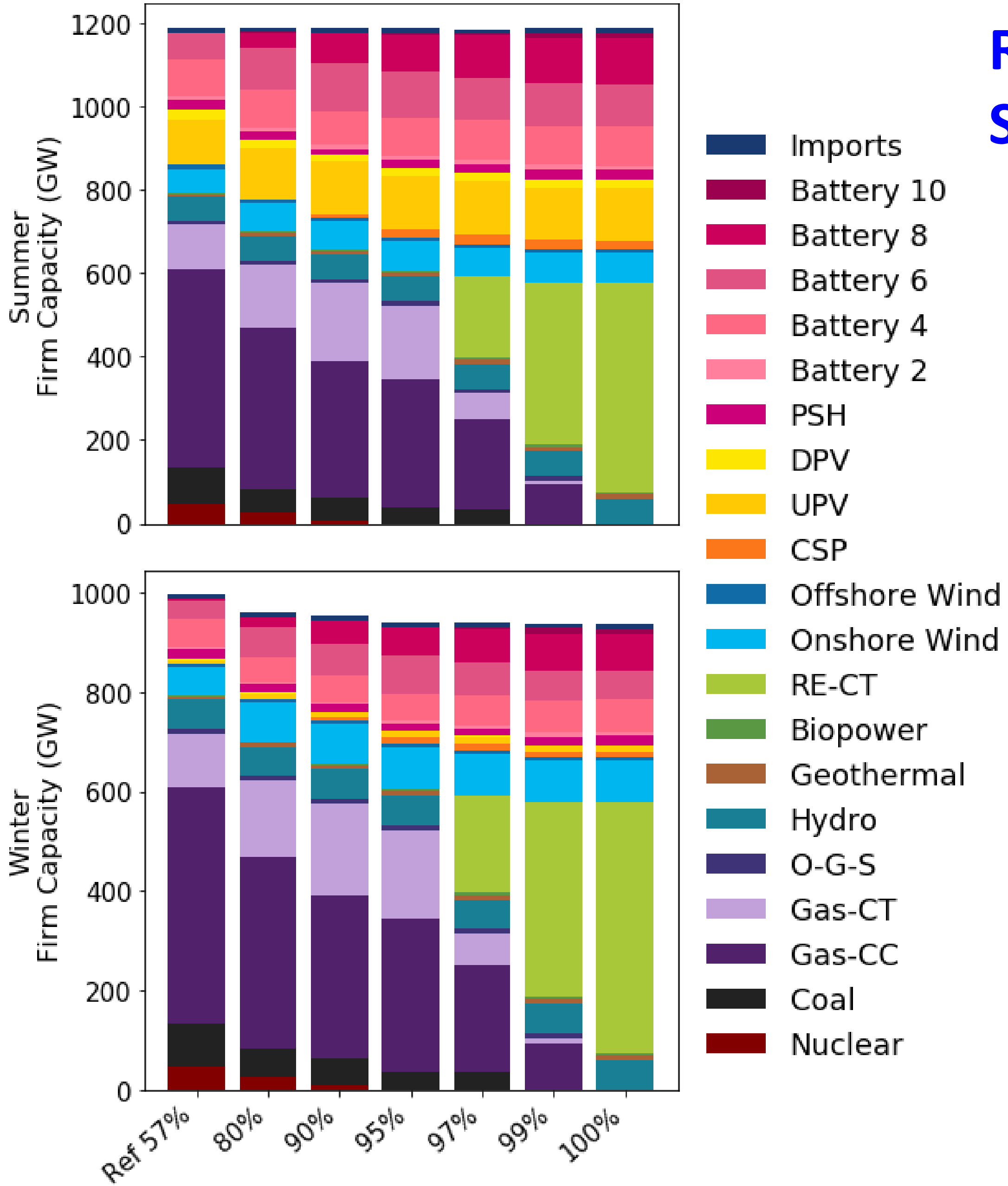


Figure SI3. RE deficit for hypothetical 100% annual energy scenarios in Texas and California demonstrating the saturation of diurnal storage. Positive numbers represent shortfalls in demand that must be met with non-RE generation and negative numbers represent excess RE generation.

Source: Denholm, et al, Joule, 2021

RE to 100% in 2050—System Capacity



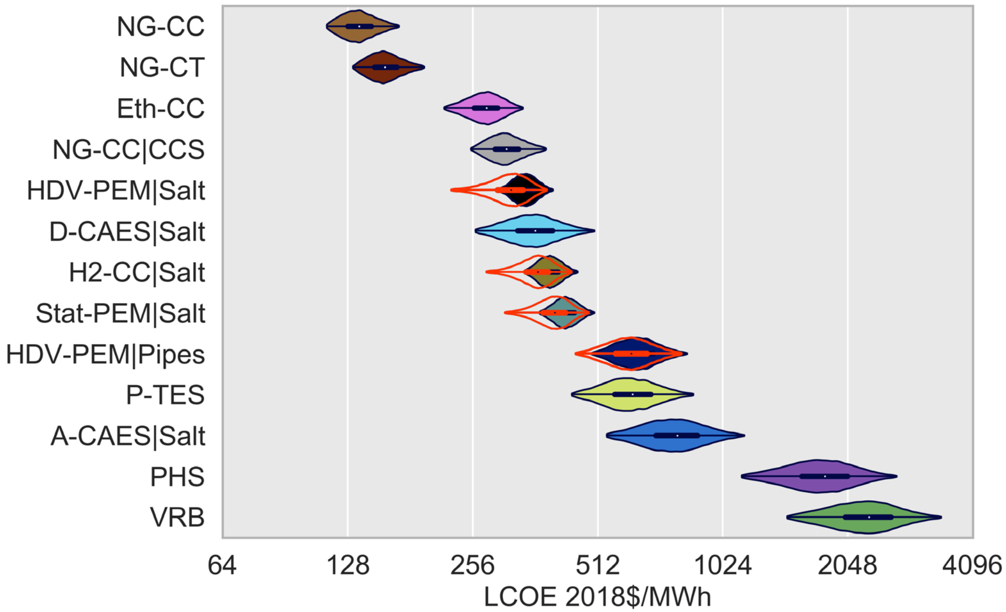
Firm capacity in summer (top) and winter (bottom) by technology type for the seven base scenarios.

Imports = hydropower imports from Canada, PSH = pumped-storage hydropower, DPV = distributed PV, UPV = utility-scale PV, RE-CT = RE-fueled combustion turbine, and O-G-S = oil, gas, and steam. The number associated with the battery entries is the duration (in hours) for that battery type

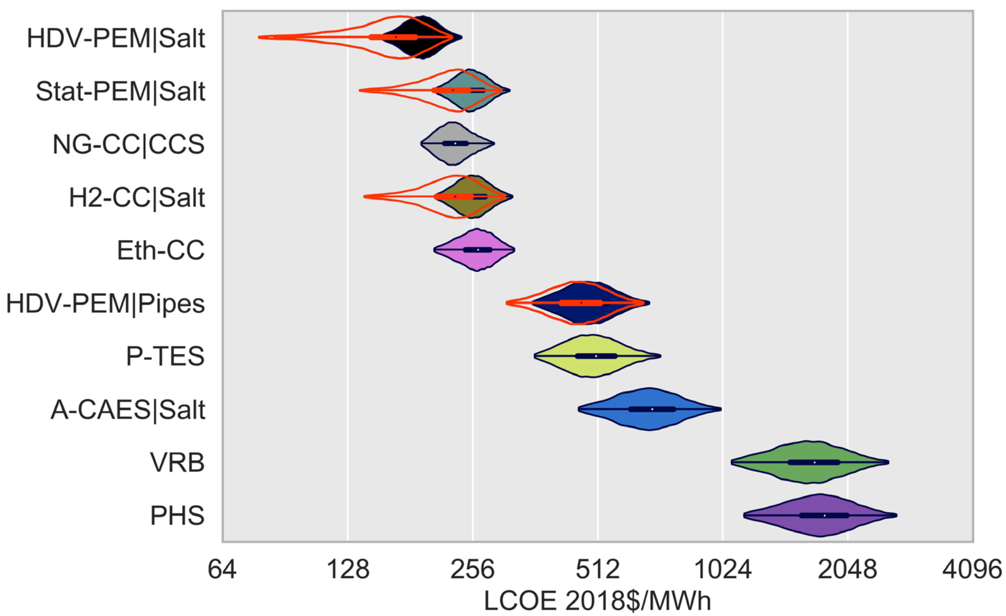
Source: Cole, et al, Joule, 2021

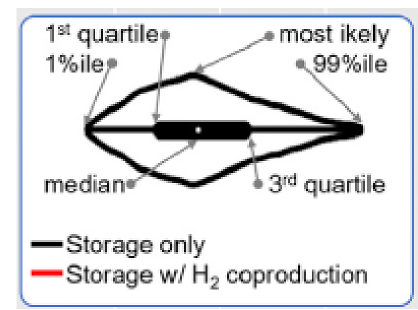
Fixed Capacity Factor, Current & Future Costs at 120h Duration

Current



Future





Source: Hunter, et al,, Joule, 2021

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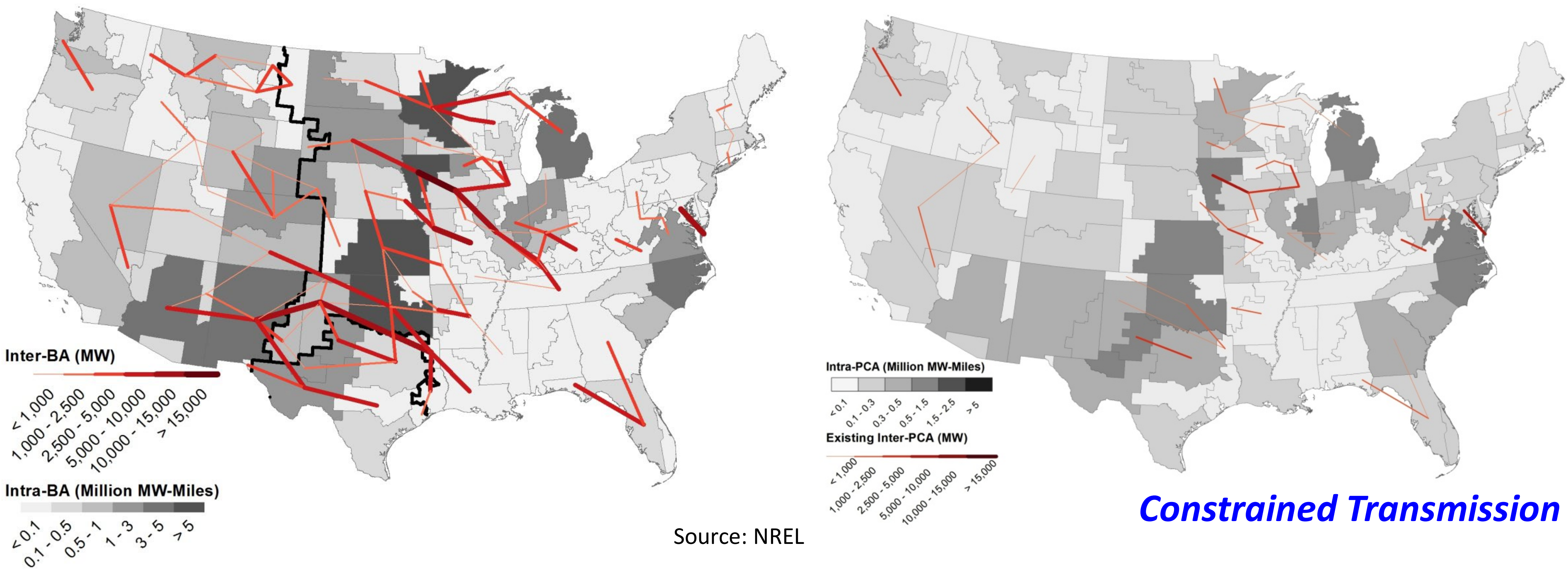
As RE deployment increases, additional transmission infrastructure is required

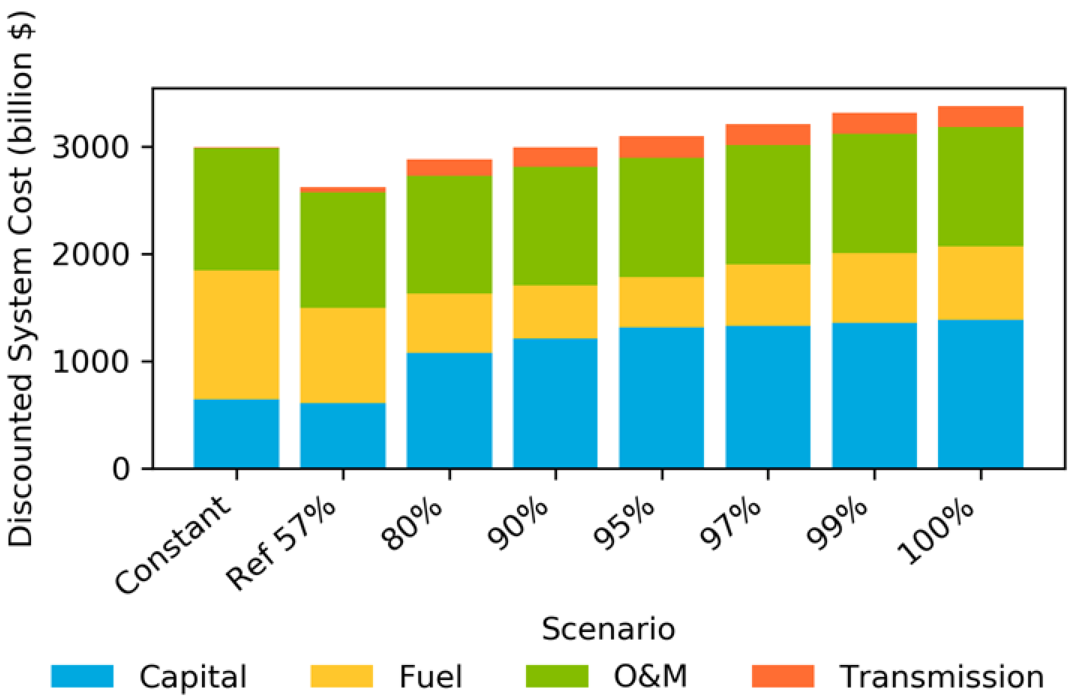


Source: NREL

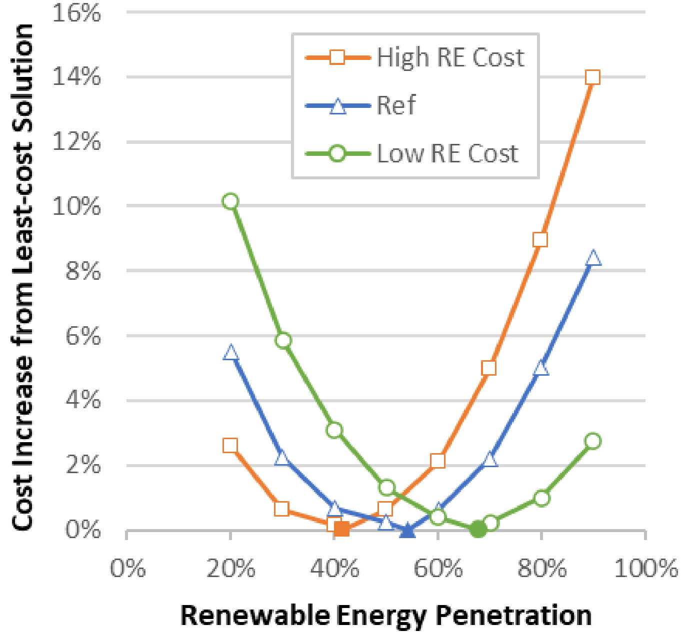
Constrained Transmission

NREL, Renewable Electricity Futures, 80%-by-2050 RE scenarios

RE to 100% in 2050—System Cost, Carbon Cost, Capacity



Source: Cole, et al, Joule 2021



Source: Cole, Gates, Mai, Electricity Journal, 2021

Average bulk power costs are \$0.030/kWh for 57% RE, \$0.033/kWh for 80%, \$0.035/kWh for 90% (and constant case), \$0.036/kWh for 95%, and \$0.039/kWh for 100%, but marginal costs increase significantly for the last few percent of penetration, particularly for 95% to 100%.

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High RE Futures Impacts on (Emissions, Water) Land Use

(Example of 80% RE from RE Futures, with NO additional electrification)

Land Use Compared:

Coal: 1 meter thick seam ➔ ~1800 kWh/m²

Solar: ➔ ~350 kWh/m² per year

Solar PV power = 1 meter thick coal seam in ~5 years

Major U.S. Coal beds, 80% are < 5m thick, average 2.3m
and produce ~half of U.S. Coal; others up to ~20m thick (Source: EIA)

Southern Appalachia Mountaintop removal = 11,000 km² +
2000 kms of stream channels buried under mining overburden

Source: Bernhardt & Palmer, doi: 10.1111/j.1749-6632.2011.05986.x

Gross Land Use Comparisons (000 km²)	
Total Contiguous U.S.	7,700
Renewable Energy*	52-81
All RE* Disrupted	4-10
Major Roads	50
Golf Courses	10
*Does not include Biomass	
Source: Renewable Electricity Futures; USDA 2010, 2012; Denholm & Margolis 2008	

Reading

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- Quadrennial Technology Review: U.S. Department of Energy, "Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities", September 2015, https://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015 and for all the appendices, see: https://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015-omnibus

Thank You!