Guidehouse

Solar Inverter Power Factor Correction Demonstration (MA21DR03) Evaluation Memorandum

Prepared for:

National Grid

Submitted by:

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Executive Summary

The solar inverter power factor correction (PFC) demonstration aims to leverage customer-owned solar inverters for PFC. The primary objective is to improve power factor via use of the voltage control capability of solar inverters. The inverter rating and controls are set to ensure no impact on solar output (kWh) from customer-owned devices.

The solar inverter PFC demonstration was offered in 2021. Customers with eligible equipment in Massachusetts and Rhode Island service areas could sign up for the offering, whether they had existing or new solar systems less than 100 kW. Participating customers are provided incentives for the right to enable PFC. Table 1 summarizes the characteristics of the offering.

Table 1. Solar Inverter PFC Summary

Program Attributes	2021 Plan
States	Massachusetts and Rhode Island
Targeted Systems*	<100 kW
Target Number of Participants	6,500 customers in Massachusetts; 1,700 customers in Rhode Island
Enrolled Participants as of November 17, 2021	1,885 customers in Massachusetts; 819 customers in Rhode Island
Participant Incentives**	$25 enrollment incentive; $20 per year incentive
Solar Inverter Manufacturer	One participating company
PFC Periods	Year-round during periods of solar production

* Interested customers with solar photovoltaic system sizes greater than 100 kW are placed on a wait list.

** An additional incentive will be provided if there is a setting error and the program administrator(s) inadvertently causes a customer to lose solar power generation.

Source: National Grid and Guidehouse analysis

Guidehouse evaluated objectives 3 and 4 summarized in Table 2 using interval data collected from enrolled solar inverters and their associated feeders and substations. Distribution load flow modeling results leveraging CYME Power Engineering software was provided by Guidehouse in August 2021, which covered evaluation objectives 1 and 2.

Table 2. Solar Inverter PFC Demonstration Evaluation Objectives

Evaluation Objectives
1. Verify that the solution successfully enables power factor correction.
2. Validate the approach used to conduct the impact analysis.
3. Confirm that the solution results in kVA savings for the utility.
4. Align on methodology to determine kVA savings.

Source: Guidehouse

Table 3 provides the evaluation results for fall 2021 analysis period spanning September 29 through November 17, 2021. Guidehouse received data for 2,637 of the 2,704 enrolled solar inverters, and interval data was not available for all these inverters until September 29, 2021. Therefore, provided results are for the period spanning September 29 through November 17, 2021. The text following the table provides further detail surrounding the findings.

Table 3. Fall 2021 Evaluation Results

	Massachusetts	Rhode Island	Total
Enrolled Inverters as of November 17, 2021	1,885	819	2,704
Total Enrolled Capacity of Inverters (kW)	12,505	5,008	17,513
Inverters in Analysis Data*	1,019	307	1,326
Total Capacity of Inverters in Analysis Data (kW)	6,594	1,747	8,341
PFC Active Inverters**	819	259	1,078
PFC Active Inverters Capacity (kW)	5,451	1,506	6,957
Feeder Average kVAR	-112	-24	-99
Percent Positive	53.8%	49.7%	53.2%
Percent Negative	46.2%	50.3%	46.8%
Feeder Average Power Factor	0.92	0.94	0.92
Inverter Average PFC Active kVAR	-1.02	-1.48	-1.10
Percent of Time Inverters PFC Active	35.9%	55.0%	38.7%
Percent of Time Absorbing VAR	34.9%	54.2%	37.7%
Percent of Time Injecting VAR	1.00%	0.75%	0.96%
Total Savings (kVAh)	**137**	**-863**	**-726**

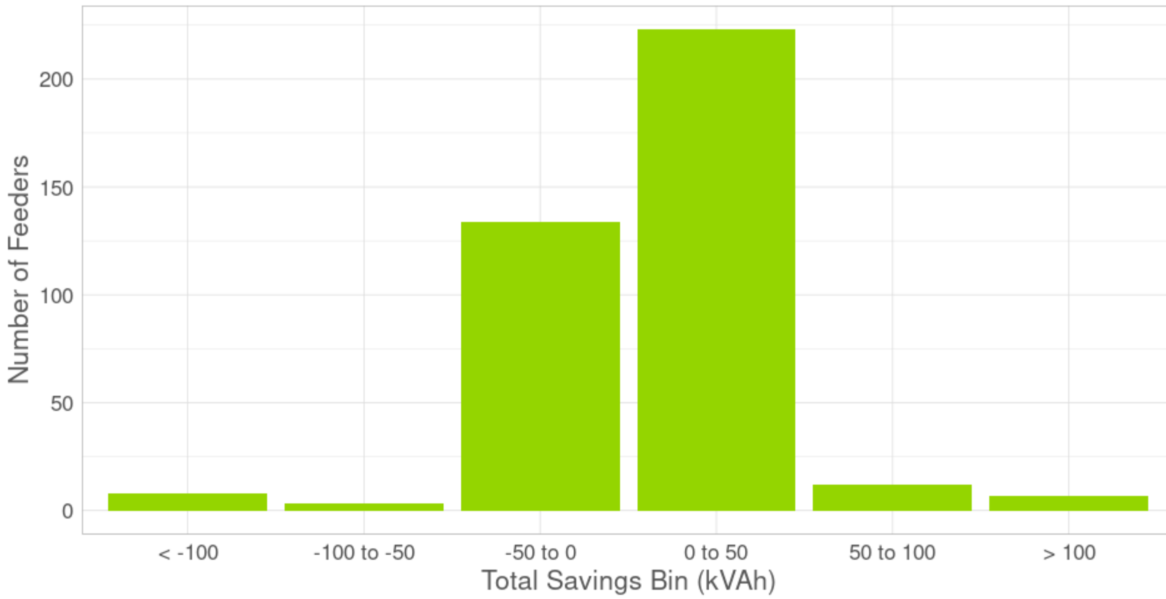
* About 48% of inverters were dropped from analysis data due to lack of Substation PI data.

** PFC Active Inverters is the set of inverters in the analysis data that were engaged in power factor correction at any point in the analysis period. Inverters will not be engaged in power factor correction for any time period if they have insufficient generation (kW output < 0.30 * Nameplate kW) or if voltage does not go above 245 V or below 235 V.

Source: Guidehouse analysis

Figure 1 illustrates the total kVAh savings observed by feeder during the fall 2021 analysis. Each feeder is placed in a bin based on total kVAh savings, with the bin counts shown on the y-axis. Across the feeders with PFC engaged, kVAh savings ranged from -824 to 366 kVAh. A large proportion of feeders experienced minimal kVAh impacts associated with solar PFC, with 92% experiencing kVAh savings ranging from -50 kVAh to 50 kVAh. Meanwhile, a handful of feeders saw total savings far from zero. The bottom 5% of feeders with the lowest savings experienced total savings of -2,805 kVAh, while the top 5% of feeders with the highest savings experienced total savings of 2,325 kVAh. The middle 90% of feeders saw total savings of -245 kVAh. This suggests observed savings are driven by a small portion of feeders. Based on further data investigation, feeders with large savings had average feeder kVAR that was negative as well as a larger amount solar inverter kVAR absorption when PFC was engaged (i.e., negative inverter kVAR). On the other hand, feeders with large negative savings (i.e., increases in kVAh) had average feeder kVAR that was positive as well as a larger amount of solar inverter kVAR absorption when PFC was engaged.

Figure 1. Frequency of Total Savings by Feeder



Source: Guidehouse analysis

Guidehouse's evaluation of the solar inverter PFC demonstration found:

- **Evaluated Savings:** During the fall 2021 evaluation period, solar inverter PFC resulted in negative total feeder savings (-726 kVAh), or an increase in kVAh. Most feeders experienced minimal savings, with 92% experiencing kVAh savings ranging from -50 kVAh to 50 kVAh. Feeder savings varied greatly between Massachusetts and Rhode Island, with savings totaling 137 kVAh in Massachusetts and -863 kVAh in Rhode Island. These savings totals were largely driven by a handful of feeders with large savings and losses. For example, 8 feeders experienced total kVAh savings of less than -100 kVAh, and 7 feeders experienced total kVAh savings of more than 100 kVAh.
- **Feeder Reactive Power:** Guidehouse observed a clear trend between feeder average reactive power, inverter reactive power, and feeder savings. Feeders with average reactive power that was negative during the fall 2021 analysis period experienced kVAh savings of 2,870 kVAh. This finding is consistent with the solar inverters, on average, absorbing reactive power when PFC was engaged during the analysis period. On the other hand, feeders with average reactive power that was positive during the fall 2021 analysis period experienced kVAh increases of 3,597. This finding is also consistent with the solar inverters, on average, absorbing reactive power when PFC was engaged during the analysis period.

In 2022 and beyond, Guidehouse recommends that National Grid:

- **Program Design:** National Grid and stakeholders should discuss either making significant design changes for the offering or consider discontinuing the offering. As the program is currently constructed, Guidehouse has identified overall increases in kVAh.

Otherwise, Guidehouse encourages National Grid to consider the following:

- **Incentives:** Consider allowing participation on all feeders, but providing annual participation incentives for customers connected to feeders with telemetry, or consider ensuring substation interval data is available for all enrolled solar inverters. National Grid provided 15-minute interval data for many substations in Massachusetts and Rhode Island. However, roughly half of enrolled inverters were removed from the analysis data due to interval data not being available. As such, calculated impacts only cover roughly half of the enrolled solar inverters.
- **Inverter Operations:** Voltage conditions measured at the participating solar inverter sites dictated when participating inverters were engaged for PFC. National Grid should consider whether there is another way to engage solar inverters for PFC, such as National Grid measuring whether each feeder has a lagging or leading power factor, then engaging enrolled inverters to engage in PFC when specific feeder power factor conditions exist.
- **Additional Analysis:** Consider incorporating additional parameters into analysis, such as capacitor bank operations, to explain findings. Additionally, consider identifying specific types of feeders that may benefit from solar inverter PFC, including certain characteristics such as feeder length, number of capacitor banks, peak loading, and distributed solar penetration to determine whether there are further ways to improve or increase kVAh savings associated with solar inverter PFC.

1. Introduction

The solar inverter power factor correction (PFC) demonstration aims to leverage customer-owned solar inverters for PFC. The primary objective is to improve power factor via use of the voltage control capability of solar inverters. The inverter rating and controls are set to ensure no impact on solar output (kWh) from customer-owned devices.

The solar inverter PFC demonstration was offered in 2021. Customers with eligible equipment in Massachusetts and Rhode Island service areas could sign up for the offering, whether they had existing or new solar systems less than 100 kW. Participating customers are provided incentives for the right to enable PFC. Table 4 summarizes the characteristics of the offering.

Table 4. Solar Inverter PFC Summary

Program Attributes	2021 Plan
States	Massachusetts and Rhode Island
Targeted Systems*	<100 kW
Target Number of Participants	6,500 customers in Massachusetts; 1,700 customers in Rhode Island
Enrolled Participants as of November 17, 2021	1,885 customers in Massachusetts; 819 customers in Rhode Island
Participant Incentives**	$25 enrollment incentive; $20 per year incentive
Distributed Solar Partners	One participating company
PFC Periods	Year-round during solar production

* Interested customers with solar photovoltaic system sizes greater than 100 kW are placed on a wait list.

**An additional incentive will be provided if there is a setting error and the program administrator(s) accidentally causes a customer to lose solar power generation.

Source: National Grid and Guidehouse analysis

1.1 Evaluation Goal and Objectives

Guidehouse evaluated objectives 3 and 4 summarized in Table 5 using interval data collected from enrolled solar inverters and their associated feeders and substations. Distribution load flow modeling results leveraging CYME Power Engineering software was provided by Guidehouse in August 2021, which covered evaluation objectives 1 and 2.

Table 5. Solar Inverter PFC Demonstration Evaluation Objectives

Evaluation Objectives
1. Verify that the solution successfully enables PFC.
2. Validate the approach used to conduct the impact analysis.
3. Confirm that the solution results in kVA savings for the utility.
4. Align on methodology to determine kVA savings.

Source: Guidehouse

1.2 Enrollment Summary

The evaluation team evaluated outcomes from the solar PFC demonstration for the fall 2021 analysis period, spanning September 29 through November 17, 2021. As of the end of November 17, 2021, the demonstration included 2,704 enrolled and connected solar inverters with a combined 17,513 kW in capacity. Enrolled solar inverters were connected to 766 feeders associated with 304 substations. Solar inverters participating in the demonstration were split approximately 70/30 between Massachusetts and Rhode Island. Table 6 summarizes enrollment in the demonstration.

Table 6. Enrollment in the Solar Inverter PFC Demonstration

	Massachusetts	Rhode Island	Massachusetts + Rhode Island
Enrolled Solar Inverters (kW)*	12,505	5,008	17,513
Enrolled Solar Inverters (#)	1,885	819	2,704
Feeders with Enrolled Inverters (#)	552	214	766
Substations with Enrolled Inverters (#)	226	78	304

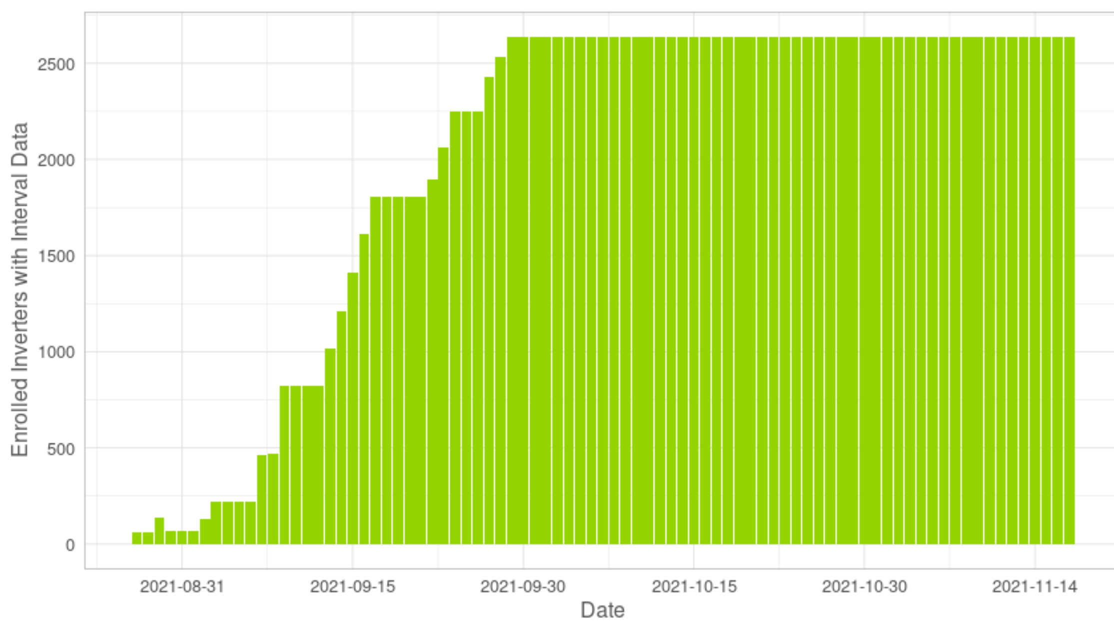
Note: Enrollment in the demonstration reflects data updated through November 2021.

* kW corresponds with the nameplate kW associated with the solar site.

Source: Guidehouse analysis

Guidehouse received data for 2,637 of the 2,704 enrolled solar inverters. Interval data was not available for all these inverters until September 29, 2021, as shown below in Figure 2. For this reason, the fall 2021 analysis period is defined as September 29 to November 17, 2021.

Figure 2. Enrolled Solar Inverters with Interval Data Available



Source: Guidehouse analysis

2. Evaluation Methodology

Guidehouse worked with National Grid to collect data to complete the evaluation. The sections that follow highlight the data sources, data quality assurance/quality control (QA/QC) processes, analysis data construction, data cleaning, and data analysis approach the team used in its evaluation.

2.1 Data Sources

Table 7 summarizes the data inputs used in the evaluation. Guidehouse obtained fields from National Grid and the National Oceanic and Atmospheric Administration (NOAA).

Table 7. Data Used for Evaluation

Data Type	Description
Distribution System Information	• Feeder characteristics, including rated primary voltage, rated capacity, feeder length, number of customers, and nominal distributed generation (DG) capacity in kW
Time Series Data	• 15-minute interval data of voltage, real power, and reactive power measured at enrolled customer solar inverter sites in Massachusetts and Rhode Island • 15-minute interval data of real power and reactive power measured at the feeder head-end for feeders in Massachusetts and Rhode Island
Enrolled Inverter Information	• Customer enrollment file containing all customer solar inverters enrolled in the demonstration, and includes information such as location of customer site, inverter identifier, substation and feeder associated with enrolled solar inverter, and maximum nameplate kW
Weather Data	• Weather data containing sunrise and sunset times for Boston Logan International Airport collected from the National Oceanic and Atmospheric Administration (NOAA)

Source: Guidehouse

2.2 Data QA/QC Process

The evaluation team reviewed all data provided once received. The QA/QC of the data included checks to confirm each of the required data inputs could be incorporated into the analysis. Examples of the QA/QC include the following:

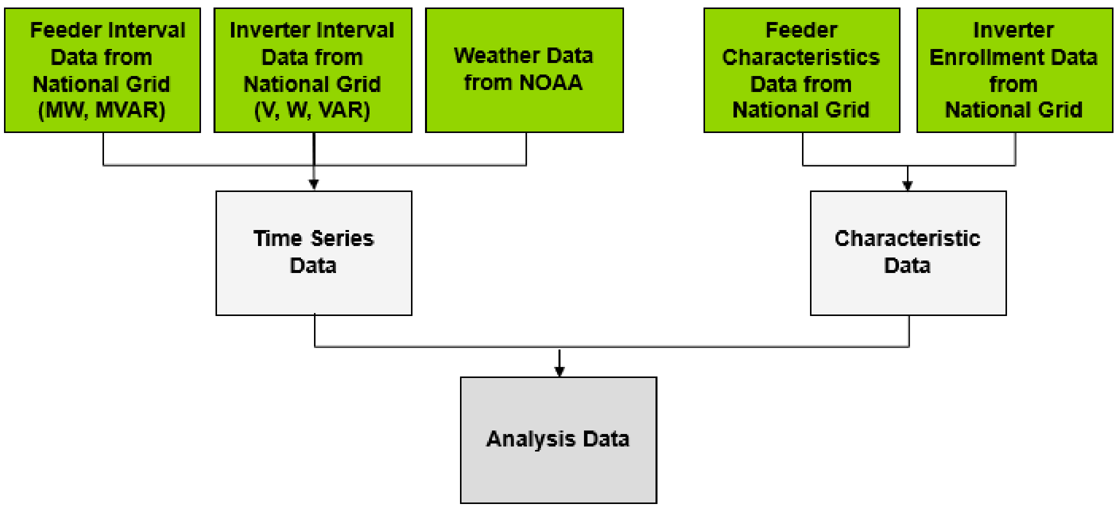
- Confirm that time series data has been provided for enrolled solar inverters, associated substations, and associated feeders.
- Confirm data received for all enrolled solar inverters.
- Confirm that time series data covers each substation and feeder with an enrolled solar inverter and includes variables needed to facilitate analysis, including voltage, real power, and reactive power.
- Verify that time series data is complete in time and extent of devices and do not include erroneous data (e.g., missing data intervals, stretches of interpolated or repeated values, and outliers).

After receiving the data, the team presented a summary of its QA/QC to National Grid, confirming receipt of the datasets and indicating quality. Additional follow-up based on standing questions occurred to confirm all National Grid-provided data could be used in the analysis.

2.3 Analysis Data Construction

To conduct this evaluation, Guidehouse compiled time series and process data to arrive at a final analysis dataset. To construct an analysis dataset, the evaluation team integrated data from several sources. Figure 3 illustrates the data integration process used to construct the final analysis dataset.

Figure 3. Analysis Data Construction Flowchart



Source: Guidehouse

To compile the time series data, the evaluation team integrated 15-minute feeder interval data and inverter interval data from National Grid. Feeder interval data contained measurements of real power and reactive power measured at the feeder head-end. Inverter interval data contained measurements of voltage, real power, and reactive power measured at the customer solar site. Lastly, Guidehouse joined weather data containing sunrise and sunset times from NOAA for Boston Logan International Airport.

To compile the process data, the team integrated available feeder characteristics data and inverter enrollment records from National Grid. Feeder characteristics data included information such as peak load, connected customers, feeder length, and connected nominal distributed generation capacity. Inverter enrollment data included information such as inverter identification number, state (Massachusetts or Rhode Island) of enrolled customer solar inverter, feeder and substation associated with the customer solar site, and maximum nameplate kW. Guidehouse joined time series and process data to construct a final analysis dataset.

2.4 Analysis Data Cleaning

After constructing the analysis datasets, the evaluation team conducted data cleaning steps to remove interval data that may bias the estimates of solar PFC impacts. Table 8 summarizes data observations made by the team and the resulting data cleaning steps that were executed.

Table 8. Data Cleaning Conducted for Evaluation

Data Observation	Data Cleaning Step
Guidehouse observed that numerous inverters did not have interval data available.	Guidehouse removed inverters without interval data available from the analysis.
Feeder interval data required to calculate impacts of inverter PFC was not available for several solar inverters.	Guidehouse removed feeders without available interval data from the analysis. Guidehouse then removed inverters without feeder interval data from the analysis.
Guidehouse has observed several time periods with interpolated or repeated interval data, which may be associated with a communications or sensor issue.	Guidehouse flagged and removed time periods with interpolated or repeated interval data to ensure data used in calculation is correct.
Guidehouse detected numerous outlier* data points in the feeder and inverter interval data.	Guidehouse flagged and removed outlier data points in the feeder and inverter interval data.

* A data point was flagged as an outlier if the data point was more than 3 standard deviations from the mean.

Source: Guidehouse

Table 9 indicates the number of data points, substations, feeders, and inverters contained in the analysis data. Prior to data cleaning, analysis data contained 7,383,600 observations spanning 304 substations, 766 feeders, and 2,637 inverters. After data cleaning, the data contained 3,774,904 rows spanning 136 substations, 370 feeders, and 1,326 inverters. Substation PI data was unavailable for roughly 48% of inverters, resulting in these inverters being removed from the analysis data.

Table 9. Summary of Data Attrition from Data Cleaning

	15-Minute Intervals	Substations with Enrolled Inverters	Feeders with Enrolled Inverters	Enrolled Inverters with Interval Data
Raw Dataset	7,383,600*	304	766	2,637
Removed	3,608,696	168	396	1,311
Cleaned Dataset	**3,774,904**	**136**	**370**	**1,326**

** Raw data interval count indicates the count of rows between September 29−November 17 spanning hours 6 am through 7 pm.*

Source: Guidehouse

In the cleaned analysis dataset, Guidehouse identified that many enrolled solar inverters with data available were only able to record the absolute value of reactive power. As illustrated in Table 10, over 80% of enrolled and connected solar inverters were affected by strictly positive VAR.

Table 10. Inverters Affected by Strictly Positive VAR

	VAR Strictly Positive		VAR Not Strictly Positive		Unknown VAR Status	
	Number of Inverters	Share of Inverters	Number of Inverters	Share of Inverters	Number of Inverters	Share of Inverters
Massachusetts	1,499	79.47%	63	3.34%	323	17.14%
Rhode Island	685	83.64%	22	2.69%	112	13.68%
Total	**2,184**	**80.77%**	**85**	**3.14%**	**435**	**16.09%**

Note: Enrolled solar inverters with an unknown inverter status were enrolled inverters that did not have interval data available at the time of the evaluation.

Source: Guidehouse analysis

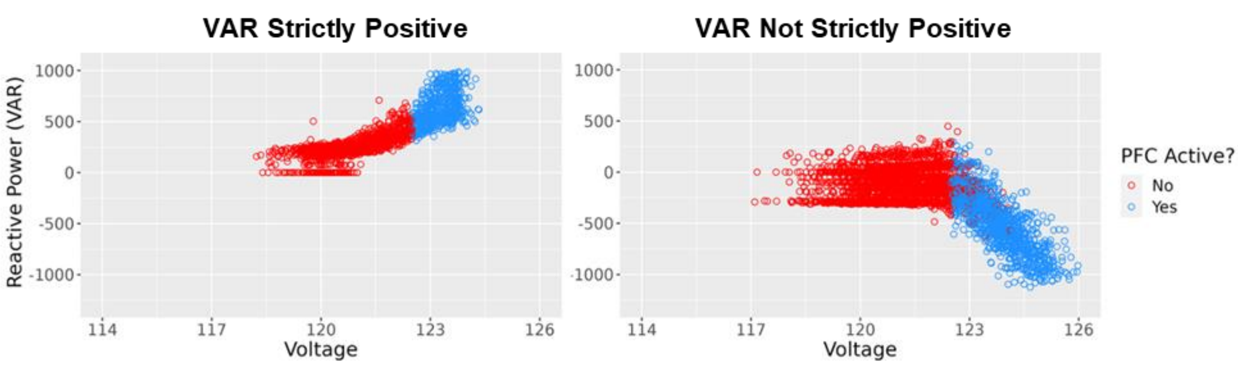
Solar inverters enrolled in the demonstration are intended to inject or absorb reactive power depending on local voltage and generation conditions. Solar inverters enrolled in the demonstration will:

- **Absorb reactive power** when voltage recorded at the site is greater than 245 (or voltage divided by two is greater than 122.5) and kW generated at the site is greater than 0.30 times the nameplate maximum kW for the site. Reactive power recorded at the solar inverter site is negative when reactive power absorption is taking place.

- **Inject reactive power** when voltage recorded at the site is less than 235 (or voltage divided by two is less than 117.5) and kW generated at the site is greater than 0.30 times the nameplate maximum kW for the site. Reactive power recorded at the solar inverter site is positive when reactive power injection is taking place.

Figure 4 presents the Volt/VAR profile for two selected solar inverters, one affected and one unaffected by strictly positive VAR. Shaded in blue are the time periods where PFC was active and absorption of reactive power was occurring. Shaded in red are the time periods where PFC was not active, which do not affect savings calculations. An inverter affected by strictly positive VAR (shown on the left) records positive reactive power values when conducting reactive power absorption. An inverter unaffected by strictly positive VAR can correctly record the absorption of reactive power.

Figure 4. Volt/VAR Profile for Inverters Affected and Unaffected by Positive VAR*



*Guidehouse presents 'voltage' as voltage divided by two.

Source: Guidehouse analysis

Without correcting data for the 80% of enrolled inverters affected by strictly positive VAR, Guidehouse would have to remove the inverters and associated feeders from analysis data. However, given the evaluation team received voltage and kW generation data for each site, the team flagged specific time periods in which PFC was active. To determine whether data for the 80% of enrolled inverters could be retained in the analysis, Guidehouse conducted manual inspection of the telemetry from each of the solar inverters that could record positive and negative reactive power to ensure reactive power absorption and injection was occurring as designed when PFC was active.

Based on manual inspection of the telemetry from these inverters, the evaluation team identified that all inverters but one were responding as designed when PFC was active. Therefore, as a final data adjustment prior to calculating impacts of PFC, the team multiplied all reactive power values for inverters with strictly positive VAR by negative one when reactive power absorption should have been occurring (i.e., when voltage recorded at the site was greater than 245 and kW generated at the site was greater than 0.30 times the nameplate maximum kW).

2.5 Analysis Approach

After the analysis data was constructed and cleaned, Guidehouse calculated the impact of solar inverter PFC on measured feeder-level apparent power. Apparent power savings achieved using customer solar inverter PFC can be calculated by comparing the apparent power with and without the PFC control. This can be accomplished by measuring real and reactive power at the feeder and reactive power injection or consumption at the inverter. Equation 1 demonstrates calculation of apparent power (kVA), derived via the square root of sum of real and reactive power squared.

Equation 1. Apparent Power Calculation

$$\begin{matrix}Apparent\\Power\\(kVA)\end{matrix} = \sqrt{\begin{matrix}Real\\Power\\(kW)\end{matrix}^{2} + \begin{matrix}Reactive\\Power\\(kVAR)\end{matrix}^{2}}$$

The evaluation team calculated apparent power savings using Equation 2. Apparent power with PFC is the observed power on the system that is calculated by using real and reactive power on the feeder. Apparent power without PFC is calculated by subtracting the reactive power contributions of the solar inverters enrolled in the program on the feeder. The difference between the two generates the power savings on the feeder that can be attributed to the reactive power contributions of the participating inverters.

Equation 2. Apparent Power Savings Associated with PFC

$$\begin{matrix}Apparent\\Power\ Saved\end{matrix} = \underbrace{\sqrt{\begin{pmatrix}Feeder\\Real\\Power\end{pmatrix}^{2} + \begin{pmatrix}Feeder\\-Reactive\\Power\end{matrix} - \sum \begin{matrix}Inverter\\Reactive\\Power\end{pmatrix}^{2}}}_{\text{Apparent Power w/o PFC}} - \underbrace{\sqrt{\begin{pmatrix}Feeder\\Real\\Power\end{pmatrix}^{2} + \begin{pmatrix}Feeder\\-Reactive\\Power\end{pmatrix}^{2}}}_{\text{Apparent Power w/ PFC}}$$

3. Evaluation Results

Table 11 summarizes evaluation results for the fall 2021 analysis period spanning September 29 through November 17. Based on telemetry data received and analyzed, inverters resulted in around -726 kVAh in total savings – an increase in kVAh – during the fall 2021 analysis period. Massachusetts experienced a slight reduction in kVAh when PFC was engaged, whereas Rhode Island experienced kVAh increases when PFC was engaged. Guidehouse provides further discussion surrounding increases and decreases in kVAh associated with solar inverter PFC in the figures below.

Table 11. Fall 2021 Evaluation Results

	Massachusetts	Rhode Island	Total
Enrolled Inverters as of November 17, 2021	1,885	819	2,704
Total Enrolled Capacity of Inverters (kW)	12,505	5,008	17,513
Inverters in Analysis Data*	1,019	307	1,326
Total Capacity of Inverters in Analysis Data (kW)	6,594	1,747	8,341
PFC Active Inverters**	819	259	1,078
PFC Active Inverters Capacity (kW)	5,451	1,506	6,957
Feeder Average kVAR	-112	-24	-99
Percent Positive	53.8%	49.7%	53.2%
Percent Negative	46.2%	50.3%	46.8%
Feeder Average Power Factor	0.92	0.94	0.92
Inverter Average PFC Active kVAR	-1.02	-1.48	-1.10
Percent of Time Inverters PFC Active	35.9%	55.0%	38.7%
Percent of Time Absorbing VAR	34.9%	54.2%	37.7%
Percent of Time Injecting VAR	1.00%	0.75%	0.96%
Total Savings (kVAh)	**137**	**-863**	**-726**

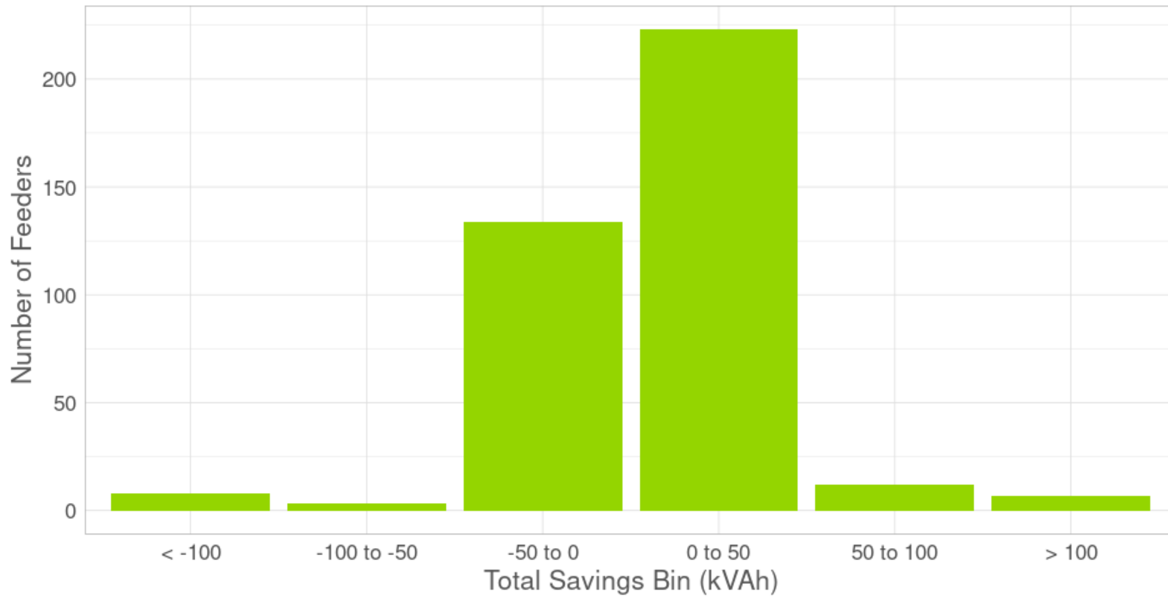
*About 48% of inverters were dropped from analysis data due to lack of Substation PI data.

**PFC Active Inverters is the set of inverters in the analysis data that were engaged in power factor correction at any point in the analysis period. Inverters will not be engaged in power factor correction for any time period if they have insufficient generation (kW < 0.30*Nameplate kW) or if voltage does not go above 245 or below 235.

Source: Guidehouse analysis

Figure 5 illustrates the total kVAh savings on feeders during the fall 2021 analysis. Each feeder is placed in a bin based on total kVAh savings, with the bin counts shown on the y-axis. Across the feeders with PFC engaged, kVAh savings ranged from -824 to 366 kVAh. Most feeders experienced minimal kVAh impacts associated with solar PFC, with 92% experiencing kVAh savings ranging from -50 kVAh to 50 kVAh. Meanwhile, a handful of feeders saw total savings far from zero. The bottom 5% of feeders with the lowest savings experienced total savings of -2,805 kVAh, while the top 5% of feeders with the highest savings experienced total savings of 2,325 kVAh. The middle 90% of feeders saw total savings of -245 kVAh. This suggests observed savings are driven by a small portion of feeders.

Figure 5. Frequency of Total Savings by Feeder



Source: Guidehouse analysis

Table 12 emphasizes the findings in Figure 5 in that a small number of feeders are driving the overall savings totals. On the positive side of the savings spectrum, the seven feeders with the greatest savings have greater summed kVAh savings (1,360 kVAh) than the sum of 206 feeders with total savings from 0 to 50 kVAh (761 kVAh). On the negative side of the spectrum, 8 feeders summed to a savings total of -2,189 kVAh.

Table 12. Total kVA Savings by Feeder Savings Bin

Total Savings	Count of Feeders	Percent of Feeders	Total kVAh Savings
< -100 kVAh	8	2.16%	-2,189 kVAh
-100 to -50 kVAh	3	0.81%	-205 kVAh
-50 to 0 kVAh	134	36.2%	-1,371 kVAh
0 to 50 kVAh	206	55.7%	761 kVAh
50 to 100 kVAh	12	3.24%	917 kVAh
> 100 kVAh	7	1.89%	1,360 kVAh
Total	**370**	**100%**	**-726 kVAh**

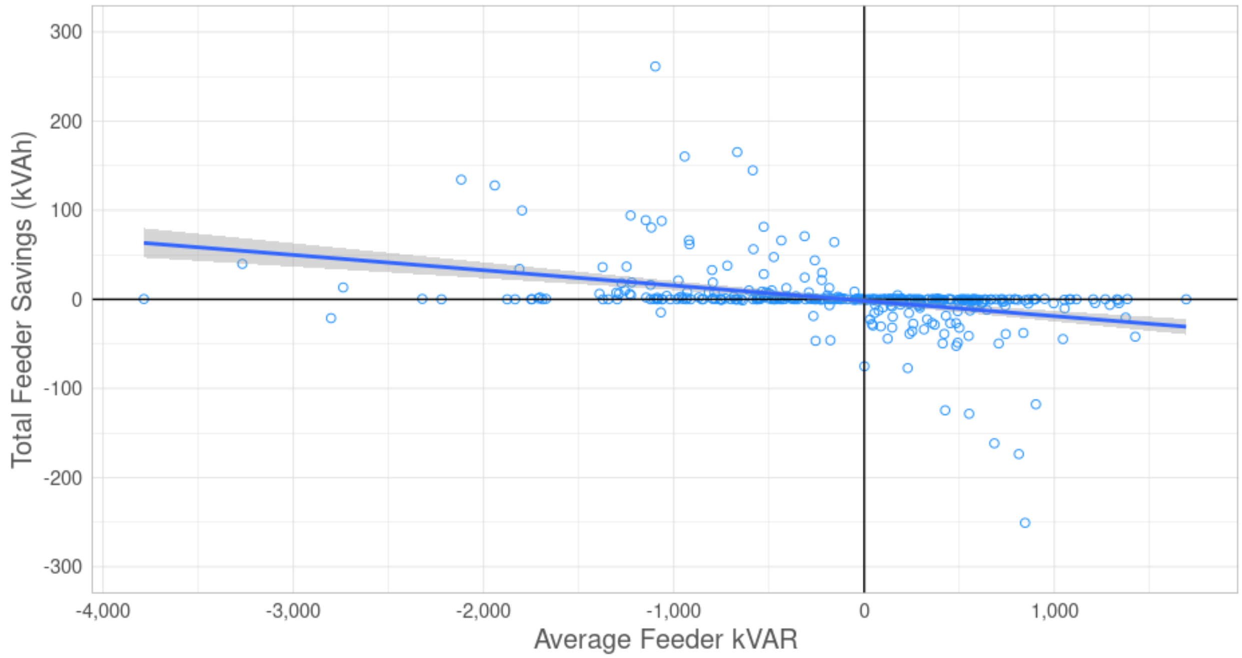
Source: Guidehouse analysis

To provide further insight into what may be driving increases or decreases in kVAh when PFC was engaged, Guidehouse analyzed trends between feeder kVAR and feeder savings. Figure 6 illustrates total feeder kVAh savings by average feeder kVAR recorded during the fall 2021 analysis period.[1] This figure reiterates that many feeders experienced roughly 0 kVAh impacts from PFC. However, for the feeders that did experience an impact, positive kVAh savings were

[1] Average feeder kVAR was recorded using kVAR measurements recorded at the feeder head-end.

generally achieved among feeders with average kVAR readings that were negative. Conversely, PFC tended to increase kVAh across feeders with average kVAR readings that were positive.

Figure 6. Total Feeder kVAh Savings by Average Feeder kVAR*

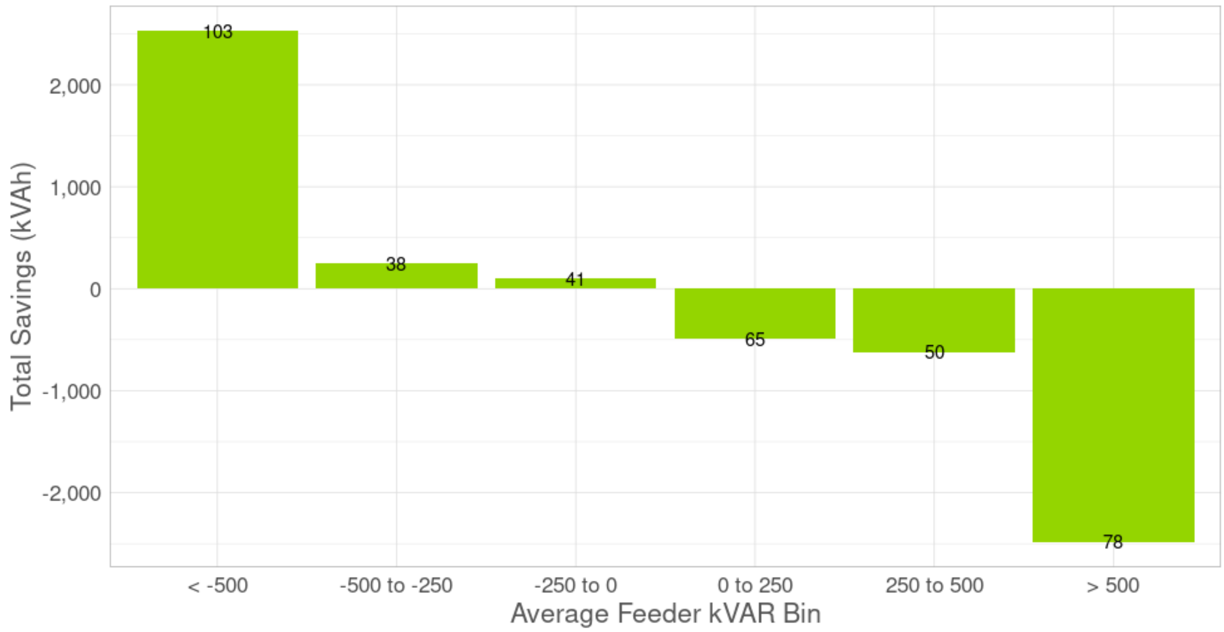


*15 feeders fell outside of plot bounds. Feeders outside of plot bounds had total kVAh savings ranging from -824 to 366 kVAh.

Source: Guidehouse analysis

Figure 7 provides a simplified view of the previous scatter plot and provides total kVAh savings by average feeder kVAR bin. The total number of feeders in each average feeder kVAR bin can be found at the top edge of each bin. As is apparent, the largest total kVAh savings were observed across 103 feeders with an average kVAR of less than -500, with these feeders experiencing 2,527 kVAh in savings when PFC was engaged. The largest increases in kVAh were observed across 78 feeders with an average kVAR of greater than 500, with these feeders experiencing an increase of almost 2,481 kVAh when PFC was engaged.

Figure 7. Total kVAh Savings by Average Feeder kVAR*

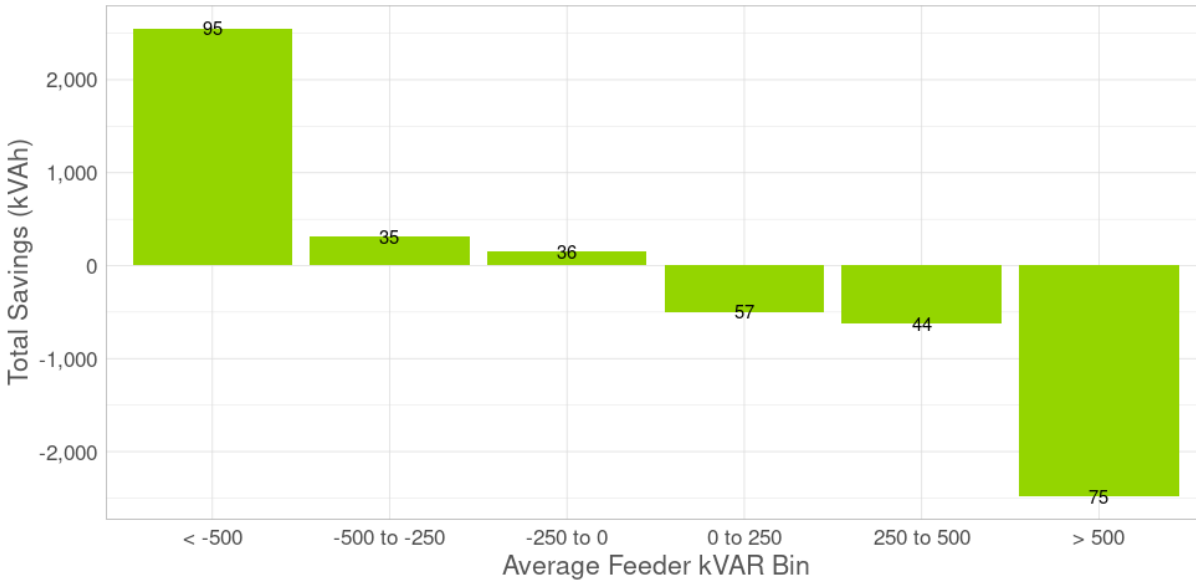


* The count of feeders within each kVAR bin is presented at the top of each bin.

Source: Guidehouse analysis

Figure 8 presents the same glance at the data, but now among the feeders that experienced solar inverters primarily absorbing VAR when PFC was engaged. For these feeders, the pattern is roughly identical to the pattern illustrated in Figure 7. Feeders with an average VAR that is negative tend to experience kVAh savings when PFC is engaged and solar inverters are absorbing VAR. Feeders with an average VAR that is positive tend to experience increases in kVAh when PFC is engaged and solar inverters are absorbing VAR.

Figure 8. Total kVAh Savings by Average Feeder kVAR – Feeders with Majority Inverter VAR Absorption*

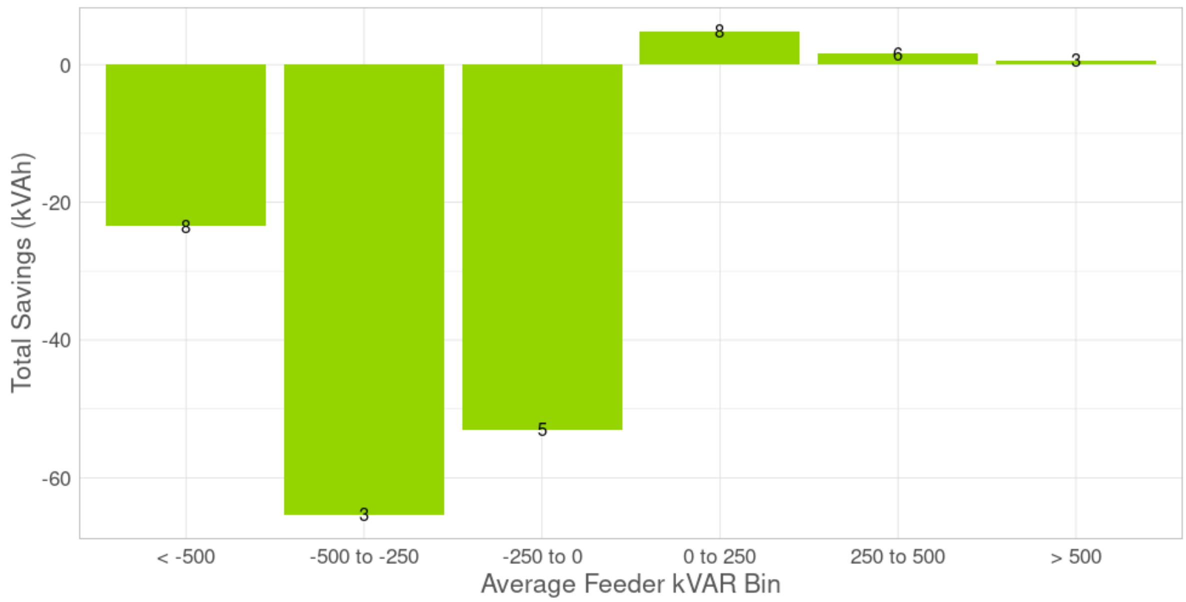


* The count of feeders within each kVAR bin is presented at the top of each bin.

Source: Guidehouse analysis

Figure 9 presents a similar glance at the data, now among the feeders that experienced solar inverters primarily injecting VAR when PFC was engaged. For these feeders, the pattern is the inverse of the prior three graphs. Feeders with an average VAR that is negative tend to experience kVAh increases when PFC is engaged and solar inverters are injecting VAR. Feeders with an average VAR that is positive tend to experience kVAh savings when PFC is engaged and solar inverters are injecting VAR.

Figure 9. Total kVAh Savings by Average Feeder kVAR – Feeders with Majority Inverter VAR Injection*



* The count of feeders within each kVAR bin is presented at the top of each bin.

Source: Guidehouse analysis

Referencing Equation 2, kVAh savings patterns are in line with what would be expected. Shown in Table 13, the equation used to determine kVA savings generates kVA savings when feeder kVAR and inverter kVAR share the same sign (i.e., both are positive, or both are negative). In fall 2021, most feeders experienced solar inverter VAR absorption (i.e., negative inverter kVAR) when PFC was engaged. Therefore, the majority of feeders fall in example feeders 2 and 4 in Table 13. Similar to this table, Figure 7 and Figure 8 illustrated cases where feeder kVAh savings were realized when feeder kVAR was negative and inverter kVAR was negative, and kVAh increases occurred when feeder kVAR was positive and inverter kVAR was negative.

Table 13. kVA Savings for Four Example Feeders

Feeder	Feeder kW	Feeder kVAR	Inverter kVAR	kVA without PFC	kVA with PFC	kVA Savings
1	1,200	500	100	1,342	1,300	42
2	1,200	500	-100	1,265	1,300	-35
3	1,200	-500	100	1,265	1,300	-35
4	1,200	-500	-100	1,342	1,300	42

Source: Guidehouse

Based on the findings above, in Table 14 the evaluation team provides savings associated with feeders that had average kVAR readings that were positive or negative. Feeders with average kVAR that was negative during the fall 2021 analysis period experienced kVAh savings of 2,870 kVAh. This finding is consistent with the solar inverters, on average, absorbing VAR when PFC was engaged during the analysis period. Feeders with average kVAR that was positive during the fall 2021 analysis period experienced kVAh increases of 3,597 kVAh.

Table 14. kVAh Savings for Feeders by Average kVAR

Feeder Group	Count of Feeders with PFC Activity	Feeder Average kVAR	Average Inverter kVAR when PFC Engaged	kVAh Savings
Feeders with Average kVAR < 0	180	-764	-0.95	2,871
Feeders with Average kVAR ≥ 0	190	477	-1.25	-3,597
All Feeders	**370**	**-99**	**-1.10**	**-726**

Source: Guidehouse

To understand why some feeders had large negative or large positive kVAh savings during fall 2021, Table 15 details some observed patterns associated with feeders with large negative and positive kVAh savings. Large negative kVAh savings feeders had an average feeder kVAR of 778 during fall 2021, while large positive kVAh savings feeders had an average feeder kVAR of -1,268 during fall 2021. In addition, relative to feeders in the moderate kVAh savings bin, feeders in the large negative and large positive savings bins experienced a greater degree of inverter kVAR absorption when PFC was engaged. Therefore, large positive savings were found amongst feeders with negative average kVAR and negative inverter kVAR when PFC was engaged, while large negative savings were found amongst feeders with positive average kVAR and negative inverter kVAR when PFC was engaged. This indicates that feeder savings (or dissavings) can be linked to (1) the sign of feeder average kVAR, (2) the sign of inverter average kVAR when PFC is engaged, and (3) the magnitude of inverter kVAR when PFC is engaged.

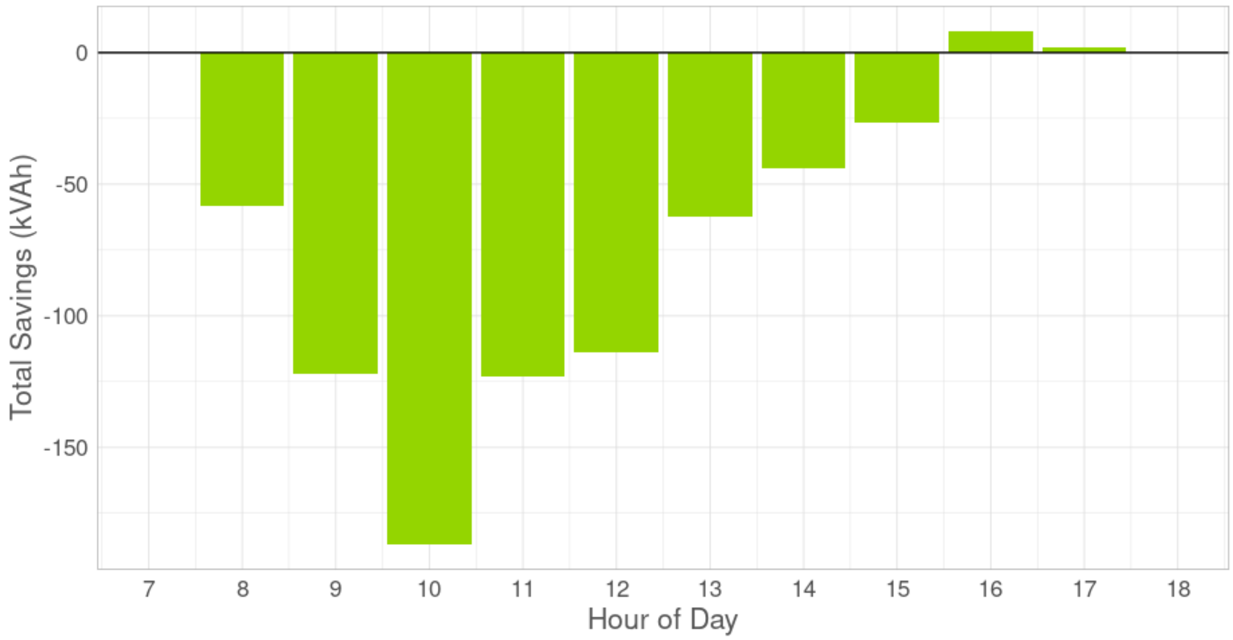
Table 15. Characteristics of Feeders by Savings Bin

Characteristic	Feeder Savings Bin			
	Large Negative Savings (< -100 kVAh)	Moderate Positive / Moderate Negative Savings (-100 to 100 kVAh)	Large Positive kVAh Savings (> 100 kVAh)	All Feeders
Number of Feeders in Bin	8	355	7	**370**
kVAh Savings for Feeders in Bin	-2,189	103	1,359	**-726**
Feeder Average kVAR	778	-120	-1,268	**-122**
Feeder Average kVAR when PFC Engaged	1,055	-64	-1,229	**-43.4**
Inverter Average kVAR when PFC Engaged	-3.02	-0.82	-2.49	**-1.10**

Source: Guidehouse analysis

Another trend in the data is between hour of day and total kVAh savings, shown below in Figure 10. Feeders generally experienced negative kVAh savings throughout the day, and kVAh increases were observed primarily across the hours spanning 10 a.m. through 2 p.m. This is consistent with solar insolation being greatest during these daylight hours during the fall 2021 analysis period.

Figure 10. Total kVAh Savings by Hour of Day



Source: Guidehouse analysis

Key Findings and Considerations

Guidehouse's evaluation of the solar inverter PFC demonstration found:

- **Evaluated Savings:** During the fall 2021 evaluation period, solar inverter PFC resulted in negative total feeder savings (-726 kVAh), or an increase in kVAh. Most feeders experienced minimal savings, with 92% experiencing kVAh savings ranging from -50 kVAh to 50 kVAh. Feeder savings varied greatly between Massachusetts and Rhode Island, with savings totaling 137 kVAh in Massachusetts and -863 kVAh in Rhode Island. These savings totals were largely driven by a handful of feeders with large savings and losses. For example, 8 feeders experienced total kVAh savings of less than -100 kVAh, and 7 feeders experienced total kVAh savings of more than 100 kVAh.
- **Feeder Reactive Power:** Guidehouse observed a clear trend between feeder average reactive power, inverter reactive power, and feeder savings. Feeders with average reactive power that was negative during the fall 2021 analysis period experienced kVAh savings of 2,870 kVAh. This finding is consistent with the solar inverters, on average, absorbing reactive power when PFC was engaged during the analysis period. On the other hand, feeders with average reactive power that was positive during the fall 2021 analysis period experienced kVAh increases of 3,597. This finding is also consistent with the solar inverters, on average, absorbing reactive power when PFC was engaged during the analysis period.

In 2022 and beyond, Guidehouse recommends that National Grid:

- **Program Design:** National Grid and stakeholders should discuss either making significant design changes for the offering or consider discontinuing the offering. As the program is currently constructed, Guidehouse has identified overall increases in kVAh.

Otherwise, Guidehouse encourages National Grid to consider the following:

- **Incentives:** Consider allowing participation on all feeders, but providing annual participation incentives for customers connected to feeders with telemetry, or consider ensuring substation interval data is available for all enrolled solar inverters. National Grid provided 15-minute interval data for many substations in Massachusetts and Rhode Island. However, roughly half of enrolled inverters were removed from the analysis data due to interval data not being available. As such, calculated impacts only cover roughly half of the enrolled solar inverters.
- **Inverter Operations:** Voltage conditions measured at the participating solar inverter sites dictated when participating inverters were engaged for PFC. National Grid should consider whether there is another way to engage solar inverters for PFC, such as National Grid measuring whether each feeder has a lagging or leading power factor, then engaging enrolled inverters to engage in PFC when specific feeder power factor conditions exist.
- **Additional Analysis:** Consider incorporating additional parameters into analysis, such as capacitor bank operations, to explain findings. Additionally, consider identifying specific types of feeders that may benefit from solar inverter PFC, including certain characteristics such as feeder length, number of capacitor banks, peak loading, and distributed solar penetration to determine whether there are further ways to improve or increase kVAh savings associated with solar inverter PFC.