# Grid Intelligent Solar

## Unleashing the Full Potential of Utility-Scale Solar Generation in Europe

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# FOREWORD

**Solar is currently the lowest cost power generation source in many regions of the world – and its cost continues to decrease rapidly. As policy makers, investors and consumers are increasingly appreciating the benefits of clean, flexible and low-cost solar power, solar technology has become the world's most popular power generation source. In 2017, more solar power capacity was installed than all fossil fuel and nuclear sources combined, and twice as much as wind. While solar is still a small fraction of the global power generation portfolio, only 2% in 2017, the situation is changing rapidly.**

SolarPower Europe anticipates 2-digit market growth in Europe in the coming years. Solar has the potential to play a major role in the European Union meeting its 32% renewables target by 2030. Bloomberg NEF, in its New Energy Outlook 2018, anticipates that renewables will cover 87% of Europe's electricity generation by 2050 in Europe, in which 1.4 TW of solar is installed and contributes to 36% of total power generation. Over two thirds of this solar energy is expected to come from utility scale power plants.

Increasing solar capacity growth 12 fold, to about 1,400 GW from the 114 GW installed in Europe at the end of 2017, will require much more utility-scale PV to unleash this untapped potential. Advanced solar markets need to leave the world of Solar 1.0 behind, when utility-scale PV plants were installed to maximize individual system yields. We are now entering Solar 2.0 – grid flexible PV plants integrated in the energy system. With the right market design, solar can already provide cost-effective flexible capacity that supports supply and demand balancing, as well as flexibility and grid reliability services, such as frequency regulation or ramp control. While solar is economically attractive enough to achieve significant grid penetration without storage, the dramatic decrease in stationary battery cost takes us into the world of Solar 3.0, where storage provides firm dispatchable solar capacity.

SolarPower Europe's "Grid Intelligent Solar - Unleashing the Full Potential of Utility-Scale Solar Generation" report was initiated by First Solar and produced with the support of BayWa, Tesla and SMA. It provides evidence of low-cost utility-scale solar's ability to keep the European grid stable and reliable, and for the European Union to meet its 2030 renewable energy targets.

## KEY TAKEAWAYS

Using intelligent plant controls, and solution-oriented plant sizing/layout, utility-scale solar can provide cost-effective flexible capacity that supports supply and demand balancing.

Utility-scale solar PV plants can support grid reliability by providing services such as ramping capability, voltage support, and fault ride-through. They can often do so more effectively than conventional plants.

Utility-scale solar plants are controllable and can provide flexible grid services, such as frequency regulation, that allow system operators to respond quickly and strategically to changing conditions.

With these services, Solar can already achieve significant grid penetration, and that without energy storage. Decreasing energy storage costs will further enable solar energy to be cost-effectively dispatched, even when the sun is not shining, enabling even more clean energy penetration on the grid .

| RECOMMENDATIONS | STAKEHOLDERS INVOLVED |
|---|---|
| Ancillary service markets should prioritize electricity generation units which are most cost effective, and efficient. | Regulator, Grid operator, Dispatch center |
| Bids should be more granular using existing reliable data and forecast information. This will allow day ahead markets to better align with loads and resources. | Grid operator, Energy trader |
| Planning, procurement and contracting processes must be modified to value power system flexibility as an asset. | Regulator, Grid operator, Developer or owner |
| Grid operators and utilities should model variable renewable energy sources as dispatchable in their integrated resources planning processes. | Grid operator, Dispatch center |
| Tender requirements for new solar capacity should value flexible dispatch capabilities, grid services and plant controls. (As is currently the case with the German innovation tenders.) | Regulator, Developer or owner |
| Electricity grid operators‘ procurement practices should give priority to plants who offer electricity in the most flexible and cost-efficient manner. | Grid operator, Dispatch center, Energy trader |
| Utility-scale PV power plants need better access to ancillary services to reduce conventional “must run” capacity and allowing PV plants to generate income from such grid services. | Regulator, Grid operator, Energy trader |

**LEGEND**

Regulator — Grid operator — Energy trader — Developer or owner — Dispatch center

Shams Maan, Jordan. © First Solar

# 1 INTRODUCTION

Solar photovoltaic (PV) electricity generation is growing rapidly worldwide. According to SolarPower Europe's Global Market Outlook 2018 – 2022, more solar PV capacity was installed globally than any other power generation technology in 2017. Solar alone deployed nearly 100 GW, which is more than fossil fuels and nuclear combined (84 GW), and almost twice as much capacity as wind power (52 GW).[1] However, increasing penetration of solar electricity raises challenges for grid operators to balance energy supply and demand in real time.

In order to manage dispatch and control costs, grid operators need to ensure all electricity generation sources can provide essential flexibility and reliability services on demand. These requirements can be met by making utility-scale solar "dispatchable" (i.e. to provide flexibility for grid operations), and by designing utility-scale solar PV projects with advanced inverter functions and sophisticated automatic "grid-friendly" power plant controllers. All of these features enable solar PV projects to provide essential ancillary services. This SolarPower Europe report provides information on the benefits of using utility-scale solar power plants for electrical networks in Europe.

## 1.1. Current situation: Utility-scale Solar in the European electricity system

The European electricity system has proven to be effective and reliable, providing a secure and affordable electricity supply to European consumers. It has also demonstrated agility in supporting the European energy transition, integrating increasing shares of variable and distributed renewables into the system.

The European grid's ability to absorb variable renewables is partly due to a certain degree of historical over-investment in technical reserves. Grids were engineered at a time when state monopolies could readily pass on costs to consumers. Hence technical standards included significant safety margins to ensure interruption-free delivery at almost any cost.

1 http://www.solarpowereurope.org/wp-content/uploads/2018/09/Global-Market-Outlook-2018-2022.pdf

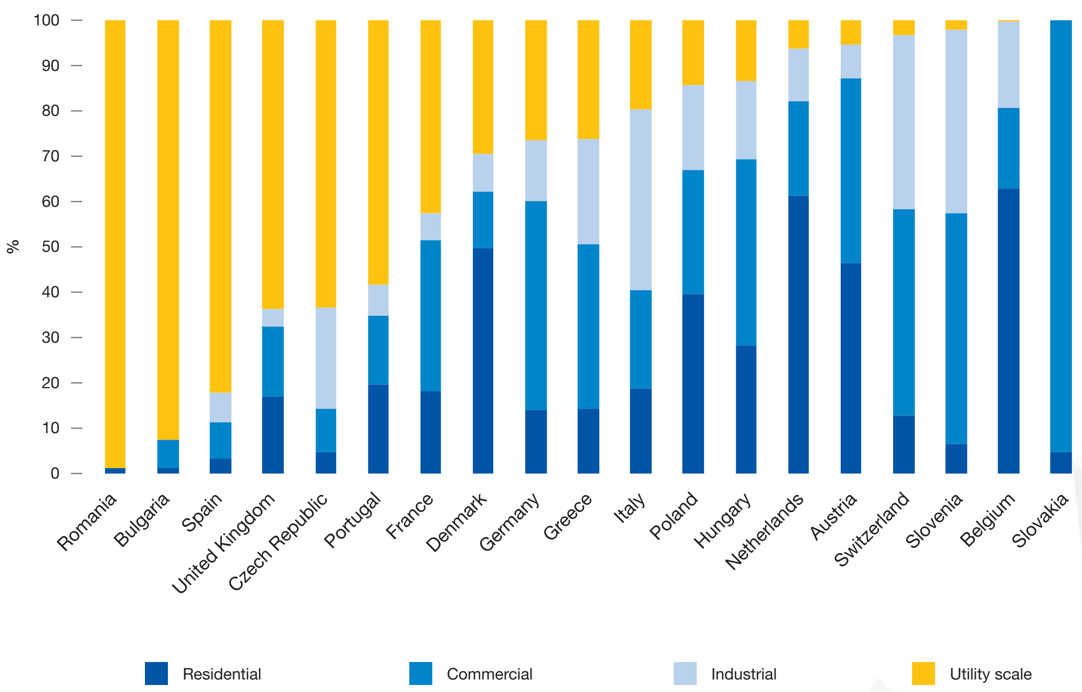
With such a solid technical infrastructure in place, advanced monitoring and new management methods can free up significant grid capacities for transmission and distribution without significant investment in the physical infrastructure. At the same time and with the advent of unbundling, and regulation aiming at reducing grid cost to consumers, there is now more pressure on grid operators to use the hidden reserves of their grids.

Given the urgent need to further increase the share of variable renewables in electricity grids, we will inevitably come to a point, where we need to do more. With overall shares of renewables in the electricity system exceeding 30% and with an increasing number of regional peaks of up to 100% renewable share, flexibility and providing active grid service becomes crucial to ensure the future reliability of the electricity system. This is all the more necessary, as large utility scale solar power plants are, already today, the cheapest new power generation option in many parts of Europe (see Section 1.2.). Solar should not only be connected behind the meter – it will become a critical component of grid connected power generation, thus decarbonizing and decreasing the cost of balancing the power sector.

Several EU members states pioneered the use of multi-megawatt ground-mounted solar in the first decade of the 21st century. However, this was followed by a period of little solar activity in countries where the solar market collapsed after the end of feed in tariff support schemes. In Spain, the UK, Romania or Bulgaria, the solar landscape is dominated by utility scale solar, unlike in most markets that have been leading EU solar developments in recent years, for example in Germany and France, where utility solar is under-represented, and far from meeting its full potential (see Fig. 1).

Worse, several countries have either introduced, or are considering, size limits for PV and capacity mechanisms for conventional power plants. The latter aimed at subsidizing polluting and obsolete assets to support the operation of electricity grids, instead of developing advanced system management processes to unlock the flexibility potential of renewables and storage capacities.

FIGURE 1 EUROPEAN SOLAR PV TOTAL CAPACITY UNTIL 2017 FOR SELECTED COUNTRIES



Why is that? Europe suffers from the misconception that grid-connected utility-scale solar is a trouble maker for the grid, rather than being part of the solution. However, this report shows that incorporating utility-scale solar solutions provides essential services to the European electricity grid. These solutions could save the EU significant money, while advancing the decarbonation process. The debate now is no longer about how to integrate renewables, but how to value them properly on the market to optimize the use of technologies that support the system's reliability and provide the flexibility needed.

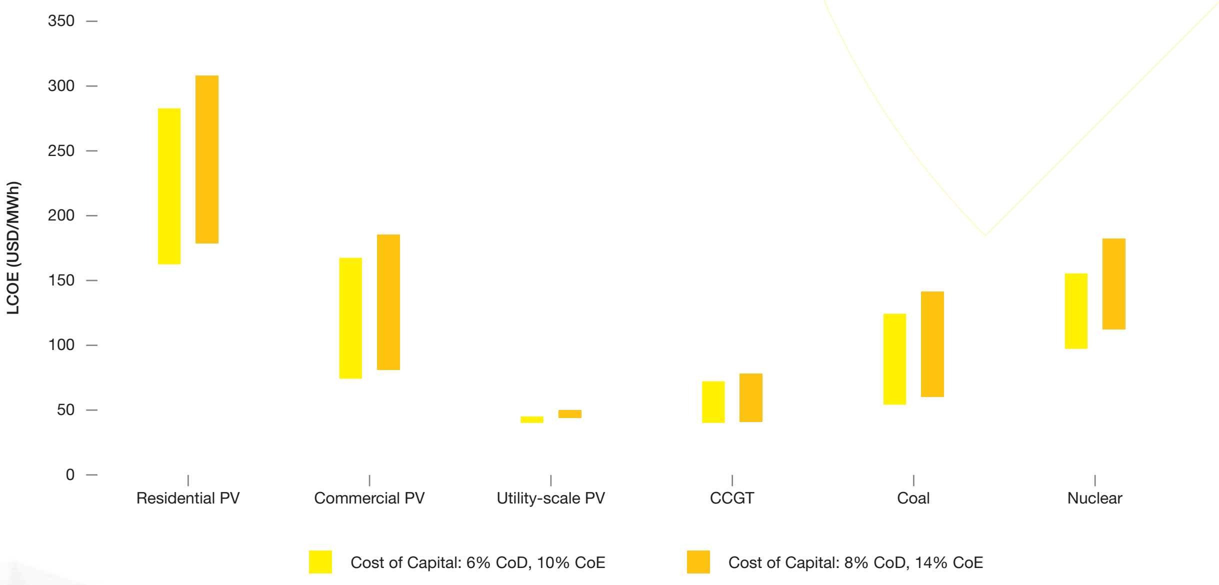
This transition requires a shift in the mindset of EU and national regulators. European policies are lagging, and the European energy market is missing the opportunities these new technologies provide. A paradigm shift (in grid operation and policy) is needed to capture the full benefits of utility-scale solar PV, enabling the technology to provide additional value to the system.

## 1.2. The cost advantage of grid-connected utility-scale Solar

The time is right for an ambitious deployment of utility-scale solar in the European Union. Lowest-cost solar, generated in utility-scale solar PV power plants, is now cheaper than energy produced by new nuclear and fossil fuel power plants (see Fig. 2). This is not only a European phenomenon. California leads the way when it comes to taking advantage of low-cost solar. In September 2018, the world's 5th largest economy, passed a bill targeting 60% renewables by 2030 and 100% carbon neutrality by 2045. Solar is essential to meet these targets. In 2017, 60% of all renewable power capacity in California came from utility scale solar.

In recent years, tender schemes have helped to decrease solar power prices to very attractive levels. However, in the EU, these schemes have often lacked ambition. In the EU's largest economy, Germany, which will likely fail to meet its 2020 $CO_2$ reduction targets, and has not reached its modest annual solar targets in years, the total tendered solar amount was only 600 MW/year. Moreover, the maximum size for ground-mounted PV plants in German tenders is capped at power capacities as low as 10 MW, a size that is too small to fully tap into economies of large-scale solar power plants.

FIGURE 2 SOLAR ELECTRICITY GENERATION COST IN COMPARISON WITH OTHER POWER SOURCES

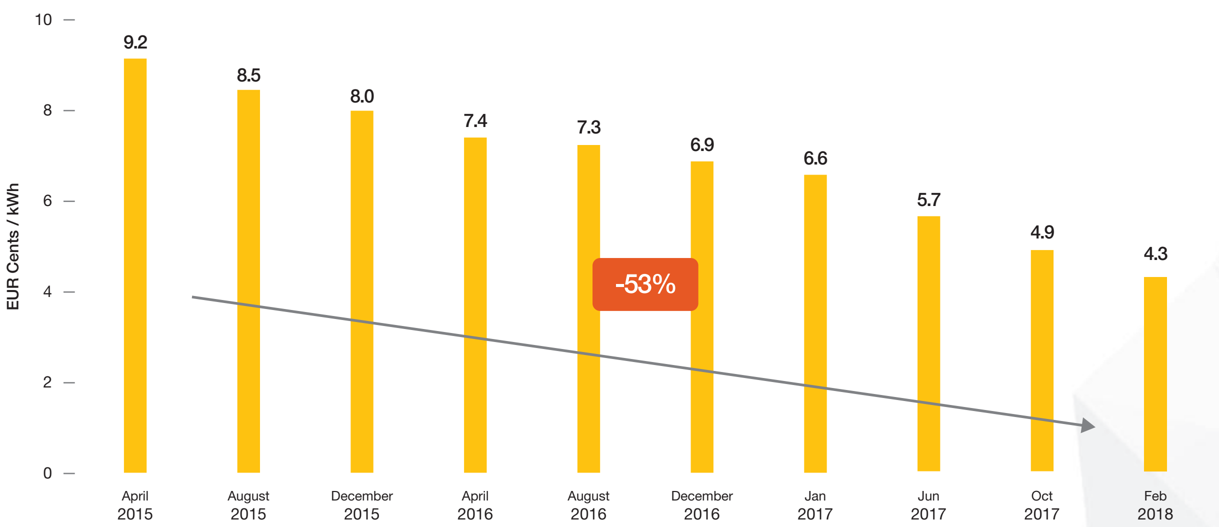



Source: Lazard (2017)

Despite this limitation, even in Germany, average awarded tariffs in solar tenders have more than halved within 2.5 years and already reached the 0.04 €cents/kWh range (see Fig. 3), with the lowest winning bids even entering the 0.03 €cents/kWh range. Already today, solar is not only cheaper than new fossil fuel and nuclear power generation, but it is often even cheaper than onshore wind. In the second Spanish renewables tender in July 2017, solar won 3.9 GW out of 5 GW; in Germany, solar won 100% in a wind/solar tender in April 2018 as well as in France in November 2018. Of course, high wind countries like the Nordics, as well as high wind sites throughout Europe, provide plenty of useful wind potential that contributes to more balanced RES generation overall – in fact, solar and wind complement each other very well and are both key to enable very high RES penetration rates.

Often, utility-scale solar is not only the lowest cost solution, but it is also a very useful tool to keep the grid stable and reliable, and as well as, if not better than, conventional generation assets, as the next chapter shows. The technology is ready, and the solar sector is ready to meet the challenge. Breakthrough innovations in system management, advanced power electronics and energy storage open new ways to tap into solar plants' potential, as a significant provider of flexibility.

FIGURE 3 AVERAGE WINNING BID SOLAR POWER PRICES IN GERMAN TENDERS




Source: German Federal Network Agency

Diego de Almagro, Atakama Desert. © ENEL

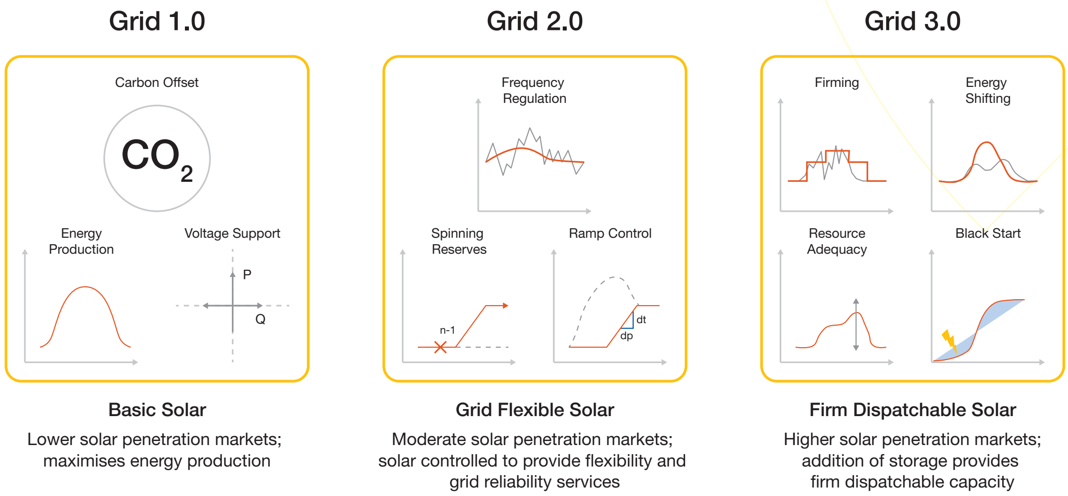
# 2 FROM SOLAR 1.0 TO 2.0:

## ENABLING GRID FLEXIBLE SOLAR

In the early days of PV power plant development, large-scale solar systems were designed to take advantage of feed-in tariff remuneration. The objective was to maximize individual system yield, not harmony with the existing infrastructure.

This Grid 1.0, 'Basic Solar' phase, works as long as there is low penetration of solar in a region. As soon as the density of solar power systems increases to a certain level, the focus must shift to Grid Flexible Solar plants that contribute flexibility and grid reliability services, such as frequency regulation or ramp control (see Fig. 4). This chapter will delve into two case studies demonstrating how a utility-scale PV plant with the technical capabilities to provide grid services can help operators meet the flexibility requirements of the grid.

FIGURE 4 THREE GRID PHASES OF SOLAR POWER PLANT EVOLUTION – BASIC SOLAR, GRID FLEXIBLE SOLAR, FIRM DISPATCHABLE SOLAR




Source: First Solar.

## 2.1. Essential Reliability Services by Utility-scale Solar PV Power Plants – CAISO 300 MW test

In 2016, the California Independent System Operator (CAISO), First Solar and the National Renewable Energy Laboratory (NREL) conducted a demonstration project on a 300 MW large utility-scale PV power plant in California to test its ability to provide essential ancillary services to the electric grid. The 300 MW plant was designed and constructed by First Solar. A key component of this PV power plant is the plant-level controller (PPC) developed by First Solar. It is designed to regulate real and reactive power output from the PV power plant so that it behaves as a single large generator.

The aerial photo of the plant using First Solar advanced thin film Cadmium-Telluride (Cd-Te) PV modules is shown in Fig. 5.

The plant PPC is capable of providing the following plant-level control functions:

- Dynamic voltage and/or power factor regulation, and closed loop VAR control of the solar power plant at the point of interconnection (POI);
- Real power output curtailment of the solar power plant when required so that it does not exceed an operator-specified limit;
- Ramp-rate controls to ensure that the plant output does not ramp up or down faster than a specified ramp-rate limit, to the extent possible;
- Frequency control (governor-type response) to lower plant output in case of an over-frequency situation or increase plant output (if possible) in case of an under-frequency situation; and
- Start-up and shutdown control.

The PPC implements plant-level logic and closed-loop control schemes with real-time commands to the inverters to achieve fast and reliable regulation of active and reactive power. The commands to the PPC can be provided through the SCADA human-machine interface or even through other interface equipment, such as a substation remote terminal unit.

The conclusions of the tests conducted on a grid-connected 300 MW PV plant demonstrated that:

- Solar PV generating plants can provide a wide range of essential reliability services. Tests showed fast and accurate PV plant response to Automatic Generation Control (AGC), frequency, voltage, power factor, and reactive power signals under a variety of solar conditions.

FIGURE 5 AERIAL PHOTO OF 300 MW PV POWER PLANT

Source: First Solar.

- Advancements in advanced inverter technology combined with advanced plant controls allow solar PV resources to provide regulation, voltage support, and frequency response during various modes of operation.
- Solar PV resources with these advanced grid-friendly capabilities have unique operating characteristics that can enhance system reliability by providing:
  - Essential reliability services
  - Voltage support (even when the plant's output is near zero)
  - Fast frequency response (inertia response timeframe)
  - Frequency response for low as well as high frequency events

**This functionality is inherent in utility-scale PV power plants today and should be recognized and encouraged by grid operators.** (For more background on the results of the CAISO 300 MW test, see Annex 2)

## 2.2. Value of Dispatching Solar Power Plants – The TECO study

**Many operational challenges can be addressed by making utility-scale solar "dispatchable" i.e., enable it to provide flexibility for grid operations**. For example, some ramping demands on conventional generation resources can be reduced if solar plants can control ramp rates during both morning and evening hours, thereby providing the means to flexibly operate the grid even in the presence of a high penetration of solar. In the previous section, we demonstrated that PV plants have the technical capabilities to provide grid services such as spinning reserves, load following, voltage support, ramping, frequency response, variability smoothing, frequency regulation, and power quality. By leveraging all these operational capabilities, utility-scale solar resources can become an important tool to help operators meet flexibility needs of the grid.

Such capability makes it possible for solar to go beyond a simple energy source and instead contribute to important system requirements more like traditional generators. To date, the economic value of including solar as an active participant in balancing requirements has not been widely studied. To quantify the value of dispatchable solar, a new study by Energy & Environmental Economics (E3), First Solar Inc. and Tampa Electric Company (TECO) demonstrated the economic value of including solar as an active participant in balancing the market.[2]

**The study explored three solar operating modes:**

1) **Must-Take**: System operators treat solar power plants as "must-take" resources, meaning solar cannot be curtailed and operational reserve requirements cannot be provided by solar. The resulting "net load" is the amount of power that must be produced by other "dispatchable" resources. It is important to note that present-day rooftop solar installations are operated as "must-take" because they are almost never visible to or curtailable by the system operator.
2) **Non-Dispatchable (Curtailable)**: System operators can curtail solar to avoid oversupply of generation in the grid. In many instances, power purchase agreements (PPA) between independent power producers (IPP) and utility off-takers have evolved to accommodate some degree of curtailment flexibility to reflect this evolving reality. Many regions (e.g., Germany, Denmark, California, Hawaii, etc.) have successfully reached higher penetrations of variable renewables – as high as 42% of annual energy in the case of Denmark[3] – by using renewable curtailment and interties with neighbouring regions as important integration tools.
3) **Dispatchable**: Solar can be fully dispatched to the needs of the grid via economic optimization of energy production and operational reserves while respecting the limits imposed by solar insolation availability. System operators can elect to use the solar resources to provide energy or essential grid services such as regulation reserves, and this choice may vary by dispatch time interval throughout the day or season-to-season.

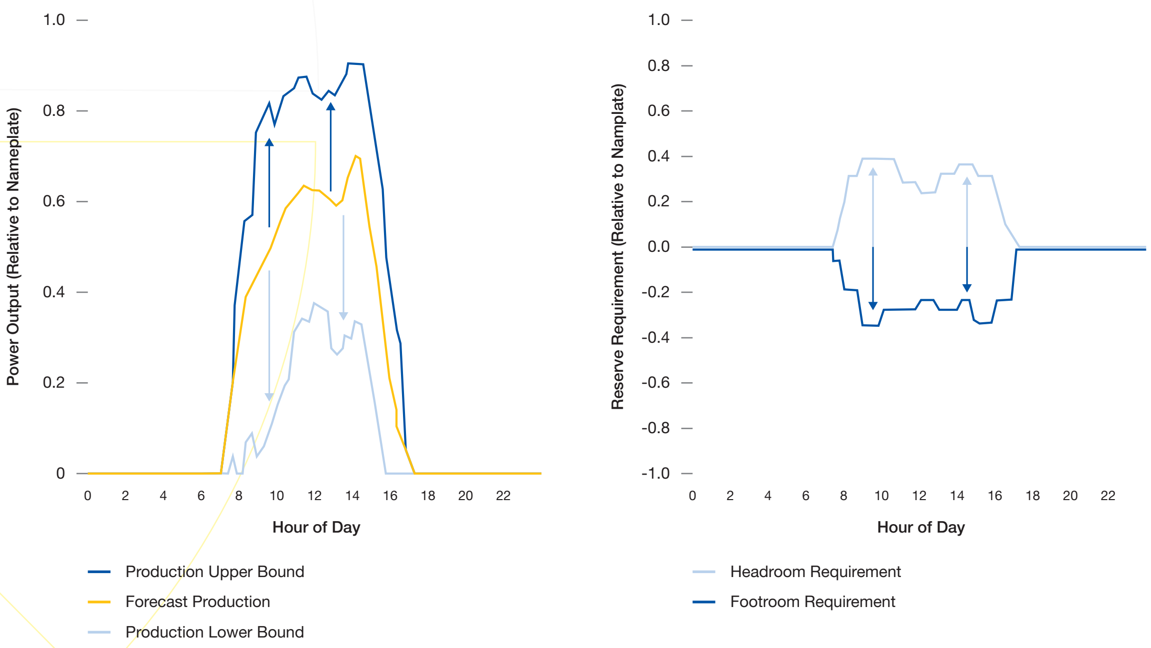
### Utilizing Solar Headroom and Footroom

The deployment of more variable renewable capacity has increased the need for "downward" flexibility, or footroom. If renewable production were to unexpectedly increase, other resources would need to ramp downward to accommodate the additional energy flowing onto the system. Dispatchable solar is not limited to providing its own footroom – it can also provide footroom to accommodate unexpected decreases in demand, with the maximum footroom

2 "Investigating the Economic Value of Dispatching Solar Power Plants", September 2018 (Jimmy Nelson, Saamrat Kasina, John Stevens, Jack Moore, Arne Olson, Mahesh Morjaria, John Smolenksi, Jose Aponte.

3 A. Bloom, U. Helman, H. Holttinen, K. Summers, J. Bakke, G. Brinkman and A. Lopez, "It's Indisputable: Five Facts About Planning and Operating Modern Power Systems," IEEE Power and Energy Magazine, 2017.

FIGURE 6 CONFIDENCE IN SOLAR FORECASTS AHEAD OF REAL TIME AND RESULTING FORECAST ERROR RESERVE LEVELS ON AN EXAMPLE PARTLY CLOUDY DAY, NORMALIZED TO SOLAR POWER PLANT CAPACITY




Source: First Solar.

limited to the lower bound of forecasted solar production potential (the distance between zero and the Production Lower Bound line in Fig. 6). In other words, dispatchable solar can be used to provide the downward regulation service that system operators have sourced from conventional generators for 100 years.

If enough solar is forecast to be online in real time, operators can plan to dispatch solar downwards if demand drops unexpectedly.

Conversely, solar can also be dispatched in a manner to provide headroom on the system. Relying on solar to provide headroom (regulation up, spinning reserve, etc.) would require:

1) Plant output to be curtailed intentionally or scheduled below the maximum available energy production (under-scheduled) in order to create headroom; and,

2) The system operator to have confidence that additional solar production potential will be realized when called upon.

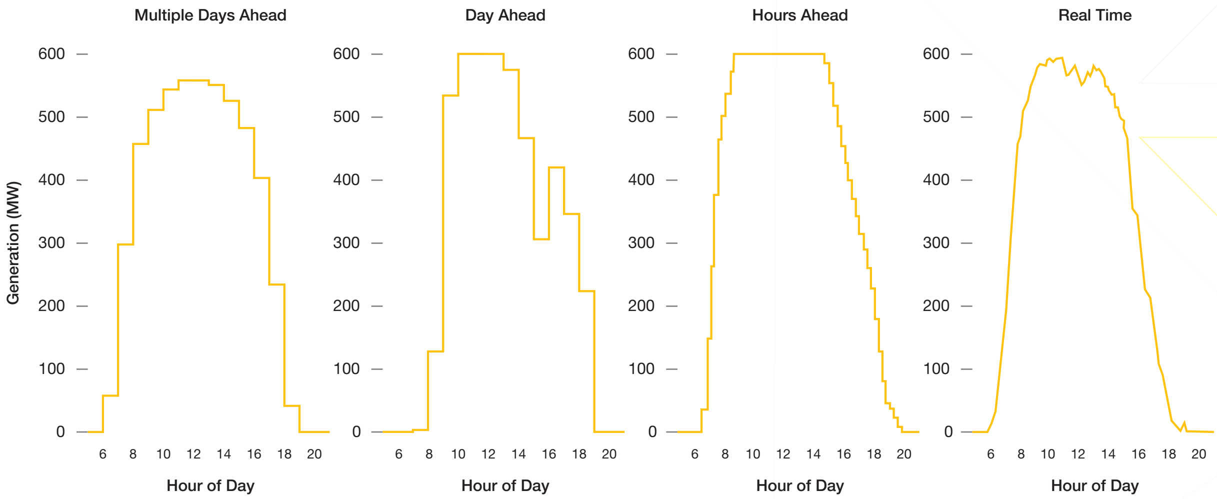
Solar can be forecast with sufficient confidence within a lower bound; however, it is understandable that system operators will naturally be conservative when relying on solar in the upward direction.

It should be possible for solar to provide these services given enough certainty on solar production potential. Also, solar power plants can ramp up much more quickly than their conventional counterparts, suggesting that solar may be particularly well suited to provide frequency regulation, synthetic inertia, or fast frequency response. This is especially true given that the supply of these fast-timescale balancing services tends to be the most limited during times of low demand and high variable renewable production.

## Analysis Overview

To demonstrate the economic value of dispatching solar, E3 used the PLEXOS Integrated Energy Model to simulate unit commitment and dispatch of an actual utility system (TECO). The range of utility-scale solar deployment levels ranged from 0% (no solar) to 28% annual energy penetration potential. The simulation was done for each penetration level for the three different solar operating modes described above. The historical solar data was collected for 15 proxy sites in TECO's services territory, where solar PV projects are either already in-service or in construction or development. The insolation data was transformed to plant output data (see Fig. 7).

FIGURE 7 SOLAR PROFILES USED FOR UNIT COMMITMENT ACROSS DIFFERENT TIMEFRAMES FROM AN EXAMPLE JUNE DAY. PROFILES ARE FOR 600 MW OF INSTALLED SOLAR CAPACITY




Source: First Solar.

With the input from the TECO system operators, the PLEXOS model was optimized for the system unit commitment and dispatch for each day of the year in four sequential stages – multiple days ahead, days ahead, hours ahead, and real time (see Fig. 8).

Thermal generators were represented using standard unit commitment and dispatch constraints, including ramping limitations, minimum uptime and minimum downtime constraints, and co-optimized energy and reserve provisioning. Generator economics were included via heat rate curves, variable operations and maintenance costs, fuel offtake at startup and startup costs. Additionally, TECO provided unit-specific maintenance and outage schedules. Market transactions with external entities were restricted to hours in which the TECO system did not have enough generation available to serve load. Market transactions were limited by hourly transmission availability data provided by TECO. Exports from the TECO system to external entities were not considered.

### Simulation and Results

First, the study explored the limits of the "**must-take**" solar operating mode. The study showed that must-take solar can be absorbed up to about 14% of annual energy penetration potential. At solar penetrations above this level, we begin to observe over-generation conditions, indicating that the system does not have enough

FIGURE 8 PLEXOS MODEL STAGES

| UNIT COMMITMENT STAGE | DISPATCH AND COMMITMENT DECISION TIMESTEP | LOAD TIMESERIES DATA (PROVIDED BY TECO) | SOLAR TIMESERIES DATA |
|---|---|---|---|
| Multiple days ahead | Hourly | Multiple days ahead forecast | Month-hour average of 5-minute real time profiles |
| Day ahead | Hourly | Day ahead forecast | NREL day ahead forecast |
| Hours ahead | Every 15 minutes | Average of day-of forecast and actual 5-minute demand | NREL 4-hour ahead forecast |
| Real time | Every 15 minutes | Actual 5-minute demand profile | Simulated 5-minute profile |

Source: First Solar.

flexibility to balance supply and demand while also accepting every MWh of solar generation. Thus, solar penetrations above 14% are infeasible in must-take operating mode. The must-take solar at high solar generation levels can cause conflicting requirements to:

1) Accept all solar generation; or,

2) Maintain headroom and footroom on thermal generation.

The results demonstrate that planning to absorb all solar generation is untenable at higher solar penetration levels and solar curtailment is a necessary tool to balance the system above a threshold level of solar penetration.

Next, the limits of **"non-dispatchable"** solar were explored. At intermediate levels of solar penetration (~15 - 25% solar energy penetration), curtailing solar generation allows what would otherwise be an inoperable system with must-take solar to become operable. Curtailing solar enables more thermal generators to be committed, thereby creating enough space within the dispatch stack to maintain adequate headroom and footroom on thermal units. While the system is operable, curtailment levels that result from this operational strategy become very high as more solar is added to the system. Adding more solar causes additional thermal units to be committed to meet increased operational reserve requirements. Committing these units causes more fuel to be burned in conventional generators, which in turn reduces the energy value of solar generation. The energy value of additional solar energy with non-dispatchable solar (the yellow area in Fig. 9) rapidly decreases above about 14% solar energy penetration. The energy value is calculated as the change in annual thermal production costs as the solar penetration increases, not including the capital cost of the additional solar resources.

The analysis for **"Dispatchable"** solar showed that sharing balancing requirements between thermal and solar generators becomes increasingly valuable and can reduce curtailment and thermal commitment (see Fig. 10). Provision of these requirements requires downward dispatch of solar, and some services require the plant operator to maintain headroom to enable upward dispatch. While this results in lost solar production, solar plants incur no measurable variable costs from providing these services. Instead, the cost of solar providing these services is an opportunity cost that can be estimated in the context of economic dispatch. It may seem paradoxical, but the simulations for dispatchable solar have more opportunities to be curtailed, but less actual curtailment is observed. The simulation results show that, with the right economic dispatch rules, solar curtailment can be minimized by allowing solar to provide the most constrained grid services at key times.

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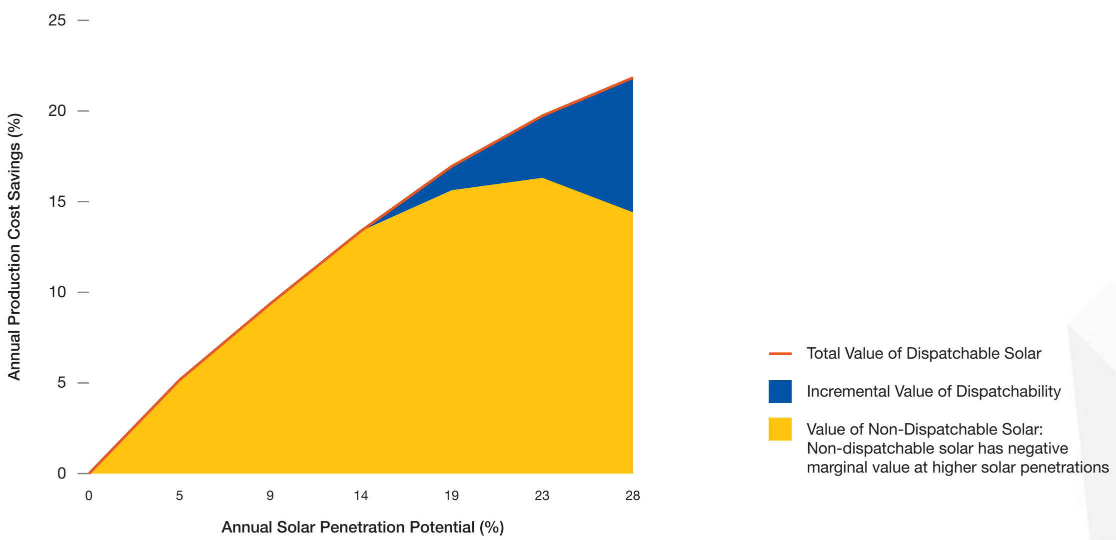
FIGURE 9 VALUE OF NON-DISPATCHABLE SOLAR AND INCREMENTAL VALUE OF SOLAR DISPATCHABILITY. VALUE IS NORMALIZED TO SYSTEM PRODUCTION COST WITHOUT SOLAR GENERATION (0% ENERGY FROM SOLAR)



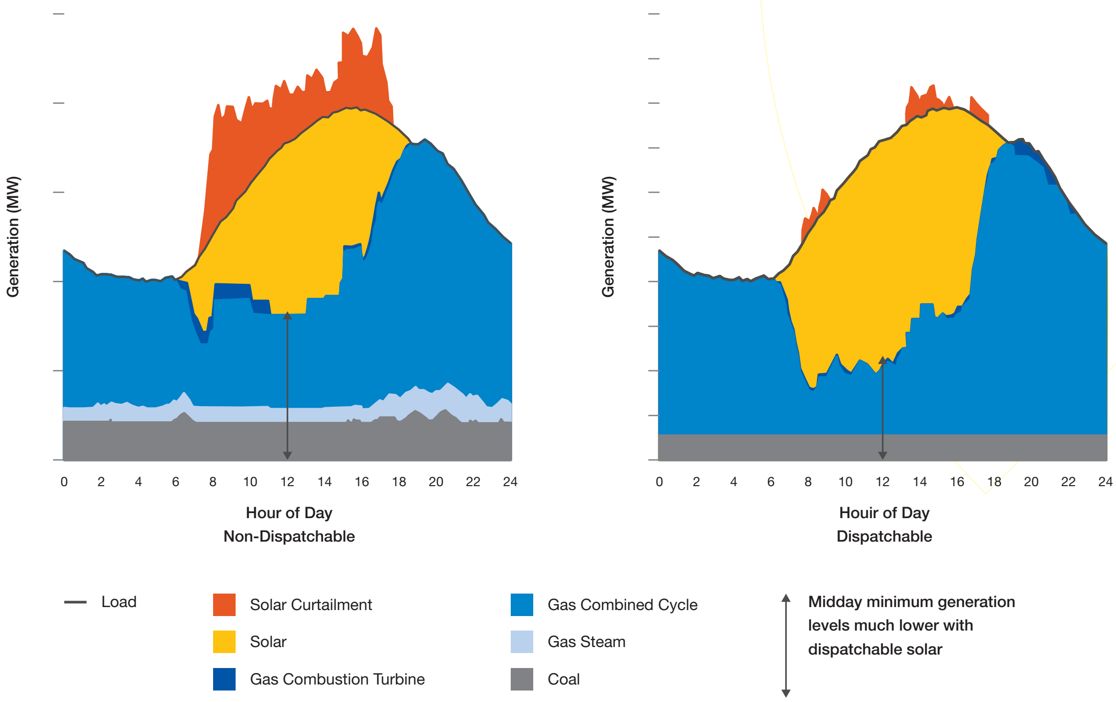

Source: First Solar.

In contrast to the non-dispatchable case, even at 28% annual solar production potential, dispatchable solar has a significant positive marginal energy value. Provision of balancing services from solar plants allows thermal generators to operate more efficiently by reducing the need for cycling and load following services, resulting in less fuel consumption and emissions. This also avoids commitment of inefficient thermal generation, reducing curtailment of solar during times of over-generation. These savings can be substantial, particularly for systems in which these services would otherwise be provided by relatively expensive or inflexible thermal generators. Fig. 10 demonstrates that dispatching solar lowered the amount of thermal generation during hours of high solar output and resulted in some thermal units not being committed to operate at all.

The analysis also demonstrated (see Fig. 11) that dispatchable solar allowed for a reduction in both thermal commitment and generation across all classes of thermal generators, and no additional large capital investments would be necessary to reduce thermal capacity factors and commitment levels – increasing solar dispatchability simply uses existing assets more efficiently, resulting in lower production costs.

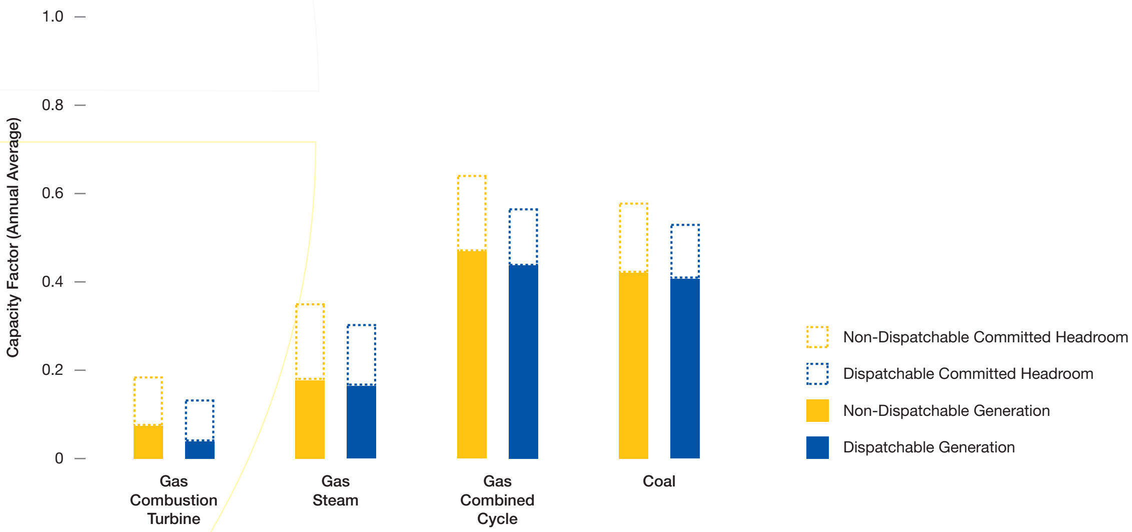
Dispatchable solar plants can provide significant reliability, financial, and environmental value relative to non-dispatchable solar plants. Dispatchable solar provides the operational means necessary for grid operators to address the challenges associated with higher penetration and cost-effectively integrate increasing amounts of solar in the generation mix. Dispatching solar will reduce $CO_2$ emissions and may reduce criteria pollutant emissions (such as NOx), which can be significantly higher for power plants that frequently ramp up and down.

FIGURE 10 SYSTEM DISPATCH AT HIGHER SOLAR DEPLOYMENT LEVELS FOR AN EXAMPLE SPRING DAY




Source: First Solar.

FIGURE 11 THERMAL GENERATOR CAPACITY FACTOR AND HEADROOM AT 28% ANNUAL SOLAR ENERGY PRODUCTION POTENTIAL




Source: First Solar.

## Next Steps for Solar 2.0

When envisioning a power system with high fractions of variable renewable energy, system planners must include information on the least cost manner to reliably operate that system in both the present and future. If system operators can dispatch variable renewable resources, the resources can be viewed as assets that help to maintain reliability rather than liabilities that create operational challenges. Bringing the operational value of dispatching variable renewables into utility resource plans may change the composition of investments that are built going forward. The flexibility brought by dispatching variable renewable generators could reduce the need for investments in other flexible resources. Dispatching renewables helps to retain their value at higher renewable penetrations, which may induce more renewable deployment, thereby increasing the need for other flexible resources.

Enabling these capabilities in incremental solar projects will require all parties to come to the table and prioritize technical requirements and commercial terms that drive flexibility and dispatchability. Without proactively addressing these and other challenges, achieving a future predominated by renewable generation will be difficult to implement.

We can observe the same fundamental challenges in Europe and the United States for the integration of high penetration of solar PV into the electrical grid. The grid flexibility is key, and can be achieved by:

- Prioritizing flexibility and dispatchability in planning and procurement activities
- Changing operational practices
- Open ancillary service market for renewables
- Shorten dispatch schedules
- Better forecasting
- More advance requirements for solar PV projects (dynamic voltage control, frequency response)
- Adding energy storage
- Increase transmission capacity

# 3

# SOLAR 3.0:

## A SWISS ARMY KNIFE FOR THE ENERGY SECTOR

Copper Mountain. © First Solar

Solar 3.0 is the combination of solar with stationary batteries. In this form, the system works like a Swiss army knife for the energy sector, as the same hardware can take on a variety of different applications with a number of benefits. In Europe, the central application of storage systems are grid services. On the one hand, it is possible to aggregate rooftop solar and small storage systems to offer such services. However, the much bigger impact will come from combining lower cost large utility scale solar plants with large storage systems. Off-grid applications have also proven especially beneficial in ecological and financial terms, but that's not relevant for the bulk of European energy demand (see case study, Annex 1.3).

In a world with vastly increasing shares of variable energy sources, such as PV and wind energy, the grid is increasingly under stress from frequent changes in energy supply. If energy supply and demand cannot be matched in a matter of seconds, the voltage drops or exceeds its optimal level. In extreme cases, this triggers blackouts which shut down large networks (e.g. in November 2006 when 10 million people in Northern Europe were left in the dark).

Today, conventional power plants are used inefficiently to produce large amounts of so-called frequency reserves in cases of high load demand. At the same time, massive amounts of energy from wind or PV are curtailed (i.e. shut down) to not overstretch today's inflexible grid infrastructure. In Germany, for example, in Q1/2018, 1.97 TWh of feed-in tariff supported RES and CHP power were curtailed, resulting in compensation claims by plant operators of around € 228 million.[4]

Storage connected to solar PV helps to calibrate the grid for the new structure of supply. If grid operators (TSOs and DSOs) are able to access large amounts of interconnected storage devices, this substantially increases efficiency gains and cost savings. These gains cannot only be expressed in financial terms, they also benefit the climate. If the grid is at its limit, and renewable energy has to be curtailed, $CO_2$ intensive energy is used while green energy is technically available. The addition of storage will compensate this inefficient situation and, consequently, facilitate massive $CO_2$ reductions.

### 3.1. Economic and Ecological Gains

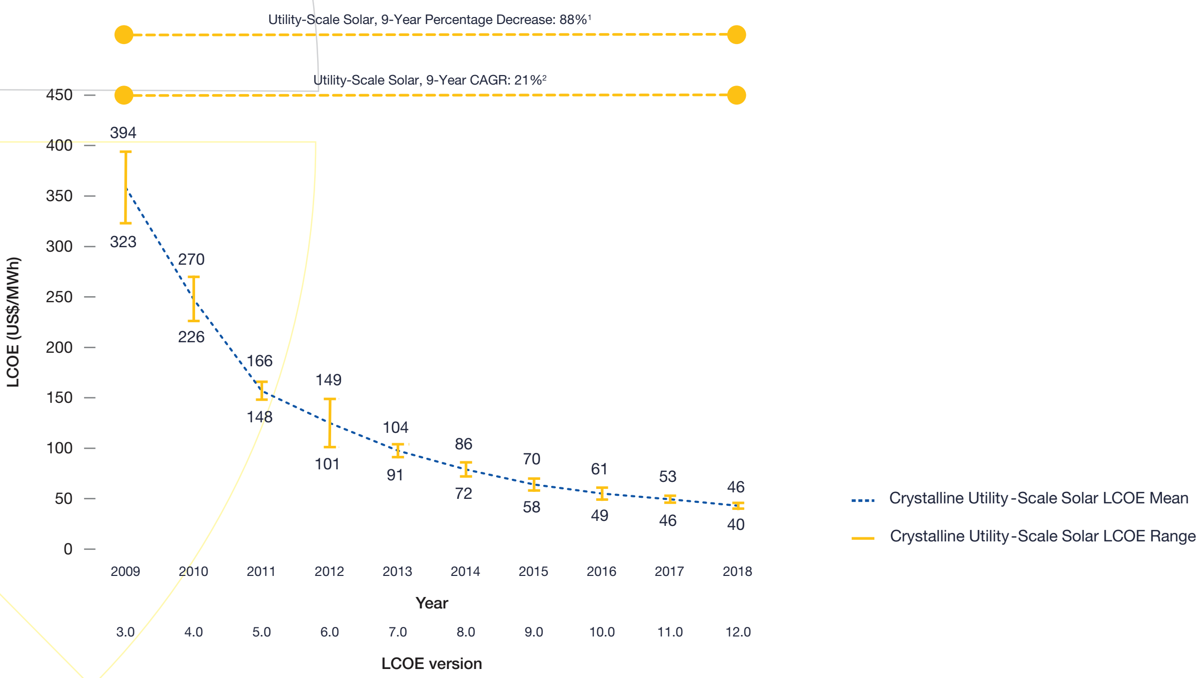
Over the past years, solar and storage have seen a rapid decrease in production and installation costs. This shortens the time span until the investment has refinanced itself. Utility-scale PV systems have seen a decrease in levelized cost of electricity production of around 88% in the US between 2009 and 2018 (see Fig. 12).[5] Even more dramatic, the costs of Li-Ion battery systems dropped by more than 60% within 27 months from 2014 to 2017 (see Fig. 13).[6]

4 https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2018/Quartalsbericht_Q1_2018.pdf?__blob=publicationFile&v=3

5 Lazard 2018: https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

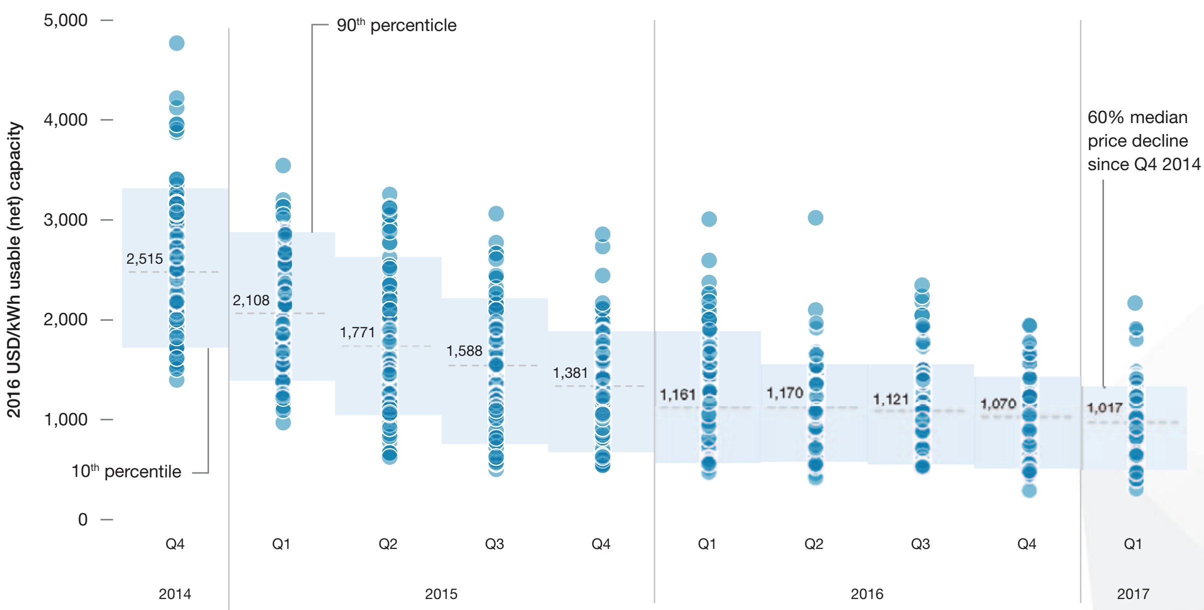
6 IRENA 2017: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

## FIGURE 12 UNSUBSIDISED SOLAR PV LCOE




Source: Lazard Capital.

## FIGURE 13 LITHIUM-ION BATTERY COST DECREASE

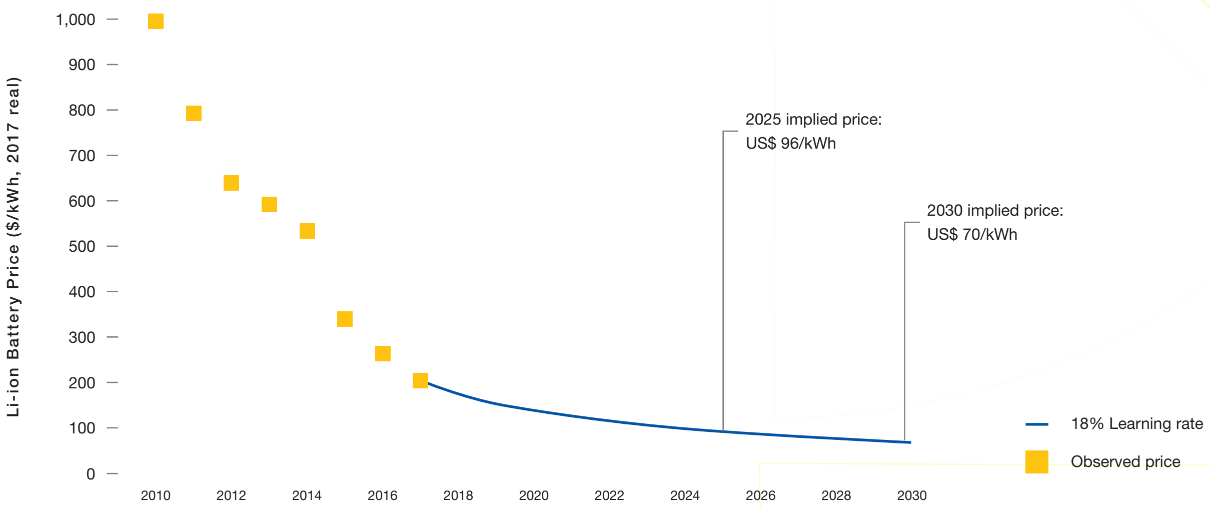



Source: IRENA.

This development is expected to continue, and even accelerate, in the next decade. With regard to battery technology, estimations expect prices to drop to 70 US$/kWh by 2030 which would enable solar and storage to disrupt the current market for grid services (see Fig. 14).[7]

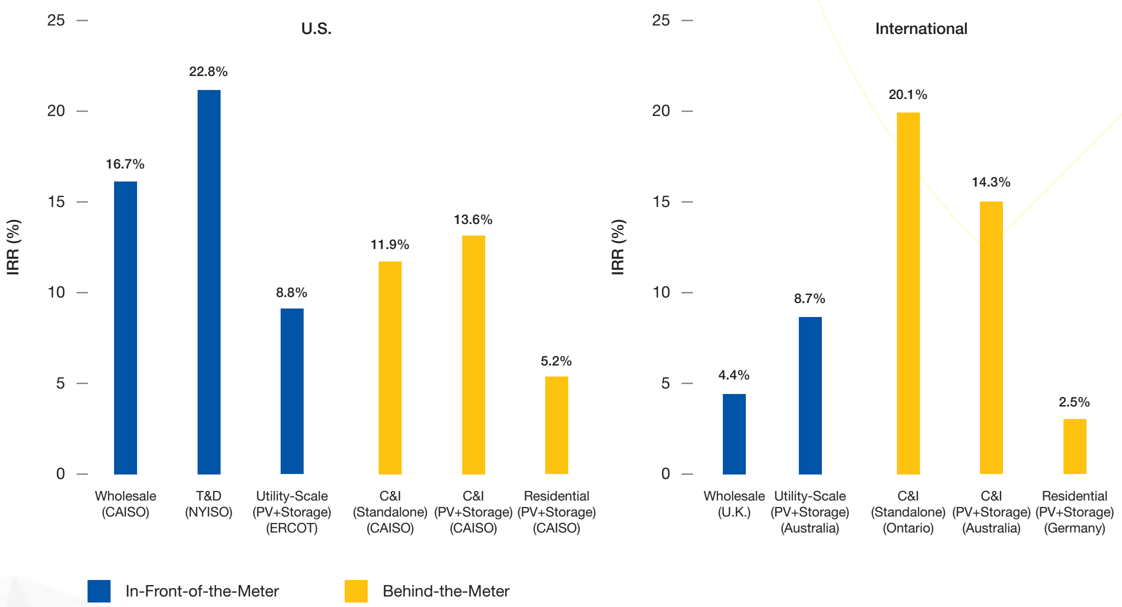
With these cost developments in mind, the advantages of Solar 3.0 can be quantified. The EU Commission's 2016 METIS study put the benefits of additional storage to test. For 2030, the study finds that a 1 GW addition of 3h storage would lead to $CO_2$ reductions between

FIGURE 14 LITHIUM-ION BATTERY PRICE, HISTORICAL AND FORECAST




Source: BNEF.

FIGURE 15 IMPROVED ECONOMICS OF BATTERY ENERGY STORAGE SYSTEMS IN FRONT AND BEHIND THE METER IN A YEAR-ON-YEAR COMPARISON




Source: Lazard Capital.

7 https://bnef.turtl.co/story/neo2018?teaser=true

130,000 tonne (UK) and 87,000 tonne (Germany). Financially, the impact of 1 GW of extra storage amounts to cost savings between € 29.85 million (UK) and € 8.17 million (Germany), including the cost of storage.[8]

The Lazard Capital Levelized Cost of Storage update, released in Nov. 2018, shows that project economics for different energy storage applications have improved year-on-year. This is due to cost improvements rather than rising revenues, which depend on local market dynamics and/or utility tariffs (see Fig. 15).[9] Ancillary service products, demand response and demand charge mitigation have the potential to become attractive revenue opportunities for storage. Combining battery storage with PV can create value by sharing infrastructure, such as inverters, reducing power output curtailment, and capturing peak solar production.

## 3.2. Solar 3.0 feedback from the field – first case studies

While technically ready, Solar 3.0 is only just starting, primarily because of regulatory obstacles. Solar & Storage need to access all markets, especially those for flexibility and ancillary services, with products that value fast and accurate services – which is often not yet the case.

There have been a number of pilot solar and storage power plants in the EU built to test the feasibility of Solar 3.0 (see below & case studies in Annex 1):

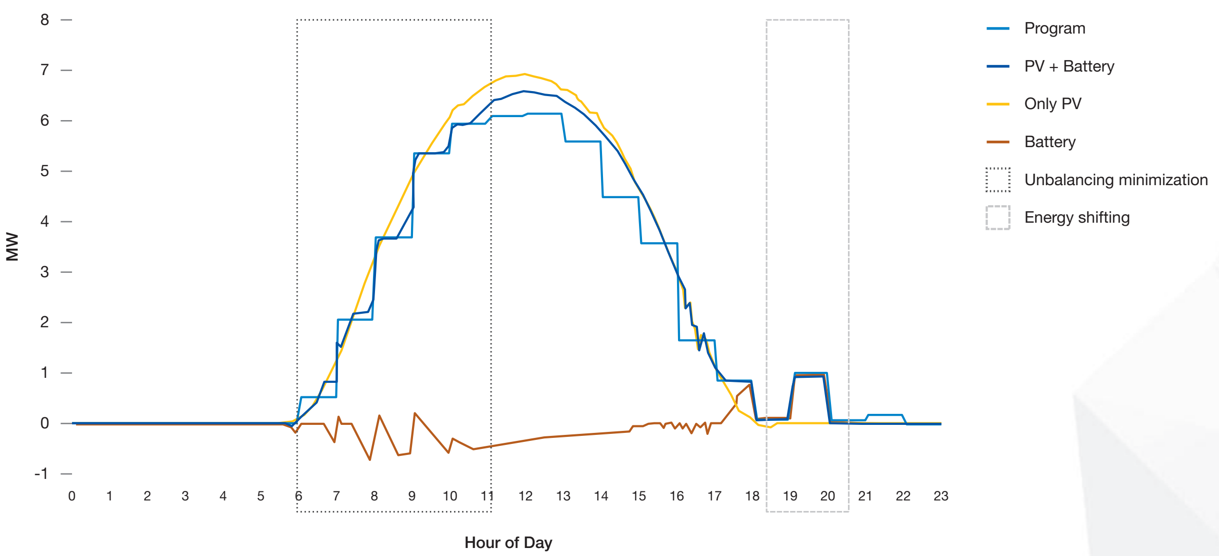
### 3.2.1. Solar & Battery Storage utility-scale plant in Catania, Sicily

ENEL, for example, installed a 10 MW solar + 1 MWh battery (NaNiCl) plant in Catania, Sicily to assess the integration of Renewable Energy Sources (RES) and Battery Energy Storage Systems (BESS), and verify the benefits when it comes to increased RES dispatchability (energy shifting and peak shaving) and providing grid services (voltage and frequency regulations) (see Fig. 16 and Annex 1.2). Enel is now working on developing a special platform to manage RES and BESS.

### 3.2.2. Clayhill Solar & Battery Storage utility-scale plant in Bedfordshire, UK

In September 2017, British renewable energy developer Anesco inaugurated the Clayhill plant in Bedfordshire, UK, which consists of 10 MW of ground-mounted solar PV plus 6 MW of lithium-ion battery storage (see Annex 1.2). The system has been receiving a lot of media attention, as it is the first subsidy-free solar farm in the

FIGURE 16 A 10 MW SOLAR + 1 MWH BATTERY PLANT IN CATANIA, SICILY WAS INSTALLED TO ASSESS INTEGRATION OF RES AND BESS, AND VERIFY THE BESS BENEFITS REGARDING INCREASED RES AND PROVISION OF SERVICES FOR THE GRID




Source: Enel.

8 Given, or a "Green Transition" Vision in which the European energy goals will be reached by 2050. European Commission 2016: METIS Studies – Study S07 – The role and need of flexibility in 2030: focus on energy storage.

9 https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

UK. It does not benefit from any solar incentive scheme, such as Contracts for Difference or Renewables Obligation, which have been reduced and withdrawn. The revenue streams are guaranteed by the battery system that allows the project to be profitable.

The Clayhill plant is used for periods of peak demand during winter. In addition, it can be used to provide ancillary services to the British TSO National Grid – the sale of these services is a source of extra revenues for the solar farm. Anesco plans to bid generated power into National Grid's "T-4" capacity market and its enhanced and fast frequency response markets. The batteries pre-qualified to bid for capacity market tenders in 2017.

In addition, the batteries are set to be contracted by aggregator Limejump, who combines a portfolio of energy storage projects and enables their participation in the UK's dynamic frequency response contracts.

### 3.2.3. Solar & Battery Storage off-grid utility-scale solar & storage plants

Although barely present in Europe, off-grid power, or mini-grids, are good testing ground for utility-scale solar & storage used in large scale application in grid-connected areas. To relieve the **Philippine island of Paluan** of their volatile power supply, Solar Philippines, in conjunction with Tesla, installed and commissioned a 1,680 kWh Powerpack 2 Microgrid system. The system is paired with 2 MWp of PV and 2 MW of diesel genset backup serving the remote community. The community of Paluan is now being provided with power 24 hours a day 7 days a week, removing the hazards of power intermittency to make outages a thing of the past. The project also provides a precedent for other renewable powered microgrid solutions to be deployed throughout isolated regions of the Philippines, enabling them to avoid traditional fossil fuel power and accelerate the world's transition to sustainable energy.

On the **island of St. Eustatius** (see Annex 1.3) in the Antilles, which is a special Municipality of the Netherlands, 4.2 MW solar capacity was combined with 5.8 MWh Li-Ion battery capacity to provide nearly 50% of total power supply. To allow diesel-free operation during the daytime, SMA developed a battery storage inverter to support grid-forming operation. It does not rely on any other voltage source but can establish grid stability by itself. The operational management of the hybrid system controller was extended to provide an overlaying voltage- and frequency-control of the grid and to include start-/stop-commands towards the diesel generation system, so that rotating generators are no longer required.[10] The same grid-forming inverter can also be operated in parallel with a large grid and then provides frequency and voltage stabilization.

### 3.3.Challenges for Solar 3.0 and way forward (policy recommendations)

To take advantage of recent cost reductions and bring about Solar 3.0, the correct regulatory framework is essential. The following considerations are essential when building the right incentives for a dramatic deployment of utility-scale solar & storage:

10 Schönbaum et al: Experiences with Large Grid Forming Inverters on the Island St.Eustatius, Portability to Public Power Grids ; 8th International Workshop on the Integration of Solar Power into Power Systems | Stockholm, Sweden | 16 – 17 October 2018.

FIGURE 17 POLICY RECOMMENDATIONS FOR SOLAR 3.0

| POLICY ASKS | EXPLANATIONS |
| --- | --- |
| "Free movement of kilowatt-hours" | Grid fees should only be levied once on every kWh fed into the grid |
| "Storage can absorb and release electricity when required" | As storage can both absorb and release energy, typical taxes, surcharges, fees, licensing requirements etc. usually levied on consumption and or generation should not apply |
| "Stacking of services" | Provision of several services simultaneously, e.g. self-consumption and ancillary services, are beneficial to the system and should be allowed |
| "Right to self-generate and store electricity"<br>"Right to grid connection" | Every household should be allowed to install and connect Solar & Storage systems without any burden |
| "Maximum asset monetization" | Solar & Storage should have access to all markets, especially those for flexibility and ancillary services, with products that value fast and accurate services |
| "Fair consumer metering costs" | Consumers should not bear unreasonable costs for metering or billing services from DSOs and TSOs |
| "Solar & storage is a new flexibility tool" | Storage should be considered as a viable alternative to traditional grid expansion |
| "Green cannot turn grey" | Stored solar electricity should be treated as other solar electricity |

Source: SolarPower Europe.


# 4 CONCLUSIONS

Several studies and operating examples across the world show that dispatchable utility-scale solar is already possible today. PV power plants, which are following an advance layout and design, and are equipped with intelligent plant controls, modern power electronics (inverters) and advance communication capabilities, are not less advanced than any conventional power generation assets when it comes to grid stabilization and ancillary services. On the contrary, PV power plants are economically more efficient, they offer frequency stabilization even faster than conventional generation, and provide intelligent grid services while they prevent the carbon emissions from running spinning reserves.

Europe needs to act on these international examples and introduce a market design and regulatory framework that requires intelligent grid services from utility-scale PV power plants. This will improve the integration of solar energy in Europe's electricity markets and enhance its contribution to Europe's security of electricity supply.

By implementing such a framework, the European Union can contain the need for grid enhancements at distribution and transmission level and ultimately accelerate the energy transition at a least cost for European consumers.

We would like to conclude this report with the following Key Takeaways and Recommendations:

## Key Takeaways

Using intelligent plant controls, and solution-oriented plant sizing/layout, utility-scale solar can provide cost-effective flexible capacity, for a more reliable electricity system.

Utility-scale solar PV plants can support grid reliability by providing services such as ramping capability, voltage support, and fault ride-through. They can often do so more efficiently than conventional plants.

Utility-scale solar plants are controllable and can provide flexible grid services, such as frequency regulation, that allow system operators to respond quickly and strategically to changing conditions.

With these services, Solar can already achieve significant grid penetration in Europe and beyond, even without energy storage. Decreasing energy storage costs will further enable solar energy to be cost-effectively dispatched, even when the sun is not shining, enabling even more clean energy penetration on the grid .

| RECOMMENDATIONS | STAKEHOLDERS INVOLVED |
|---|---|
| Ancillary service markets should prioritize electricity generation units which are most cost effective, and efficient. | Regulator, Grid operator, Dispatch center |
| Bids should be more granular using existing reliable data and forecast information. This will allow day ahead markets to better align with loads and resources. | Grid operator, Energy trader |
| Planning, procurement and contracting processes must be modified to value power system flexibility as an asset. | Regulator, Grid operator, Developer or owner |
| Grid operators and utilities should model variable renewable energy sources as dispatchable in their integrated resources planning processes. | Grid operator, Dispatch center |
| Tender requirements for new solar capacity should value flexible dispatch capabilities, grid services and pant controls. (As is currently the case in the German innovation tenders.) | Regulator, Developer or owner |
| Electricity grid operators ‘s procurement practices should give priority to plants who offer electricity in the most flexible and cost-efficient manner. | Grid operator, Dispatch center, Energy trader |
| Utility-scale PV power plants need better access to ancillary services to reduce conventional “must run” capacity and allowing PV plants to generate income from such grid services. | Regulator, Grid operator, Energy trader |

**LEGEND**

Regulator · Grid operator · Energy trader · Developer or owner · Dispatch center

SolarPower Europe stands ready to discuss the findings of this report in bilateral discussions and would be glad to put interested parties in touch with experienced experts from its membership at any time.

# ANNEX 1 – CASE STUDIES

## CASE STUDY: CATANIA, SICILY

Catania, Sicily, has been home to the first Enel Green Power ("EGP") pilot plant featuring a stationary storage system integrated into a commercial-scale renewable power plant. The 1 MW/2 MWh Sodium Nickel Chloride storage system has been fitted to the "Catania 1" 10 MWp photovoltaic plant whose capacity is limited to 8 MW by grid constraints.

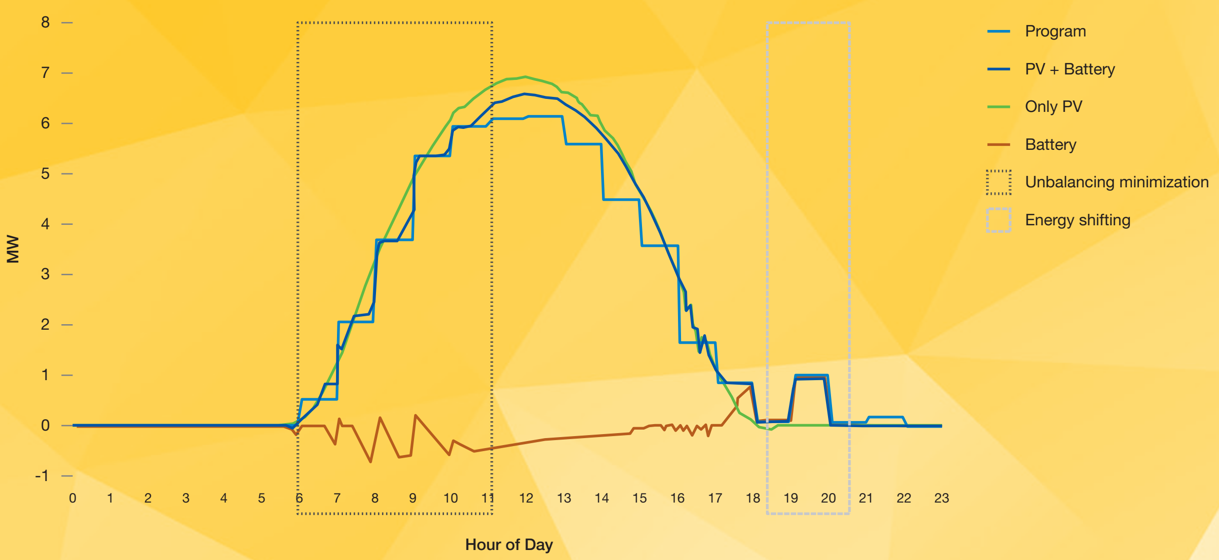
The pilot plant has been running since May 2015, making it possible to carry out tests focused on setting the specifications for the system as a whole and assessing advanced energy management applications. These comprise first and foremost of energy-shifting and of reducing the imbalance between predicted and actual production. During the test phase the integration of the battery with the solar facility allowed Enel to reduce the gap between production forecasts and actual production by 20%. The feasibility of using this system to deliver ancillary services is also being assessed, given that the storage system may also make this possible for plants running on non-programmable renewable sources.

Catania, Sicily, has been home to the first Enel Green Power pilot plant featuring a battery stationary storage system integrated into a commercial-scale renewable power plant. © Enel

TABLE 1 CATANIA 1 PLANT CHARACTERISTICS

| **SYSTEM CHARACTERISTICS** | | **REVENUE STREAMS** | |
|---|---|---|---|
| Owner / Operator | EGP | Capacity markets | x |
| Location | Catania 1 | Ancillary services (e.g. frequency regulation) | x |
| Year | 2015 | RES dispatchability (energy shifting, peak shaving) | ✓ |
| PV size | 8 MW | Energy arbitrage | ✓ |
| Storage size (power) | 1 MW | Government subsidies (y/n, specify) | x |
| Storage size (capacity) | 2 MWh | Power Purchase Agreements (y/n, specify) | x |
| Storage technology | Sodium Nickel Chloride | Other (specify) | Test and development of Storage SCADA for EGP fleet |

FIGURE 18 A 10 MW SOLAR + 1 MWH BATTERY PLANT IN CATANIA, SICILY WAS INSTALLED TO ASSESS INTEGRATION OF RES AND BESS, AND VERIFY THE BESS BENEFITS REGARDING INCREASED RES AND PROVISION OF SERVICES FOR THE GRID




Source: Enel.

The pilot plant is used to for system tests, which comprise first and foremost energy-shifting and reducing the imbalance between predicted and actual production.

### CASE STUDY: CLAYHILL, BEDFORDSHIRE

British renewable energy developer Anesco inaugurated in September 2017 the first subsidy-free solar farm in the UK. Located in Bedfordshire, the Clayhill plant consists of 10 MW of ground-mounted solar PV plus 6 MW / 6 MWh of battery storage. Anesco used its own funds to provide financing of the plant, therefore there was no need for debt financing. It does not benefit from any subsidy scheme such as Contracts for Difference or Renewables Obligation, which have been reduced and withdrawn. The revenue streams granted by the battery system allow the project to be profitable.

The plant generates revenues through energy arbitrage – storage of inexpensive electricity to sell at a higher price later – while the availability of dispatchable solar energy is particularly profitable in periods of peak demand during winter. In addition, the plant can be used to provide ancillary services (balancing mechanism and fast frequency response) to the British TSO National Grid. The sale of these services to the TSO are a source of extra revenues to the solar farm.

In addition, Anesco originally planned to bid generated power into National Grid's "T-4" capacity market, which is used to ensure sufficient electricity supply at times of peak demand. However, the UK's capacity market has been recently suspended after a landmark ruling from European Court of Justice. At the present stage, it is unclear how the situation will evolve in the future.

All the battery revenues – from arbitrage, balancing mechanism and fast frequency response – are derived through an aggregator, who combines a portfolio of energy storage projects. Anesco signed a PPA with the aggregator for the provision of these services.

Clayhill solar farm (left). Anesco Chairman Steve Shine with Claire Perry, UK Minister for Climate Change (right). © Anesco

TABLE 2 CLAYHILL PLANT CHARACTERISTICS

| SYSTEM CHARACTERISTICS | | REVENUE STREAMS | |
|---|---|---|---|
| Owner / Operator | Anesco | Capacity markets | x* |
| Location | Bedfordshire, UK | Ancillary services (e.g. frequency regulation) | ✓ |
| Year | 2017 | RES dispatchability (energy shifting, peak shaving) | ✓ |
| PV size | 10 MW | Energy arbitrage | ✓ |
| Storage size (power) | 6 MW | Government subsidies (y/n, specify) | x |
| Storage size (capacity) | 6 MWh | Power Purchase Agreements (y/n, specify) | ✓ |
| Storage technology | Lt-Ion battery | Other (specify) | |

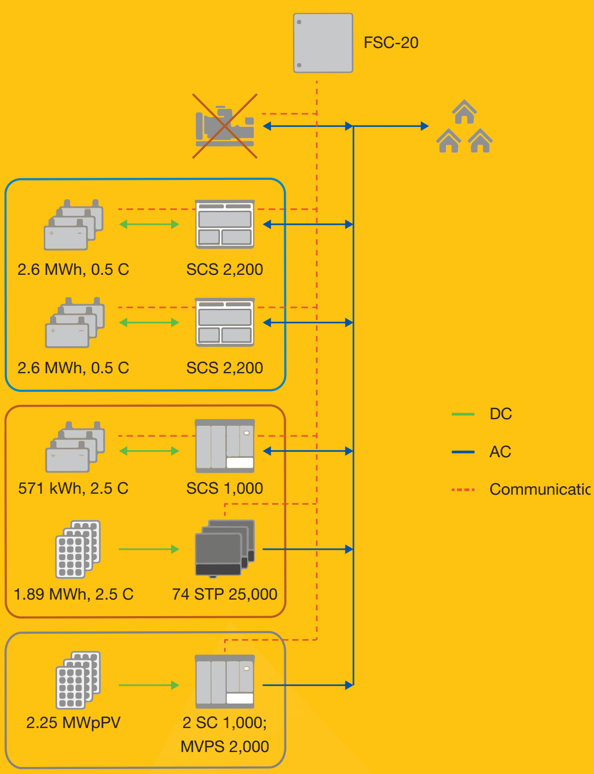
* Potential revenue stream depending on change of UK legislation.

## CASE STUDY: ST. EUSTATIUS

**Large-Scale Island Electrification**: St. Eustatius is an island with about 4,000 inhabitants in the Caribbean. Since November 2017 solar energy covers 46% of its electricity need. Grid forming Sunny Central Storage battery inverters allow to operate the island grid for 10.5 hours in Diesel Off-Mode with 100% solar power fraction. A 5.9 MWh Li-Ion storage facility has been integrated for energy shifting and grid services.

The SMA Fuel Save Controller is responsible for real-time energy and power management and synchronizes diesel and battery operation intelligently and fully automatically. Within milliseconds, the system compensates for the PV array's power fluctuations caused by, for example, the exceptionally fast-moving clouds in this region in particular. This means that the diesel generators can be switched off completely during the day - unnoticed by electricity consumers.

FIGURE 19 ST. EUSTATIUS PLANT STRUCTURE



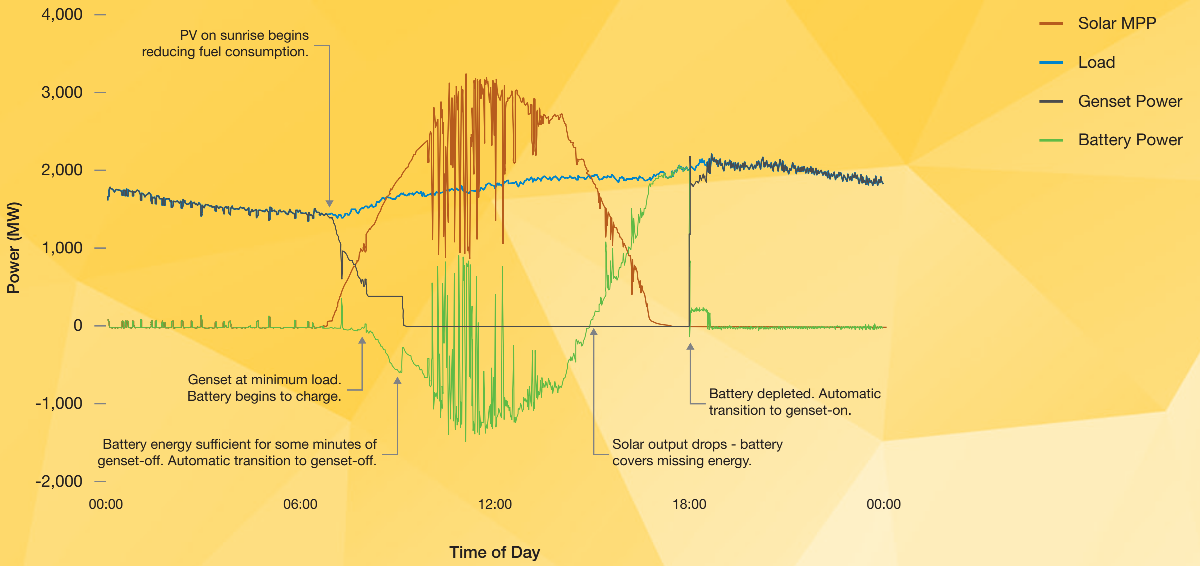

Source: SMA.

Grid forming Sunny Central Storage battery inverters allow to operate the island grid for 10.5 hours in Diesel Off-Mode with 100% solar power. © SMA

TABLE 3 ST. EUSTATIUS PLANT CHARACTERISTICS

| SYSTEM CHARACTERISTICS | | REVENUE STREAMS | |
|---|---|---|---|
| Owner / Operator | Statia Utility Company | Capacity markets | |
| Location | St. Eustatius, NL Antilles | Ancillary services (e.g. frequency regulation) | Frequency (deviation 0.005 Hz), Voltage (deviation 0.4 %), Spinning reserve provision, energy management, power management, automatic synchronization (diesel on / diesel off), short circuit clearance within milliseconds |
| Year | 2016 / 2017 | RES dispatchability (energy shifting, peak shaving) | Energy shifting with peak shaving |
| PV size | 4.15 MWp | Energy arbitrage | |
| Storage size (power) | 5.4 MW | Government subsidies | ✓ |
| Storage size (capacity) | 5.9 MWh | Power Purchase Agreements | ✓ |
| Storage technology | 3 Sunny Central Storage battery grid forming inverters, Samsung Lithium-Ion NCM batteries | | |

FIGURE 20 ST. EUSTATIUS PLANT DAILY ENERGY GENERATION. FUEL SAVE CONTROLLER "DIESEL OFF MODE" DAYTIME WITHOUT DIESEL




Source: SMA.

The pilot plant is used to for system tests, which comprise first and foremost energy-shifting and reducing the imbalance between predicted and actual production.

# ANNEX 2 – ESSENTIAL RELIABILITY SERVICES BY UTILITY-SCALE SOLAR PV POWER PLANTS

In 2016 the California Independent System Operator (CAISO), First Solar, and the National Renewable Energy Laboratory (NREL) conducted a demonstration project on a 300 MW large utility-scale photovoltaic (PV) power plant in California to test its ability to provide essential ancillary services to the electric grid. The 300 MW plant was designed and constructed by First Solar. A key component of this PV power plant is the plant-level controller (PPC) developed by First Solar. It is designed to regulate real and reactive power output from the PV power plant so that it behaves as a single large generator.

The aerial photo of the plant using First Solar advanced thin film Cadmium-Telluride (Cd-Te) PV modules is shown in in Fig. 21.

The plant PPC is capable of providing the following plant-level control functions:

- Dynamic voltage and/or power factor regulation, and closed loop VAR control of the solar power plant at the point of interconnection (POI);
- Real power output curtailment of the solar power plant when required so that it does not exceed an operator-specified limit;
- Ramp-rate controls to ensure that the plant output does not ramp up or down faster than a specified ramp-rate limit, to the extent possible;
- Frequency control (governor-type response) to lower plant output in case of an over-frequency situation or increase plant output (if possible) in case of an under-frequency situation; and,
- Start-up and shutdown control.

The PPC implements plant-level logic and closed-loop control schemes with real-time commands to the inverters to achieve fast and reliable regulation of active and reactive power. The commands to the PPC can be provided through the SCADA human-machine interface or even through other interface equipment, such as a substation remote terminal unit.

Fig. 22 illustrates a general block diagram overview of the plant control system[11] and its interfaces to other devices in the plant. The PPC monitors system-level measurements and determines the desired operating conditions of various plant devices to meet the specified targets.

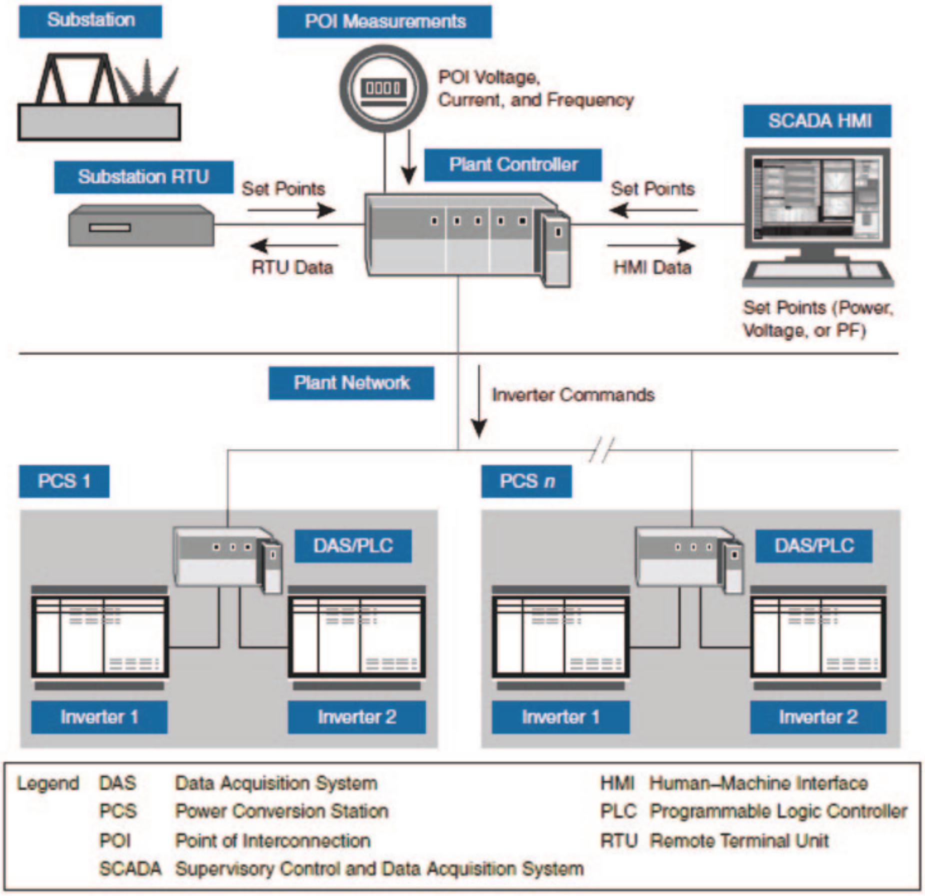
FIGURE 21 AERIAL PHOTO OF 300 MW PV POWER PLANT

Source: First Solar.



11 M. Morjaria, D. Anichkov, V. Chadliev, and S. Soni. "A Grid-Friendly Plant." IEEE Power and Energy Magazine May/June (2014).

FIGURE 22 GENERAL DIAGRAM OF PPC CONTROLS AND INTERFACES



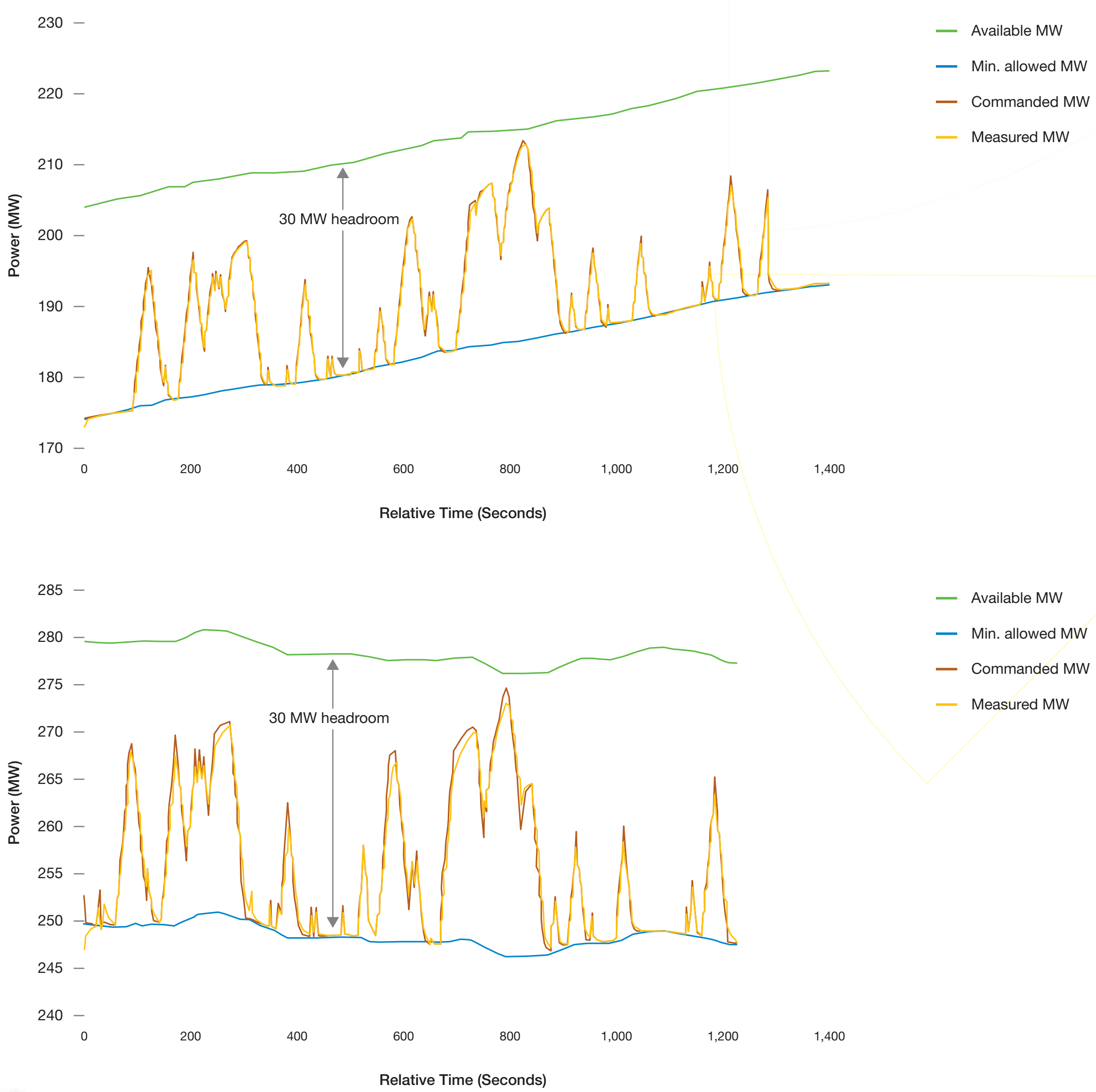

Source: NREL.

### AGC Participation Test

The purpose of the Automatic Generation Control (AGC) tests is to show the power plant capability to respond to new active power points set that is typically provided by transmission operators in order to support grid frequency. When in AGC mode, the PPC initially set the plant to operate at a power level that was 30 MW lower than the estimated available peak power to have headroom for following the up-regulation AGC signal.

The AGC tests were conducted across three different solar conditions: sunrise, middle of the day and during sunset. Examples of AGC test results for sunrise and middle of the day are shown in Fig. 23. Each test was conducted by using historical 4-second AGC signals provided by CAISO just like it would be done for any other generator of the same size. The historical AGC signal provided by CAISO had a regulation range of 30 MW, or 10% of rated power.[12]

FIGURE 23 SUNRISE AGC TEST (LEFT), AND MIDDAY AGC TEST (RIGHT)




Source: NREL.

12 C. Loutan, M. Morjaria, V. Gevorgian, et al. "Demonstration of Essential Reliability Services by a 300-MW PV Power Plant", NREL report, March 2015, https://www.nrel.gov/docs/fy17osti/67799.pdf

The test started when the plant was commanded to curtail its production to a lower level (orange trace), which was 30 MW below its available peak power (green trace). The AGC signal was then fed to the PPC (red trace), so the plant output (yellow trace) was changing accordingly. The AGC response demonstrated excellent AGC performance by following the set point during this period of smooth power production.

Normally, CAISO measures the accuracy of a resource's response to energy management system (EMS) signals during 15-minute intervals by calculating the ratio between the sum of the total 4-second set point deviations and the sum of the AGC set points. The plant's monitored delayed response time and the accuracy of the plant's response to the regulation set point changes were used to calculate its regulation accuracy values, which are shown in Fig. 24.[13] By comparing the PV plant testing results from other resource technologies in CAISO, a conclusion can be made that regulation accuracy by the PV plant is 24–30 points better than fast gas turbine technologies.

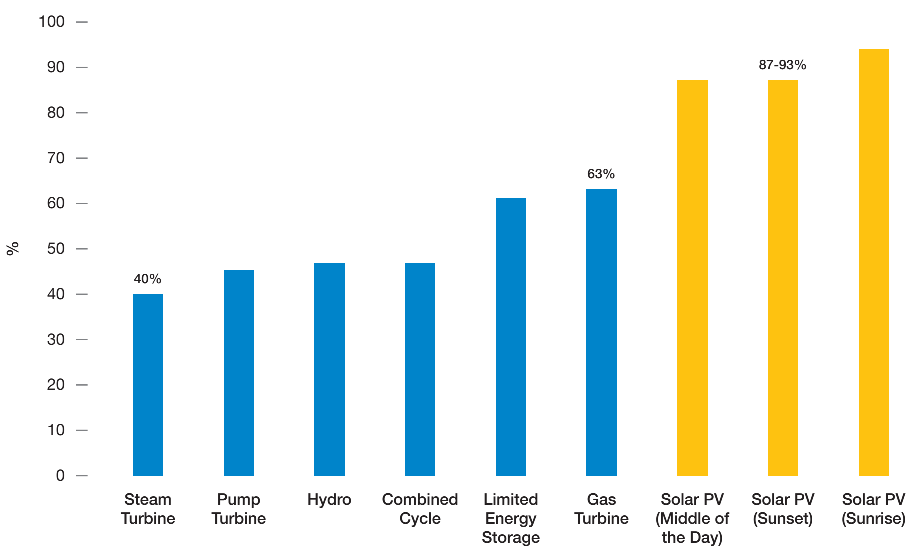
**Frequency Droop Control tests**

The ability of a power system to maintain its electrical frequency within a safe range is crucial for stability and reliability. Frequency response is a measure of an interconnection's ability to stabilize the frequency immediately following the sudden loss of generation or load. An interconnected power system must have adequate resources to respond to a variety of contingency events to ensure rapid restoration of the balance between generation and load. The objective of the frequency response test conducted under this project was to demonstrate that the plant can provide a response in accordance with 5% and 3% droop settings through its governor-like control system.

Example results of one 3% droop test during the morning hours are shown in Fig. 25. The plant's active power response in MW to the underfrequency event was measured by the phasor measurement units at the plant's POI (Fig. 25, left). The droop response of the plant can be observed on the X-Y plot shown in Fig. 25 (right) wherein a linear dependence between frequency and measured power can be observed once the frequency deviation exceeded the deadband.

Similarly, 3% and 5% droop tests were conducted during midday (peak solar production period) and during the afternoon for both under-frequency and over-frequency events.

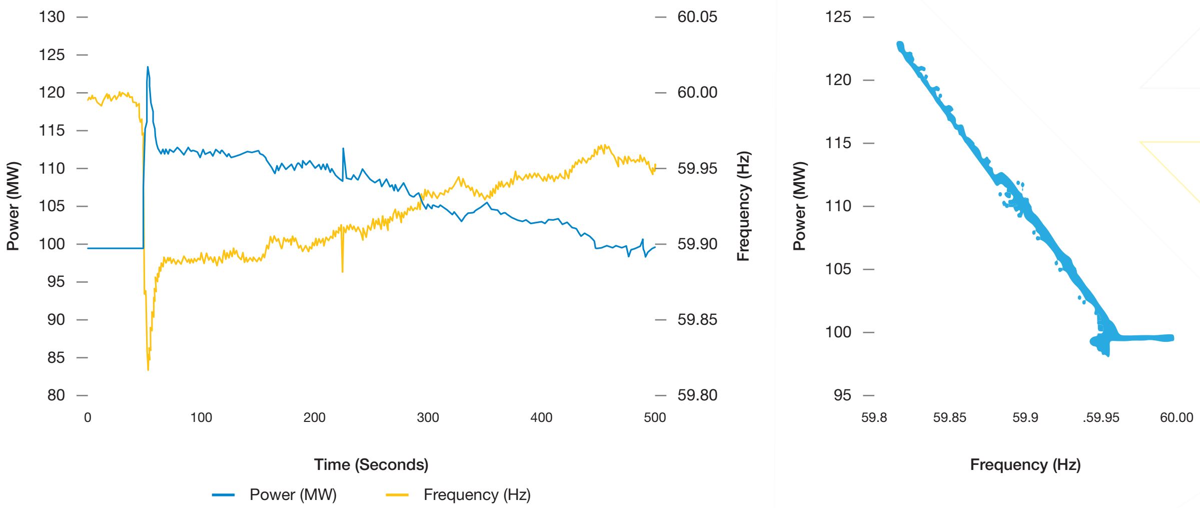
FIGURE 24 REGULATION ACCURACY BY PV PLANT IS ABOUT 24-30% POINTS BETTER THAN FAST GAS TURBINES




Source: First Solar.

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

FIGURE 25 EXAMPLE OF THE PLANT'S RESPONSE TO AN UNDER-FREQUENCY EVENT (3% DROOP TEST DURING SUNRISE)



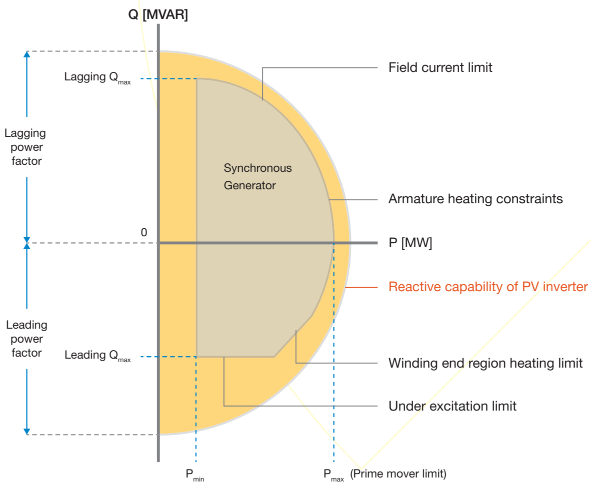

Source: NREL.

### Voltage Control Tests

Grid voltage is normally regulated by generator operators, which are typically provided with voltage schedules by transmission operators.[14] The growing level of penetration of variable wind and solar generation has led to the need for them to contribute to power system voltage and reactive regulation because in the past, the bulk system voltage regulation was provided almost exclusively by synchronous generators. In its proposed reactive power capability characteristics for asynchronous generation, CAISO defined the requirements for dynamic and continuous reactive power performance by such resources.[15] **The primary objective of the reactive power test was to demonstrate the capability of the PV plant to operate in voltage regulation mode within the power factor range of 0.95 leading/lagging.**

Conventional synchronous generators have reactive power capability that is typically described as the "D curve", as shown in Fig. 26. The reactive power capability of conventional power plants is limited by many factors including their maximum and minimum load capability, thermal limitations due to rotor and stator current carrying capacities, and stability limits. The ability to provide reactive power at zero load is usually not possible with many large plant designs. The reactive power capability of a PV inverter is determined by its current limit only. With proper MW and MVA ratings, the inverter should be able to operate at full current with reactive power capability similar to the yellow area shown in Fig. 26.

FIGURE 26 COMPARISON OF REACTIVE POWER CAPABILITY FOR SYNCHRONOUS GENERATOR AND PV INVERTER OF SAME MVA AND MW RATINGS



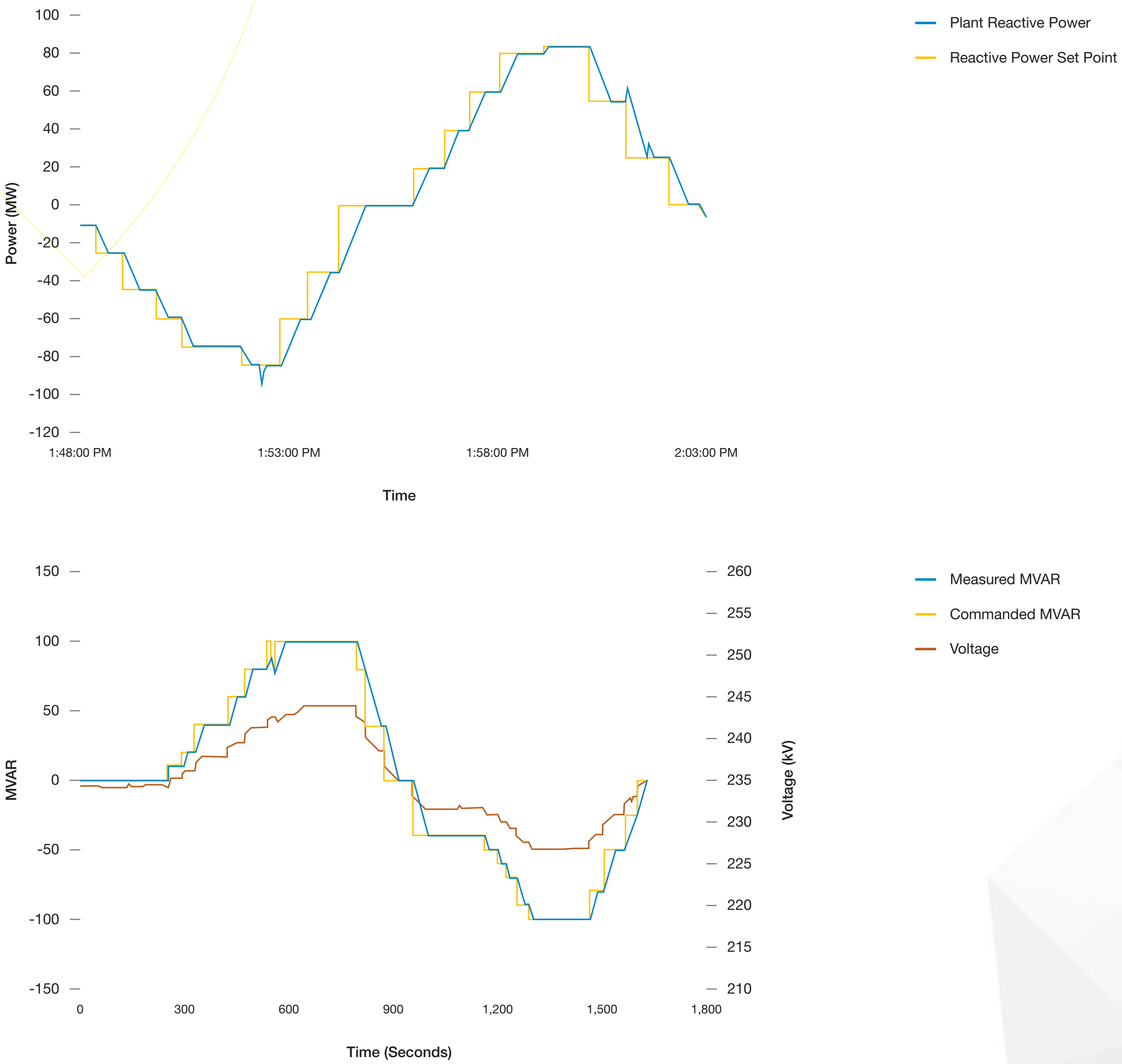

Source: NREL.

14 NERC, Balancing and Frequency Control (Technical Report) (Atlanta, GA: January 2011).

15 CAISO, Reactive Power and Financial Compensation: Draft Final Proposal (Folsom, CA: November 2015).

The PPC has the ability to maintain the specified voltage set point at the high side of the generator step-up bank by regulating the reactive power produced by the inverters. Tests were conducted at three different real power output levels: (1) maximum production during the middle of the day, (2) during sunset when the plant is at approximately 50% of its maximum capability, and (3) during sunset when the plant is close to zero production. Measurements were conducted to verify the plant's capability to absorb and produce reactive power, within a range of ±100 MVAR during various levels of real power output. First, the plant's reactive power capability was measured during a number of tests when the plant was producing high levels of active power (250 MW and more). Then the reactive power capability was measured at extremely low levels of MW production (less than 5 MW). The results of both tests are shown in Fig. 27.

FIGURE 27 REACTIVE POWER CONTROL TEST (TOP) & REACTIVE POWER CONTROL TEST WITH PLANT CURTAILED DOWN TO 5 MW OUTPUT LEVEL (BOTTOM)




Source: NREL.

### Active power curtailment tests

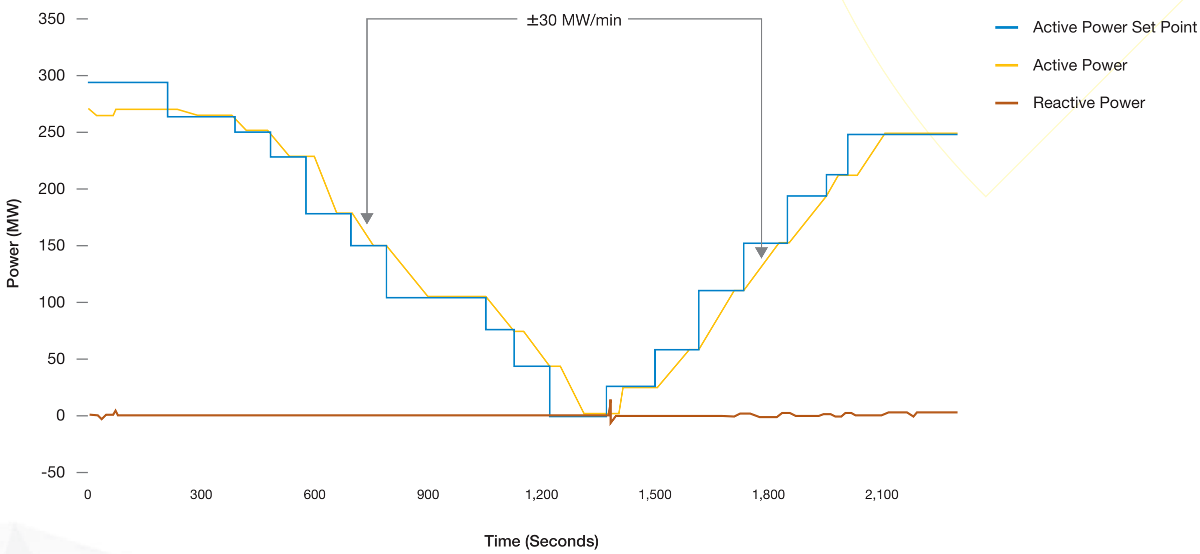
The curtailment control test was conducted to demonstrate the plant's ability to limit its active power production and then restore it to any desired level. The results of the test are shown in Fig. 26. The plant accurately followed the active power set point from nearly full production level to zero level with a pre-set ramp rate of 30 MW/min (however it can be reconfigured for any ramping rate on the request of a system operator). The plant's active power was then commanded to increase in accordance to increasing set points. It is important to note that the reactive power of the plant remains unchanged at nearly zero MVAR for the whole range of active power levels. This is an indicator of the capability to independently control active and reactive power by PV inverters. The curtailment control test also demonstrates that PV generation can also provide additional ancillary services in the form of spinning reserves. According to the CAISO's definitions, spinning reserve is a standby capacity from generation units already connected or synchronized to the grid and that can deliver their energy in 10 minutes when dispatched. With a demonstrated 30 MW/min ramp rate capability, the PV plant under test is capable of deploying 300 MW of spinning reserve in just 10 minutes for some hypothetical case of full curtailment.

### Conclusions

- Solar PV generating plants can provide a wide range of essential reliability services. Tests conducted on a grid-connected 300 MW project showed fast and accurate PV plant response to AGC, frequency, voltage, power factor, and reactive power signals under a variety of solar conditions.
- Advancements in advanced inverter technology combined with advanced plant controls allow solar PV resources to provide regulation, voltage support, and frequency response during various modes of operations.
- Solar PV resources with these advanced grid-friendly capabilities have unique operating characteristics that can enhance system reliability by providing:
  - Essential reliability services
  - Voltage support (even when the plant's output is near zero)
  - Fast frequency response (inertia response timeframe)
  - Frequency response for low as well as high frequency events

This functionality is inherent in utility-scale PV power plants today and should be recognized and encouraged by grid operators in Europe.

FIGURE 28 ACTIVE POWER CURTAILMENT TEST




Source: NREL.

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