Solar and BESS co-location: value streams and technical configurations options

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In the pursuit of sustainable energy solutions, the integration of Battery Energy Storage Systems (BESS) with renewable generation technologies has emerged as a promising strategy. Co-located assets offer a synergistic approach to maximise revenue generation.

Among the various renewable energy technologies, solar PV is most commonly co-located with BESS due to their complementary operational profiles. This is because, unlike other renewable energy technologies, solar generates energy during a specific segment of the day and not at all at night. Peak demand is usually early morning and in the evening, which is when the power prices are higher. With solar power, excess generated energy (clipped energy) can be captured and redirect to storage for use at those peak demand times, thus reducing energy wastage, maximising resource usage and profit by selling the energy at peak power price times (driven by peak demand).

The intermittent generation profile of solar energy creates a perfect opportunity and aligns well with the optimal charging and discharging profile of BESS. Additionally, coupling solar PV with batteries decreases project development costs and construction costs compared to developing the projects separately.

Solar PV + BESS Value Streams

A project is deemed feasible if it demonstrates economic returns that justify its construction and operational costs. Co-located solar PV and BESS value streams can be broadly split between contracted revenue and merchant markets.

Contracted revenues streams are based on agreements between the project developer and the offtaker, the party purchasing the service (the power output) provided by the utility-scale project (typically referred to as PPAs – power purchase agreements). The project is committed to provide the service as stipulated in the agreement, and the offtaker is committed to purchase these services under agreed-upon conditions and price for a specified duration, typically spanning 10 to 15 years.

Conversely, merchant markets present revenue opportunities subject to power market fluctuations. While merchant markets involve greater risk due to price volatility, they offer potentially higher revenues compared to long-term contracted agreements.

Time Shifting / Peak Shaving

Peak loads pose significant challenges for grid operators, as they necessitate substantial infrastructure investments to handle fluctuating demand patterns, which ultimately increase electricity costs for consumers. Time-based rate structures incentivise both consumers and generators to optimize their operations during periods when energy prices are more favourable.

Time shifting and peak shaving are essential strategies that enhance the economic viability of solar PV + BESS by optimising energy production and consumption to align with periods of high demand and high electricity prices. These strategies aim to reduce grid-related costs, improve energy efficiency, and support grid reliability. By storing energy during periods of low demand or when energy is inexpensive, and discharging it during peak demand times, solar PV + BESS help to stabilise the grid, lower costs, and maximise returns for both utility operators and end-users.

Time shifting involves storing excess solar energy generated during daylight hours when demand is low, and electricity prices are often at their lowest. This stored energy is then discharged during peak demand periods, typically in the early morning and evening, when solar generation is minimal or absent, and electricity prices are higher. By shifting the timing of energy production to align with consumption patterns, solar PV + BESS can better match supply to demand, allowing operators to capture higher revenue from energy sales or avoid purchasing more expensive peak power from the grid. This can be particularly advantageous in merchant markets, where energy prices fluctuate based on supply and demand, allowing operators to adapt to real-time market conditions and capitalise on price differentials.

Peak shaving is particularly valuable in regions where utility tariffs include demand charges based on the highest level of energy consumption during specific intervals. These charges incentivise consumers to reduce their peak demand to avoid steep fees. Solar PV + BESS are well suited for peak shaving, as they can store energy when demand and costs are low and release it when demand spikes. By reducing peak loads, energy consumers can significantly lower their demand charges, leading to substantial cost savings. Moreover, on the generation side, producers can discharge stored energy during peak periods to profit from the higher rates typically paid for energy during those times.

Peak shaving can directly benefit large energy consumers subject to demand charges, which are calculated based on their highest levels of power consumption. By levelling out their demand profile and avoiding short-term peaks, these consumers can achieve substantial savings. For example, commercial and industrial facilities with high energy use can leverage solar PV + BESS to strategically reduce their peak loads, thereby lowering their overall energy costs and increasing their competitiveness in the market.

From a grid operator's perspective, time shifting and peak shaving help alleviate stress on the grid, particularly during times of high demand. By flattening demand peaks, solar PV + BESS can reduce the need for costly grid infrastructure upgrades that would otherwise be necessary to accommodate peak loads. This contributes to grid stability and reduces the likelihood of blackouts or service disruptions, benefiting both utilities and consumers by maintaining a reliable power supply.

However, while time shifting and peak shaving can provide substantial benefits, they also involve frequent cycling of the battery, which can lead to degradation over time. To minimise the impact on battery life, operators must consider factors such as depth of discharge, charge rate, and operating temperature. Employing predictive maintenance strategies and ensuring that the BESS is properly sized and managed can help mitigate the effects of degradation, prolong battery life, and ensure the long-term viability of the system. The decision to implement time shifting and peak shaving should be informed by a thorough economic analysis that considers factors such as energy price, demand and revenue streams. BESS developers and operators usually rely on the forecast and analysis from aggregators and optimisers to capture revenue lines that might otherwise be missed.

Arbitrage

Energy arbitrage is a financial strategy that leverages temporal variations in electricity prices to buy energy during low-cost periods and sell it when prices are higher. In co-located solar PV and BESS, arbitrage involves storing excess solar energy generated during daylight hours, when demand and prices are typically lower, and discharging this stored energy during periods of higher demand, such as in the early morning and evening. By exploiting these price differentials, solar PV + BESS enhance both resource utilisation and economic profitability, making them more financially attractive to investors and developers alike.

In the UK, solar PV generation typically peaks during midday when the sun is at its highest, coinciding with periods when demand might not be at its peak. During these times, energy prices are often lower because supply exceeds demand, especially in regions with significant solar generation. Conversely, in the early morning and evening, demand generally rises as residential and commercial consumers increase their electricity use, leading to higher prices. By strategically storing solar energy during low-price periods and selling it when prices surge, solar PV + BESS can yield substantial profits from these cyclical market fluctuations.

Implementing arbitrage strategies with solar PV + BESS requires careful consideration of both technical and operational factors to optimise revenue. Key considerations include:

1. Battery Efficiency and Cycle Life. Each cycle of charging and discharging the battery degrades its overall capacity, which means that frequent cycling to capture price differentials must be weighed against the potential impact on the battery's operational life. High-efficiency, long-lasting batteries are thus crucial for maximising profits while maintaining the system's viability over time.

2. Round-Trip Efficiency. This measures the amount of energy retained from charge to discharge and is a critical factor in determining the financial viability of arbitrage. Energy losses during the conversion and storage processes can reduce the net energy available for sale, impacting profitability. Systems with higher round-trip efficiencies are generally more effective in arbitrage scenarios, as they enable greater retention of stored energy and, consequently, higher revenue potential.

3. Market Price Forecasting and Optimisation. Successful arbitrage relies on accurate market forecasting and predictive analytics to determine optimal charge and discharge times. Advanced algorithms and models must be employed to analyse historical price data and predict future trends, enabling operators to schedule storage and dispatch activities in a way that maximises financial returns. This role, as per the time shifting and peak shaving, is usually performed by aggregators and optimisers.

Solar PV + BESS that engage in arbitrage can help mitigate the issue of solar curtailment, where solar energy generation is reduced to avoid overloading the grid. By storing excess solar generation, these systems prevent energy wastage and allow operators to profit from energy that would otherwise be curtailed, further enhancing overall system efficiency.

Capacity Firming

Capacity firming aims at stabilising power output to ensure a consistent and reliable energy supply. In solar PV + BESS configurations, capacity firming addresses the intermittent and variable nature of solar energy by leveraging energy storage to smooth out fluctuations and maintain a stable power supply. By storing excess solar generation and discharging it as needed, the BESS can provide supplemental power to bridge gaps in solar output caused by weather variations, diurnal cycles, or unexpected events. By integrating BESS with solar PV, operators can transform variable solar generation into a more predictable and manageable power source. This is especially beneficial for meeting contractual power delivery obligations, supporting grid resilience, and enhancing the market competitiveness of solar energy.

In capacity firming, the BESS stores surplus solar energy during periods of high generation. During times when solar output dips, whether due to cloud cover, sunset, or sudden weather changes, the BESS discharges the stored energy to compensate for the shortfall, thus maintaining a stable power output. This mechanism ensures that power delivery remains consistent and aligned with demand, regardless of solar generation variability.

Capacity firming also contributes to frequency and voltage regulation by supplying or absorbing power in response to grid conditions. Solar PV + BESS can modulate power output to maintain grid stability, helping to balance supply and demand fluctuations. By responding rapidly to grid frequency changes, these systems support grid operators in maintaining optimal operating conditions, which is crucial for preventing issues like voltage sags, frequency deviations, or even blackouts.

Many solar projects operate under Power Purchase Agreements (PPA) that specify minimum delivery commitments or require a consistent level of output. Capacity firming enables solar PV + BESS to meet these contractual requirements by ensuring that power delivery remains stable and predictable. In this way, capacity firming not only enhances grid stability but also helps project operators avoid penalties or additional costs associated with underperformance.

Capture Clipping

Solar clipping refers to the utilisation of excess solar energy generated by the PV system that cannot be immediately converted or exported to the grid due to limitations at the point of connection (POC) or inverter capacity. This excess energy, often termed "clipped" energy, would typically go to waste. However, by co-locating BESS with solar PV, this surplus power can be stored in the batteries, and then be discharged when needed. Capturing and utilising clipped energy increases overall system efficiency, maximises energy production, and enhances the profitability of the solar PV + BESS configuration.

Solar PV systems are frequently designed with an oversized DC capacity relative to the AC capacity of the inverter, known as the DC/AC ratio. This is done to extend the production curve, as PV modules can generate more power than the inverter is capable of converting at peak times. When solar irradiance is high, the excess energy that exceeds the inverter's capacity is clipped and is thus unavailable for immediate export to the grid. Through the co-location of the BESS, this excess DC energy can be stored and converted later, allowing the system to capture otherwise lost energy and discharge it during periods of lower solar generation or higher demand.

At times, PV systems might be required to curtail output to avoid overloading the grid or exceeding POC limitations. For instance, during peak solar generation, local grid constraints may limit the amount of energy that can be exported, forcing a portion of the generation to be curtailed or clipped. By utilizing BESS, the curtailed energy can be stored for later use, thereby mitigating energy losses and aligning generation with grid capacity constraints. This stored energy can be discharged during generation non-peak hours (early morning and evening) when grid capacity becomes available or when demand and prices are high.

By capturing clipped energy, solar PV + BESS systems can enhance their total energy yield, translating into higher revenues. This revenue stream can significantly enhance the financial performance of a PV project, helping to justify the initial investment in BESS and improve overall project economics.

The potential for capturing clipped energy depends on factors such as the sizing of the PV array, the inverter capacity, and the BESS capacity. Oversizing the PV system relative to inverter capacity increases the amount of clipped energy available but may necessitate a larger and more costly BESS to store it. A thorough economic analysis is essential to determine the optimal system configuration that maximises returns without over-investing in storage capacity.

The practice of capturing clipped energy may result in increased cycling of the BESS, which can impact battery life and maintenance costs. Frequent cycling can lead to accelerated degradation of battery components, potentially shortening the system's lifespan. To manage this, operators must consider the trade-off between maximising energy capture and minimising wear and tear on the battery. Predictive maintenance strategies, along with robust warranties or extended service agreements, can help mitigate these risks and ensure the long-term viability of the storage system.

Solar PV + BESS Configurations

The integration of BESS and solar PV can be achieved through two primary configurations, AC coupling and DC coupling. Each configuration has its own set of technical and economic considerations, and the choice between them should be informed by the specific project requirements, business model, and preferred revenue streams.

AC-coupled PV + BESS

An AC-coupled configuration integrates solar PV and BESS on the AC side of their respective inverters, connecting both to the grid through a shared connection point. This configuration is characterised by its flexibility, as it allows the solar PV and BESS to operate independently while sharing a common grid connection. In AC coupling, the solar PV system and BESS each have their own inverter, which converts the direct current output from each system into AC power before feeding it into the grid or powering loads. The shared grid connection allows for independent control and optimisation of both assets, which can be advantageous in various applications and market scenarios.

In an AC-coupled configuration, the solar PV and BESS systems function autonomously with their inverters. The solar PV system generates DC electricity that is converted to AC by its inverter for immediate use, export to the grid, or delivery to the BESS. Equally, the BESS can charge either from the grid or from the solar PV system, storing energy during periods of low demand or low electricity prices and discharging it when demand peaks or prices are favourable. Each set of inverters can be controlled independently, allowing for optimised operation based on the specific requirements of the PV system or the BESS.

Since both the solar PV and BESS are connected to the grid at the AC level, each asset can export power directly to the grid without relying on the other.

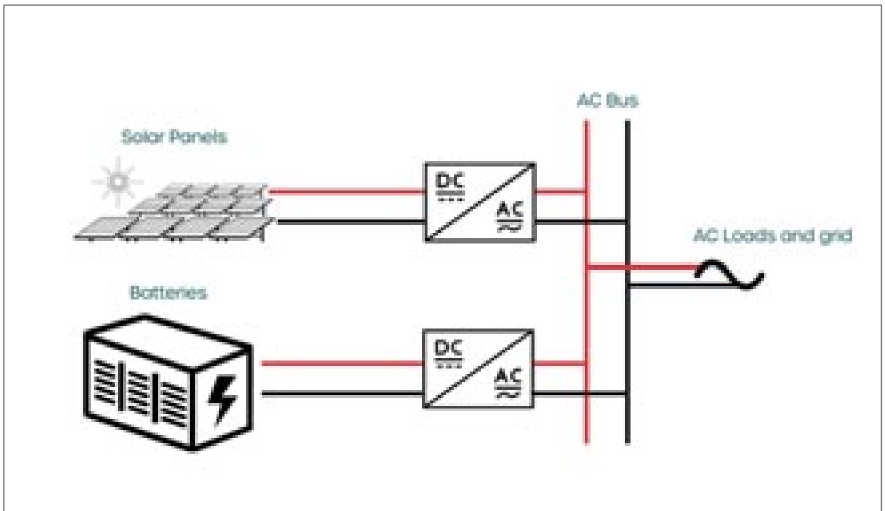

Figure 1. AC-coupled Battery Storage System

This direct connection to the grid offers significant operational flexibility, allowing the BESS to provide additional services, such as frequency regulation or ancillary grid support, independently of the solar PV system. This ability to interact directly with the grid makes AC-coupled systems well-suited for participation in various energy markets, including arbitrage, demand response programs, and other grid services such as spinning reserve, reactive power support, and black start capabilities, which are valuable to grid operators and can generate additional revenue for the project. This capability is especially beneficial in markets with high renewable penetration, where grid stability services are increasingly in demand.

One of the primary benefits of an AC-coupled configuration is its modularity. Because the solar PV and BESS operate independently, it is relatively easy to add or scale each component without significantly impacting the other. This flexibility makes AC-coupled systems highly adaptable.

Although AC-coupled systems offer flexibility, they require import grid capacity, usually not available unless the grid is upgraded. Also, AC-coupled systems are often associated with additional conversion losses due to the need for multiple DC-AC and AC-DC conversions. For example, when charging the BESS from the solar PV system, energy must be converted from DC to AC and then back to DC, which can lead to cumulative losses and reduce the round-trip efficiency of the system. While these losses are typically modest, they can impact the overall efficiency and cost-effectiveness of the system, particularly in projects with high energy storage requirements.

The need for separate inverters and associated infrastructure can increase the initial capital expenditure for an AC-coupled system compared to a DC-coupled configuration. Each inverter requires its own installation, maintenance, and protection equipment, which can contribute to higher upfront costs and ongoing operational expenses. Additionally, the transformer and protective devices required for the shared grid connection can add to the complexity and cost of the system, particularly for large-scale installations.

AC-coupled systems are also generally less efficient at capturing clipped energy(see above). In a DC-coupled system, this excess energy can be diverted directly to the BESS for storage, whereas in an AC-coupled system, this energy is often lost unless the inverters are significantly oversized. As a result, AC-coupled systems may experience lower overall energy capture, particularly during periods of high solar irradiance when the solar PV system is generating at or near its maximum output.

AC-coupled configurations are ideal for retrofitting existing solar PV systems with energy storage capabilities. By adding a BESS to an established solar PV installation, operators can enhance the system's performance without requiring significant changes to the original setup. This approach is particularly attractive in mature solar markets where existing infrastructure can be leveraged to meet evolving energy demands or participate in new market opportunities.

DC-coupled PV + BESS

A DC-coupled configuration integrates solar PV and BESS at the direct current level, allowing both systems to share a common set of inverters and electrical infrastructure, lowering equipment costs and simplifying system design. The reduced complexity also translates into lower maintenance costs, as there are fewer points of failure to manage over the system's operational lifetime.

In this setup, the solar PV and BESS are connected via a DC bus, where their outputs are combined before being converted to alternating current by shared inverters. This configuration is known for its high efficiency, as it minimises the number of conversion stages,

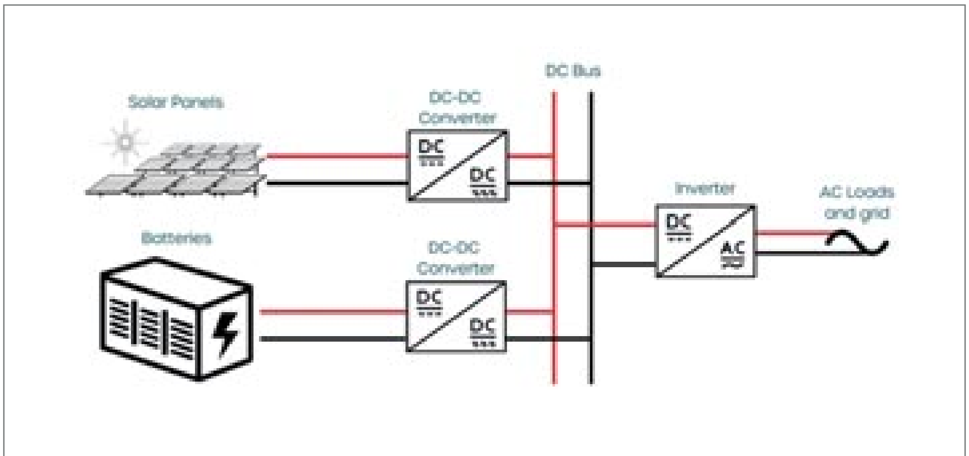

Figure 2. DC-coupled Battery Storage System

reducing energy losses and improving overall system performance.

DC coupling also enables the direct transfer of energy from the solar PV system to the BESS without the need for intermediate DC-AC and AC-DC conversions, as is required in AC-coupled systems. This capability reduces conversion losses and enhances the overall efficiency of the system, making it especially advantageous in applications where energy efficiency and conservation are critical. The DC bus serves as the central point for managing energy flows, allowing excess solar generation to be directly stored in the BESS or converted to AC for export to the grid, depending on the system's real-time requirements.

The solar PV system's voltage is influenced by factors such as irradiance and panel configuration, while the BESS voltage is determined by its state of charge and internal configuration. Since the voltage levels of the solar PV and BESS differ, a DC-DC converter is required in DC-coupled systems to harmonise these voltages at the DC bus. Additionally, a SCADA unit is needed to control these synergies. The DC-DC converter plays a crucial role in synchronising these voltages, ensuring that the energy flows smoothly between the solar PV and BESS and that the combined output is suitable for conversion to AC at the inverters.

DC-coupled systems are inherently more efficient than AC-coupled systems because they avoid multiple conversion stages, minimising losses and improving round-trip efficiency.

One of the key advantages of DC-coupled systems is their ability to capture "clipped" energy, enhancing the overall energy capture of the solar PV system, increasing its effective capacity and improving project economics. In addition, these systems do not require a separate AC import, removing the need to upgrade the grid with the relevant cost and time implications.

DC coupling is particularly well-suited for new installations or projects where the solar PV and BESS are designed to function as an integrated system and is ideal for applications that prioritise efficiency and rely on solar energy as a primary power source. Unlike AC-coupled systems, which allow the solar PV and BESS to operate independently, the dependency between solar PV and BESS in DC-coupled systems can limit the ability of the BESS to provide certain grid services, such as frequency regulation or other ancillary services. Managing the voltage levels within a DC-coupled system can be complex, particularly as the voltages of the solar PV and BESS fluctuate based on operating conditions.

The reliance on a single set of inverters in DC-coupled systems creates a potential single point of failure. If the inverters experience a fault or require maintenance, both the solar PV and BESS components may be temporarily offline, impacting the system's ability to generate or store energy. While redundancy measures can be implemented, such as the use of backup inverters or bypass mechanisms, these measures can add to the overall cost and complexity of the system.

Conclusions

The integration of BESS with solar PV represents a crucial advancement in renewable energy technology, addressing the inherent variability of solar power and enabling more efficient, reliable, and profitable energy systems. As the demand for clean energy solutions continues to rise, co-locating BESS with solar PV offers a versatile and scalable approach to meet the evolving needs of both grid operators and consumers. By facilitating energy storage, time-shifting, and various value streams, solar PV + BESS systems enhance grid stability, optimise energy dispatch, and create new revenue opportunities, making them a vital component of the modern energy landscape.

When evaluating the optimal configuration for solar PV + BESS, stakeholders must carefully weigh the benefits and trade-offs of AC versus DC coupling. Each approach offers unique advantages that cater to different project goals and operational requirements.

The financial viability of co-located solar PV + BESS systems hinges on several factors, including capital costs, operational efficiencies, market conditions, and regulatory frameworks. Both AC and DC coupling configurations offer unique financial implications.

As the energy market evolves, with increased penetration of renewables and a greater emphasis on grid resilience, the demand for flexible, reliable, and responsive energy systems will intensify. Solar PV + BESS, with their ability to provide firm capacity, reduce peak demand, and facilitate energy arbitrage, are well-positioned to play a pivotal role in this transition.

As governments and organisations around the world commit to ambitious decarbonisation targets, solar PV + BESS will be instrumental in reducing reliance on fossil fuels and supporting the integration of other renewables like wind and hydro. Their ability to store and dispatch clean energy during periods of high demand will enhance their role in global efforts to achieve net-zero emissions.

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