SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Grid Integration Track

Solar Energy Technologies Office

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Director

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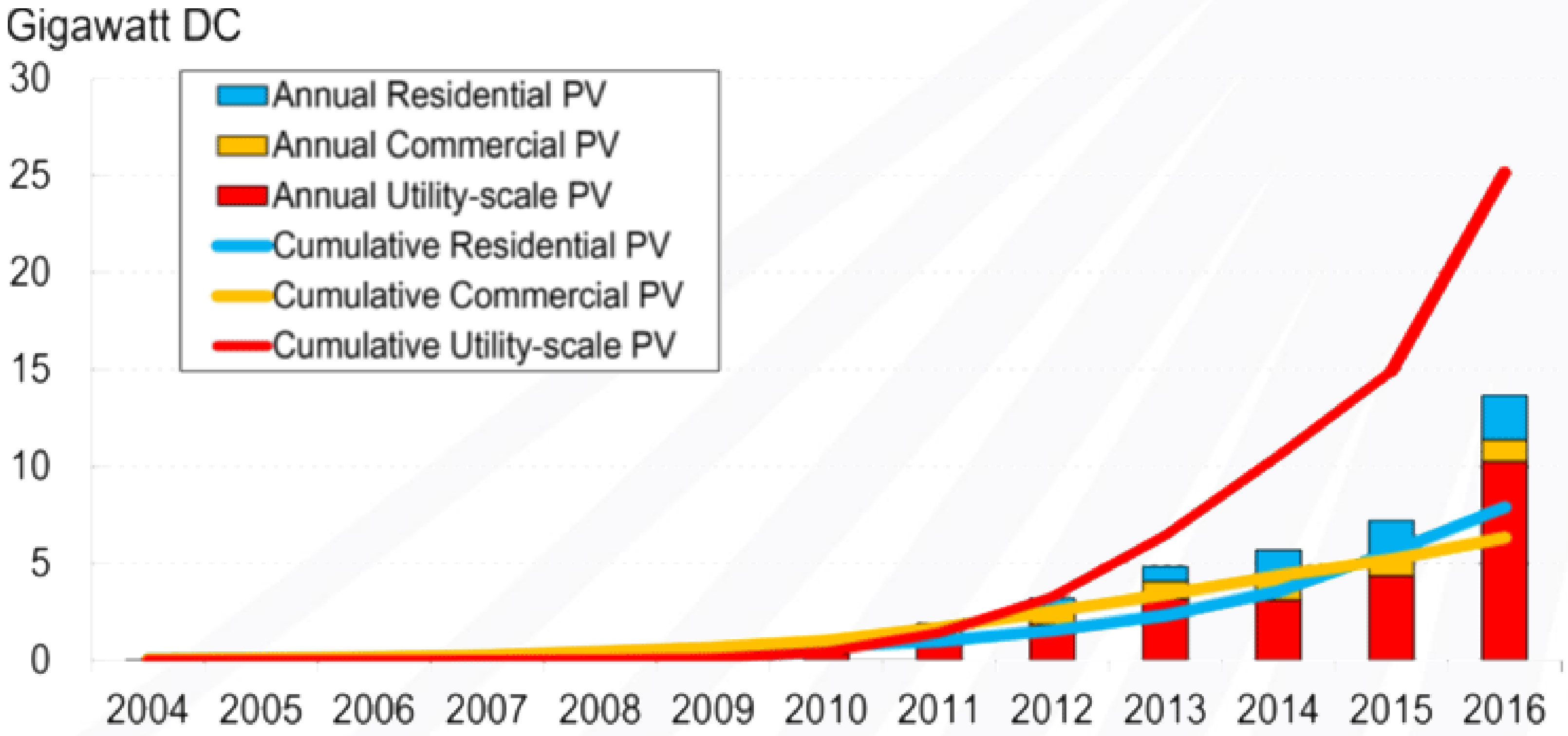
energy.gov/solar-office

The U.S. DOE Solar Energy Technologies Office

US PV Market

- Annual U.S. PV installations grew 100x from 2006 to 2017, with over 50 GW-DC of cumulative installations
  - In 2017 PV represented 29 % of all new U.S. generating capacity
- The U.S. energy market consists of many different state, regional, and local markets
  - PV is much more competitive in certain areas and penetration levels vary dramatically California, which has represented approximately ½ of the U.S. market, received approximately 16% of its electric generation from solar in 2017.

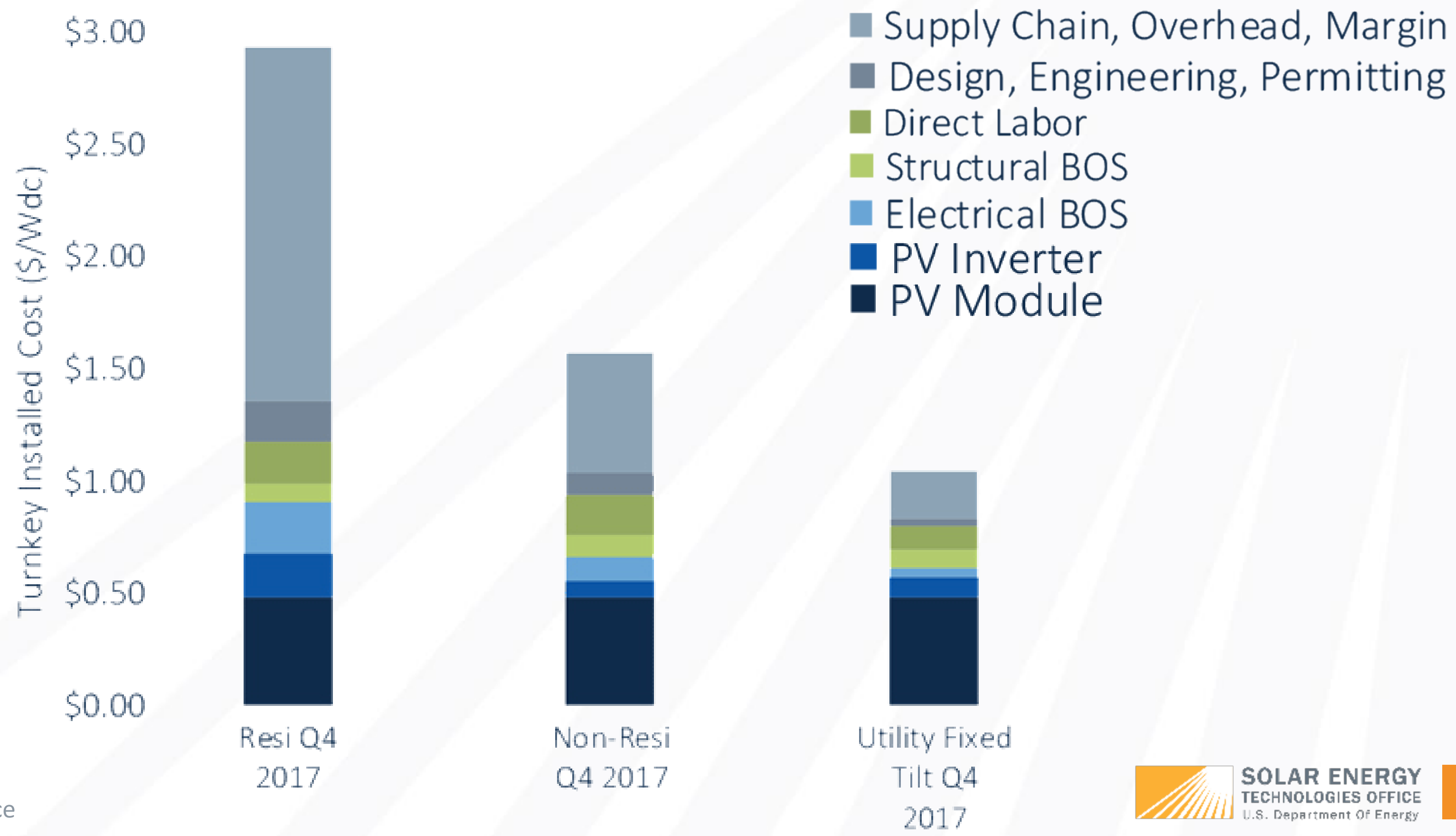
US Solar PV Market Growth



U.S. PV market growth, 2004–2016, in gigawatts of direct-current (DC) capacity (Bloomberg 2017)

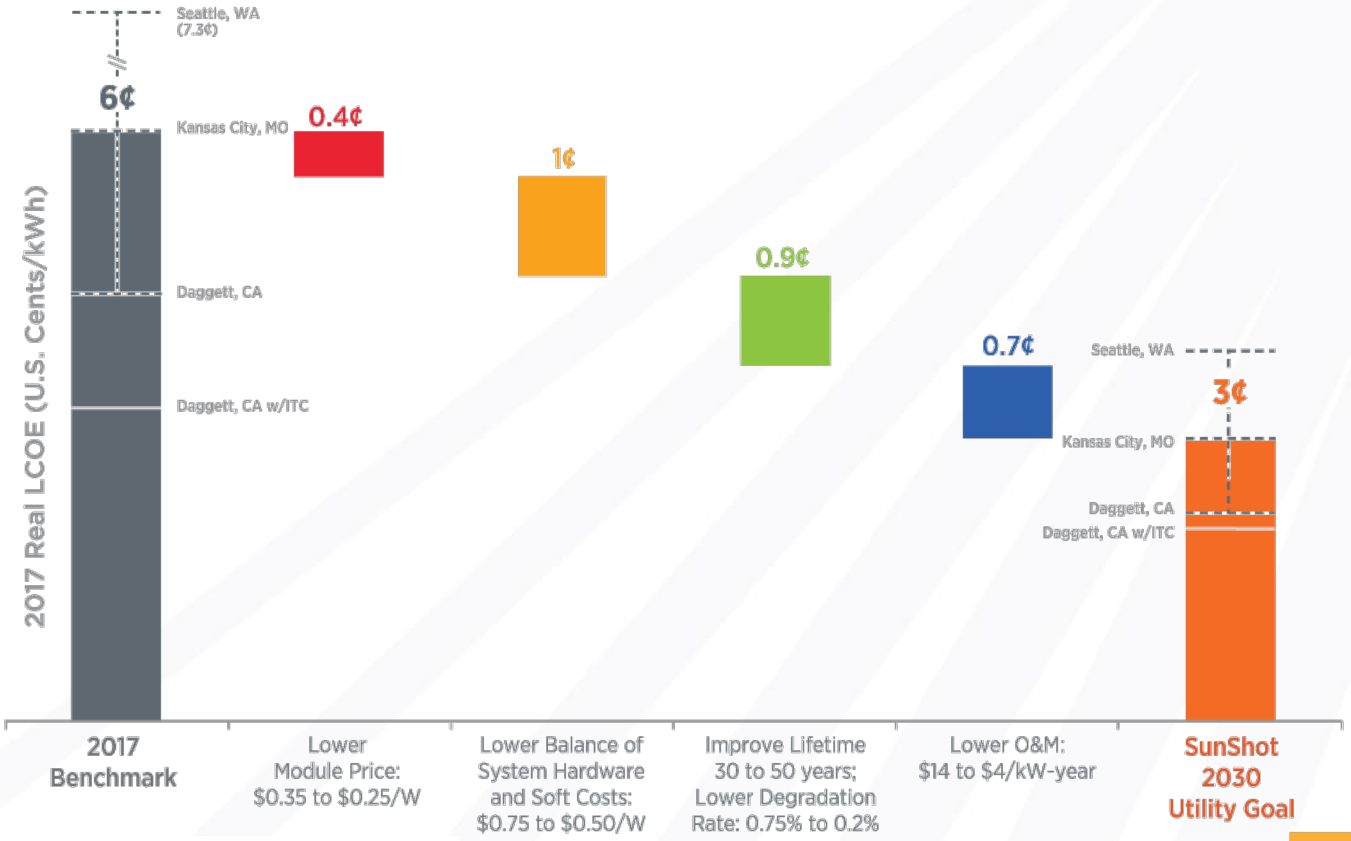
Source: NREL/PR-6A20-68580

Modeled U.S. National Average System Costs by Market Segment, Q4 2017



Source: GTM

A Pathway To 3 Cents per kWh for Utility PV



100 $MW_{(DC)}$ One-Axis Tracking Systems With 1,860 $kWh_{(AC)}/kW_{(DC)}$ First-Year Performance. Includes 5 Year MACRS. Horizontal Lines Indicate Low, Median, and High U.S. Solar Resources.

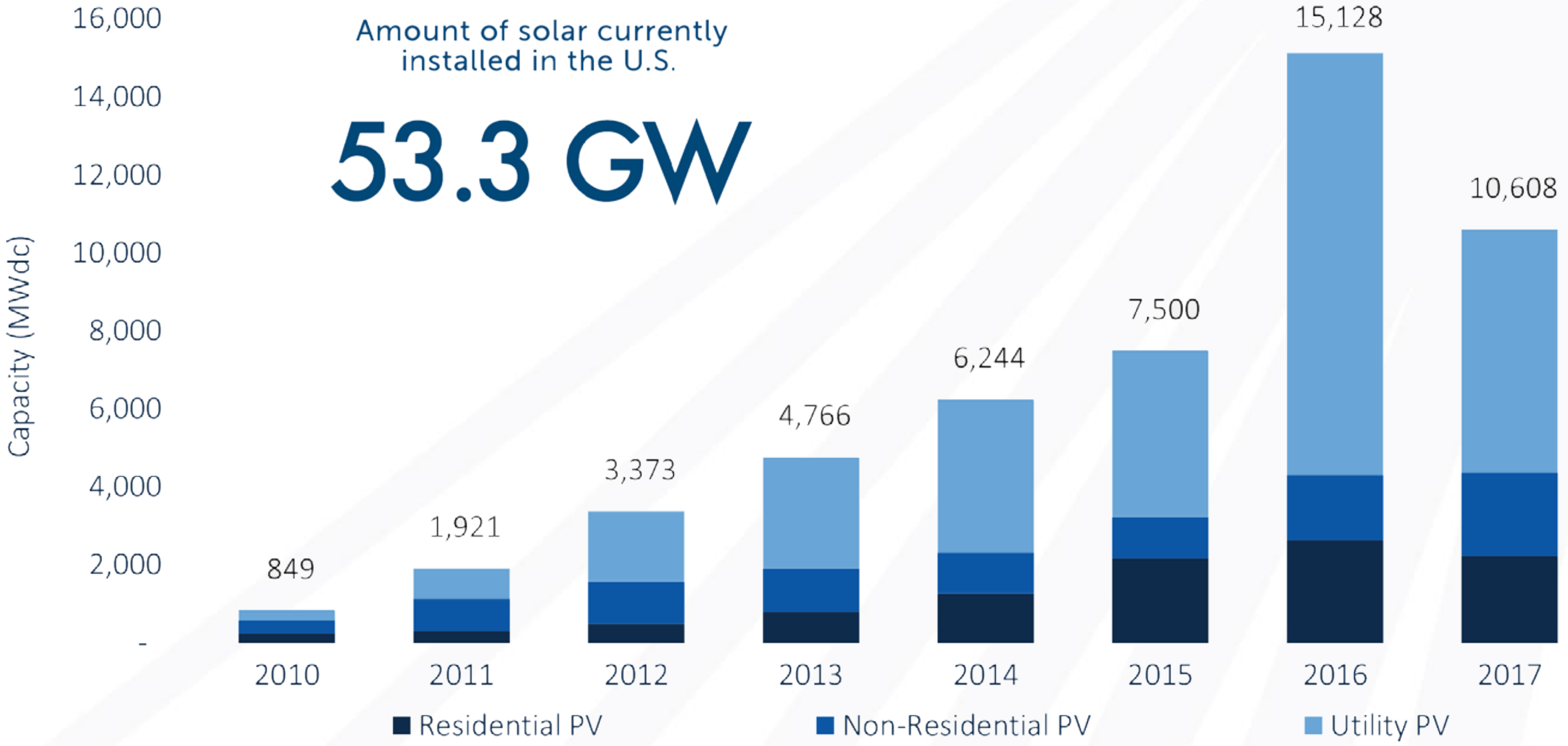
The Accelerating Pace of Change

Levelized cost of energy at a couple of the preeminent utility-scale solar sites around the world is going below **3¢/kWh** the SunShot 2030 cost goal

- October 2017: Saudi Arabia's 300 MW PV plant was bid at **1.79¢/kWh**
- September 2016: Abu Dhabi Electricity and Water Authority's 350 MW PV plant accepted a bid from JinkoSolar–Marubeni at **2.42¢/kWh**

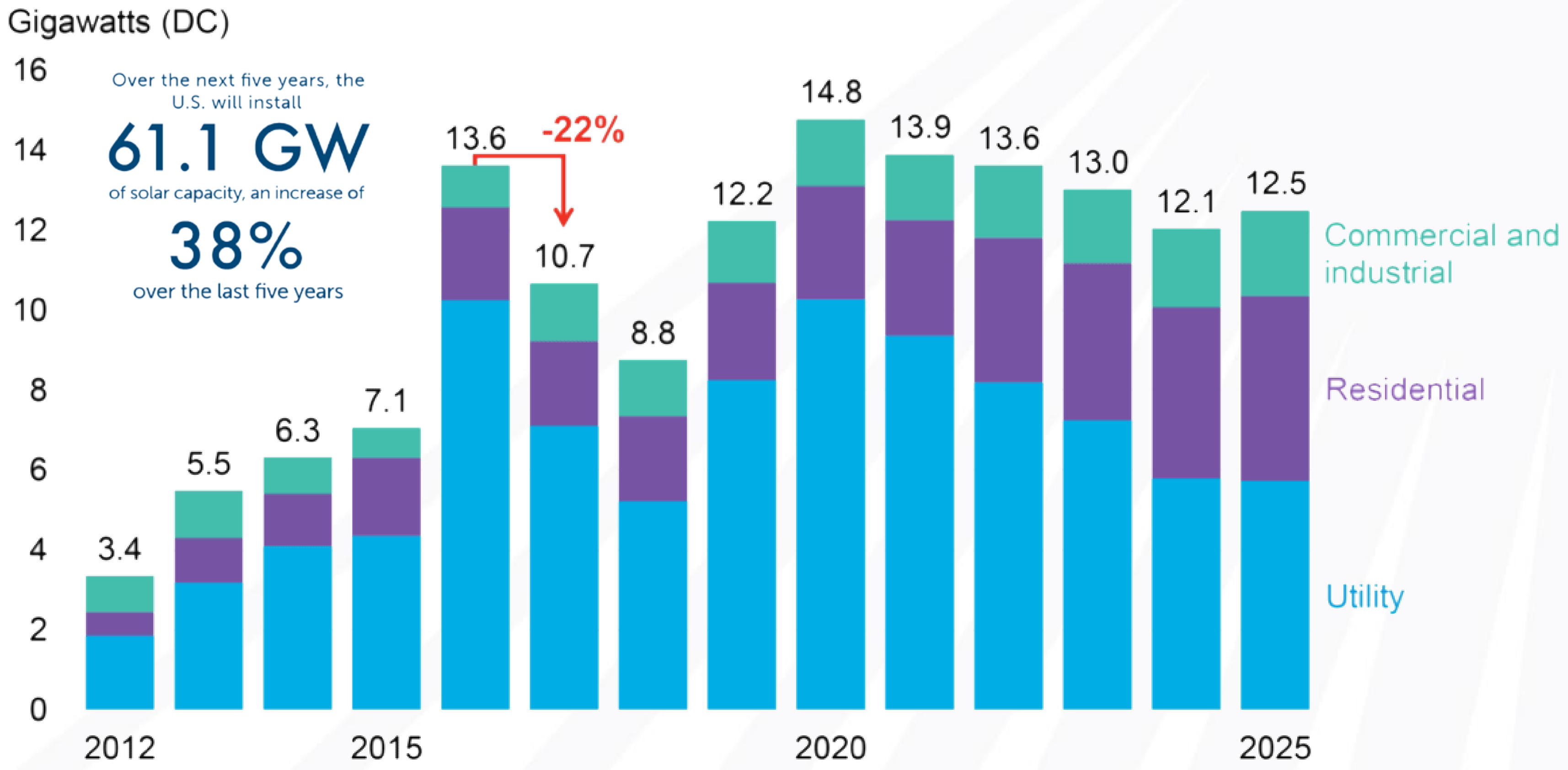
The **full cost of renewable energy** includes:
Backup generation capacity
Enhanced transmission and distribution systems
Energy storage

U.S. Annual PV Installations, 2010-2017



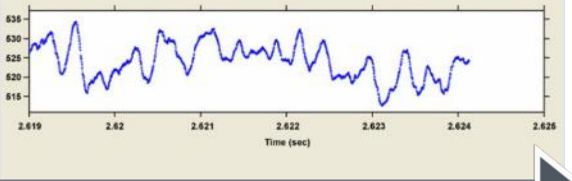
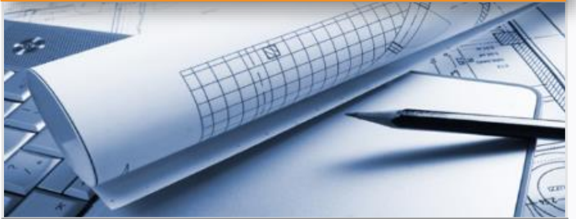
Source: GTM

U.S. Market by Segment



Source: Bloomberg New Energy Finance (2H 2017 U.S. Renewable Energy Market Outlook)

PV Intermittency and the Power Grid

Grid Controls	Scheduling	Power Systems Planning & Design
		
Milliseconds to Minutes	Hours to Days	Years

- PV solar intermittency raises grid stability and reliability concerns
- PV Variability increases operational complexity
- Higher PV penetration requires increased grid flexibility

Source: First Solar

Flexible & Dispatchable Solar … Key to Market Expansion & Value Retention

Solar 1.0: Traditional

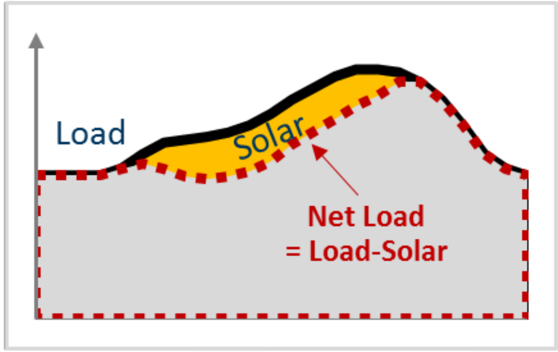
- Solar is part of mid-day load offsets peak or near-peak demand
- **Energy-Only Value**

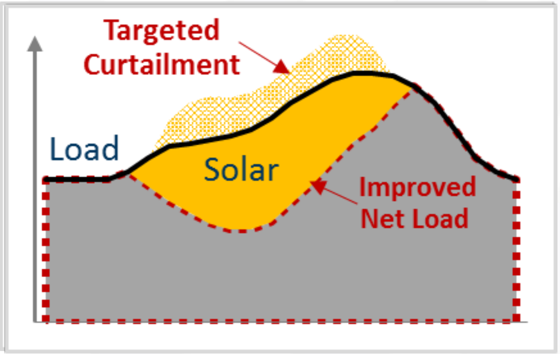
Solar 2.0: Dispatchable

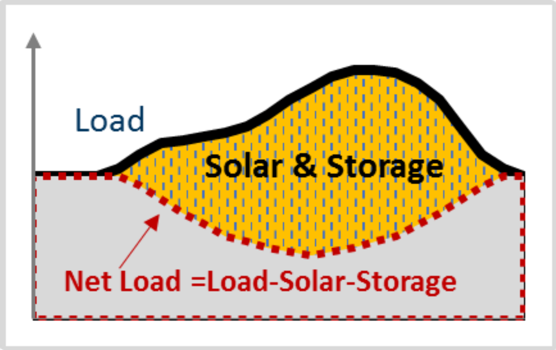
- Solar mitigates value erosion through plant controls
- Adds **Grid Reliability Services & Flexibility** Value

Solar 3.0: Fully Dispatchable

- Storage (hours, not days) time-shifts solar - dispatchable
- Adds **Firm Generation Capacity** Value







US Grid Facts (2016)

Installed generation capacity (all sources) = 1,177 GW

Annual Energy = 4,077 TWh

Installed Wind capacity = 82 GW

Installed Solar capacity = 35 GW (US 2017 estimate of 53GW)

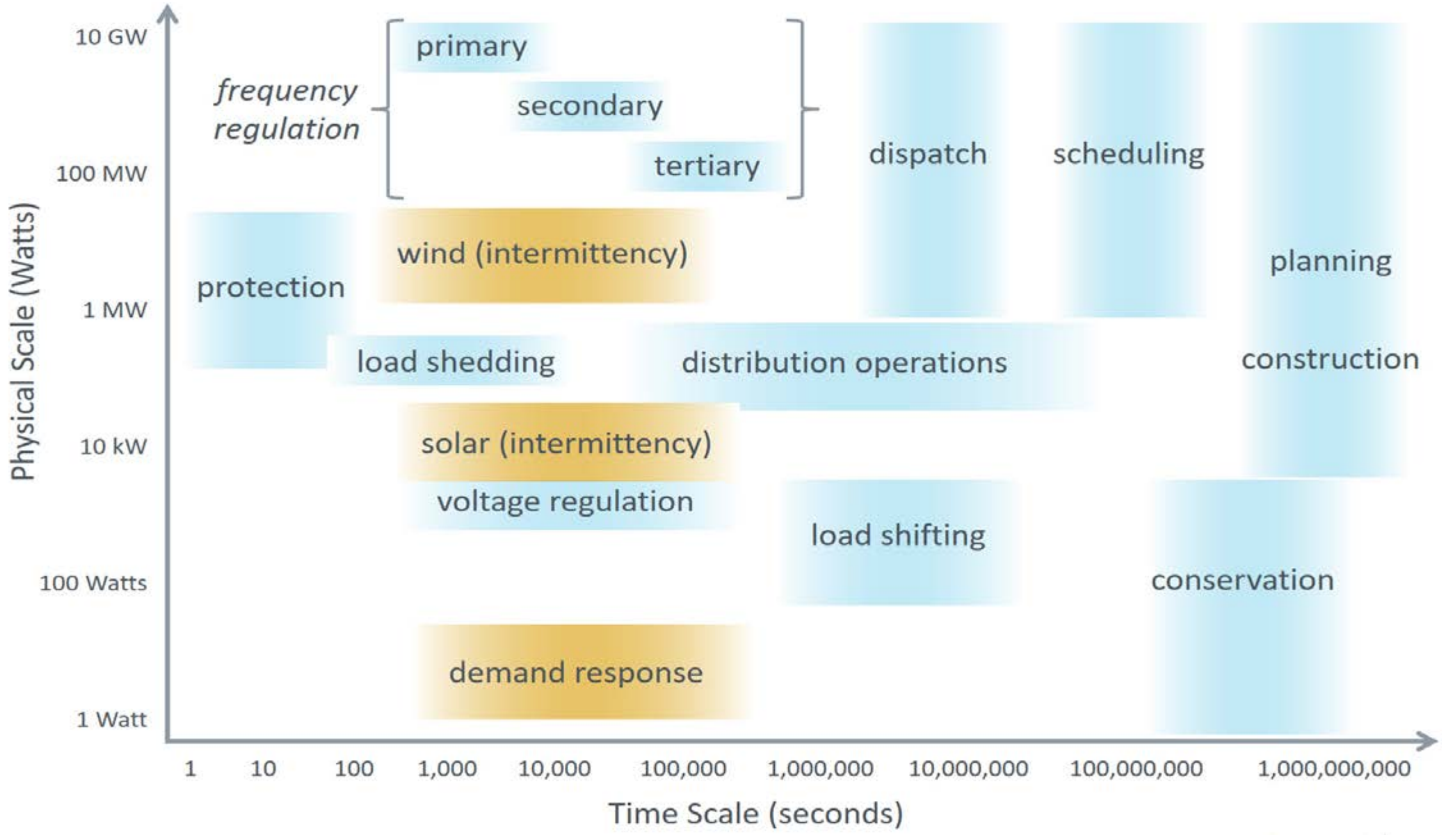
Installed Conventional Hydro = 79 GW

Installed Pumped Hydro = 21 GW

Batteries = 1.5GW world-wide

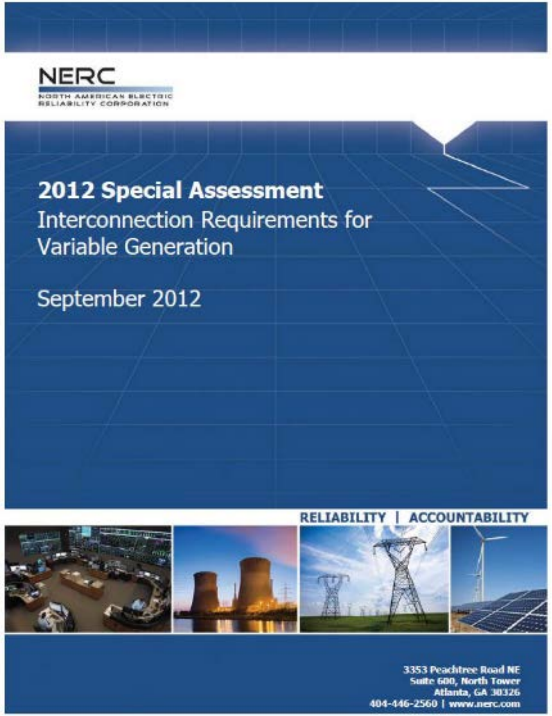
Sources:
EIA - http://www.eia.gov/electricity/annual/html/epa_04_03.html
GTM Research / SEIA U.S. Solar Market Insight Report

Multi-scale Grid Optimization



“Solar Intermittency Raises Grid Stability & Reliability Concerns”

NERC Task Force on Intermittent Resources Impact to the Grid



"Modern solar plants can now contribute to the ***reliability and efficiency*** *of grid operation by offering the following capabilities:"*

- ✓ Voltage, VAR control and/or power factor regulation
- ✓ Fault ride through
- ✓ Real power control, ramping, and curtailment
- ✓ Primary frequency regulation
- ✓ Frequency droop response
- ✓ Short circuit duty control

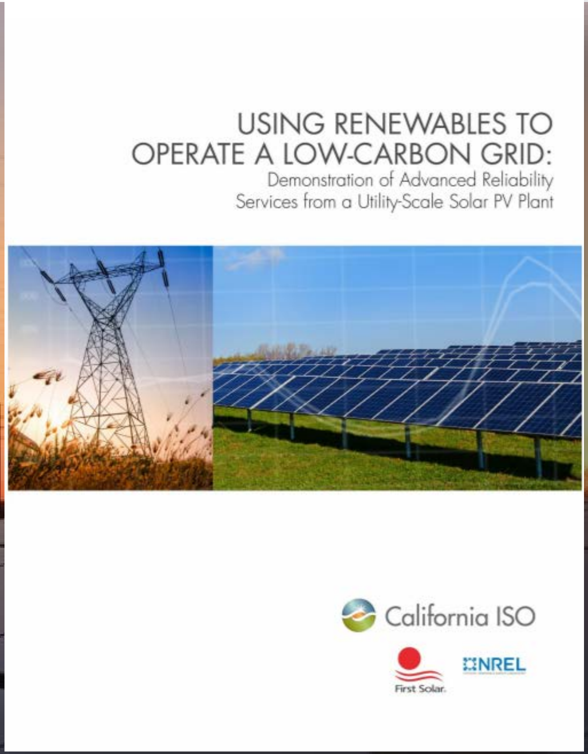
Utility-scale plants provide these feature
… but how about Distributed PV?

Source: NERC: 2012 Special Assessment Interconnection Requirements for Variable Generation

Source: First Solar

Tests Successfully Conducted on 300 MW Solar PV plant

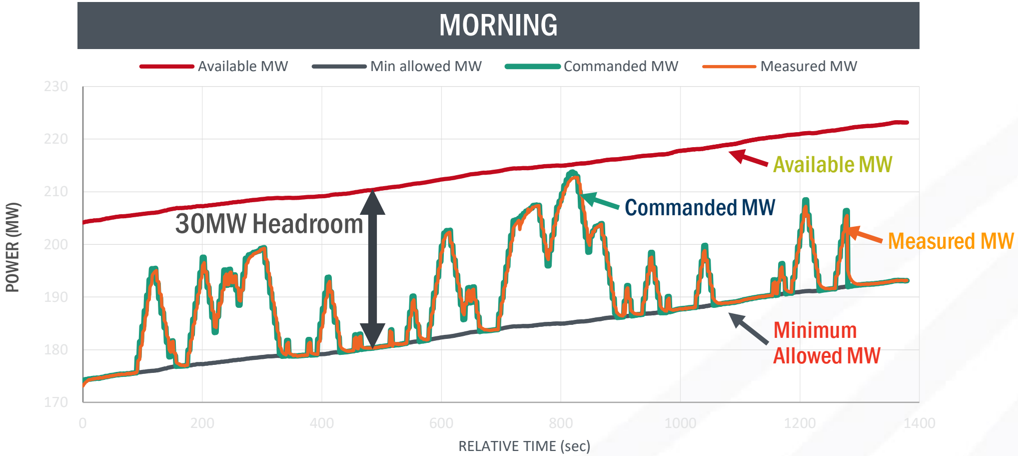
- Power Ramping
  - ✓ Ramp its real-power output at a specified ramp-rate
  - ✓ Provide regulation up/down service
- Voltage Control
  - ✓ Control a specified voltage schedule
  - ✓ Operate at a constant power factor
  - ✓ Produce a constant level of MVAR
  - ✓ Provide controllable reactive support (droop setting)
  - ✓ Provide reactive support at night
- Frequency
  - ✓ Provide frequency response for low frequency & high frequency events
  - ✓ Control the speed of frequency response
  - ✓ Provide fast frequency response to arrest frequency decline

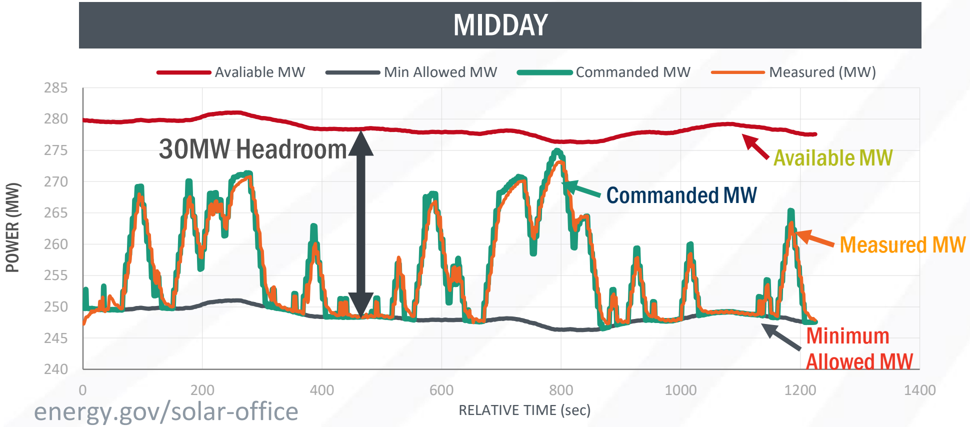

USING RENEWABLES TO OPERATE A LOW-CARBON GRID:
Demonstration of Advanced Reliability Services from a Utility-Scale Solar PV Plant

California ISO
First Solar.
NREL

Utility-Scale PV Plant Contributes to Grid Stability & Reliability Like Conventional Generation

300 MW PV Plant Stability





- 30MW headroom
- 4-sec AGC signal provided to Plant Controller
- Tests were conducted for
  - Sunrise
  - Middle of the day
  - Sunset

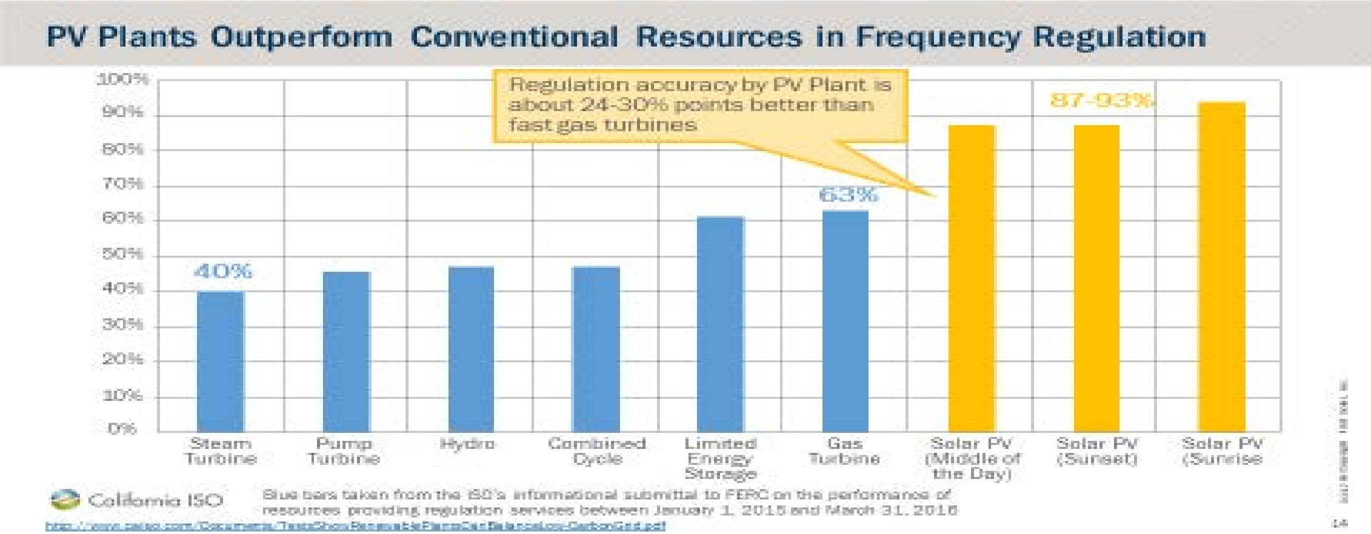
Properly Designed Utility-Scale Solar Can Support Grid Reliability & Stability

Concern

Solar creates reliability Issues

Reality

Utility scale solar provides technical capabilities essential for reliability services, like conventional plants



Source: First Solar

Dispatchable PV Plant

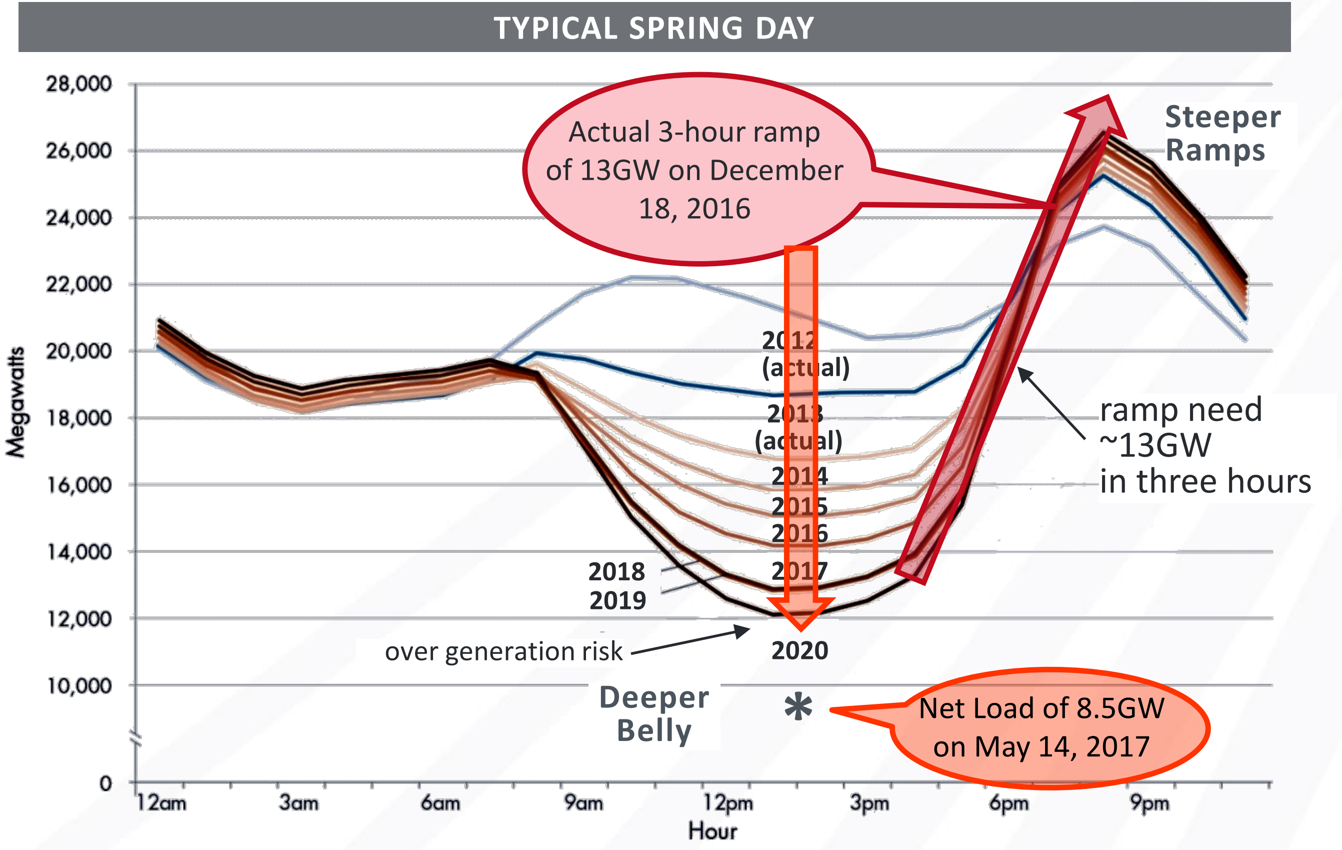
- CAISO, NREL and First Solar pioneering demonstration of advanced reliability services
- Solar can provide NERC-identified essential services to reliably integrate higher levels of renewable resources, including:
  - Frequency Control
  - Voltage Control
  - Ramping capability or flexible capacity
- Automated Generation Control (AGC) regulation accuracy of 24-30 %points better than fast gas turbines
- Reduces need for services from conventional generation
  - Goes beyond simple PV energy value
  - Enables additional solar
  - Reduces need for expensive storage

CAISO: "Grid Friendly Utility-Scale PV Plants are Essential for Large-Scale PV Integration"

http://www.caiso.com/Documents/TestsShowRenewablePlantsCanBalanceLow-CarbonGrid.pdf

“Increasing Solar Penetration Challenges Grid Flexibility”

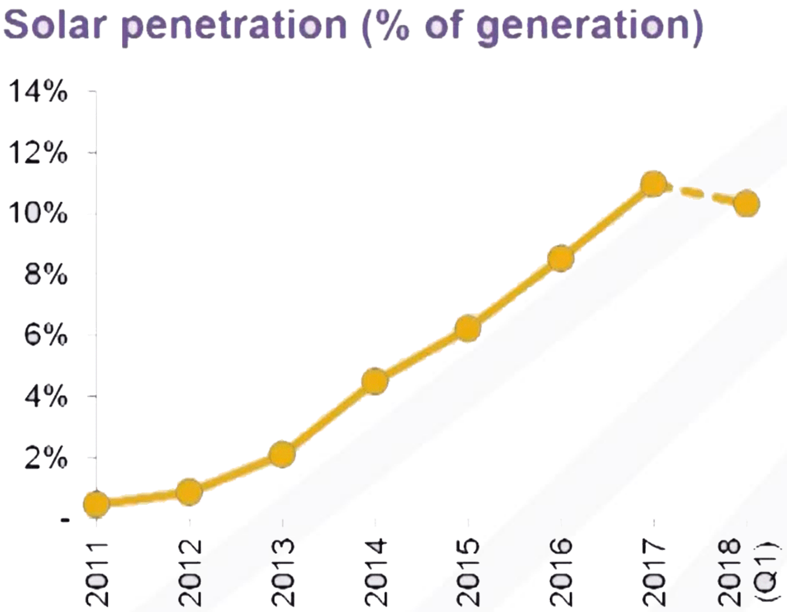
Inflexible Solar Saturation Already Evident on the CAISO Grid



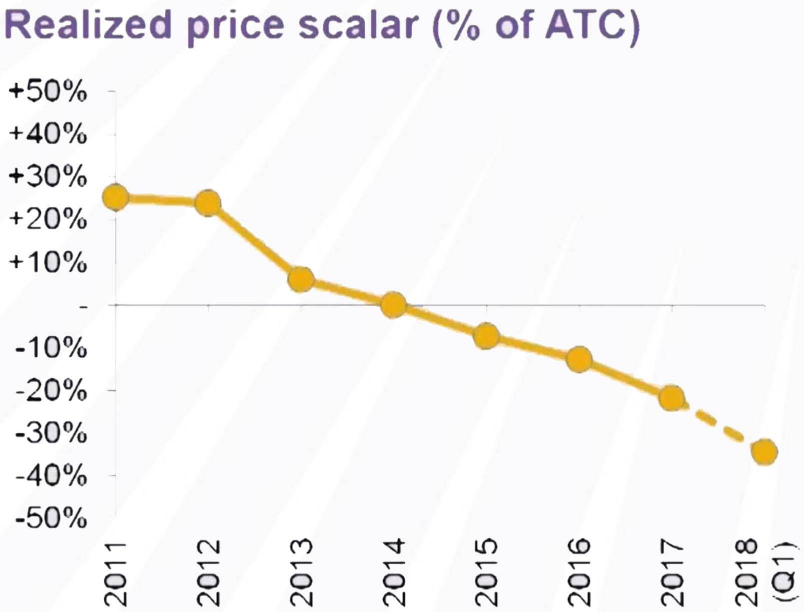
- The "duck" chart elegantly captures oversupply misperception
- Two Concerns:
  - Low Net Load: flexibility to reduce must-run generation resources is limited
  - High Ramp Rates in Evening: flexibility of other generation to ramp up is limited

Challenges : Curtailment

California Independent System Operator Data

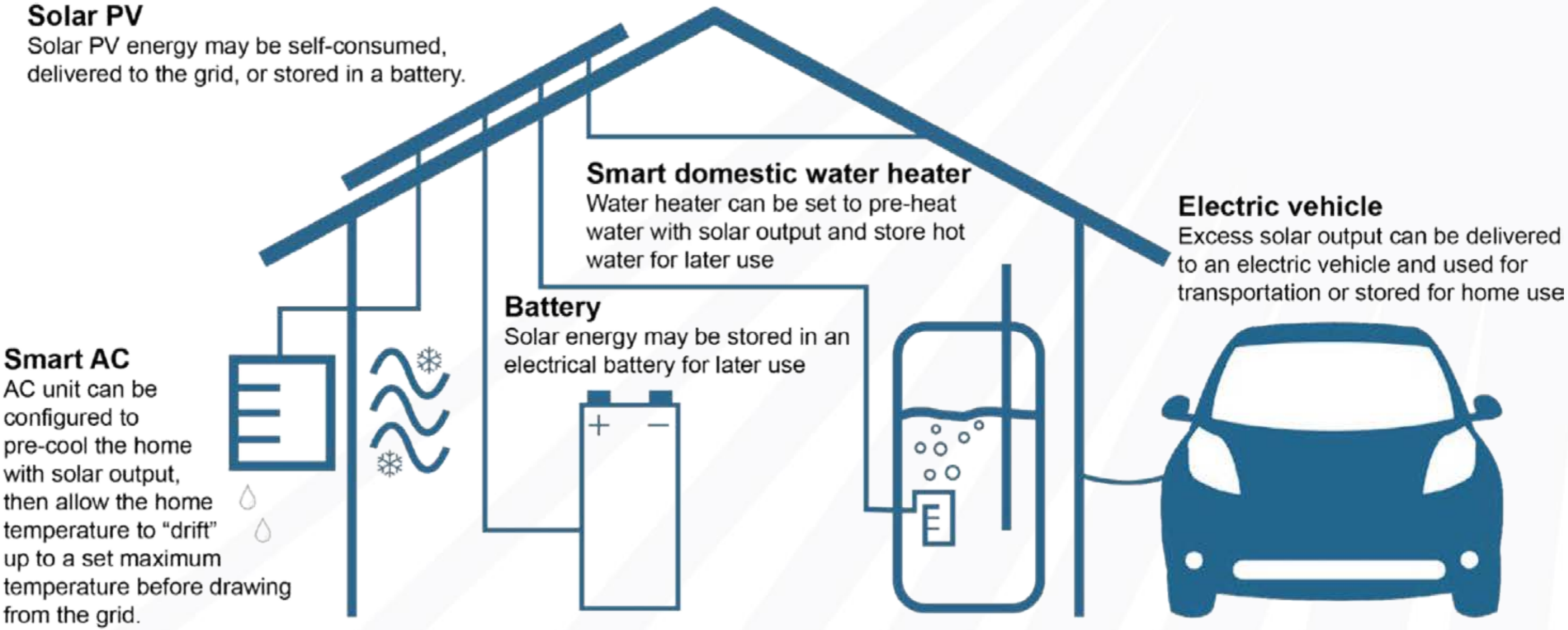


Includes utility-scale solar only. Does not include behind-the-meter.

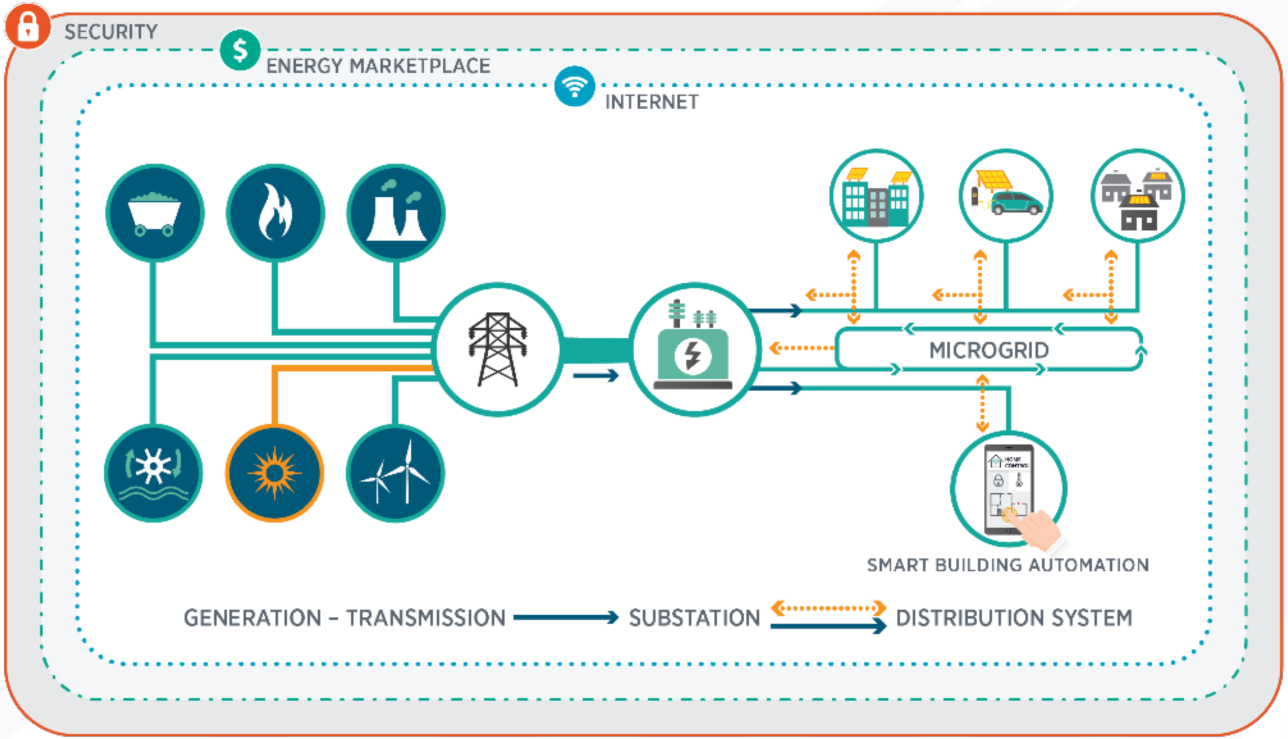


Measured against Day-Ahead, SP15 power prices.

Dispatchable Solar is on the Way

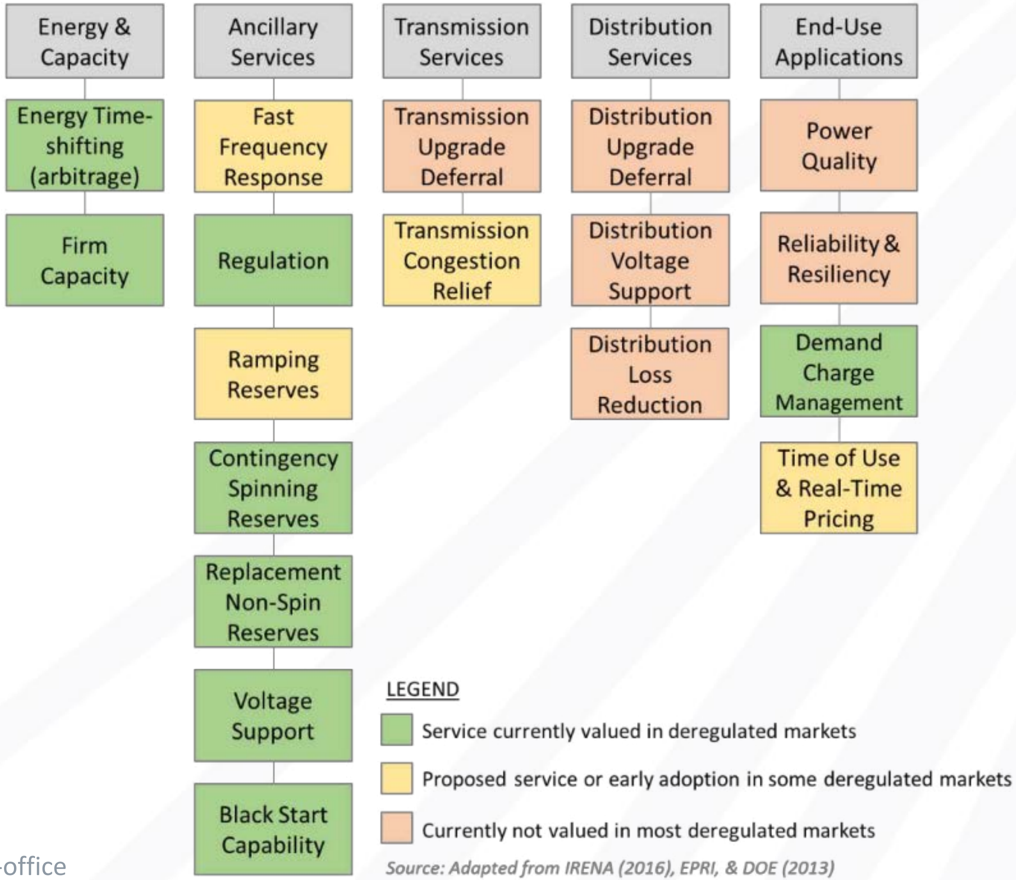


Modern Electric Grid: Two Way Energy and Data Flow



Goal: Centralized and distributed generation optimized with finely tuned, 2-way load balancing

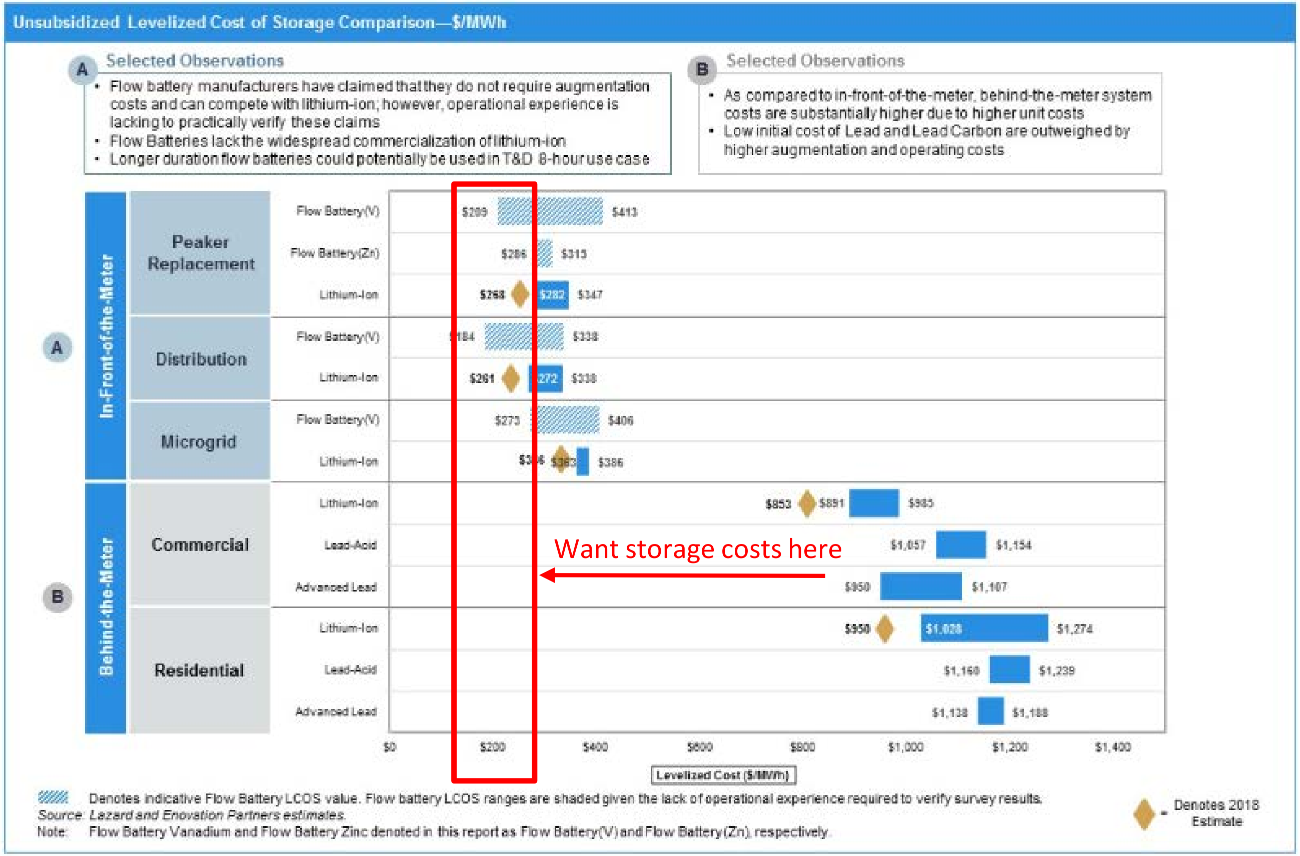
What can Energy Storage do for the grid?



Source: Adapted from IRENA (2016), EPRI, & DOE (2013)

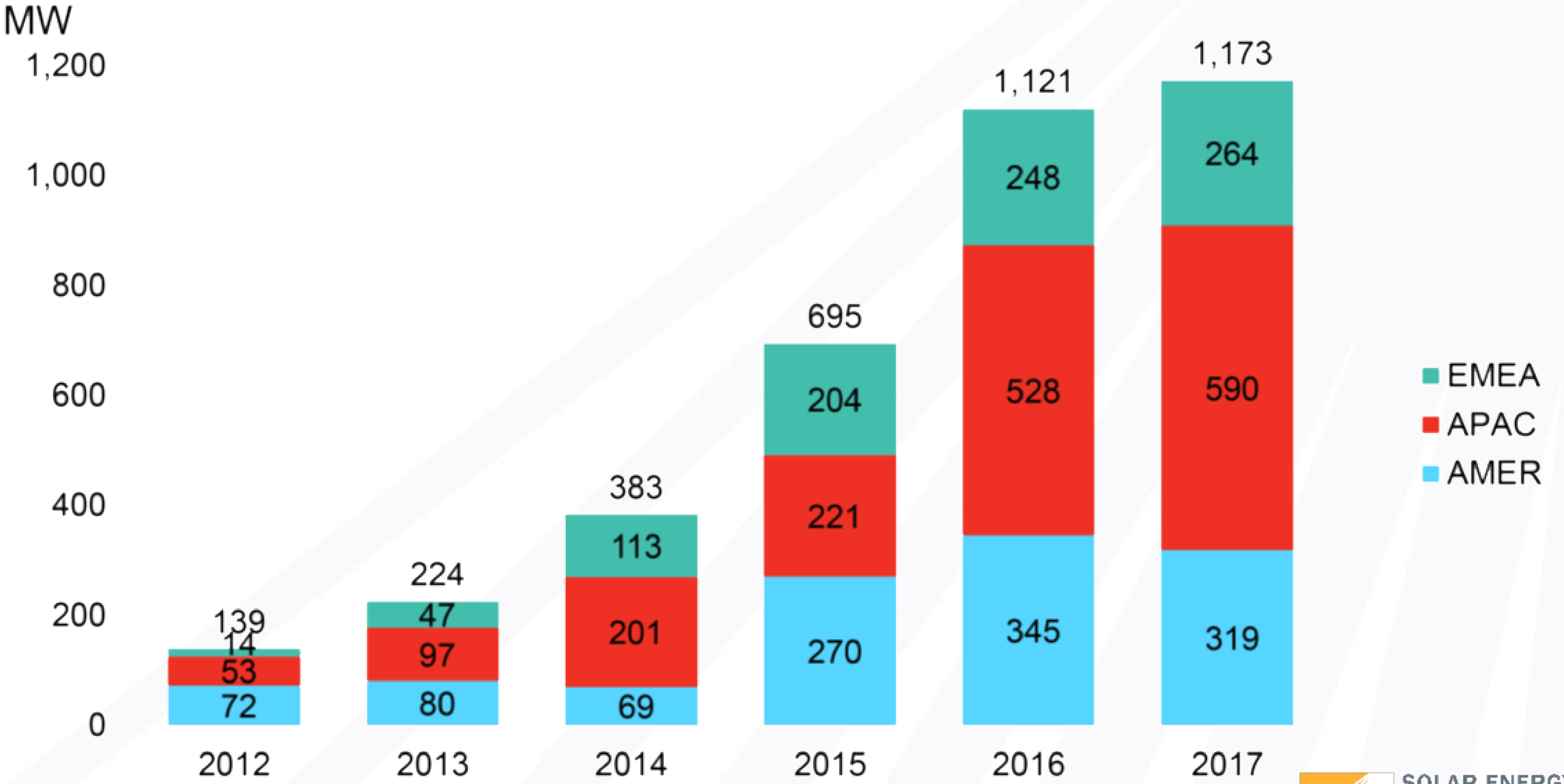
Maintaining Balance, D. Stenclick, P. Denholm, B. Chalamala, IEEE Power and Energy Magazine, November/December 2017

Mapping the Value of Storage



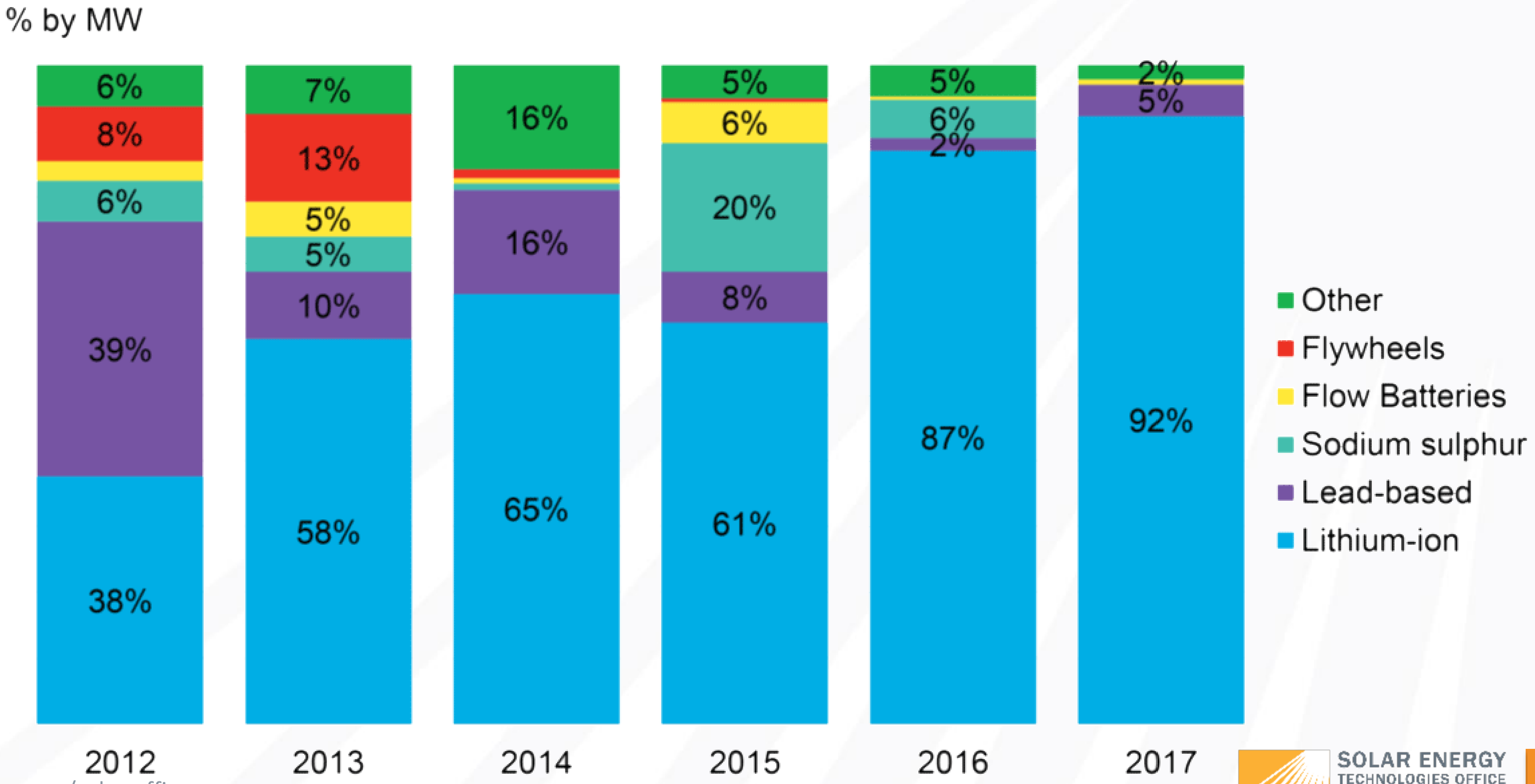
Source: Lazard's Levelized Cost of Storage Analysis (LCOS 3.0) - https://www.lazard.com/perspective/levelized-cost-of-storage-2017/

Global combined behind-the-meter and utility-scale storage deployments



Source: Bloomberg New Energy Finance. Note: excludes pumped hydro and compressed air.
This a corrected chart as of February 14, 2018.

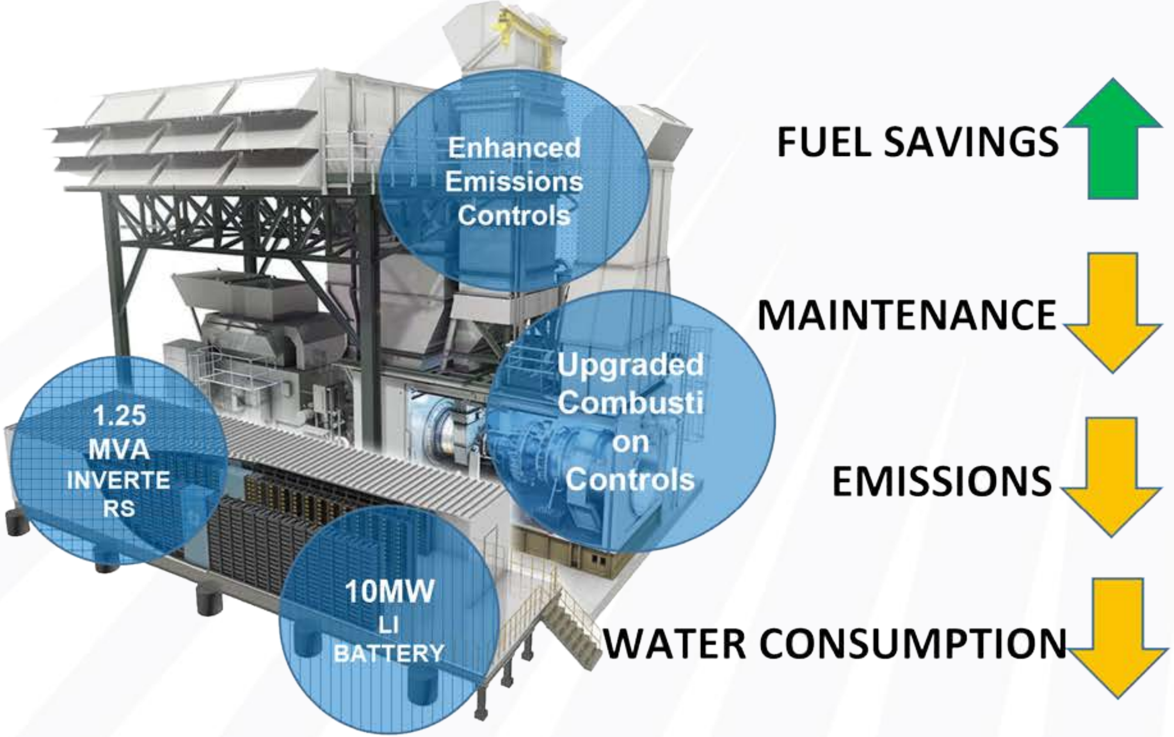
Technology mix of globally commissioned utility-scale energy storage



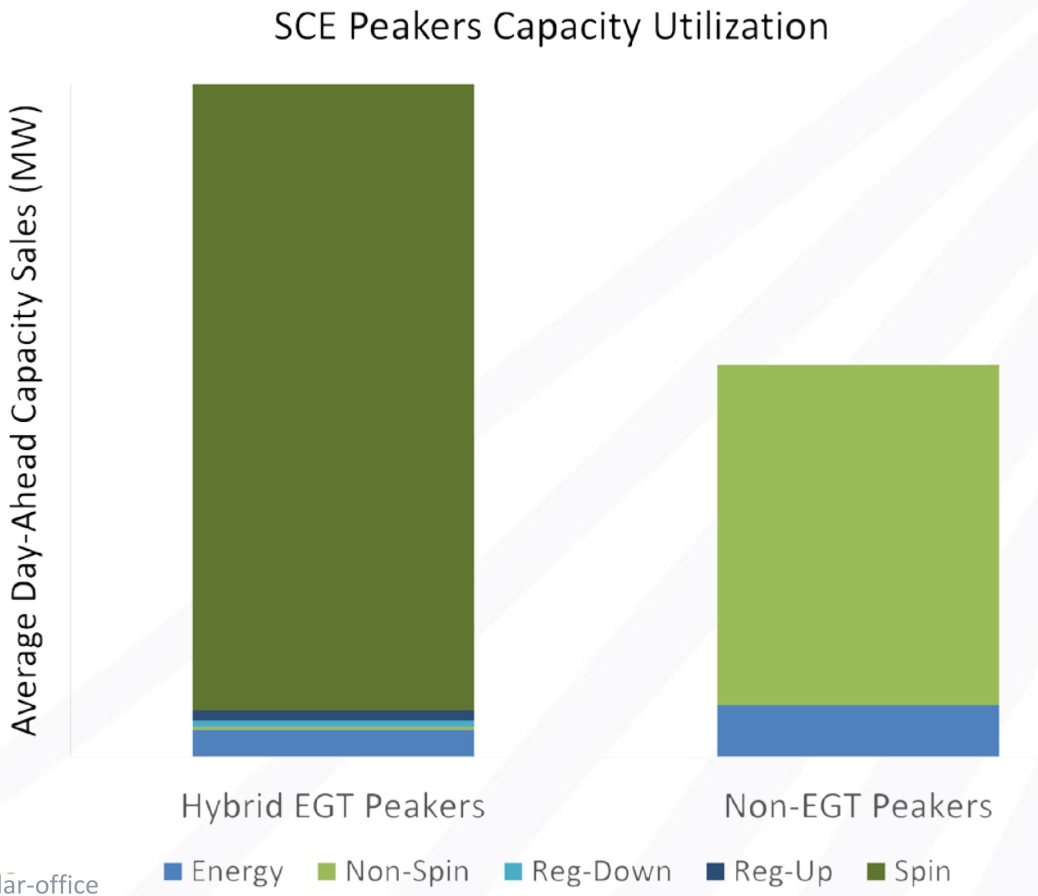
Source: Bloomberg New Energy Finance

Hybrid Enhanced Gas Turbines (EGT)

- Built in partnership with GE and Wellhead Energy Solutions
- Combines a Gas Turbine (GT) and Battery Energy Storage System (BESS)
- BESS online end of 2016
- GT and BESS integrated Q1 2017



Hybrid EGT Market Results – Value



Compared with SCE's non-hybrid peakers over the same period:

- Higher capacity utilization
- Lower fuel gas usage
- Lower emissions
- Higher market revenues

MW-Scale Project Examples

The Zhangbei Project - State Grid / Sparton Resources

2MW Vanadium Redox Flow Battery

- Renewables Energy Time Shift

http://www.energystorageexchange.org/projects/2026

SDG&E El Cajon Substation

37.5MW Li-ion Battery

- Electric Energy Time Shift
- Electric Supply Capacity
- Renewables Capacity Firming
- Renewables Energy Time Shift

http://www.energystorageexchange.org/projects/2218

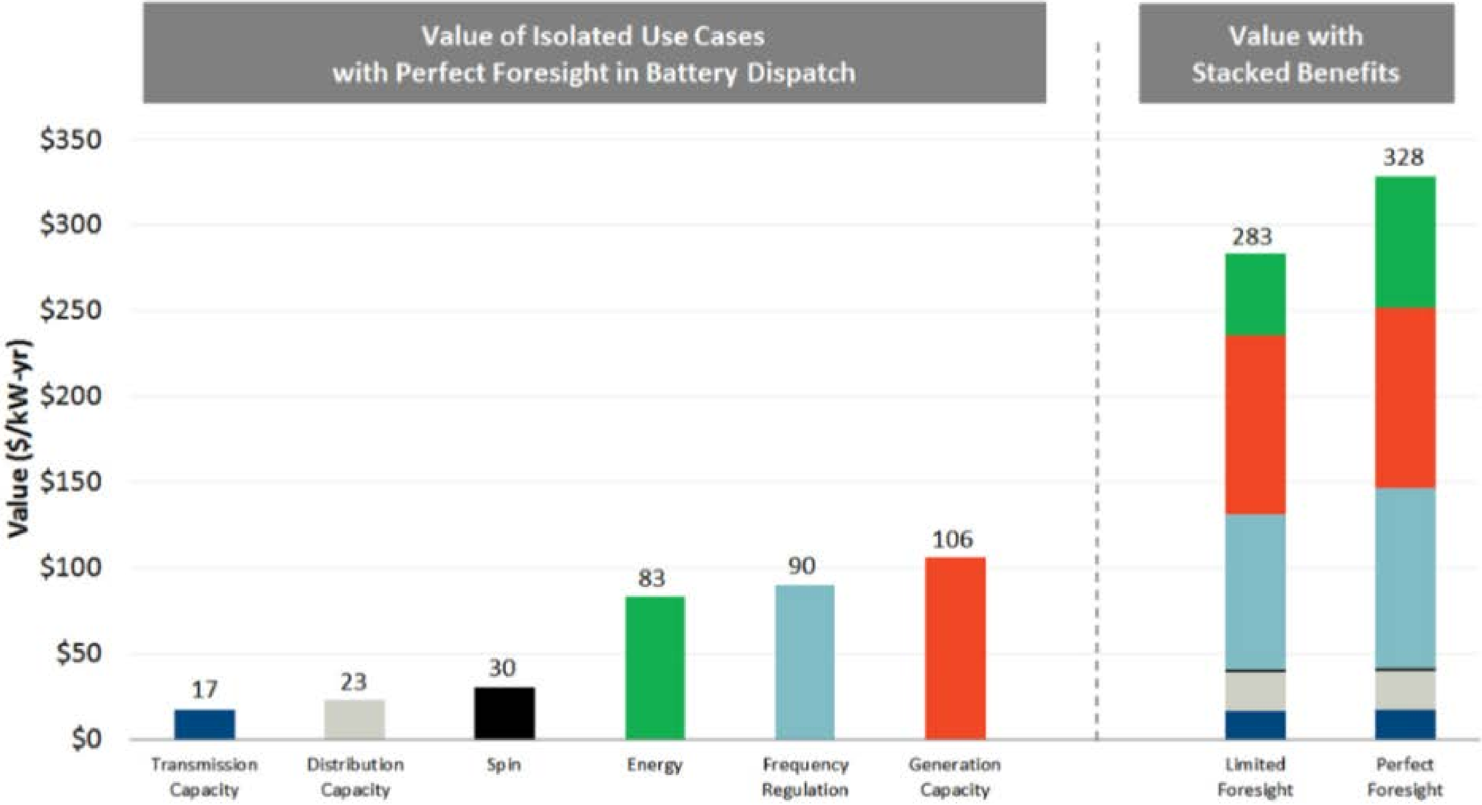
Hornsdale Power Reserve ($323.5/kWh)

100MW Li-ion Battery

- Frequency Regulation
- Renewables Capacity Firming
- Renewables Energy Time Shift

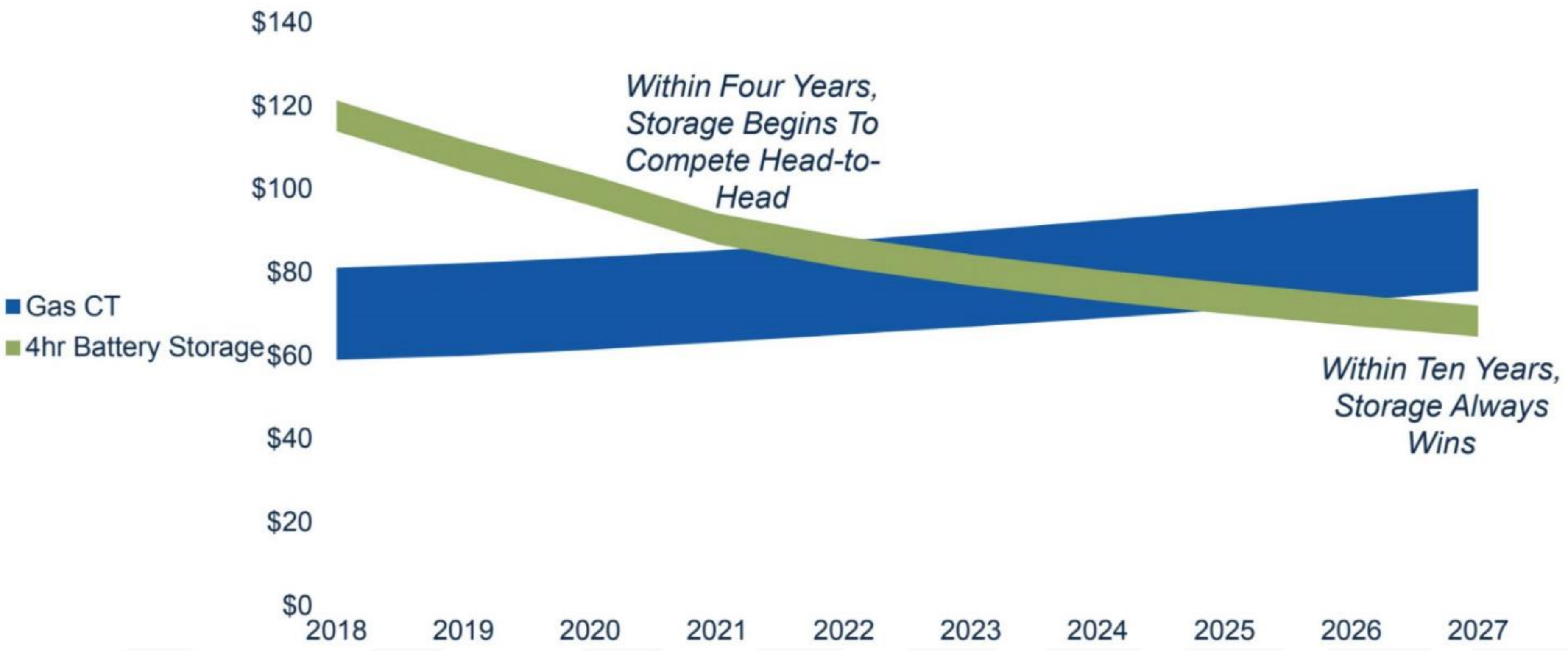
http://www.energystorageexchange.org/projects/2271

Stacking Up the Benefits



Stacked Benefits: Comprehensively Valuing Battery Storage in California, R. Hledik, R. Lueken, C. McIntyre, and H. Bishop, Sept. 2017. http://files.brattle.com/system/publications/pdfs/000/005/494/original/stacked_benefits_-_final_report.pdf?

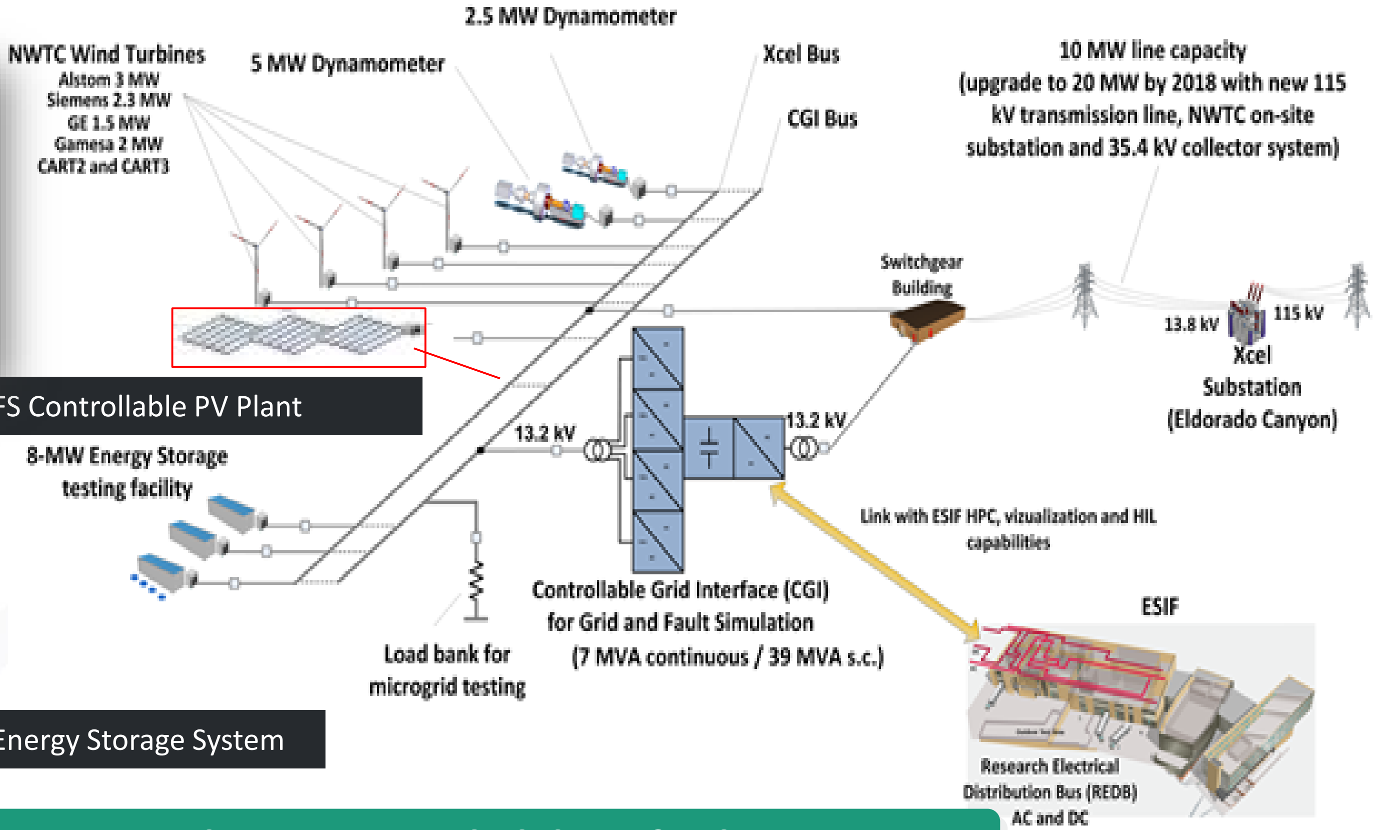
Projected Battery Storage vs Combustion Turbine Peaking Plants



NREL/First Solar R&D Program on PV & Storage

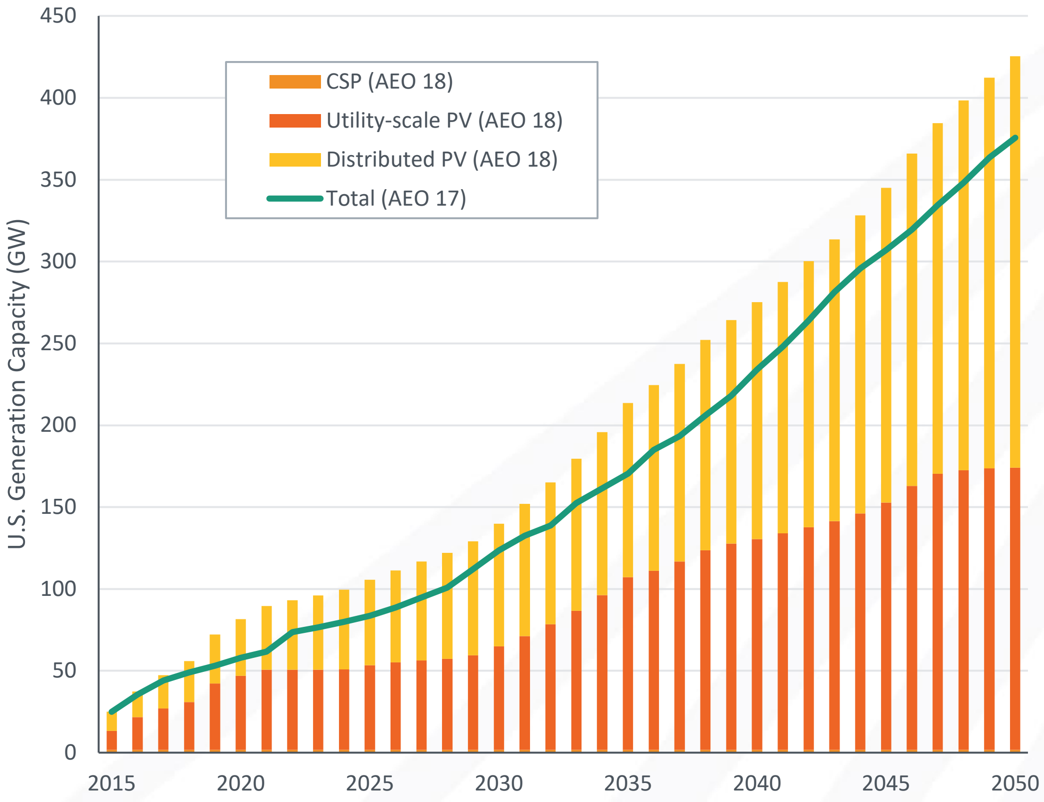
FS Controllable PV Plant

Energy Storage System



Enhance Dispatchability of Solar

EIA's Preliminary 2018 Annual Energy Outlook



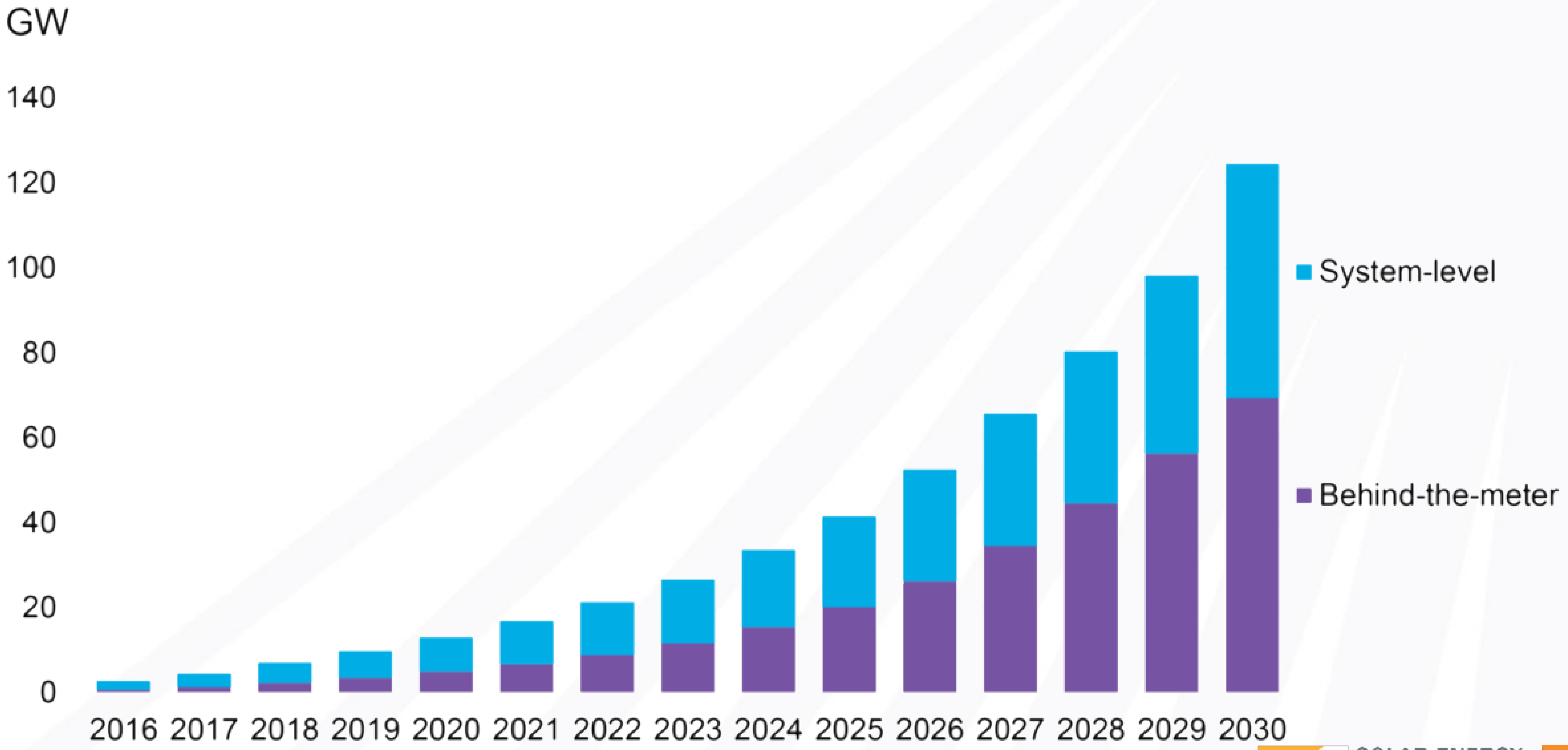
EIA released its preliminary Annual Energy Outlook (AEO) 2018, projecting that U.S. solar installed capacity will grow to 425 GW by 2050

- Of the total, 251 GW is projected to be distributed PV, 172 GW utility-scale PV, and 2 GW of CSP
- 425 GW of solar would represent approximately 24% of total U.S. installed capacity, supply 16% of total U.S. electricity – all renewables are projected to supply 34%
- Distributed PV is projected to surpass utility-scale PV, in installed capacity, by 2026

2050 capacity represents a growth of 17% above AEO 2017 capacity projections, however still well below other analyst projections

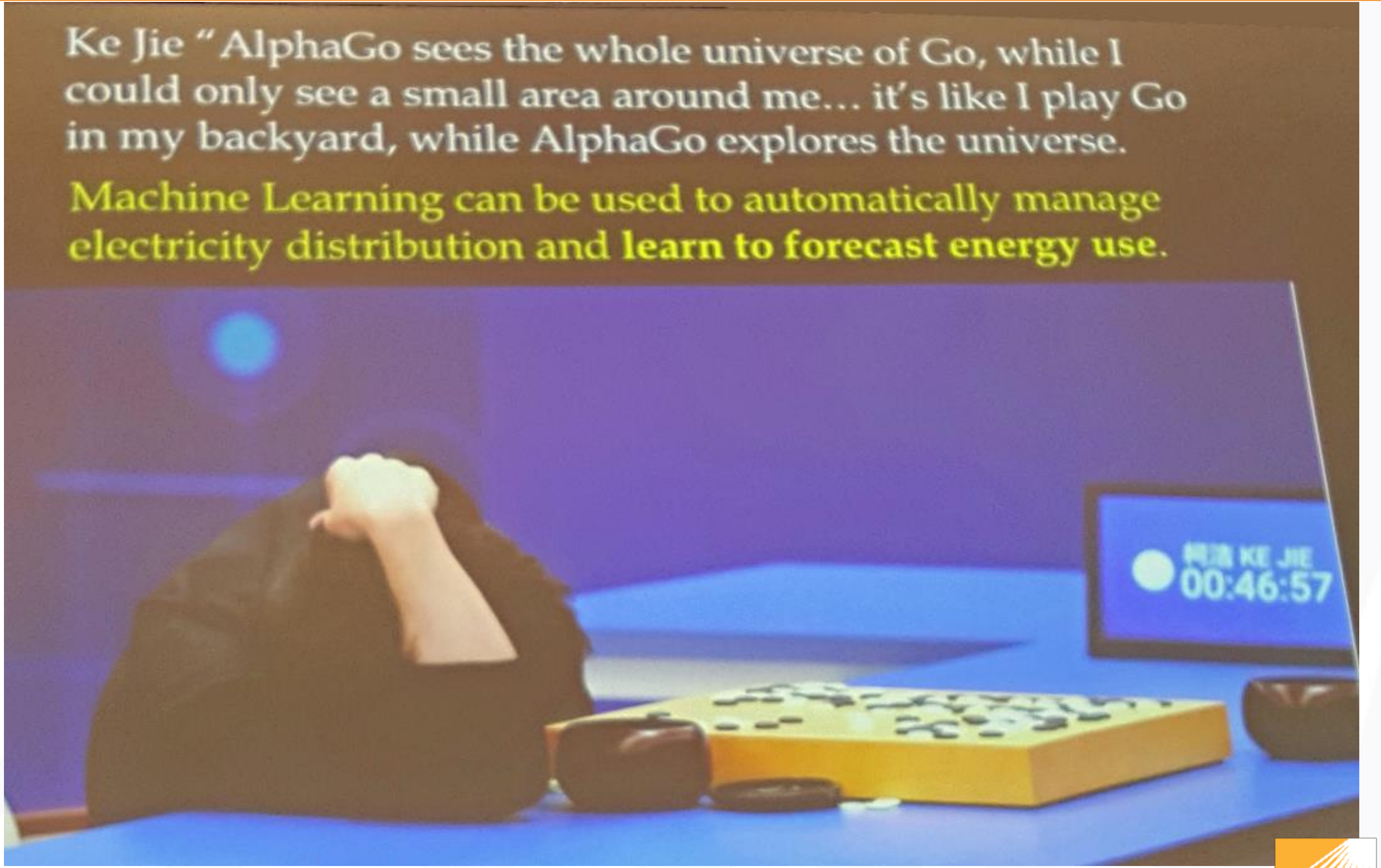
- BNEF projects there will be 400 GW of PV by 2040 in the U.S., compared to 287 GW from AEO 2018

Global energy storage will increasingly be behind-the-meter



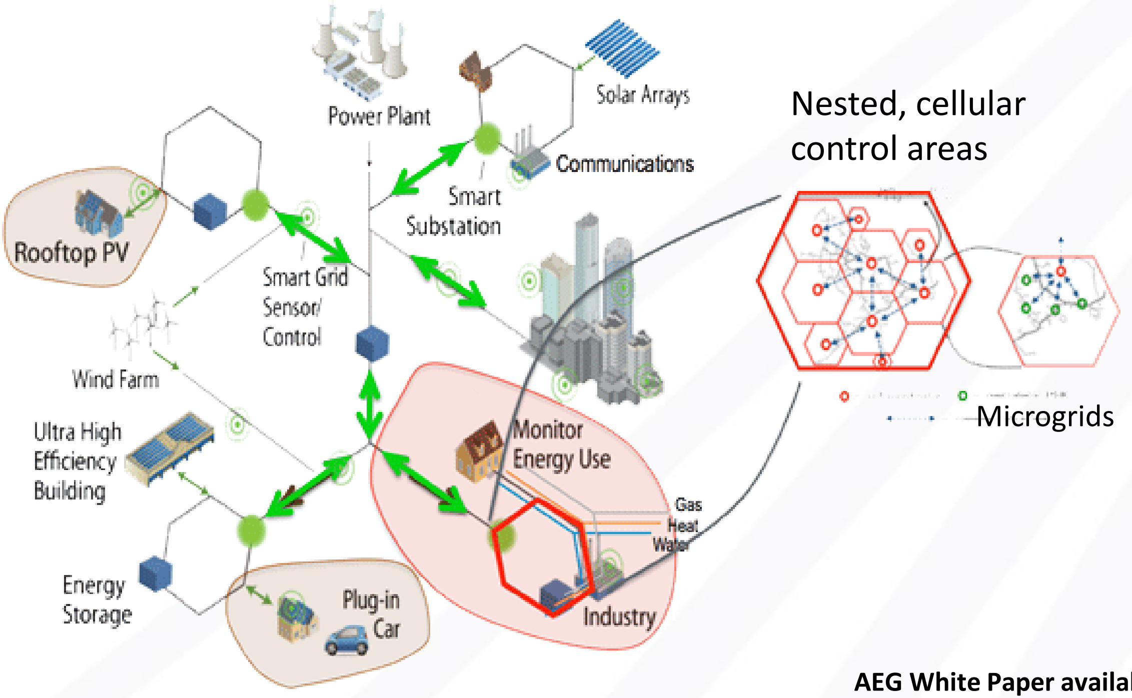
Source: Bloomberg New Energy Finance. Note: System-level refers to projects that provide system services independent of where they are connected to the grid.

Role of Artificial Intelligence



Autonomous Energy Grids (AEGs)

Optimized for secure, resilient and economic operations



Key Features of AEGs

- **Autonomous** – Makes decisions without operators
- **Resilient** – Self-reconfiguring, cellular building blocks, able to operate with and without communications
- **Secure** – Incorporates cyber and physical security against threats
- **Reliable and Affordable** - Self optimizes for both economics and reliability
- **Flexible** – Able to accommodate energy in all forms including variable renewables

AEG White Paper available at:
https://www.nrel.gov/docs/fy18osti/68712.pdf

Connections : We Need Collaborators

- Electricity is not easily stored in native form
- Need to convert to some other form (chemical, mechanical, thermal) to store energy

- There are alternatives to energy storage
  - Generator ramping (constrained by min/max operational levels and ramp speed)
  - Load ramping (constrained by customer needs)
  - Geographic electricity moving/shifting (transmission)