Advances in Utility-Scale PV Plants – Key Lessons Learned

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VP, PV Systems

Enabling a world powered by reliable, affordable solar electricity.

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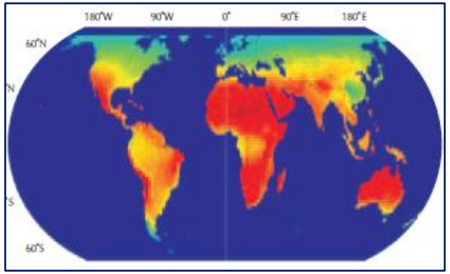
Key Messages – Advances in Utility-Scale PV Plants

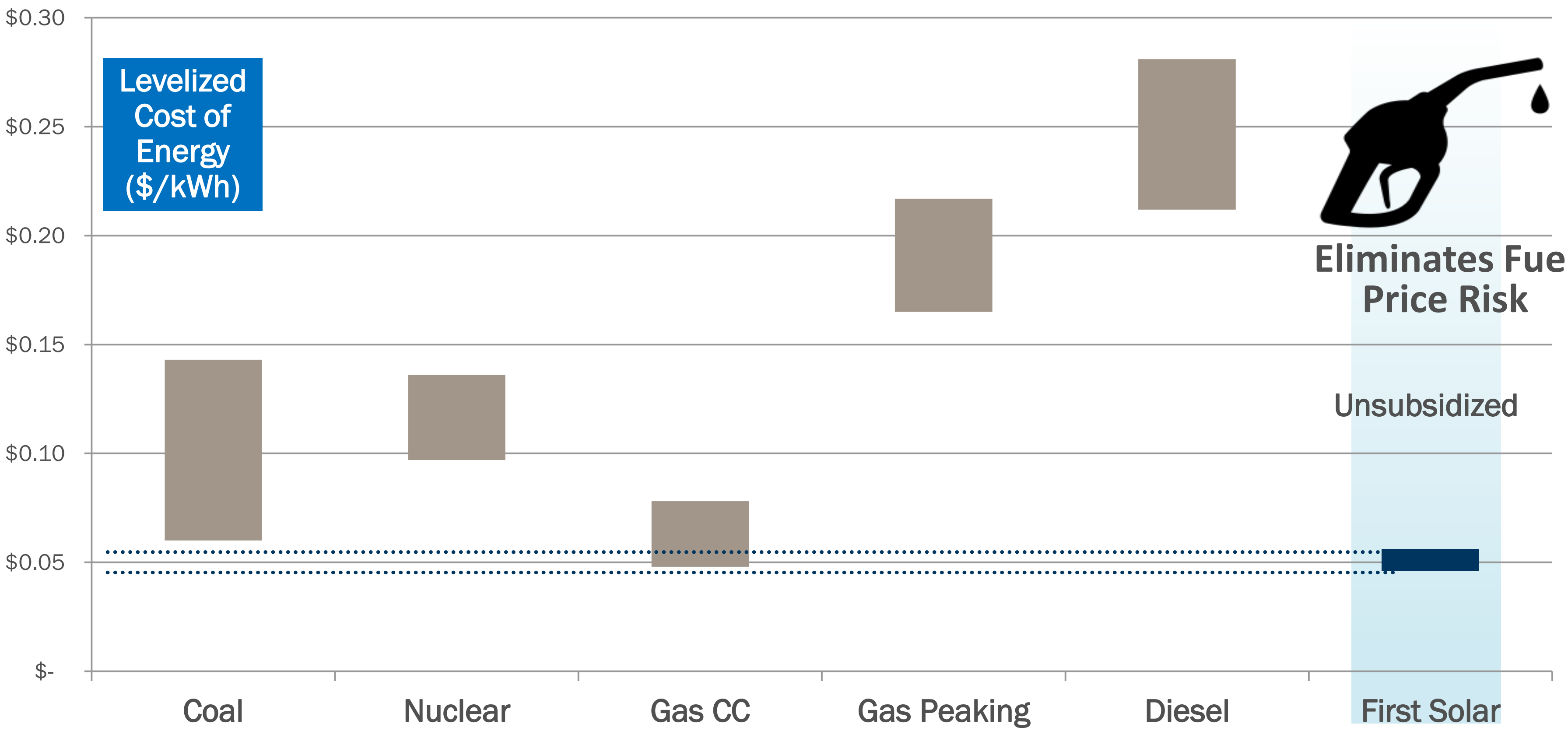


- Utility-scale solar electricity **now costs less** than conventional generation in many markets[1]
  - Less expensive than rooftop PV by a factor of 2-3
- Key cost reduction drivers include:
  - Module **cost reduction & efficiency improvement**
  - BOS & Plant **design innovations**
  - Improved Investment Climate
- Need to address grid challenges to grow solar substantially[2]
  - Maintain **grid stability and reliability** while integrating large-scale solar into electricity grid system
  - **Increase grid flexibility** to increase solar penetration and reduce curtailment

Sources: 1 Lazard Levelized Cost of Energy Analysis – Version 10; GTM Research Global Solar PV Demand Monitor Q2017. . 2. Beyond 33% Renewables: Grid Integration Policy for a Low--Carbon Future, CPUC White Paper

Solar is Competitive Today

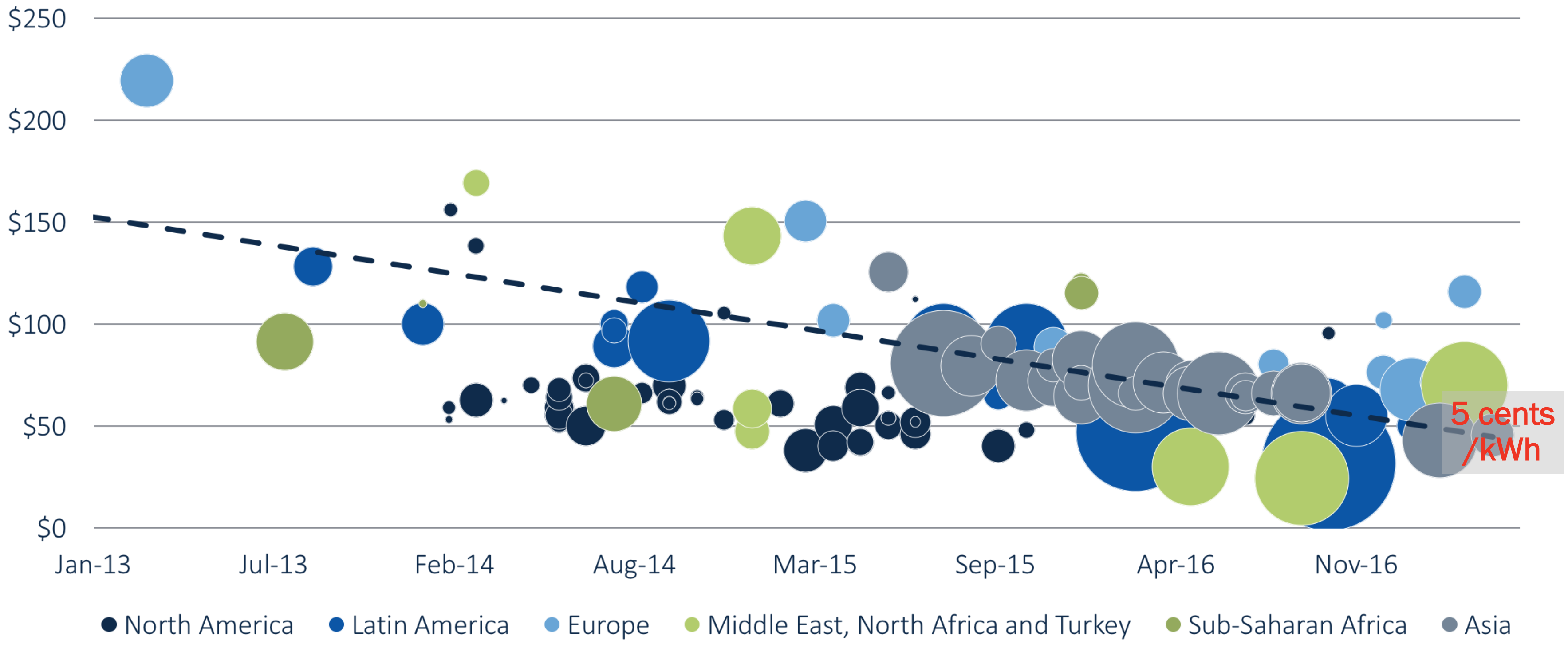
Utility-Scale Solar Energy is Competitive Today … *Eliminates Fuel Price Volatility*



Source: Lazard Levelized Cost of Energy Analysis – Version 10;

Globally, Projects Are Growing and Prices are Falling

Global Tendered Solar Projects by Bid Price ($/MWh) and Capacity (MWdc)



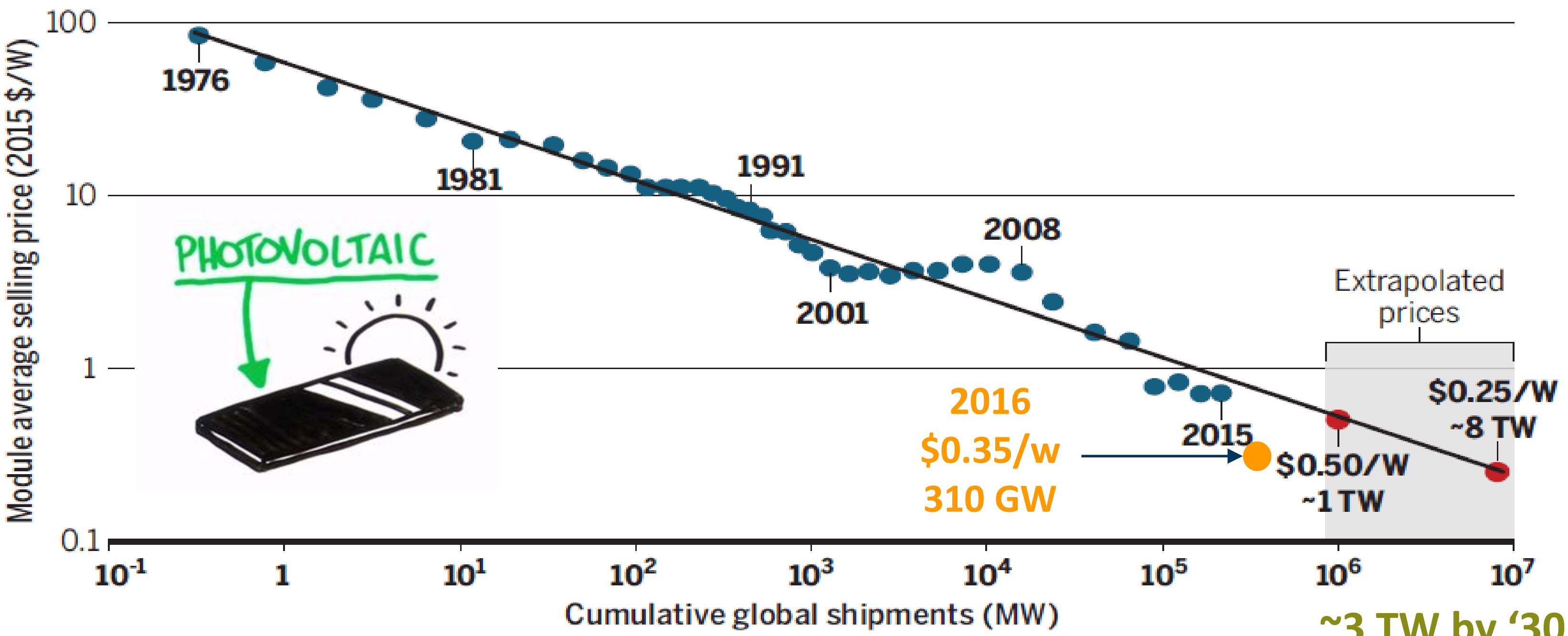
Source: GTM Research *Global Solar Demand Monitor Q1 2017*

Note: Bubble size denotes auctioned capacity (MWdc)

Source: GTM Research

PV Module Experience Curve – Key Driver for Low-Cost Solar

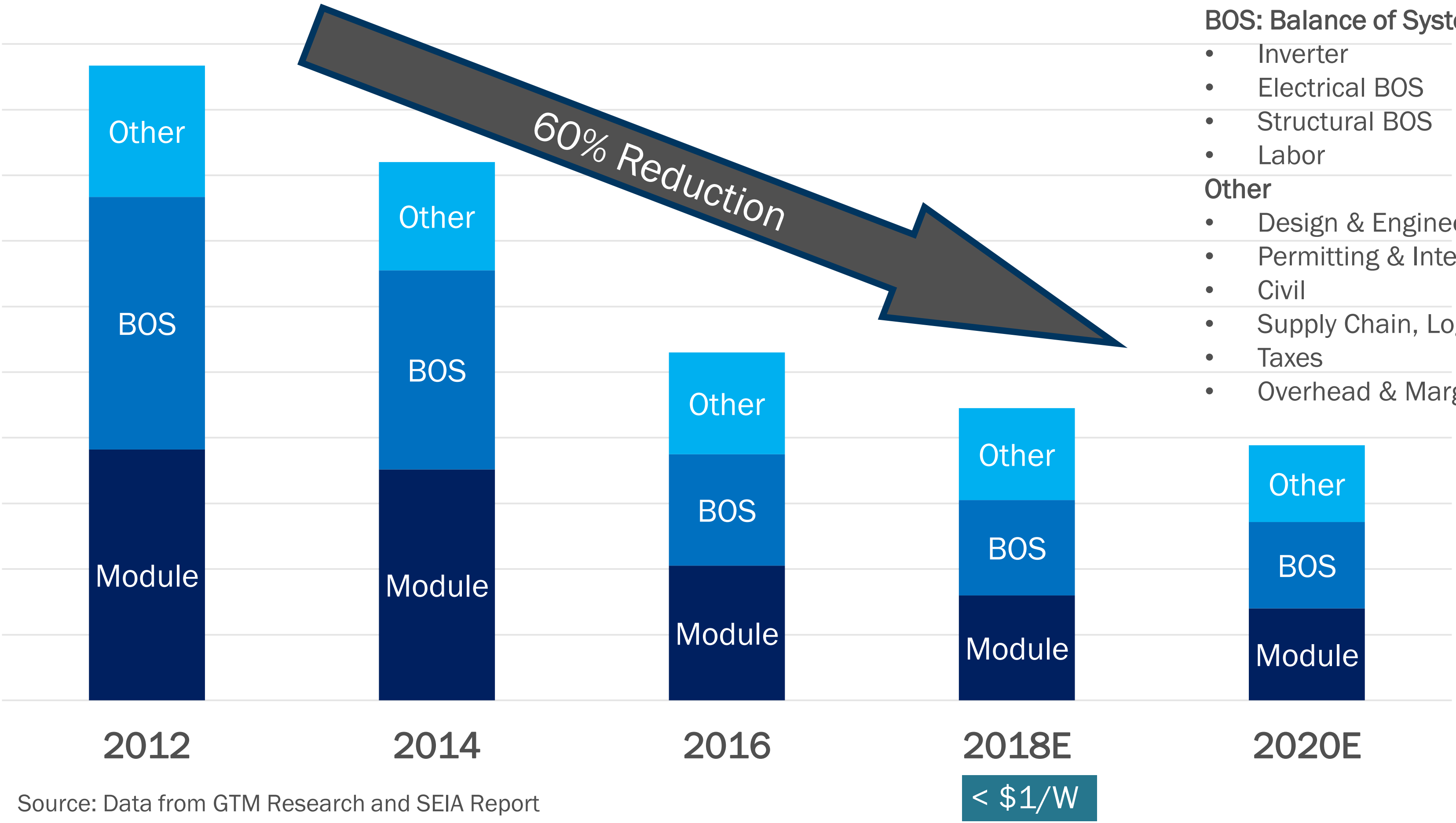
Historically, module prices have decreased as a function of cumulative global shipments (blue dots reflect historical data, red dots reflect extrapolated prices for 1 TW and 8 TW based on the historical trend line). See supplementary materials for data sources.



~3 TW by ‘30

“Terawatt-scale photovoltaics: Trajectories and challenges”, Haegel et al, , Science Mag, 14 APRIL 2017, VOL 356 ISSUE 6334

BOS Has Been Critical As Well In Reducing Utility-Scale PV Plant Cost



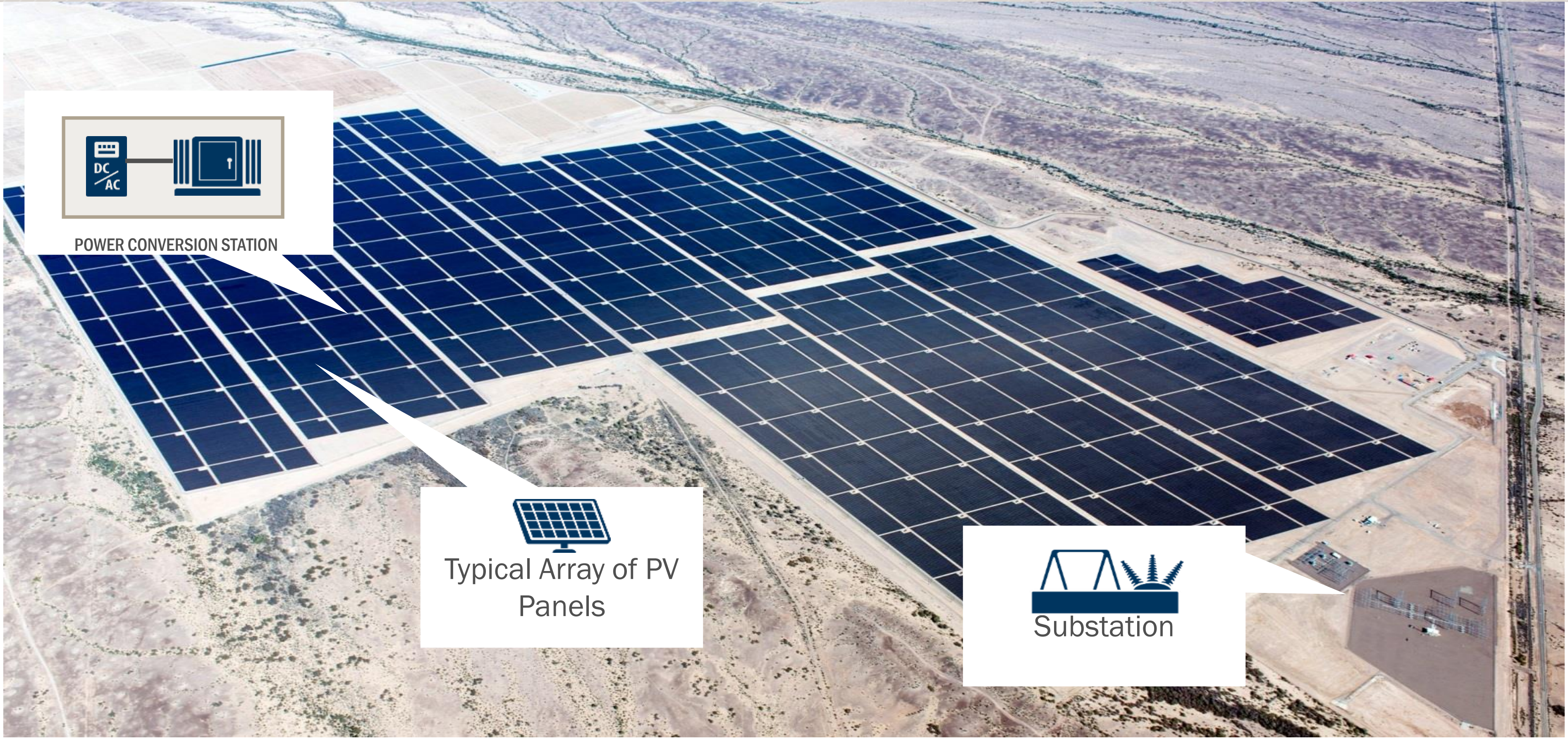
BOS: Balance of Systems
- Inverter
- Electrical BOS
- Structural BOS
- Labor

Other
- Design & Engineering
- Permitting & Interconnection
- Civil
- Supply Chain, Logistics & Misc
- Taxes
- Overhead & Margin

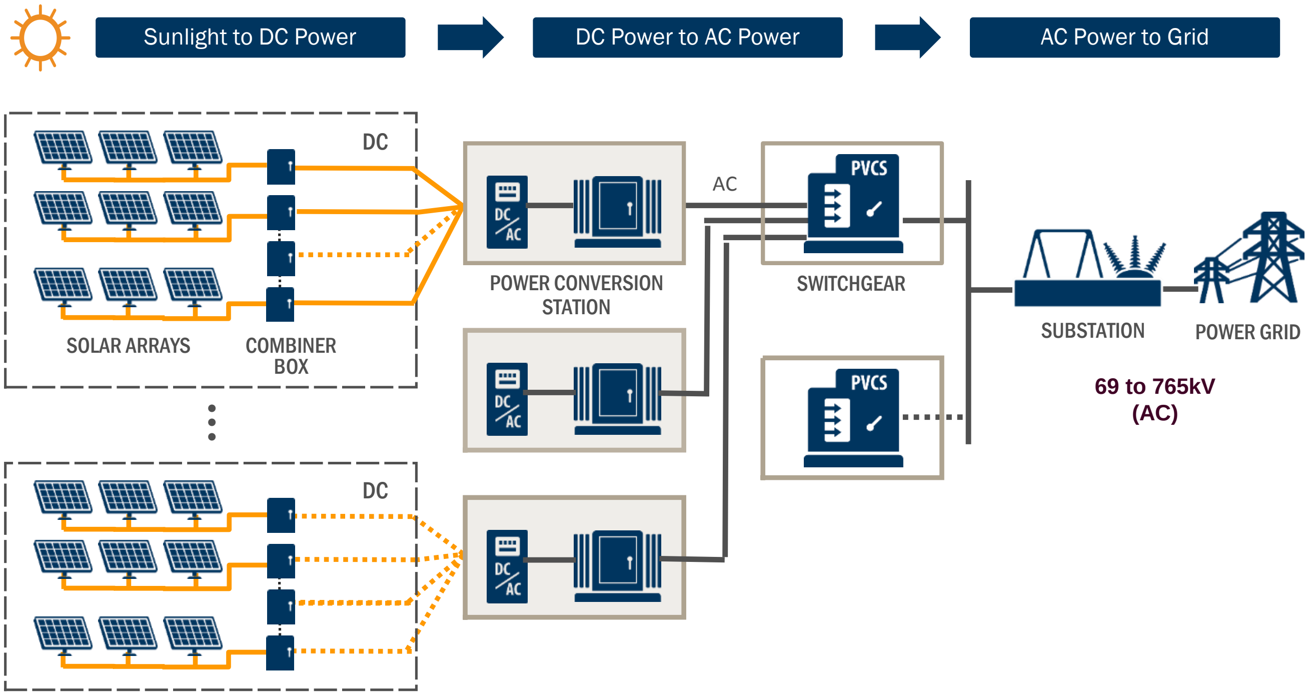
Source: Data from GTM Research and SEIA Report

Utility-Scale PV Plant

Typical Utility-Scale PV Plant



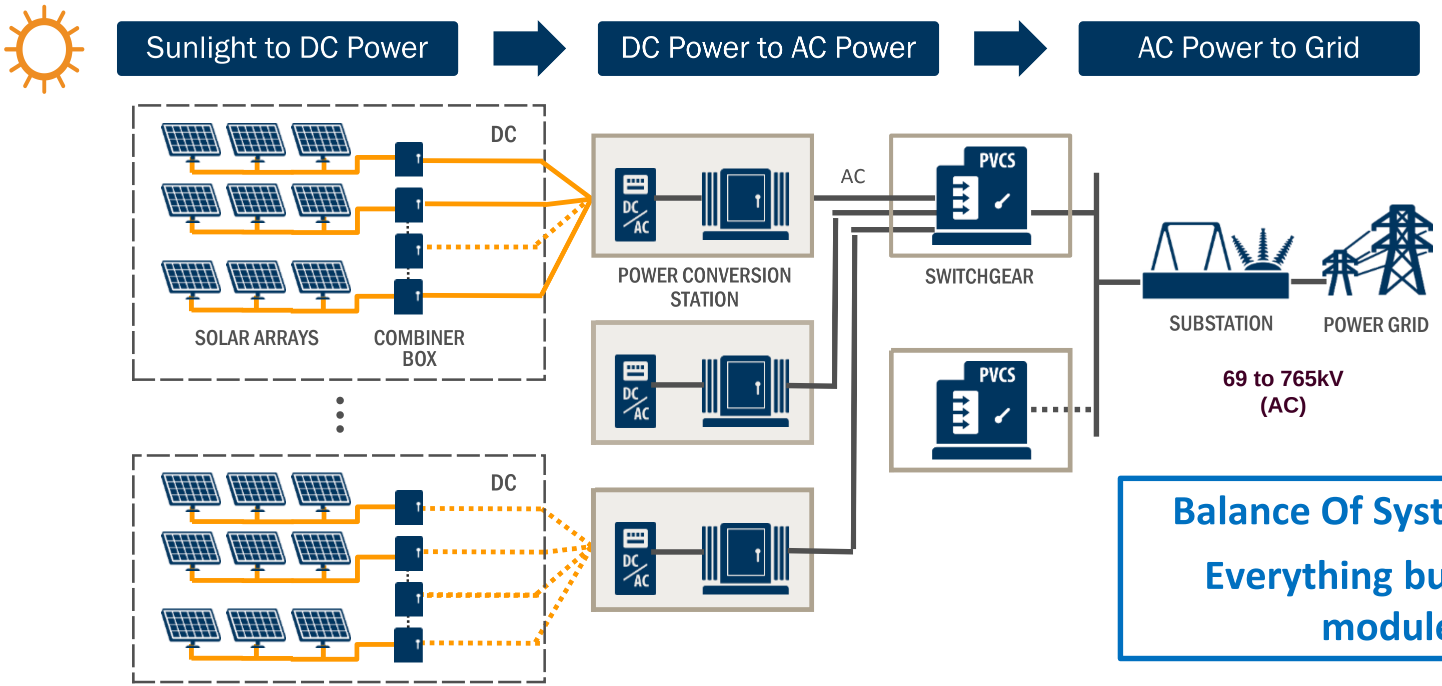
PV Plant Schematic



Typical DC Voltage 1kV or 1.5kV

Typical AC Collection Voltage 34.5kV
(Alternatives 4.16kV to 27.6kV)

Power Plant Overview/BOS Definition



Balance Of System (BOS): Everything but the PV modules

Typical DC Voltage 1kV or 1.5kV

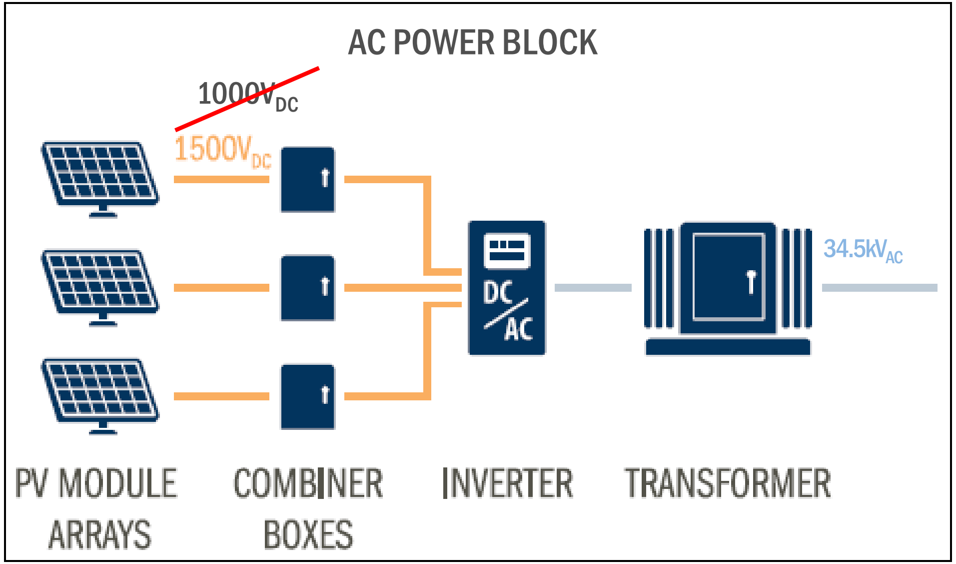
Typical AC Collection Voltage 34.5kV
(Alternatives 4.16kV to 27.6kV)

Variable or DC BOS (DC Field)

Efficiency Dependent

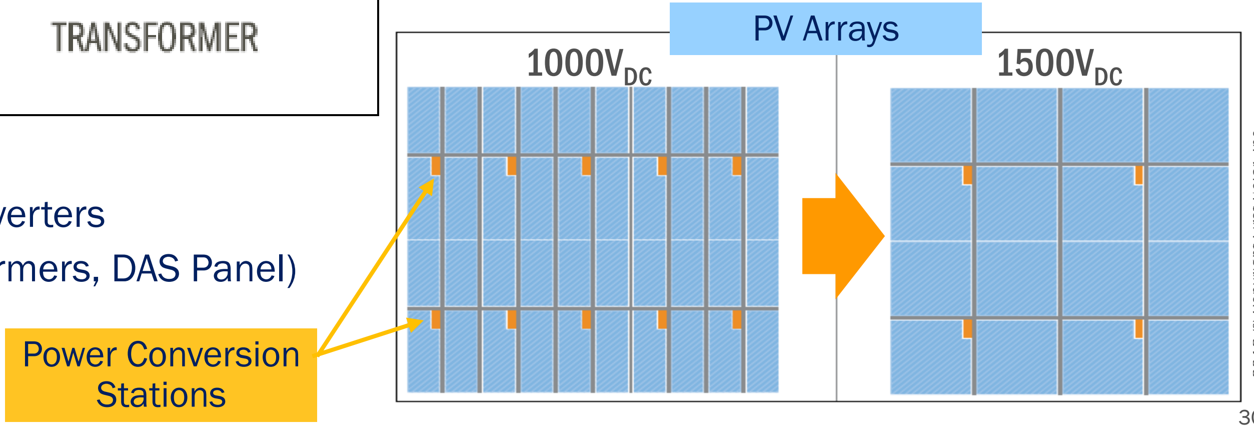
Fixed or AC BOS (AC Field)

Lower Cost PV Plant Architecture … Moving from 1kV to 1.5kV DC Design

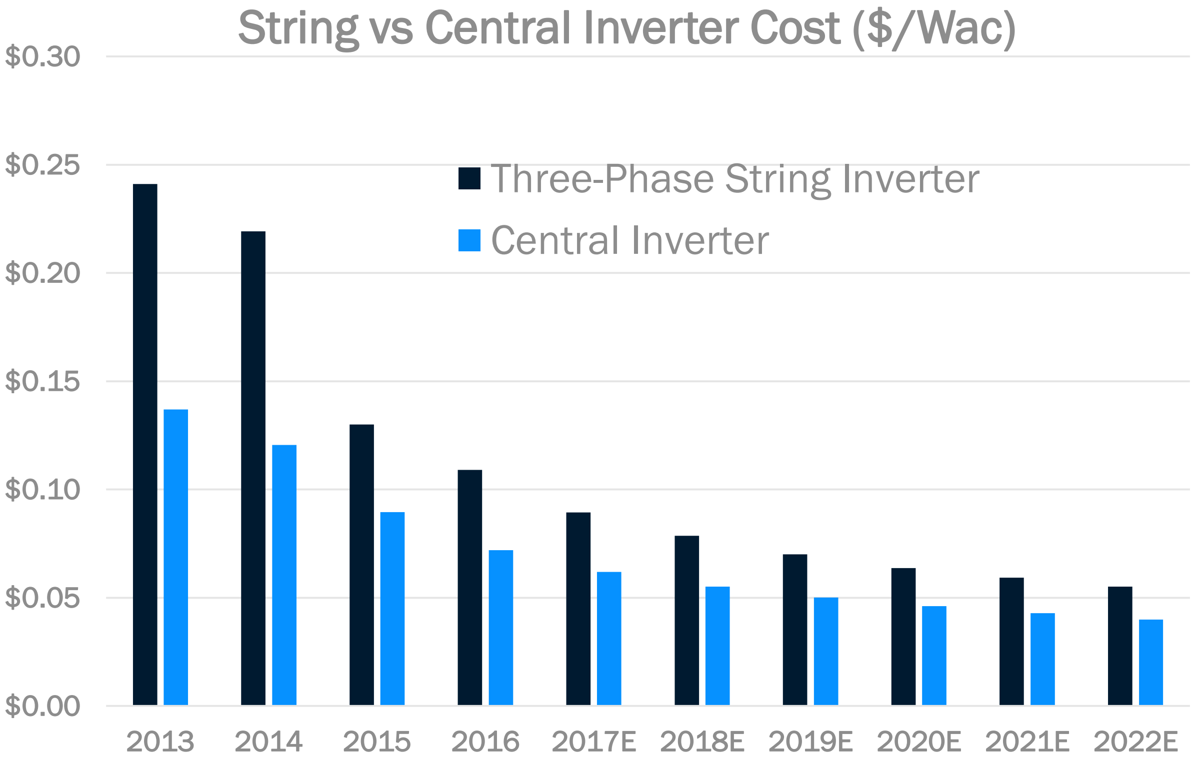


Cost savings from

- Larger, more cost-effective inverters
- Fewer PCS (Inverters, Transformers, DAS Panel)
- DC & AC Wiring Impact
- O&M



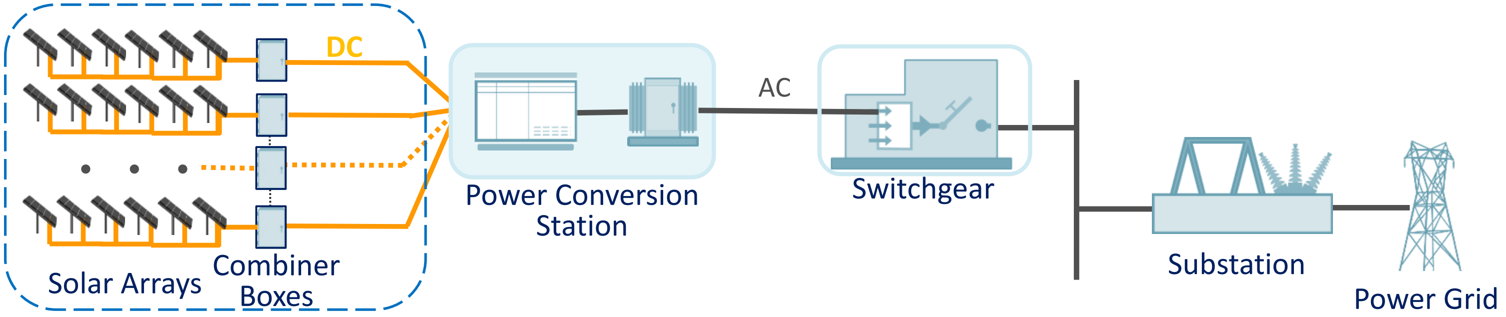
3-Phase PV Inverter Price Have Continued to Fall ...and Converge



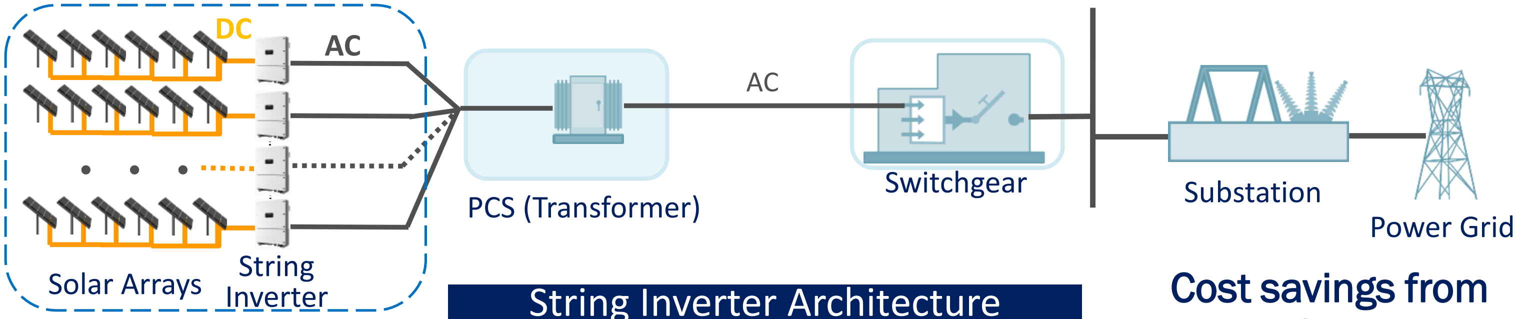
Source: The Global PV Inverter and MLPE Landscape H1 2017, GTM Research

PV Plant Schematic – Central vs String Inverters

Sunlight to DC Power → DC Power to AC Power → AC Power to Grid



Central Inverter Architecture

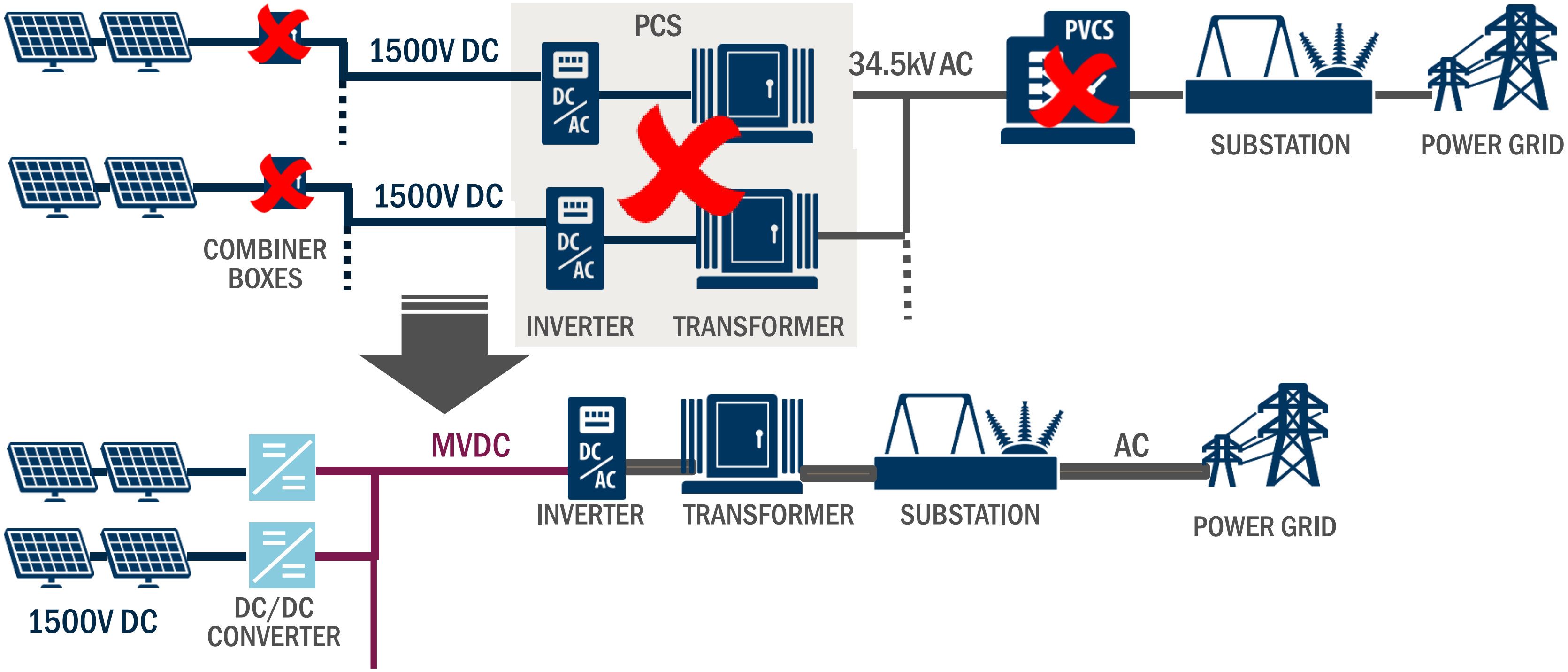


String Inverter Architecture

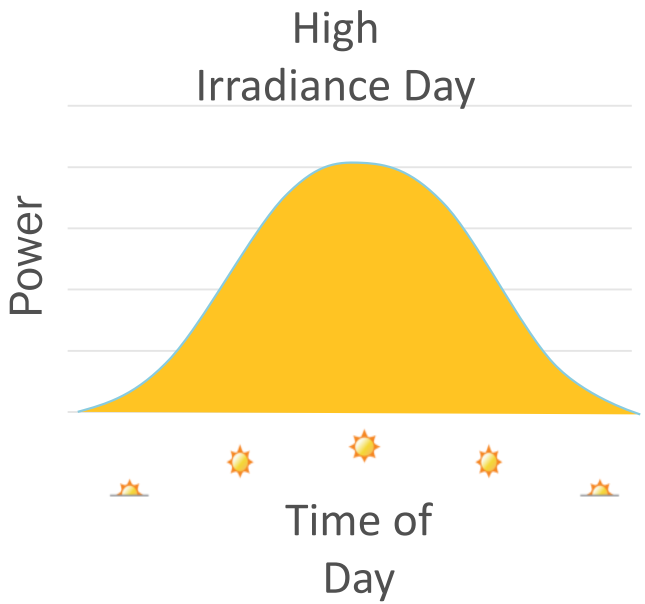
Cost savings from

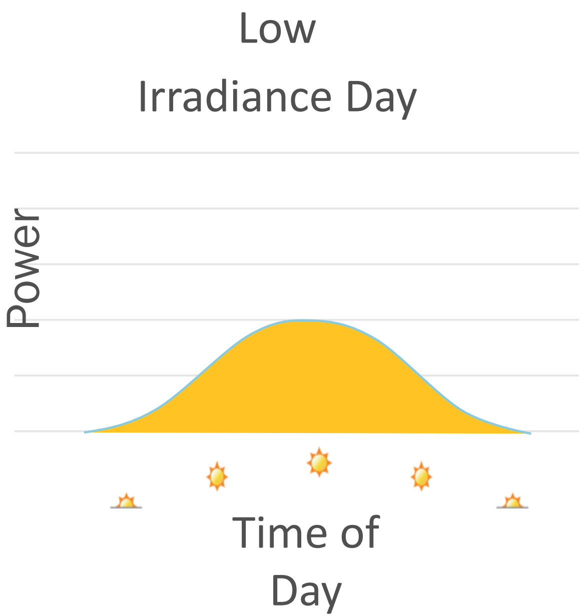
- No Combiner Box
- Improved O&M

Yet Another PV Architecture: Medium Voltage DC Plant (MVDC)

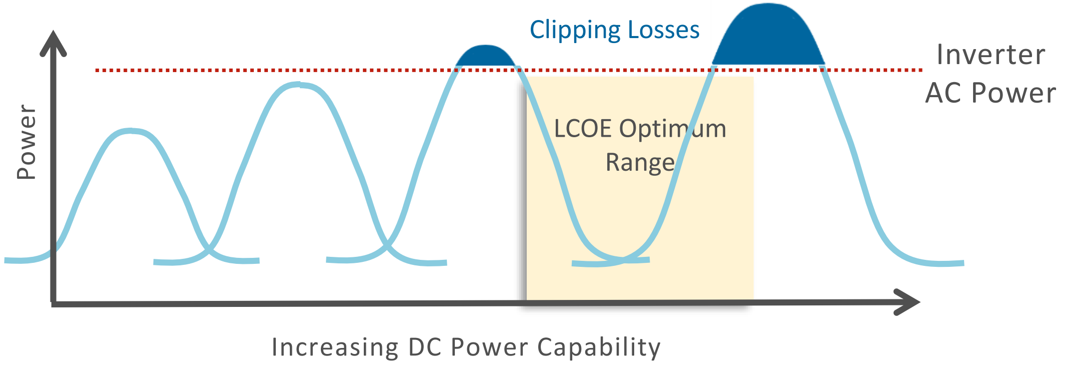


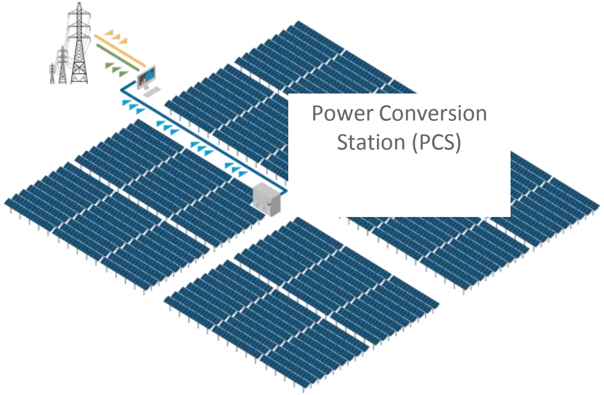
Daily Power Production

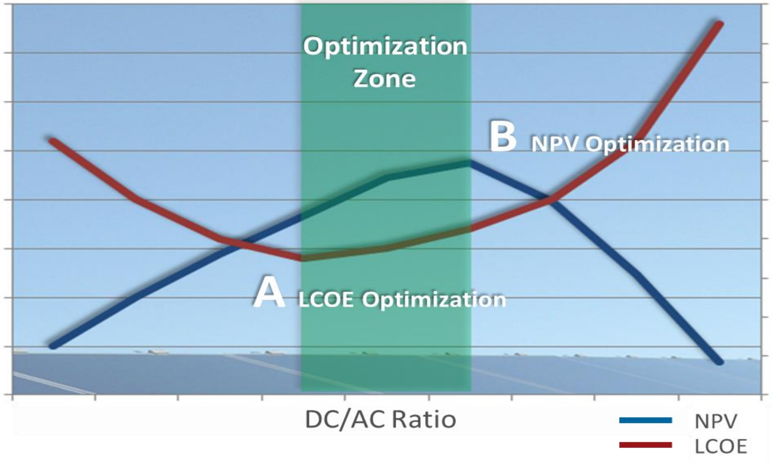




Plant Design Optimization: DC/AC Ratio Case Study



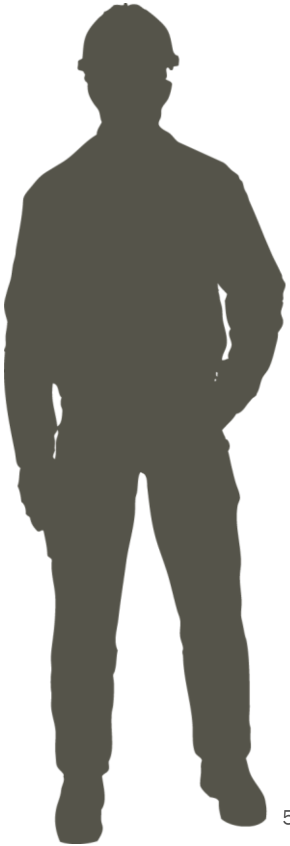




First Solar Module Advances

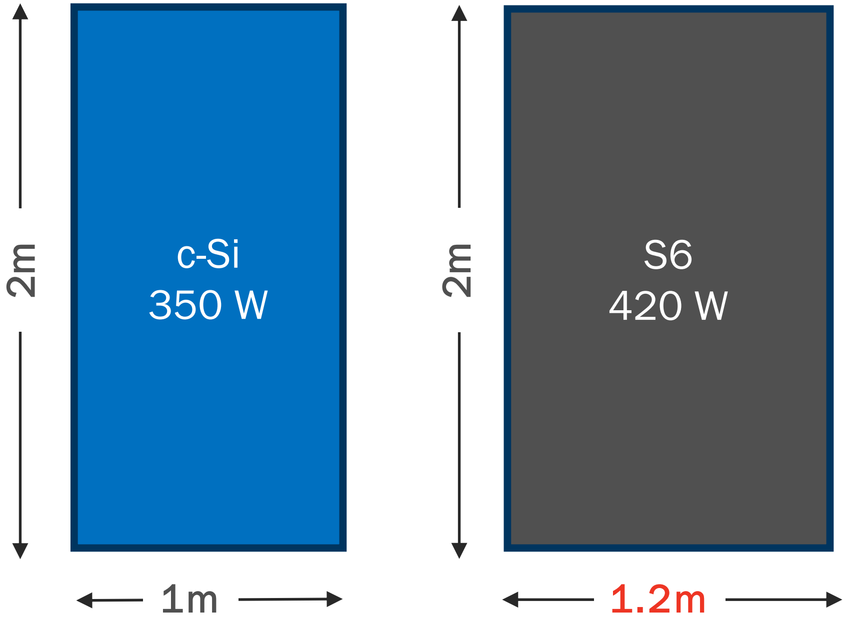
Series 6: Compelling For Us And Our Customers

- Same proven manufacturing process
- Same reliable, high energy-yield cell
- Higher Efficiency
- Improved BOS installation cost
- Framed with standard structure compatibility



Introducing Larger Format Series 6 Module … *reduces BOS Cost*

Physical Dimensions for Equal Efficiency



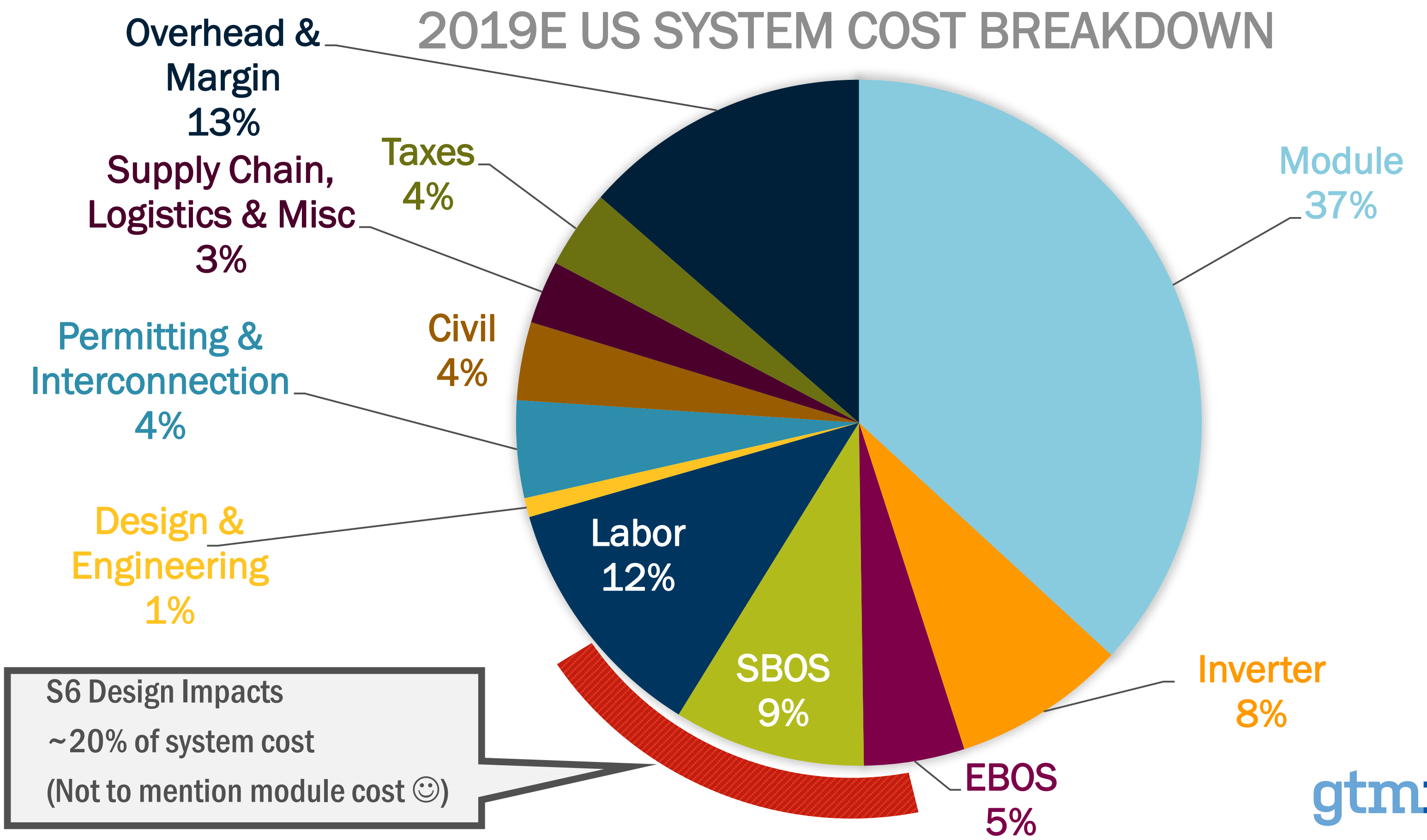
Large Format

MORE WATTS PER INSTALL OPERATION

Framed

SIMPLIFIED MOUNTING TO COMMON INDUSTRY STRUCTURES

The BOS Opportunity



S6 Design Impacts

~20% of system cost

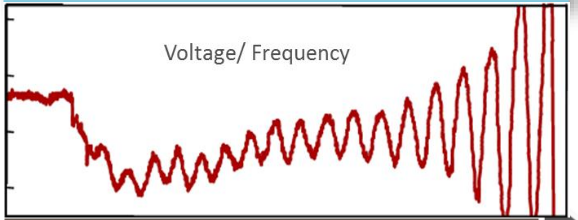
(Not to mention module cost ☺)

gtmresearch

Grid Integration

Solar PV Impact on Power Grid – Key Topics

Grid Stability & Reliability



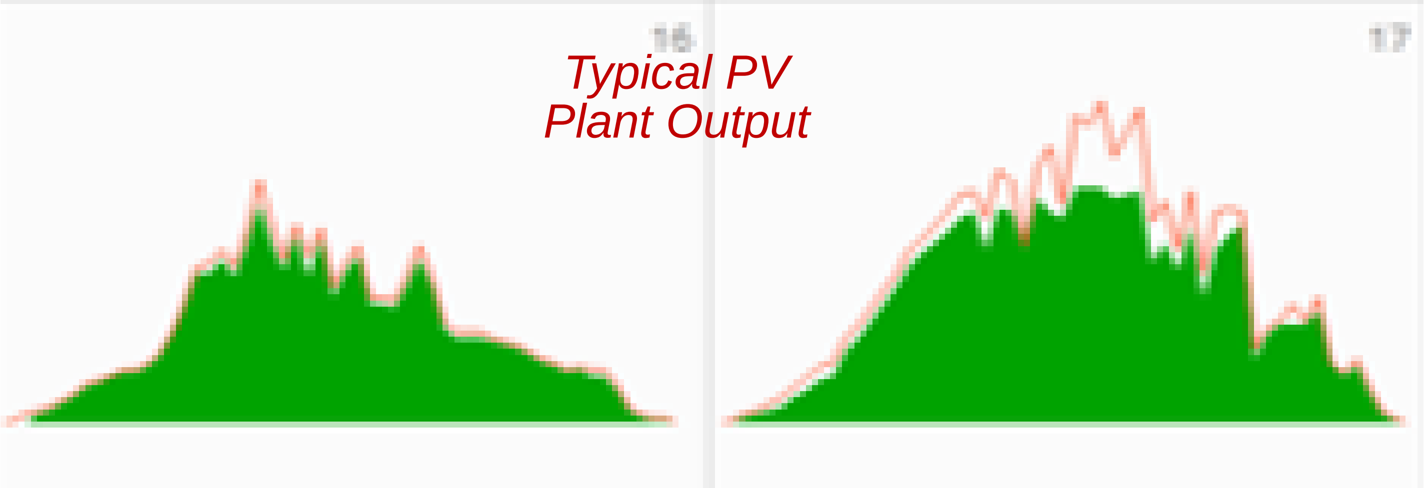
Milliseconds to Minutes

<u>Two Key Conditions for Grid Stability</u>

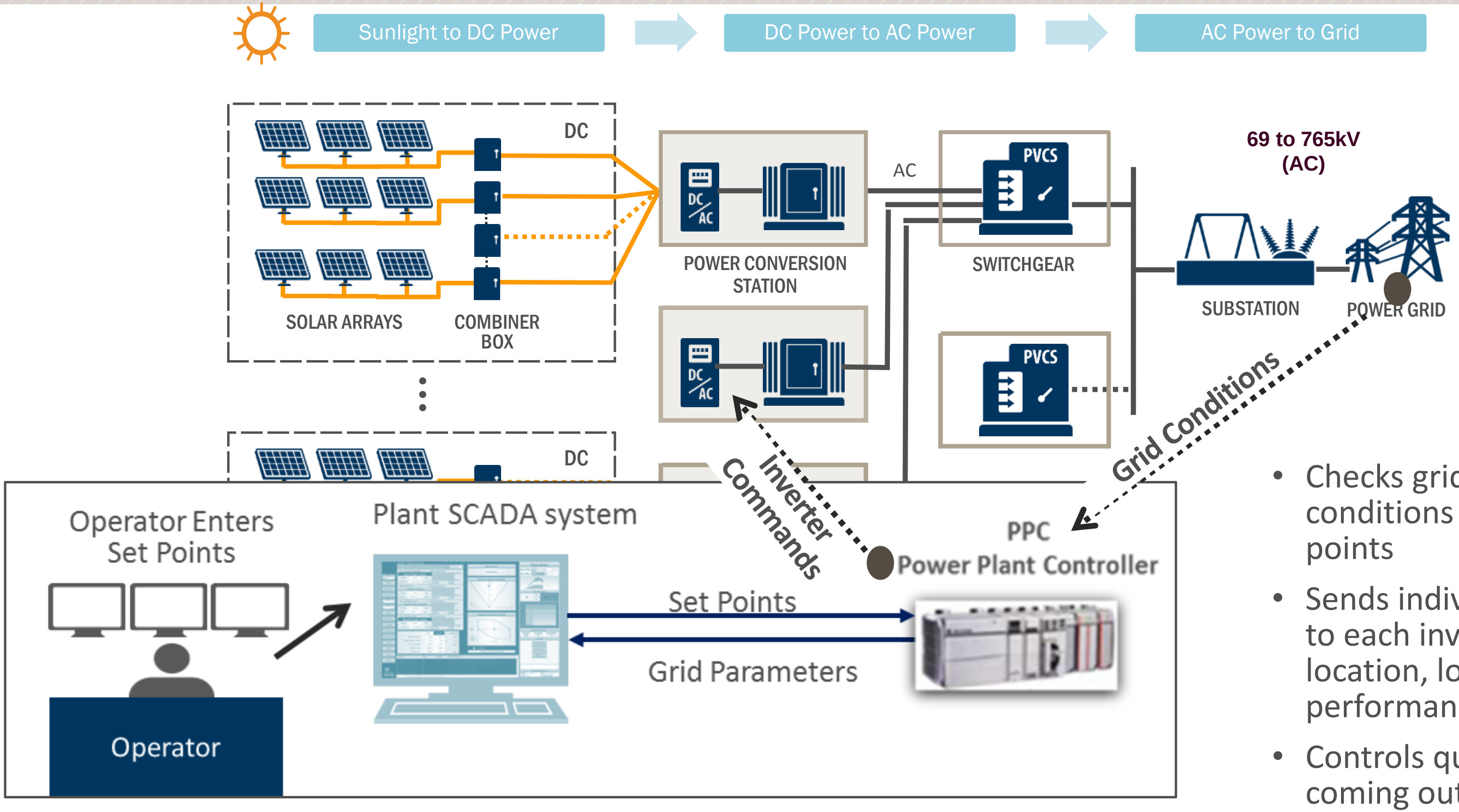
- **Voltage** is maintained within Normal Range
- **Frequency** is maintained within Normal Range

  i.e., Generated Power = Loads (+ Grid Losses)

  at every instant



Plant Control System Enables Grid Friendly Features

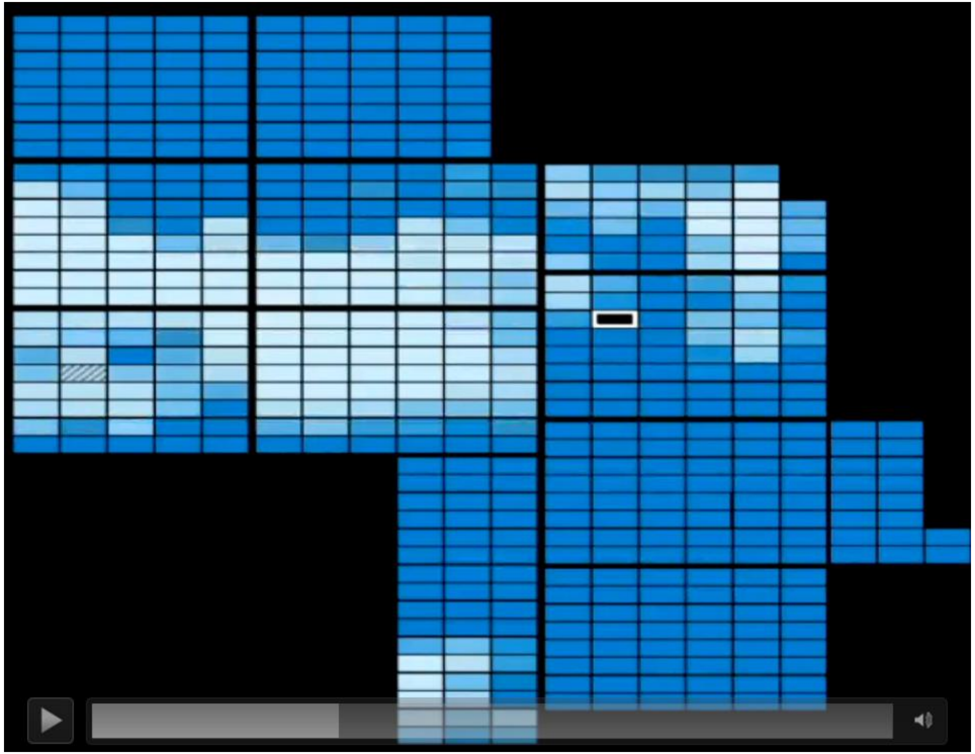


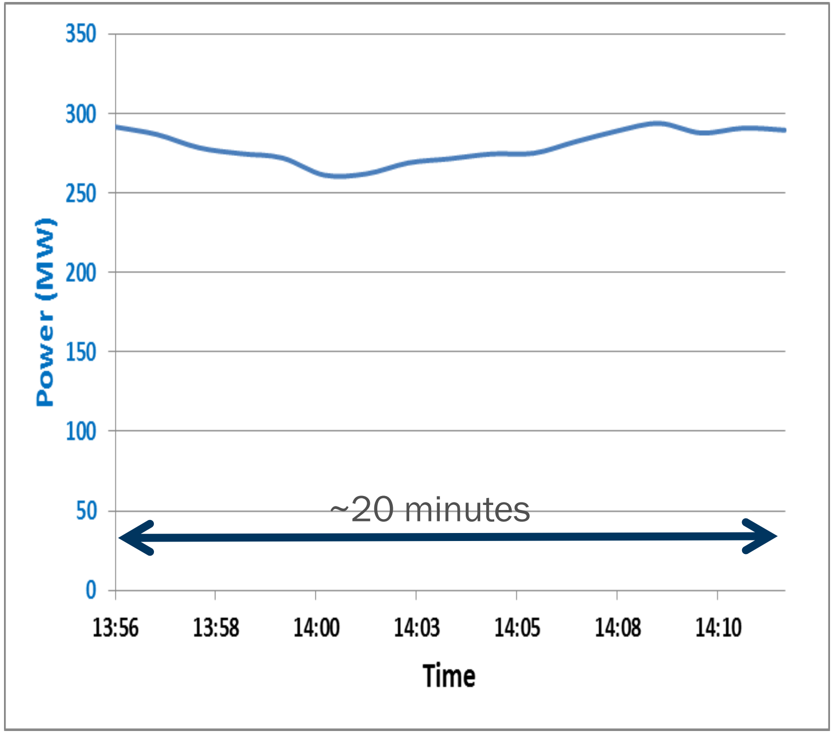
- Checks grid's actual conditions and required set points
- Sends individual instructions to each inverter based on location, losses, and performance
- Controls quality of power coming out of the PV plant

Closed-loop controls at 100 milliseconds!

Patent No. 8,774,974. Real-time photovoltaic power plant control system

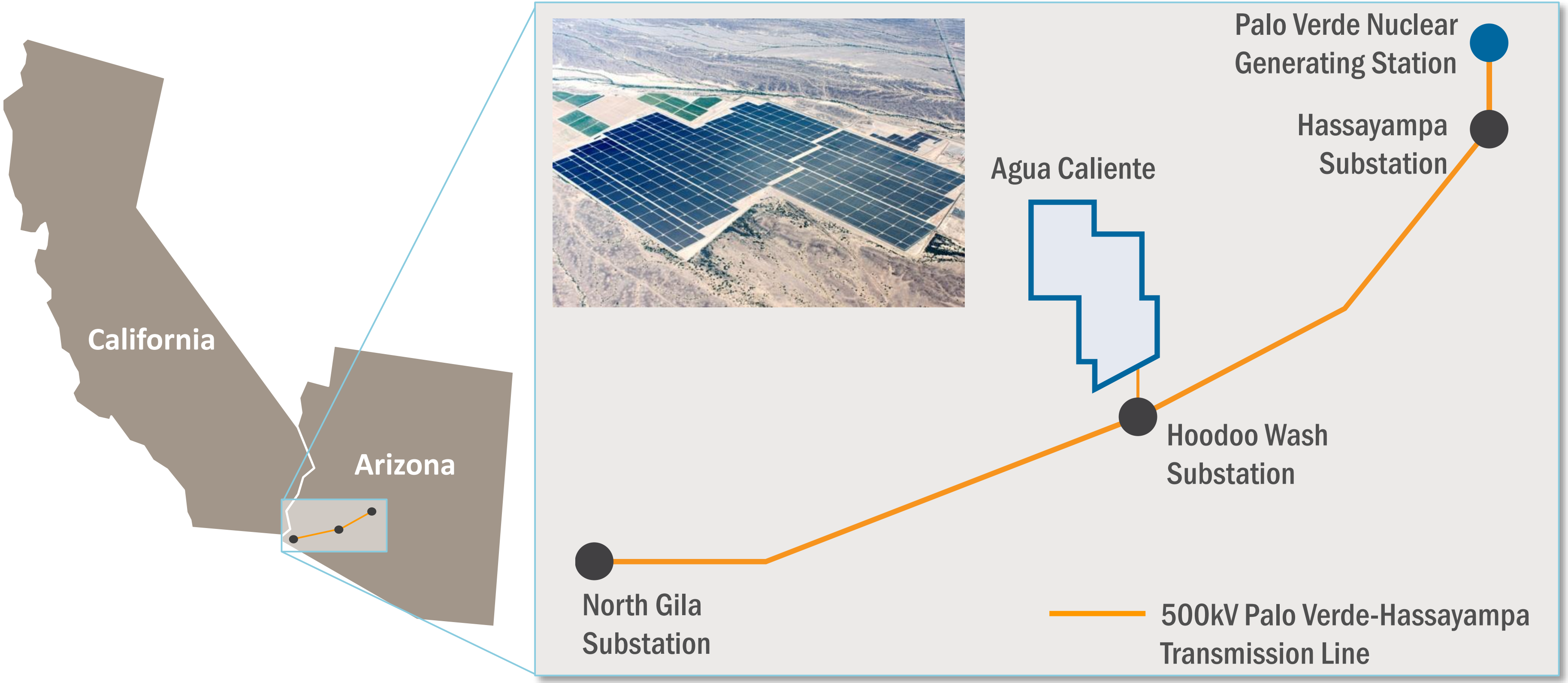
Passage of Clouds at a 290 MW PV Plant



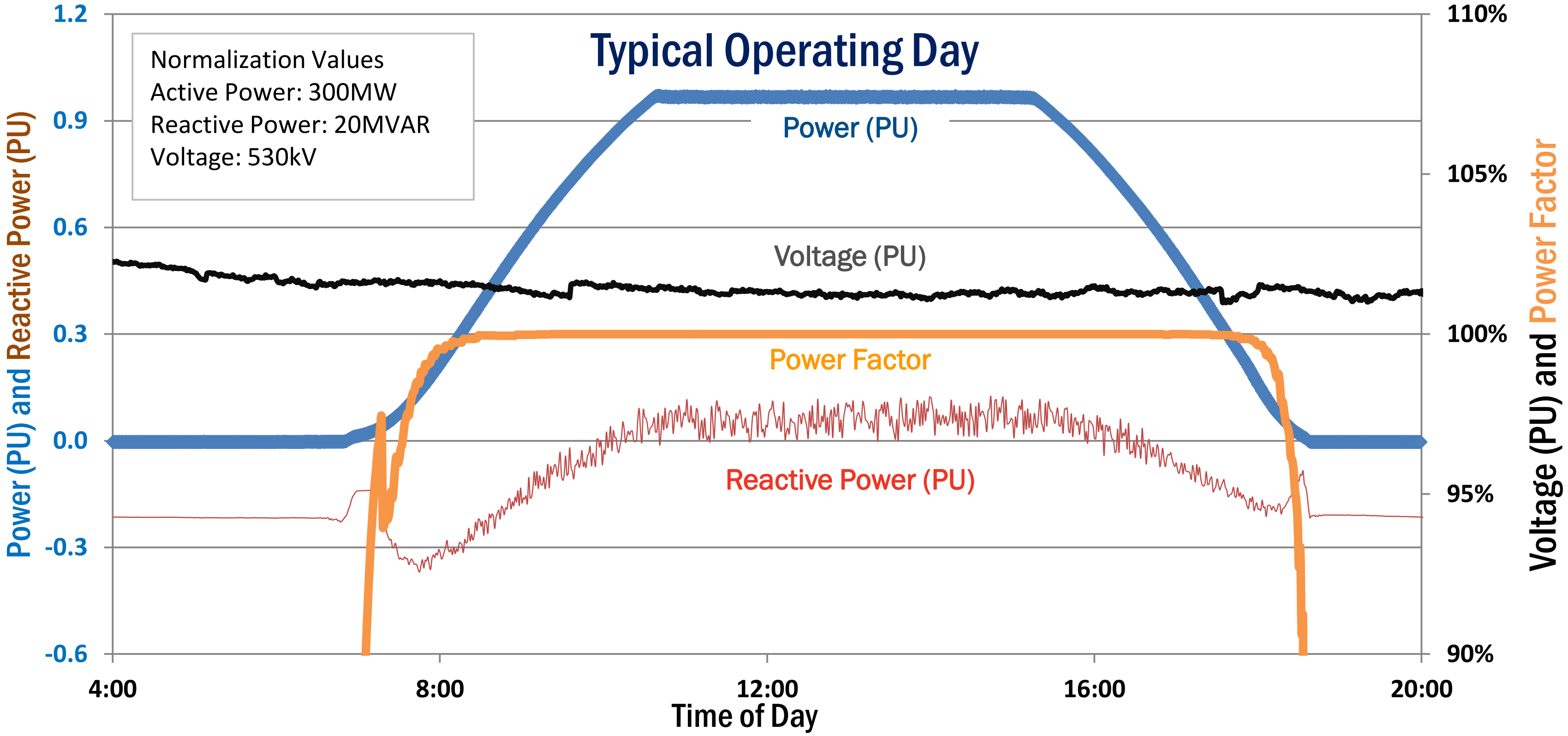


Large Plant Size Attenuates Impact of Cloud Passages on Power Output

AGUA CALIENTE 290MW AC | CONNECTING ON 500 KV TRANSMISSION LINE

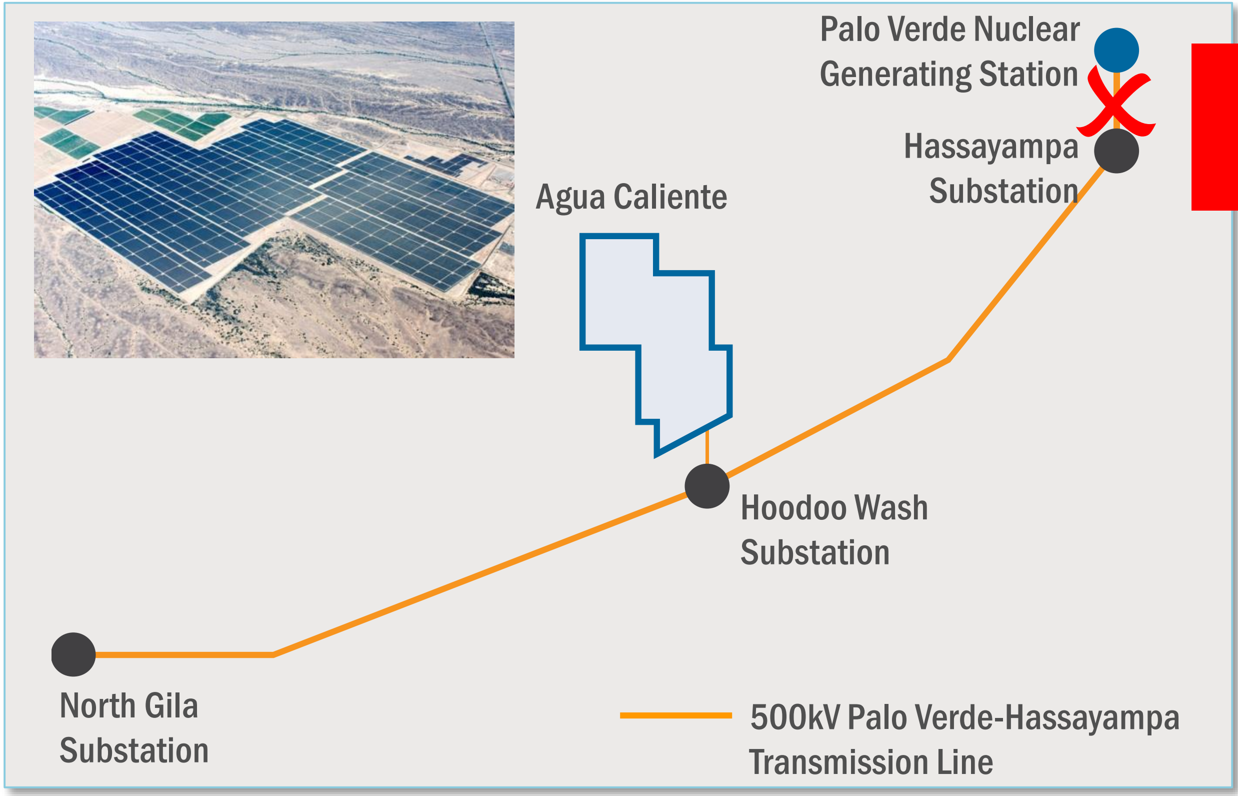


TYPICAL PLANT OPERATION (UNITY POWER FACTOR)



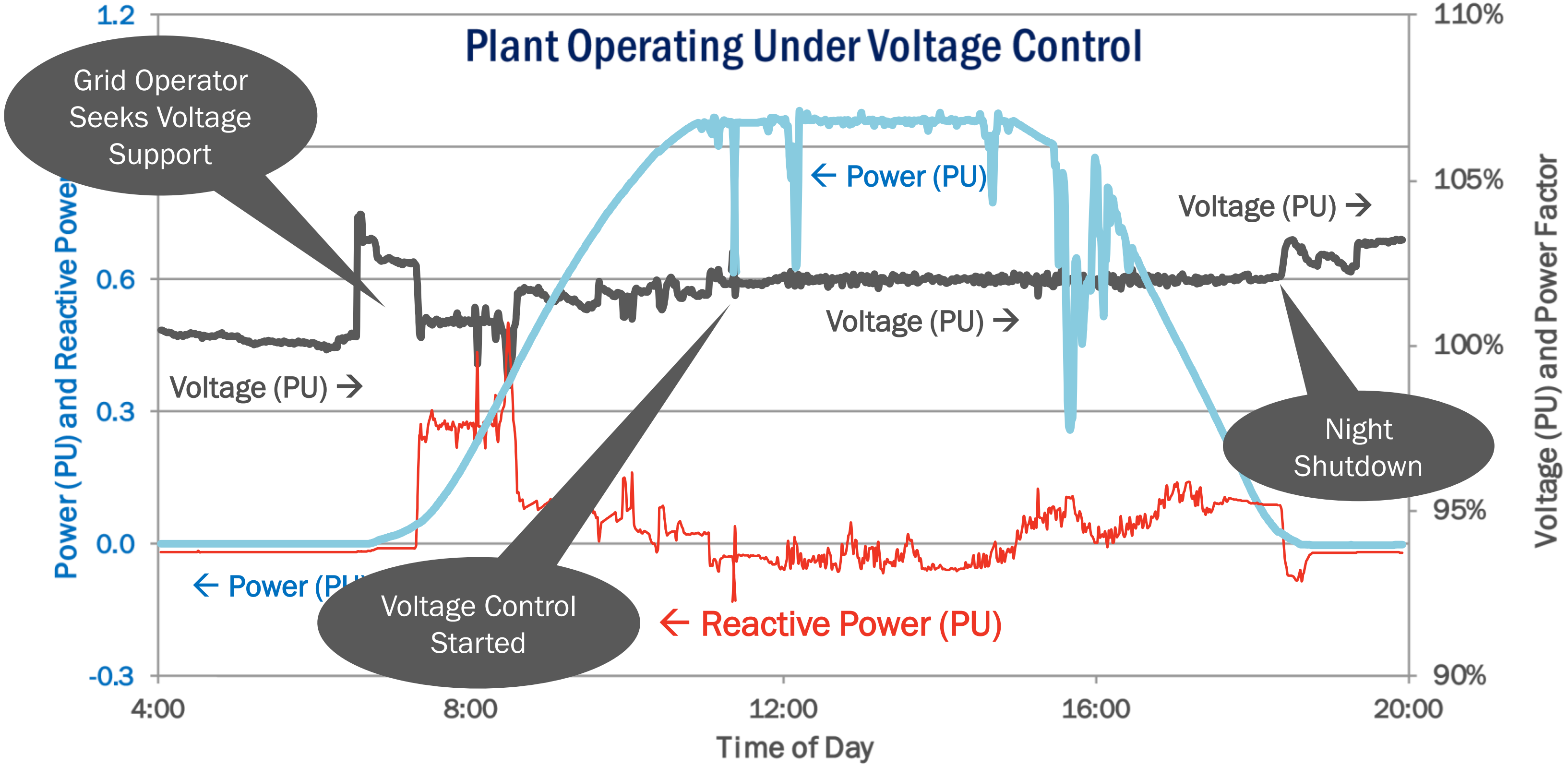
Plant Is Maintained At Constant Power Factor as Required

MARCH 21ST 2014 EVENT



Line Taken Out of Service

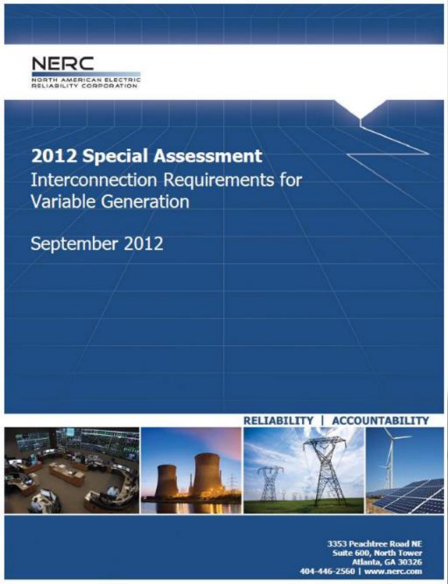
VOLTAGE SUPPORT FROM PV PLANT



Maintain Voltage Even Under Changing Power Conditions

Role of Utility-Scale PV Plants In Grid Stability & Reliability

- NERC identified essential reliability services to integrate higher levels of solar resources
- Utility-Scale PV Plants Provides
  - **Grid Friendly Features Required by NERC**
    - ✓ Voltage regulation
    - ✓ Real power control, ramping, and curtailment
    - ✓ Primary frequency regulation
    - ✓ Frequency droop response
    - ✓ Short circuit duty control
    - ✓ Fault ride through



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

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

Essential Reliability Services

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Demonstration of Essential Reliability Services by a 300-MW Solar PV Power Plant

California ISO

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Can variable energy resources provide essential reliability services to operate the grid?

- NERC identified three essential reliability services (ERS) to integrate higher levels of renewable resources
  1. Frequency Control
  2. Voltage Control
  3. Ramping capability or Flexible Capacity

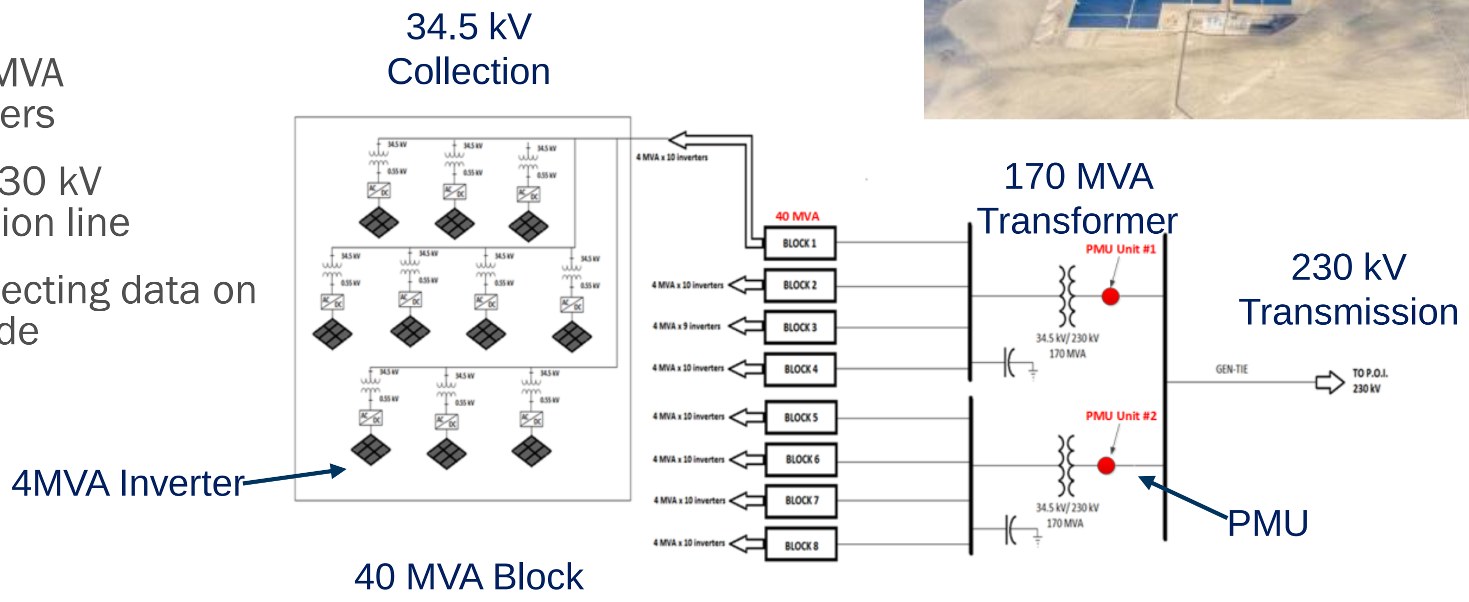
- Test results demonstrated utility-scale PV plant has the capability to provide these essential reliability services

- Advancement in smart controls technology allows these plants to provide services similar to conventional resources

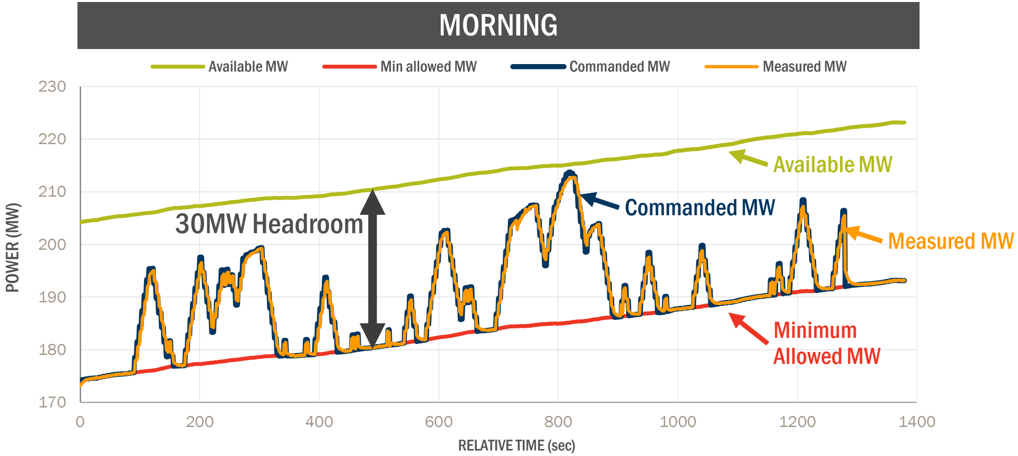
- VERs (Variable Energy Resources) with the <u>right operating characteristics</u> are necessary to decarbonize the grid

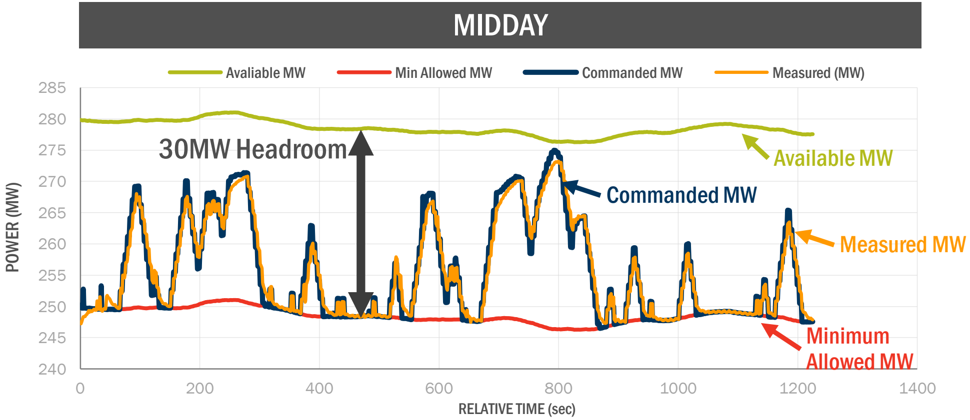
PV Power Plant Description

- First Solar PV modules
- 4 MVA PV inverters
- 8 x 40 MVA blocks
- 34.5 kV collector system
- Two 170 MVA transformers
- Tie with 230 kV transmission line
- PMUs collecting data on 230 kV side



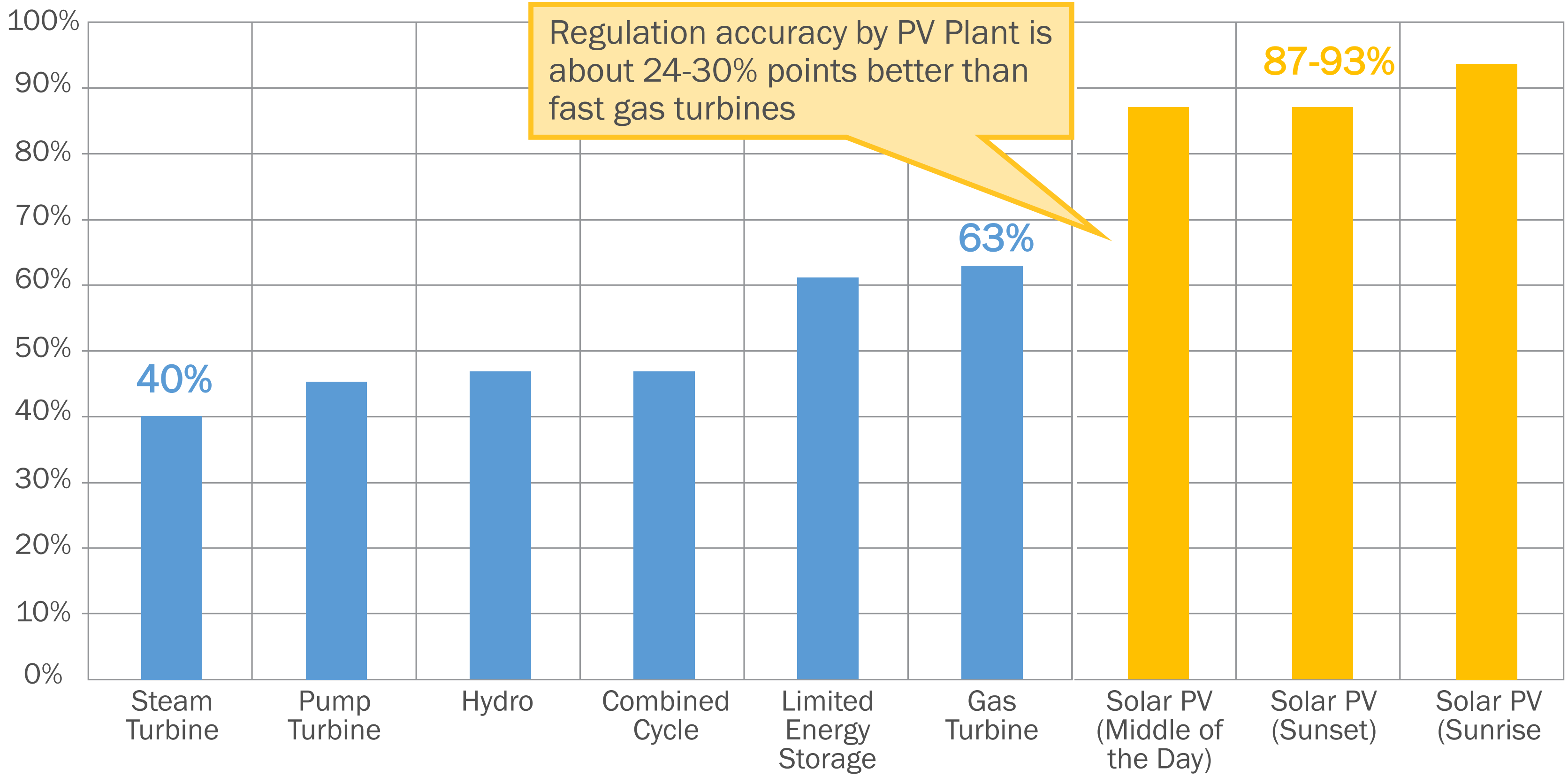
AGC Participation Tests – 300 MW Utility-Scale PV Plant





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

PV Plants Outperform Conventional Resources in Frequency Regulation



California ISO

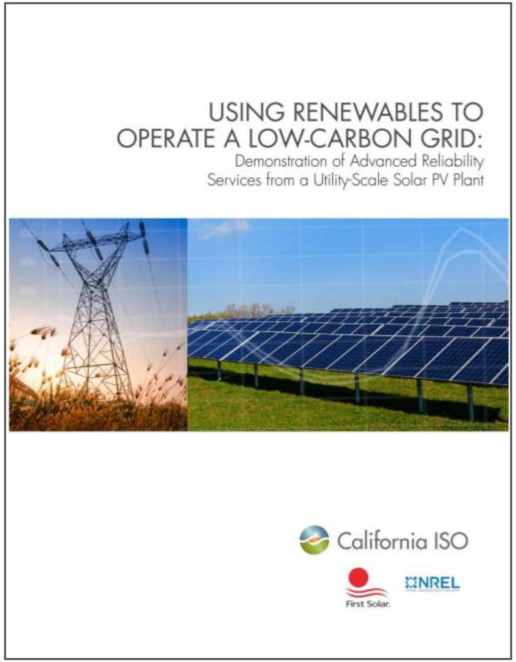
Blue bars taken from the ISO's informational submittal to FERC on the performance of resources providing regulation services between January 1, 2015 and March 31, 2016

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

Reality: Utility-scale PV Solar is a Flexible Resource that can enhance grid reliability

Dispatchable PV Plant

- Solar can provide NERC-identified essential reliability services to integrate higher levels of renewable resources, including:
  - Frequency Control
  - Voltage Control
  - Ramping capability or flexible capacity
- Automated Generation Control 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



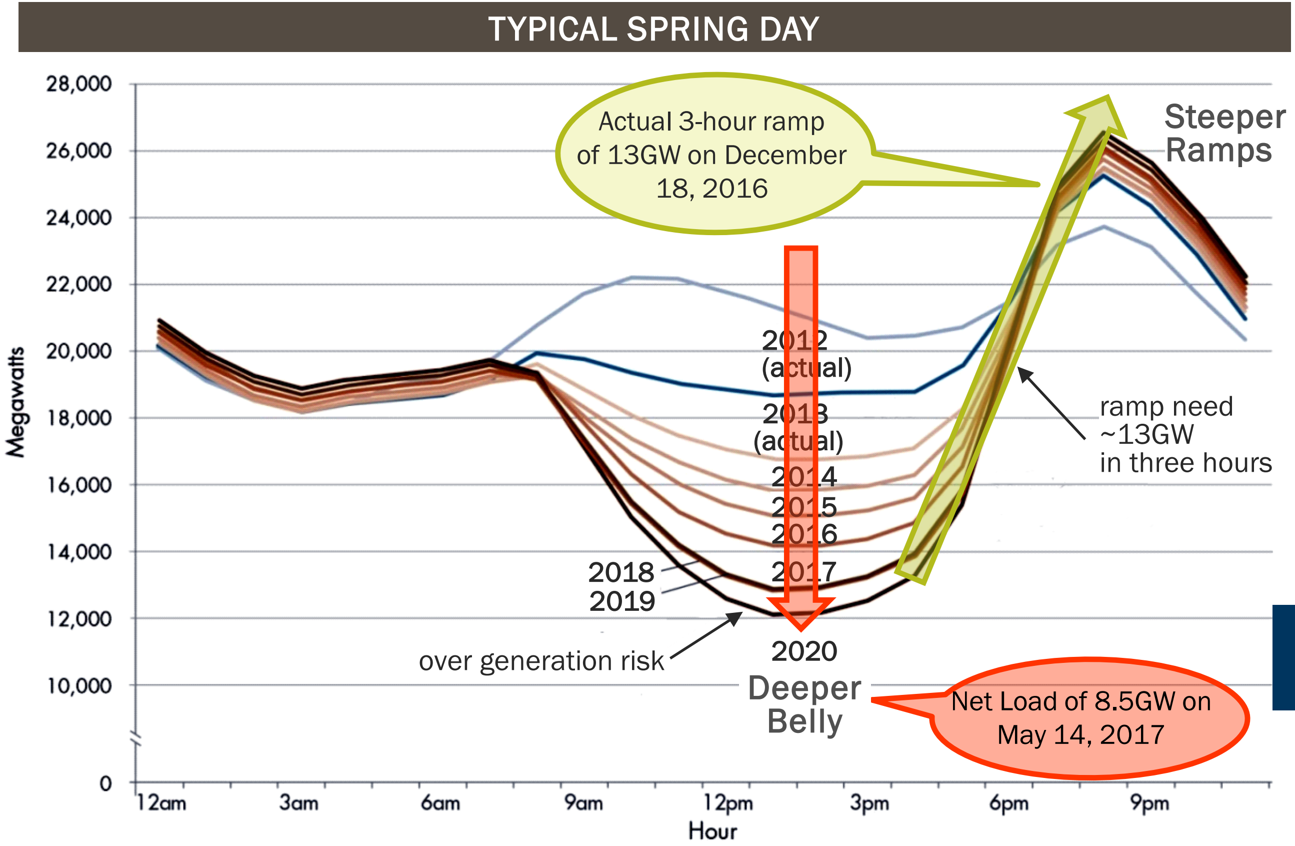
"Grid Friendly Utility-Scale PV Plants are Essential for Large-Scale PV Integration"

— CAISO

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

"Too Much Solar Already?"

The Perception of Solar Saturation

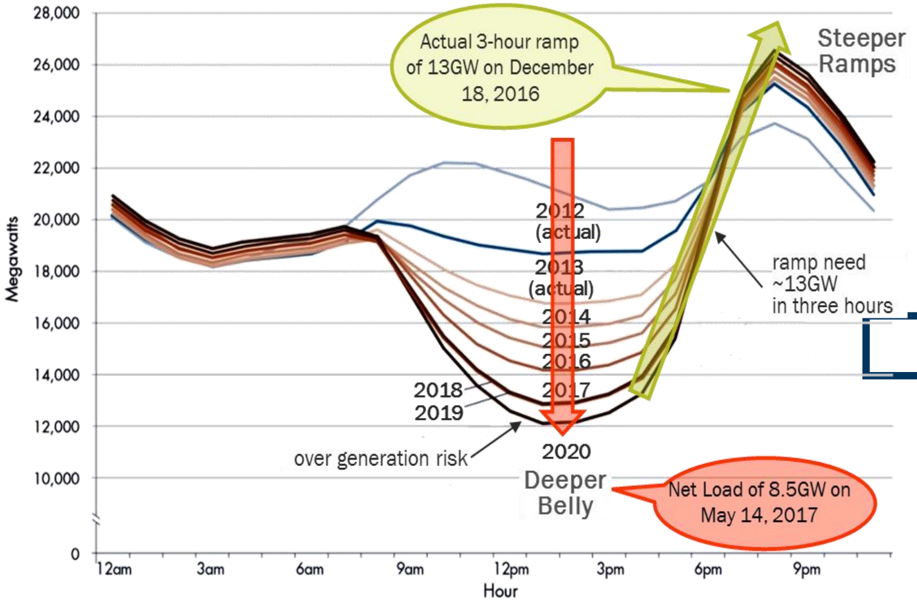


- The "duck" chart elegantly captures oversupply misperception
- Two Concerns:
  - Low Net Load: flexibility to reduce must-run generation resources is limited
  - High Ramp Rates in Evening: flexibility of other generation to ramp up is limited

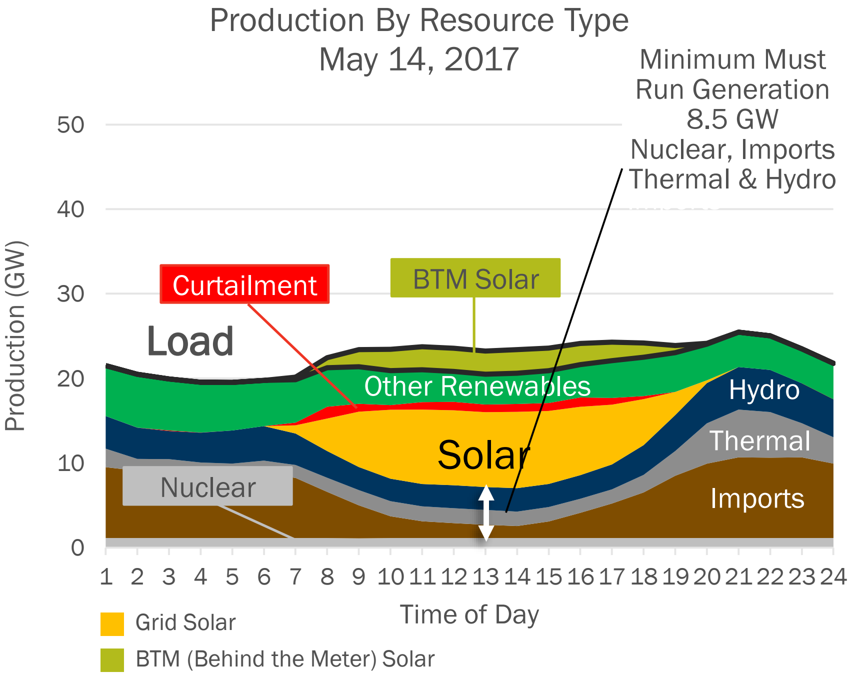
Not a Reliability Issue!

Looking at Duck Chart in Detail …

TYPICAL SPRING DAY



LOW LOAD DAY

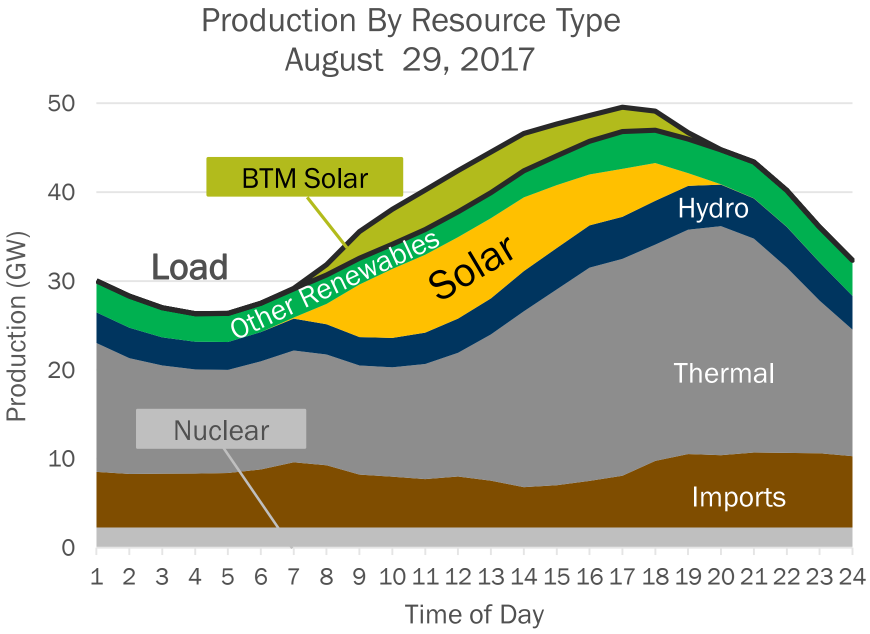


"Solar Overgen" is an Economics Issue *Not Reliability*

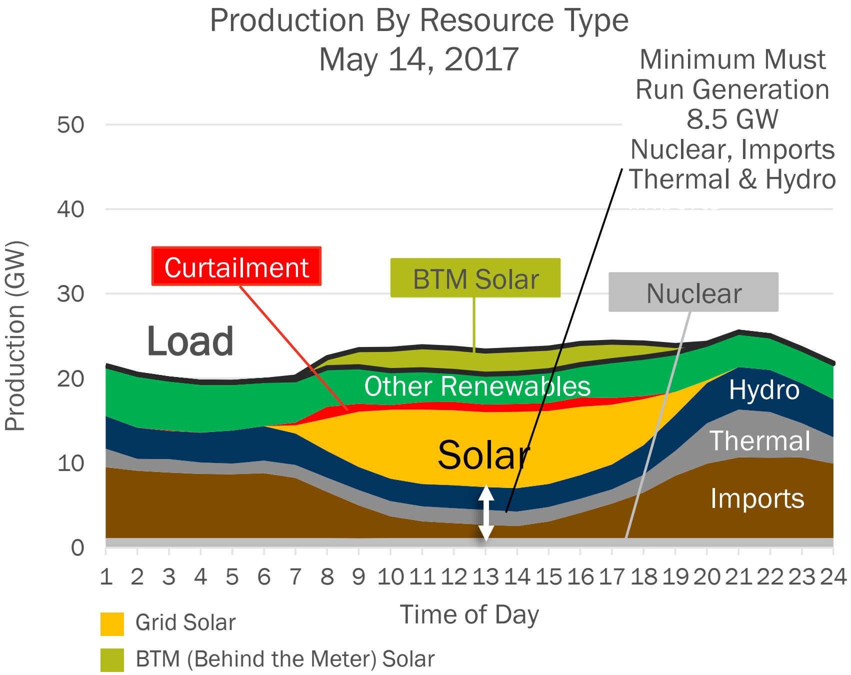
Source: CAISO Data. BTM Solar: Behind the Meter Solar: Estimated Based on CEC Data

Comparing Generation High Load and Low Load Day

HIGH LOAD DAY



LOW LOAD DAY

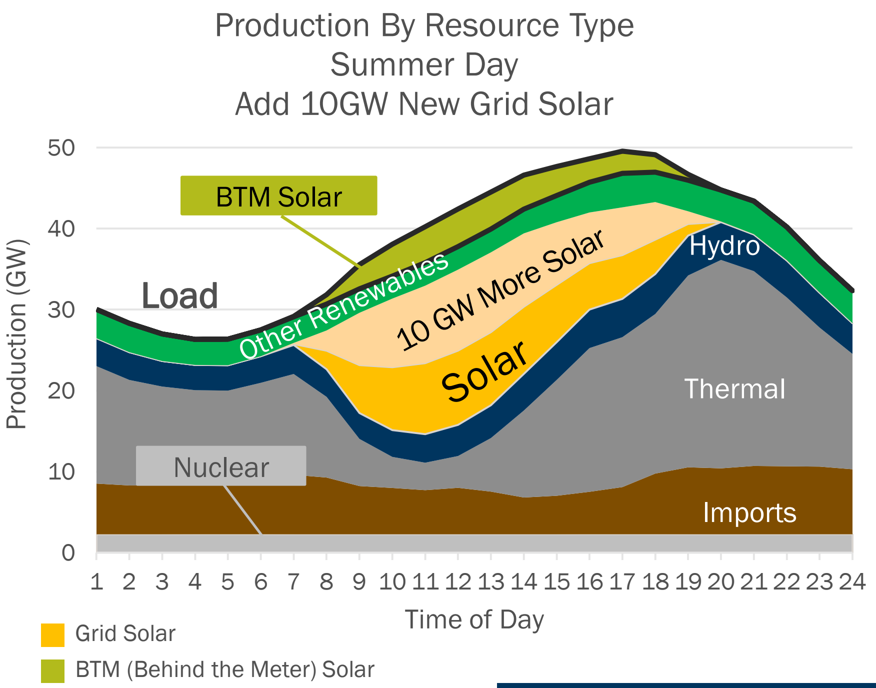


Solar Generation During High Load Days (Summer) is More Valuable

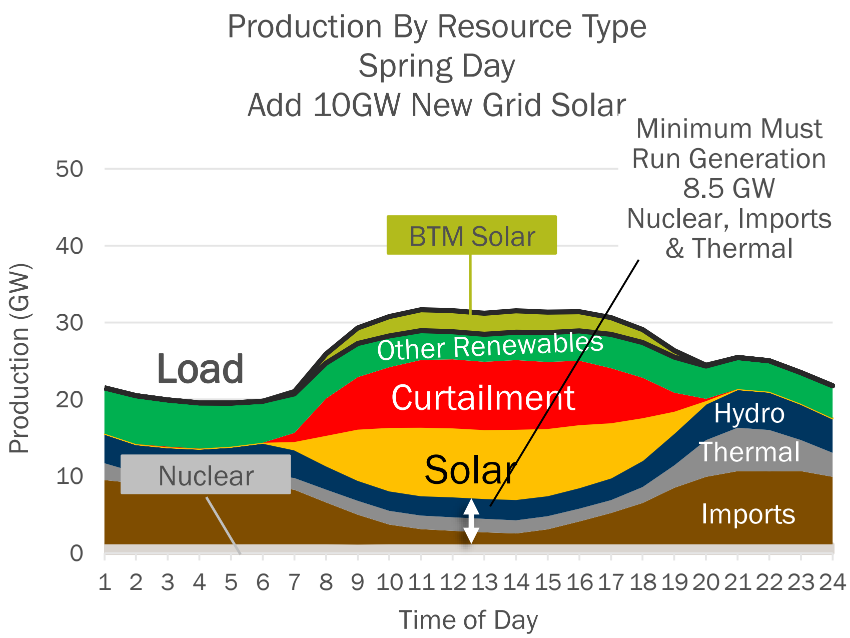
Source: CAISO Data. BTM Solar: Behind the Meter Solar: Estimated Based on CEC Data

Increasing Solar While Maintaining Minimum Must Run Constraint (Hypothetical!)

HIGH LOAD DAY



LOW LOAD DAY



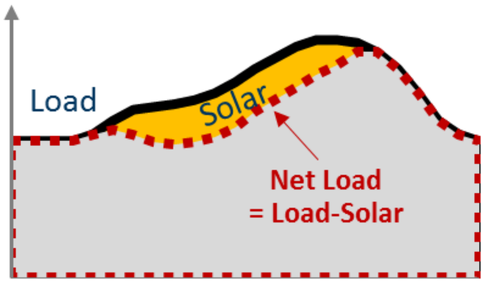
It May Be Economical to Add Flexible & Controllable Solar ... Even If It Leads To More Curtailment During Low Load Days

Source: CAISO Data. BTM Solar: Behind the Meter Solar: Estimated Based on CEC Data

BETTER INTEGRATION AND SCALE THROUGH FLEXIBILITY

Solar 1.0: Traditional

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



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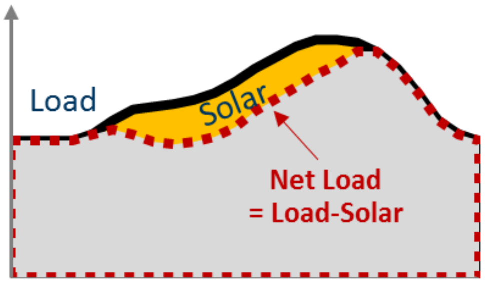
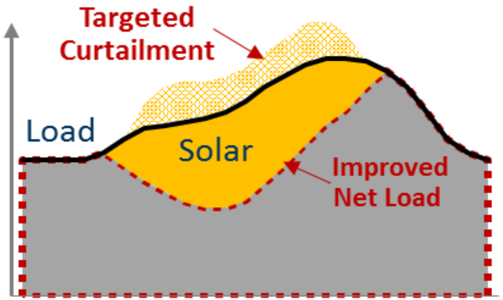
Solar 2.0: Dispatchable

- Advanced plant controls enable greater integration
- Adds **Grid Reliability Services & Flexibility** Value





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Solar 2.0: Dispatchable

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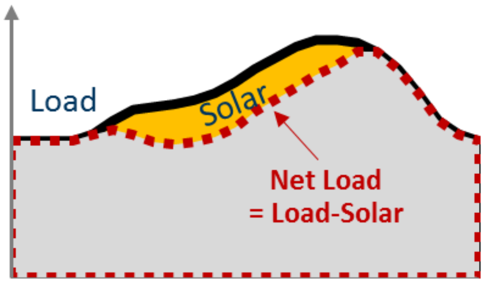
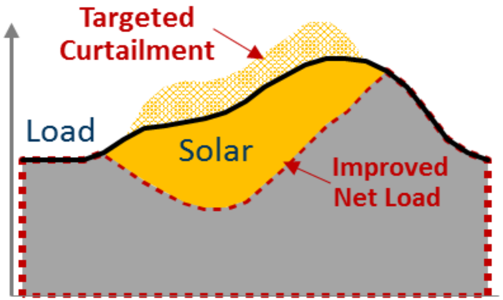
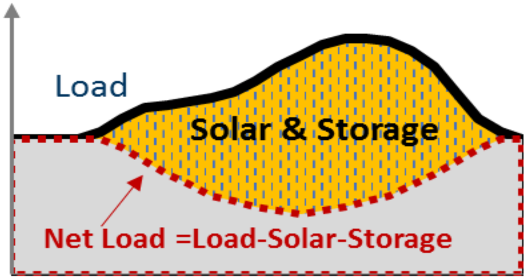
Solar 3.0: Fully Dispatchable

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

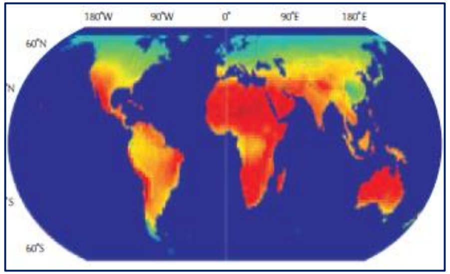






Flexible & Dispatchable Solar … Enables Market Expansion & Value Retention

Key Summary – Advances in Utility-Scale PV Plants



- Utility-scale solar electricity **now costs less** than conventional generation in many markets[1]
  - Cheaper than rooftop PV by a factor of 2-3
- Key cost reduction drivers include:
  - Module **cost reduction & efficiency improvement**
  - BOS & Plant **design innovations**
  - Improved Investment Climate
- Need to address grid challenges to grow solar substantially[2]
  - Maintain **grid stability and reliability** while integrating large-scale solar into electricity grid system
  - **Increase grid flexibility** to increase solar penetration and reduce curtailment

Sources: 1 Lazard Levelized Cost of Energy Analysis – Version 10; GTM Research Global Solar PV Demand Monitor Q2017. . 2. Beyond 33% Renewables: Grid Integration Policy for a Low--Carbon Future, CPUC White Paper