



2024 Renewable Integration Study

An evaluation of the integration costs of solar resources on the Southern Company System



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# Abbreviations Used in Report

2.5G 2,500 MW

5G 5,000 MW

7.5G 7,500 MW

10G 10,000 MW

15G 15,000 MW

20G 20,000 MW

25G 25,000 MW

BESS Battery Energy Storage Systems

CAPLOLE Capacity LOLE (a measure representing capacity shortfall events)

CT Combustion Turbine

DG Distributed Generation

EMC Electric Municipal Cooperative

EUE Expected Unserved Energy

IRP Integrated Resource Plan

JOU Jointly Owned Units

LOLE Loss of Load Expectation

MEAG The Municipal Electric Authority of Georgia

NERC North American Electric Reliability Corporation

SERVM Strategic Energy and Risk Valuation Model

# Executive Summary

The purpose of this study is to determine the integration costs associated with a range of solar penetration scenarios on the Southern Company system, including scenarios representing the existing and committed solar resources on the system. The intermittent nature of solar resources creates unexpected swings in the momentary net demand on the system, which must be met using the inherent flexibility of the system, especially the flexibility associated with available operating reserves. If these unexpected swings in net demand become greater than the system’s inherent ability to manage through its existing operating reserve profile, the result will be the inability of the system to meet NERC operating standard requirements. The integration costs identified by this study represent those costs associated with any increase in operating reserves necessary to make sure the Southern Company system maintains its ability to meet those reliability standard requirements.

The table below indicates the five solar penetration scenarios considered.

Table 1. Base Case Solar Penetration Scenarios

|  |  |
| --- | --- |
| Scenario | Solar Penetration |
| 1 | 7,500 MW |
| 2 | 10,000 MW |
| 3 | 15,000 MW |
| 4 | 20,000 MW |
| 5 | 25,000 MW |

In addition, the study considered how the addition of Battery Energy Storage System (“BESS”) resources would impact the ability of the system to integrate solar resources. The benefit associated with the addition of these resources was translated into a BESS flexibility credit and was not assumed to reduce solar integration costs. Two levels of BESS penetration were considered. First, BESS penetrations equivalent to 15% of the Base Case solar tranches were considered as indicated in the table below.

Table 2. 15% BESS Penetration Scenarios

|  |  |  |
| --- | --- | --- |
| Scenario | Solar MW | BESS MW |
| 1 | 7,500 | 1,125 |
| 2 | 10,000 | 1,500 |
| 3 | 15,000 | 2,250 |
| 4 | 20,000 | 3,000 |
| 5 | 25,000 | 3,750 |

Second, each scenario was then evaluated to determine the penetration of BESS resources necessary to reduce the number of flexibility violations (Flex Violations) to the original, no-solar benchmark. This breakeven penetration assumed that as BESS resources are added to the system, at least one hour of storage will be held in reserve for use in managing renewable integration issues. This level of penetration represents the maximum flexibility credit (in dollars) available to the BESS resources at those solar penetration levels.

The three tables below reflect the results of the analysis for each of the 5 scenarios in each of the three portfolio groups: (1) the Base Case (i.e., solar only) portfolio group; (2) the solar plus 15% BESS portfolio group; and (3) the solar plus BESS penetration necessary to return the system to no-solar Flex Violation levels, respectively. A graphical representation follows each table, with results extrapolated down to 2.5 GW.

Table 3. Base Case Mitigation Costs

|  |  |  |
| --- | --- | --- |
| Scenario | Solar  MW | Mitigation Cost ($/MWH) |
| 1 | 7,500 | 2.29 |
| 2 | 10,000 | 2.53 |
| 3 | 15,000 | 2.95 |
| 4 | 20,000 | 3.27 |
| 5 | 25,000 | 3.50 |

An additional 6th scenario was run at 5 GW, but a mitigation cost could not be directly determined due to several factors. However, the figure below shows integration costs extrapolated down to 2.5 GW. See Section 4.1 for more details.

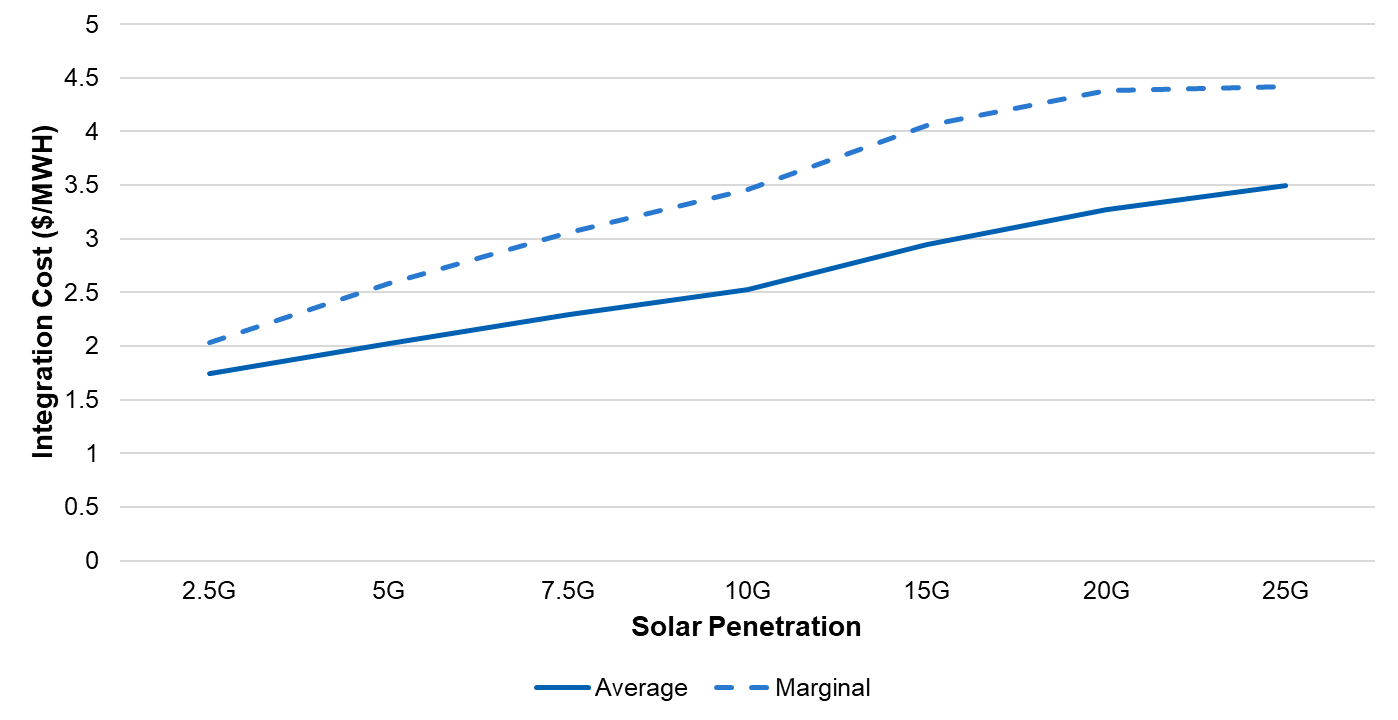


Figure 1. Base Case Integration Costs

Table 4. 15% BESS Case Flexibility Credits

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario | Solar  MW | BESS  MW | Flex Credit ($/Kw-Yr) |
| 1 | 7,500 | 1,125 | 27.31 |
| 2 | 10,000 | 1,500 | 33.00 |
| 3 | 15,000 | 2,250 | 44.23 |
| 4 | 20,000 | 3,000 | 49.11 |
| 5 | 25,000 | 3,750 | 52.53 |

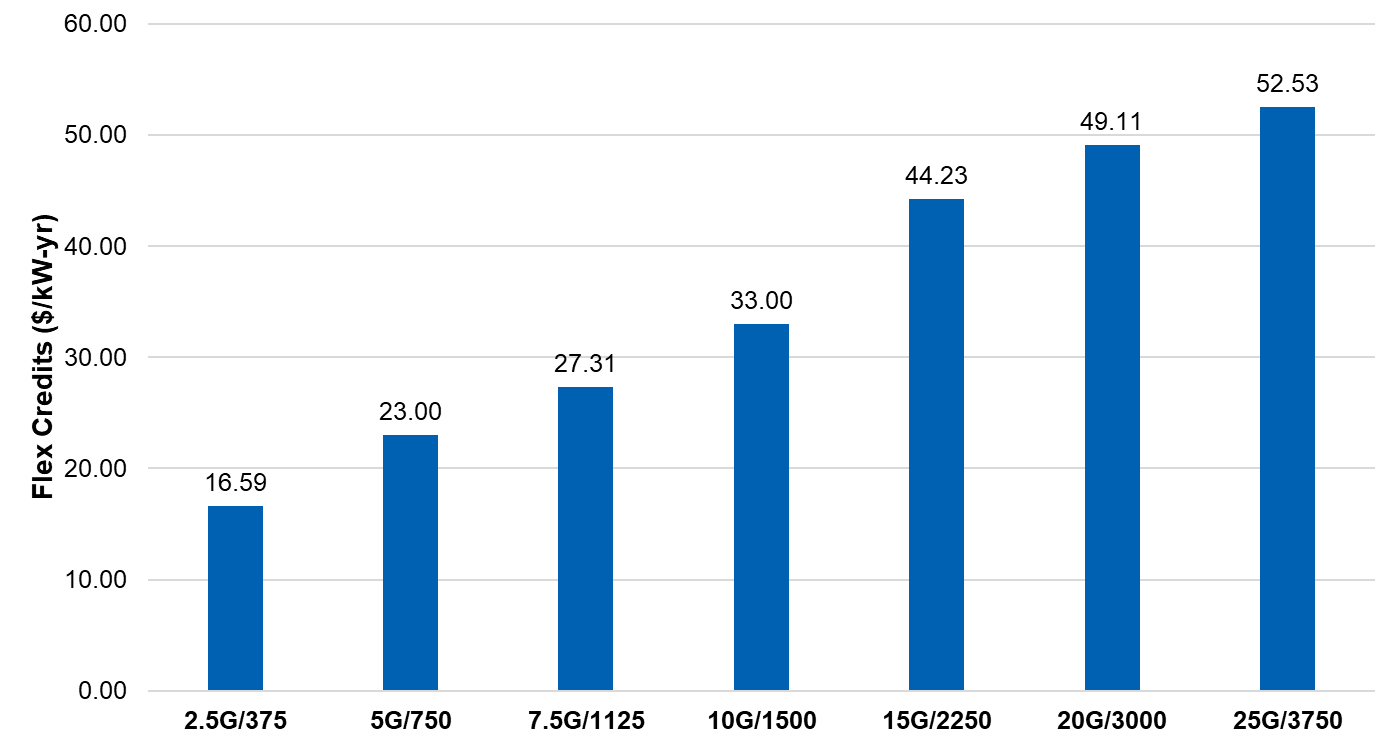


Figure 2. BESS Case Flexibility Credits

Table 5. BESS Breakeven Penetration Levels

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario | Solar  MW | BESS  MW | Flex Credit ($/kW-Yr) |
| 1 | 7,500 | 1,500 | 25.72 |
| 2 | 10,000 | 1,700 | 33.48 |
| 3 | 15,000 | 2,200 | 45.24 |
| 4 | 20,000 | 2,500 | 58.93 |
| 5 | 25,000 | 2,600 | 75.77 |

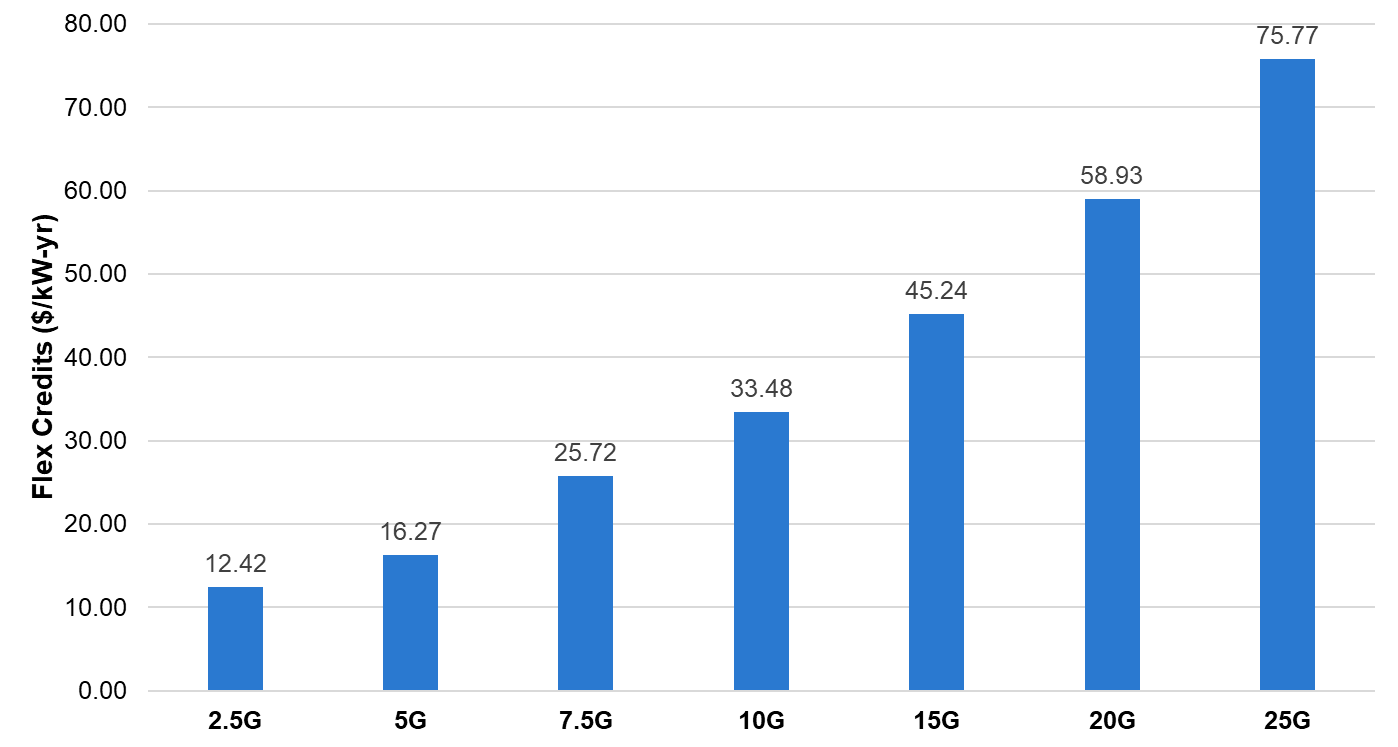


Figure 3. BESS Breakeven Case Flexibility Credits

While the breakeven BESS flexibility credits represent the maximum dollar flexibility benefit, it may not necessarily represent the maximum $/kW-yr benefit.

Using these analyses, a tool was developed and provided to Southern Company that provides average and marginal solar integration costs and BESS flexibility credits for any combination of solar and BESS resources up to the maximum of 25,000 MW of solar and 2,500 MW of BESS resources. However, BESS resources above the breakeven penetrations identified above result in a declining flexibility credit as no additional dollars of benefit are achieved and thus the maximum dollar benefit is being spread across more MW of BESS resources. This manifests itself in the tool as a zero marginal flexibility credit.

In addition to the above sets of scenarios, a wind sensitivity that looked at the incremental integration cost of a 1,000 MW tranche of wind was also performed. The wind sensitivity, which was evaluated assuming 10 GW of underlying solar, indicated no increase in mitigation cost. While a wind-only analysis may have resulted in non-zero integration costs, these results, reinforce the synergistic relationship between solar and wind.

Table 6. Sensitivity Results

|  |  |
| --- | --- |
| Sensitivity | Mitigation Cost ($/MWH) |
| Wind | No Incremental Cost |

# Scope of Analysis

The analysis associated with this study involved the evaluation of the integration costs of five different scenarios, representing tranches of solar penetration as follows:

Table 7. Solar Penetration Scenarios

|  |  |
| --- | --- |
| Scenario | Solar Penetration |
| 1 | 7,500 MW |
| 2 | 10,000 MW |
| 3 | 15,000 MW |
| 4 | 20,000 MW |
| 5 | 25,000 MW |

Each of these solar penetration scenarios would be compared against a reference case containing no solar resources. Two reliability criteria were established for the study:

The first reliability criterion was a Loss of Load Expectation (“LOLE”) for capacity (CAPLOLE) of ~0.1 days/year. This criterion was established to ensure comparability. All the scenarios as well as the Base Case were calibrated to the same level of reliability, specifically a CAPLOLE of ~0.1 days/year. The Case Development section describes how this was subsequently determined.

The second reliability criterion was a measure of the intra-hour flexibility of a given system, measured in terms of flexibility violations. A Flex Violation benchmark was established to determine the integration cost for each renewable tranche. This represented the primary analysis for the study, with the flexibility for each of the solar penetration scenarios benchmarked to the Flex Violation levels established in the no-solar reference case. The Study Methodology section describes how this benchmarking was accomplished and how the resulting integration cost was determined.

In addition to the integration costs for each of the five solar penetrations, flexibility credits were calculated for five levels of BESS resources – one for each of the five solar tranches – with BESS penetrations corresponding to 15% of the solar tranche penetration. The following table shows the BESS penetration for each of the five solar tranches.

Table 8. 15% BESS Penetration Scenarios

|  |  |  |
| --- | --- | --- |
| Scenario | Solar MW | BESS MW |
| 1 | 7,500 | 1,125 |
| 2 | 10,000 | 1,500 |
| 3 | 15,000 | 2,250 |
| 4 | 20,000 | 3,000 |
| 5 | 25,000 | 3,750 |

In addition to the 15% of solar tranche penetrations, each BESS scenario was then evaluated to determine the penetration of BESS resources necessary to reduce the number of Flex Violations to the original, no-solar benchmark. This breakeven penetration assumed that as BESS resources are added to the system, at least one hour of storage will be held in reserve for use in managing renewable integration issues. This level of penetration represents the maximum flexibility credit (in dollars) available to the BESS resources at those solar penetration levels.

Additionally, the study included a wind sensitivity analysis on the incremental cost of integrating 1,000 MW of wind with 10 GW of underlying solar.

# Case Development

The following sections describe the process used to develop the Base Case and solar penetration scenarios. The Strategic Energy and Risk Valuation Model (SERVM) was utilized for this study. The SERVM model used for this study is the same model used for resource adequacy evaluations performed by Astrapé for utilities nation-wide including (among others) such utilities as

The Tennessee Valley Authority (TVA),

Duke Energy,

Louisville Gas and Electric,

Pacific Gas and Electric (PGE),

Ameren Corporation,

DTE Energy,

Xcel Energy, and

Public Service Company of New Mexico (PNM).

## The Base Case

The starting point for the development of the Base Case was the Southern Company 2024 SERVM base case provided by Southern Company Services. To prepare this base case for the solar integration analysis, all solar and BESS resources were removed from the case.

To ensure the proper identification of integration costs without dilution from interactions with outside entities, the Southern Company base case was evaluated as an islanded system, which included the joint dispatch of Southern Company generation resources with firm commitments to serve Southern Company load. Since they are a partial requirements customer that is served in part by Southern Company resources and thus can impact the availability of resources needed to meet flexibility requirements, the analysis also included the joint dispatch of resources owned by the Municipal Electric Authority of Georgia (“MEAG”). This included both jointly owned units (“JOU”) dispatched by Southern on MEAG’s behalf and units owned and dispatched by MEAG itself.[[1]](#footnote-2)

Southern Company’s operating reserve requirements (and thus the ancillary service values in the base case provided by Southern Company) are contingent upon the number of solar resources on the system. Removing the solar also required appropriately adjusting the ancillary services to levels reflecting no solar resources on the system.

The following table shows the ancillary services modeled in the Base Case.

Table 9. Base Case Ancillary Services

|  |  |
| --- | --- |
| Ancillary Service | Value |
| Regulating Reserves Requirement | 500 MW |
| Spinning Reserves Requirement | 750 MW |
| Quick Start Reserves Requirement | 500 MW |
| Load Following Reserves Target | 1% of Load |

The no-solar reference case was then simulated for the 2028 study year using weather years representing historical weather from 1973-2022 to establish its inherent reliability at a target 0.1 days/year LOLE. Generic “CT” resources were added until the target reliability was met. Because of inherit intra-hour vs. hourly peak load differences, the reliability of the system was also verified on an intra-hour basis and adjustments to capacity were made as appropriate to ensure LOLE remained at approximately 0.1 days/year.

## Solar Scenarios

Each of the resulting scenarios were created via the following three step process:

1. Creating the solar resources and adding them to the case
2. Creating the intra-hour solar volatility parameters and incorporating them into the appropriate solar group
3. Benchmarking the resulting case back to a CAPLOLE of ~0.1 days/year

The following describes each of those three steps for the five solar penetration scenarios.

## Solar Resource Additions

The base case database provided by Southern Company Services contained a total of 71 active solar resources in the study year, which together represented approximately 4,488 MW of solar capacity. Several of these modeled resources included an aggregation of a geographically diverse set of aggregated distributed generator (“DG”) solar resources. Together, these resources are reasonably representative of the future geographic diversity that could be expected on the Southern Company system. Therefore, each of the solar scenarios were created by scaling the capacity of these resources until the total capacity of the portfolio reached the desired tranche size. A list of these resources can be found in Appendix A.

## Intra-Hour Solar Volatility Parameters

To develop the intra-hour solar volatility parameters, it was necessary to develop a series of aggregate 5-minute solar profiles for one year for each tranche of solar. These profiles were provided to Astrapé by Southern Company Services. To develop these profiles, Southern Company Services used the NREL NSRDB[[2]](#footnote-3) 5-minute data and pvlib[[3]](#footnote-4) to model the 5-minute solar volatility profiles for use in this study. A demonstration of this workflow is available in an open-source code repository[[4]](#footnote-5) using solar plant locations and specifications from Energy Information Administration (“EIA”) data. The final volatility profiles provided to Astrapé included a diverse set of plant locations and specifications based on current, online resources and interconnection applications.

These 5-minute profiles were then imported into SERVM to create an associated divergence profile (i.e., the frequency at which a given level of divergence from the smooth profile would occur). SERVM then applies volatility parameters established from those divergence profiles to create intra-hour solar output from the hourly solar profiles for each weather year. The figure below shows the divergence profile for each of the five of the five solar penetration scenarios.

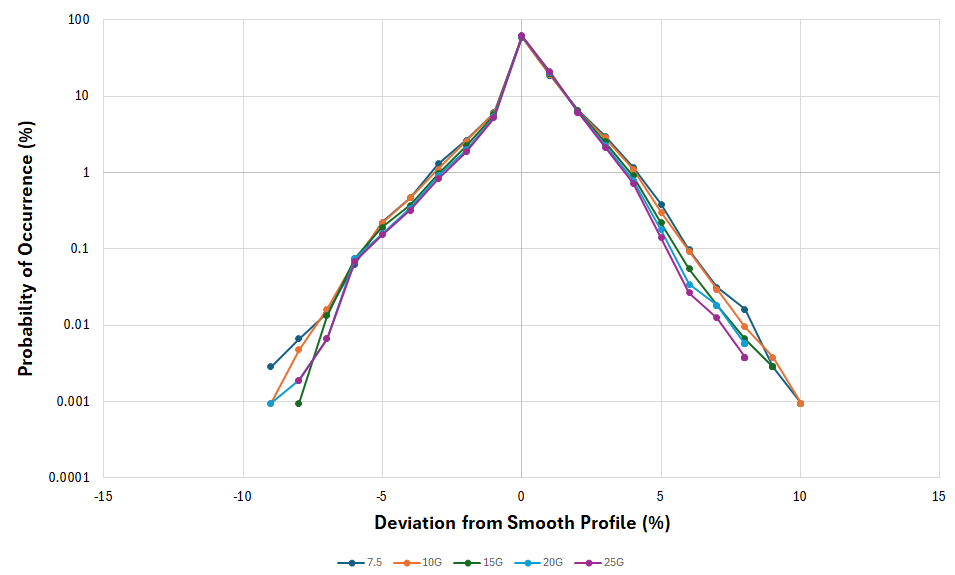


Figure 4. Solar Volatility Divergence Profiles

Another way to view the volatility data is to look at a given probability of occurrence and compare the divergence at that probability of occurrence. The graph below shows the 95th percentile of divergence for each solar tranche and can be interpreted as follows: 95% of all observations are at or below the percent deviation indicated by the curve.

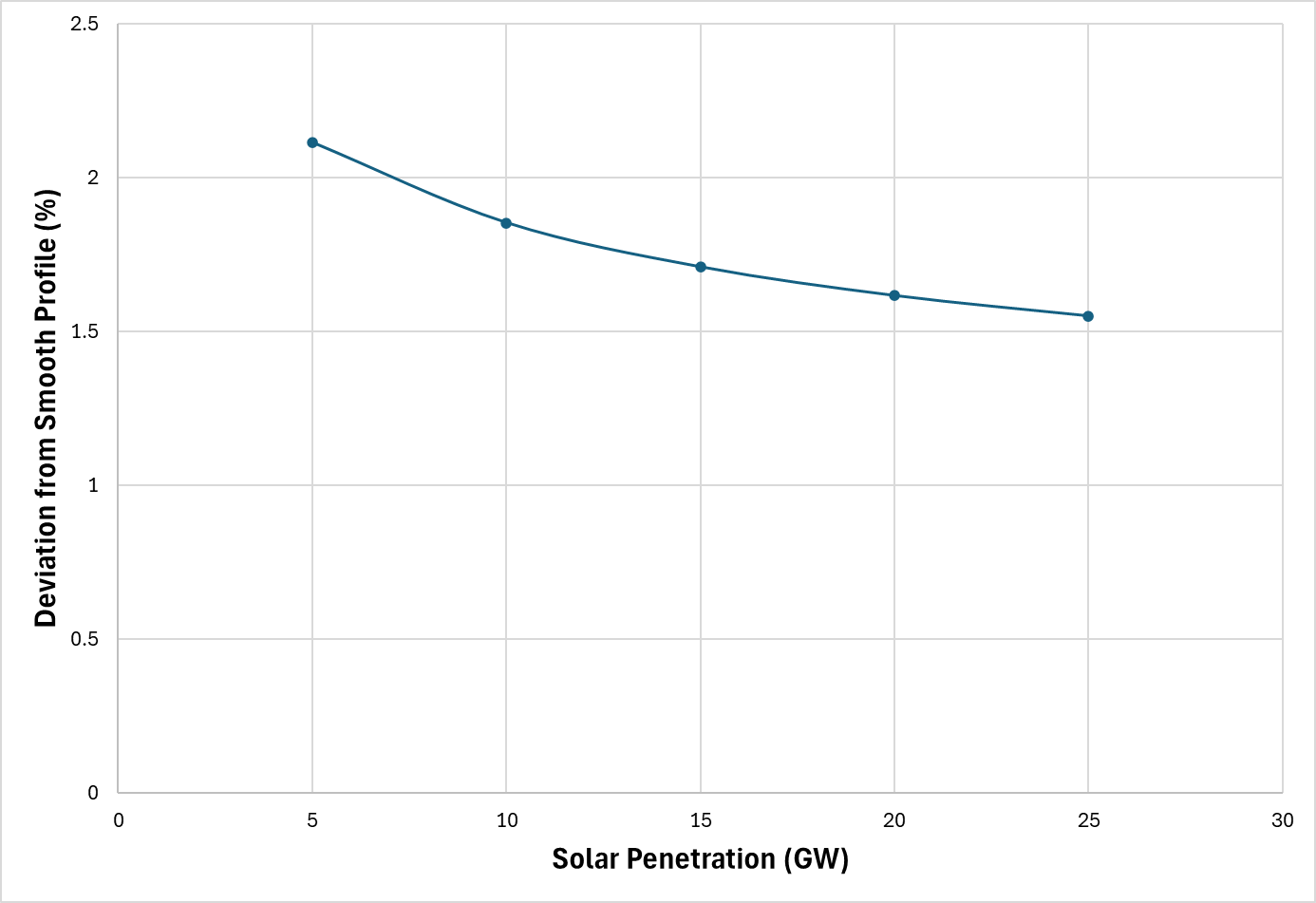


Figure 5. 95th Percentile of Solar Volatility

## Benchmarking LOLE

To ensure each of the five solar scenarios had a starting point capacity reliability that was comparable to the no-solar reference case, CT resources were removed until the reliability of the system returned to 0.1 days/year LOLE.

## BESS Scenarios

The BESS resources were modeled as a series of 250 MW resources to achieve the desired portfolio size for each scenario, each containing the following parameters:

Table 10. BESS Modeling Parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Dispatch Capacity | 250 MW |
| Charging Capacity | 250 MW |
| Minimum Dispatch Capacity | 0 MW |
| Minimum Charge Capacity | 0 MW |
| Cycle Efficiency | 0.85 |
| Storage Size | 2 Hours |
| Quick Start Capability | Yes |
| AGC Capability | Yes |
| Target Storage Level | 50% |
| Reliability Dispatch Price | $1000/MWH |

The 2-hour storage size was assumed to model a resource that is responsive for purposes of providing flexibility benefit. By setting the target storage level to 50%, the BESS resource is assured to always have one hour of upward flexibility and one hour of downward flexibility available except when deployed for flexibility or reliability purposes. These parameters are further assumed based on the expectations that regardless of the size, storage capability, or reason that BESS resources would be added to the system, they would always be operated in such a way as to preserve at least one hour of storage capability for reliability and flexibility purposes.

The addition of BESS resources resulted in a lowering of the LOLE, which had to be returned to 0.1 days/year with the removal of additional CT resources as necessary.

## Wind Sensitivity

This sensitivity was performed by adding 1,000 MW of wind resources to the 10 GW solar scenario. Wind volatility data was provided by Southern Company. Wind integration cost would be determined by comparing the mitigation cost of this sensitivity to the 10 GW solar only scenario.

# Study Methodology

The following describes the procedure used to calculate the integration cost for each of the solar penetration scenarios.

## Establish Flex Violation Benchmark Target

The Flex Violation benchmark is a measure of the intra-hour flexibility of a given system. Computationally it is calculated based on days in which the system was unable to balance load and resources plus the required level of regulating and spinning reserve listed in table 9 for five minutes or longer. However, because of the frequency bias and response of the interconnect, a flexibility violation event does not likely represent an actual loss of load. Rather, such an event represents negative pressure on the system’s ability to meet NERC Reliability Standard BAL-001-2. Therefore, the Flex Violation metric should not be interpreted as actual outage conditions, but rather as a measure of the ability of the system to manage flexibility. An increase in the flexibility metric equates to a deterioration of the system’s ability to manage unexpected deviations in load or resource availability on a 5-minute basis.

The philosophical approach taken in this analysis was to ensure that the integration of solar resources will not create negative pressure on the Southern Company System’s ability to meet NERC Reliability Standard BAL-001-2 beyond that which would exist in the system without the presence of the solar resources. While SERVM does not model the moment-to-moment fluctuations in the system and thus cannot quantify Area Control Error (“ACE”), the challenges with balancing load and generation on a 5-minute basis in the simulations are expected to be correlated with actual violations of ACE limits, which in turn contribute towards the limits established by the NERC standard. As such, the Flex Violation benchmark target was established based on the Flex Violations in the no-solar reference case, which had a Flex Violation metric of 2.02 days/year. Recognizing that the current system and operating guidelines produce compliance with the NERC standard, configuring the simulations to maintain a similar level of flexibility violations ensures the ability to maintain compliance in the future.

As part of the evaluation, each intra-hour Flex Violation and its associated energy deficit (measured in MWh) was captured and converted into a 12x24 matrix representing the expected 24-hour profile of intra-hour flexibility-based energy deficit for each of the 12 months of the year (i.e., the weighted summation of all deficient energy in that hour of the month/year). Each instance of energy deficit contributes towards the Flex Violation metric. Thus, mitigating short duration energy deficiencies is the mechanism by which Flex Violations are mitigated. The 12x24 matrix of intra-hour energy deficiencies described above was therefore used to help establish the time periods in which mitigation was necessary as described in the steps below.

## Determine Pre-Mitigation Cost/Reliability Parameters

To determine the integration cost of a given solar penetration scenario, it was first necessary to establish the pre-mitigation cost and reliability parameters of each scenario. Specifically, the pre-mitigation total production cost and the pre-mitigation Flex Violations were established. Other metrics, such as generation curtailment and average load following supplied per hour were also kept. SERVM models curtailment whenever load plus required operating reserves are above the combined minimum dispatch levels of all online generation. The addition of solar resources can increase the frequency and magnitude of such generation curtailment. Lower net load periods and more volatile net load periods associated with increased solar penetration make committing dispatchable resources to follow net load more challenging and result in curtailment. Also, since mitigating solar volatility can include committing more resources, managing flexibility violations can also contribute to system curtailment. Thus, both the solar resources themselves and the actions taken to mitigate flexibility violations associated with those resources contribute to greater risks of generation curtailment.

In addition, each intra-hour failure to balance load and resource and the associated energy deficiencies were captured and converted into a 12x24 matrix like that established for the no-solar reference case. These were used to identify which hours of the year to target for potential mitigation efforts.

## Establish Mitigation Impact Profile

Using the no-solar reference case and scenario case 12x24 profiles of intra-hour energy deficiencies, a mitigation impact profile was developed by directly comparing the reference case intra-hour 12x24 energy deficiency profile to the scenario intra-hour 12x24 energy deficiency profile. Each hour of the reference case profile was subtracted from the scenario profile. The resulting differences represented those periods of time in which additional load following reserves would be necessary. The table below is a theoretical example of such a resulting impact profile but does not necessarily represent any specific result of this analysis.

Table 11. Example Mitigation Impact Profile (MWH)



The values in the table are MWH values representing the difference in the intra-hour energy deficiencies between the solar penetration scenario and the reference case, and therefore, the table can be understood as the increase in flexibility violations caused by the solar penetration scenario. The magnitude of energy deficiency in the table is correlated to the amount of mitigation that may be necessary to return the system back to reference case reliability conditions. Higher levels of energy deficiency would therefore require greater levels of operating reserves to mitigate the flexibility violations, as described in the next section below.

## Mitigation Using Load Following Reserves

The three primary types of operating reserves modeled in SERVM are regulating reserves, contingency reserves (including spinning reserves and quick start reserves) and load following reserves.

Regulating reserves are generally used to manage the moment-to-moment fluctuations on the system caused by momentary changes in load but would also include the type of moment-to-moment fluctuations that may be caused by intermittent resources such as solar. Regulating reserves are always online and ready to be deployed as needed.

Contingency reserves are used to recover from the sudden loss of a generation resource resulting from a forced outage. Contingency reserves are often split into spinning reserves (i.e., those that are online are ready to dispatch at a moment’s notice) and quick start reserves (i.e., those that are not online but can be brought online at a moment’s notice).

Load following reserves represent the amount of additional spinning reserves that are available on an hourly basis to manage the change in load from hour to hour due to commitment decisions made to serve load during the peak of the day.

For purposes of this analysis, load following reserves were used to determine the amount of mitigation necessary to return the reliability of the system to Base Case conditions. Load following reserve targets for the no-solar reference case were set at 1% of load.

As solar penetration increases, the level of intra-hour Flex Violations also increases. To mitigate the increase in Flex Violations, load following reserves were iteratively increased in hours containing intra-hour energy deficiencies until the system returned as closely as possible to the Base Case Flex Violation benchmark of 2.02 days/year. Each new iteration required the calculation of a new mitigation impact profile and subsequent adjustments to the load following reserve targets in each hour. Hours with higher levels of incremental energy deficiencies would necessarily require higher levels of load following. The figure below demonstrates this iterative process.

Diagram

Description automatically generated

Figure 6. Mitigation Flowchart

The table below shows a theoretical example of the resulting 12x24 load following profile that may result from this process. The table shows the amount of additional MW above the 1% of load reference case load following targets that would need to be followed in each hour of the respective month to ensure adequate intra-hour flexibility.

Table 12. Example Load Following Target Profile (MW)



It should be noted that this process is not automated and requires engineering judgment as to the amount and timing of the load following reserves added to the system. There are numerous combinations of load following reserve targets that could each result in a mitigated system. While effort was taken to optimize the mitigation profile to the greatest extent possible, there is no way to ensure the final mitigated system represents the optimal solution. As such, results were trended and smoothed to minimize any inconsistencies between scenarios that may result associated with this iterative approach. An initial smoothing was performed from the raw results to be used in the battery flexibility cost calculations (see Section 3.6 below), and then a final smoothing was performed after the battery flexibility and battery breakeven analyses were performed (see Section 3.8 below).

## Integration Cost Calculations

Once the mitigated system achieved Flex Violations of approximately equal to the no-solar reference case, the mitigation cost could be determined in accordance with the following equation:

SMC = (TPCpost – TPCpre)/MWHscenario

Where,

SMC ≡ Scenario Mitigation Cost in $/MWH,

TPCpost ≡ Total Production Cost of the Scenario post mitigation,

TPCpre ≡ Total Production Cost of the Scenario pre mitigation, and

MWHscenario ≡ The megawatt hours of solar generation associated with the scenario.

This SMC value represents the cost of the required increase in load following reserves. The costs associated with increases in curtailment are implicitly included in these calculations since the production costs associated with the additional energy that was generated but did not serve load are included in TPCpost.

## Battery Flexibility Credit Calculations

The same mitigation process was used for the battery scenarios as was used for the solar scenarios. While BESS technology portfolios are very flexible resources and improve the response of the system, the addition of these technologies may still require an increase in load following reserves to return the Flex Violations to reference case levels. However, the amount of mitigation required with BESS resources on the system would be reduced. The savings associated with that reduction can then be translated into a Flexibility Credit for those BESS resources.

Once the BESS scenarios are mitigated so that they achieve Flex Violations consistent with the no solar reference case, the flexibility credit could be determined in accordance with the following equation:

BFC = (SMCsolar – MCBESS)/KWBESS

Where,

BFC ≡ Battery Flexibility Credit in $/kW-Year,

SMCsolar ≡ Mitigation cost, in dollars, of the solar only scenario containing the same amount of solar penetration as the BESS scenario,

MCBESS ≡ Mitigation cost, in dollars, of the BESS scenario,

KWBESS ≡ The kilowatts of BESS in the BESS scenario.

In the above equation, SMCsolar represents the initial, preliminary smoothed mitigation costs rather than the raw mitigation costs.

## Battery Breakeven Analysis

In addition to the 15% of solar penetration BESS scenarios, BESS scenarios were also run to determine the point at which the batteries alone, with no additional load following, would reduce the Flex Violations to those consistent with the no-solar reference case. This would represent the maximum amount of mitigation benefit (in dollars) that could be achieved via adding BESS resources. While adding more BESS resources than this breakeven level may further increase the flexibility capability of the system, it would not provide any incremental solar integration cost benefit because it would represent a condition that is more flexible than the no-solar benchmark.

This breakeven amount was determined by iteratively adding (or removing) BESS resources until the Flex Violations roughly equaled the no-solar reference case Flex Violations.

## Integration Cost and Battery Flexibility Credit Smoothing

With three sets of mitigation costs – preliminary smoothed solar only, BESS at 15% of solar, and BESS at no-solar breakeven Flex Violations – it is possible to perform two-dimensional trending and smoothing across both the solar and battery penetration levels. This provides two advantages to the analysis. First, it smooths any irregularities out of the average solar integration costs so that marginal costs are well behaved. Second, it provides for the ability to develop a “dense matrix” of solar integration and battery flexibility credit costs so that both integration costs and battery flexibility credits could be determined for any combination of solar and battery penetrations. Without this two-dimensional smoothing process, it would be difficult to easily interpolate between the discreet scenarios evaluated and obtain well-behaved average and marginal costs.

The trending and smoothing process was accomplished using the following steps:

1. Known mitigation costs (in dollars) for the solar only results were trended.
2. Trended mitigation cost results from step 1 above were trended along the BESS penetration axis so that mitigation results could be calculated for a greater granularity of BESS penetrations. Each solar penetration level was trended independently.
3. Trended results from step 2 above were then trended along the solar penetration axis and results for a greater granularity of solar penetrations was determined. Each BESS penetration level was trended independently.
4. Results from step 3 above were trended again along the BESS axis, with each penetration of solar being trended independently.
5. Results from step 4 above were trended again along the solar axis with each penetration of BESs being trended independently.
6. Using the results from step 5 above, solar integration and battery flexibility credits were determined as follows:
   1. Smoothed mitigation costs at zero BESS penetration were divided by MWH of solar energy to get solar integration costs, and
   2. Smoothed mitigation costs for non-zero BESS penetrations were all subtracted from the zero BESS penetration mitigation costs to determine the reduction in mitigation costs, which was then divided by the kilowatts of battery penetration to get the flexibility credit.

# Results

The results from each of the scenarios for each of the three analyses (solar only, 15% BESS penetration, BESS breakeven penetration) are detailed in the following sections. Following the discussion of the three technology portfolios is a discussion concerning the impact of the solar tranches and the associated mitigation on expected generation curtailments.

## Solar Integration Costs

The first set analyses were to determine the solar integration costs assuming a system with only solar resources (i.e., no BESS resources). The table below shows the resulting integration costs for each of the five solar penetration scenarios evaluated.

Table 13. Portfolio 1 Base Case Mitigation Costs

|  |  |  |
| --- | --- | --- |
| Scenario | Solar  MW | Mitigation Cost ($/MWH) |
| 1 | 7,500 | 2.29 |
| 2 | 10,000 | 2.53 |
| 3 | 15,000 | 2.95 |
| 4 | 20,000 | 3.27 |
| 5 | 25,000 | 3.50 |

The figure below shows the same information graphically and includes both average and marginal integration costs.

A graph with a line

Description automatically generated

Figure 7. Portfolio 1 Mitigation Costs

It should be noted that in addition to the five solar tranches identified in Table 13 above, a sixth solar tranche was also run at 5 GW of solar. Unfortunately, the model could not resolve an integration cost for this tranche. When combined with the fact that the no-solar reference case already contained a load following requirement of 1% of load, the 5 GW solar tranche fell within the flexibility of the base case system. This does not, however, mean that the integration costs at 5 GW of solar are negligible, and solar resources should not get a “free ride” on the back of the existing system flexibility. Therefore, the appropriate way to determine these costs would be to extrapolate based on the results of the higher penetration tranches. Figure 7 above reflects this extrapolation.

The values shown in the table and figure above are the result of the post-smoothing process. The detailed integration cost calculations for pre-smoothing vs. post-smoothing for the five solar only scenarios are included in Appendix B.

As an example of the load following profiles necessary to achieve this level of mitigation, the following table shows a 12x24 heat map of the Scenario 1 (7,500 MW) Solar Only scenario load following results.

Table 14. Scenario 1 Solar Only Load Following Requirements (MW)



The MW represented in the table are in addition to the underlying 1% of load assumption in the no- solar reference case.

Load Following heat maps for the solar only scenarios are included in Appendix C.

## 15% BESS Penetration Flexibility Credits

The second set of analyses performed determined the BESS flexibility credits assuming a battery penetration of 15% of the corresponding solar portfolio. This analysis was performed in the same manner as the solar only mitigation cost analysis except the difference in mitigation cost was translated into battery flexibility credited as shown in the table below.

Table 15. 15% BESS Penetration Flexibility Credits

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario | Solar  MW | BESS  MW | Flex Credit ($/Kw-Yr) |
| 1 | 7,500 | 1,125 | 27.31 |
| 2 | 10,000 | 1,500 | 33.00 |
| 3 | 15,000 | 2,250 | 44.23 |
| 4 | 20,000 | 3,000 | 49.11 |
| 5 | 25,000 | 3,750 | 52.53 |

The figure below shows the same information graphically. Values below 7.5 GW of solar are extrapolated.

A graph with blue bars

Description automatically generated

Figure 8. 15% BESS Penetration Flexibility Credits

The values shown in the table and figure above are the result of the post-smoothing process. The detailed integration cost calculations for pre-smoothing vs. post-smoothing for the five battery scenarios are included in Appendix B.

Load Following heat maps for the BESS scenarios are included in Appendix C.

## BESS Breakeven Flexibility Credits

The third set of analyses was to determine the breakeven point at which BESS penetrations would return the system back to no-solar condition. This analysis was performed by adding various levels of BESS penetration to the solar scenarios until the flex violations returned to the no-solar level. The table below shows the breakeven penetrations and the resulting battery flexibility credits.

Table 16. BESS Breakeven Flexibility Credits

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario | Solar  MW | BESS  MW | Flex Credit ($/kW-Yr) |
| 1 | 7,500 | 1,500 | 25.72 |
| 2 | 10,000 | 1,700 | 33.48 |
| 3 | 15,000 | 2,200 | 45.24 |
| 4 | 20,000 | 2,500 | 58.93 |
| 5 | 25,000 | 2,600 | 75.77 |

The figure below shows the same information graphically. Values below 7.5 GW of solar are extrapolated.

A graph with blue bars

Description automatically generated

Figure 9. BESS Breakeven Flexibility Credits

As compared to the 15% BESS penetration scenario, the 15G solar penetration breakeven BESS penetration was essentially the same as the 15% penetration level. In the case of the 7.5G and 10G solar penetration levels, additional BESS resources were needed to achieve breakeven than were evaluated in the 15% penetration case. In the case of the 20G and 25G solar penetration levels, less BESS resources were needed to achieve breakeven than the 15% case. There are two factors driving these results. Southern’s current regulation + spinning reserve requirement is 1,250 MW. First, BESS is very effective at providing these ancillary services requirements and the SERVM model prioritizes ancillary services provision over flexibility support. Thus, the first 1,250 MW of BESS resources are being assigned to provide ancillary services, which is detrimental to their ability to provide flexibility support. Thus, they are less effective at doing so. Second, because of geographic diversity, solar volatility decreases on a percentile basis with increasing levels of penetration as shown in Figure 5 above. Therefore, while the MWs of volatility increases, as a percentage of nameplate capacity, the volatility is actually decreasing. Thus, a fixed 15% of nameplate solar BESS penetration means that at higher penetrations, the BESS are more effective at mitigating the solar than at lower penetrations. Therefore, above 1,250 MW of BESS capacity (i.e., past the ancillary service requirement), the BESS resources are incrementally more effective at mitigating volatility. Coincidentally, the breakeven point for the 15G solar scenario is approximately 15%. Therefore, scenarios above 15G solar require less than 15% BESS to return the system to the no-solar condition.

## Integration/Flexibility Cost Tool

The results of the three sets of analyses above are, in part, influenced by the trending and smoothing of the raw SERVM results as described in Section 3.8 above. The results of that trending and smoothing also allowed for the expansion of results beyond the five discrete points evaluated and reported above. The trending and smoothing process allowed for the calculation of results for any combination of solar and BESS resources within the bounds of what was evaluated, trended, and smoothed. The figure below shows a surface plot of the BESS flexibility credits as a function of solar penetration.

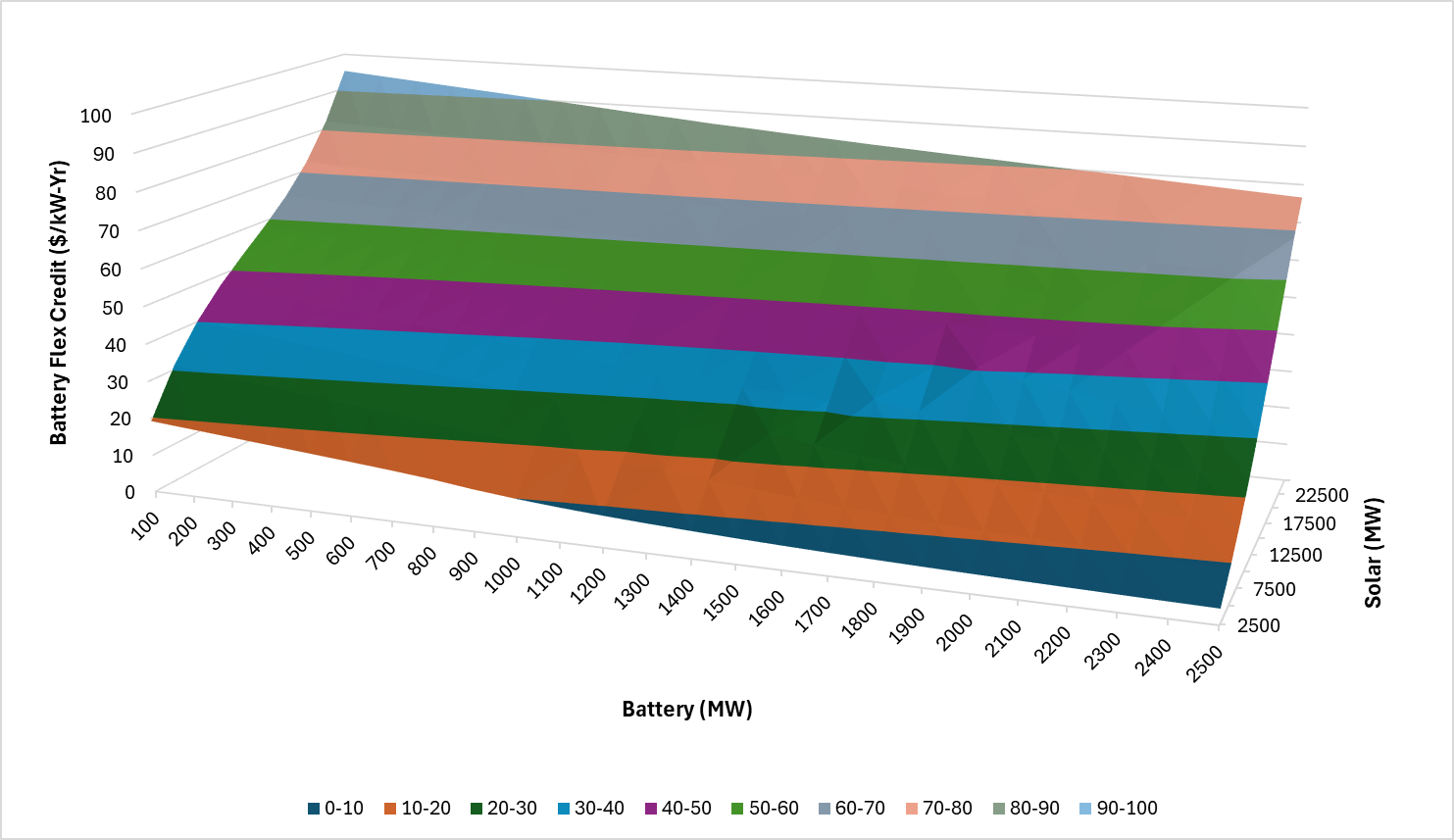


Figure 10. Battery Flexibility Credits as a Function of Solar Penetration

To find the flexibility credit for a given combination of solar and BESS penetrations, find the point at which the two points cross on the horizontal axes and then come up the vertical axis until the surface is reached to determine the flexibility credit. For example, the point at 2,500 MW of BESS and 12,500MW of solar intersect the surface in the light blue band, representing the 30-40 $/Kw-year range. A tool was developed to interpolate and find the exact point of intersection, which in this case intersects the surface 30.95 $/kW-year. The tool also provides average and marginal solar integration costs for any level of solar penetration between 2,500 MW and 25,000 MW. This tool was provided to Southern Company.

## Wind Sensitivity

The addition of wind resources to a system with 10 GW of solar resulted in less mitigation cost than the system with just 10 GW of solar alone. This decrease in mitigation cost reflects the synergies associated with a portfolio that has both technologies. As with solar and storage combined, however, this does not mean that solar integration costs should be reduced. However, it likewise does not suggest that wind should get a flexibility credit. While this study did not evaluate a wind-only system, such an evaluation would reflect a non-zero integration cost. Therefore, the only conclusions that can be drawn from this analysis is that the addition of 1 GW of wind to a system that already has a significant penetration of solar will not increase integration costs and would likely benefit the system.

## Observations

The following are some key observations regarding the results of the analysis.

1. The addition of solar has an impact on the flexibility needs of the system. The volatility of the net load profile after the addition of solar necessitates mitigation either through increasing load following or adding more flexible capacity or some combination of the two solutions. In an environment where not only Southern Company, but also its neighbors are increasing solar penetration, solar integration must be addressed rigorously.
2. Southern Company operates its fleet with appropriate safety margins, adhering to NERC balancing standards. There is no excess capacity to manage net load volatility via the reliance on neighboring systems. Southern Company currently increases its operating reserves to manage solar volatility.
3. While there is no industry standard for ideal levels of flexibility violations, Southern’s compliance with NERC Reliability standards provides an appropriate benchmark to maintain as the resource mix changes. Adjusting the flexible capacity on the system and increasing operating reserve guidelines along with assigning the associated costs of such actions to incremental renewable energy as integration costs appropriately balances economic and reliability considerations.
4. With the new assumptions, there does not appear to be an inflection point in the solar integration costs up through 25,000 MW of solar.
5. Because of the declining per unit volatility of solar resources with increased penetrations, BESS resources have greater effectiveness at reducing flex violations at higher penetrations, but below 1,250 MW, BESS effectiveness is significantly hindered because of regulation and spin requirements. The same would be true of any flexible resource that could meet ancillary services requirements.

## Impacts on Generation Curtailment

Generation curtailment is a metric that represents conditions in which load falls below a point at which the online generation is no longer able to reduce output to match load. This phenomenon is sometimes referred to as overgeneration. In the real world, this condition is remedied either by allowing frequency to slightly rise, selling excess generation to a neighboring utility, or decommitting online generation. In this study, an increase in the generation curtailment metric relative to the base case is an indication of the increased risk that such conditions will materialize in the real world as a direct consequence of the additional solar generation.

For this analysis such conditions are presumed to be mitigated by curtailing solar generation and thus not receiving the energy otherwise available from the resource. The cost of this curtailment is the direct cost of not receiving the solar energy, measured by the expected purchase price or assessed value of the solar energy. This cost is not captured in the solar integration cost analysis. However, there are two ways in which the cost of generation curtailment should be considered.

First, there is the increase in generation curtailment from the pre-mitigated case to the base case, referred to here as the Pre-Mitigated Curtailment Impact. This represents the amount of renewable generation that would not be received simply because the system mix cannot manage the day-to-day swings in net load resulting from the renewable resource. This cost should be considered in the ***initial evaluation*** of the economic value of the resource.

The second way in which generation curtailment costs should be considered is in the difference between the post-mitigated case and the pre-mitigated case for the same scenario, referred to here as the Post-Mitigated Curtailment Impact. The Post-Mitigated Curtailment Impact represents the incremental amount of solar energy that was not received because of the additional operating reserves needed to mitigate flex violation. The incremental curtailed energy must be served by other resources, resulting in an increase in production cost, which is included as part of the solar integration costs.

The tables below show the pre-mitigation and post-mitigation curtailment for the solar only scenarios. The pre-mitigation is shown incremental to the base case and the post-mitigation is shown incremental to the pre-mitigation. All values are in MWH/year

Table 17. Solar Only Curtailment Impact

|  |  |  |
| --- | --- | --- |
| Solar MW | Pre-mitigation | Post-mitigation |
| 7,500 | 26,126 | 14,242 |
| 10,000 | 239,461 | 105,481 |
| 15,000 | 1,650,660 | 479,135 |
| 20,000 | 4,955,704 | 1,119,181 |
| 25,000 | 10,451,639 | 1,669,896 |

Batteries have the advantage of reducing solar curtailment as a portion of the excess solar energy can be used to maintain battery charge. The table below shows the pre-mitigation and (where applicable) post-mitigation incremental solar curtailment for the 15% BESS scenarios. The pre-mitigation is incremental to the no-solar case and the post-mitigation is incremental to the pre-mitigation case. For those scenarios where the pre-mitigation flex violations were at or below the no-solar case, no post-mitigation curtailment is available.

Table 18. 15% BESS Curtailment Impact

|  |  |  |
| --- | --- | --- |
| Solar MW | Pre-mitigation | Post-mitigation |
| 7,500 | 5,120 | 5,160 |
| 10,000 | 75,255 | 27,218 |
| 15,000 | 1,222,368 |  |
| 20,000 | 4,505,168 |  |
| 25,000 | 9,321,178 |  |

As an example of the timing throughout the year of when such curtailment may occur, the following table shows a heat map of the expected total system curtailment (after mitigation) for the 10,000 MW solar only scenario. The table shows the total MWHs of curtailment by hour by month for the scenario. As the heat map shows, the greatest concentration of curtailment occurs during periods of low load combined with periods of high solar output, such as during the middle of the day during spring, fall, and winter months. Other scenarios would be similar, but with varying quantities based on the level of solar penetration.

Table 19. Heat Map of MWHs of Curtailment (10,000 MW Solar Only Scenario)



# Appendix A – Solar Resources Modeled

The following tables indicate the solar resources and associated nominal capacity modeled as part of this solar integration study. Several of these modeled resources included an aggregation of a geographically diverse set of aggregated distributed generator (DG) solar resources.

Table 20. Solar Facilities Modeled

|  |  |
| --- | --- |
| Unit Name | Capacity |
| Solar\_2019 IRP DG | 89.0 |
| Solar\_AMEA\_BLACKBEAR | 100.0 |
| Solar\_ANNISTON\_AD | 7.4 |
| Solar\_ASI Classic DG | 78.2 |
| Solar\_ASI Prime DG | 78.6 |
| Solar\_CB\_ENERGY | 3.3 |
| Solar\_CCSP\_DG | 25.0 |
| Solar\_CLASI\_BUTLER | 20.0 |
| Solar\_CLASI\_DECATUR | 18.9 |
| Solar\_CLASI\_DUBLIN | 4.1 |
| Solar\_CLASI\_HECATE\_OLD\_MIDVILLE | 20.0 |
| Solar\_CLASI\_RICHLAN | 20.0 |
| Solar\_CLASI\_RINCON | 16.0 |
| Solar\_CLASI\_SOGLYNN | 17.7 |
| Solar\_COMMSOLAR\_COMER | 2.2 |
| Solar\_COMMSOLAR\_GUYTON | 3.6 |
| Solar\_COMMSOLAR\_WAYNESBORO | 2.4 |
| Solar\_FALCONS | 1.0 |
| Solar\_FORT\_VALLEY\_STATE | 10.8 |
| Solar\_FT\_BENNING | 30.0 |
| Solar\_FT\_GORDON\_1 | 30.0 |
| Solar\_FT\_RUCKER | 10.6 |
| Solar\_FT\_STEWART | 30.0 |
| Solar\_GPC\_LSS\_HSH\_PEMBROOKE | 1.0 |
| Solar\_GPC\_LSS\_SIMON\_SOLAR\_FARM | 30.0 |
| Solar\_GPC\_LSS\_SOLAR\_CAMILLA | 16.0 |
| Solar\_GPC\_LSS\_SOLAR\_CAMP\_MERIWETHER | 3.0 |
| Solar\_HATTIESBURG\_FARM | 50.0 |
| Solar\_KINGS\_BAY | 30.2 |
| Solar\_MARINECORP\_LB | 31.2 |
| Solar\_MOODY\_AFB | 49.5 |
| Solar\_MS\_SOLAR\_2 | 52.0 |
| Solar\_ORIGIS\_LAF | 72.0 |
| Solar\_PRASI\_BUTLER | 100.0 |
| Solar\_PRASI\_DECATUR | 79.9 |
| Solar\_PRASI\_LIVEOAK | 51.0 |
| Solar\_PRASI\_PAWPAW | 30.0 |
| Solar\_PRASI\_WHTOAK | 76.5 |
| Solar\_PRASI\_WHTPINE | 101.3 |
| Solar\_PS\_Wing\_Solar | 80.0 |
| Solar\_REDI DG | 86.7 |
| Solar\_REDI DG CS | 36.0 |
| Solar\_REDI\_COOL\_SPRINGS | 213.0 |
| Solar\_REDI\_CS2 | 3.0 |
| Solar\_REDI\_DOUGHERTY | 120.0 |
| Solar\_REDI\_HICKORY\_PARK | 195.5 |
| Solar\_REDI\_QUITMAN | 150.0 |
| Solar\_REDI\_QUITMAN\_II | 150.0 |
| Solar\_REDI\_SOUTHERN\_OAK\_SOLAR | 160.0 |
| Solar\_REDI\_TANGLEWOOD | 57.5 |
| Solar\_REDI\_TWIGGS | 200.0 |
| Solar\_ROBINS\_AFB | 128.0 |
| Solar\_RTOFWAY\_SOLAR | 0.8 |
| Solar\_SPC Cedar Creek Solar | 2.0 |
| Solar\_SPC Hazelhurst 3 | 300.0 |
| Solar\_SPC Hazlehurst 1 | 20.0 |
| Solar\_SPC Middle Georgia Community Solar | 1.1 |
| Solar\_SPC Sandhills\_1 | 32.1 |
| Solar\_SPC SR Arlington | 20.0 |
| Solar\_SPC SR Clay | 106.0 |
| Solar\_SPC SR Perry | 68.0 |
| Solar\_SPC SR Snipesville | 200.0 |
| Solar\_SPC SR Snipesville III | 107.0 |
| Solar\_SPC SR Terrell | 200.0 |
| Solar\_SPC Tri-County Community Solar | 1.1 |
| Solar\_SPC Turnipseed Solar | 3.0 |
| Solar\_SR\_MERIDIAN\_3 | 52.5 |
| Solar\_UGA | 1.0 |
| Solar\_US\_TIMBERLAND | 140.0 |
| Solar\_US\_WADLEY | 260.0 |
| Solar\_WALNUT\_GROVE | 1.3 |

# Appendix B – Integration Cost Calculation Details

This appendix shows the integration cost details for each of the 18 scenarios evaluated. The integration costs are calculated as the increase in production cost from the pre-mitigation scenario case to the post-mitigation scenario case divided by the solar energy associated with the scenario case. As a point of reference, the no-solar reference case production cost was $6,094 million.

As described in the study methodology section above, the initial mitigation costs were calculated based on raw SERVM results. Those results were then smoothed (Preliminary Smoothed below) to provide a basis for calculating BESS flexibility credits. Along with the breakeven battery penetrations (i.e., the battery penetration required to get the system back to no-solar conditions without additional operating reserves), the solar mitigation costs and battery mitigation costs were then smoothed together to obtain the final smoothed integration costs below. The table below shows the pre-mitigation production cost, post-mitigation production cost, raw delta production cost, preliminary smoothed mitigation cost, final smoothed mitigation cost, solar generation, and resulting final integration cost for each of the five solar only scenarios.

Table 21. Base Case Integration Cost Calculations

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Tranche (MW) | Pre-Mitigation Cost (M$) | Post-Mitigation Cost (M$) | Delta (M$) | Preliminary  Smoothed  (M$) | Final  Smoothed (M$) | Solar GWH | Integration Cost  $/MWH |
| 7,500 | 5,414 | 5,447 | 34 | 39.4 | 38.6 | 16,868 | 2.29 |
| 10,000 | 5,241 | 5,314 | 73 | 57.9 | 56.9 | 22,491 | 2.53 |
| 15,000 | 4,961 | 5,054 | 93 | 99.5 | 98.1 | 33,266 | 2.95 |
| 20,000 | 4,730 | 4,880 | 150 | 146.3 | 147.1 | 44,991 | 3.27 |
| 25,000 | 4,505 | 4,694 | 190 | 197.2 | 196.8 | 56,241 | 3.50 |

As described in the study methodology section above, the preliminary smoothed solar mitigation costs were used as the basis for determining the battery flexibility credit, calculated as the difference between the mitigation cost with and without the batteries. Along with the breakeven battery penetrations and the solar mitigation costs, the BESS mitigation costs were then smoothed so that a smoothed battery flexibility credit could be determined. The table below shows the raw BESS mitigation and preliminary smoothed solar penetration used to calculate the initial battery flexibility credit. The table also shows the final, smoothed battery flexibility credit.

Table 22. 15% BESS Flexibility Credit Details

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Solar (MW) | BESS (MW) | BESS Mitigation (M$) | Solar Mitigation (M$) | Flexibility Credit (M$) | Flex Credit Smoothed (M$) | Flex Credit ($/kW-Yr) |
| 7,500 | 1150 | 41 | 39 | -2 | 31 | 27.31 |
| 10,000 | 1500 | 21 | 59 | 37 | 50 | 33.00 |
| 15,000 | 2250 | - | 100 | 100 | 100 | 44.23 |
| 20,000 | 3000 | - | 146 | 146 | 147 | 49.11 |
| 25,000 | 3750 | - | 197 | 197 | 197 | 52.53 |

# Appendix C – Load Following Heat Maps

The following tables contain heat maps reflecting the load following requirements needed to successfully mitigate the flex violations associated with the five solar only scenarios. These heat maps reflect the raw SERVM results (i.e., pre-smoothed) and thus would not be considered optimized to be consistent with the final, published integration costs. They do, however, represent a set of ancillary services profiles that achieve mitigation. Tables show the incremental MW requirement by hour over and above the no-solar requirement assumption of 1% of load.

Table 23. 7.5G Solar Only Load Following Heat Map



Table 24. 10G Solar Only Load Following Heat Map



Table 25. 15G Solar Only Load Following Heat Map



Table 26. 20G Solar Only Load Following Heat Map



Table 27. 25G Solar Only Load Following Heat Map



The following tables contain heat maps reflecting the load following requirements needed to successfully mitigate the flex violations associated with the BESS scenarios. Note that only the 7.5G Solar (1,125MW of BESS) and 10G Solar (1,500 MW of BESS) scenarios required mitigation.

Table 28. 7.5 GW Solar/1,125MW BESS Load Following Heat Map



Table 29. 10 GW Solar/1,500MW BESS Load Following Heat Map



1. There are several Combustion Turbine (CT) resources committed to Southern Company load but owned and operated by certain Electric Municipal Cooperatives (EMC) in Georgia which can only be called upon on a day-ahead basis during the winter months. This commitment constraint was modeled in SERVM. [↑](#footnote-ref-2)
2. https://nsrdb.nrel.gov/ [↑](#footnote-ref-3)
3. Anderson, K., Hansen, C., Holmgren, W., Jensen, A., Mikofski, M., and Driesse, A. “pvlib python: 2023 project update.” Journal of Open Source Software, 8(92), 5994, (2023). https://doi.org/10.21105/joss.05994 [↑](#footnote-ref-4)
4. https://github.com/williamhobbs/solar-fleet-subhourly-modeling [↑](#footnote-ref-5)