Business & Technology Surveillance

Optimizing Solar PV Plus Battery Storage

By Daniel Walsh, Dale Bradshaw, Alice Clamp and Kristen Russell

DECEMBER 2020

NRECA
America's Electric Cooperatives

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SUBJECT MATTER EXPERT ON THIS TOPIC

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This article is a product of the **Generation, Environment, and Carbon Work Group**

ARTICLE SNAPSHOT

WHAT HAS CHANGED IN THE INDUSTRY?

The cost for solar PV systems continues to decrease, such that now in many locations in the United States, utility solar PV levelized cost of electricity can compete with total operating costs for fossil generation. In addition, the installation of distributed solar PV for industrial and commercial customers is growing.

WHAT IS THE IMPACT ON ELECTRIC COOPERATIVES?

Solar PV is intermittent, not dispatchable, and not always coincident with electric cooperative peak loads. To a large degree, coincidence of solar generation with peak is driven by geographic location, including position within a time zone. The solar PV provides little power and energy during the morning and evening peak loads (with the magnitude of the non-coincidence depending on whether the solar PV panels are fixed or are single-axis tracking, facing to the south or west). Solar PV output is maximized during the middle of the day. Also, solar PV output is significantly impacted by the weather, smoke and cloud cover, and snow or ice events. As a result, the value can be significantly improved, optimized and maximized, if the solar PV can be stored.

WHAT DO COOPERATIVES NEED TO KNOW/DO ABOUT IT?

When evaluating the addition of solar PV in the future, electric cooperatives need to determine the optimal orientation of their fixed solar PV arrays (maximum energy is provided when facing south, and maximum power during the afternoon peaks is provided when facing southwest or west), or use single-axis tracking to always be optimally-oriented to the sun. Additional economic analysis of the axis tracking systems should be performed to determine if the extra cost will add sufficient value to the cooperative. The value of solar PV power and energy can be maximized by integration with battery energy storage to shift the solar PV power and energy to the morning and late afternoon. In addition, it can provide spinning reserve and frequency regulation as ancillary services. It also can provide additional dynamic voltage support. When the energy storage is DC-coupled to the solar PV inverter, the cost for the energy storage inverter is eliminated. Energy storage can capture energy lost/clipped by solar PV systems during the middle of the day when the solar PV system has a high DC-to-AC ratio, low voltage and low power; and energy lost in the morning, late afternoon, and due to cloud cover can also be captured.

Important Note:
As examples, this article briefly includes mention of some vendors currently offering battery energy storage platforms on the market. This is not an exhaustive list, and NRECA encourages co-ops to conduct their own due diligence to determine vendors and offerings that best meet their specific needs.

Introduction

One of the challenges affecting the electric industry is the increased penetration of renewables. The variability of renewable sources, such as wind and solar, complicates matching supply to demand in real time and causes dips and spikes in real power as well as voltage. However, one cooperative with solar reports that it sees no dips or spikes in voltage from its high penetration renewables. According to the co-op, reactive power can be quite steady, even when real power moves around because of clouds.

When dips and spikes in real power do occur, they result in the need for flexible operations of thermal plants, which can lead to many negative impacts.[1] Thermal plant cycling and operation at minimal load result in equipment damage, increased forced outage rates, reduced reliability, lower efficiency, and increased emissions.[2] The worst damage occurs if thermal plants have to shut down and perform a hot start-up on a daily basis, shut down and perform a warm start over a weekend or—the most damaging operation—shut down and perform a cold start. The total cost impact associated with increased operation and maintenance costs, loss of capacity reserve, and replacement energy purchases can range from $6/MWh to $13/MWh, as presented by Dale Bradshaw, expert consultant to NRECA, at an AREGC conference. In order for renewables to become more flexible, energy storage has been identified as a necessary component.

As battery technology costs decrease, solar-plus-storage systems are becoming more widespread. Whether it is at the utility level or commercial level, to get the most out of battery storage, it is important to consider multiple factors. Evaluating the system architecture, using smart unidirectional or bidirectional inverters, and having a battery recycling plan can boost the economics and lower the environmental impact of energy storage.

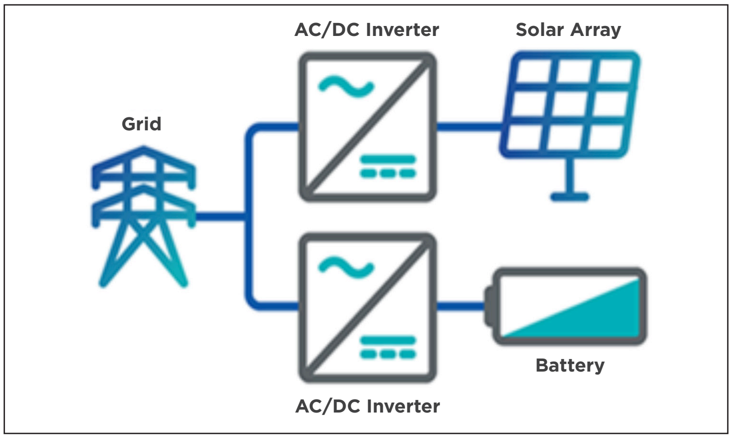

FIGURE 1: AC-coupled System[4]

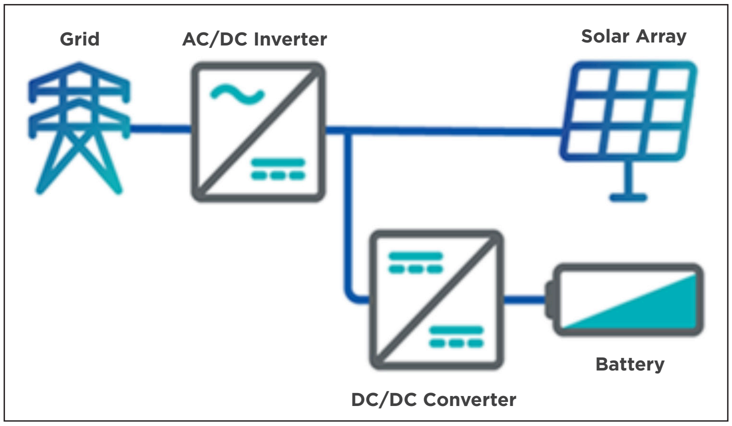

FIGURE 2: DC-coupled System[4]

Systems Configurations

There are two main configurations that developers can choose from to build a system that best meets their needs. The difference between these options is the coupling of the solar PV plus battery system: AC- vs DC-coupling. *Coupling* describes the way the solar energy connects to the utility grid or commercial circuit and the battery system.[3]

Solar panels produce direct current (DC) energy, and batteries store DC energy. However, the electrical grid, as well as a commercial main panel, uses alternating current (AC). AC- and DC-coupled systems differ based on whether DC energy is immediately turned into AC, or kept as DC until conversion to AC is needed. This is dictated by the arrangement of inverters, which are the devices that capture the DC power and convert it into usable AC power. Each unique system can be optimized to perform its targeted services by the number and types of inverters used.[4]

Figures 1 and 2 are diagrams of the AC-coupled versus DC-coupled system configurations.

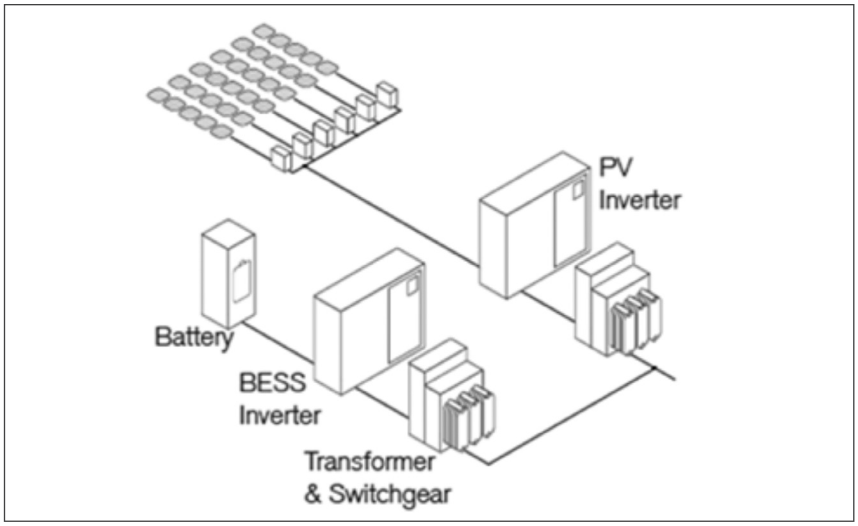

FIGURE 3: AC-coupled Utility System[6]

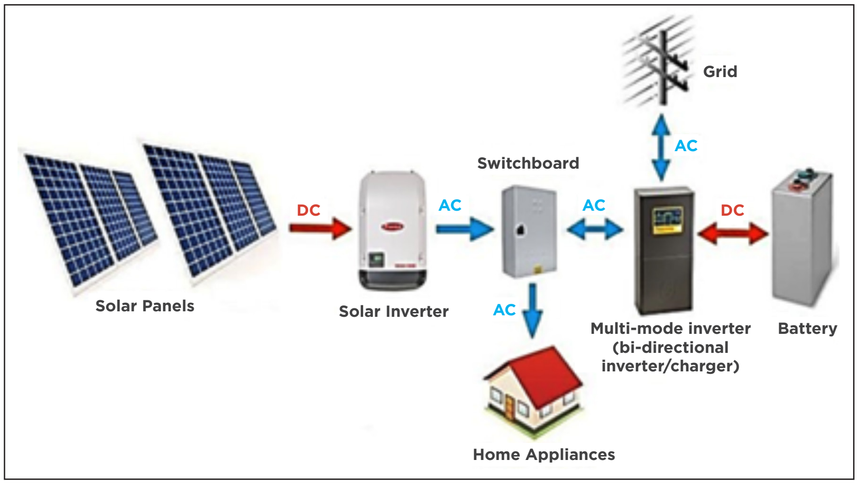

FIGURE 4: AC-coupled Residential System[7]

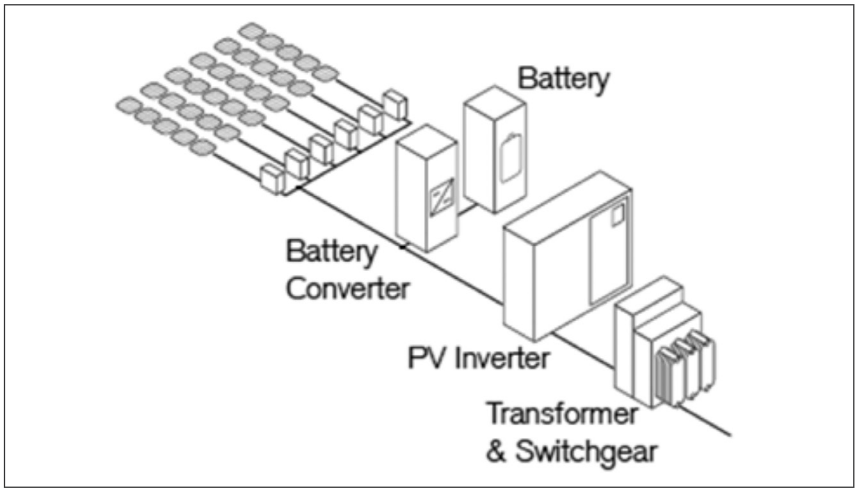

FIGURE 5: DC-coupled Residential System[7]

AC-Coupling

In an AC-coupled system, DC output from the solar array is instantly converted to AC through a solar inverter. On the other side of the system, the battery can receive AC energy from the solar array or the grid. It uses a bidirectional (also known as *multi-mode*) inverter that allows it to charge and discharge its DC energy with the grid. This has been the most common configuration for large-scale systems, due to its flexibility (see Figure 3). Some AC systems, such as ones produced by **Enphase**, use microinverters that are smaller inverters connected to each individual solar PV panel/module, converting the DC from the module to AC. This makes monitoring easier and is more reliable than centralized string inverters (a *string inverter* converts DC current and voltage from a string of solar PV panels hooked in series into AC), but can be costly to remove and replace. It is typically only seen on the residential level (see Figure 4) and is most likely going to be more expensive and slightly less efficient than string inverters.[5]

DC-Coupling

With a DC-coupled system, the solar arrays' DC output can directly charge the battery or transfer DC current through an inverter to create AC energy and power. In this type of system, the battery and solar array are both connected to one inverter. Since this inverter connects to both solar and storage, it is typically referred to as a *hybrid inverter*. There are hybrid inverters that can be bidirectional for the battery, or designed so that the solar array is the only energy source for the battery. The battery can also be connected to a DC-DC converter (also known as a *power optimizer*) to maximize the energy harvested from the photovoltaic (PV) system and to control the voltage.[8] Historically, this configuration has been used for small capacity power systems.[7] (See Figure 5 for an example of the configuration for a DC-coupled residential system.) With recent advancements in inverter technology, a number of companies are deploying new large-scale inverters for DC-coupled solar-plus-storage systems.

Evaluation: AC- vs. DC-Coupling

Utilities and developers must analyze the trade-offs between systems when adding storage to new or existing solar farms to find the highest net benefit. There are advantages to both AC- and DC-coupled solar-plus-storage systems, depending on the application. As more projects are deployed, more quantifiable economic analysis will need to be performed for each of these benefits. From a technological standpoint, AC-coupled batteries are better for adding to existing systems, while DC-coupled batteries added to solar PV provide more advantages, reducing capital costs for new energy storage plus solar PV projects by the energy storage and the solar PV sharing a common inverter.

AC-Coupling Advantages

FLEXIBILITY

Because the battery packs are not directly connected to the solar array in an AC-coupled system, there is a lot more flexibility with the battery location. In a utility-scale or commercial use case, it gives the owner more options for conveniently placing the battery around the utility-scale or commercial facility. For utility use, the batteries can be located outside the solar PV system and tied into the local grid to provide real and reactive power to compensate for the spikes and dips in real and reactive power caused by the variable generation of spacially distributed solar PV. This may possibly make maintenance work quicker and easier, but also allow the battery system to charge from the grid, as well as from solar when energy prices on the grid are low or negative. The battery can discharge when energy prices are high, while providing valuable ancillary services, like fast frequency regulation and spinning reserve.[9] If the joint project is benefitting from the solar tax credits, the owner should evaluate the intended use verses the IRS determinations carefully.

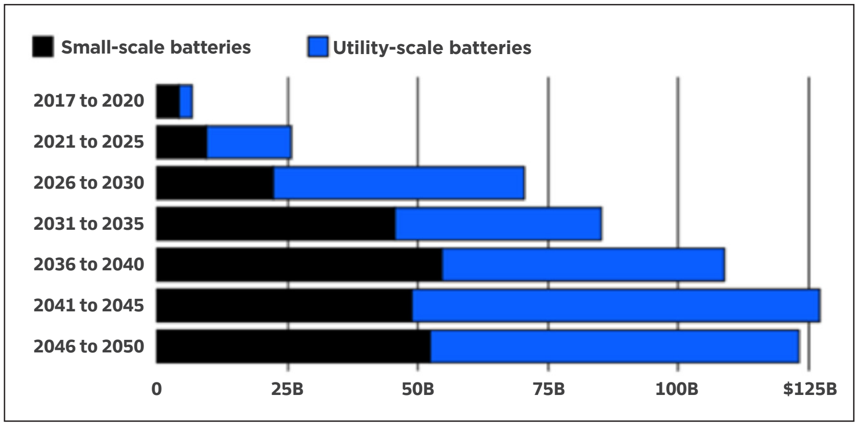

FIGURE 6: Estimated Investment in Battery Storage through 2050[11]
Source: Bloomber NEF

RETROFITS

An AC-coupled system tends to be more practical for adding battery storage to existing PV arrays. If the PV inverter is still in good condition, it is simple to install a new bidirectional battery-based inverter along with the batteries. For a DC-coupled system, the PV inverter would have to be removed, which would require substantial rewiring plus the addition of DC-to-DC choppers (also known as a boost converter) to match the DC voltages.[9] [10] It is even easier to install newer AC-coupled batteries that consist of a battery cell, battery management system, and inverter/charger all in one compact unit. The most well-known one is the **Tesla Powerwall 2**, along with Sonnen Batteries for residential and commercial applications.

It is also important to note the ability to upgrade and replace batteries, because because their service life is usually around 10 to 15 years, whereas solar panels can last approximately 25 to 35 years. Therefore, owners will most likely have to get a new battery power pack during the system's life. There is no particular advantage for an AC- or DC-coupled system when just replacing the batteries. However, investment in battery storage is growing rapidly and is only expected to increase, as shown in Figure 6. No one can predict the next breakthrough technology, but increased funding will help accelerate commercialization. By the end of a battery's lifecycle, there might be more advanced battery technology on the market that is cheaper and more efficient. Having a separate PV inverter from the battery bidirectional inverter, as in an AC-coupled system, would allow less complicated integration of new types of battery storage system technologies.

DC-Coupling Advantages

EFFICIENCY

Every time there is a conversion between AC and DC, there is energy loss. Conversion can reduce efficiency by 1% to 4%, depending on the inverter. Since there is an extra conversion step with an AC-coupled system, it has a slightly lower roundtrip efficiency for battery charging than a DC-coupled system, which directly charges the battery.[3] [9] [12]

There are some losses going through a DC/DC converter (because of matching voltages), but much less than with AC and DC conversion.

INVERTER LOAD RATIO (ILR)

The ILR (also known as *DC-to-AC ratio* or written as *DC:AC*) is the ratio of power between the DC solar array and the AC inverter. When a solar array produces more DC power than the inverter can convert to AC (exceeding the ratio), the energy is lost or "clipped." DC:AC ratios have been increasing over the years due to ever declining solar costs. This provides more annual energy from the system, but increases the amount of clipping. For example, a solar plant with a 1:10 DC:AC ratio might never experience any clipping because the losses from panels to inverters may line up with the ratio rather evenly. With solar plants having DC:AC ratios these days, there is ever more clipping during the mid-day period, when the DC output far exceeds losses going to the inverters, so that energy is lost.

Over the past 10 years there has been a dramatic reduction in the cost of solar PV panels versus the much slower reduction in the cost of inverters. Thus, the DC-AC ratio—or ILK—has been increasing. Figure 7 shows the potential energy loss and the increasing solar PV energy going into a battery for a DC-AC ratio greater than 1:2. This issue does not apply to

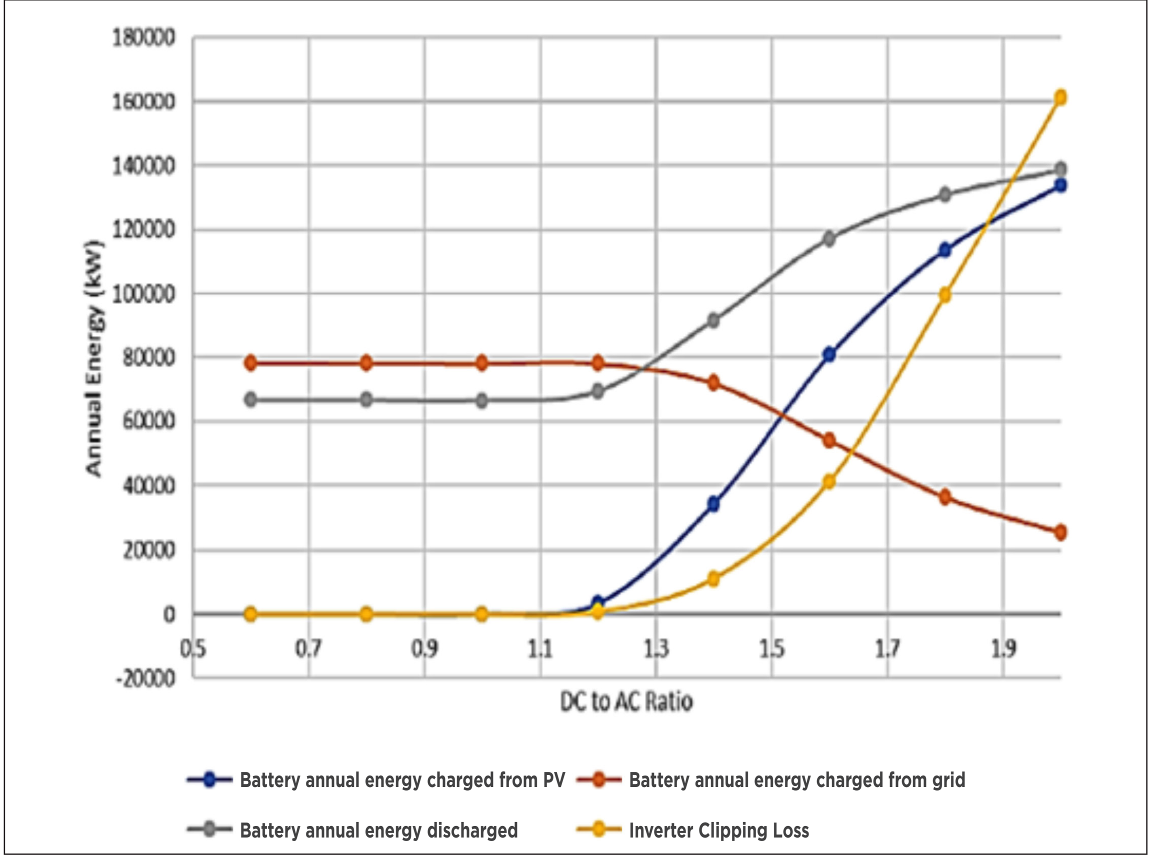

FIGURE 7: Annual Energy Loss due to Inverter Clipping with for AC-coupled systems[13]

DC-coupled systems because the solar array can send the extra DC energy that would normally be slipped to directly to the battery. This enables higher ILRs in DC-coupled systems and will generate more revenue from the excess power harvested. [4] [9]

In Figure 8, the solar PV has the capability to provide DC voltage and current following the blue line throughout the hours in the day, but with a high DC-to-AC ratio of 1:3 to 1:5, the AC output is clipped at 1 MW AC, and the energy from late morning to early afternoon is lost. But, if the battery is DC-coupled to the solar PV, the clipped energy in the red striped region is harvested. If the power grid limits the ramp rate of the solar PV to the red line (though the solar PV can produce power along the blue line), then there is additional energy harvested when the solar PV rapidly ramps up, charging the battery. Thus, the clipped energy harvested and the energy harvested from allowing fast ramps is stored in the battery. A higher ILR results in more energy production, which could offset the higher capital cost and result in lower levelized cost of energy. Figure 8 shows the reduction in net present value of a solar PV system with increasing DC-to-AC ratio.

Note that for this particular case (with financial assumptions used in reference 13) the optimal net present value decreases slowly from approximately 1 to approximately 1.4 and then rapidly decreases unless the clipped energy is harvested by a DC-coupled or a hybrid DC and AC battery storage system, which will allow higher DC-to-AC ratios.

Figure 9 on the next page shows that net present value decreases at higher ratios due to a severe decrease in annual AC energy produced.

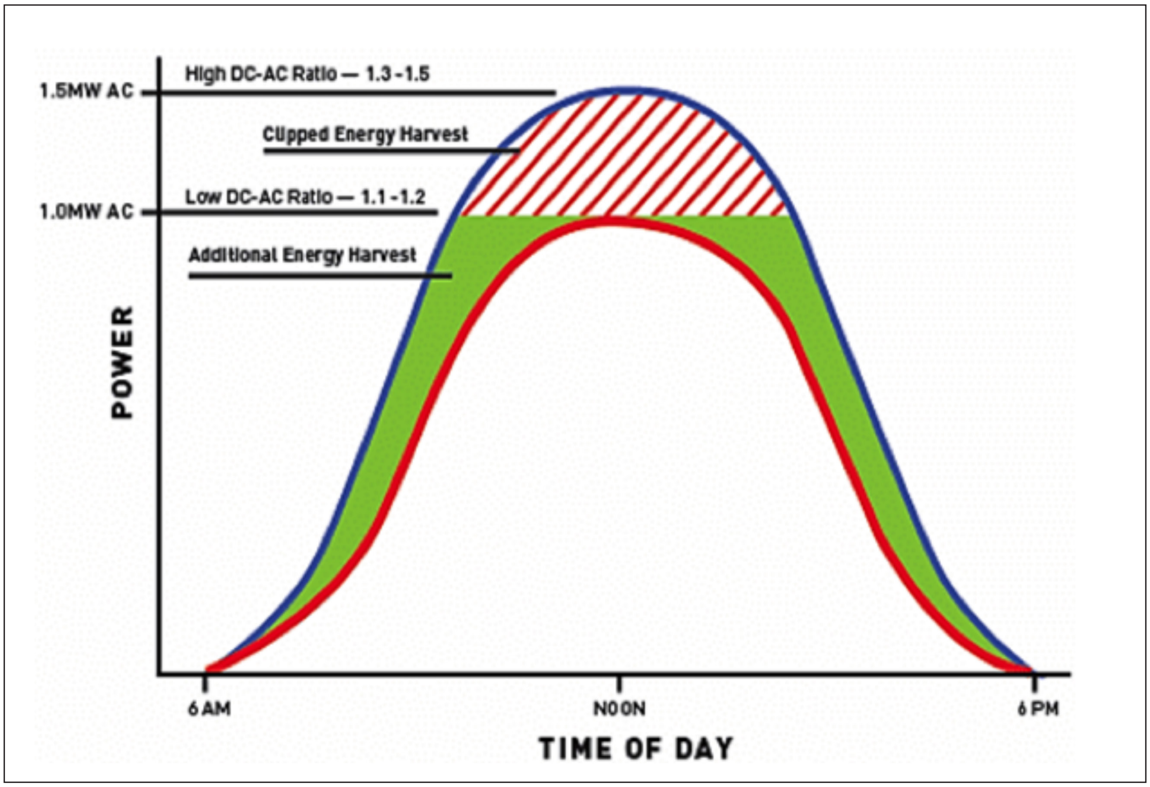

FIGURE 8: Clipping Recapture Opportunity for DC-Coupled Systems[8]

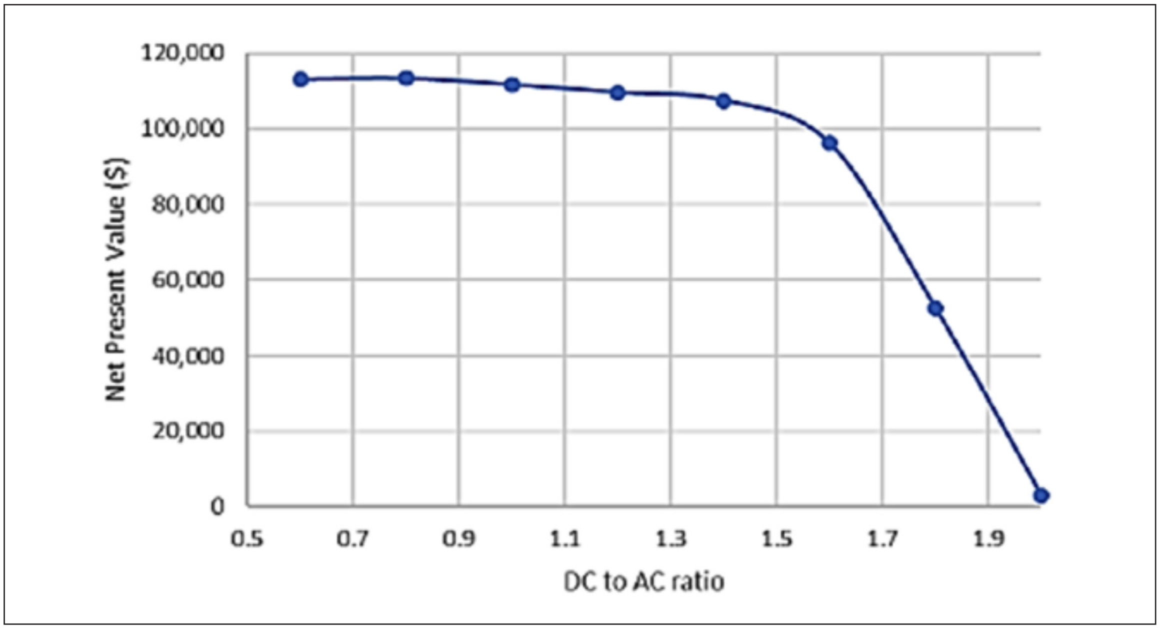

FIGURE 9: Reduction in NPV with Increasing DC-to-AC ratios for Stand-Alone PV Systems[13]

LOW VOLTAGE (LOW-POWER) HARVESTING

Inverters typically require a minimum DC bus voltage to operate. For instance, according to Dynapower for a 1,500V_{DC} nominal system, this threshold voltage would be approximately 500V_{DC}.[8] As a result, in the morning and evening, when voltage, current and power are lower than the solar generated, power and energy are not captured.

This also takes place during dense cloud coverage. With a DC-coupled system, the DC-DC converter can capture this energy during periods of low power and charge the battery. This gives a small advantage to DC-coupled systems, because it helps to slightly decrease the slope of solar variability while giving other systems more time to ramp up and down when load following.

Figure 10 shows the results of California's DC-coupled solar-plus-storage net metering rule. The rule allows solar-plus-storage asset owners to export battery power to the grid.

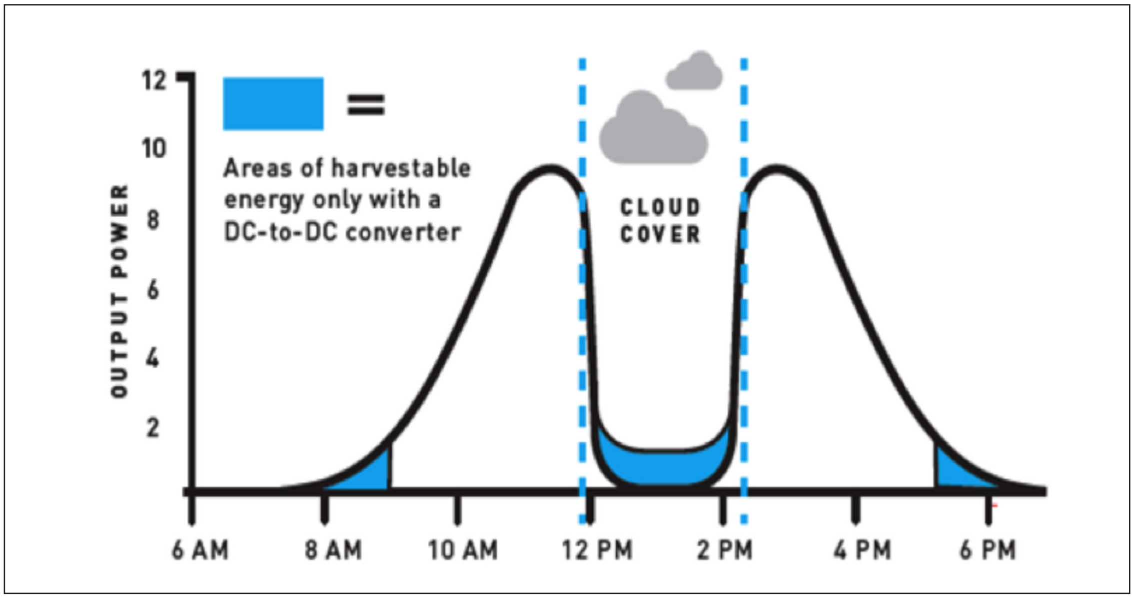

FIGURE 10: The Complexity of AC- and DC-coupled Energy Storage Before the CPUC NEM Decision[15]

SMART INVERTERS

A device is considered "smart" if it can operate efficiently and autonomously with little operator intervention. The role of an inverter is to operate as an interface between generation and consumption points. It is not limited to AC-DC conversion, but also has the ability to control the power flow, sense faults, provide voltage support, and perform various other functions.

Using a smart inverter can optimizes solar-plus-storage systems by achieving higher functionality, efficiency and reliability, using improved control algorithms.[16] (See Figure 11 for features of a smart inverter.) This enables owners to profit more from services, such as demand management, ancillary services, voltage support, decentralized power control (e.g. islanding), ramp rate control, fault tolerance, soft start capability, and microgrid support.

With batteries and inverters taking on more complicated and digitally enabled tasks, streamlined communication interfaces and architectures between them will become essential for further growth. This need has resulted in partnerships between smart inverter technology and battery developers that will result in more standardized components to link the two technologies.[17]

For instance, Chinese battery manufacturer **BYD** has partnered with an inverter maker, **Kostal**, to improve their storage solution services, offer commercial and residential batteries that are more compatible with the customer's system and can be either AC- or DC-coupled.[18] In addition, **SolarEdge**, a PV

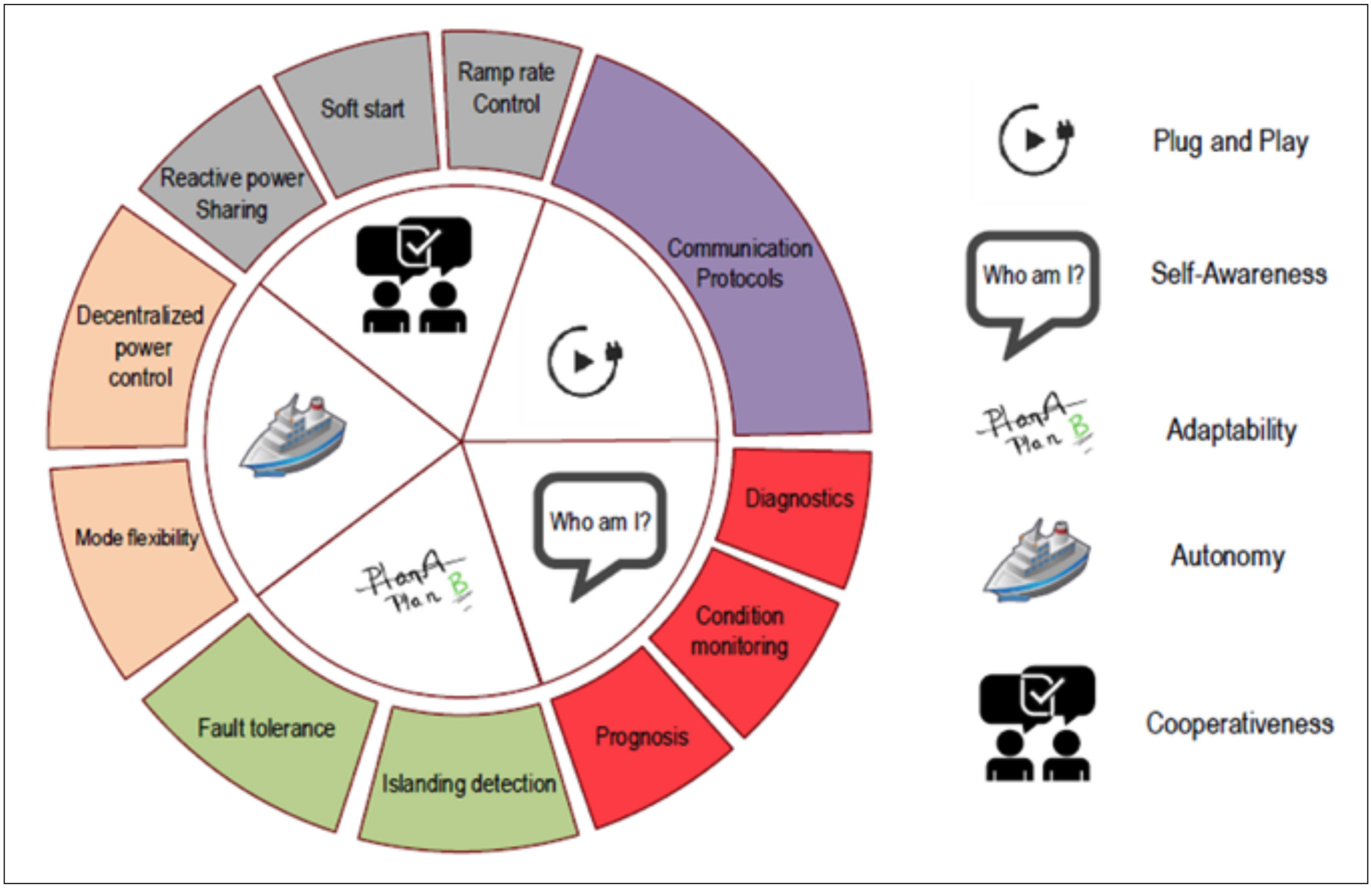

FIGURE 11: Smart Inverter Features[16]

1 For questions about IEEE 1547 and UL 1741, please contact Robert Harris, NRECA's senior principal for transmission & distribution engineering: **Robert.Harris@nreca.coop**

inverter system provider, recently announced the availability of its new smart inverters with HD wave technology that integrates energy management of solar, storage and home energy use. It will result in more standardized components to link the two technologies.[17]

The increased interfacing between inverters and batteries also requires communication protocols and standards (e.g., **IEEE 1547** and **UL 1741**[1]) that are continuing to be updated and followed carefully by industry stakeholders. The Interstate Renewable Energy Council hosts a national forum on inverter grid integration and has created a document to help inform utilities on specific requirements to ensure inverters are correctly selected and commissioned: *A Guide to Selecting Inverters and Settings in Jurisdictions Without Grid Support Functionality Requirements*.[19] Even though smart inverters are commercially available, only the ones that follow the current utility codes should be implemented.

CONCLUSION

As more people become interested in solar-plus-storage systems, it is important to look at areas that can be modified to help keep costs low. Since these projects are fairly new, the results from each system still need to be compared in order to obtain quantifiable data on best practices. From a technical standpoint, there are options in system configuration, smart inverters, environmental considerations and battery recycling that could help improve solar-plus-storage systems' overall cost analysis.

There are advantages and disadvantages to choosing either an AC- or DC-coupled system. DC-coupled systems are recommended for new projects because of their higher efficiency and energy harvesting capabilities. By DC-coupling batteries to solar PV, it will be possible to optimize the levelized cost of energy for solar PV by increasing the DC-to-AC ratio. This will allow the system to harvest the clipped energy, as well as harvest low-power energy when the solar PV voltage and current are low. Every time there is a conversion between AC and DC, energy is lost. Conversion can reduce efficiency by 1% to 4%, depending on the inverter. Since there is an extra conversion step with an AC-coupled system, it has a slightly lower roundtrip efficiency for battery charging than a DC-coupled system, which directly charges the battery.[3] [9] [12]

DC-coupling the battery to the solar PV will reduce the cost of the bidirectional inverter for the battery and avoid the risk of losing flexibility in battery use. AC-coupled systems are more practical for retrofits and might be more optimal when preparing for evolving battery technology. In addition, both AC- and DC-coupled systems can generate additional stacked benefits in energy markets by providing frequency regulation, spinning reserve and capacity credits, and eventually ramping services and inertia. However, there are other factors that need to be taken into consideration, making each project case specific.

A tool for proper energy management that can be applied to almost any solar PV plus energy storage project is using smart inverters. It increases efficiency and allows the system to potentially provide more valuable services. Many companies are offering the combination of smart inverters with batteries to increase their capabilities. As regulatory policy and technological changes occur, it is important to make sure that smart inverters follow current standards and codes.

Owners also need to follow protocols for solar panel and battery disposal. With PV panels achieving higher life expectancy, this concern is negated over time. However, with more spent batteries piling up, there is a potential for a growing issue of waste disposal. In addition, the recycling and reuse of batteries will become more economical, potentially reducing the cost of battery energy storage systems in the future. It would be beneficial to energy storage users to consider the cost of different recycling options during their planning phases.

There are continual technological advancements around solar and storage. Staying informed will help owners make the best decisions for the future of their systems. ■

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Dale Bradshaw was formerly an industry expert and consultant with NRECA's Business and Technology Strategies department and provided significant expertise and guidance on this article. *Unfortunately Dale passed prior to the publication of this article and will be greatly missed by all.*

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Kristen Russell was an intern working with NRECA's Business and Technology Strategies department during the summer of 2019. She worked with the Generation, Environment and Carbon work group and contributed research and writing for this article.

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