



PPL Electric Utilities Corporation  
2025 DER Management Report  
to the  
Pennsylvania Public Utility Commission



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## Introduction

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PPL Electric Utilities Corporation (“PPL Electric” or the “Company”) hereby submits this annual report for Program Year 3 (“PY3”) of its Distributed Energy Resource (“DER”) Management Pilot Program (“DER Pilot” or “Pilot”). The DER Pilot is the first of its kind in North America, communicating with and managing DERs down to the individual residential installation level for the purposes of improving power quality, safety, and hosting capacity, expanding operational awareness, and avoiding otherwise necessary capital or maintenance expenses. The DER Pilot’s goal has been to understand, demonstrate, and quantify the benefits of active management, their associated costs, and the overall impact on the distribution system and DERs’ performance. The Pennsylvania Public Utility Commission’s (“Commission” or “PUC”) authorization of this program has yielded significant benefits and will continue to enable the growth of clean energy in Pennsylvania while maintaining system reliability, power quality, and affordability.

During the DER Pilot’s PY3, which spanned March 22, 2024, to March 21, 2025, the Company achieved significant progress in the integration and management of DERs, pursuant to the goals of the Pilot. PY3 continued the DER Pilot’s success in executing DER interconnection and management processes, along with thorough analysis, documentation, and forecasting of the Pilot’s benefits. Over PY3, the Company’s service territory saw 3,976 new solar DER installations with a total nameplate capacity of 74.1 MW. 2,772 of those solar DERs, which have a combined nameplate capacity of 42.5 MW, became participants in the DER Pilot. From the Pilot’s inception through PY3, a total of 9,678 DERs have become Pilot participants while 7,154 other DERs have interconnected but not become participants in the Pilot. Overall, PPL Electric’s DER Pilot showcases a successful model of integrating DERs in a manageable, scalable manner that benefits the Company, its customers, solar developers, and the Commonwealth.

Specifically, based on the data gathered through PY3, PPL Electric has calculated that the DER Pilot could reduce planned capital expenditure by approximately \$18.7 million and operation and maintenance expenses by approximately \$51.4 million.<sup>1</sup> By comparison, the total capital costs and operation and maintenance expenses associated with the DER Management device costs were approximately \$12.3 million and \$986,000, respectively. When considering the additional start-up costs associated with the DER Pilot, the total capital costs and operation and maintenance expenses were approximately \$17 million and \$3.7 million, respectively. Therefore, the DER Pilot has produced substantial benefits compared to its costs. The DER Pilot has improved the reliability and performance of the distribution system, increased DER hosting capacity, and facilitated the interconnection of more DERs, all the while reducing the Company’s capital costs and expenses that would be passed onto customers. Furthermore, PPL Electric’s continued learning and adaptations have allowed additional program savings related to the overall cost of the DER Management device installation and provisioning.

PPL Electric continues to evaluate methods to expand the benefits produced by DER management, particularly to adopt to higher levels of DER penetration in the future. The Company’s analyses are detailed within 19 whitepapers and include the use cases set forth in the DER Pilot’s Pilot Implementation Plan.<sup>2</sup> The continued analysis of current and potential application of active management and monitoring has been a critical component of the DER Pilot and will help develop and expand on ways to facilitate and encourage DER deployments, while maintaining and improving the safety, reliability, and adequacy of electric service.

For example, DER hosting capacity increases continue to help interconnection a greater number of DERs at a reduced cost to interconnection applicants. At the conclusion of PY3, hosting capacities for monitored, autonomous, and active

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<sup>1</sup> The DER Pilot has increased hosting capacity by an estimated 98 MW. If that additional 98 MW were fully utilized as of March 21, 2025, it would have produced additional generation and reduced distribution and transmission losses valued at approximately \$11.3 million.

<sup>2</sup> <https://www.puc.pa.gov/pcdocs/1694930.pdf>.



management were calculated to be 63 MW, 80 MW, and 98 MW respectively, demonstrating one of the key, incremental benefits of active management compared to relying solely on inverters' autonomous functions.

In addition, PPL Electric continues to expand the number of approved inverters that can be safely connected to and used with the Company's DER Management devices. As of March 21, 2025, PPL Electric's Approved Inverter List has 309 inverters from 18 different manufacturers, up from 241 inverters and 12 different manufacturers as of April 22, 2024. Also, inverters from 5 manufacturers are currently undergoing the review and approval processes. PPL Electric reviews and approves inverters expeditiously. Therefore, as new inverters come to market, PPL Electric can review and approve them for use so long as they meet the applicable requirements. Taken together, the high volume of DER installations and continued availability of many inverter models show that the Company is committed to facilitating DER interconnections.

PPL Electric's DER Pilot also showcases the significant benefits of active management in achieving dynamic grid optimization. Unlike autonomous systems that operate on predefined rules and have limited adaptability, active management of DERs facilitates real-time operational adjustments. This dynamic approach optimizes grid performance in response to changing conditions, enhancing grid reliability, safety, and affordability. Moreover, actively managed DERs boast scalability and flexibility because they are capable of being adjusted for growth without the need for extensive in person reprogramming or physical changes required by autonomous systems.

This active management strategy has yielded notable customer benefits within PPL Electric's Pilot. PPL Electric expects these benefits to grow as more actively managed DERs connect to the distribution system. Key to this success is the implementation of power factor management, which has resulted in shorter durations and lower magnitudes of voltage violations on feeders with actively managed DERs. As more actively managed DERs are incorporated, customer outcomes on these feeders improve in tandem, highlighting the effectiveness of PPL Electric's voltage management approach. Contrasting with the limitations of autonomous curves, which only react to local voltage conditions, PPL Electric's active management of the DERs optimizes all available resources. This improves power quality for customers with minimal impact on the ability for such customers to generate real power, underlining the additional benefits of active management in enhancing grid performance.

In sum, active management and monitoring of DERs is crucial as the proliferation of DER and electrification technologies continues. The ongoing application of DER monitoring and management not only effectively improves interconnection capacity but also plays a pivotal role in reducing both infrastructure and interconnection costs for customers. This forward-looking approach emphasizes PPL Electric's commitment to innovatively addressing the evolving needs of the energy grid and its users.



## DER and Management Device Installations

### ***Per Implementation Plan Section G.1.1 -The number of DERs Installed and the Number of DER Management Devices Installed***

PPL Electric has enrolled 9,678 DER participants from the start of the DER Pilot through PY3. DER adoption continues to increase annually, beyond the limits of the Pilot. Under the Commission-approved Settlement establishing the Pilot, no more than 3,000 DER Management devices can be installed in a calendar year. PPL Electric hit that annual cap in 2023 and 2024. Any DERs placed in-service during the calendar year after the annual cap is hit are not enrolled in the Pilot and do not have DER Management devices installed for them.

- Control Group 1 (CG1)
  - o PY3 participants: 342
  - o Installed within the first 75 participating feeders
  - o Does not include any Pilot DER assigned within the Active Management control group
- Control Group 2 (CG2)
  - o PY3 participants: 0
  - o Consists of the first 1,000 Pilot participants and includes participants within Control Group 1, until threshold has been achieved
  - o In total there are 999 Pilot participants within Control Group 2, with 205 being also assigned within Control Group 1
- Active Management Group (AM)
  - o PY3 participants: 2,429
  - o All DER Pilot participants that have DER Management devices installed and can have their DERs actively managed
- Non-Pilot Participants or Grandfathered
  - o PY3 installations: 1,204
  - o No DER Management devices installed

### Communications Methodology

At the DER Pilot's inception, PPL Electric utilized ConnectDER devices to monitor and actively manage DERs participating in the Pilot. PPL Electric added its Cellular Gateway devices in September 2023, expanding Pilot participation to include IEEE 2030.5-compliant devices. Before the addition of the Cellular Gateway devices, DERs' inverters that were only compatible with this communications standard were excluded from the Pilot.

A detailed list of Pilot participating DERs and initially programmed Volt-VAR Curves (VVC) is set forth in Appendix A.

### DER Management Device Installations

From the DER Pilot's start through PY3, a total of 9,678 DER Management devices have been installed at participating DERs, representing slightly more than 100 MW of nameplate capacity. During PY3, a total of 2,789 DER Management devices were installed, as detailed within Table 1.



Table 1. DER Management Devices Installed per Year

	Year 1	Year 2	Year 3	Total
ConnectDER Generation 1 DER Management Device	1,197*	1	0	1,198
ConnectDER Bridge	2,769	2,688	1,936	7,393
Cellular Gateway	0	234	853	1,087
<b>Total</b>	<b>3,966</b>	<b>2,923</b>	<b>2,789</b>	<b>9,678</b>

\*The total number of ConnectDER Generation 1 DER Management devices installed within PY1 has been updated to 1,197, as opposed to the 1,219 listed in the PY1 and PY2 Annual Reports. This update was made after the Company reconciled the data in its internal records and its Work Management Systems.

## DER Management Pilot Participant Programming

*Per Implementation Plan Section G.1.2 - A list of participating DERs that includes for each DER: (a) a unique customer identifier; (b) the nameplate capacity; (c) the initial settings established for that DER's smart inverter; and (d) the type of DER (e.g., solar, solar plus storage)*

A full list of participating DERs, along with the applicable DER attributes and the assigned Volt/VAR curves, has been provided in Appendix A.

### Autonomous DER Management Parameters

PPL Electric has created unique Volt-VAR Curves ("VVC") for each DER Pilot participant. These curves consider the influence of the transmission system, distance from the substation, and the observed variations in the customer's voltage. From the results of the VVC analysis, unique curve points are assigned, similar to those indicated within the sample curve, Figure 1, *infra*. These unique values correspond to the following:

- Points X1 - X6
  - Each of these values corresponds to specific per unit voltage values, progressing from low voltage (X1) to high voltage (X6).
  - These values represent the calculated transition points of the VVC.
- Points Y1 - Y6
  - Each of these values corresponds to the required reactive power output values of the inverter.
  - Note: the maximum and minimum inverter output is fixed at +/- 44%.

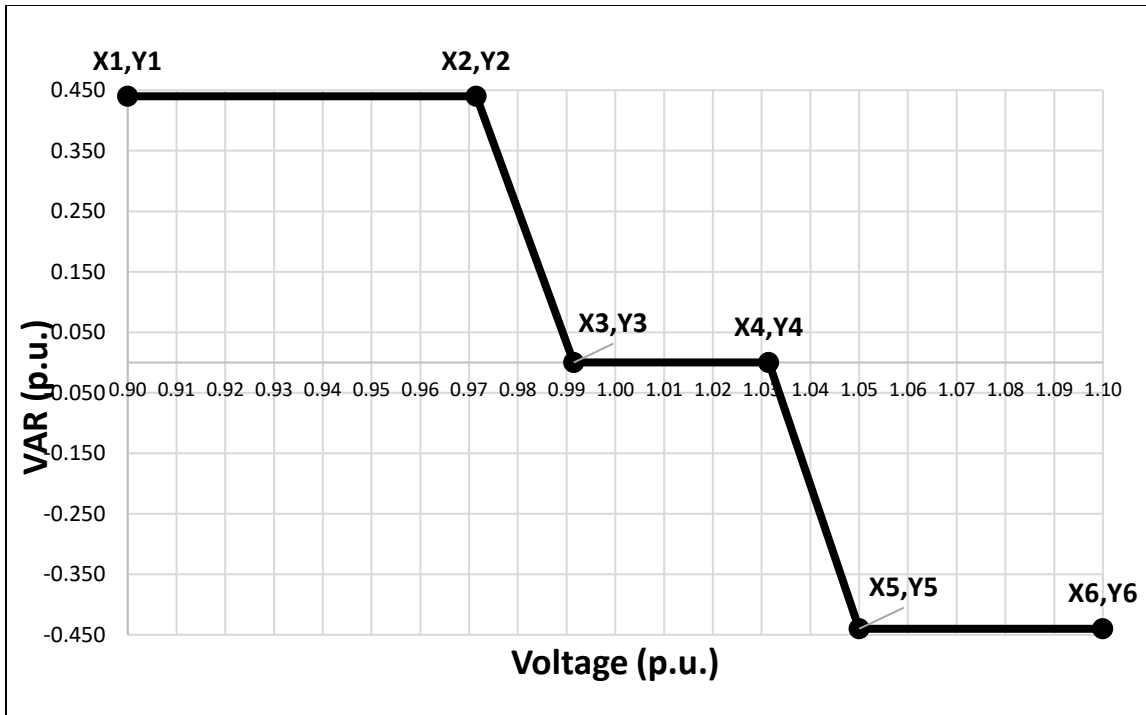


Figure 1. Sample Volt-VAR Curve (VVC)

### Ride-Through Curve Parameters

All participating DERs are programmed with the latest approved standardized voltage and frequency ride-through parameters. Revisions to these settings, once initial programming has been completed, are only permitted for actively managed DERs. The latest revision of these parameters was approved in 2023. The actively managed DERs’ inverters have had their ride-through curve parameters updated to the latest revision in order to improve their response to voltage and frequency variations.

DER Pilot participants in Control Groups 1 and 2 are only permitted to be programmed with the then-current ride through parameters at the time of initial programming. All non-Pilot participating DERs are not required to utilize PPL Electric-specific ride through settings, but they may be required to follow the minimum guidelines as detailed within PJM Guideline for Ride Through Performance of Distribution-Connected Generators<sup>3</sup> (2019).

### Current PPL Electric Standard Ride-Through Curve Points

As noted previously, PPL Electric’s current standard ride-through parameters were approved in 2023. The following tables detail those parameters.

Table 2. Current Standard Under Voltage Requirements

<u>Under Voltage Requirements</u>		
<i>Shall Ride Through and Shall Trip curves are identical (overlapping) and defined in this table.</i>		
Shall Trip Function	Voltage (p.u. of nominal voltage)	Time (sec)
UV1	0.88	2.1
UV2	0.5	0.6

<sup>3</sup> <https://www.pjm.com/-/media/DotCom/planning/plan-standards/pjm-guideline-for-ride-through-performance.ashx>



Table 3. Current Standard Over Voltage Requirements

<u>Over Voltage Requirements</u>		
<i>Shall Ride Through and Shall Trip curves are identical (overlapping) and defined in this table.</i>		
Shall Trip Function	Voltage (p.u. of nominal voltage)	Time (sec)
OV1	1.1	2.1
OV2	1.2	0.2

Table 4. Current Standard Under Frequency Requirements

<u>Shall Trip – Under Frequency Requirements</u>		
Shall Trip Function	Frequency (Hz)	Clearing Time (sec)
UF1	58.5	301
UF2	56.5	0.2

Table 5. Current Standard Over Frequency Requirements

<u>Shall Trip – Over Frequency Requirements</u>		
Shall Trip Function	Frequency (Hz)	Clearing Time (sec)
OF1	61.2	301
OF2	62	0.2

**Legacy Ride-Through Parameters**

As noted previously, because PPL Electric is not permitted to modify the ride-through settings of existing inverters within Control Groups 1 and 2, there are some systems which still utilize the legacy ride-through settings identified below. All such systems are marked accordingly in the “Legacy Ride Through” column in Appendix A.

Table 6. Legacy Under Voltage Requirements

<u>Under Voltage Requirements</u>		
<i>Shall Ride Through and Shall Trip curves are identical (overlapping) and defined in this table.</i>		
Shall Trip Function	Voltage (p.u. of nominal voltage)	Time (sec)
UV1	0.88	2.0
UV2	0.5	0.5

Table 7. Legacy Over Voltage Requirements

<u>Over Voltage Requirements</u>		
<i>Shall Ride Through and Shall Trip curves are identical (overlapping) and defined in this table.</i>		
Shall Trip Function	Voltage (p.u. of nominal voltage)	Time (sec)
OV1	1.1	2.0
OV2	1.2	0.16

Table 8. Legacy Under Frequency Requirements

<u>Shall Trip – Under Frequency Requirements</u>		
Shall Trip Function	Frequency (Hz)	Clearing Time (sec)
UF1	58.5	300
UF2	56.5	0.16

Table 9. Legacy Over Frequency Requirements

Shall Trip – Over Frequency Requirements		
Shall Trip Function	Frequency (Hz)	Clearing Time (sec)
OF1	61.2	300
OF2	62	0.16

## Pilot Expenditures

### *Per Implementation Plan Section G.1.3 - Capital costs and expenses associated with the purchase, installation, ownership, and maintenance of DER management devices*

The capital costs and expenses associated with the purchase, installation, ownership, and maintenance of the DER management devices utilized throughout the Pilot are presented in Tables 10 and 11, *infra*. These capital costs and expenses cover the start of the DER Pilot on January 1, 2021, through March 21, 2025.

Table 10. Pilot Total DER Management Device Purchase and Installation Costs

Purchase Costs	Pilot Total
ConnectDER Simple Collar	\$ 98,559.60
ConnectDER Generation 1 DER Management Device	\$ 856,535.34
ConnectDER Bridge Device	\$ 4,842,744.21
Cellular Gateway	\$ 1,231,241.75
<i>Sub Total (Purchase)</i>	<b>\$ 7,029,080.90</b>
Installation Costs	
ConnectDER Simple Collar	\$ 76,576.09
ConnectDER Generation 1 DER Management Device	\$ 300,598.68
ConnectDER Bridge Device	\$ 3,847,150.80
Cellular Gateway	\$ 1,065,784.07
<i>Sub Total (Installation)</i>	<b>\$ 5,290,109.64</b>
<b>Total Capital Costs</b>	<b>\$ 12,319,190.54</b>

Table 11. Total Maintenance Costs

Maintenance Costs	Pilot Total
ConnectDER Simple Collar	\$ 84.00
ConnectDER Generation 1 DER Management Device	\$ 195,929.98
ConnectDER Bridge Device	\$ 500,122.25
Cellular Gateway	\$ 62,903.39
IT	\$ 227,001.26
<b>Total Maintenance (Expense)</b>	<b>\$ 986,040.88</b>

The average per unit cost of each DER Management device has been detailed within Table 12. These costs consider the total material, labor (installation and troubleshooting), and maintenance costs, divided by the total number of the respective devices currently installed, as detailed within Table 1.

Table 12. Average Total Cost per Unit by Device Type (Materials, Labor, Maintenance)

Device Type	Average Total Cost Per Unit
ConnectDER Generation 1 DER Management Device	\$ 1,152.88
ConnectDER Bridge Device	\$ 1,265.67
Cellular Gateway	\$ 2,194.49

PPL Electric notes that the average per unit cost of the ConnectDER Generation 1 device has decreased compared to the PY2 Annual Report, while the average per unit cost of the Bridge and Cellular Gateway has increased. Those increases were driven by higher labor costs for installing the Bridge and Cellular Gateway devices in PY3. PPL Electric is actively investigating potential ways to reduce those labor costs, including a decreased reliance on contractors to install the DER Management devices.

Additionally, the Company is phasing out the current generation of the Bridge and Cellular Gateway devices later in 2025. The new versions of the devices will be significantly cheaper to procure. Specifically, the per-unit procurement cost for the new Bridge device will likely be at least 40% cheaper, while the per-unit procurement cost of the new Cellular Gateway device will likely be at least 60% cheaper. By moving to these new and less expensive versions of the devices, PPL Electric will significantly reduce the procurement costs for the devices.

## DER Management Device Intervention

### *Per Implementation Plan Section G.1.4 - Number of times, locations, and duration for active management*

Through the DER Pilot, PPL Electric Pilot participants, within the active management control group, have been able to be centrally managed, via the Advanced Distribution Management System's ("ADMS") Load and Voltage Management ("LVM") module. In addition to being centrally managed, the programmed settings of a subset of these participants have also been able to be updated, as indicated within Table 13.

Table 13. Grid Support Function - Total Event Counts, by Pilot Year

	Year 1 (Jan 21 - Mar 23)	Year 2 (Mar 23 – Mar 24)	Year 3 (Mar 24 – Mar 25)
Volt-VAR Curve Overrides	0	12	0
Power Factor Setting Changes	768	221,394	298,391
Ride-through Setting Changes	0	4,138	0
Remote On/Off	0	0	0
Volt-Watt Curve Overrides (where applicable)	0	0	0

The year-over-year increase in the number of power factor management events can be attributed to: (1) the continued refinement of PPL Electric's ADMS and Distributed Energy Resource Management System ("DERMS"); and (2) an increase in the number of actively managed DERs. Appendix B details the average duration of each power factor adjustment event, by distribution feeder, with the total number of events identified within Table 13 above. Further, each indicated event accounts for all actively managed DERs within an event. This results in potential variances between the total number of events listed within Table 13 and Appendix B.

Currently, in the Pilot's Active Management Group, each participant has a maximum fixed power factor duration, prior to restoring its autonomous functionality. For a large portion of these DERs, the maximum duration has been established at 10 hours. During PY3, 298,391 events occurred, of which 94,670 returned the DERs to unity power factor, restoring

autonomous functionality. The return to unity power factor is not intended to provide grid benefits; rather, it acts as a failsafe to ensure customers do not experience excessive generation curtailment if the DER Management device were to fail to return the system to Volt/VAR management mode as programmed. A-10-hour reset time was selected to restore the inverter to unity power factor after a full day of daylight operation. A power factor management event occurring as a result of this function does not indicate that the device failed, but rather that PPL Electric's failsafe to protect customers is working as intended.

## Observed DER Management Benefits

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PPL Electric's DER Pilot continues to showcase the significant benefits of the integration of autonomous DER functionality and centralized active management, providing dynamic grid optimization. Throughout the DER Pilot, PPL Electric has increased the total number of DERs that can positively impact distribution system voltage and power factor. This dynamic approach optimizes grid performance in response to changing conditions, cost-effectively enhancing electric reliability, safety, and power adequacy. As a result, the Pilot has yielded notable customer benefits that are anticipated to continue, as more DER Management devices are interconnected with the distribution system. With these additional devices, opportunities to leverage all participating DERs to further address power quality issues will be possible. Continued implementation of power factor management is a key to future DER Management success and will result in a reduction in instances, durations, and severity of voltage violations.

### Autonomous Benefits

The use of autonomous VVC has enabled participating DERs to help maintain PPL Electric's distribution system voltage within mandated voltage ranges.<sup>4</sup> As noted previously, within the description of Figure 1, each DER begins to adjust its kVAR output- once the measured voltage extends outside of the deadband range (X3 – X4) according to the programmed VVC. Each inverter's influence on overall distribution system voltage is dependent on the programmed VVC and its ability to restore system voltage within the deadband area. Through these efforts, each DER's programmed VVC is tailored to its location in order to provide the maximum support necessary without sacrificing DER output.

Validating autonomous benefits is more difficult to quantify than those detailed within active management interventions. This is due to the instantaneous influence occurring via the programmed VVCs, versus the centralized commands issued by PPL Electric to actively managed DERs. Near real time autonomous response can occur via the observed voltage at the DER and the anticipated location within each VVC. The impact of each inverter's output can be assessed against the observed feeder voltage violations by utilizing the Company's smart meter data.

### Active Management Benefits

#### ***Per Implementation Plan Section G.1.5 - Grid benefits achieved for each instance of active management***

PPL Electric's DER Pilot continues to showcase the significant benefits of active management in achieving dynamic grid optimization. Unlike autonomous systems, operating on predefined rules, DER active management utilizes a centralized overview of a feeder to facilitate near real-time operational adjustments, of inverter outputs. Active management swiftly responds to larger events, beyond the capabilities of an autonomous DERs, through a centralized overview and

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<sup>4</sup> See 52 Pa. Code § 57.14.



simulation of potential power factor adjustment iterations before enacting them. As a result, PPL Electric can modify DER power factors to respond to a global requirement, providing a coordinated response to an event.

Through PPL Electric's DER Pilot, the Company has defined the parameters of grid benefits for each instance of active management intervention. As with the results detailed in the PY2 Annual Report, the Company has seen continued improvements in system voltage event resolution. While not all violation events are fully resolved, the use of actively managed DERs continues to help reduce the number, duration, and severity of voltage violations. Continued growth in actively managed DERs will support a greater number of voltage violations being resolved and provide additional support towards resolution of events that were not previously able to be resolved.

The Company defines "grid benefits achieved" for real-time constraint mitigation as the change in the number or severity of voltage violations present on the system in the time intervals before and after the active management of one or more DERs. The intent is to capture observed changes which result directly from the influence of an active management on a per-event basis. Voltage is also influenced by a multitude of factors that can contribute to each customer's observed voltage within an interval. The variability of these factors can mask the attribution of the positive impact of actively managed DER. This is particularly true within feeders and substations whose actively managed DERs are only a small portion of the total DERs present. As noted previously, isolating the portion of observed voltage change attributed to each specific actively managed DER is not currently possible at scale.

Further, the change in customer observed voltage violations, for each active management event, is calculated by evaluating the reported average smart meter voltages for the reporting interval immediately preceding and immediately following the active management event. Each active management event may include one or more DERs supplied from the same distribution bus. Also, the total number of events may differ between the number of DER power factor settings changes and the identified violations indicated elsewhere within this report. Additionally, PPL Electric's ADMS/DERMS estimates the number of voltage violations resolved, due to the active management of each DER. A description of these calculations and the results can be found within the active management operational descriptions section of this report. The complete table of grid benefits achieved for each instance of active management has been compiled as Appendix C.

Manually modeling the specific effects of each active management event is impractical, due to the volume and scale of analysis that would be required. However, several specific events have had comprehensive studies completed. The results of these studies are detailed within the Use Case section of the report below.

Active management has established the ability to incorporate telemetered DER data and leverage each participating DER's output into future control system strategies, yielding notable customer benefits. Through continued DER penetration growth, these benefits are anticipated to continue to grow. This will enable an increase in the opportunity to leverage all participating DERs to contribute to resolving voltage issues, power quality issues, or both on the grid. As noted previously, a key observation to the continued successful implementation of centralized DER output management is a reduction in the number, duration, and severity of voltage violations on feeders with actively managed DERs. As more actively managed DER are incorporated, it is anticipated that these results will continue to improve, highlighting the effectiveness of PPL Electric's centralized voltage management approach.

Contrasting with the limitations of autonomous curves, which only react to local voltage conditions, PPL Electric's active management of DER optimizes all available resources, locally and globally. This improves power quality for customers with minimal impact on their ability to generate real power, underlining the additional benefits of active management in enhancing grid performance.



## Net DER Generation Impact Due to Active Management

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### ***Per Implementation Plan Section G.1.6 - Net generation gain or loss due to active management***

PPL Electric has created a detailed report capturing the net generation loss or gain due to PPL Electric's active management of grid support functions, for each device intervention. That report can be found in Appendix D. The total active power generation reduction identified, as a result of these active management events, continues to represent a very small portion of overall system generation capabilities.

Specifically, on average, actively managed DERs experienced a net generation reduction of 0.099465kWh per event, totaling 29,679 kWh across 298,391 events.

## Distribution Capital Investment Avoidance Due to DER Hosting Capacity

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Among other benefits, PPL Electric's DER Pilot helps avoid distribution system upgrades by increasing distribution circuits' hosting capacity. Based on the data collected through PY3, the Pilot has increased available DER hosting capacity by 98 MW.

To derive that amount, PPL Electric utilizes a nodal analysis approach, whereby the Company evaluates the maximum amount of DERs that can be added to each feeder node without triggering any violation criterion (i.e., device overload, voltage violation, potential islanding etc.). The results have been compiled within Appendix E.

In addition to the detailed nodal DER hosting capacity, the maximum DERs permitted to interconnect on each substation's 12 kV bus has also been compiled. These indicated values, within this second portion of the analysis, represent the point at which reverse power flow occurs on the 12 kV bus or violates load and voltage criteria. These values are also contained within Appendix E, under Columns F and G (Nameplate – Max Hosting Capacity (kW) and Monitored – Max Hosting Capacity (kW)).

PPL Electric has also calculated an estimated maximum DER hosting capacity for nameplate and monitored scenarios. This total was calculated by identifying the largest amount of DERs that could be accommodated on each substation transformer bus, when supplying more than one feeder, and adding these values for all non-parallelled substation buses. These buses are generally independent of each other, as tie switches, and breakers, are normally open. Thus, the calculated values represent a reasonable approximation of the system-level DER hosting capacity, assuming no constraints are observed within the transmission system.

An overview of the hosting capacity results is provided in Table 14. As seen in that table, active management continues to prove beneficial and reduce or avoid capital investments in the distribution system.

Table 14. DER Hosting Capacity Results, by Reporting Year (in MW)

	Year 1	Year 2	Year 3
<b>Nameplate vs Monitored</b>	6.6	18.1	63
<b>Monitored vs Autonomous</b>	1.4	5.7	17
<b>Autonomous vs Actively Managed</b>	1.0	4.9	18
<b>Monitored vs Actively Managed</b>	9.0	28.8	35

### Capital Investment Avoidance Attributed to Increased DER Hosting Capacity - Monitoring

#### ***Per Implementation Plan Section G.1.7 - Distribution system upgrades avoided due to increased hosting capacity attributed to monitoring***

PPL Electric is required to develop a report which compares the computed circuit hosting capacity when all DERs are evaluated at nameplate kW only versus the hosting capacity of each circuit with actual kW output, gained via monitoring, while keeping Grandfathered DERs at nameplate kW. Results indicate that the availability and use of actual DER system production data results in a noticeable increase in a circuit's calculated hosting capacity in most cases. Cost-effective increases in hosting capacity are critical to enabling the renewable energy transition by reducing and avoiding costs for future interconnections of renewable resources.

As of the end of PY3, PPL Electric's ability to monitor DERs has resulted in an increase of 63 MW of DER hosting capacity.

### Capital Investment Avoidance Attributed to DER Hosting Capacity – Autonomous Functions

#### ***Per Implementation Plan Section G.1.8 - Distribution system upgrades avoided due to increased hosting capacity attributed to autonomous grid support functions***

PPL Electric has developed a report which compares the computed circuit hosting capacity with actual kW gained via monitoring only versus the scenario where those DERs are equipped with autonomous grid support functions, while keeping grandfathered DERs at nameplate kW. Autonomous functions provide additional benefits in the form of improved hosting capacity by allowing DERs to respond to local voltages to help mitigate high or low voltage constraints.

As of the end of PY3, the utilization of PPL Electric-calculated VVCs has resulted in an estimated 17 MW of DER hosting capacity.

### Capital Investment Avoidance Attributed to DER Hosting Capacity – Active Management Functions

#### ***Per Implementation Plan Section G.1.9 - Distribution system upgrades avoided due to increased hosting capacity attributed to active management***

PPL Electric has developed a report which compares the computed circuit hosting capacity when all DERs are evaluated at the nameplate kW only, without any monitoring or active management, versus the hosting capacity of each circuit with actual kW output gained via active management, while keeping grandfathered DERs at nameplate kW. Active management shows additional improvements in feeder hosting capacity when compared to autonomous only scenarios. This results from the ability of active management to utilize DER to respond to voltage violations holistically, rather than relying on DERs to adjust themselves based on local measurements.

As of the end of PY3, PPL Electric’s ability to actively manage DERs has increased DER hosting capacity by 18 MW when compared to autonomous functions and by 35 MW when compared to monitored results.

## Reliability Improvements

### ***Per Implementation Plan Section G.1.10 - System operation comparisons of circuits under autonomous inverter grid support functions versus active management***

PPL Electric has compiled customer meter voltage data and has developed observations pertaining to customer meter voltage performance between DER Pilot participants and non-participants. The non-participants have been identified as grandfathered (“GF”), whereas Pilot participants are classified further as Control Group 1 (“CG1”), Control Group 2 (“CG2”), and Active Management Group (“AM”). Through these initial observations, the Company has developed a comparison of customer voltage between each DER control group at the customer point-of-interconnection. PPL Electric completed a further comparison of all customer meter data between feeders with actively managed DERs versus those with CG1 DERs. Within the feeder comparison, GF DERs may also exist.

PPL Electric’s voltage performance metrics have been designed to improve overall understanding of distribution system voltage performance, while closely following industry established reliability practices. In particular, PPL Electric based its voltage metrics on System Average Interruption Frequency Index (“SAIFI”) and System Average Interruption Duration Index (“SAIDI”). While SAIFI and SAIDI are outage focused, the Company utilized these standardized metrics to create its own voltage metrics: System Average Voltage Violation Frequency Index (“SAVVFI”) and System Average Voltage Violation Duration Index (“SAVVDI”). The calculation of these metrics utilizes the following datapoints:

$$\text{SAVVFI} = (\text{Total number of voltage violation events experienced by all customers in a set}) / (\text{total number of customers in the set})$$

$$\text{SAVVDI} = (\text{Total duration in minutes of voltage violation events experienced by a set of customers}) / (\text{total number of customers in the set})$$

In addition to the frequency (SAVVFI) and duration (SAVVDI) metrics previously detailed, PPL Electric also developed additional metrics to quantify the severity of voltage violations observed within each control group, (non) pilot participant. Within this context, a voltage violation’s severity is the relative difference between the measured customer meter voltage and the permissible voltage range, per the Commission’s regulations (0.95 to 1.05 per unit).<sup>5</sup>

For DER Point of Interconnection (“POI”) analysis, SAVVDI, SAVVFI, and voltage severity values have been calculated separately for the GF, CG1, CG2, and AM groups. Pilot participants identified as CG12, who were assigned to both CG1 and CG2 control groups, will be included within CG1 and CG2 analysis. All calculations within this analysis only consider daylight hours.

### DER POI SAVVDI and SAVVFI Historical Trends

Prior to completing an examination of the DER POI voltage violation data, the Company reviewed historical voltage violation trends that had been present before and the participating DER had been installed. The data within Figure 3 shows the SAVVDI and SAVVFI trends, at customer metering locations, before any Pilot DERs were interconnected. Pilot participants, as well as grandfathered DERs, interconnected by December 31, 2024, encompass the dataset for the results presented in Figure 2. Within these results, it is evident that a number of voltage violations were present in each

<sup>5</sup> See 52 Pa. Code § 57.14.



Pilot group (CG1, CG2, and AM) prior to any DER Management devices being installed. The use of these periods can be utilized as pre-Pilot baselines and used as a measure of comparison going forward.

Similarly, within this analysis, the DERs identified as grandfathered are those that have been installed after the Pilot commenced but are non-Pilot participants. Continued analysis of these DER, in the future, can also consider this data set as a pre-installation baseline, like the aforementioned Pilot participants. The remaining grandfathered DERs, which were installed prior to the Pilot, have been excluded from the remaining analysis detailed below.

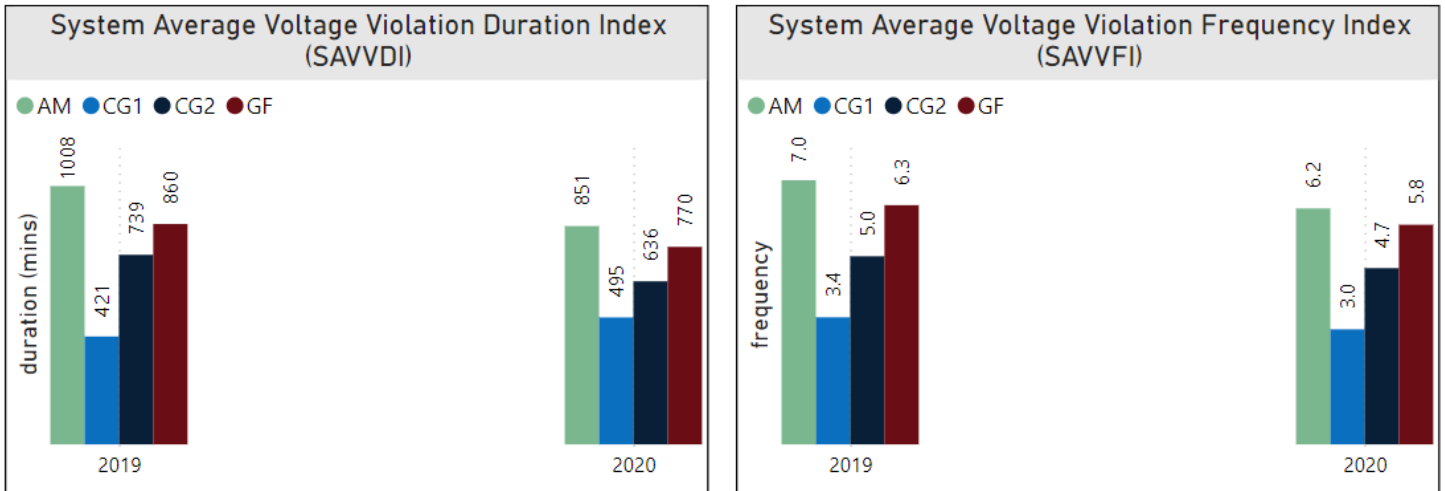


Figure 2. DER Customer Historical SAVVFI & SAVVDI by Calendar Year

Figure 3 and Figure 4 present a continuation of the trends depicted in Figure 2, as the DER Pilot commenced. However, it is important to recognize that voltage violation data for the GF, CG1, CG2, and AM groups starts being collected for each customer location from the date that the DER is connected and (in the case of AM and control group DERs), programmed with a VVC. As a result, the corresponding SAVVDI and SAVVFI results have an upward trend, as additional customer meter data is included within the analysis. The Pilot participating DERs (CG1, CG2, and AM groups) have a smaller impact on the SAVVDI and SAVVFI calculations, while the non-Pilot participating GF DERs have had a significant increase in both SAVVDI and SAVVFI. There continues to be significant increases in the number of Pilot participating DERs within the AM group, with the ability to positively impact voltage violations. DERs assigned within the AM group function autonomously via their uniquely assigned VVCs until ADMS/DERMS intervention.

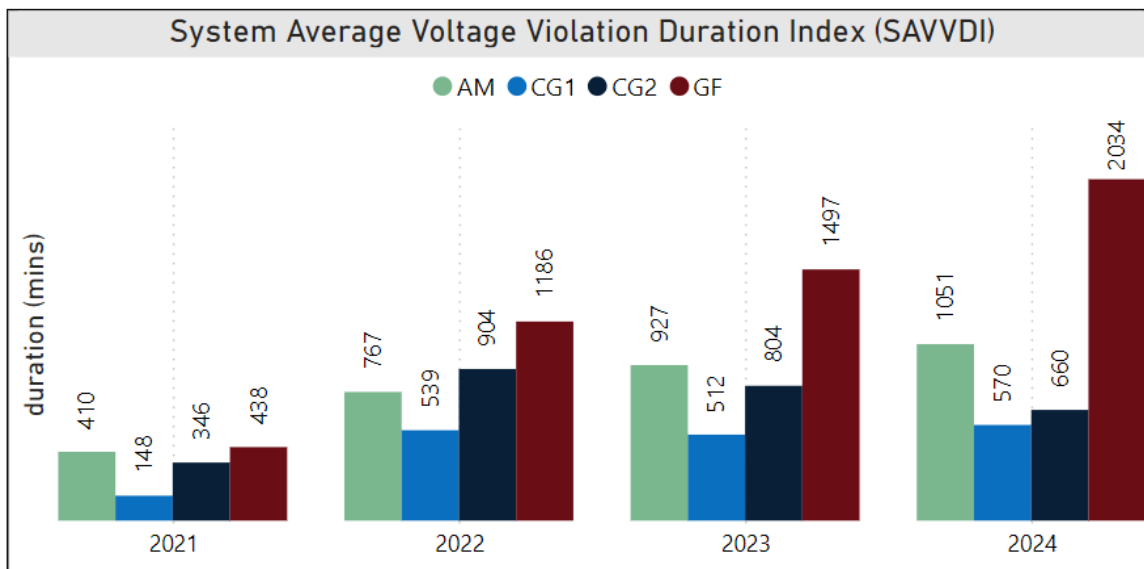
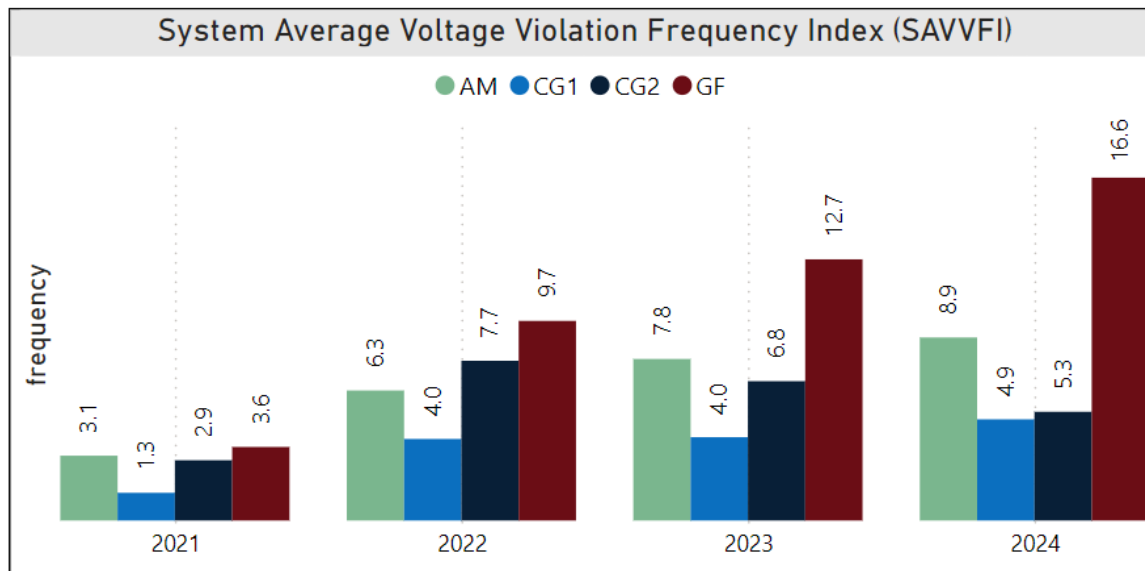


Figure 3. DER Customer SAVVDI with Fixed Customer Set by Calendar Year



**Figure 4. DER Customer SAVVFI with Fixed Customer Set by Calendar Year**

On its own, the voltage data at the DER customer location does not paint a complete picture of the impact of VVCs and active management on customer voltages and power quality. To capture the full impact, the voltages at all customer locations, both those with and those without DERs, must be considered. Both PPL Electric’s VVC design process and the execution of active management consider both the local DER customer voltage as well as the impacts to voltage elsewhere on the system. The existence of CG1 provides a more direct way of evaluating the impact of active management capabilities on customer voltage violations. In Figures 9 and 10 later in this report, SAVVFI and SAVVDI have been calculated for all customers on CG1 feeders as well as for all customers on feeders with actively managed DERs. Because this data considers each meter on a given set of feeders (CG1 or AM), low sample size is not an issue, even for relatively smaller numbers of actively managed DERs because those DERs are spread across many different feeders and, consequently, a high volume of voltage measurement datapoints.

### DER POI SAVVDI and SAVVFI Throughout Pilot

PPL Electric also completed an analysis that directly compares voltage trends and performance of non-Pilot participating DERs installed before the Pilot started (assigned within the grandfathered control group) versus Pilot participating DERs (assigned within CG1, CG2 and AM groups). Similar to the previous analysis, smart meter voltage data, for customers within each dataset, was collected and assessed. An overview of the modifications to the previous analysis includes:

1. Inclusion of pre-Pilot DERs, within the GF group, i.e., placed in-service to the January 1, 2021 start of the Pilot.
2. Inclusion of all Pilot participating DERs (CG1, CG2, and AM groups).

**Note:** The number of Pilot participants continued to grow throughout this analysis, whereas the number of GF group members was constant.

In the first year of the DER Pilot, the number of Pilot participants was relatively small. Due to the initial small sample set, the 2021 results are significantly lower than subsequent years and may be excluded in the development of any long-term trend analysis. Additionally, no DERs were assigned to the AM group in 2021. After Q2 2022, the AM group’s size and ability to influence the distribution system voltage grew significantly, as illustrated within Figure 5 and Figure 6.

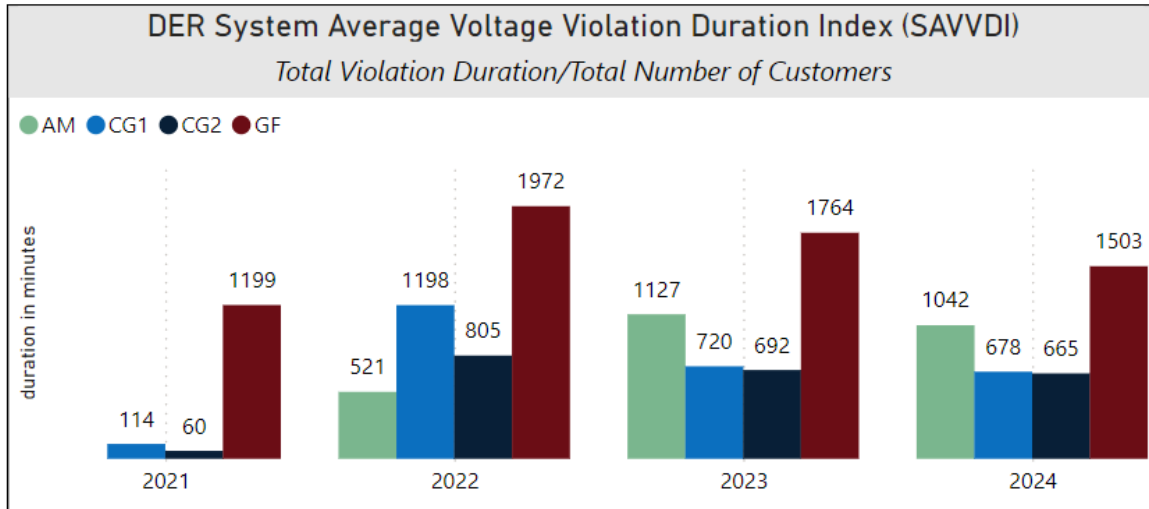


Figure 5. DER Customer SAVVDI Results by Calendar Year

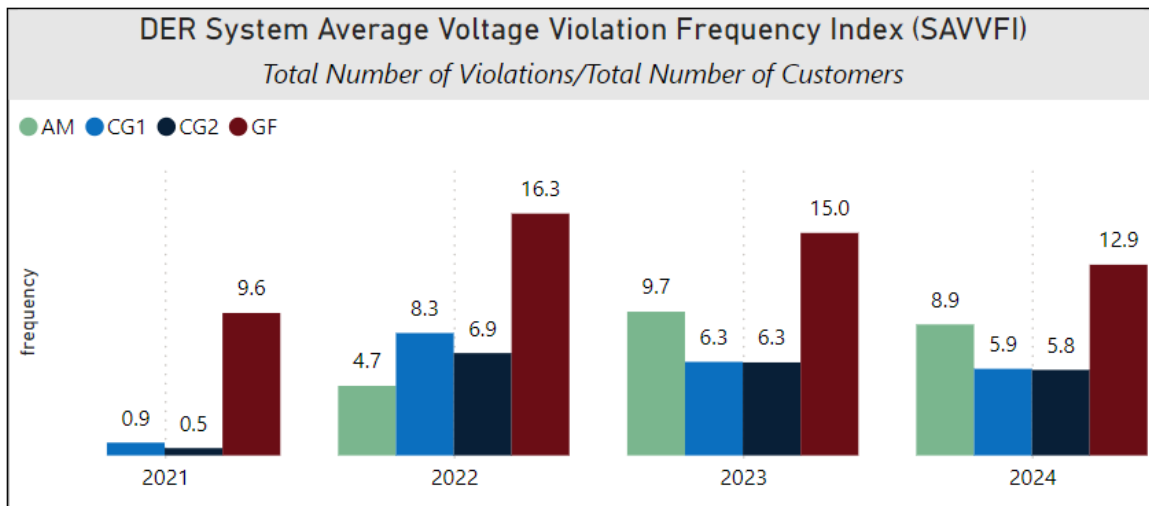


Figure 6. DER Customer SAVVFI Results by Calendar Year

### DER POI Voltage Violation Severity

PPL Electric has continued to expand on its SAVVDI and SAVVFI analysis by adding a metric depicting the voltage violation severity, as a percentage, at the POI. The compilation of this data is limited to daylight hours and details the number of customer meter readings within each depicted percentage band. By compiling the metered data, voltage violations have been observed to occur less at Pilot participating customer meters, than non-participating meters. Additionally, the overall recorded voltage violations represent an extremely small portion of customer meter readings for Pilot and non-Pilot participants.

The compilation of these results is set forth in Figure 7.

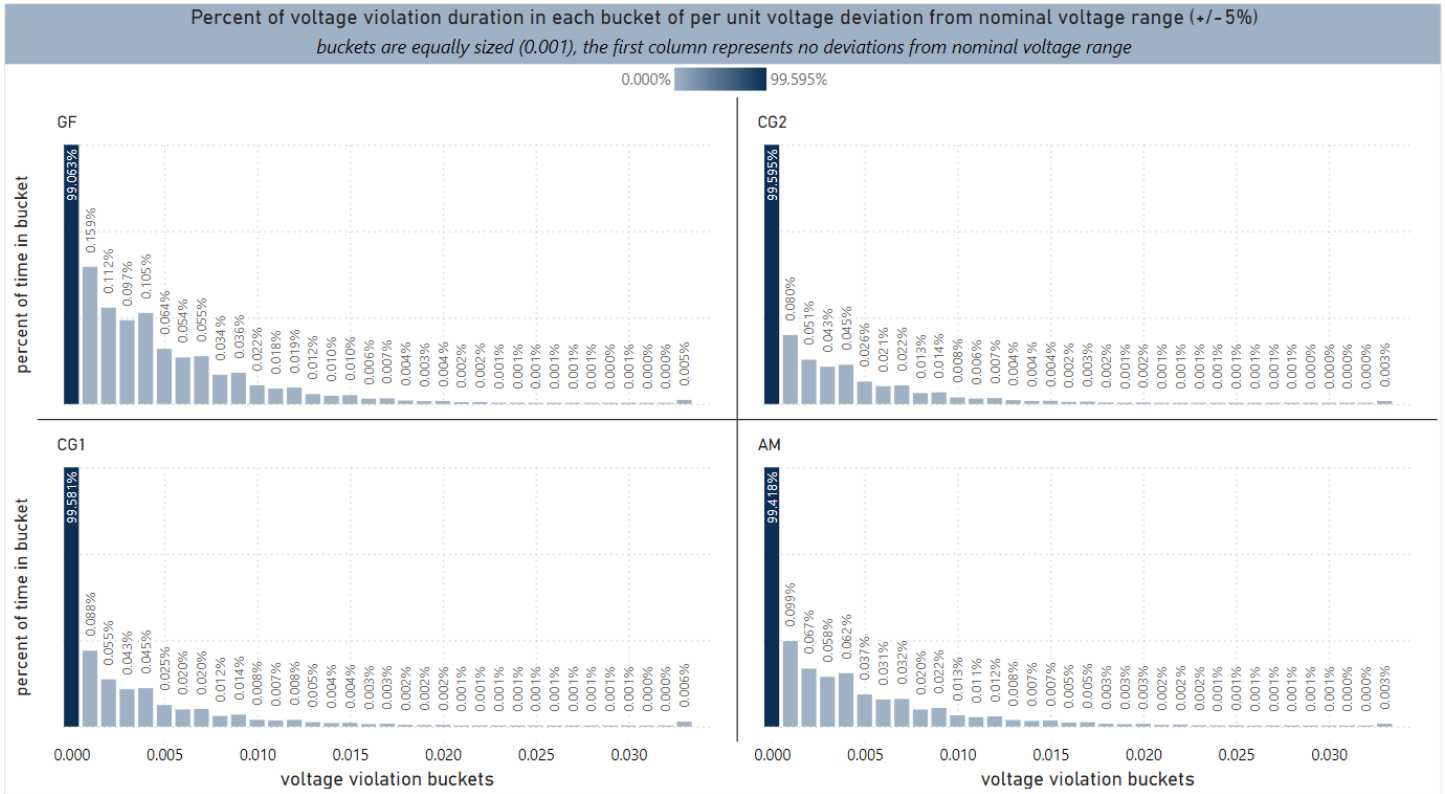


Figure 7. Voltage Severity Results by Pilot Group

Presenting the voltage violation severity results in a different form, Figure 8 excludes the customer meter periods without any voltage violations. The remaining data points have been converted to percentages. Through this revision of the data presentation, the cumulative number of periods in which a customer’s voltage has fallen within each area of violation severity have been accumulated as a percentage of the total voltage violations observed. Non-pilot participating DERs (GF) tend to have higher voltage violation severities, for a larger number of periods, than Pilot participants (CG1, CG2, and AM). Accordingly, participation in the DER Pilot appears to have reduced the overall severity of voltage violations.

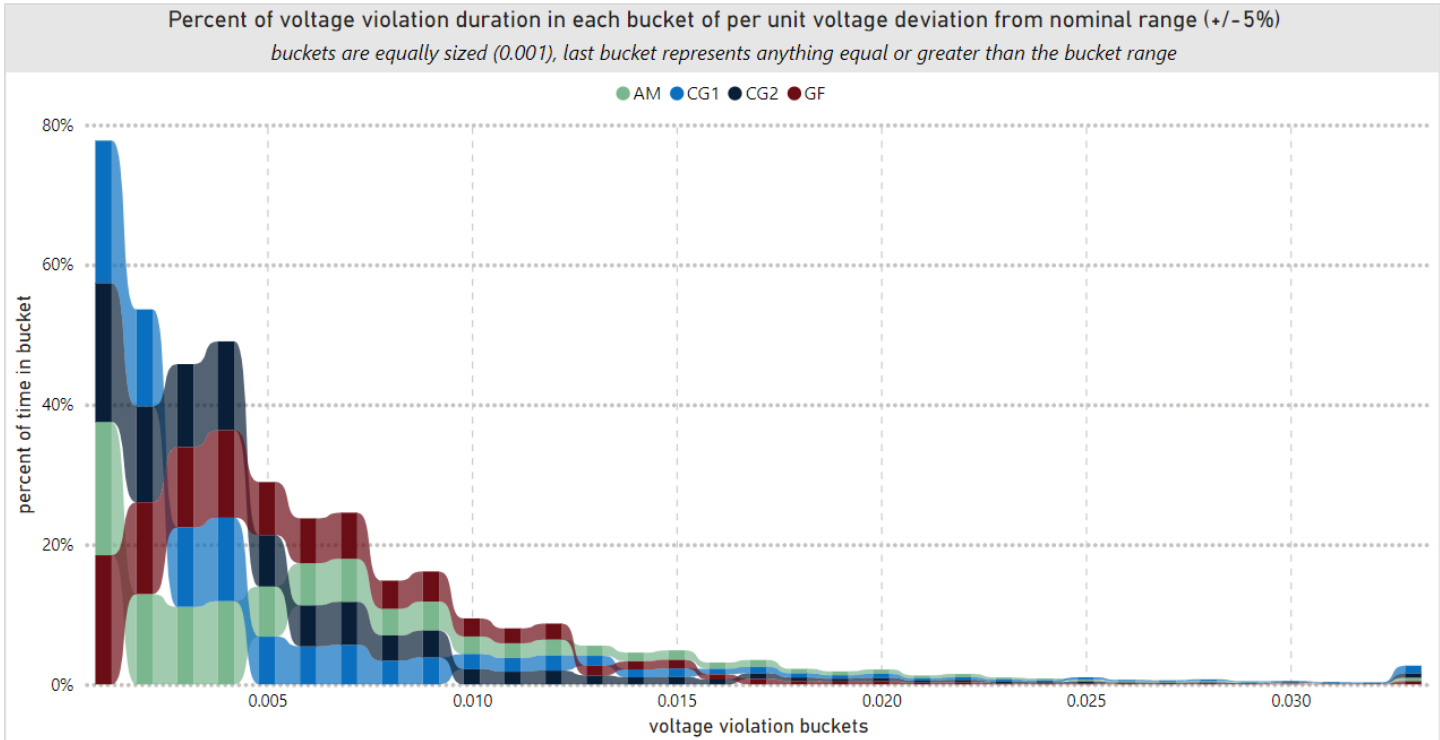


Figure 8. Voltage Severity Comparative Results by Pilot Group, Y-axis is stacked by size from smallest to largest percentage

From the analysis presented within Figure 7 and Figure 8, participation in the DER Pilot has helped reduce voltage violation severity, when compared against non-Pilot participating DERs. As non-Pilot participating DERs are most likely present on all feeders with Pilot participating DERs, the impact of Pilot participation may be potentially masked by the influence of the non-Pilot participating DERs.

### Pilot Feeder SAVVDI and SAVVFI - Historical Trends

While customer meter voltage data, on its own, indicates the performance of each DER (participants and non-participants of the Pilot alike), such data does not fully encompass the voltage performance throughout the supplying feeder. Improving the overall understanding requires examining the DER penetration rate and all other parameters potentially influencing the feeder’s overall voltage performance. When accounting for the DER penetration rate, the Company’s data shows that DERs participating in the Pilot can improve the feeder’s overall voltage performance. Further, the inclusion of those components reveals the influence and effectiveness of uniquely assigned VVCs and active management of DERs.

PPL Electric collected customer meter data to demonstrate the improvements of SAVVFI and SAVVDI performance on feeders in the DER Pilot. The data was parsed into AM and CG1 feeders. The annual SAVVFI and SAVVDI calculations are presented within Figure 9 and Figure 10. Unlike the previous analysis iterations, the data presented includes all Pilot feeders, from pre-Pilot implementation through to the end of 2024. As noted previously, DER adoption has continued to increase throughout the Pilot’s duration. Through this increase, participation within the DER Pilot has increased to the maximum annual threshold from 2023 onward. With the increase in Pilot participation, the positive impact of VVCs and active management have demonstrated their influence in resisting voltage variations, as observed within the SAVVDI and SAVVFI calculations presented in Figure 9 and Figure 10 below.

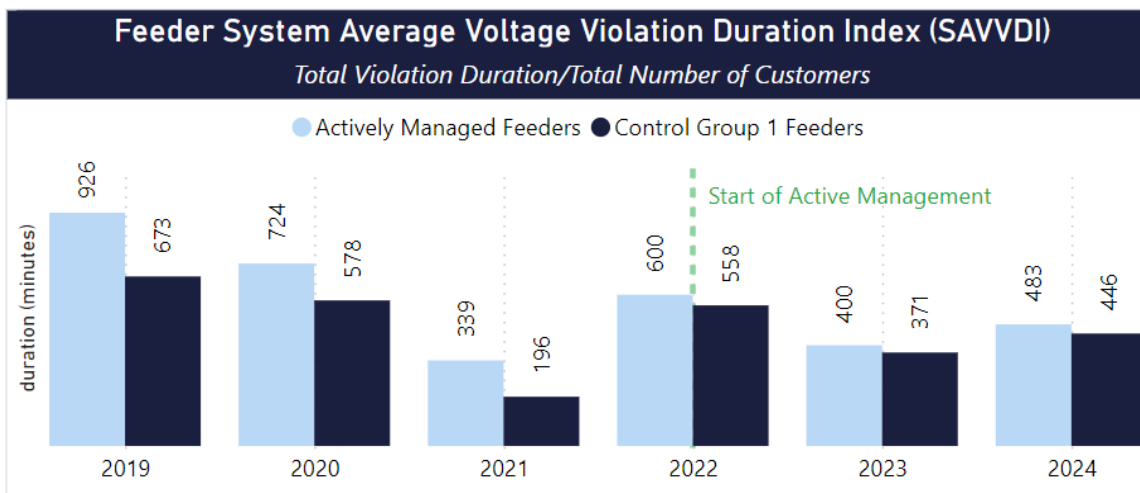


Figure 9. Feeder-Level SAVVDI Comparison Results by Calendar Year

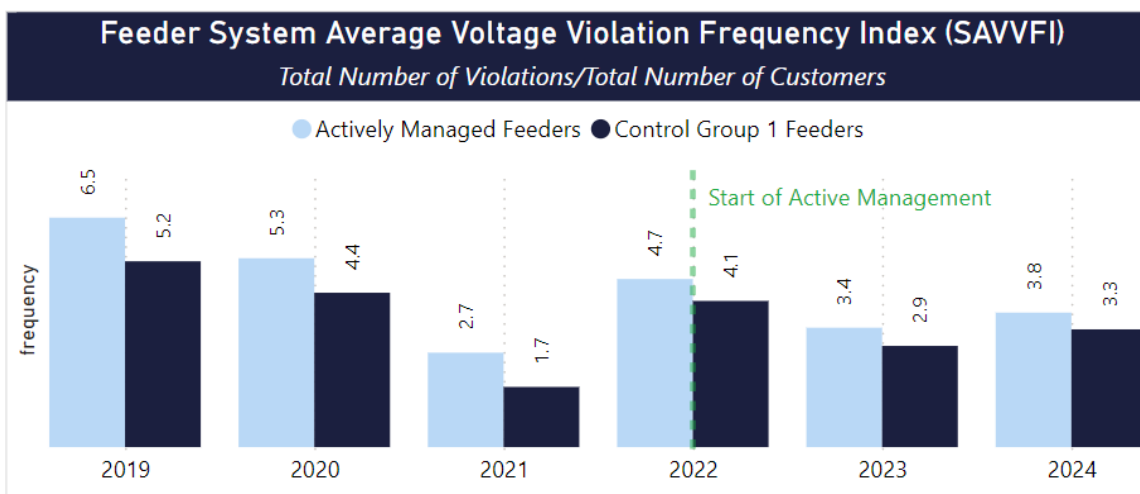


Figure 10. Feeder-Level SAVFI Comparison Results by Calendar Year

In summary, Figure 9 and Figure 10 illustrate SAVVDI and SAVFI for each feeder group and the incremental improvements seen, starting prior to the-Pilot’s commencement (2019-2020) through observed DER penetration increases (2023 onwards). Figure 11 is an extension of Figure 9 and Figure 10 and demonstrates the difference within the SAVVDI and SAVFI calculations between the two feeder groups, throughout the review period. From these three figures, the average system voltage violation has reduced more for actively managed feeders than it has for the CG1 feeders, following the commencement of DER active management in 2022. This highlights the anticipated benefits of active management in maintaining system voltage.

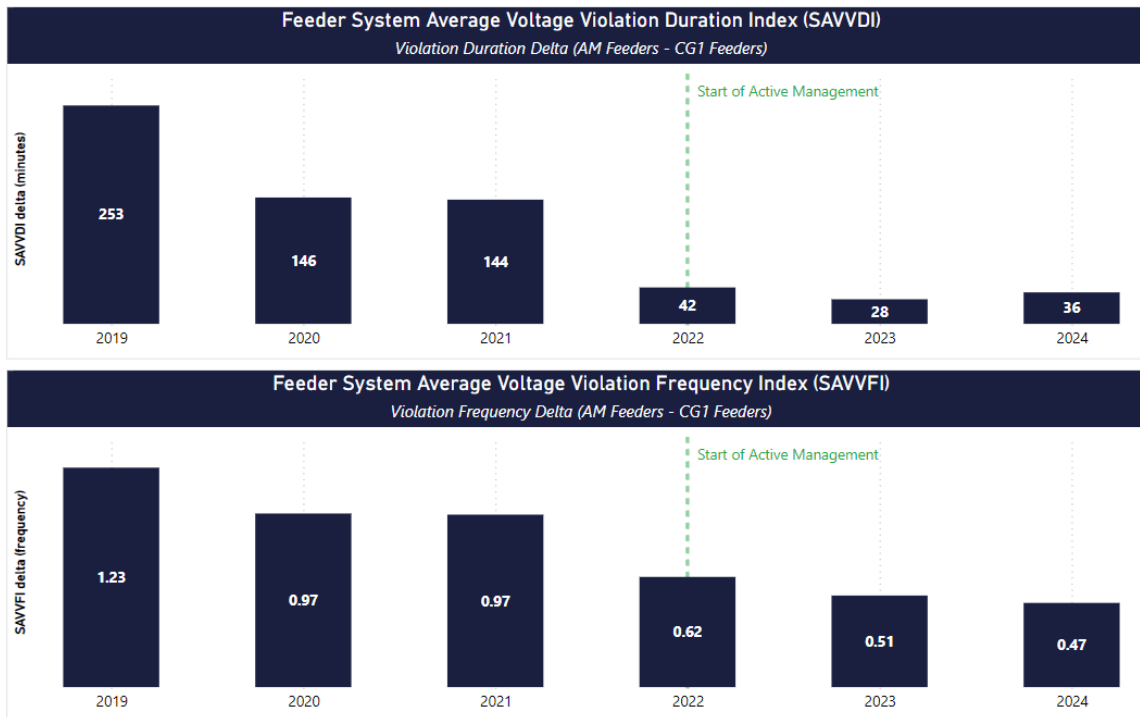


Figure 11. Feeder- SAVVDI & SAVVI Comparison By Control Method by Calendar Year

### Feeder Voltage Violation Severity

As a continuation of the SAVVDI and SAVVI calculations above, calculating voltage violation severity at a feeder level provides a more significant comparison between CG1 feeders and those with DERs that can be actively managed. A review of the impact of autonomous only feeders (CG1) versus autonomous and AM illustrates the cumulative impact of integrating both Pilot management types, as seen within Figure 12. While CG1 feeders demonstrate the benefit of autonomous functions, AM feeders demonstrate the added benefit of active management.

As noted previously, through the inclusion of each of these feeder categories, from the Pilot’s inception forward, the total nameplate capacity of DERs has continued to increase. Further, DER installations continue to increase on the AM feeders at a larger rate than observed amongst the 75 feeders comprising CG1. Non-Pilot participating DERs continue to be interconnected and disbursed throughout PPL Electric’s distribution system, potentially influencing the results of both examined feeder categories.

As denoted within Figure 12, prior to the start of active management events in 2022, customers on feeders with actively managed DERs experienced a relatively lower incidence of the most severe voltage violations when compared to their peers on CG1 feeders. This gap widened by the end of 2023 due to the number of actively managed DERs and active management events significantly increasing. Although this gap narrowed in 2024, PPL Electric’s Pilot data has shown that active management can have a clear impact on customer power quality.

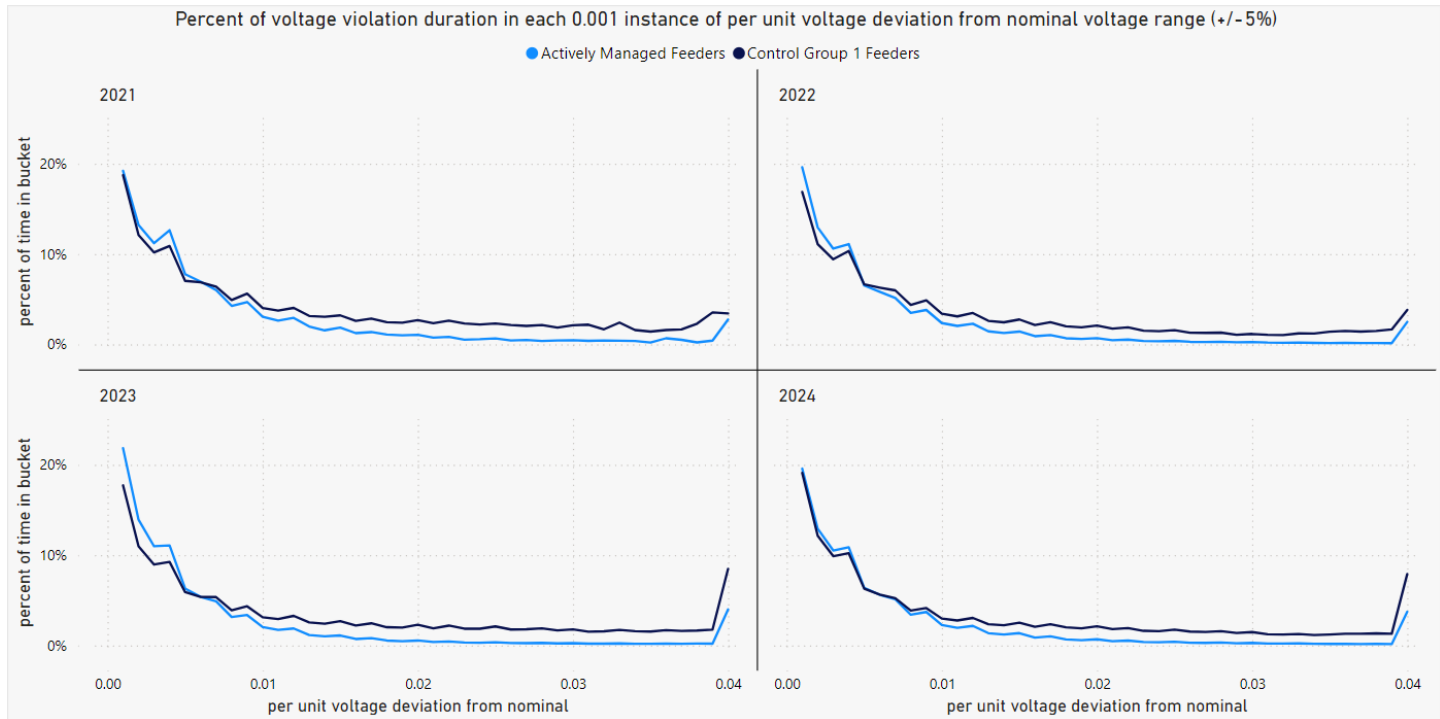


Figure 12. Feeder Level Voltage Severity Results Comparison

## Voltage Violation Conclusions

Key takeaways from the comprehensive review of the figures in this section and their associated explanations are

1. **Trend of Shorter and Less Frequent Violations:** The Grandfathered Group has longer and more frequent voltage violations than Control Group 1, Control Group 2, and the Active Management Group. The trend of shorter and less frequent voltage violations for the latter three groups demonstrates that the DER Pilot is improving grid conditions.
2. **Historical Challenges in Actively Managed Feeders:** Feeders with actively managed DER historically faced a higher frequency of voltage violations, compared to those in CG1. However, the disparity in violation frequency between these groups has started to decrease beginning in 2022, showcasing how actively managing the DERs has gradually improved the feeders' performance.
3. **Response vs. Prevention:** PPL Electric's systems, including ADMS/DERMS, are configured more towards responding to existing voltage violations, rather than preventing them. This reactive approach results in less pronounced impacts on violation frequency, as interventions are primarily aimed at resolving the current sustained issues or preventing a recurrence within the same day. However, with DER management, the potential exists for significant enhancements in how voltage violations are managed through advancements in operational forecasting. With better predictive capabilities, it may become feasible to proactively manage and reduce the frequency of voltage violations before they occur, shifting from a reactive to a preventative management style.
4. **Quantifying Severity:** The development of new metrics to understand the severity of voltage violations adds another layer of depth to grid management. These metrics help quantify the delta between the permissible



range and the voltage measured, providing a clearer picture of the feeder's health and the effectiveness of voltage regulation strategies.

5. **Understanding Impact Over Time:** The analysis of severity across different times and conditions (such as daylight time intervals) helps in understanding the dynamic nature of voltage violations and the operational effectiveness of DER management across different scenarios.

## Operational Efficiency Improvements Attributed to Active Management

Active management commands are communicated to the required devices via PPL Electric's ADMS and its accompanying LVM module. Through LVM, several scenarios are simulated, based on the incoming SCADA telemetry and customer meter data, to assess the needs of the distribution system. The resulting LVM solution is an optimally selected scenario and specifies the number of actively managed DERs to be included. Through the execution of these scenarios, a portion of the reported voltage violations is anticipated to be resolved.

Further analysis of these resolutions has led to the development of a metric indicating the number of potential technician site visits reduced, due to the resolution of voltage violations. Within each LVM plan period, a portion of impacted customers is anticipated to have their voltage violations resolved. With this, the number of customers with at least one voltage violation resolved, within an LVM plan period, is multiplied by the completion rate of LVM plans, which is currently 84.3%. The completion of an LVM plan includes the initiation and resolution of planned actions. Customer count is used rather than violation count to avoid counting multiple resolutions for a single customer as multiple truck rolls, and because not all resolutions are directly attributable to active management.

The completion rate is then multiplied by 75%, which is the frequency that PPL Electric deploys a truck and personnel in response to a voltage violation complaint based on the Company's power service problem ("PSP") data. The resulting figure is then multiplied by the cost PPL Electric incurs per truck roll to resolve a voltage violation. This provides an estimate of the overall cost effectiveness of active management in identifying, mitigating, and resolving voltage violations.

**Table 15. Avoided Truck Roll Cost, per year, Attributed to DER Management Influence**

Year	Truck Roll Rate	Voltage Violations that could have resulted in Truck Rolls	Total Cost to Respond to Voltage Violations that were Avoided
2022	\$711	796	\$565,956.00
2023	\$535	13,586	\$7,268,510.00
2024	\$656	17,624	\$11,561,493.00
2025*	\$263	3,062	\$603,935.00
<b>Total</b>			<b>\$19,999,894.00</b>

\*2025 values are inclusive of the end of PY3, March 21,2025.

## DER Management Functions and Operations

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### Active Management Functionality and Operation

#### ***Per Implementation Plan Section G.1.11 - Operational descriptions of how active management was executed and implemented***

PPL Electric has compiled a report of data captured from the ADMS/DERMS system. This report identifies the operational issues faced, the active management action taken, and the expected resulting impact of the action for each instance of active management. As noted previously, within the Active Management Benefits portion of this report, the data has been exported from the ADMS/DERMS event logs and presented within Appendix F. The data indicates the number and severity of voltage violations present before and after ADMS/DERMS executes the management plan. In contrast to the approach detailed previously within the Active Management Benefits, smart meter measured data is utilized but does not determine the relative role of each DER.

Prior to the execution of an active management event, ADMS/DERMS completes an iterative simulation of the impacted feeder to determine which devices will be included and their necessary power factor adjustments. The results reflect the best information available at the time the management action was taken and incorporates some voltage and load measurements received through SCADA but does not include measured smart meter voltages.

When the ADMS/DERMS is managing system voltage, it identifies voltage violations within the operational model, determines an optimal plan to mitigate voltage violations, and then calculates the hypothetical future state expected to result from that plan. The pre- and post-plan calculated values are recorded within the event log files, as well as the participating DERs and issued commands. From the pre and post event data, the estimated number of voltage violations, resolved by the ADMS/DERMS action, are calculated.

The calculated voltage violations resolved are higher than the observed voltage violations resolved, due to a variety of factors. Slight variances between the simulated and measured results are to be expected. ADMS power flow calculations incorporate real time data and utilize trend data for very near-term forecasting to project the simulated results in study area. Most observed voltage violations occur slightly outside of permissible voltage limits, as presented in Figure 8. Through the integration of the power flow solution within the active management simulations, an overestimation (and sometimes underestimation) of event responses may occur. Each power flow and optimization cycle, currently occurring approximately every 15 minutes, is largely independent from the previous cycle, potentially resulting in the same set of customer voltage violation resolutions being attributed to multiple system interventions. Additionally, the estimated voltage violation resolutions do not account for any failed communication with a participating DER Management device, resulting in a decrease in anticipated participation and subsequently realization of anticipated benefits. Finally, the power flow solution does not fully account for the actions of autonomously operating devices outside of the system's control, such as switchable capacitors and voltage regulators, which are capable of changing state or position independently of the scheduled system intervention of DER Management devices. The ability to operate independently between the pre-and post-plan results further adds to the variance between anticipated and actual voltage violation resolutions.

ADMS/DERMS also attempts to reduce the severity of voltage violations, as part of the voltage management process. While there may not yet be sufficient penetration of actively managed DERs to resolve voltage violations in all areas, ADMS/DERMS still utilizes the available resources to improve system voltage conditions. The results of these actions are also presented within Appendix F, on a per event basis.



### Active Management Validation

To validate the performance of the ADMS/DERMS in addressing voltage violations, PPL Electric has compared DERMS plan logs to the observed customer voltages impacted during the 15-minute meter intervals prior to and after the execution of the planned event. The customer meter data has been sourced via the smart meter data repositories. Given the fluidity of the distribution system within each smart meter 15-minute interval, there are a multitude of contributing factors influencing distribution system, as well as customer service voltages, thereby increasing the difficulty in attributing the resolution of a voltage violation solely to DER management. It is possible, however, to assess whether the ADMS/DERMS plans generally align with and support voltage changes that are needed to improve voltage violation conditions.

Successful DER management utilizes DERs to positively impact customer and distribution system voltages during periods of high and low voltages. This has contributed to a reduction in observed customer voltage violations. PPL Electric has examined the ADMS/DERMS event logs to identify events in which a portion of participating DERs had been directed to influence the observed voltage, in the same direction so as to resist the violation. From these events, customer smart meter voltages, on the same feeder and phase as the managed DERs, are examined pre and post event to determine the influence of the subject planned event.

Due to the complexity and factors impacting the distribution system’s voltage, certain events involve a mixture of DER management actions; with a portion of the DERs increasing kVAR absorption and others increasing the kVAR injection. These multi-directional events are difficult to analyze at scale and have been excluded from this analysis, to increase the clarity and understanding of DER Management action effectiveness. The results illustrated in Figure 13 below exclude said complex events.

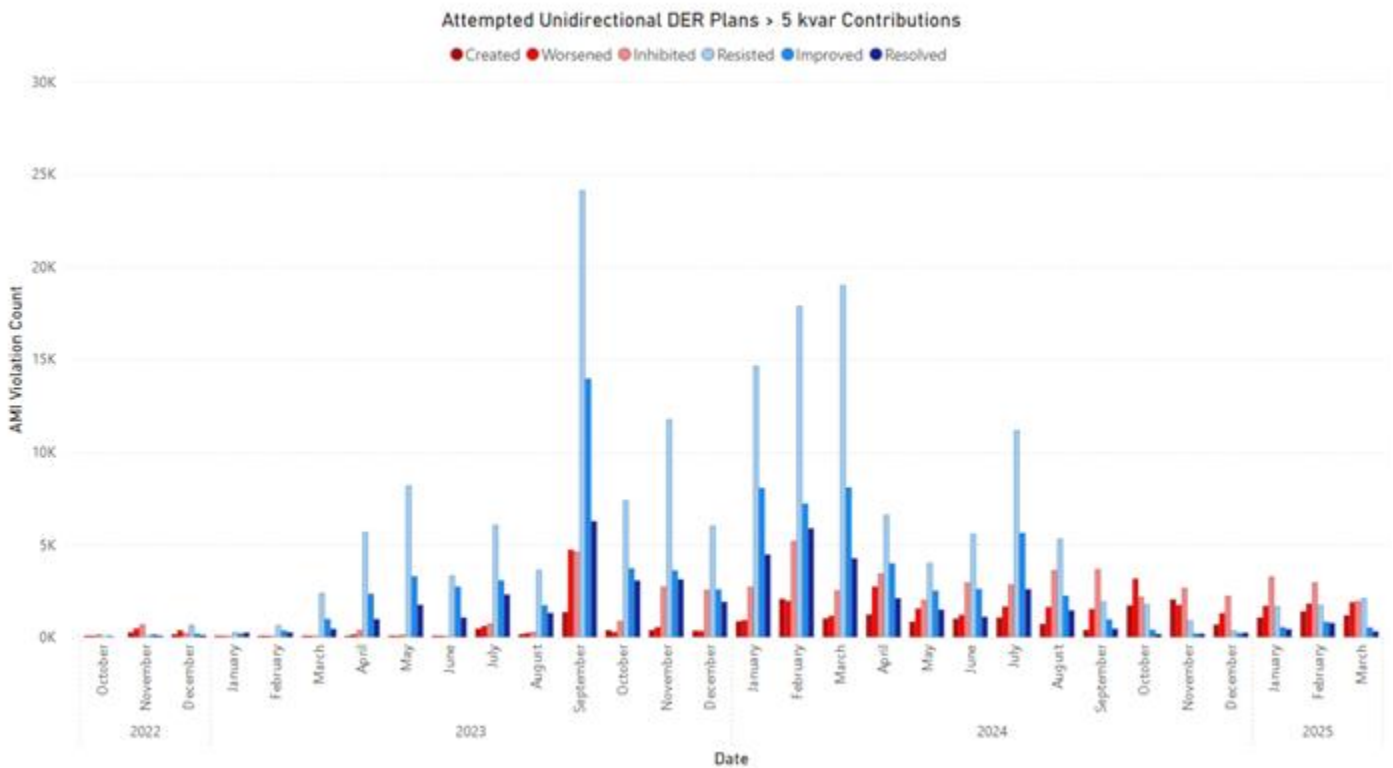


Figure 13. DER Management Plan Contribution Results

Within Figure 13, the contribution of each DER management’s contribution to the change of voltage violation was categorized as follows:



- *Created*: A new voltage violation has been observed after the execution of a DER management plan, at the end of a smart meter reporting period, that did not exist prior to the management action
  - Ex: A participating DER injects kVAR which would raise system voltage, and a customer's voltage changes from 1.049 per unit to 1.051 per unit
- *Worsened*: A voltage violation was more severe in the direction of the DER management planned voltage contribution, at the end of a smart meter reporting period, than prior to the management action
  - Ex: A participating DER injects kVAR which would raise the voltage, and a customer's voltage changes from 1.051 to 1.052 per unit
- *Inhibited*: A voltage violation was less severe at the end of a smart meter reporting period, but the DER management plan's voltage contribution was in the opposite direction
  - Ex: A participating DER injects kVAR which would raise the voltage, and a customer's voltage changes from 1.052 to 1.051 per unit.
- *Resisted*: A voltage violation was more severe at the end of a smart meter reporting period, despite the DER management plan's voltage contribution in the direction opposite the violation
  - Ex: A participating DER absorbs kVAR which would lower the voltage, and a customer's voltage changes from 1.051 to 1.052 per unit.
- *Improved*: A voltage violation was less severe at the end of a smart meter reporting period in the direction of the DER management plan's voltage contribution
  - Ex: A participating DER absorbs kVAR which would lower the voltage, and a customer's voltage changes from 1.052 to 1.051 per unit.
- *Resolved*: A voltage violation existed at the start of a smart meter reporting period that did not exist at the end of the period and attributed to the DER management plan's voltage contribution
  - Ex: A participating DER absorbs kVAR which would lower the voltage, and a customer's voltage changes from 1.051 to 1.049 per unit.

Within one of the incremental software updates PPL Electric's ADMS/DERMS had received, modified the allowable minimum power factor for actively managed DERs. The ADMS/DERMS restricted impacted devices from operating outside of +/-90% power factor. Due to this process revision, the subject DERs were removed from operating autonomously, via their unique VVC, and issued power factor adjustment commands, to raise (or lower) their power factor to the +/-90% threshold, reducing available kVAR support. Previously, these DERs would have remained following their autonomous VVC settings and been permitted to contribute (or absorb) kVAR up to the programmed 44% of the kW nameplate rating, as outlined within IEEE 1547-2018. Through the issuance of these power factor adjustments, the subject DERs' contribution to local voltage violations had been reduced, resulting in the potential to contribute to an increase in the observed voltage violations, as presented within Figure 13, after September 2024. This and other potential contributing factors are currently being examined by PPL Electric, with solutions forthcoming.

Through the DER Pilot, participating DERs help support the distribution system's voltage autonomously, via unique VVCs and active management. As DER penetration continues to increase, the intertwined DER management effectiveness has become evident. Through each Pilot DER's autonomous VVC settings, DER are capable of instantaneously resisting any voltage variations outside of the individual VVC deadbands. Through this resistance to voltage changes, each DER attempts to restore the measured voltage, at the inverter, within the deadband range. During periods of excessive and/or sustained voltage outside of the DER's VVC deadband, the Company's ADMS/DERMS can intervene and establish a suitable solution and include additional actively managed DERs, if necessary. Through these solutions, commands are dispatched to DERs to improve the observed voltage and resist further voltage variances, while influencing attempts to restore the distribution system voltage within its permissible limits. Through the use of autonomous and active management techniques, PPL Electric's participating DERs have aided in the resolution of observed voltage violation conditions, improved voltage violation magnitudes (severity), and resisted other factors that contribute to the



occurrence of or increase the severity of voltage violations. While creating, worsening, or inhibiting the resolution of voltage violations are not generally desirable, nor the intention of the DER Pilot, the optimization of the distribution system is very complex and can result in trade-offs, with overall net positive results continuing to be observed. For example, creating one new voltage violation with a relatively small magnitude in order to resolve five voltage violations elsewhere on the system is a significant net positive from the system perspective.

The results of active management provided to date are a direct result of the growth in number and nameplate of actively managed DERs. As DER penetration continues to increase, the total amount of available reactive power support will continue to increase as well. While the existing DER penetration throughout PPL Electric’s distribution system varies, those areas that have transitioned from low to medium, or medium to high, penetration throughout the Pilot have increased their resiliency because of the additional support provided through actively managing DERs. Active management has contributed to a decrease in instances, duration, and severity of voltage violations, as the use of fixed power factors provides a larger area of influence than available with autonomous scenarios. From Figure 14 below, most of the executed DERMS plans resulted in less than 20 kVAR, of change within the managed DER. This is attributed to the average active management DER participant’s nameplate being slightly less than 16.3 kW.

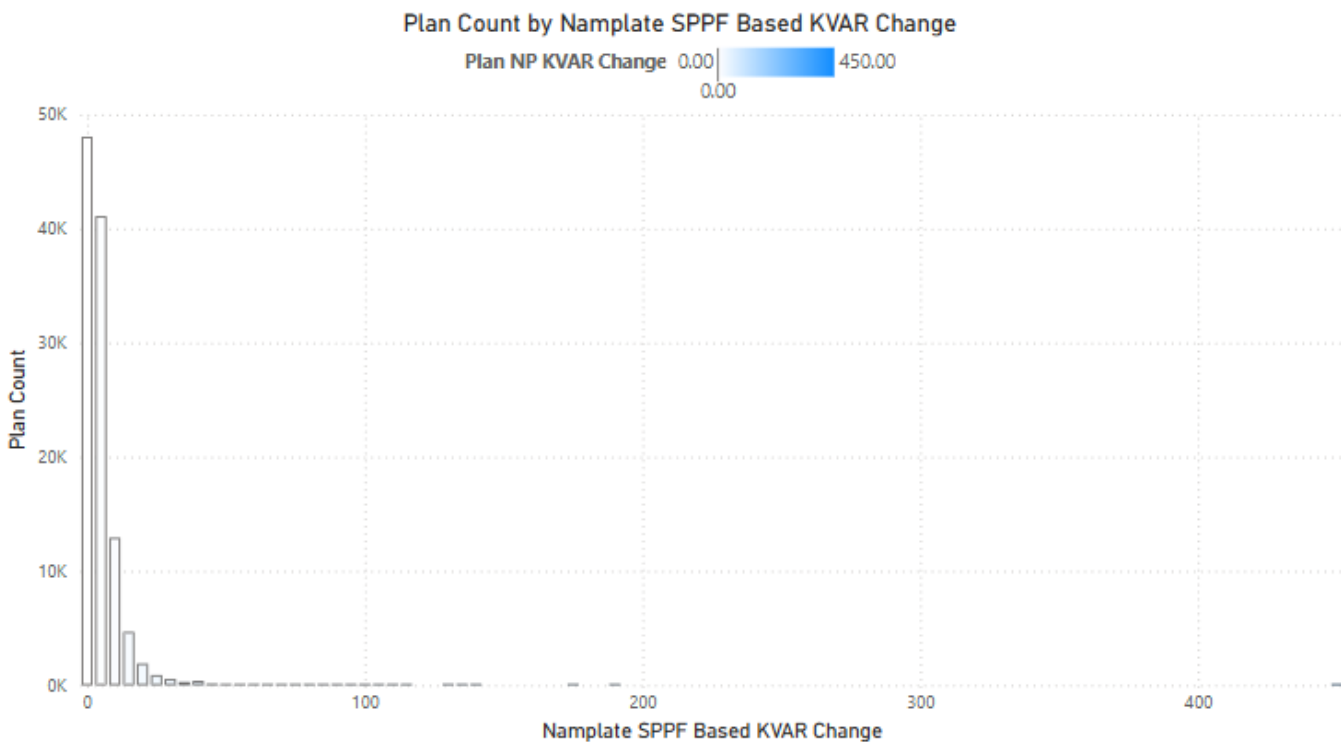


Figure 14. Relative Frequency of Total Planned kVAR Change

### Active Management Communications Performance Measures

**Per Implementation Plan Section G.1.12 - Performance measures related to active management**

PPL Electric has developed performance tracking metrics to monitor communication reliability and overall data quality for each DER Management device installation. PPL Electric’s communication systems continue to perform at a high level, even as the number of DER Management devices has increased. As noted within Table 1, the total number of device installations at the end of PY3 has reached 9,678. PPL Electric remains committed to maintaining and improving the reliability of its AMI network.



PPL Electric monitors communication between each participating customer’s communication device and the AMI head-end system, ensuring overall reliability and performance of the AMI network layer. Within the AMI network, commands are transmitted via the AMI head-end system to the endpoint devices, and each endpoint device responds to the head-end system’s command. One execution of this cycle is called a “round trip.” The AMI layer of communications reliability and performance is measured by the percentage of successful round trips. PPL Electric strives to maintain an overall communications success rate of 95% between the AMI head-end system and DER Management devices.

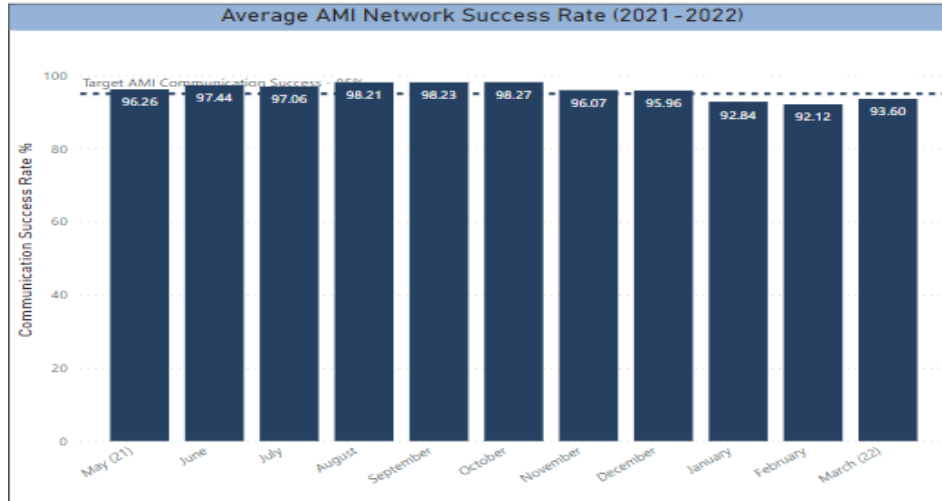


Figure 15. Average AMI Communication Success Rate by Month, 2021-2022

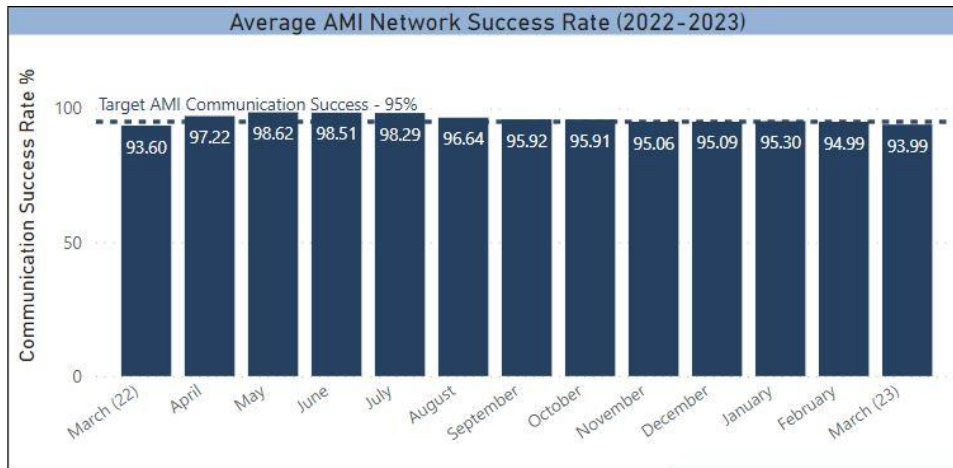


Figure 16. Average AMI Communication Success Rate by Month, 2022-2023

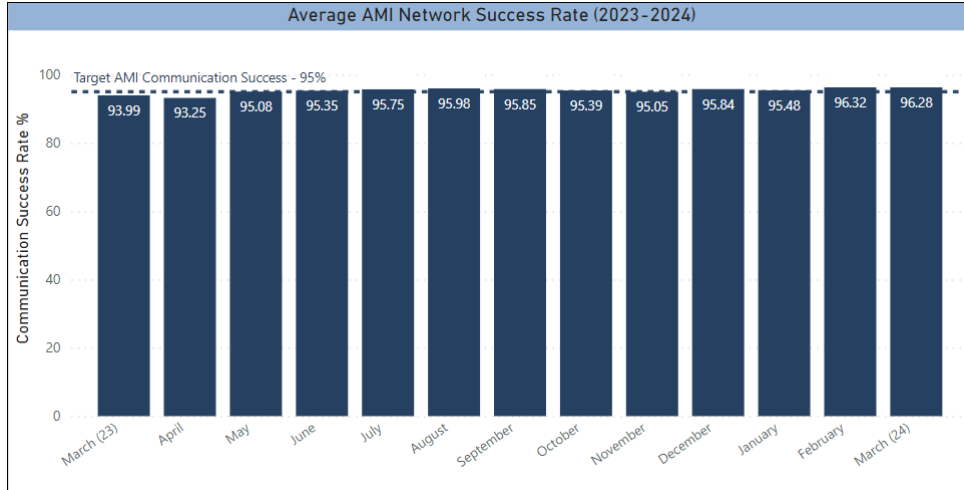


Figure 17. Average AMI Communication Success Rate by Month, 2023-2024

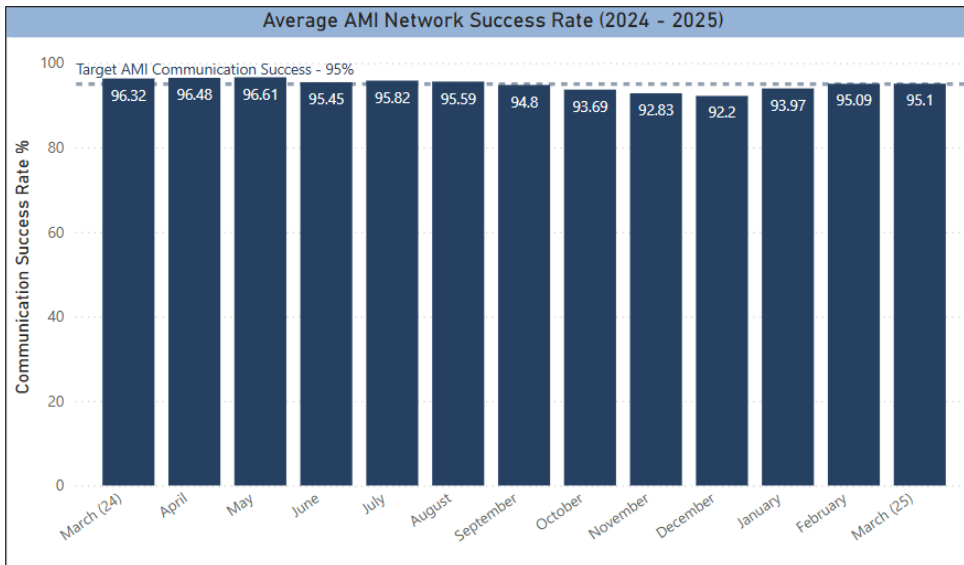


Figure 18. Average AMI Communication Success Rate by Month, 2024-2025

Within Figure 15 to Figure 18 above, the AMI communication success data excludes locations where AMI communication could not be established, as their performance is not indicative of overall network performance. As of March 2025, 587 devices have been removed from this data set. This accounts for 6.07% of DER installations enrolled in the Pilot. These locations are being investigated by PPL Electric.

Another important AMI network performance indicator is Average Round-Trip Time. This indicator measures the amount of time it takes for a command to be sent from the head-end system and the response to be returned by the radio. PPL Electric strives to maintain 60 seconds as a maximum duration of the average round trip time, to ensure reliable communications performance. Based on historical performance data, an improved target of 30 second round trip time target had been implemented for the 2023-2024 reporting timeframe and beyond. Through these decreases, round trip time monitoring continues to indicate no significant changes in network performance have occurred.

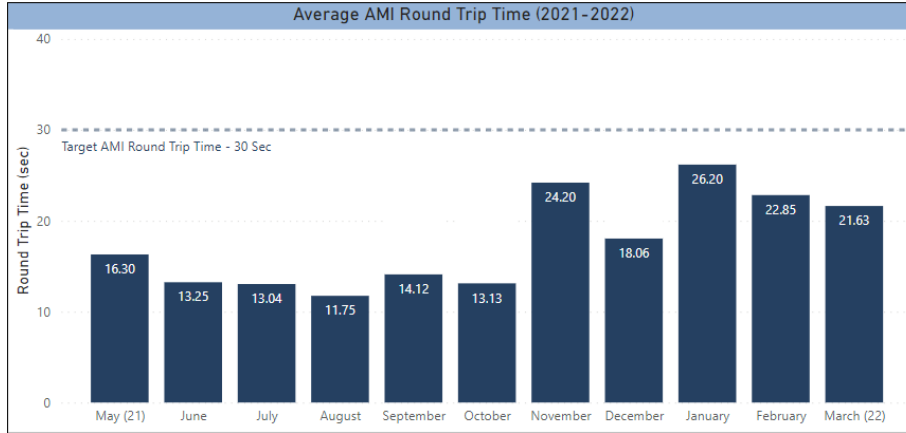


Figure 19. Average AMI Round Trip Time by Month, 2021-2022

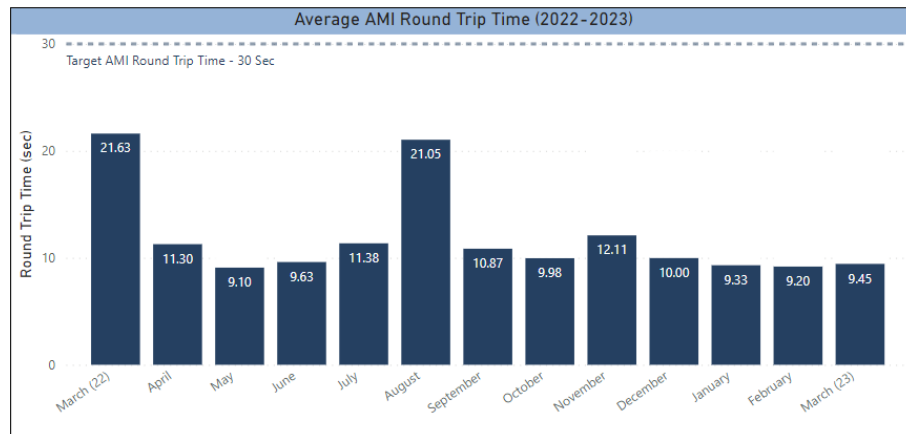


Figure 20. Average AMI Round Trip Time by Month, 2022-2023

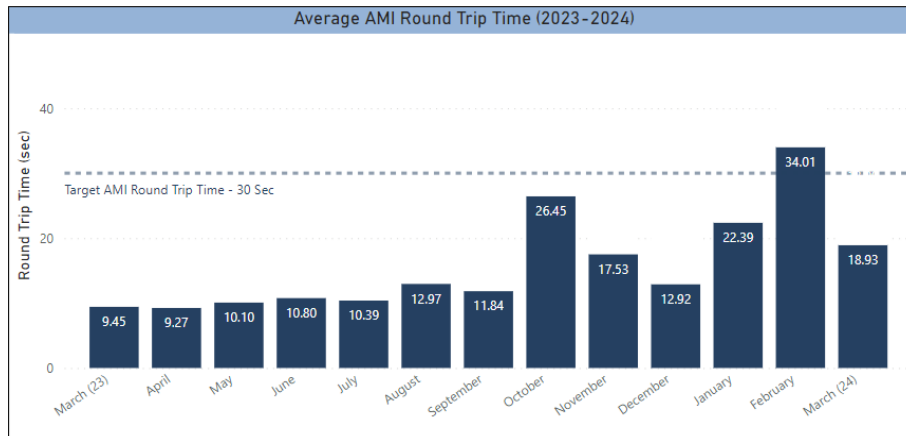


Figure 21. Average AMI Round Trip Time by Month, 2023-2024

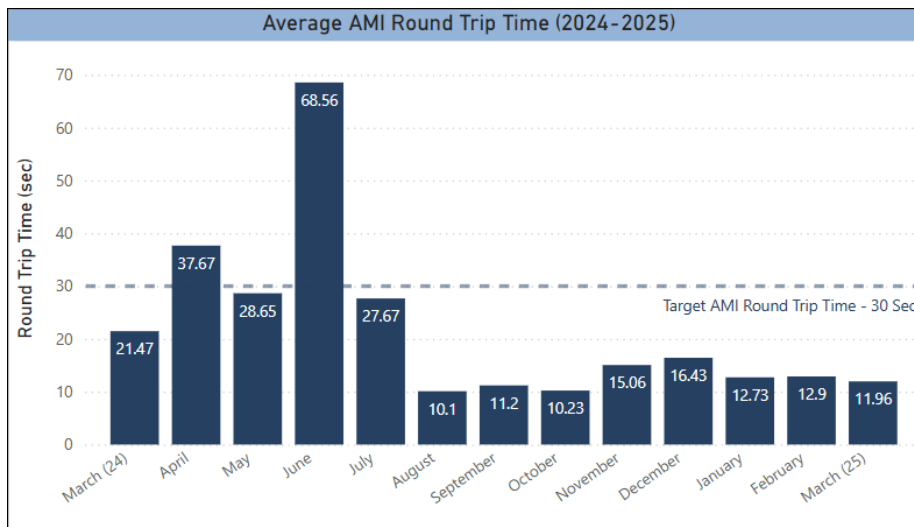


Figure 22. Average AMI Round Trip Time by Month, 2024-2025

Each DER Management device provides 5-minute interval data, increased from customer smart meters’ 15-minute interval. Through this increased sampling rate, data quality is pivotal to overall communications health. With respect to active DER management, a communications interval is determined to be a “quality” interval when at least one reading within any 15-minute interval during daylight hours (5AM – 9PM) is received and the data is within reasonable limits for key parameters (i.e. voltage, kW, Volt-VAR curve points, etc.). Within the historical DER data, a new challenge had been observed: a number of inverters reported real power measurements above their rated nameplate, at times exceeding the nameplate by more than 10%. This has potential to negatively impact data quality, despite other parameters being within expected ranges.

Quality data intervals, between March 22, 2024, and March 21, 2025, decreased to 86.50% of communications intervals, from the 89.93% previously reported. PPL Electric continually monitors data quality and has identified and implemented enhancements to improve overall data quality and is committed to continuing these efforts for the foreseeable future.

## Use Case Findings and Details

### ***Per Implementation Plan Section G.1.13 - Findings and information on PPL Electric’s use cases***

PPL Electric has continued to compile and investigate information within each of the eight use case areas identified in the Pilot Implementation Plan. Additional investigations have also been completed, providing support for future DER Management Plan iterations. Each investigation includes a comparison of benefits between Pilot and non-Pilot participation, with related benefits detailed. Through the completion of each study, PPL Electric’s knowledge base continues to expand, enhancing the Company’s the benefits of active management.

The total number of uses cases, per category and reporting year, are presented in Table 16 below. As noted previously, additional detailed studies have been completed. Those studies pursued further areas of Pilot-related study but do not fall within the defined categories.

Table 16. DER Management Pilot Supporting Use Cases by Program Year

	Year 1	Year 2	Year 3
<b>Use Case 1</b>	0	0	
<b>Use Case 2</b>	6	9	10
<b>Use Case 3</b>	0	2	3
<b>Use Case 4</b>	0	1	2
<b>Use Case 5</b>	0	1	1
<b>Use Case 6</b>	4	5	3
<b>Use Case 7</b>	3	3	
<b>Use Case 8</b>	0	0	
<b>Supplemental</b>	0	2	3

### Use Case #1 – Voltage Violation at DER Point of Interconnection (POI)

PPL Electric must maintain its distribution voltage within the parameters set forth by the Commission’s regulations.<sup>6</sup> The threshold voltages detailed are similar to those indicated within ANSI C84.1. Maintaining the distribution system voltage within these limits is a component of ensuring safe and reliable power quality for customers. As DER penetration continues to increase, there is potential for the distribution system voltage to be negatively influenced, particularly at the POI, leading to customer voltage falling outside the allowable limits, for periods of time. The introduction of DER Management devices has increased PPL Electric’s overall visibility of its distribution system. Through continuous monitoring of distribution system and customer meter voltages, PPL Electric has been able to observe and detail the benefits each Pilot group has contributed to the distribution system’s voltage performance, including aiding in the mitigation of voltage violations.

For the PY3 period, 40,409 voltage violations were recorded at the meters of Pilot participants (i.e., CG1, CG2, and AM groups). As noted previously, as the number of Pilot participants increases, the number of documented POI voltage violations is anticipated to increase, based on the increasing sample sizes year over year.

Table 17. POI Voltage Violation Counts by Program Year

	Year 1	Year 2	Year 3
<b>POI Voltage Violations</b>	6,559	39,156	40,409

### Use Case #2 – Voltage Violation Mitigated by DER on the Circuit

As noted previously, increased DER penetration can create or intensify voltage issues, particularly if no measures are in place help mitigate them. As DER penetration continues to increase, system operations and planning engineers will continue to struggle with the challenges associated with various levels of DER penetration throughout PPL Electric’s distribution system. Through DER Pilot, the Company has increased visibility and management capabilities throughout its distribution system.

The Company has conducted detailed reviews of past voltage events to determine the measurable impact of active DER management. Most of these examinations have considered the integration and impact of all existing DERs. Additionally, detailed examinations of DERMS operations have detailed the influence of specific DERMS actions on the observed voltage violations.

<sup>6</sup> See 52 Pa. Code § 57.14.

As of March 21, 2025, 10 whitepapers focusing on this use case have been completed. From Table 18, 8 of these studies show a total of 887 potential voltage violations being mitigated through the application of autonomous VVCs and an additional 878 voltage violations being mitigated via active management. Additionally, PPL Electric has conducted a detailed examination of one DER management event by comparing the DERMS-calculated voltage violation mitigation estimates against the actual smart meter data readings over the same intervals. This examination indicated 3 voltage violations were mitigated via active management intervention, during the intervals identified within the DERMS calculation.

**Table 18. Use Case 2 - Voltage Violation Studies, Program Year 3**

	Trigger	Customers Violations	Violations Resolved - Autonomous	Additional Resolved – Active Management
<b>WP-0050</b>	Switching	136	90	46
<b>WP-0053</b>	High Voltage	436	78	289
<b>WP-0055</b>	High Bus Voltage	743	439	113
<b>WP-0060</b>	Switching	151	34	117
<b>WP-0061</b>	Ride Through Settings	n/a	n/a	n/a
<b>WP-0063</b>	High Bus Voltage	152	49	103
<b>WP-0064</b>	Low Voltage	202	194	8
<b>WP-0065</b>	High Voltage	223	3	199
<b>WP-0066</b>	LVM Review	49		3
<b>WP-0072</b>	Customer Reporting	n/a	n/a	n/a

### Use Case #3 – Voltage Violation During Planned Switching

Portions of the distribution system must be reconfigured routinely under planned switching events. Through these events, all or a portion of a feeder may be transferred from its normally assigned source to an alternate, placing the impacted areas in an abnormal state. These events enable planned maintenance and upgrade activities to be completed and can allow for portions of the distribution system to be de-energized.

Through each planned switching event, all interconnected DERs within the transferred area are transferred to the new source. These transfers may increase the potential for an increase in observed voltage violations. Before these events are executed, PPL Electric completes proactive switching reviews to identify any loading and voltage issues that may be anticipated and determines the paths to mitigate these issues. Attempts to mitigate these are assessed based on the complexity of implementation (i.e., adjustments to voltage and power factor correcting device settings, phase balancing, additional load transfers, etc.).

The DER Management team may further examine these studies in detail to assess the potential impact DER Pilot participants may have in providing an alternate or supportive function in resolving the anticipated voltage issues. Through these examinations, both autonomous and active management functions are assessed to determine their potential impact throughout the abnormal configuration period.

As of March 21, 2025, 3 studies have been completed that have identified the ability to utilize DER Management participants to reduce anticipated voltage violations and aid in the reduction of additional reconfigurations or installation of temporary voltage and power factor correcting devices. Through these examinations, a potential reduction of \$499,000 in planned switching costs has been determined, as illustrated in Table 19.

Table 19. Potential Cost Savings Attributed to Use Case 3 – Voltage Violations During Planned Switching Studies, Program Year 3

	Trigger	Potential Cost Savings
<b>WP-0049</b>	Substation Maintenance	\$154,000
<b>WP-0051</b>	Substation Maintenance	\$ n/a
<b>WP-0052</b>	Substation Maintenance	\$345,000

## Use Case #4 – System Restoration

If an outage occurs for a period longer than the programmed ride-through settings (as detailed within Ride-Through Curve Parameters, above), all IEEE 1547-2018 compliant devices are programmed to disconnect from the distribution system in order to avoid potential unintentional islanding. Currently, all Pilot participating DERs are programmed with a 5-minute delay, upon restoration occurring, while non-Pilot participants do not have this delay programmed. During this restoration window, the feeder/substation is required to supply all customer load, via the supplying transmission system, without any support from the aforementioned DERs. Therefore, the observed cold load pick-up at the point of restoration is dependent on the outage duration and includes the native load, without DER masking, and a reduction in load diversity.

Throughout PY3, PPL Electric has not identified any system restoration events that have resulted in overloaded equipment attributed to the inclusion of masked load (load masked by DERs) during cold load pick-up periods. Analysis has been completed on several feeders, with an emphasis on assessing potential risks in the future due to these conditions. A further examination considering the impact of residential EV charging during system restoration, has also been examined, as highlighted within Table 20 below.

Table 20. Use Case 4 – System Restoration Switching Studies, Program Year 3

	Driver
<b>WP-0067</b>	Evaluation of masked loading towards ability to defer capital investments
<b>WP-0071</b>	System Restoration with consideration of residential EV charging

## Use Case #5 – Masked Load Impact on Load Forecasting

PPL Electric reviews each feeder's summer and winter peak loading to assess potential device overloading risks. In addition to these semi-annual assessments, a review of the current load masked by DERs, throughout the distribution system, is conducted. The assessment of masked load is required within native load calculations and determines non-telemetered DERs' contributions to the distribution system. The calculated masked load, along with the telemetered DERs and measured load, comprise the native load. The completion of native load calculations within load forecasting helps ensure that capital investments are appropriately timed, particularly for periods when DERs may not be available.

As of the end of PY3, PPL Electric has calculated 38.8 MW of masked load, during system peak loading period, July 2024. This value was calculated by monitoring the output data from 64.08 MW of DER nameplate capacity at the system peak. Detection of the masked load has resulted in 25.28 MW of additional system capacity during these peak loading periods. PPL Electric has also performed analysis on several feeders to evaluate the potential impact of masked load on future load forecasting, with these results detailed within the associated studies referenced within Table 21.

Table 21. Use Case 5 - Masked Load Impact on Load Forecasting White Paper Results, Year 3

Driver	
<b>WP-0067</b>	Evaluation of masked loading towards ability to defer capital investments
<b>WP-0069</b>	Evaluation of masked loading towards ability to defer capital investments

## Use Case #6 – DER Management Impact on Voltage Management

PPL Electric’s DER Pilot has increased the overall number of telemetered devices deployed throughout the distribution system. With the addition of these new telemetered devices and the previous deployment of smart meters, PPL Electric can better study and monitor its distribution system’s operation. In particular, the addition of these devices has increased the resolution within reliability focused investigations and has enabled a greater overall understanding of each feeder’s profile.

PPL Electric’s DER Pilot also enables the Company to assess participating DERs’ impact on feeder and substation voltage. Based on this analysis, participating DERs have reduced the overall number, duration, and severity of voltage violations. As DER penetration continues to increase, the ability for participating DER to positively impact the distribution system voltage will continue.

As part of each interconnection and DER management study, PPL Electric investigates DERs’ impacts on distribution system voltage. Modeling accuracy has continued to increase by integrating DER Pilot telemetered data as well as smart meter data for each participating DER customer location. This has enabled a greater number of scenarios to be examined, reducing the deviation between simulated/anticipated results and observed results. Within these studies, the assignment of existing and new DERs into the appropriate group enables further assessment of anticipated impacts throughout a variety of situations.

At the conclusion of DER Pilot’s PY3, 3 studies have been completed, assessing potential interconnection capital investment reductions, attributed to DERs becoming Pilot participants. An overview of each of these studies, and corresponding potential capital avoidance, can be found in Table 22 below.

Table 22. Use Case 6 - DER Management Impact on Voltage Management White Paper Results, Program Year 3

	Trigger	Avoided Capital	Violation Reduction
<b>WP-0048</b>	3MW DER Addition	\$105,000	34
<b>WP-0057</b>	3MW DER Addition	\$900,000	n/a
<b>WP-0059</b>	21MW DER Addition	\$560,440	153

## Use Case #7 – DER Active Management Impact on Hosting Capacity Increase and Deferral of Capital Upgrade

Hosting capacity is the amount of DERs that can be added to a portion of the distribution system before system reinforcements are needed to prevent a load or voltage violation. The cumulative value for each feeder and/or substation bus represents the total DER hosting capacity available, based on the dates and times selected for the completed analysis. Currently, DER hosting capacity is calculated annually, in support of preparing this report. Through the DER Pilot, PPL Electric has increased the total number of DER telemetry points available and has improved each successive iteration of the DER hosting capacity calculations as well as DER system impact examinations.

The DER hosting capacity compares four iterations of DER output and management to assess variances: DER nameplate capacities, monitored output, autonomous functions and active management. While the first iterations of the



comparison utilize all PV DER within the calculations, the latter two iterations are dependent on the DER Pilot group assignments, as not all DERs are Pilot participants.

Based on customer DER interconnection applications, the scenarios detailed above are utilized to determine whether participating DERs can alleviate interconnection restrictions or reduce potential customer funded capital investment requirements. At the conclusion of PY3, only one study has been completed, within this use case category.

**Table 23. Use Case 7 - DER Active Management Impact Study Results, Year 3**

Trigger	DER Hosting Capacity Increase – Autonomous	DER Hosting Capacity Increase – Active Management
<b>WP-0072</b> Year 3 DER Hosting Capacity	18 MW	35 MW

### Use Case #8 – DER Operations in Emergency Conditions and in Active Work Zones

Every utility needs to be prepared to respond to emergency situations, as they arise. Through PPL Electric’s preparedness, field personnel are dispatched to investigate and support the resolution of reported fires, gas leaks, downed conductor, etc. Through these responses, portions of the distribution system may need to be de-energized, to ensure public and equipment safety, during this time. With the DER Pilot, PPL Electric system operators can remotely disconnect Pilot participants, within these work areas, reducing the potential for areas to be accidentally re-energized. While reductions in potential safety hazards may be possible within work areas, continued vigilance and safety measures are still necessary.

There were 1,723 outage events during PY3, where DER Pilot participants were present and potentially presented a risk of unintentional islanding, though continued operation. Because of Pilot participation, the status of the impacted DERs was able to be verified, and no instances of unintentional islanding were detected. Also, in PY3, there were no instances where a participating DER was intentionally disconnected through communications with the inverter.

### Additional Study: Flexible Interconnection

In addition to the studies detailed within the Pilot Implementation Plan, 3 flexible interconnection investigations were completed. Each of these studies examined the integration of DERs with additional parameters beyond those currently available under the DER Pilot. The future integration of flexible interconnection will enable an increase in local DER penetration, while avoiding costly capital investments, by reducing participating DERs’ output during peak distribution congestion periods. An overview of the results of these studies can be found in Table 24 below.

**Table 24. Additional Areas of Study - Flexible Interconnection Study Results**

Driver	Avoided Capital Investment
<b>WP-0058</b> 10 MW DER Addition	\$1,480,000
<b>WP-0062</b> 2.5 MW DER Addition	\$365,000
<b>WP-0068</b> 21 MW DER Addition	\$560,440



## Appendix A: Volt-VAR Curve Programming

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## Appendix B: Aggregate Active Management Event Count

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## Appendix C: Grid Benefits Achieved in Each Instance of Active Management

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## Appendix D: Generation Loss or Gain Event Table

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## Appendix E: DER Hosting Capacity

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## Appendix F: Active Management Operational Implementation Event Logs

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