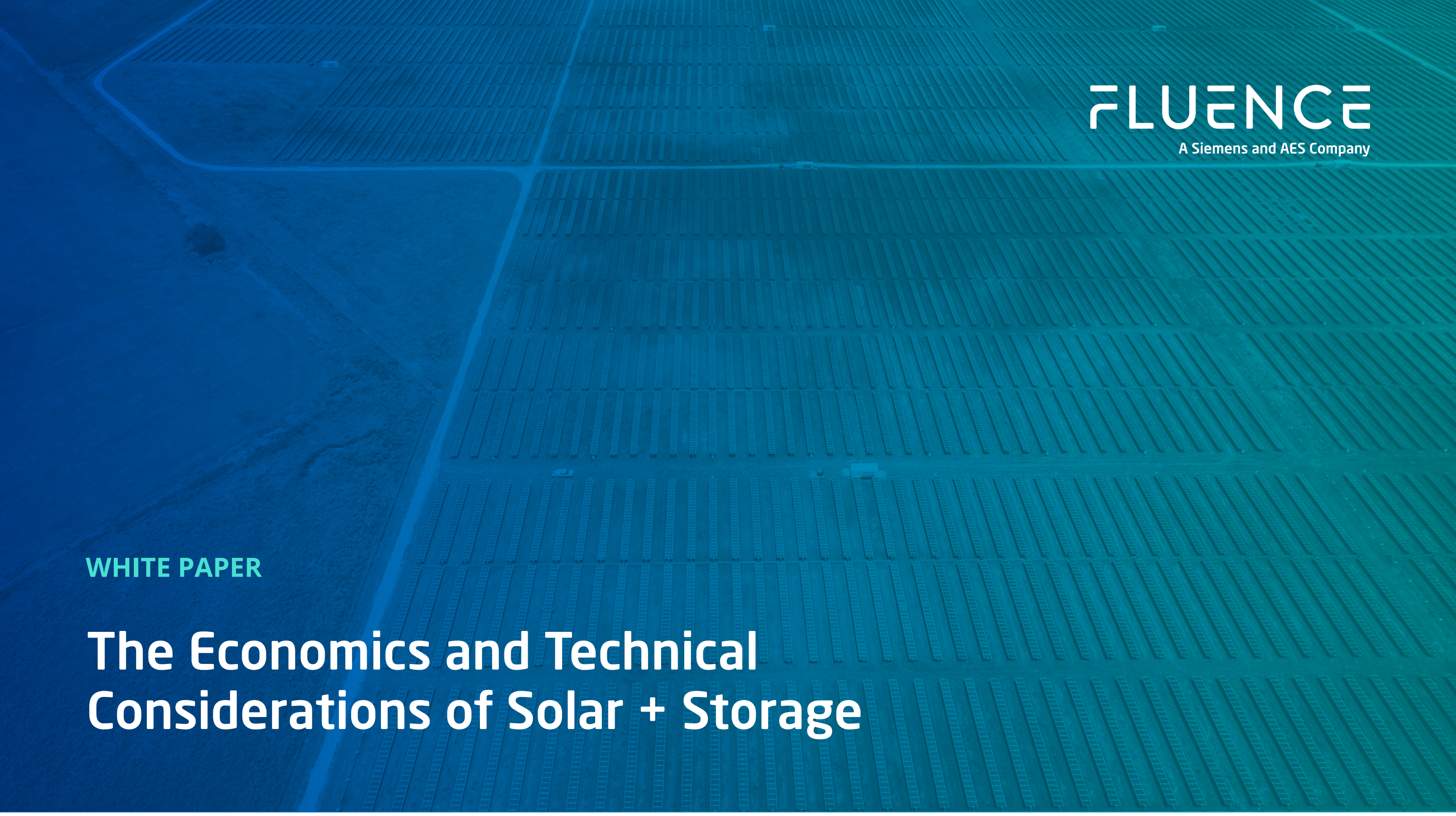

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WHITE PAPER

The Economics and Technical Considerations of Solar + Storage

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Summary

2018 is poised to be a record-breaking year for solar globally. Wood Mackenzie Power & Renewables projects that solar PV installations in 2018 will be the same as all solar installations pre-2013 combined. Certainly, in the short to medium term, solar power has a strong outlook. In the long term, however, solar power's outlook is not so clear. As solar PV penetration increases, the value of additional solar energy on the grid decreases due to falling capacity value. This has been shown by studies[1] as well as empirical data from grids with large 'duck curves' like California which need to curtail solar when there is more solar generation than the grid can support.

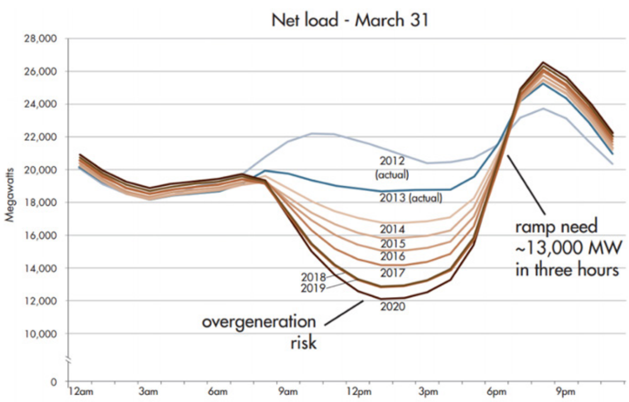
Looking ahead, solar will be on a perpetual cost treadmill to make sure the cost of adding new solar remains below the declining value of additional solar on the grid. If the marginal value of one additional unit of solar falls below the marginal cost, it will be hard to justify additional solar investment. For society to capture the full benefits of solar energy, in both the short term and long term, we must find solutions to prevent solar value deflation caused by higher levels of solar penetration. In fact, solar installations in the US declined in 2017[2] for the first time, in part due to the declining value of additional solar energy.

One solution to ensuring the long-term growth of solar is to deploy solar with energy storage either co-located or as standalone systems. Solar + energy storage provides flexible capacity by both absorbing over-generation midday and discharging it during the evening hours when carbon-free energy is needed. A paired solar + storage resource has greater capability to provide grid services than standalone solar as well. This allows grid operators to use a clean, carbon-free resource to provide enough capacity to serve their customers during peak demand periods rather than relying on traditional polluting fossil fuel plants.

1 *https://www.nrel.gov/docs/fy17osti/68737.pdf*
2 *https://www.greentechmedia.com/articles/read/us-residential-and-utility-scale-solar-see-installations-fall-first-time*

It's happening faster than we think.

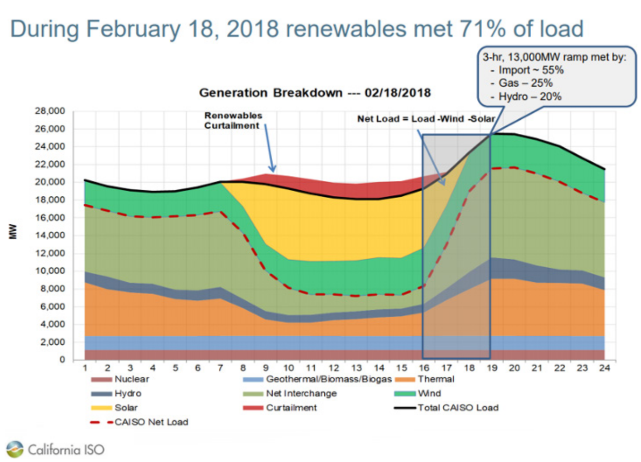
In 2013, the California Independent System Operator (CAISO) attempted to predict how the influx of renewables, particularly solar energy, would impact the grid overall[3]. Their predictions are summarized in an infamous net load curve affectionately known as The Duck Curve (or The Duck Chart).



Source: CAISO

The graph indicates that as solar resources are added to the grid, there is a risk of generating too much power during the daylight hours while not having enough to firm capacity as the sun sets for the needs of people as they return home, cook dinner, and use electronic devices. In 2013, CAISO estimated that by 2020 the grid would need to ramp 13,000 MW in three hours.

In the years since, California has demonstrated that the load and ramping demands for power are even higher and are occurring at a faster pace than was predicted in 2013. February 18, 2018 is a perfect example of how ramping and curtailment issues are already creating issues on electricity grids today.



Source: CESA 2018 Market Development Forum

Due to inflexible generation that cannot ramp up or down quickly, CAISO had to curtail renewables while keeping traditional thermal generators online to meet the evening ramp. In total, CAISO curtailed approximately 13 GWhs of renewables over 10 daytime hours in order to meet the evening ramp and peak. This resulted in a net load (load minus solar and wind generation) of ~7,500 MW, which is approximately half of the minimum net load CAISO had predicted back in 2013.

February 18th illustrates how solar generation is a great carbon-free energy resource to offset fossil generation during the day, but that without mitigating the duck curve, any additional solar energy generated in these hours will be curtailed and will not contribute to emissions reductions.

So what can we do about it?

As solar becomes a bigger portion of energy generation, grid operators will need solar resources to provide more than just zero-marginal-cost energy. Solar resources will need to provide firm, flexible energy commitments even when the sun goes down, as well as critical grid services like frequency regulation and spinning reserves to stabilize the grid. We believe that solar + storage is a valuable tool to aid grid operators around the world and will ensure that the future of solar continues to be bright.

In the upcoming sections we will dive into more detail about the technical and economic considerations for pairing solar with energy storage. We strive to answer how to determine whether AC or DC coupling is the best fit for a project, how to optimize the storage-to-solar ratio of a project, and finally how to determine the optimal inverter loading ratio for DC-coupled solar + storage systems.

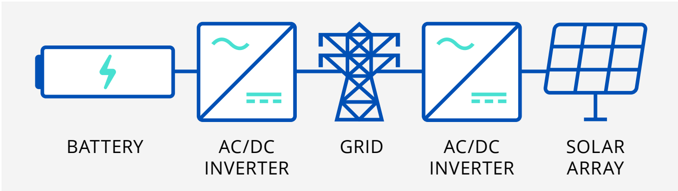
AC vs. DC Coupling

Although the phrase "solar + storage" is thrown around in energy circles frequently, little attention is usually given to what kind of solar + storage people are actually referring. Generally speaking, solar + storage can be configured in three possible ways:

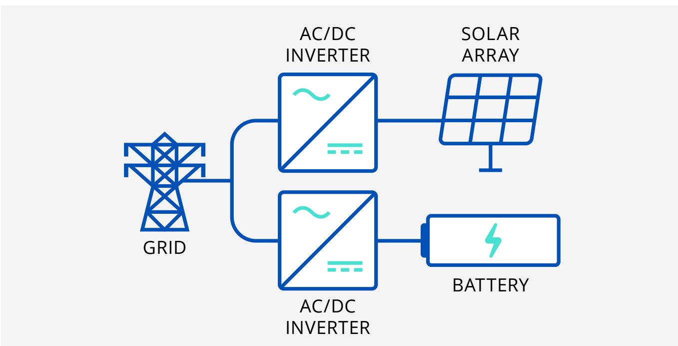
1. AC coupled, standalone: The energy storage is located on a separate site independent of solar generation. This

3 *https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf*

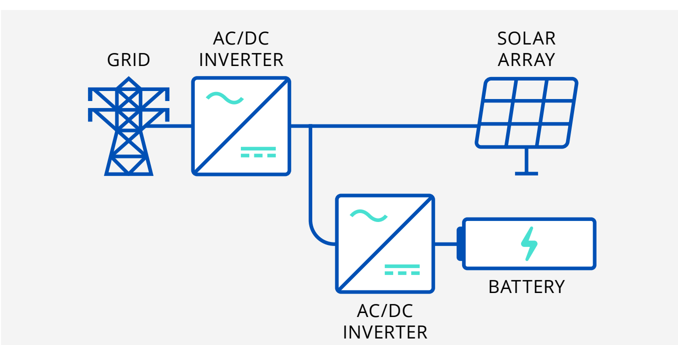
type of installation is often sited in a local load pocket to serve capacity constrained regions.



2. AC coupled, co-located: The solar and energy storage are located at the same site and either share a single point of interconnection to the grid or have two separate interconnections. However, the solar and storage systems are connected to separate inverters, and the energy storage is sited next to the solar generation. They can be dispatched together or independently.



3. DC coupled, co-located: The solar and energy storage are located at the same site and share the same interconnection. In addition, they are connected on the same DC bus and use the same inverter. They can be dispatched together as a single facility.



Solar + Storage Benefits

Solar and storage do not have to be co-located to unlock their mutual benefits. No matter where it is located on the grid, a standalone energy storage facility can provide grid services and shift blocks of firm renewable energy to the evening peak. If solar resources are located far from congested load centers the optimal physical configuration can be to locate standalone storage near load centers. For example, Fluence built a 30 MW four-hour duration battery near San Diego to ensure local reliability and increase renewable energy use. Utilities and developers should focus on locating storage systems wherever they have the highest net benefits, which may or may not be co-located with solar.

The Advantages of Co-location of Solar + Storage

In many circumstances, there are substantial advantages to colocating storage and solar. By co-locating, the solar + storage project can share the balance of plant costs including the cost of land, labor, project management, permitting, interconnection, operations and maintenance. In the United States, project owners can also claim the Investment Tax Credit on most of the storage capital costs if it is charged with solar energy.

Co-located systems can either be AC coupled, where the storage and solar PV are physically sited in the same location, but do not share an inverter; or it can be DC coupled, where solar PV and storage are coupled on the DC side of a shared bi-directional inverter. The cost savings from sharing the balance of plant costs are substantial. An NREL study[4] estimated that for co-located AC-coupled and DC-coupled solar + storage, balance-of-system costs were 30% and 40% lower, respectively, by 2020.

To DC or not to DC, that is the question

There are key factors to consider when evaluating DC-coupled solar + storage systems. The main advantages of DC-coupled systems are:

- Eliminating the need for one set of inverters, MV switch gear, and other balance of plant costs, which reduces equipment costs.
- Higher round trip efficiency when charging from solar.
- Allowing the solar PV farm to capture solar energy that is normally lost, or clipped, when the inverter loading ratio is greater than 1, which can enable the plant to generate additional revenue. DC-coupled solar + storage opens the door to increasing the panel to inverter (DC/AC) ratio to much higher levels than solar-only plants.
- Easier to contract solar + storage together under a single commercial structure.

4 *https://www.nrel.gov/docs/fy17osti/68737.pdf" NREL study*

The one potential drawback of DC-coupled systems is they have less operational flexibility than their AC-coupled cousins because they can be limited by inverter capacity when there is excess interconnection capacity. For example, if a solar developer expects high demand during hours of peak solar production, it may not be able to simultaneously discharge the battery to supply the load. While this is a potential drawback, we do not expect this to be a big issue in most markets.

See a summary of DC- vs. AC-coupled systems below:

	AC	DC
Separate dedicated inverters for solar elements and energy storage elements of the project	X	
Increased amount of PV energy that can be delivered through same interconnection		X
Eliminates one set of MV switch gear for interconnection		X
Higher round-trip efficiency when >50% solar charged		X
Can store energy generated by the solar project or from the grid	X	X
Simplified interconnection process due to single inverter		X
Eligible for ITC, but must demonstrate that 75% of battery charging is from PV	X	X
Takes advantage of solar project DC/AC ratio oversize to charge storage system		X
Use cases 1. Grid stability 2. T&D deferral 3. Renewable Plant Stability 4. Renewable Firm Energy 5. Ancillary Services	ALL	ALL

We believe that a DC-coupled system is the optimal system configuration for providing firm solar energy for long blocks of time, for example 4-6 hours, because of its ability to capture clipped energy, increase round trip efficiency, and reduced balance of plant costs due to the shared bi-directional inverter. We expect to see an increase in DC-coupled deployments in the coming years as grid operators increasingly confront growing duck curves.

Our recommendation for the best solar + storage configurations for different energy storage use cases is as follows:

	STANDALONE	CO-LOCATED
AC COUPLED	• Local flexible capacity • Transmission and distribution enhancement • Grid services	• Grid services • Renewable plant stability • Flexible capacity
DC COUPLED	• Small microgrids	• Firm renewable energy • Grid services • Flexible capacity

Just Right: How to Size Solar + Storage Projects

Say you are a developer and you have decided to co-locate solar and energy storage in a DC-coupled configuration. How do you decide how much solar and storage to build? Let's now explore the considerations for determining the optimal storage-to-solar ratio.

What is the problem you are trying to solve with energy storage?

The first question to ask yourself when sizing energy storage for a solar project is "What is the problem I am trying to solve with storage?" If you cannot answer that question, it's impossible to optimally size storage. Usually the problem you are trying to solve falls into one of three buckets:

A. Plant stability: I need to stabilize the output of variable renewable energy plants in order to connect to the grid (e.g. Puerto Rico's minimum technical requirements for solar)

B. Grid stability: I need to provide grid services (e.g. ancillary services) to stabilize the grid or want to increase the revenue potential from the project.

C. Firm renewable energy or peaking capacity: I need to be able to deliver firm energy commitments during certain hours of the day (i.e. dispatchable solar).

The third application (firm renewable energy) is what most people think about when they hear solar + storage: the ability to deliver firm energy commitments during certain hours of the day (i.e. semi-dispatchable solar). Two years ago, we noted in a blog post that solar had broken the $30/MWh barrier in an auction in Chile. Now we routinely see mid- to low- $20's per MWh PPAs in the US[5], and a solar PPA in Saudi Arabia broke $20/MWh at $17.9/MWh[6]. The fuel for energy storage is only getting cheaper. An important aspect of helping utilities and other off-takers benefit fully from a solar + storage "peaker" is getting the sizing of each resource right.

One way to think about solar + storage is as two separate contracts: one for solar energy on a per MWh basis and one for storage on a per kW-month basis. This structure allows off-takers to explicitly see how storage competes against traditional capacity resources like natural gas peakers. Another way is to have a volumetric based contract that requires delivery of energy in certain hours or pay a premium for energy delivered in certain hours.

Below are the needed inputs and analysis required to determine how to properly size energy storage for renewable firm energy.

INPUTS

Vertically integrated utility:

- When does the grid need firm energy (hours of day and months of year)?
    - i. Given by RFP or utility modeling

Deregulated market:

- How many hours of dispatchable energy does the grid need?
    - i. Grid operator rules for qualifying to provide capacity
    - ii. Expected retirements
    - iii. Expected load growth
    - iv. Expected new builds
    - v. Hourly solar generation profile

Both

- Hourly solar generation profile

ANALYSIS

Vertically integrated utility:

- Determine power (MW): Determine the capacity value of solar during the capacity delivery period, and subtract that from the total MW capacity need.
- Determine energy (MWh): Based on above needs for total power capacity, perform a dispatch analysis to determine needed duration (typically 2 hours to 5 hours).

Deregulated market:

- Determine power (MW): Using your forecast on future power prices, experiment with different storage sizes such that marginal revenue = marginal cost.
- Determine energy (MWh): Based on pricing forecasts above, perform an SOC analysis to determine needed duration to capture majority of high price events (typically 2 hours to 5 hours). *See below for more details.*

To do this duration analysis, you will need to:

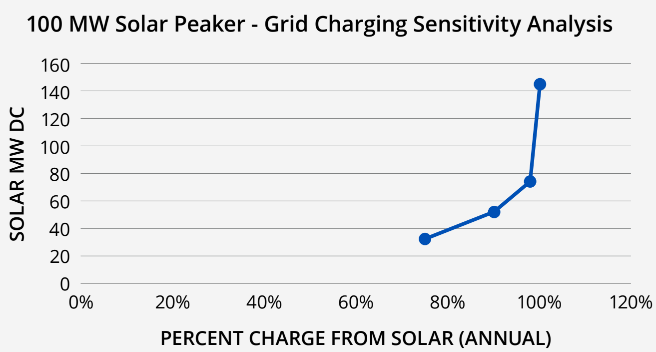
1. Determine the value of additional firm solar energy. This will likely be based on the avoided cost of existing generators or the cost of new capacity additions modeling.

2. Determine the amount of firm energy delivery for different durations. This will require a granular analysis, likely at the hourly level, to determine how much firm energy can be delivered for different durations. As a simple rule of thumb, we recommend you start with the duration 30% shorter than duration you initially plan, increasing to 30% above the initial plan. The analysis should be focused on the period when firm energy is most valuable, which is likely going to be during summer mid-day-evenings, or a period defined in an RFP or identified by an off-taker. At first order, this analysis can be done using solar output derived from location-specific typical meteorological year (TMY) solar files[7] or from your preferred solar modeling software provider. The sizing can be further optimized by considering the difference in sizing needed for P90 and P50 solar output scenarios. The key to optimally sizing the storage system probabilistically is understanding the tradeoff between marginal cost of additional solar

5 *https://www.greentechmedia.com/articles/read/nevada-beat-arizona-record-low-solar-ppa-price*
6 *https://www.bloomberg.com/news/articles/2017-10-03/saudi-arabia-gets-cheapest-ever-bids-for-solar-power-in-auction*
7 *https://nsrdb.nrel.gov/tmy*

or storage and the penalty for being unavailable to meet a peak in a rare situation. For example, being willing to charge from the grid during non-peak hours for a small percentage of time can make a big difference in the required size of solar PV. Said another way, with a fixed amount of solar PV (if you are land-constrained, for example), you can provide more firm capacity with the same amount of storage if you are willing to charge from the grid sometimes. See figure below:

Solar capacity, in MW, required to create a 100 MW renewable peaker. In this example, we are sizing solar for a 100 MW, 4 hour battery. The storage requirement is 100 MW due to the time of day the peak occurs, and we want to know how much solar PV to build to "fuel" the peaker. As you can see, the more stringent the requirement to avoid charging from the grid, the quicker the solar capacity (and the CAPEX) increases.



3. Determine the marginal change in energy delivery for change in duration. Determine how much additional firm energy can be delivered for each increase in duration.

4. Determine the value of the marginal firm energy changes. For each duration, multiply the value of the energy calculated in step 1 by the marginal energy calculated in step 3.

5. Determine the marginal cost to change duration. This should include the cost of the batteries and balance of plant, such as building/container size, HVAC, and racks.

6. Determine the duration where the value, based on a net present value of revenues or avoided costs, of the marginal firm energy increase/decrease equals the marginal costs of longer durations.

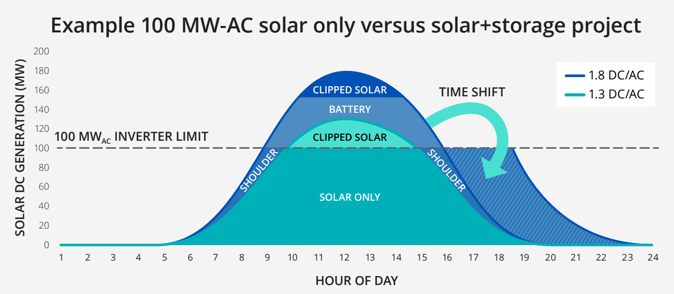
How to Optimize your Inverter Loading Ratio for Solar + storage projects

We will discuss how to properly size the inverter loading ratio on DC-coupled solar + storage systems of a given size.

One of the main benefits of DC coupling is enabling more energy to be delivered to the grid by storing energy that otherwise would have been clipped. In most regions, solar developers already overbuild their systems with extra PV panels to increase the total energy output of the system. For example, it is typical to see solar projects with 1.3 MW of PV panels per 1 MW of inverter capability. This oversizing of the PV panels in relation to the inverter size will maximize the total energy output of the system throughout the year, particularly during months with reduced solar irradiation. Unfortunately, increasing the inverter loading ratio, which is the DC capacity of the solar panels divided by the AC capacity of the inverter, leads to some energy being lost or clipped during the sunniest hours of the year.

$$\text{INVERTER LOADING RATIO} = \frac{\text{DC Capacity of Solar Panels}}{\text{AC Capacity of Inverter}}$$

One of the advantages of a DC-coupled solar + storage system is that the battery can store this energy that would normally be clipped, while an AC-coupled system cannot. Furthermore, a DC-coupled solar + storage system will allow the developer to increase the overall inverter loading ratio for the project, which increases the amount of delivered energy to the grid without the risk of clipped energy. See figure:



Once you have decided on the size of your energy storage system, you now need to decide how many panels and inverters to install in order optimize the cost. This optimization will take into account the additional energy a DC-coupled system can deliver. The optimization is similar to the one done for solar-only projects, with a minor increase in complexity to account for the state of charge of the energy storage. The inverter loading ratio determines the amount of additional energy that can be cost-effectively sold. Generally, the maximum inverter loading ratio for solar + storage systems will be limited by:

1. Land: a limited amount of land on which to install solar panels

2. Interconnection: an interconnection agreement which limits the amount of power they can inject into the grid

3. Economics: will there be enough additional revenues to cover the extra costs and a reasonable rate of return

Imagine a project developer who followed the steps to size a DC-coupled solar + storage system to determine she should pair a 50 MW/4hr storage system with her 100 MW (AC) solar project. Based on this configuration, she is unsure about the optimal inverter loading ratio for the project and ultimately how many solar panels she should buy. The project will be limited by the 100 MW interconnection and she has space to add up to 250 MW (DC) of panels, so economics will determine the best inverter loading ratio.

To perform the analysis, she can follow these steps:

1. Revenue: Determine the additional revenue that can be earned at different inverter loading ratios

a. Determine the amount of energy delivered at different inverter loading ratios. This will require a granular analysis, likely at the hourly level, to determine how much energy is delivered for different inverter loading ratios, either from adding more panels or reducing the number of inverters. We recommend you start with the inverter loading ratio you would use without storage, which is commonly 1.3. The simplest analysis for each hour would be:

DELIVERED ENERGY = MIN (DC SOLAR GENERATION, INVERTER SIZE + BATTERY CAPACITY)

Note: *Battery capacity will need to account for the battery power ratings and hourly state of charge. Detailed analyses should also account for losses of the different equipment.*

Depending on the storage size, the battery will be able to absorb all the energy, but on the sunniest days, it likely will not be able to absorb all of it. The analysis should also take into account timing the delivery of energy to the grid according to the energy offtaker's preferences. This step requires detailed modeling of the dispatch of the combined battery and PV system, and is often the most time consuming.

b. Determine the marginal change in energy delivery for change in inverter loading ratio. Determine how much energy is delivered for each increase in inverter loading ratio. For example, if the total energy delivered for a 1.6 inverter loading ratio is 254,400 MWh and for a 1.7 inverter loading ratio is 269,600 the marginal change in energy delivery is 269,600 MWh - 254,400 MWh = 15,200 MWh.

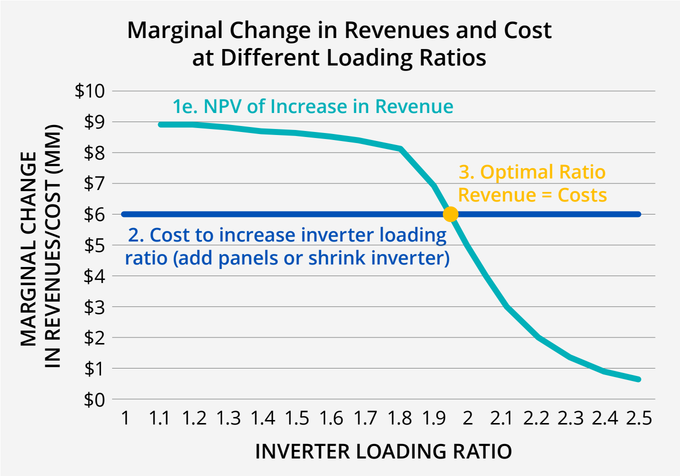
c. Determine the value of firm and non-firm solar energy. This will be based on the costs of existing generation, tariff price, expected PPA price, and/or the costs expected for other projects that could be substitutes. For this project we will assume the value of firm and non-firm solar energy are both $50/MWh. Note that most projects pairing storage with solar PV will value the dispatchability of the combined asset, necessitating variable pricing for energy delivered in different times of day.

d. Determine the value of the marginal energy changes. For each inverter loading ratio, multiply the value of the energy calculated in step 1c ($50/MWh) by the marginal energy calculated in step 1b.

e. Determine the net present value of these cash flows across the length of the contract.

2. Determine the additional costs for changing inverter loading ratios. If you are interconnection limited, determine the marginal increase in costs (including balance of plant) for adding more panels to increase the inverter loading ratio. If you are land limited, determine the marginal decrease in costs of the inverters and other balance of plant equipment for each increase in the inverter loading ratio. The developer in our example is interconnection limited and she estimates that it will cost an additional $600/kW to add additional panels and the corresponding DC balance of plant. To increase the inverter loading ratio by .1 it requires an additional 10 MWdc, which costs $6 million.

3. Determine the inverter loading where the value of the marginal energy increase/decrease equals the marginal costs/savings. As shown in the figure below this occurs for our developer at a 1.9 inverter loading ratio. At this point the cost of adding more panels is recovered, including a rate of return, by the additional energy that can be captured by the energy storage.



Following the steps outlined above, project developers can optimize the inverter loading ratios for DC coupled solar + storage projects, enabling them to offer lower cost systems to customers and increase the returns of investors.

We hope that this white paper has been a good introduction into the economics and technical considerations of solar + storage. If you have any questions, we look forward to connecting with you.

ABOUT FLUENCE

Fluence, a Siemens and AES company, is the global market leader in energy storage technology solutions and services, combining the agility of a technology company with the expertise, vision and financial backing of two well-established and respected industry giants. Building on the pioneering work of AES Energy Storage and Siemens energy storage, the company's goal is to create a more sustainable future by transforming the way we power our world. Providing design, delivery and integration, Fluence offers proven energy storage technology solutions that address the diverse needs and challenges of customers in a rapidly transforming energy landscape.

The company currently has more than 2.1 gigawatts of projects in operation or awarded across 22 countries and territories worldwide. Fluence topped the Navigant Research utility-scale energy storage leaderboard in 2018 and was named one of Fast Company's Most Innovative Companies in 2019.

To learn more about Fluence, please visit fluenceenergy.com.