Photovoltaic plus Storage – Part 1, Technology

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1. Introduction

"Everything passes, but nothing entirely goes away."

— Jenny Diski, English writer

And such are the subjects I write about, but occasionally I need to be reminded how long it has been since I wrote about something. If I were writing about the fall of the Roman Empire or the latest anvil technology, I could wait a few decades for a new update. But I write about several technologies that are moving at the speed of light.

A reader asked me a question recently, and the answer (that included the link below) reminded me that it had been about six months since I have posted a good paper on the titled technologies, and this was mainly on the latter. Then I checked on-line to see what transpired since then, and was not totally surprised to see the answer was "lots", thus this paper.

https://www.energycentral.com/c/cp/large-battery-energy-storage-systems

There was so much new information that this "paper" ended up being a two-part series. Part 1 of this paper is on new technologies for utility-scale PV, utility-scale storage, PV plus storage systems, and the evolution of their missions. Part 2 will describe recent major U.S. PV plus storage projects and new twists on residential PV plus storage.

2. Developments

2.1. Utility-Scale PV

Even though current (silicon-based) photovoltaics (PVs) are a mature technology, prices continue to come down rapidly. In a utility-scale projects there are four or five major subsystems: PV panels, power electronics, mounting/tracking systems, protective systems and control systems. Each of these continue to make incremental improvements, and as volumes increase with time, manufacturing efficiency increases and prices continue to decline rapidly.

The figure at the top of the next page is most recent thorough cost breakdown for utility-scale PV projects.[1] Note that the X-axis is for different sized projects.

2.1.1. PV Panels:

There are two emerging technologies: PERC and bifacial. These are each explained below, and, yes they can be combined on the same panel. Each of these work in a different way to increase the efficiency of each panel. PERC operates through the way light is processed inside each cell, and bifacial actually captures light from the front of the panel and the back of the panel.

[1] Ran Fu et al, NREL, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017", Technical Report NREL/TP-6A20-68925, September 2017, https://www.nrel.gov/docs/fy17osti/68925.pdf

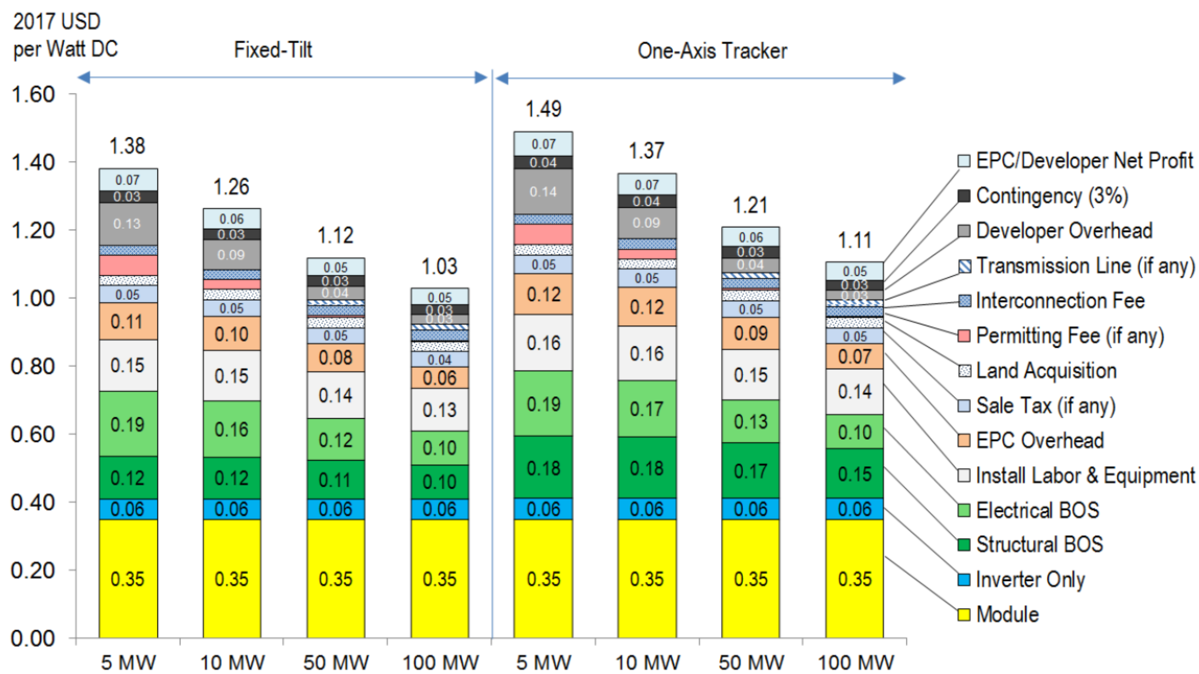
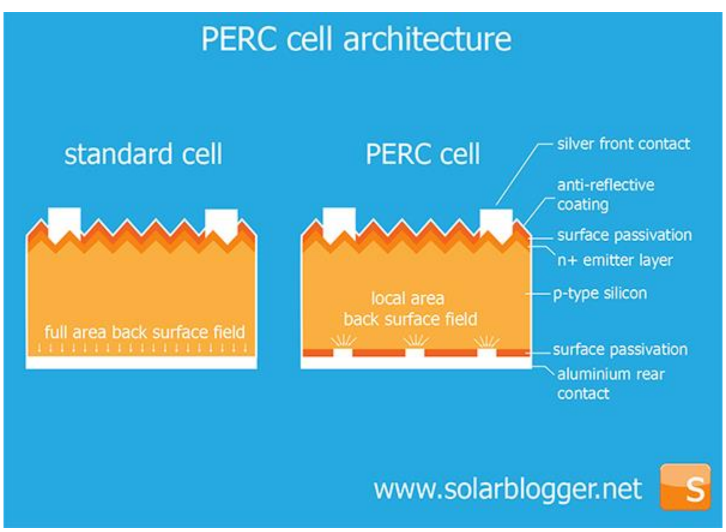


Figure 28. Q1 2017 U.S. benchmark: utility-scale PV total cost (EPC + developer), 2017 USD/Wdc[25]

PERC: stands for Passivated Emitter Rear Cell. The description of how these cells work is primarily from the source referenced at the end of this sentence with some edits by me.[2]

The production of a PERC solar cell requires two additional steps vs. a conventional silicon solar cell: first, a rear passivation film is applied. Then, either lasers or chemicals are used to open up tiny pockets in the film through which the rear conducting layer can contact the silicon above the passivation layer. The figure below compares the configurations of conventional and PERC PV cells.



[2] Dr. K.T. Tan, Technical Director at Viridian Solar, The Solar Blogger, "What is a PERC Solar Cell?", April 6, 2017, http://www.solarblogger.net/2017/04/what-is-perc-solar-cell.html

The above technique enables the efficiency of the solar cell to be improved in three ways:

By minimizing surface recombination: The atoms at the surface of a silicon wafer have 'dangling bonds' which can capture charge-carrying electrons and pull them back into the silicon crystal structure (a process called surface recombination). As a result, when an electron reaches the back surface of a conventional solar cell, it is likely to be captured and does not contribute to the cell's current. However in a PERC solar cell, a passivated film is grown on the back surface of the solar cell and reduces this effect by tying up the 'dangling bonds'. A charge carrying electron that strays too close to the back surface is allowed to continue on its way and there is a chance it will reach the emitter and contribute to the electric current produced by the solar cell.

Longer wavelengths (red light) generate electrons near the back surface, compared to shorter wavelengths (blue light). Since the PERC solar cell helps prevent surface recombination, it will still be able to capture these wavelengths. This capability increases the solar cell performance during early mornings and late afternoons when longer wavelengths are present, which leads to the claims of better weak light performance by many manufacturers.

By Increasing Internal Reflectivity to Capture More Light: The rear film reflects the light that passes through the solar cell without being absorbed. This provides the light with more opportunity for a second absorption attempt. In other words, the efficiency of energy conversion is higher.

By Reflecting Counter-productive Wavelengths: Generally, silicon solar cells stop absorbing light-wavelengths above 1180 nm, instead they are absorbed by the backside metallization layer and tuned into heat. The rear passivated film reflects these counter-productive wavelengths out of the solar cell and hence maintains cooler temperatures. As a result, PERC solar cells are considered to have better heat resistance.

All of the above, if manufactured correctly, will undoubtedly increase the solar cell efficiency. The current commercially available PERC solar cells have efficiencies in excess of 20% with a record efficiency of nearly 23%.

The main attraction to this technology is that PERC production requires minimum modifications to existing solar cell manufacturing lines. The existing lines can easily be upgraded to produce PERC solar cells without having to invest in large capital expenditures or completely overhaul the entire lines. Thus a firm can increase the solar cell efficiency without having to take huge financial risks.

In 2019 41% of global module manufacturing capacity will be dedicated to monocrystalline PERC production, up from 36% in 2018, 25% in 2017 and just 15% in 2016.

Bifacial: Conventional PV panels are monofacial, meaning that their electrical power output is a function of the direct and diffuse radiation captured on the front side of the module only. By contrast, bifacial modules convert light captured on both the front and back sides of the panels into electrical power. Bifacial design improves PV system energy capture—dramatically in some cases—and rewrites conventional system design rules in interesting ways.[3]

"Today's thin-film monofacial PV cells commonly use a fully metallized backside. This feature involves a moderately thick metal contact for reduced series resistance and is relatively inexpensive to produce. By contrast, bifacial cells incorporate selective-area metallization schemes to allow light between the metallized areas. The lower amount of metal changes how cell performance is optimized, potentially requiring tighter (i.e., more expensive) specs on the silicon and thin-film material used and also increasing series resistance concerns. Furthermore, bifacial cells may employ different metals, such as copper and nickel, and/or deposition methods, such as plating or inkjet printing, which, in part, requires different equipment and entails a potentially more complex manufacturing process. Consequently, the backside metal represents a non-trivial impediment to manufacturing bifacial cells with high performance and low cost. This added complexity and cost needs to be offset by the performance gain from increased light collection."[4]

So bifacial panels are significantly more expensive than conventional or PERC monocrystalline PV Panels. In order to offset this they offer the following performance advantages: In the proper application (specially the physical configuration) they offer improved light collection and a corresponding increased output (in the 5% to 30% range). This results in corresponding reductions in the balance of system (BOS) costs, especially in mounting systems.

Bifacial panels also offer improved durability. This comes from the fact that most bifacial panels use a glass-on-glass design (glass on both the front and back of each panel). This design makes the panels more rigid (less damage in shipping and installation) and seals out contaminants better. Also many of these panel designs incorporate frameless designs with no aluminum frames. This reduces opportunities for potential-induced degradation.[5]

The difference in design approach for a ground-mount bifacial system mainly focuses on getting as much light as possible to the back of the panel. This mainly includes using a light-colored ground-cover under the arrays and designing the mounting system to minimize shading (while making sure the front of the panels receive optimum insolation).

Currently bifacial project installations are at less than 10% of overall PV installations. The first bifacial PERC designs are just starting to be deployed now. In order to drive down the manufacturing costs, the volume needs to increase. Bifacial panels higher cost make this tough, but not impossible. High land cost might accelerate bifacial deployments (also see the next subsection for other technologies that solve land-cost issues).

[3] David Brearley, Solar Pro, "Bifacial PV Systems", April, 2017, https://solarprofessional.com/articles/design-installation/bifacial-pv-systems?v=disable_pagination&nopaging=1#.XFog4KYm6Uk
[4] EPRI Report on Bifacial Solar Photovoltaic Modules, September, 2016, https://www.epri.com/#/pages/product/000000003002009163/?lang=en-US
[5] PV Manufacturing.org, "Potential Induced Degradation", https://pv-manufacturing.org/potential-induced-degradation/

2.1.2. Mounting Systems

Mounting systems (a.k.a. racking systems, including trackers) for utility-scale projects are generally the second highest cost components in a project ("Mechanical BOS" in the above Benchmark Chart). These costs have dropped by approximately 50% between 2013 and 2017 (see reference 1) and will continue to drop, driven by economy of scale and design improvements.

We will look at two new trends in utility-scale mounting systems: floating PV mounting systems and high PV mounting systems that allow other land-use under the PV panels.

Floating PV Mounting Systems: Floating PV Systems were developed in the U.S., with the first system deployed on an irrigation pond in Napa Valley, California. However, this concept has not really taken off in the U.S., but it has elsewhere. In the U.S. there are only seven floating PV projects, but world-wide there are over 100. A large majority of these are in Asia, where the cost of land is sometimes very expensive, with many also found in Europe.[6]

Floating PV systems are most applicable for areas where the cost of land is high, but they also have benefits for the small bodies of water where they might be deployed, including reduced evaporation, and reduced algae formation.

High PV Mounting Systems: These are most commonly used for solar parking lot covers (a.k.a. solar carports, solar canopies). About 80% of current utility-scale projects use single-axes trackers. Are solar parking lot covers available with this, or are they all fixed-tilt? After much searching, I found that Sunpower appears to offer this feature, but just barely (little information available on this design).

There is an emerging class of PV projects that that use high-mount systems, dual-use solar installations that are sometimes called agrivoltaics. These are photovoltaic arrays that are raised far enough off the ground and spaced in such a way that some crops can still grow around and beneath the panels. The goal is to help farmers diversify their income through renewable energy generation, while keeping land in agricultural use and reducing greenhouse gas emissions.

There are a few demonstration projects in Asia, Europe, and the U.S. Massachusetts seems to be taking the lead with these installations. They have high land-values, strong renewable power goals and also would like to increase the percentage of food-crops that are consumed and produced in-state.[7]

The author has also seen a large high-mount PV arrays (with trackers) poking up in the spaces between nut tree orchards in the California's Central Valley (Stanislaus County, just east of Livermore where I live). These use Panelized Solar assemblies[8]. See the figure below, but note that the assemblies shown in this picture are not as highly elevated as the ones that I've seen.

[6] NREL, News Release: NREL Details Great Potential for Floating PV Systems, December 27, 2018, https://www.nrel.gov/news/press/2018/nrel-details-great-potential-for-floating-pv-systems.html

[7] Sarah Shemkus, Salon, "Agrivoltaics: Solar Panels on farms could be a win-win", February 9, 2019, https://www.salon.com/2019/02/09/agrivoltaics-solar-panels-on-farms-could-be-a-win-win_partner/

[8] http://www.panelizedsolar.com/index.html

There are three other applications for high-mount systems listed below.

- Solar shading canopies for outdoor areas (like large patios)
- Elevating solar arrays above ground clutter like buildings or trees
- Elevating solar arrays above equipment on flat-roof buildings

2.1.3. Inverters

Inverters are part of a larger class of apparatus: power electronics, and these are based on semiconductor components. As such they benefit from Moore's Law. Although this is normally applied to microprocessors, and similar components that are produced by the billions, power electronic components are only produced by the millions. However, given the growth-curve of PV and battery-based power systems (next section), this only means that they are much lower on the Moore's Law curve than microelectronics and will continue to become less expensive for decades. For the record (based on reference 1), Inverters costs decreased by about half between 2013 and 2017. Also see comments about increasing volume in the next section, since utility-scale storage (and their close relatives, electrified mobility) are also growing exponentially and use power electronics.

2.2. Utility-Scale Storage

A stand-alone battery energy storage system (BESS) includes batteries, power electronics, enclosure (including cooling), protective systems and control systems. Also, BESS have made incremental improvements, but the main factor driving down costs are the cost of the batteries. The cost of lithium-ion (LiIon) batteries has dropped “about 90 percent” in recent years, says Garrett Fitzgerald, manager in the Mobility Transformation Project for the Colorado-based Rocky Mountain Institute. Prices that had been as high as $1,000 a kilowatt-hour (kWh) are now “sub $200/kWh,” and falling.[9] This rapid decline is mainly caused by a similar rapid increase in electric vehicle (EV) volumes.

Although LiIon batteries for EVs typically use different chemistry and protective systems than those used for BESS, their configuration and materials are basically the same. Thus the economies of scale of EVs and BESS are largely additive. And what is their scale? The U.S. deployed 61.3 MW of storage overall during Q3 2018, a 44% increase over Q3 2017, according to S&P Global Market Intelligence. The pipeline of orders predicts annual additions of approximately 660 MW in 2019, 1,700 MW in 2020 and over 3,850 MW by 2023.[10]

Recent history for U.S. EV sales (battery electric vehicles (BEV) plus plug-in hybrids) is 2018: 361,307 vehicles, 2017: 199,826 vehicles, 2016: 158,614 vehicles and 2015: 116,090 vehicles.[11] So far Tesla, Chevrolet and Nissan are the only volume BEV manufacturers offering these in the U.S. Their production in 2018, respectively was approximately 200,000 BEVs, 18,000 BEVs and 15,000 BEVs, The only recent new market entrant is Jaguar (I-Pace SUV) which entered the U.S. Market in late 2018, and to date they have only produced about 600 BEVs.

The bottom line is that EV growth going forward will be primarily dependent on Tesla (who has done a pretty good job so far) until 2021 and 2022, when VW will (hopefully) enter the market, complete a U.S. plant and start cranking out reasonably-priced vehicles. I expect more EVs from Ford and Chevrolet by then also, and the Koreans (Kia and Hyundai) probably will crank up their volume by then.

Then there are the plug-in hybrids whose range is inching up. The only models with 2018 sales over 10,000 vehicles were Prius Prime (27,600), Honda Clarity PHEV (18,600) and Chevy Volt (18,300). The latter will cease production this March.[12]

Regarding power electronics used for BESS see the above comment in section 2.1.3. Also, power electronics are used in EV Supply Equipment (chargers) which are expanding at the same rate as EVs.

2.3. Integrated PV and Storage

More than 55 percent of annual energy storage deployments are expected to be paired with solar by 2023. As the market expands and evolves, system architecture will become an important consideration when developing solar-plus-storage projects.[13]

[9] David C Wagman, IEEE Spectrum, "Arizona Utility Opts for Solar and Storage to Meet Peak Demand", 5 Mar, 2018, https://spectrum.ieee.org/energywise/energy/renewables/arizona-utility-opts-for-solar-and-storage-to-meet-peak-summer-demand

[10] Herman K. Trabish, Utility Dive, " As solar-plus-storage surges, can smart devices help overcome deployment barriers?", Jan 29, 2019, https://www.utilitydive.com/news/deployment-barriers-remain-as-solar-plus-storage-forecast-to-continue-growt/546930/

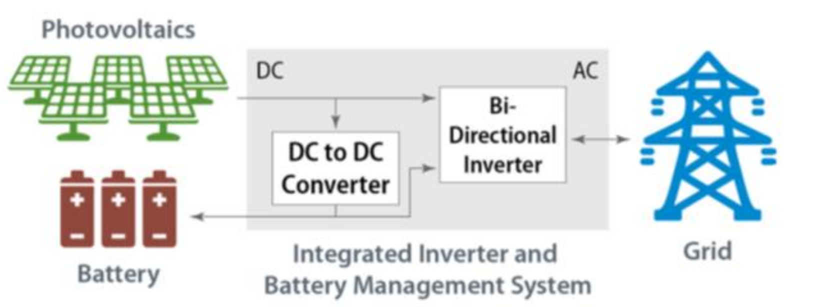
[11] Inside EVs Monthly Plug-In EV Sales Scorecard, https://insideevs.com/monthly-plug-in-sales-scorecard/

[12] Eric Loveday, Inside EVs, "UPDATE: GM To Shut Down Chevy Volt Factory: Volt Confirmed Dead", Nov 26, 2018, https://insideevs.com/general-motors-shut-down-chevy-volt-factory/

[13] Mitalee Gupta, Greentech Media, "DC-Coupled Solar-Plus-Storage Systems Are Gaining Ground", February 12, 2019, https://www.greentechmedia.com/articles/read/dc-coupled-solar-plus-storage-gaining-ground?utm_medium=email&utm_source=Storage&utm_campaign=GTMStorage#gs.8AIvgoJR

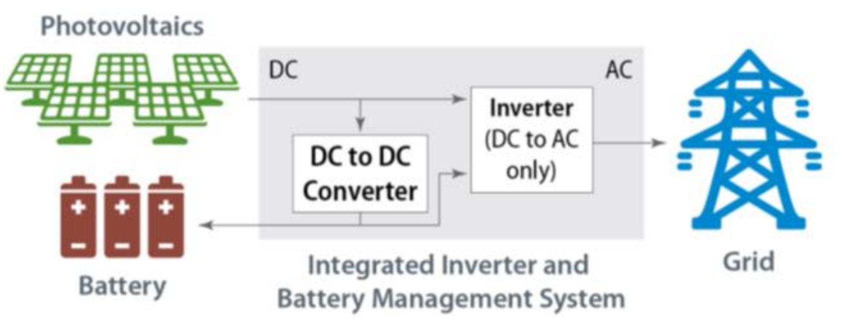
There are any number of ways of integrating PV and storage. Below we will just explore two variants of tightly-integrated systems that are generally implemented as a single project.

In the figure below, the two subsystems are DC-coupled, and the storage can either charge from the PV or the grid.[14]



The DC coupling provides increased efficiency, and the grid charging provides more mission flexibility.

A similar design (figure below) limits the inverter to DC to AC only, which precludes grid-charging of the BESS. Depending on the specifics of the mission of a given project, the cost savings from a simpler inverter design may or may not be offset by the potentially greater revenue that might arise from more flexible charging. Regarding commercial and industrial (behind the meter) systems see the CPUC staff proposal reference in Part 2 of this series, section 3.



Both of the above configurations only have a single connection point to the grid. Depending on the size of the system, interconnection costs can make up anywhere from 20 to 35 percent of the balance-of-systems cost stack, and just having single point of interconnection reduces these costs (see chart in section 2.1).

This single point of interconnection in a DC-coupled system also makes it economically viable to oversize the PV system and store excess generation in batteries, thus supporting cost-effective time-shifting of excess solar.

[14] Paul Denholm, Josh Eichman, and Robert Margolis; National Renewable Energy Laboratory, "Evaluating the Technical and Economic Performance of PV Plus Storage Power Plants", NREL/TP-6A20-68737, August 2017, https://www.nrel.gov/docs/fy17osti/68737.pdf

2.4. Missions

Battery energy storage systems (BESS) are superbly suited to frequency regulation at the ISO level if implemented properly. PJM was a pioneer in implementing this mission, and (of course) first had to learn how not to do it.

In 2012, PJM's ancillary services market introduced a frequency regulation product designed to compensate generation resources that can quickly adjust power output but the initially implemented systems were limited by the time they can sustain that output.[15]

Since then, utility-scale battery storage capacity in PJM has increased from 38 MW in 2012 to 274 MW in 2016. More than 90% of this region's installed battery capacity assists with frequency regulation. Utility-scale battery storage installations in PJM tend to have relatively large power capacities, averaging 12 MW, and short discharge durations, averaging 45 minutes.

As PJM introduced battery use into its market system, PJM experienced operational issues in its frequency regulation market. Battery storage systems could not sustain output through the daily periods when electricity demand quickly increases. During these periods, battery systems were quickly switching to charging mode, accelerating the increase in electricity demand.

To address this issue, PJM changed its regulation signals in January 2017. However, following these new signals requires battery systems to charge and discharge twice as often, which shortens their expected lifetime. PJM's changes to its regulation signals are the subject of pending complaints filed with the Federal Energy Regulatory Commission (FERC) by the Energy Storage Association and two storage project developers.

In 2013, the California Public Utilities Commission (CPUC) set an energy storage mandate (in response to AB 2514) requiring the state's regulated utilities to procure 1,325 MW of energy storage capacity by 2020. As of early August 2018, California's three largest IOUs have procured or are seeking approval to procure almost 1,500 megawatts (MW) of energy storage related to AB 2514 requirements.[16]

CPUC requires generation resources to provide at least four hours of output to contribute to reliability requirements. As a result, utility-scale battery storage installations in California tend to have small power capacities, and long discharge durations, averaging slightly less than 4 hours. Installations in California also tend to serve a wider array of applications than those in PJM because many have been procured by regulated utilities to serve multiple applications.

Brattle economists released a 2018 study (referenced below) examining the current state and potential future growth of the U.S. market for electricity storage. The study finds that storage market potential could grow to 50,000 MW over the next decade if storage costs continue to decline and state regulatory policies build on the recently-

[15] DOE-EIA, "The design and application of utility-scale battery storage varies by region", Feb 28, 2018, https://www.eia.gov/todayinenergy/detail.php?id=35132
[16] California Energy Commission – Tracking Progress, Energy Storage, Aug 2018, https://www.energy.ca.gov/renewables/tracking_progress/documents/energy_storage.pdf

issued FERC Order 841 to remove barriers that prevent storage resources from realizing multiple value streams.[17]

The Brattle study estimates that at least half of the total value that storage can provide would be achievable in wholesale electricity markets, with the remainder accruing at the transmission and distribution (T&D) and customer level. FERC's order is an important step in unlocking the value in wholesale energy, ancillary services, and capacity markets. However, to fully realize the value of electricity storage, including benefits related to reduced T&D costs and reduced customer outages, the FERC wholesale market reforms will have to be matched with similar efforts at the state regulatory level. The Brattle study shows that combining the FERC policy with state-level initiatives that enable storage to capture all available value streams will likely increase its market potential by three to five times compared to a future that limits storage to capturing only wholesale market benefits.

[17] The Brattle Group, " Brattle Study: FERC Order Sets Course for 50,000 MW U.S. Storage Market", Feb 200, 2018, http://www.brattle.com/news-and-knowledge/publications/getting-to-50-gw-the-role-of-ferc-order-841-rtos-states-and-utilities-in-unlocking-storages-potential