Solar + Storage as a Mid-Merit, Utility-Scale Generating Asset[1]

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Executive Summary

In recent years, a consensus has emerged across the energy industry – and among regulators – that utility-scale solar-plus-storage (S+S) is now an economically viable alternative to natural gas peaker plants. In this study, we take the next step. We ask under what conditions, if any, S+S can compete against the mid-merit, load-following capabilities of natural gas combined cycle (NGCC) power plants. Based on analysis of data from 435 NGCCs across the United States, we find that such conditions exist for several regions of the country.

For example, a hypothetical S+S facility in the California Independent System Operator (CAISO) service territory would have a net levelized cost of energy (net LCOE, defined below) of $39-$48 per megawatt-hour (MWh). In this example, the S+S is sized with storage of six-hour duration, provides ancillary services and uses the full 30% federal investment tax credit. The net LCOE for a comparable NGCC plant is $60-$116 per MWh. The range of LCOE for the two technologies is due to the high variability in the dispatch profiles we found for existing NGCC plants.

[1] ***Important Notice:*** This document is part of an industry-sponsored project that was completed in the fall of 2018 by a group of MBA students from Carnegie Mellon's Tepper School of Business. The industry sponsor was Fluence Energy, LLC. The methods, models, and results of this analysis are localized to the scope of that project and are in no way exhaustive in identifying methods and structures to solve the project scope. The members of the student team were Matt Beers, Panagiotis Bourtsalas, Ben Cerroni, Dave Deckelman, Brian Freeman, Zack Lippert, Tom Reeves. The faculty supervisors were Jay Apt and Chris Telmer.

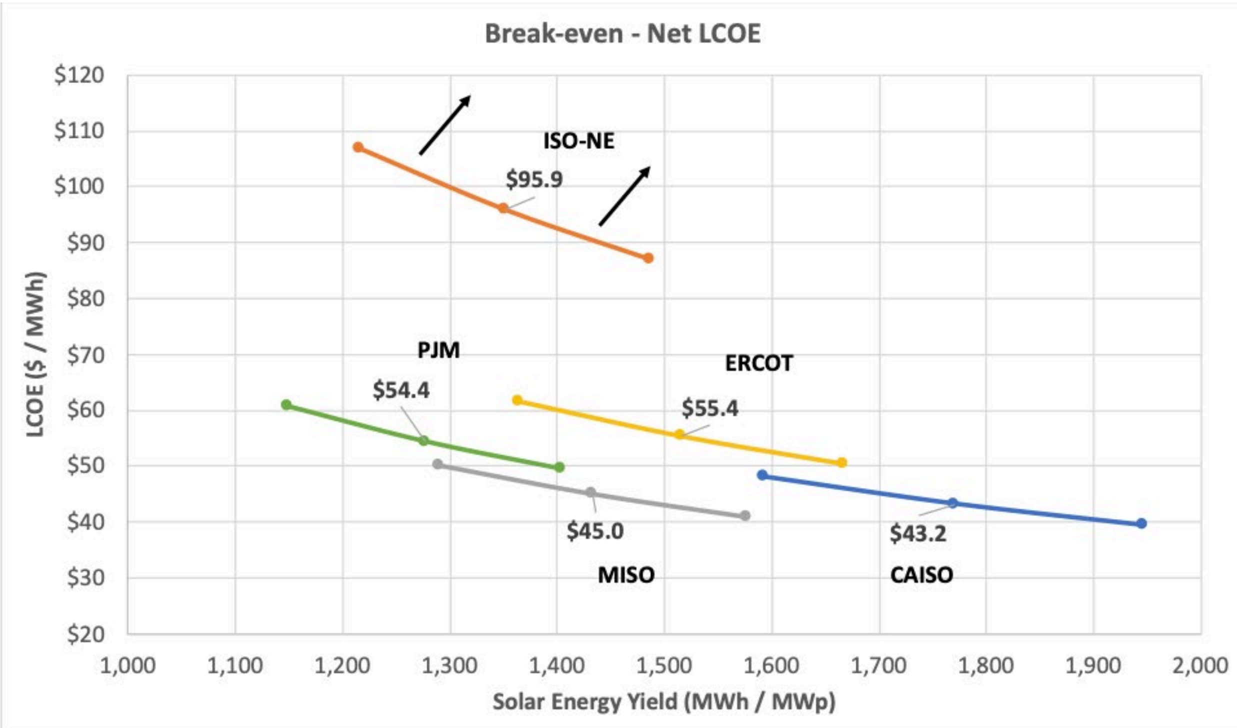


Figure A: Break-Even Frontier for Cluster 1 (Net LCOE)

The study methodology was developed by MBA students at the Tepper School of Business at Carnegie Mellon University, based on three innovative approaches.

- **A "jobs to be done" framework:** Though widely used in the business world as a driver for innovation and new product development, this customer-centric approach – based on finding out what customers want – has not been widely applied in the energy industry and specifically not to the analysis of generating facilities. In this study, we define the demand profiles of different types of NGCC plants – that is, what they actually do -- as "jobs to be done" and then compare them with an S+S facility sized to perform that "job."

- **Clustering:** As part of the "jobs" framework, we obtained hourly generation and capacity data for 435 existing NGCC plants in the U.S. from the Environmental Protection Agency (EPA) Air Markets Program. We then developed a clustering algorithm, which resulted in six groups or "clusters" based on the similarity of their power generation profiles see (see Appendix 1). The generation profiles of these clusters represent the different "jobs" these NGCC plants perform in their respective power markets. Five of the six clusters produced load profiles that then required an S+S facility with storage providing six hours of duration; only one required storage with a four-hour duration.

- **Net LCOE:** While the levelized cost of energy (LCOE) has long been the standard measure for comparing costs of different forms of generation, its use for valuing S+S has raised concerns. On the one hand, S+S projects are not sized to reflect what a comparable NGCC plant does, resulting in what some critics say is an unfairly low

LCOE. Others have argued that the S+S LCOE is overvalued because it provides benefits that thermal generation cannot. To solve this dilemma, we develop a metric we call the “net LCOE,” which differs from gross or traditional LCOE by factoring in the additional benefits, such as ancillary services, that an S+S or thermal asset provides to the grid and subtracts them from the numerator of the traditional LCOE equation (see Methodology section below).

Combining these approaches, we then map out scenarios comparing S+S and NGCC plants in service territories of five independent system operators (ISOs) and regional transmission operators (RTOs) across the U.S. The five are CAISO, Midcontinent Independent System Operator (MISO), PJM Interconnection (PJM), the Electric Reliability Council of Texas (ERCOT) and ISO New England (ISO-NE).

Our findings encompass a variety of different assumptions about potential revenue streams and the specifics of what mid-merit generation facilities actually do.

- **Net LCOE:** Given the current formulation of the ITC, and if revenue streams from ancillary services are maintained in their current form for the next 30 years, S+S is cost-competitive performing the same “jobs” as mid-merit NGCCs in the CAISO, MISO, ERCOT and PJM markets. In ISO-NE, S+S can compete in only one out of the six different “job” types.
- **Net LCOE (no freq reg):** Since the frequency regulation market is one of the smaller markets for ancillary services, we analyze a scenario in which the value of frequency regulation drops to zero as more and more storage is connected to the grid. In this scenario, S+S can compete with NGCCs in CAISO and ERCOT in all but one “job” type, and in ISO-NE, MISO and PJM, in one case only.
- **Gross LCOE:** If no ancillary service revenue streams are included, S+S can compete with NGCCs in some cases in CAISO, and in only one case in ERCOT.

We also examine the levelized savings of an S+S solution compared to an NGCC plant under the same technical and financial scenarios. Levelized savings are defined as net $LCOE_{NGCC}$ – Net $LCOE_{S+S}$. Positive values for levelized savings can be interpreted to mean that S+S is more economically viable. Again, CAISO remains competitive for S+S over NGCC, even without the support of the federal ITC and using S+S cost assumptions for a 2020 date for commercial operation.[2]

Based on these findings – and our analysis of the supporting data – the following considerations may become increasingly essential for utilities and planners evaluating different technologies to provide load-following generation:

[2] We use $1,100 per kilowatt (kW) and $1,500/kW as capital costs for four-hour and six-hour duration storage, respectively, with commercial online dates of 2020.

- It is critical to accurately describe the “jobs” that a new mid-merit generation asset is needed to do. Such descriptions are necessary to size and configure an S+S asset so it can be accurately compared to an NGCC on a net LCOE basis.
- The net LCOE methodology described in this paper allows a utility to compare different technologies on an apples-to-apples basis, which is necessary to value the benefits of an S+S facility with a comparable NGCC plant.
- The methods used in this paper to value mid-merit generation resources are flexible and extensible. Net LCOE can be modified to include additional benefits that are not considered here, such as a carbon price or ramping service.

Note on terminology
A mid-merit or load-following plant is one that adjusts its output in response to daily fluctuations in power demand, as opposed to a peaker plant, that is brought online to meet sudden or steep ramps in demand (as seen in the California duck curve). In general, power from load-following plants is valued at a mid-range price, versus the often very expensive cost for peaking power.

Solar + Storage as a Mid-Merit, Utility-Scale Generating Asset

Introduction

Solar plus storage (S+S) has previously been shown to be economically competitive with natural gas peaker plants. The next logical question is whether S+S can move to the subsequent level of generation assets, namely, mid-merit, load-following plants. The goal of this project is to identify if and under what circumstances S+S can compete technically and financially with mid-merit natural gas combined cycle (NGCC) power plants – and ultimately replace them. To answer this question, we applied a "jobs to be done" framework to how NGCC plants operate and the services or "jobs" they perform on the grid. Specifically, we analyzed the time and level of operation (capacity factor) of 435 NGCC plants over the course of a year. With this information, we determine whether given types of NGCC plants' generation can be replaced with S+S, and the parameters within which S+S can compete on economic grounds with NGCC plants.

Methodology

To begin our analysis, we use a "jobs to be done" framework, according to which we identify what services ("jobs") NGCC plants perform for the grid. Though widely used in the business world as a driver for innovation and new product development, this customer-centric approach – based on finding out what customers want – has not been widely applied in the energy industry and specifically not to the analysis of generating facilities. Our goal is to identify archetypal production curves – "jobs" -- against which we match an S+S solution.

We apply this framework to plant production data from the U.S. Environmental Protection Agency (EPA) for 435 NGCC plants across the United States. We then identify groups, or "clusters," of these plants that have similar generation profiles and use these profiles to examine the technical and financial feasibility of the S+S solution.

Hourly generation level, represented by an hourly capacity factor, is used rather than hourly production in order to minimize the effect of plant size (nameplate capacity) on the analysis. Understanding that plants with higher utilization (annualized capacity factor) generate higher returns than plants that are underutilized, we identify how each plant operates against its theoretical maximum.

We use k-means cluster analysis to group together plants with similar generating profiles. Initially, our algorithm generated fifteen clusters from the 435-plant data set.[3] After analyzing

[3] The set of generating profiles for NGCC plants comes from the EPA Air Markets Program Data. URL: https://ampd.epa.gov/ampd/

those clusters, we removed three from our dataset, as they had high capacity factors, indicating that they operate as base load plants.

The remaining 270 plants --- representing 62% of the total number of plants located in 40 states --- have capacity factors below 50%. A second analysis of these plants results in eight clusters. Within the eight, six of the clusters display characteristics of mid-merit generation (Appendix 1), with the other two clusters having low capacity factors, indicating they are peaker plants. A summary of the eight clusters is shown in Figure 1.

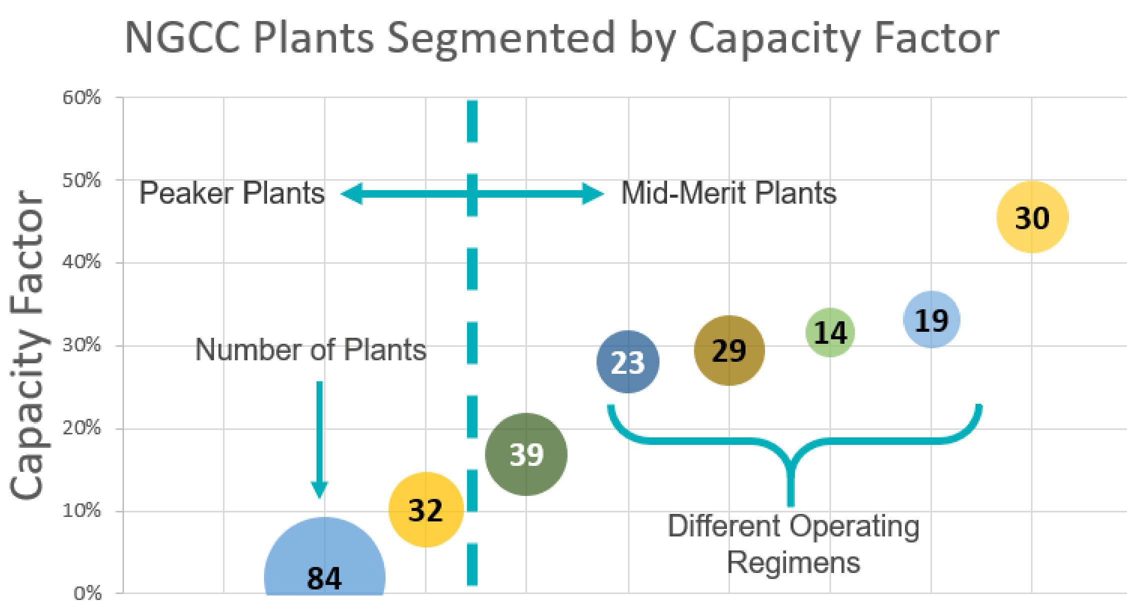


Figure 1 – NGCC Power Plant Cluster Summary. Numbers indicate the number of plants in each of the eight clusters, six of which are mid-merit shoulder plants.

With six mid-merit clusters identified, we create financial models to compare the costs and benefits of building and operating an NGCC plant with those of an S+S plant. The levelized cost of energy (LCOE) is the standard measure for comparing different forms of generation; however, it can be calculated in different ways, and its use for valuing S+S has been problematic.

On the one hand, S+S projects are not sized to reflect what a comparable NGCC plant does, resulting in what some critics say is an unfairly low LCOE. Others have argued that the LCOE for S+S may be too high because S+S provides benefits that thermal generation cannot. More to the point is the basic contention that since storage has a finite duration and solar only produces energy during the day, S+S cannot be fairly compared to NGCC, which can run continuously as long as gas is supplied.

This critique of storage as a peaking resource has been put to rest as utilities continue to select storage – either standalone or paired with renewables -- over traditional thermal peakers.[4] The story is more complicated for mid-merit generation resources since their use patterns are more varied than peakers. Our solution is to match the dispatch of a S+S asset to the "clusters" of NGCC profiles described above before comparing them on a cost basis. Five of the clusters required S+S assets with storage of six-hour duration, while only one cluster (Cluster 5) had storage duration of four hours.

We then develop a metric we call the "net LCOE," which differs from gross or traditional LCOE by factoring in the additional benefits, such as ancillary services, that an S+S or thermal asset provides to the grid and subtracts them from the numerator of the traditional LCOE equation.

The difference is illustrated in equations below:[5]

$$LCOE\ [\frac{\$}{MWh}] = \frac{\text{CAPEX} + \text{NPV(OPEX)}}{\text{Energy Delivered (MWh)}}$$

$$Net\ LCOE\ [\frac{\$}{MWh}] = \frac{\text{CAPEX} + \text{NPV(OPEX)} - \text{NPV(Freq. reg.} + \text{Spinning reserve} + \text{Other benefits)}}{\text{Energy Delivered (MWh)}}$$

To undertake the financial comparison, we then use the net LCOE as the appropriate metric to compare energy resources such as NGCC plants, versus capacity resources such as peaker plants.

Participation in ancillary services or real-time and day-ahead markets is also assumed for both NGCC and S+S plants. Ancillary service prices and regimes vary significantly across different markets. In addition, how ancillary service prices may evolve in the future remains uncertain, as we already see market saturation in certain cases, especially in the frequency regulation market.

To account for this market variability, we generate results based on three different LCOE variants:

- **Net LCOE**: Assuming participation in all ancillary services and energy sales.

[4] As supported by Arizona Public Service Corporation's (APS) February procurement of 850 MW of energy storage, following on the heels of the utility's 2018 procurement of 50 MW of energy storage and solar peaker, the arguments against energy storage as a peaking resource are dwindling. Analysts from across the energy industry widely view energy storage as being able to beat traditional peakers economically. Fluence's Ray Hohenstein has shown that "range anxiety" or concern over the duration limitation of energy storage can be assuaged by analyzing the peaking need and matching resources appropriately.
[5] Detailed LCOE and net LCOE equations are provided in Appendix 2.

- **Net LCOE (No freq reg)**: Assuming participation in energy sales and all ancillary services, except for frequency regulation.
- **Gross LCOE:** Assuming no participation in ancillary services, just energy sales.

In this way, we can quantify the effect of participation in frequency regulation services and overall ancillary services on the economics of each plant (see Appendix 2).

The models use the hourly generation profiles from the clusters to determine how much energy must be supplied and for how long by an S+S system to match the output of a typical NGCC plant in each cluster. These profiles and the solar generation of particular locations determine the size of an S+S array that would be required to match the output of a 100-megawatt (MW) NGCC power plant. The models incorporate revenues from both energy sales and ancillary services.

To capture the variability of ancillary service prices across different ISOs and RTOs, we run each of our model's variants in each of the five different regions: CAISO, ERCOT, MISO, PJM and ISO-NE. The key to successfully replicating the NGCC plant generation profile is the load-shifting capability that the energy storage system provides to the solar asset. With this capability, an S+S asset can provide the grid a more controllable ramp-up and ramp-down, comparable to what a mid-merit plant offers. Figure 2 shows the ability of the S+S asset to match the NGCC generation profile during a representative day in July.

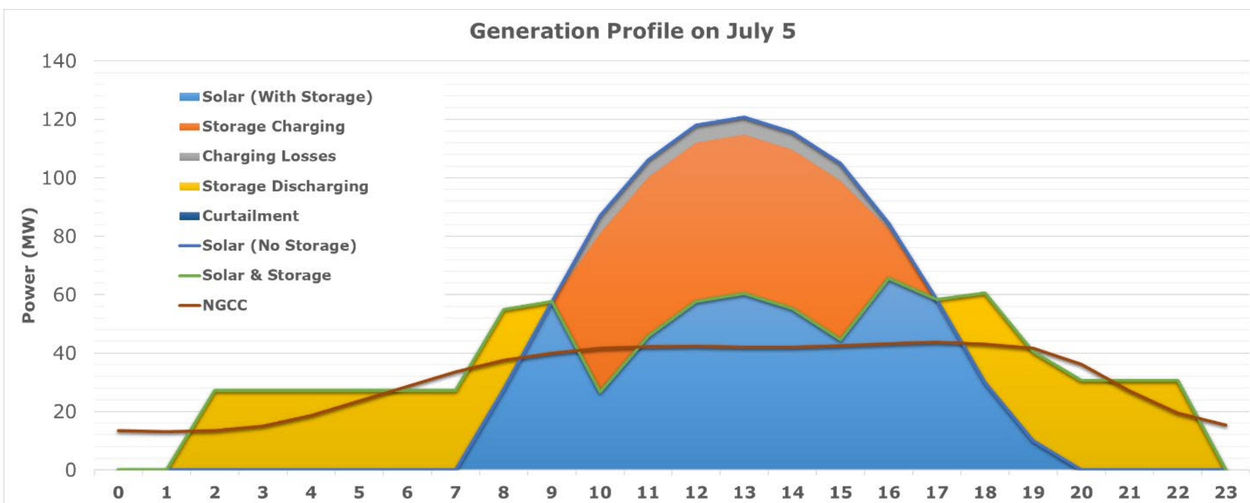


Figure 2 – Load Shifting with S+S versus NGCC, Cluster 1, CAISO

To draw a fair comparison, the S+S and NGCC models include the same high-level assumptions for project development. The modeled power plants all have 100 MW of AC output. The project lifetime is assumed to be 30 years, with the first year of operation beginning in 2020. The cost of equity is 10%, and no debt financing is used. Because NGCC and S+S plants have different technical limitations, the revenues from energy sales and ancillary services are calculated differently for each technology.

Three components are considered when calculating the revenue from ancillary services: economics, technology and flexibility. The S+S model optimizes the participation of the batteries to achieve the highest price. The NGCC model considers the marginal cost of operating the plant according to the efficiency (heat rate) curve of a combined cycle plant.

Both models include technical constraints. The S+S plant – even with a six-hour duration -- is constrained by the state of charge and the level of excess capacity available in either direction (charging or discharging). The NGCC model is constrained by the technical minimum under which a plant can operate and its available capacity in either direction, in this case, either above its technical minimum set point or below its nameplate capacity.

Finally, the flexibility of each technology is modeled. Because the S+S model includes the tax benefits of the ITC, a constraint is placed on the ancillary services calculation, preventing the battery from bidding into ancillary services that would require the battery to charge from the grid for the first five years. The NGCC plant is limited in its ability to bid capacity up and down based on the industry average for ramp rates of a combined cycle facility.

Our final metric, levelized savings, is simply the net LCOE for NGCC minus the net LCOE for the comparable S+S: $LCOE_{NGCC}$ – Net $LCOE_{S+S}$.

Results

We select an area in Arizona with high solar insolation as our first test case, using the generation profile of Cluster 1 NGCC, which includes 14 plants and has an average capacity factor of 31.6%. Since Arizona is a regulated market, the energy prices and value of ancillary services are not publicly available. Therefore, we use prices from the nearest electricity trading node in California as a proxy. The NGCC model uses natural gas prices based on U.S. Energy Information Administration (EIA) projections for the Southwest region.

The calculated net LCOE for the S+S plant is $43.25/MWh, while for the NGCC plant, it is $72.90/MWh (see Figure 3 below). The net LCOE difference is due to three main factors.

- First, as anticipated, utilization (capacity factor) significantly affects the economics of the NGCC plant. Since the Cluster 1 plants have a low capacity factor of 31.6%, the net LCOE of the NGCC model is relatively high.
- On the other hand, the flexibility of the energy storage asset offers opportunities for additional revenue streams from participating heavily in the ancillary services market. Thus, participation in ancillary services represents 52% in the S+S revenue breakdown, as opposed to only 15% for the NGCC plant.
- Assuming construction starts in 2019, an S+S plant can take full advantage of the 30% ITC, further reducing the plant's net LCOE by $26.10/MWh. Without the ITC, net LCOE would be $69.39/MWh, only marginally less than the NGCC shoulder plant for this location. It is worth noting that S+S costs are expected to decline significantly in the

coming years.[6] Even as the ITC phases out through 2023, reductions in S+S costs will improve the combined technologies' economics over NGCC plants.

While the solar asset helps the project's economics by allowing the storage asset to take advantage of the ITC, storage unlocks significant value for solar as well. Breaking down the net LCOE in the above example shows that besides the value provided by participation in ancillary services, storage offers significant value through load shifting.

The waterfall chart in Figure 3 highlights the costs and benefits of adding storage with six hours of duration to a solar array. If we assume that the stand-alone solar asset can sell all the energy generated, then storage improves the net LCOE by $5.12/MWh. However, following the "jobs to be done" framework, and thus selling the energy only when it is valuable (matching the NGCC curve), the storage asset provides a net LCOE reduction of $45.61/MWh. In addition to the quantifiable aspect of the net LCOE, load shifting provides additional value for solar, as it offers the capability to tap into a totally new market: mid-merit generation.

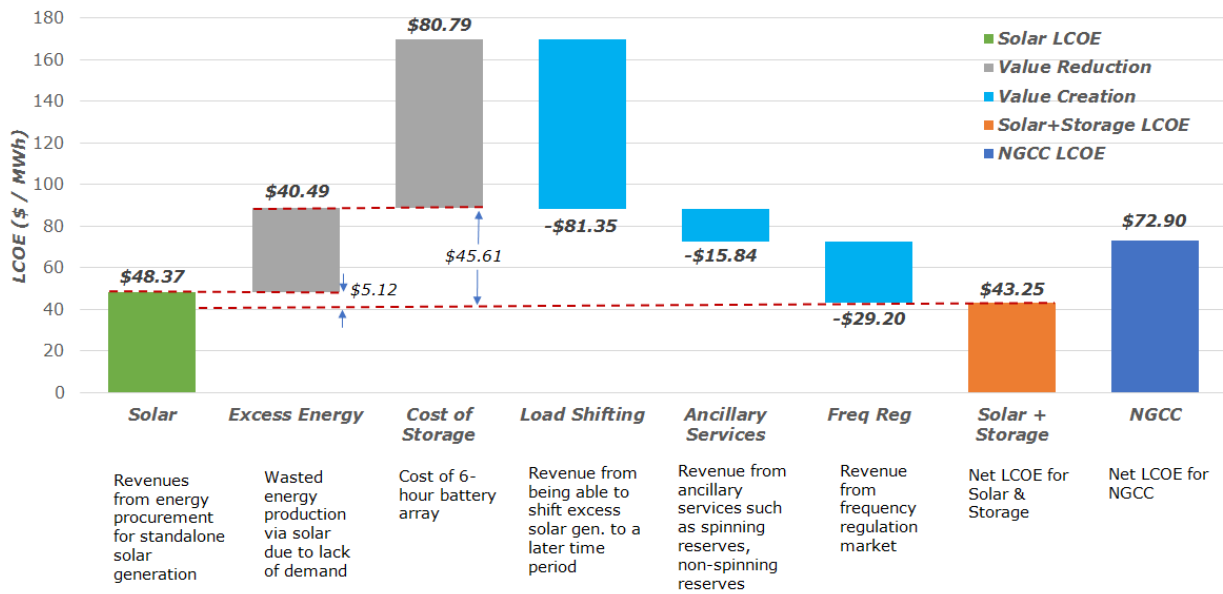


Figure 3: The Value of Storage for Solar (Values rounded to the nearest cent)

We repeat the above comparison for the four other regions, each representing a different ISO or RTO. Since solar irradiance varies across different locations and for different lengths of time, the size of the solar arrays and batteries must be adjusted for each location to match the Cluster 1 energy output. Figure 4 shows the values used for each location.

[6] Wood Mackenzie Power and Renewables forecasts a 6% and 8% annual reduction in all-in cost for front-of-the-meter solar PV and energy storage, respectively, between 2018 and 2022.

Location	Solar			Storage			
	AC Power (MW)	DC Power (MW)	Power Ratio	Storage:Solar Ratio - DC	Power (MW)	Duration (h)	Energy Capacity (MWh)
Arizona	100	170	1.7	0.40	68.0	6	408
Boston	100	220	2.2	0.30	66.0	6	396
Minneapolis	100	200	2.0	0.35	70.0	6	420
Texas	100	190	1.9	0.35	66.5	6	399
Virginia	100	230	2.3	0.25	57.5	6	345

Figure 4: Solar and Storage Sizing Information

Break-Even Frontier

Once the results have been generated for each of the locations, we run a ±10% sensitivity analysis on the energy output of the solar plant for each site to show how selecting sites with higher or lower amounts of sunlight could affect the net LCOE of an S+S plant. Using the above data, the break-even frontier between the S+S and NGCC can be plotted, as shown in Figure 5 below. For each region, the break-even frontier shows the minimum net LCOE under which an S+S plant could economically replace an NGCC.

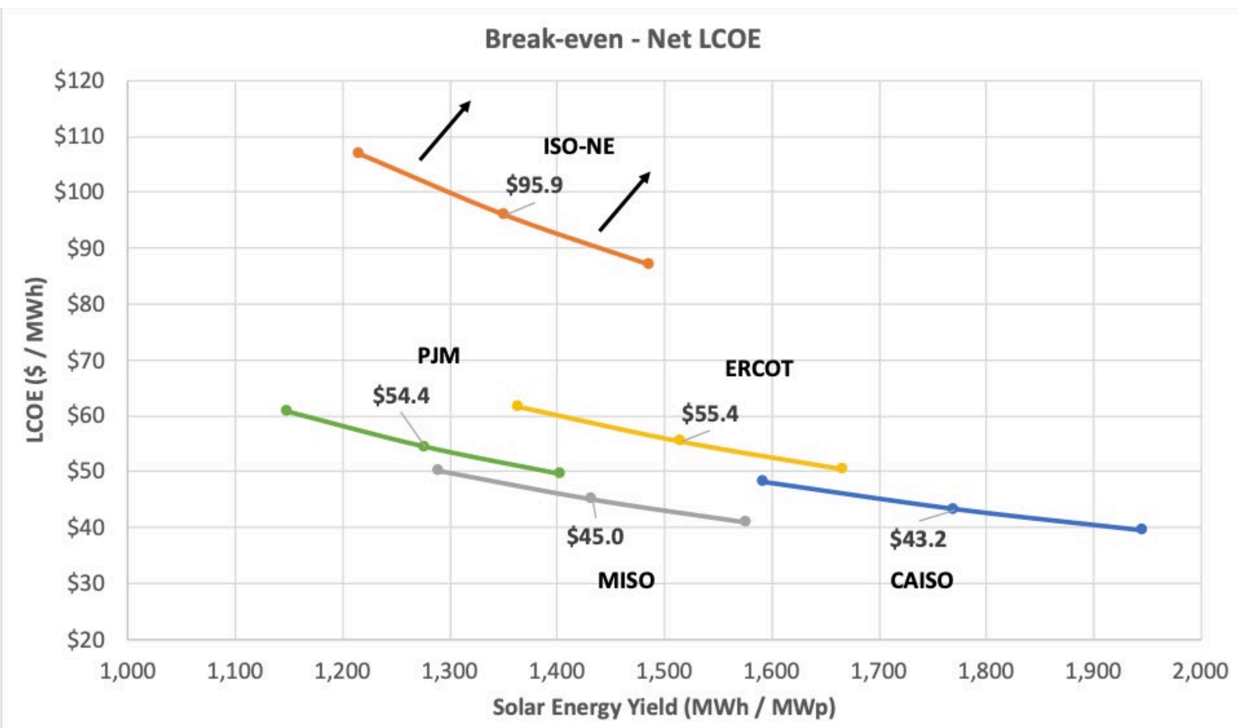


Figure 5: Break-Even Frontier for Cluster 1 (Net LCOE)

The main drivers that affect the break-even frontier are the level of solar energy yield, based on the location; and the existence of lucrative prices for ancillary services, based on the territory. As a result, the lowest net LCOE frontiers are seen in locations either with high solar resources, such as CAISO, or in territories with high prices for ancillary services, such as MISO. The impact of these two factors becomes more obvious when we plot the break-even frontier for each of the three LCOE variants for CAISO and MISO, illustrating the ancillary services effect on the LCOE (Figure 6).

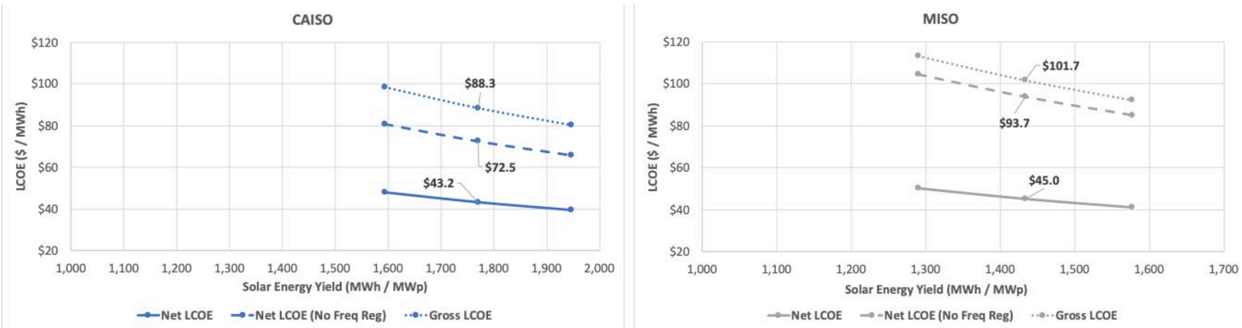


Figure 6: LCOE Ancillary Services Spread for Cluster 1

Additionally, the ITC contributes significantly to the above results across all territories, leading to an average reduction of about 34% in the net LCOE. The effect of the ITC is illustrated in Figure 7, again for CAISO and MISO.

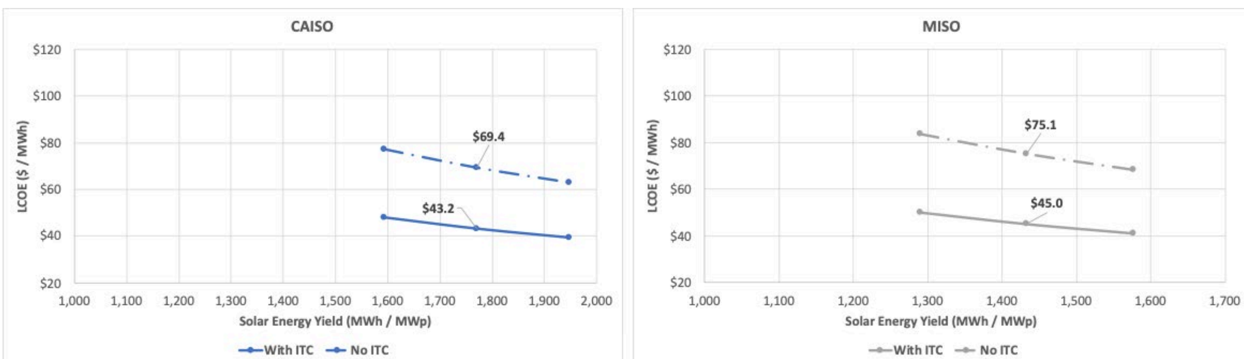


Figure 7: LCOE ITC Spread for Cluster 1 (Net LCOE)

Levelized Savings

The next metric we examine is the levelized savings of an S+S solution compared to an NGCC plant under the same technical and financial scenarios. Levelized savings are defined as net $LCOE_{NGCC}$ – Net $LCOE_{S+S}$. Positive values for levelized savings can be interpreted to mean that S+S is more economically viable. Levelized savings are calculated for net LCOE, net LCOE (No freq reg), and gross LCOE (No ancillary services), as defined in the Methodology section.

Figure 8: Levelized Savings for Cluster 1 (Net LCOE with ITC)

If we strip out the ITC, we can also see more clearly the effect of a solar system with a low capacity factor on the financial performance of the S+S asset. Nevertheless, as noted in Figure 9 below, in locations with high solar irradiance or attractive prices for ancillary services – again, CAISO, and to a certain extent, MISO – an S+S asset can compete financially with an NGCC, even without the ITC, using current cost assumptions for 2020.

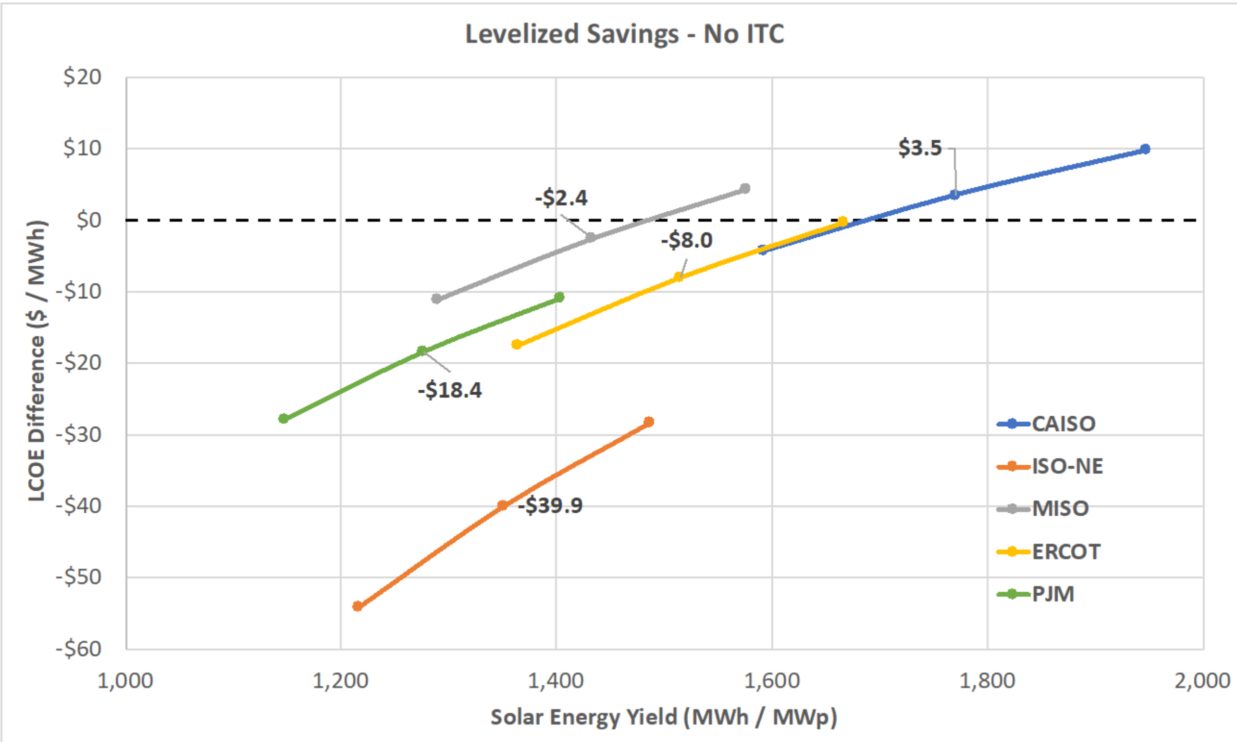


Figure 9: Levelized Savings for Cluster 1 (Net LCOE, without ITC)

Levelized savings are analyzed for all six mid-merit clusters and all five deregulated markets (for a total of 90 levelized savings analyses), with results shown in Figure 10. It is important to note that levelized savings are dependent on and have a positive correlation with solar irradiance, but have a negative correlation to a plant's capacity factor (the percentages shown in red in Figure 10).

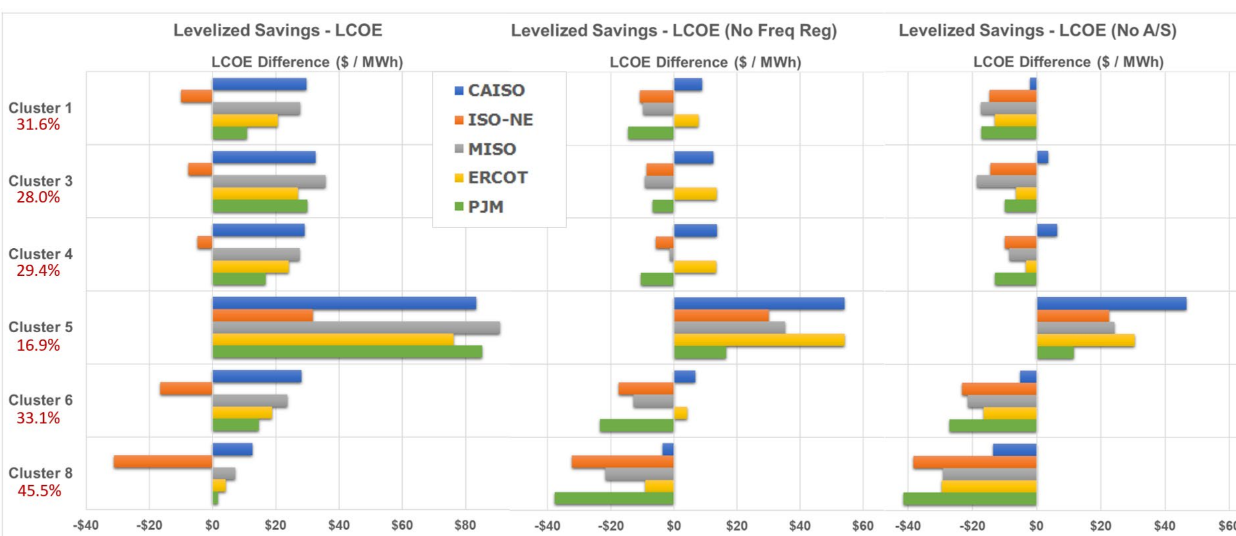


Figure 10: Levelized Savings by Cluster, Market and Ancillary Services Scenario (Percentages = Capacity factors)

Risk and Benefits

Within the mid-merit generation space, S+S offers considerable benefits compared to NGCC plants. In particular, S+S offers flexible operational configurations that cannot be matched by steam and gas turbines. S+S contributes to a company's renewable portfolio standard and state-level energy storage targets. Financially, S+S – specifically, the increased flexibility storage provides -- allows these facilities to bid heavily into ancillary service markets. In addition, the falling cost curve of S+S will continue to make the comparison to NGCC plants even more favorable and will help mitigate the effects of the ITC phase-out in the coming years.

While these benefits are attractive to power generators, S+S also poses inherent challenges; for example, the essential variability of solar irradiance, which can be offset by allowing storage to charge from the grid. Deploying these projects also requires large up-front capital and real estate, both of which can be mitigated through financing and contracting with bankable solar and storage technology providers.

NGCC plants have their own unique benefits and risks when compared to S+S solutions. Like S+S, NGCC plants are dispatchable, meaning they can be turned on at any time and, if needed, can operate 24/7. They also have lower up-front costs, and since natural gas is cheap at present, power generators interested in quicker returns may gravitate toward an NGCC solution.

At the same time, the price of natural gas is volatile and on an upward trend – a definite risk for generators -- which could intensify if demand for liquid natural gas exports continues to grow. Lastly, NGCC plants are affected by regional carbon price legislation and can be subject to penalties due to emissions.

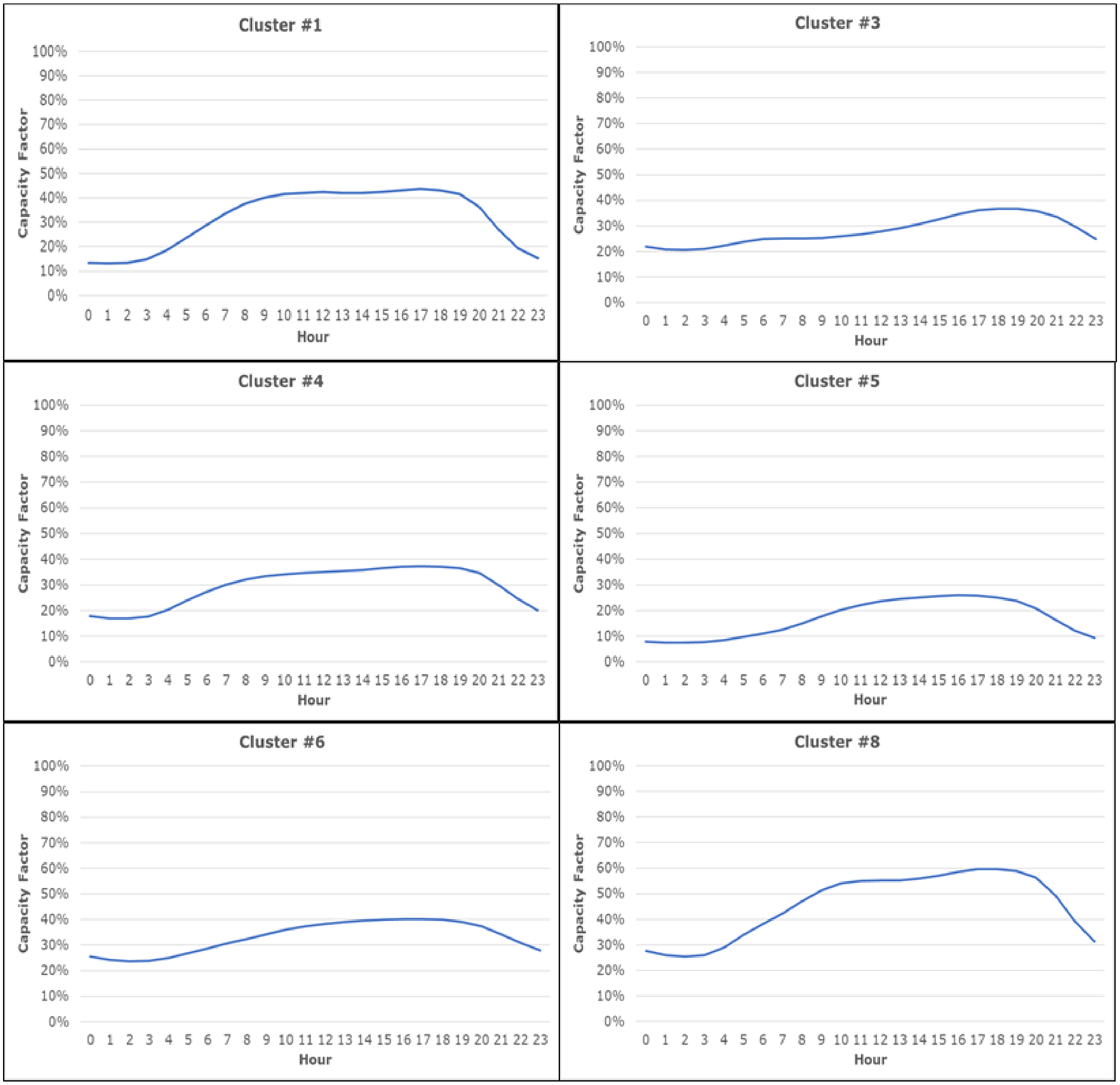
Looking ahead, the considerations derived from this analysis are significant for utilities and planners evaluating different technologies for mid-merit generation.

- It is critical to accurately describe the production profile, or "job," that a new mid-merit generation asset is needed to provide. Careful and detailed description is necessary to size and configure an S+S asset that can be accurately compared with an NGCC plant on a net LCOE basis. Capacity factor alone is insufficient for modeling what a mid-merit resource will do, as highlighted by the clustering analysis of the operating profiles of 435 NGCC plants.
- Using the net LCOE methodology described in this paper allows a utility to compare different technologies on an apples-to-apples basis, which is essential to value the benefits of an S+S facility compared to an NGCC plant.
- Finally, the methods described in this paper to value mid-merit generation and S+S resources are flexible and extensible. Net LCOE can be modified to include additional benefits that are not considered in this paper, such as a carbon price or value of ramping service. It can also be extended to any comparison across different technologies that

provide energy services. For example, net LCOE could be used to compare a fleet of wind, solar, batteries and aggregated demand response to a baseload thermal resource.

Appendix 1: The 6 “jobs” of mid-merit NGCC generation

Each of the following generation profiles represents the average hourly generation of the typical NGCC plant that the clustering algorithm associated with each of the six clusters that it identified. Aside from what is visually apparent --- Clusters 1 and 8 ramp up relatively early in the day, for example, with Cluster 8 being higher capacity --- we were unable to associate systematic characteristics with each cluster. For example, we ran regressions involving dummy variables for each of the states in which the plants were located, the existence and intensity of renewable portfolio standards, the penetration of wind and solar in the plants’ ISO or RTO region, the distance to load, and other variables. We were unable to reliably correlate such variables to the six clusters. Therefore, the reader should simply interpret our cluster analysis as having identified reliable, reduced-form patterns in the generation profiles --- the “jobs” – that constitute our dataset.


Cluster #1
Cluster #3
Cluster #4
Cluster #5
Cluster #6
Cluster #8
Capacity Factor
Hour
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

Appendix 2: LCOE Variants

Summary table for LCOE variants

Notation used in paper	Revenue Streams			Description	Notes
	Energy Procurement	Ancillary services			
		Frequency Regulation Service	Other Ancillary services (except Freq reg)		
Net LCOE	Yes	Yes	Yes	Assuming the asset sells energy into the grid and bids into all ancillary services, including frequency regulation	Captures the case where the current ancillary services prices persist
Net LCOE (No freq reg)	Yes		Yes	Assuming the asset sells energy into the grid and bids into all ancillary services except for frequency regulation	Captures the case where frequency regulation prices collapse due to market saturation
Gross (or Traditional) LCOE	Yes			Assuming the asset sells energy into the grid and does not bid into ancillary services	Captures the case where all ancillary services prices collapse due to market saturation

General equations for each LCOE variant

$$\textbf{Net LCOE} = \frac{\sum_{i=0}^{N} [\frac{(I_i + O_i - ITC_i - (FR_i + AS_i))}{(1+r)^i}]}{\sum_{i=0}^{N} [\frac{(E_i)}{(1+r)^i}]}$$

<u>Where:</u>

N: Asset operation life

I_i: Capital expenditures (investment cost) in year i

O_i: Operating and maintenance costs in year i

ITC_i: Federal investment tax credit in year i

FR_i: Frequency regulation bidding revenues in year i

AS_i: Other ancillary services (spinning reserve, responsive reserve, etc.) bidding revenues in year i

E_i: Energy generated and injected into the grid in year i

r: Weighted average cost of capital (WACC)

<u>Note:</u> The AS and FR revenues are calculated based on a model year, using the dispatch profile of the asset and clearing prices for ancillary services at respective nodes for the year 2017.

$$\textbf{Net LCOE (No Frequency Regulation)} = \frac{\sum_{i=0}^{N} [\frac{(I_i + O_i - ITC_i - (AS_i))}{(1+r)^i}]}{\sum_{i=0}^{N} [\frac{(E_i)}{(1+r)^i}]}$$

$$\textbf{Gross LCOE} = \frac{\sum_{i=0}^{N} [\frac{(I_i + O_i - ITC_i)}{(1+r)^i}]}{\sum_{i=0}^{N} [\frac{(E_i)}{(1+r)^i}]}$$