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.
Key Messages – 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. \(^1\) 2. Beyond 33% Renewables: Grid Integration Policy for a Low–Carbon Future, CPUC White Paper
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

Note: Bubble size denotes auctioned capacity (MWdc)
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.

“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

- Inverter
- Electrical BOS
- Structural BOS
- Labor
- Design & Engineering
- Permitting & Interconnection
- Civil
- Supply Chain, Logistics & Misc
- Taxes
- Overhead & Margin

Source: Data from GTM Research and SEIA Report
PV Plant Schematic

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

Solar Arrays → Combiner Boxes → DC Power Conversion Station → AC Power Conversion Station → Switchgear → AC Power to Grid

Substation → Power Grid
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
Typical DC Wiring for S4 Modules

- 15 S4 Modules per 1500VDC String
- Female MC4
- Male MC4

S4 Module

4 String Harness

Sunny Side

MC4 Connectors
DC Wiring Improvement – Trunk Bus Solution

4 String Harnesses

IPC Connection

DC Trunk Buses

Combiner Box

4 String Harnesses

Jumpers

Whips

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

String vs Central Inverter Cost ($/Wac)

- Three-Phase String Inverter
- Central Inverter

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)
Medium Voltage DC Plant Architecture (MVDC) – BOS Simplification

Potential Benefits

- Fewer Components/Reduced Wiring
- Higher Plant Efficiency
- Reduced O&M
- Robust Grid Capability
- Ready for Storage Architecture
Reducing Energy Storage Costs ... Opportunities for Fully Dispatchable Solar

Rack-level battery price history and projections ($/kWh of storage)

Levelized Cost of Storage (LCOS) ($/MWh)

Assumptions:
- RTE losses not included (e.g., “free” energy from curtailed PV)
- 300 cycles per year
- IRR= 8.75%
- Includes ITC benefit for storage
- 50+ MWh in custom building
PV + Storage (PVS): Fully Dispatchable Clean Energy Plant

- Increase the PV array size
- Store excess energy in Energy Storage
- ESS provides flexibility to generate desired profile
- Amount of battery capacity is set by desired dispatch profile and solar irradiance
- Shared Infrastructure costs (interconnect, development, O&M)

Game Changer: Clean energy plant
More cost-effective than conventional generation?
### Shifting Energy to Increase Output During Target Period (~10 MWdc PV)

**Delivered energy Heatmap (20 yr average)**

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### Storage (
hrs) | TPCF
---|---
0 | 48%
1 | 68%
2 | 87%
4 | 98%

- **4 Hr Storage Will Get 98% Firm Capacity During Target Period (TPCF)**

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**Game Changer: Clean Energy Plant Less Costly than New Conventional Generation**

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

**Physical Dimensions for Equal Efficiency**

- **c-Si 350 W**: 2m x 1m
- **S6 420 W**: 2m x 1.2m

**Large Format**
- More Watts per Install Operation

**Framed**
- Simplified Mounting to Common Industry Structures
<table>
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<th><strong>TOPAZ SOLAR PLANT</strong></th>
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<td><strong>Site:</strong> San Luis Obispo, CA USA</td>
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<tr>
<td><strong>Owner:</strong> MidAmerican Energy Holdings Company</td>
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<td><strong>Size:</strong> 550MW</td>
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<td><strong>Const. Time:</strong> 2011–2015</td>
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<td><strong>Acres:</strong> ~7,500 site</td>
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<td><strong>Modules:</strong> ~9 million</td>
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One of the largest utility scale solar plant in the world
Solar PV Impact on Power Grid – Key Topics

Two Key Conditions for Grid Stability

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

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

Typical PV Plant Output
Plant Control System Enables Grid Friendly Features

- **Operator Enters Set Points**
- **Plant SCADA system**
  - Set Points
  - Grid Parameters
- **Inverter Commands**
- **Power Plant Controller (PPC)**
- **Grid Conditions**
  - 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!*

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**Diagram Notes:**
- **SOLAR ARRAYS**
- **COMBINER BOX**
- **DC Power Conversion Station**
- **Switchgear**
- **SUBSTATION**
- **POWER GRID**
- **Sunlight to DC Power**
- **DC Power to AC Power**
- **AC Power to Grid**

**Typical DC Voltage:** 1kV or 1.5kV

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

**69 to 765kV (AC)**
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

- North Gila Substation
- Agua Caliente
- Hoodoo Wash Substation
- Hassayampa Substation
- Palo Verde Nuclear Generating Station

California
Arizona

500kV Palo Verde-Hassayampa Transmission Line
TYPICAL PLANT OPERATION (UNITY POWER FACTOR)

Plant is maintained at constant power factor as required.

Typical Operating Day

<table>
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<tr>
<th>Time of Day</th>
<th>Voltage (PU)</th>
<th>Power (PU)</th>
<th>Reactive Power (PU)</th>
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Normalization Values
Active Power: 300MW
Reactive Power: 20MVAR
Voltage: 530kV
MARCH 21ST 2014 EVENT

Agua Caliente

Palo Verde Nuclear Generating Station

Hassayampa Substation

Hoodoo Wash Substation

North Gila Substation

500kV Palo Verde-Hassayampa Transmission Line

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

Source: NERC: 2012 Special Assessment Interconnection Requirements for Variable Generation
Demonstration of Essential Reliability Services by a 300-MW Solar PV Power Plant
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

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

Regulation accuracy by PV Plant is about 24-30% points better than fast gas turbines.

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.

**Frequency Droop Tests**

\[ Droop = \frac{\Delta P / P_{\text{rated}}}{\Delta f / 60\text{Hz}} \]

- 3% and 5% under and over-frequency tests
- 20% headroom
- ±36 mHz dead band
- Used actual frequency event time series measured in the U.S. Western Interconnection
**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

Solar Curtailment is to be Expected with Higher Penetration

**Perception**

Perception of solar saturation/over-generation

**Reality**

To get to the lowest cost/best fit option, some saturation is to be expected
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

![TYPICAL SPRING DAY Graph](image)

- Actual 3-hour ramp of 13GW on December 18, 2016
- Net Load of 8.5GW on May 14, 2017
- Not a Reliability Issue!
The Perception of Solar Saturation

**TYPICAL SPRING DAY**

- Actual 3-hour ramp of 13GW on December 18, 2016
- Ramp need ~13GW in three hours
- Deeper Belly
- Net Load of 8.5GW on May 14, 2017

**LOW LOAD DAY**

- Production By Resource Type
  - May 14, 2017
  - Minimum Must Run Generation
    - 8.5 GW
    - Nuclear, Imports
    - Thermal & Hydro

- Curtailment
- BTM Solar

**“Solar Overgen” is an Economics Issue Not Reliability**

Source: CAISO Data. BTM Solar: Behind the Meter Solar: Estimated Based on CEC Data
Comparing Generation Low Load and High Load Days

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!)

LOW LOAD DAY

Production By Resource Type
May 14, 2017

- BTM Solar
- Nuclear
- Other Renewables
- Solar
- Thermal
- Imports
- Hydro

Minimum Must Run Generation 8.5 GW
Nuclear, Imports, Thermal & Hydro

Curtailment

HIGH LOAD DAY

Production By Resource Type
Summer Day
Add 10GW New Grid Solar

- BTM Solar
- Nuclear
- Other Renewables
- Solar
- Hydro
- Thermal
- Imports

It is 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
Optimal portfolio balances solutions with overbuild (conceptual!)

Some curtailment is necessary to achieve the least cost/best fit solution.
“Solar is the New Hydro”

- Renewable
- Clean
- Affordable
- Abundant
  - Occasional Spill is Routine

Source: E3 – Solar is the New Hydro
Here Comes Solar ... “Every One Else Make Way For It?”, Not a Sustainable Approach

- Solar today is like a privileged vehicle without any controls that all other vehicles have to make room for on the highway

- As solar penetration goes up ... congestion increase, solar must be controllable and flexible to achieve sustainable growth
Curtailment is Indeed Growing ... In Frequency & Magnitude

Energy Imbalance Market (EIM) has helped CAISO avoid renewable curtailments this year, although avoided curtailments are down from previous years. | CAISO

Total solar output was reduced by about 1.6% due to real-time economic dispatch instructions and curtailments in 2016

Increasing Grid Flexibility to Meet Challenges of High Renewable Penetration

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