Smarter Grid Solutions | National Renewable Energy Laboratory: Active Management Integration

June 2015 – November 2016

Smarter Grid Solutions, Inc.

Prepared under Subcontract No. NCS-5-42326-03

NREL Technical Monitor: Andrew Hudgins

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National Renewable Energy Laboratory

Active Network Management Integration

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2. EXECUTIVE SUMMARY

This report presents the project results for the NREL INTEGRATE demonstration project: *Active Network Management (ANM) Integration.* Consistent with the INTEGRATE program's objective of increasing the grid's clean energy hosting capacity and providing grid services in a holistic manner, the project demonstrated the use of ANM to enable very high penetrations of solar PV and wind energy systems. Results obtained using a representative North American distribution system showed ANM's autonomous distributed control doubled the interconnected wind and solar systems by managing thermal and voltage constraints in real-time. These generators flexibly interconnected to the grid via ANM's end-to-end control architecture, and were managed and coordinated with other smart distributed energy resources (DER; e.g. EVs, battery ESS, controllable load) to unlock the grid's dynamic hosting capacity. As a smart grid application to standardize grid integration of diverse renewable generation sources, ANM provides the industry with a scalable, cost-effective alternative to traditional transmission and distribution (T&D) reinforcements.

This project considered three use cases of the application of ANM: a Smart Home demonstration of ANM control of residential scale devices (PV, EV, and battery ESS); a Smart Campus demonstration of high penetration megawatt-scale DER (PV, EVs, battery ESS, and controllable load) behind a single point-of-common-coupling (PCC), and a Smart Distribution demonstration that combined prior use cases along with additional community/utility-scale DER at very high aggregate penetration levels. The Smart Distribution use case provided an integrated perspective of ANM across all distribution grid DER device scales (incorporating aggregated Smart Homes and the Smart Campus) in order to showcase how these devices can support smart grid services to manage DER related constraints in a safe and reliable manner; and likewise how ANM integrates with grid modernization initiatives.

The ANM system was deployed in NREL's Energy Systems Integration Facility (ESIF), and project industry advisors attended an on-site demonstration and a set of workshops in order to review project outcomes and evaluate the relevance of ANM for increasing the grid hosting capacity. The outcomes of this effort include an assessment of opportunities for field deployment of ANM to address existing interconnection challenges, as well as consolidating project advisor suggestions for investment in ANM and potential future pilots for more advanced schemes. Some key outcomes include:

- **A need to move from passively managed distribution grids to actively managed distribution grids:** smart grid investments should enable DER grid services that support rising penetrations of solar, wind, and other DER. Yet, single large Distributed Generation (DG) projects (e.g. greater than 500 kVA) can have prohibitively high interconnection costs under the passive approach to grid integration.
- **The ANM enabled dynamic grid hosting capacity allows for much higher penetrations of solar and wind energy:** grid edge ANM controls can support variable renewable generation interconnection allowing for DG capacity of more than 50% of peak load through flexible interconnection agreements.
- **ANM's real-time grid edge controls enable cost-effective investments by "unlocking" grid capacity/assets**: under this scenario hosting capacity is set by the market, whereby DER developers choose either firm interconnection via traditional T&D reinforcements, or flexible interconnection via grid edge autonomous control, whichever presents itself as more economic. This ultimately translates to lower cost of energy for the rate payer.

- **ANM's autonomous, deterministic control ensures safety and reliability:** ANM manages DER through an end-to-end, mission critical control systems philosophy that is time-bounded, predictable and repeatable. As demonstrated through the INTEGRATE use cases, ANM can respond to a variety of diverse operating scenarios without the need for forecasting and energy storage. Although not required for initial ANM flexible interconnection schemes, given the way ANM has been architected, it can incorporate forecasting, energy storage, and demand response, contributing to an overall improved business for very high penetration scenarios.
- **Flexible interconnection is relevant today:** DER interconnection limits can be breached by individual projects, particularly for larger projects. Flexible interconnection curtailment solutions are already proven to provide economic solutions for developers by significantly increasing hosting capacity. Curtailment risk for a few ten to a hundred hours of the year can be much more economic for some developers compared to traditional T&D upgrades for a firm interconnection. ANM can be deployed on circuits lacking historical data and without the need for an accurate, area-wide distribution models because it is a data-driven application.
- **ANM platforms support grid modernization today:** ANM deployments align with grid modernization efforts to improving observability and controllability efforts by actively managing distribution resources. Moreover, such approaches augment the ongoing work on LMP+D+E and transactive grid initiatives, and support efforts for alternative utility revenue for utilities of the future.

Taking these outcomes together, Smarter Grid Solutions' *ANM Integration* project successfully demonstrated that DER can be integrated to the grid in a safe, reliable, and cost effective manner to increase grid hosting capacity well beyond 50% of peak load.

This report further details the ANM system components, the use cases and testing scenarios, and the outcomes and industry relevance assessments. The report concludes with key project takeaways and a discussion of the opportunities for field deployments of ANM-enabled flexible DER interconnection in the US market.

3. INTRODUCTION

Smarter Grid Solutions' NREL INTEGRATE project – *ANM Integration* – provided the opportunity to test Active Network Management (ANM) technology approaches for increasing grid hosting capacity for North American grid scenarios. ANM arose out of the United Kingdom (UK) in the mid 2000's to address distributed and grid edge control needs for moving from passive to active grid operations. ANM enables greater value from existing grid assets by combining the need for cost effective DER grid integration with second-to-second time-bounded control for grid constraint scenarios in a safe and reliable manner that is extendable and scalable for future DER. Figure 2 below conceptually presents some ANM grid-edge control scenarios, such as bi-directional power flow management, active voltage control, demand response, circuit reconfigurations, and other real-time grid operations as described by Ofgem – the electricity regulator for Great Britain. ANM arose as a product category to fill second-to-second control needs in a distributed fashion[1] as compared to protection (local & <1s control) and SCADA (centralized & minute+ control) – as seen in Figure 2. ANM schemes in the UK have been proven commercially – today managing over 270 MW of flexible interconnected generation that otherwise had been cost prohibitive under traditional firm interconnection schemes. In the course of this INTEGRATE project, the joint utilities in the UK published an ANM best practices guide[2] to reflect how ANM schemes and procurement processes have initiated an initial technology standardization phase in their development. The NREL INTEGRATE program is the first US demonstration of these ANM technologies.

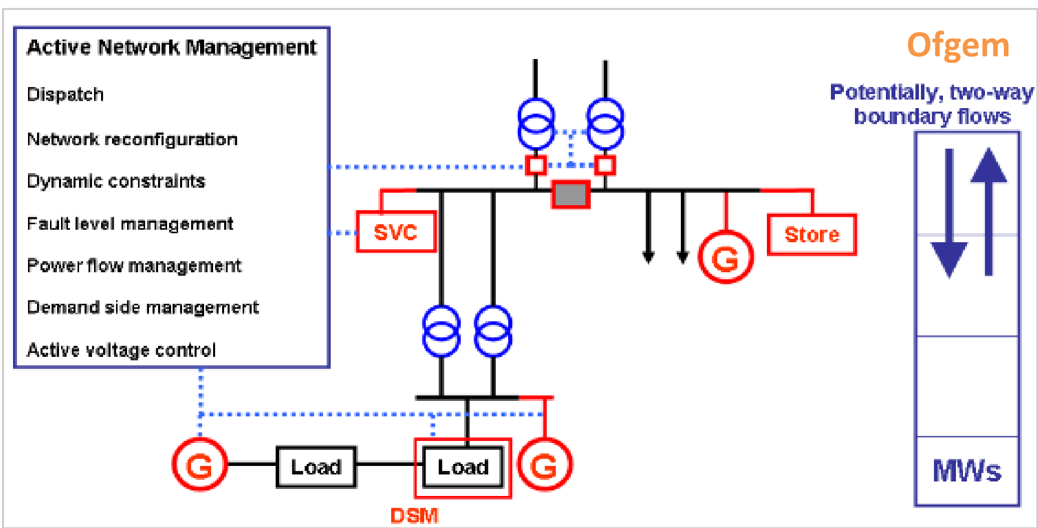

Figure 1: Conceptual Representation of Active Network Management (ANM)

[1] Note that the most similar product term to ANM in the U.S. is Distributed Energy Resource Management Systems (DERMS). It is beyond the scope of this report to detail the functional characteristics of ANM vs DERMS, especially given how DERMS functionality has not been standardized similar to how ANM schemes and procurement processes in the UK have begun to standardize. See for instance footnote 2 for a UK ANM best practices guide. At the same time, Advanced Distribution Management Systems (ADMS) have begun to standardize in the US, and ADMS characteristics represent distinct functionality differences compared to ANM – see Section 8.8 for a brief comparison.

[2] http://www.energynetworks.org/assets/files/news/publications/1500205_ENA_ANM_report_AW_online.pdf

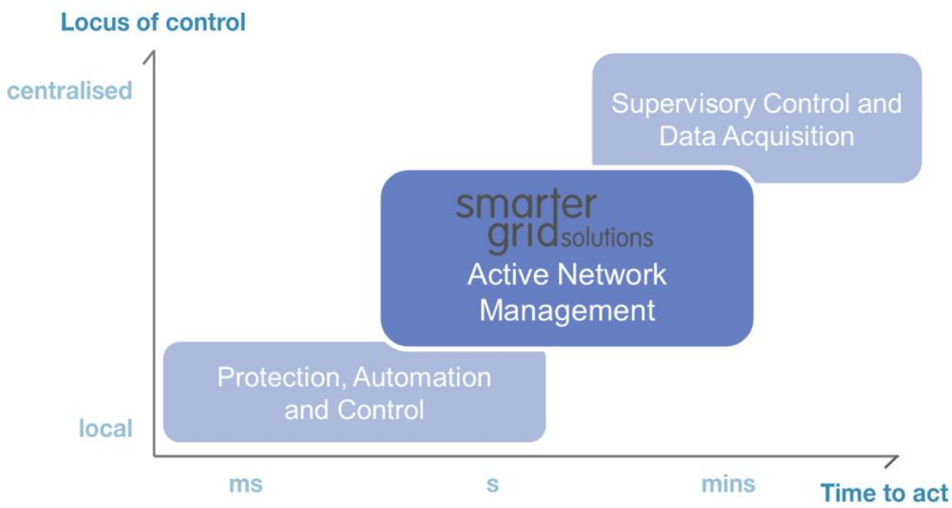

Figure 2: Locus of Control of ANM Relative to other Distribution Engineering Control Concepts

Real-time ANM control enables increased hosting capacity by providing real-time visibility of critical constraint locations and can adjust DER output in a predictable, repeatable, and time-bounded fashion in response to the real-time dynamic grid hosting capacity. These characteristics then permit operation of the grid beyond the "fit and forget" approach of static system planning and DER integration - giving utilities a control system that meets DER customer requirements for faster and cheaper interconnection compared to traditional grid reinforcements. In so doing, an ANM-enabled distribution feeder transitions from passive to active control and increased grid hosting capacity – resulting for instance in doubling interconnected solar and wind for the Smart Distribution use case.

ANM is at the heart of this control concept, and has been deployed in numerous projects in the UK that have proven the benefits of this way of thinking, with deployments now taking place in New York and California. The architecture of the ANM platform consists of a part-centralized application layer, integrated with grid edge controllers at each DER through a communication gateway. This ANM architecture allows the smart DER devices to behave as a coordinated and managed resource that is scalable and extendable into a larger smart distribution control system.

3.1. Project Background

The objective of Smarter Grid Solutions' NREL INTEGRATE project is to demonstrate an integrated energy system incorporating Active Network Management (ANM) technology to deliver increased hosting capacity for Distributed Energy Resource (DER) interconnection. The demonstration leverages the power hardware in the loop grid simulation capabilities available at the National Renewable Energy Laboratory (NREL) using the REDB test network and the real-time grid simulator.

This document is the final report for the project. It describes the overall project outcomes and suggested next steps, as well as summarizing the three *ANM Integration* use cases. All testing and simulation took place at the NREL Energy Systems Integration Facility (ESIF), with the ANM system incorporated into a power hardware in the loop (PHIL) scheme with real-time grid simulation. The on-site demonstration included workshops to engage the project industry advisory board members for assessing the technology and evaluating near-term deployment opportunities.

The ANM Integration project included three phases corresponding to the three use cases:

- **The Smart Home use case** was designed to demonstrate how ANM's automation and control can be used to enable smart domestic energy devices for real-time grid services. The results of this use case were incorporated into the Smart Distribution use case by combining Smart Homes into an aggregator services deployment model. The aggregator model reflects short-term ANM deployment opportunities to further unlock distribution grid assets without requiring storage or other expensive behind the meter resources, while also recognizing that direct ANM integration with domestic devices requires further ANM component cost reductions.
- **The Smart Campus use case** was designed to test and demonstrate very high penetrations of solar PV at a single point of common coupling (PCC). Without ANM this single PCC would have triggered cost prohibitive reconductoring. Testing demonstrated that a PV-only scenario controlled by ANM is capable of cost effectively integrating the solar PV and managing voltage and thermal constraints without the need for storage or other DER devices. Validating this PV-only scenario is critical to ensure grid operations remain safe and reliable through ANM control schemes, but likewise essential to reflect curtailment risks to DER using ANM enabled flexible interconnection. A second test included aggregated EV charging, a battery ESS, and controllable load alongside the solar PV in order to demonstrate the real-time coordination and optimization of these resources to minimize/negate PV curtailment during the grid constraint periods. The results of this use case were incorporated in the Smart Distribution use case to showcase how these DERs can provide grid services, and demonstrate how they can be included in future ANM schemes with even higher solar and wind deployments.
- **The Smart Distribution use case** was designed to demonstrate how ANM's real-time and autonomous distributed control can be used to manage multiple DERs and multiple constraints associated with very high DER penetrations on a distribution grid. As a result of constraint mitigation, it was shown that dynamic DER control can allow for higher penetrations of PV, wind and other smart DER devices than would otherwise be permitted using traditional static grid planning and operations processes. For the purposes of the overall project objective of demonstrating increased grid hosting capacity for clean energy, the Smart Distribution use case was designed to demonstrate how ANM's real-time monitoring, automation and control can be used to manage multiple DER and multiple constraints associated with high penetrations of DER on a distribution grid. As a result of constraint mitigation, it is shown that dynamic DER control can allow for higher penetrations of PV, wind and other smart DER devices than would otherwise be permitted using traditional static grid planning and operations processes.

3.2. Industry Context

When interconnecting DERs on a distribution grid, it is the utility's responsibility to ensure that the grid operates in a safe and reliable way, maintaining power flows and voltages within equipment ratings and in compliance with regulations. Connection of DER to the grid may result in power flow or voltage limits being breached – a situation that happens today when a DER developer seeks to interconnect large DG (e.g. 0.5MW+) too far from a substation or to long/rural feeders. Commonly, when DER interconnection is planned, the distribution utility is entitled to pass on the cost of any necessary infrastructure upgrades to the developer. ANM flexible interconnection can be used as an alternative to traditional infrastructure upgrades as it manages power flows and voltages on the grid in real-time to ensure that they are maintained within safe operating limits. For constrained grid scenarios, ANM has the advantage of providing quicker and cheaper grid connections to DER customers while also increasing grid hosting capacity.

Currently both planning and operation of the grid have an impact on the interconnection process and the capacity made available to DERs. In certain states capacity planning screens use conservative methodologies based on historical precedents that in many cases are no longer appropriate for many inverter and non-inverter connected DERs. Static planning limits are overly conservative for a number of reasons, including their failure to take into account the additional capacity that exists because of N-1/N-2 contingency planning redundancy, the variable nature of renewable generation export, and the variability of demand load beyond recorded maximums and minimums. In reality it is the average of real-time capacity (i.e. power exported/imported) over a period, which is the useful capacity to DERs. Static planning limits based on infrequent and worst case engineering scenarios poorly utilize existing utility assets and do not meet the requirements of DER developers under high penetration scenarios.

For a DER developer who is primarily concerned with total project economics, a lower cost ANM-enabled flexible interconnection that results in generation curtailment risk may be more attractive than a firm interconnection with high associated grid upgrade costs. At the time of an interconnection request, allowing the DER developer to choose the most economical of firm versus flexible interconnection shifts grid hosting capacity from utility defined static limits for passive grid operations to market defined active grid operations. Under the flexible interconnection arrangement, ANM offers the functionality and characteristics required to manage constrained grid DER interconnections without impacting demand consumers or utility reliability targets.

3.3. Conceptualizing Grid Hosting Capacity

Distribution utilities assess a generation project's interconnection application by applying a series of defined screens based upon the proposed capacity. These screens are derived from various sources, some of which include the Federal Energy Regulatory Commission's (FERC) Small Generator Interconnection Procedures (SGIP), or a state's particular Standardized Interconnection Requirements (SIR). If a given screen's permissible capacity threshold is breached, traditional reinforcement measures are triggered in order to raise this capacity threshold. Typical screens include maximum generation and minimum load, equipment thermal ratings, fault current and protection equipment ratings, step voltage changes, and so forth.

The cost of these reinforcements can vary widely from a few thousand dollars for simple reconductoring to millions for entire substation rebuilds. The traditional hosting capacity of a given circuit can be viewed as the maximum capacity permissible through a given set of static snapshot utility interconnection screens before reinforcement costs render the generation project uneconomical. This cost barrier is relative to the size of the generation project, making the hosting capacity a function of interconnection capacity. It should also be noted that this assumes the generation is connecting to what can be interpreted as a single point on the circuit. Connecting multiple generators distributed across a circuit could also affect the hosting capacity.

In terms of grid modernization for increasing grid hosting capacity, it is important to clarify capacity increase in terms of 'static' versus 'dynamic' hosting capacity. Grid modernization investments via traditional T&D reinforcement follow a static or passive approach by resolving grid constraints via grid equipment upgrades (cables, transformers, etc.) that do not require changes to grid operations. This can be compared to smart grid investments which use software and changes in behavior to dynamically resolve grid constraints via active DER control approaches. In many scenarios the active approach is more cost effective compared to the very expensive T&D hardware reinforcements.

Static hosting capacity is a function of: (1) location, (2) existing feeder equipment sizing/arrangement/etc., and is (3) time-varying due to current and future real-time load demand. For defining hosting capacity, traditionally the industry has used the static capacity approach, for instance:

"The concept of hosting capacity is used to study how much PV can be placed on a feeder before negative effects on normal distribution system operation and power quality occur. Hosting capacity is typically expressed as the megawatt value of PV spread across any locations on the feeder that causes the first violation of operating constraints." NREL/Sandia/MIT/SunShot (2016). "On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System", pg 20.

"Hosting capacity is defined as the amount of DER that can be accommodated without adversely impacting power quality or reliability under existing control configurations and without requiring infrastructure upgrades." EPRI (2016). "Defining a Roadmap for Successful Implementation of a Hosting Capacity Method for New York State", pg 2.

The essential characteristics of these definitions is that they presume no operational changes to the grid and from a DER grid integration perspective the utility does not monitor or control these devices. Hence this approach aligns with a 'static' snapshot of grid capacity: worst case planning and no operational changes given the utility applies a 'fit & forget' approach to interconnect DER.

Based upon a proposed DER's location on the circuit, generation would be traditionally limited by applying the appropriate FERC screens, the most typical of which include:

- Limiting generation to 15% of peak load to prevent possible islanding conditions;
- Limiting a generator's contribution to the circuit's maximum fault current at the point on the high-voltage (primary) level nearest the point of common coupling to less than 10%;
- Limiting generation to 90% of short circuit interrupting capability of sub breakers, fuse cutouts, line reclosers, as well as any other protective equipment;
- Voltage at any point on the circuit must remain within the requirements of ANSI C84.1 Range A (126-114V on a 120 V basis);
- Limiting generation so that it does not cause utility equipment to exceed 20% of its rating[3].
- Ensuring that voltage flicker does not breach the IEEE guidelines as a result of generation interconnection.

Applying these screens and extracting capacity limits provides the static benchmark to which the increased dynamic hosting capacity can be measured. Given that these screens reflect static and infrequent worst case scenario conditions, ANM schemes can connect additional large distributed generation to manage against dynamic, or real-time, constraints that together reflect a higher grid hosting capacity for clean energy.

[3] SGS has advised utilities and regulators that this is very conservative, and in one instance the utility changed its standards to allow 75% loading (without ANM). ANM enabled circuits have in the UK, and can for US utilities allow loading much closer to the design limit and even exceed it at times due to seasonal variations (e.g. summer thermal limits lower than winter)

For the INTEGRATE project objective of evaluating the increase in grid hosting capacity, the Smart Distribution test circuit traditional hosting capacity was estimated by applying the typical FERC screens and determining the related maximum generation capacity (MW). Relative to this static hosting capacity definition, these generators have a 'firm' interconnection and their integration with the grid does not require grid operations changes for these variable renewable energy resources. Generators who interconnect beyond these static grid limits require in many instances expensive T&D reinforcements that are cost prohibitive, thus ANM smart grid techniques allow these generators to connect via flexible interconnection and management of the grid constraints in real-time. The particular economics of a given project depend upon a wide number of factors that are beyond the scope of this project. It is moreover important to state that ANM schemes for flexible interconnection are not incompatible with firm interconnections: the critical relationship is that when submitting an interconnection request, DER developers can choose the most cost effective solution for the given site. ANM-enabled dynamic hosting capacity corresponds to the flexible interconnection generation capacity (MW) beyond the static limits.

3.3.1. Hosting Capacity of an ANM-Enabled Circuit

Adding real-time control capability on the circuit through Active Network Management (ANM) constraint management can significantly increase grid hosting capacity. ANM manages the DER and grid constraints in real-time, thus enabling the dynamic hosting capacity.

The dynamic hosting capacity is a function of: (A) all the same static hosting capacity variables 1-3, plus (B) smart grid technologies and DER market solutions that are mutually acceptable to the DER developer and the Utility in terms of both financial impact and grid safety & reliability. ANM systems have proven to be effective grid edge smart grid investments to unlock grid assets for supporting the real-time dynamic grid hosting capacity for DER. The dynamic hosting capacity can be defined as:

"The active management of DER and grid equipment to resolve thermal and voltage constraints that arise due to the interconnection of those DER. The DER interconnect to the grid at a level where they contribute to thermal and voltage violations. Without traditional reinforcement, managing these constraints requires active real-time and autonomous smart grid management techniques. These DER are flexibly interconnected to the grid via distributed smart grid controls to resolve the thermal and voltage violations in real-time, and therefore subject to the financial impacts of curtailment risk. The dynamic hosting capacity therefore implies operational integration of the DER through Active Network Management distributed control technologies – a smart grid investment to unlock grid assets for additional DER hosting capacity." [4]

DER that are managed via ANM are said to be 'flexibly' interconnected to the grid: the DER are controlled in order to resolve the grid constraints and can be regulated down or disconnected from the grid if necessary – hence the financial risk of curtailment and generator tripping. In assessing their

[4] It is important to note that recent smart inverter efforts align with another hosting capacity definition, referred to as the quasi-dynamic hosting capacity. Autonomous smart inverter functionality to address voltage rise and other power quality factors at the PCC does increase solar and other inverter-based site hosting capacity. Distributed control systems like ANM further increase dynamic hosting capacity through field communication to coordinate and manage multiple sites with each other and likewise grid equipment. In so doing, ANM allows additional DER interconnection by enabling operation closer to grid equipment margins with higher action thresholds. Quasi-dynamic hosting capacity is therefore enabled via inverter power electronics functionality, and additional dynamic hosting capacity is enabled through integrated distributed controls and communications to managed multiple DER and multiple constraints in real-time.

interconnection options, ANM therefore allows DER developers a choice of 'firm' versus 'flexible' interconnection – with DER developers choosing the most economic option for their given site. When Utilities allow DER developers this firm versus flexible interconnection choice – this causes hosting capacity to shift from utility defined (i.e. static limits that do not consider operational integration of DER) to market defined (i.e. DER developers deciding on the most economic option when ANM enabled DER are operationally integrated for grid services to resolve constraints).

Both static and dynamic limits apply to any circuit, and are relative for a given location on a circuit and vary over time due to changing generation and load profiles. A visual representation of this concept as it applies generally to any given circuit is presented in Figure 3 and Figure 4 below.

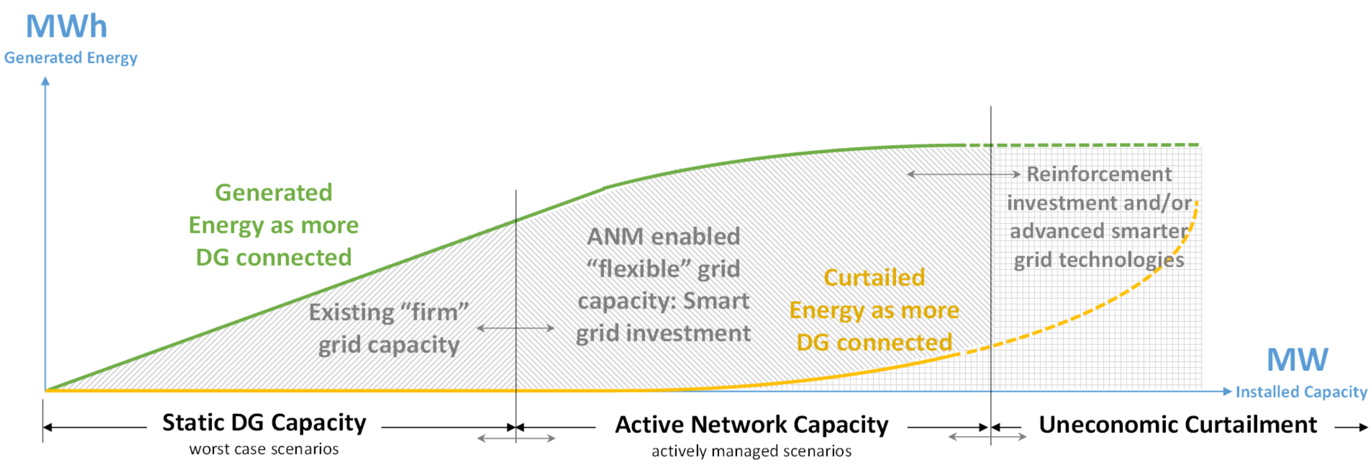

Figure 3: Real-time Active Network Hosting Capacity

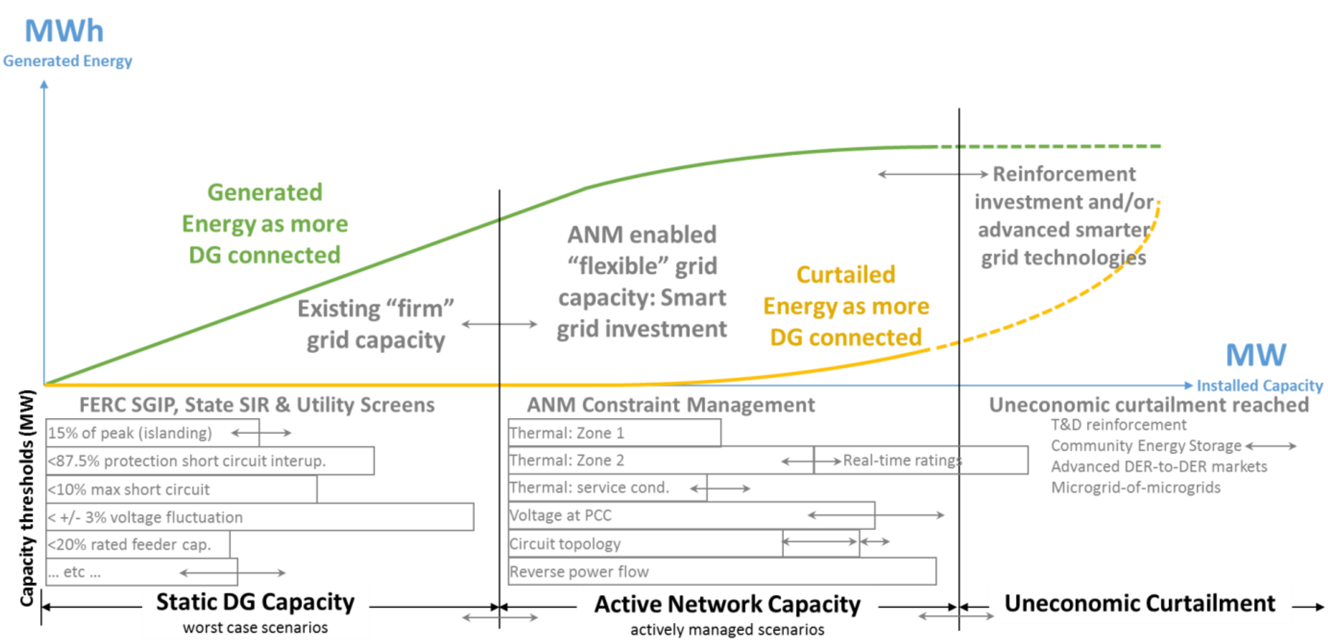

Figure 4: Static and Dynamic Grid Constraints

3.3.2. Conditions to Enable Dynamic Hosting Capacity

ANM constraint management is able to increase grid hosting capacity by monitoring the constraint(s) associated with the breached utility limits and controlling the DER so that the utility's operating limits are respected at all times. Three conditions must be satisfied for deploying ANM and enabling the dynamic grid hosting capacity:

- The cost of implementing a new or updating an existing ANM scheme must be less than the traditional upgrades being triggered by the interconnection screens;
- The cost of implementing or being adopted within an existing ANM scheme must be economical to the generation developer;
- The amount of energy lost due to generator curtailment in response to ANM constraint management must not render the generation project uneconomical.

In relation to the third bullet, a curtailment analysis is applied that provides an estimation of the amount of curtailment a given amount of generation capacity is likely to incur over the course of a year. Applying a full annual analysis allows the diurnal effects to be captured as well as the seasonal effects.

Capturing the effects of all seasons, DG developers and financiers of DG projects can then use the curtailment analysis to predict revenue streams and assess whether the cost items associated with the first two bullets are indeed cost effective for a given project. For purposes of this project, it was assumed that any curtailment analysis identifying curtailment exceeding 10%[5] of the uncontrolled DG production will be deemed unacceptable to DG developers. When incorporating energy storage and other smart DERs that are actively managed concurrently,[5] this curtailment is significantly reduced.

For each constraint that has multiple DER resources associated with it, a priority stack is established based upon principles of access that determine the order in which the resources are accessed in order to relieve a constraint breach. For example, to avoid curtailment an available ESS might be charged first, or to adhere to the respective generators' right to export as per a 'last in first out' (LIFO) approach – referred to as the Principles of Access (POA) framework[6].

A POA priority stack is also established for all of the constraints themselves, which determines the order in which the constraints are solved. This is representative of how the ANM system operates in the field. Factors that influence the order of constraints include adhering to generator power export rights, as per the element priority stack, as well as minimizing curtailment by first targeting those constraints that have the greatest benefit for the circuit as a whole.

[5] The 10% maximum annual curtailment is based on Smarter Grid Solutions' U.K. experience advising utilities and DG developers that have successfully interconnected up to this level. Financial viability will vary for every project, thus curtailment risk factors must be mutually evaluated by the DG developer and utility. For the Phase 2 Smart Campus demonstration, SGS demonstrated that the 10% curtailment is significantly reduced when incorporating energy storage. Additional context can be found in the Smart Campus reports.

[6] See POA report from UKPN's FPP project: http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Plug-and-Play-(FPP)/Project-Documents/FPP_Principles_of_Access_report_final.pdf, and also Kane, L. and Ault, G. (2014). "A review and analysis of renewable energy curtailment schemes and Principles of Access: Transitioning towards business as usual." Energy Policy 72, p67–77.

The principles of access approach within an ANM scheme can also have a significant effect on curtailment results. In general, any commercial agreement should limit the factors that have the potential to affect curtailment results in the project's lifetime. This is in order to provide the required security of investment to all interested parties.

3.4. Document Structure and Smart Distribution Use Case

The remainder of this document is structured as follows:

- **Section 4 ANM Architecture**: ANM technology architecture and relationship to utility operational technologies
- **Section 5 ANM System Components and Applications**: describes the control functionality to increase grid hosting capacity and the roles of each component.
- **Section 6 Use Cases**: the testing and analysis during each of the smart home, smart campus, and smart distribution use cases. Includes outcomes from stakeholder workshops during the smart distribution on-site demonstration.
- **Section 7 Summary of Overall Project Outcomes**: main project outcomes, impact and suggestions for next steps in terms of testing and deployment
- **Section 8 Appendix**: background information on curtailment assessments, description of managed DER interconnections, and the distinction between ANM and advanced distribution management systems (DMS)

3.5. References

This document references the following external sources of information:

[1] 200285 01A NREL INTEGRATE RCS-4-42326;
[2] 200285 05A NREL INTEGRATE Overall Project Test Plan;
[3] 200285 06A Overall Project Requirements Specification;
[4] 200285 07A Overall Project Interoperability Plan;
[5] 200285 24B Smart Home Final Report;
[6] 200285 33A Smart Campus Final Report;
[7] 200285 34A Smart Distribution Requirements Specification;
[8] 200285 36A Smart Distribution ANM Modeling and Simulation Report;
[9] 200285 37A Cyber Security Report;
[10] 200285 39A Smart Distribution Acceptance Test Specification & Final Test Plan;
[11] 200285 43B Smart Distribution Final Report.

3.6. Terminology

Table 1 describes the terminology used within this document.

Table 1: Terminology

Term	Definition
ANM	Active Network Management
DER	Distributed Energy Resource
DG	Distributed Generator (Note: Unless stated otherwise, use of the word 'generator' refers to a generator subject to ANM control)
ESS	Energy Storage System
ESIF	Energy Systems Integration Facility
EV	Electric Vehicle
MP	Measurement Point
PLC	Programmable Logic Controller
PCC	Point of Common Coupling
PHIL	Power Hardware in The Loop
POA	Principles Of Access
p.u.	Per Unit (i.e. normalized per unit voltage for a circuit)
PV	Photovoltaic
REDB	Research Electrical Distribution Bus
RTU	Remote Terminal Unit
SGS	Smarter Grid Solutions
SP	Set Point
NREL	National Renewable Energy Laboratory

4. ANM ARCHITECTURE

ANM 100 is the SGS end-to-end control system software product designed to provide Distribution Utilities with a robust and reliable approach to a number of Distribution Control Use Cases for the integration of DERs on increasingly congested MV and HV networks. SGS technology exhibits the following characteristics:

- **Real-time**: Modern grids need to handle fast-changing volumes of data. That is why our control platform uses critical systems industrial controls technology.
- **Autonomous**: The need to respond rapidly to large volumes of data make operator-in-the-loop control impractical.
- **Deterministic**: Control decisions must be predictable, reliable, safe, secure and repeatable.

We use this technology to create our Active Network Management (ANM) products that:

- **Monitor**: critical grid locations, communications status and the operating status of Distributed Energy Resources (DERs) are monitored in real-time.
- **Action**: When measurements from critical locations exceed thresholds, communications fail or DERs breach defined schedules, ANM operate autonomously in a pre-determined, repeatable and time-bounded manner to issue setpoints and signals to DERs.
- **Deliver**: ANM guarantees an end-to-end control response from DERs and other grid devices to balance electricity flows, maximize power system hosting capacity and deliver grid reliability improvements.

The ANM system comprises a real-time control and dispatch platform with constraint management and DER coordination applications. ANM 100 uses SGS' real-time control and dispatch platform in a dual-redundant configuration to provide hot standby failover in an instance of device failure.

For the Smart Distribution use case, the ANM 100 is deployed across 4 HP DL380 servers split into dual redundant sgs core and sgs comms hub.

Illustrated in Figure 5, the ANM Platform consists of centralized and decentralized components. This enables the autonomous coordination of highly variable resources across a geographic area, while accommodating the variability of communications performance.

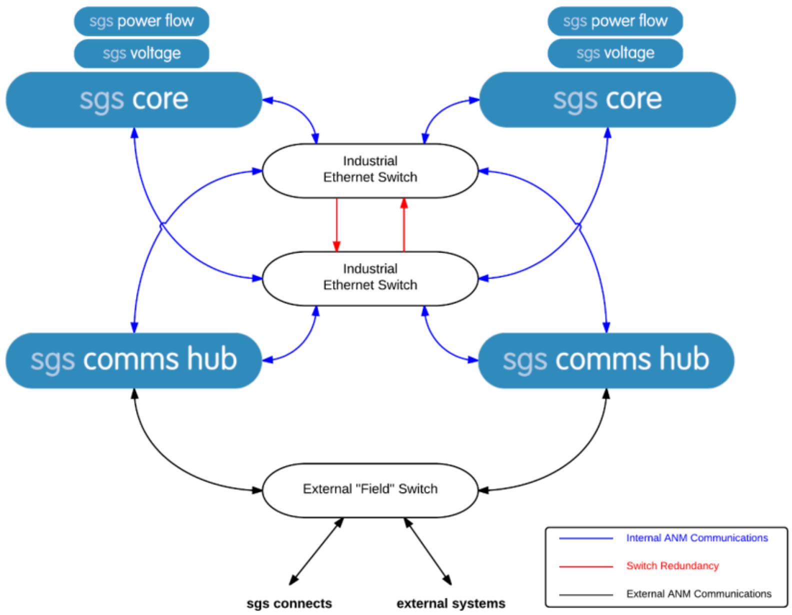

Figure 5: ANM Servers and Interconnections

The central components of the ANM platform are made up of a communications gateway (sgs comms hub) connected to an application host (sgs core) via a real time data cluster. The data cluster is based on the open standard Data Distribution Standard (DDS) for real-time systems. Physically, these can be located to meet the needs of the individual grid operator, e.g., at electricity substation level, or at a regional level, such as a control room or a data center.

The decentralized component of the ANM platform (sgs connect) is located at each DER under active management, and performs a number of local control and fail-to-safe functions. As a modular solution, the ANM platform can be scaled to the needs of individual customers and projects, while remaining tightly aligned with the smart grid applications.

As a distributed control architecture, ANM components interface in an end-to-end fashion reflecting the emerging systems of systems approach to grid modernization. Figure 6 conceptualizes this approach for the latest ANM Strata Distributed Energy Resource Management Systems (DERMS) architecture.

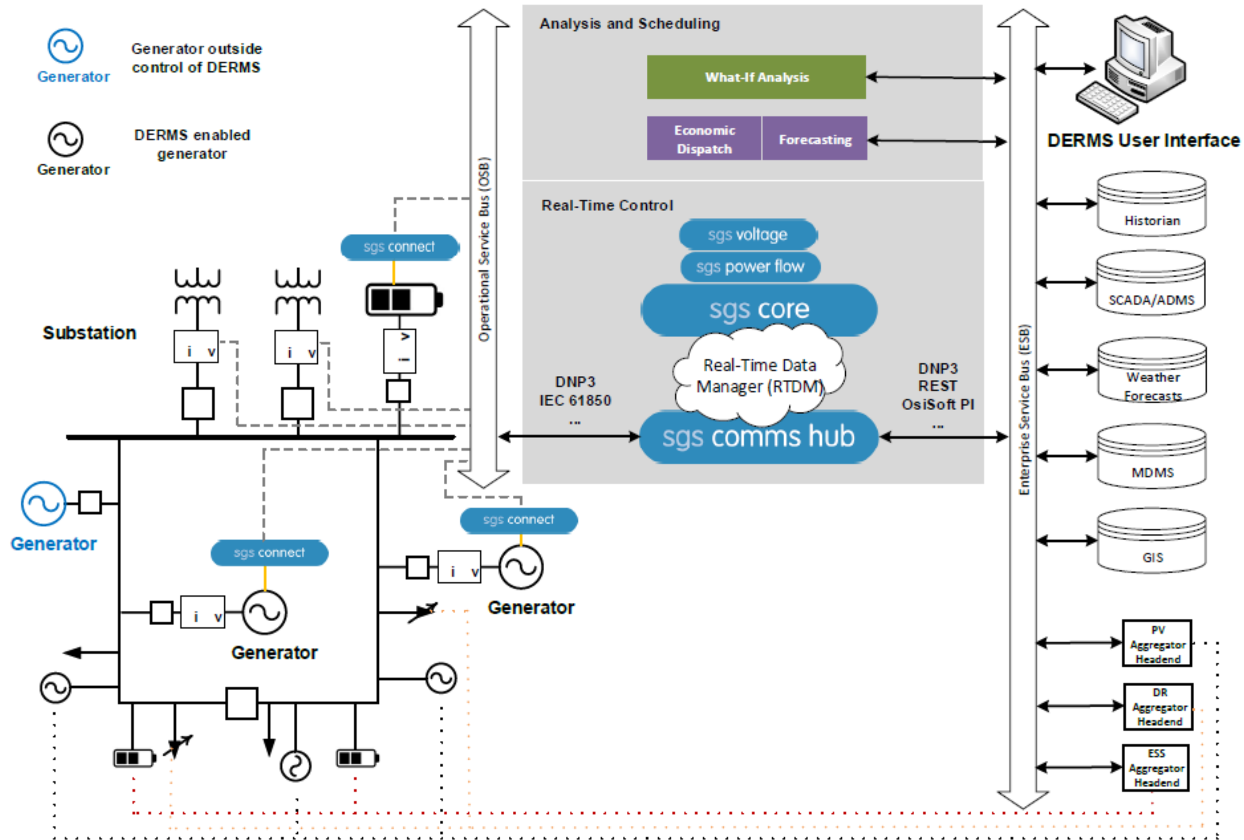

Figure 6: Systems Integration of ANM Strata to Field Devices and Utility Back-office Operational and Informational Technologies

5. ANM SYSTEM COMPONENTS AND APPLICATIONS

ANM provides real-time deterministic control at constraint locations in the electricity network. Figure 7 shows the high-level functionality overview of the ANM Application.

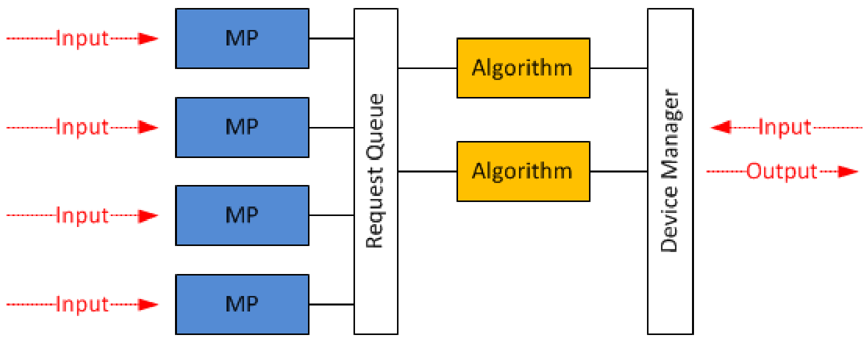

Figure 7: ANM Application, High-level Functionality Overview

Field inputs are monitored by measurement point state machines (in blue), which trigger a request for regulating actions based on breaches of thresholds. Additionally, measurement points issue releasing actions to allow devices to move back towards their preferred setpoints when the measured value returns to a safe operating region. Each of the control actions requested by measurement points are placed into a request queue, making them available to algorithms.

Multiple control algorithms can be hosted, each of which can choose to monitor control requests from all measurement points, or from a subset. For example, one algorithm may respond only to voltage control requests while another may respond only to real power control requests. Algorithm implementations consist of the following components:

- a calculation engine that, given a request from a measurement point, produces a set of requests to be issued to devices; and
- an arbiter that, given multiple requests for the same device, picks the highest priority request to be issued to the device.

The Device Manager provides algorithms with the ability to discover the devices available for control and to issue control requests to them.

5.1. Measurement Points

The measurement points (MPs) are responsible for monitoring current, voltage and power measurements and issuing control requests to either resolve a breach of a defined threshold or allow devices to release back to their preferred setpoints after resolving a breach.

5.1.1. Hierarchical State Machine

The measurement points are implemented as a hierarchy of multiple state machines. As Figure 8 illustrates, each threshold configured within the measurement point is represented by its own state machine. These state machines independently monitor an individual threshold and issue control requests (i.e. a target reduction/increase in amps, volts or power; or trip request) when there is a requirement to regulate the measured value.

A separate Threshold Set state machine receives the requests from all the Thresholds configured for the MP and is responsible for two functions:

- selecting the control request from the highest priority threshold of the MP; and
- passing it onto the MP state machine and performing the release process.

The Threshold Set state machine passes its control requests (whether from a release operation or relayed from a Threshold state machine) on to the MP state machine, which is responsible for three functions:

- relaying control actions from the Threshold Set when the MP is online;
- issuing failsafe control actions when the MP is offline; and
- performing the process of re-configuring the MP.

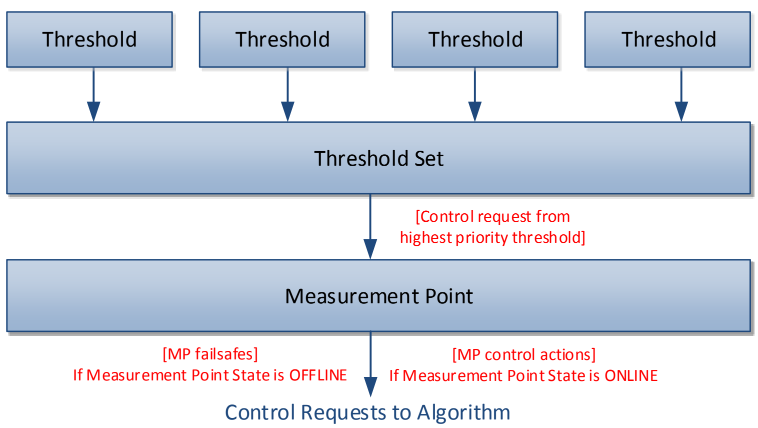

Figure 8: MP Hierarchical State Machines

5.2. SGS Core

sgs core hosts the real-time ANM applications. It uses software to represent the various critical constraint locations and controlled devices within the scope of the ANM system, using them to identify control actions needed to maintain the grid within safe operating limits.

For the demonstration activities at NREL, sgs core is configured to run either the sgs power flow application to control grid power flow for the reverse power flow demonstration, or the sgs voltage application to control the voltage for the voltage rise demonstration.

5.2.1.SGS Power Flow

The sgs power flow application monitors thermal constraint locations on the circuit and controls the power produced by multiple generators in order to maintain power flows within static, seasonal or dynamic thermal limits.

The sgs power flow software application is deployed on the sgs core platform and uses sgs comms hub to:

- Monitor specific field measurements including current or power flow at critical grid constraint locations;
- Monitor controlled device parameters (e.g. how much power is being exported by a generator);
- Monitor status indications (e.g. circuit breaker status); and
- Deliver control instructions to controlled devices.

To allow control of power flow at constraint locations sgs power flow uses a series of escalating control actions to ensure that circuit power flows remain within safe limits. These control actions are triggered by constraint location power flows breaching limits known as thresholds. A typical sgs power flow deployment has four main and two secondary threshold sets for each constraint location as shown in Figure 9.

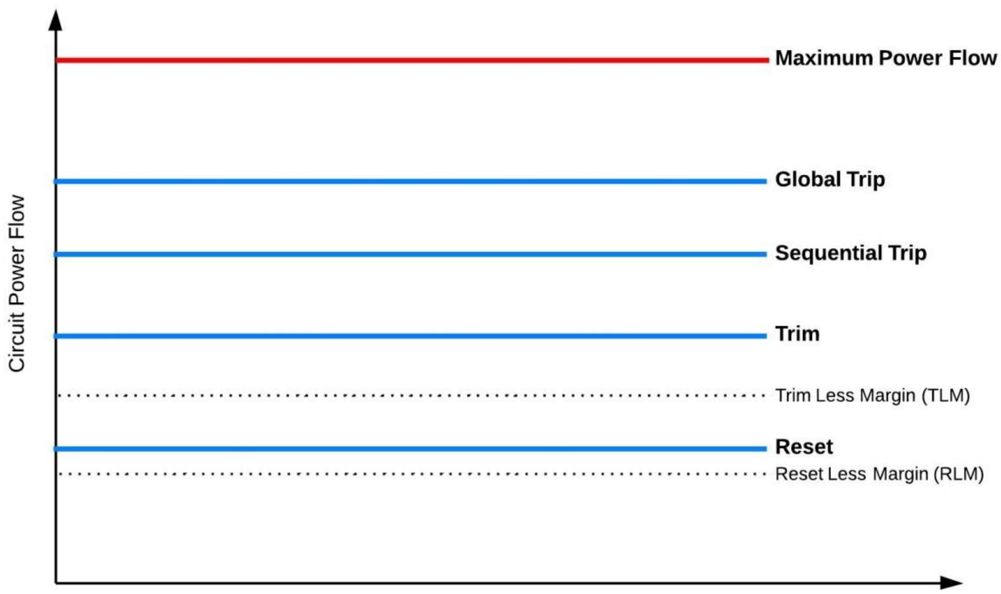

Figure 9: sgs power flow Thresholds

The threshold levels are set such that the maximum power flow of the circuit concerned is not breached.

The main thresholds are as follows:

Reset This is the safe value the ANM system will attempt to bring the current to following a breach of higher thresholds.

Trim If this threshold is breached the ANM system issues curtailment to associated DERs in order to reduce the power flow at the constraint location to below the Reset threshold.

Sequential Trip If this threshold is breached the ANM system trips associated generators in turn until the current has fallen below the Sequential Trip threshold, which initiates the normal actions for a breach of the Trim threshold.

Global Trip If this threshold is breached the ANM trips all associated generators.

The secondary thresholds are as follows:

Reset Less Margin (RLM) This threshold is used by the ANM as the target for power flow on the circuit during a trim event. It is used to ensure that the curtailment is sufficient to ensure the power flow at the constraint location falls below the Reset threshold.

Trim Less Margin (TLM) This threshold is used by the ANM as the target for power flow on the circuit during a release event. It is used to ensure that the release of a DER does not cause the power flow at the constraint location to breach the Trim threshold.

5.2.2.SGS Voltage

The sgs voltage application monitors voltage constraint locations on the circuit and controls the real and reactive power produced by multiple generators in order to maintain voltage within acceptable limits.

To allow control of voltage at constraint locations sgs voltage uses a series of escalating control actions to ensure that circuit voltage remains within limits. These control actions are triggered by constraint location voltage breaching thresholds. A typical sgs voltage deployment has two main and two secondary threshold sets for each constraint location as shown in Figure 10.

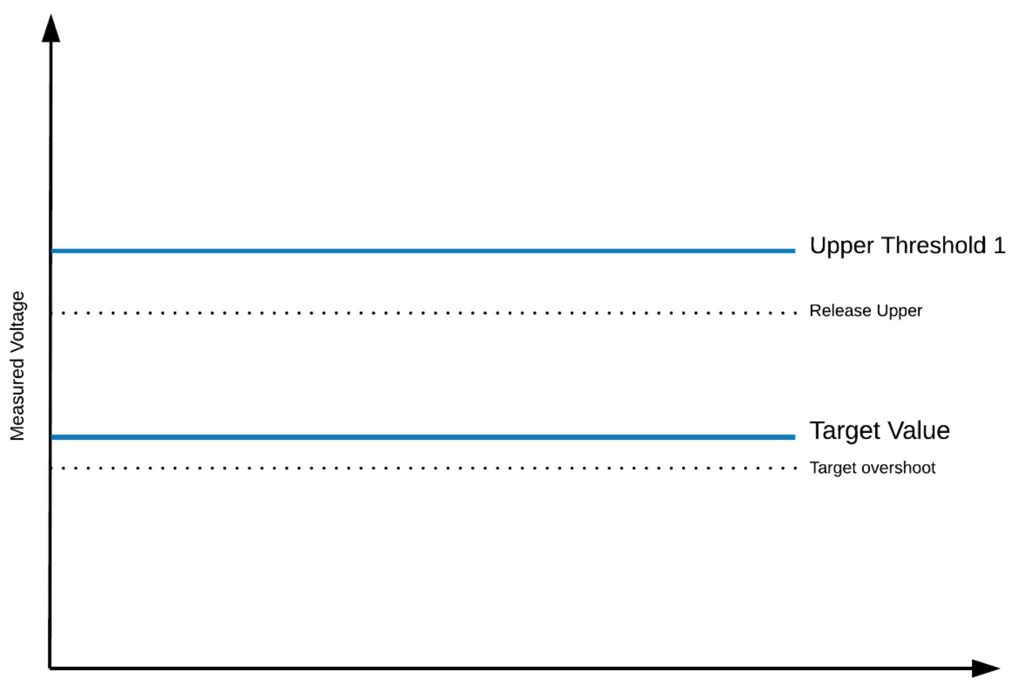

Figure 10: sgs voltage Thresholds

The threshold levels are set such that the maximum allowable voltage not be breached.

The main thresholds are as follows:

Target Value This is the safe value the ANM system will attempt to bring the voltage to following a breach of higher thresholds.

Upper Threshold 1 If this threshold is breached the ANM system issues updated real and/or reactive power set-points associated DERs in order to reduce the voltage at the constraint location to below the target value.

The secondary thresholds are as follows:

Target Overshoot This threshold is used by sgs voltage as the target for voltage during an Upper Threshold 1 breach event. It is used to ensure that the curtailment is sufficient to bring the voltage at the constraint location below the Target Value threshold.

Release Upper This threshold is used by the ANM as the target for a voltage release event. It is used to ensure that the release of a DER does not cause the power flow at the constraint location to breach the Upper Threshold 1.

5.2.3. Dynamic thresholds

The threshold values can be altered. Thermal constraints for instance can consider seasonal ratings or use a rating value supplied by a real-time thermal ratings system, also sometimes known as dynamic line rating (DLR). Sudden changes in threshold values could cause unnecessary escalation of control actions, such as a trip request. To avoid this, the threshold values are updated through a state-driven approach.

When re-configuring the settings of a measurement point, the *Safe Zone*, identified by its upper and lower limits in Figure 11 and Figure 12, is the zone that the measured value must be within before the configuration can be changed. Figure 13 illustrates this principle using a live measurement point; when the measured variable calls below the safe line this initiates a change to the new set of thresholds. When this threshold set changes, the *Safe* Zone can change, but does not need to. On the day of demonstration, the *Safe Zone* was not changed because it was pre-defined at a level that did not cause any threshold breaches even with the lower Trim threshold. The measurement point issues control requests in an attempt to drive the measured value to within the safe zone before applying a new configuration.

The new configuration is validated before being applied and can be rejected if it is incorrect. New configurations can only be applied when measured value is below a pre-defined safe threshold, ensuring that no threshold breach occurs during the transition. Figure 11 and Figure 12 illustrate this for threshold increase and decrease respectively.

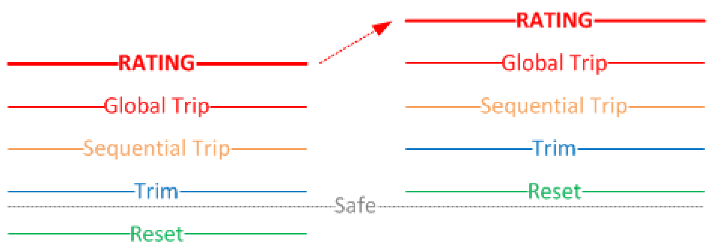

Figure 11: Dynamic Threshold Increase

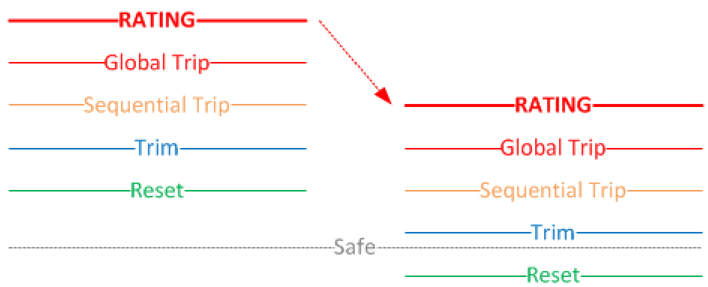

Figure 12: Dynamic Threshold Decrease

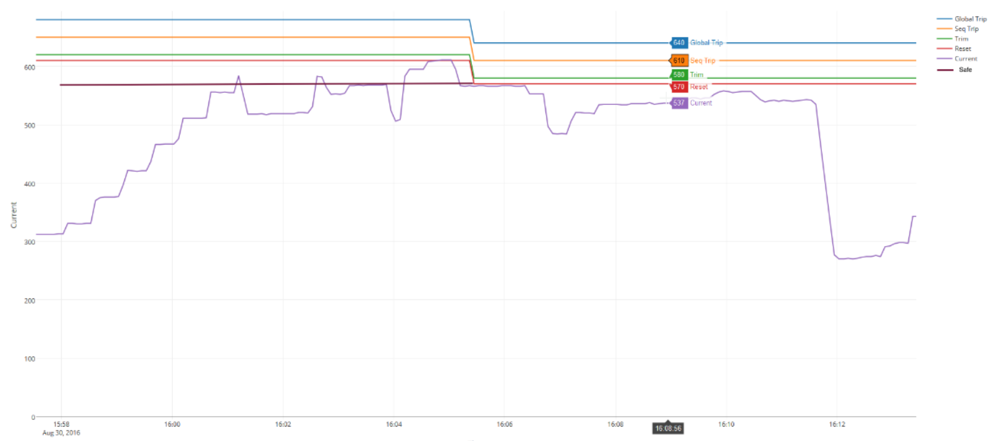

Figure 13: Threshold Decrease with Constant Safe Line Defined by the New Reset Threshold

5.3. SGS Comms Hub

sgs comms hub handles and processes all data for sgs core and interfaces with external grid management systems, field measurements and the controllable devices on the grid.

It interacts with different sources of data e.g. voltage and current transformers, device controllers and with other systems, to present all data to sgs core. This enables integration of sgs core and associated applications with the grid operator's existing grid management systems.

For the NREL Demonstrations, sgs comms hub is configured with the following data interfaces:

- DNP Master – For communication to sgs connect
- Modbus Master – For communication to Opal RT.

5.4. SGS Connect

sgs connect devices are installed at each ANM controlled DER site and are responsible for managing data communications to sgs comms hub, issuing set-points, collating measured DER data and implementing failsafe responses.

The sgs connect application executes on an IEC 61131 compatible PLC or RTU – for this use case at NREL a Brodersen RTU32 was used. sgs connect supports interfaces to the DER control system, a local HMI display and to sgs comms hub. Figure 14 presents a typical hardware configuration.

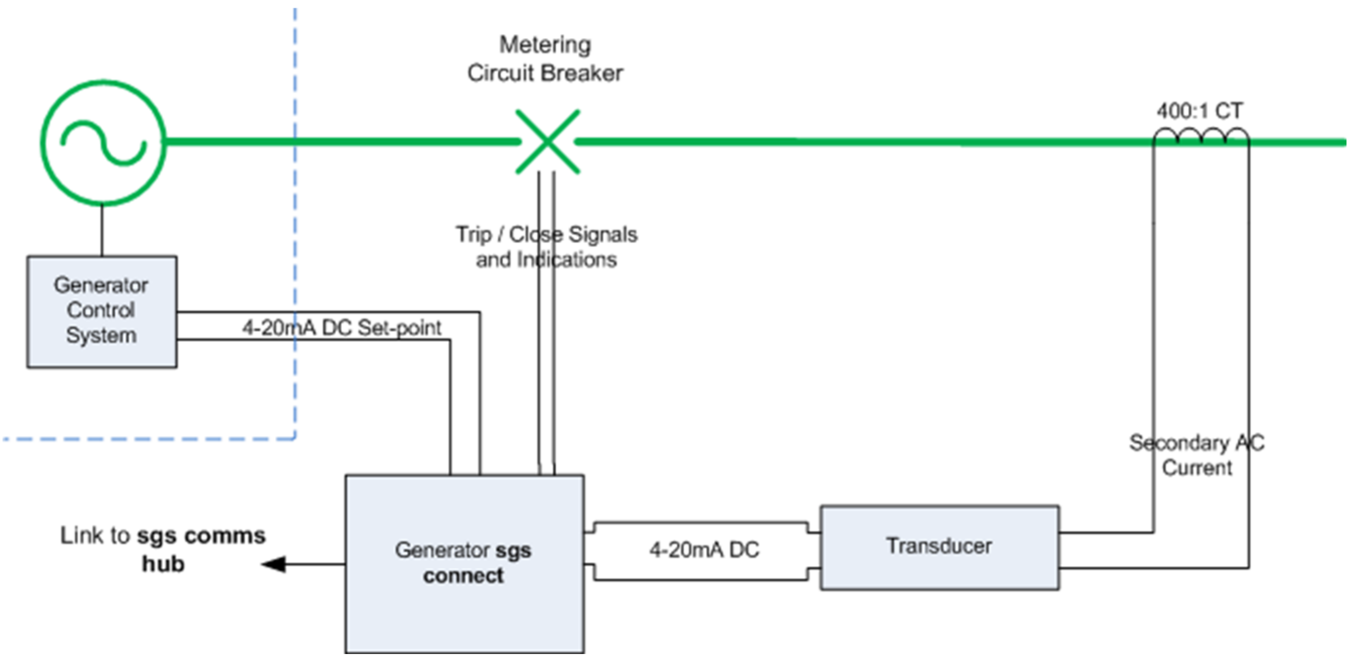

Figure 14: Example sgs connect Schematic Diagram

6. USE CASE RESULTS

6.1. Smart Home Use Case Outcomes

The following sub-sections present results and outcomes from the Smart Home use case. See [5] for the complete set of outcomes and final report.

Summary:

- The Smart Home use case is designed to demonstrate how ANM's real-time monitoring, automation and control can be used to manage constraints associated with high penetrations of DER at the domestic level. As a result of constraint mitigation, it is shown that DER control can allow for higher penetrations of PV interconnection or controllable load at the home level than would otherwise be permitted.
- Prevailing hardware costs associated with the DER device controller (sgs connect) currently restrict its application for domestic scale devices. The inclusion of smart homes within the Smart Distribution use case demonstrates how using aggregator services is a practical and cost effective way to incorporate domestic sized devices in ANM schemes. The Smart Home control system architecture is a simple standalone SGS CONNECT+ home controller that integrates these functions and all local DER assets and monitoring points, which are either local or can be provided as remote constraint points from the utility's system. This then allows the smart devices to behave as a resource that is more diverse than a single DER and could ultimately be brought into a larger hierarchical control system, as was considered in subsequent use cases.
- Under restricted solar PV export, the following figure shows for instance the net power flow results of the smart home with solar PV, EV charging, and a battery ESS. For this scenario the power export control threshold is 0kW – all positive (export) values are above the permitted operational grid limits. Although a situation like this is unlikely with a single home it is common in areas with high PV penetration where the collective impact of many homes causes issues, as is seen in some states already. Moreover, this example is directly applicable to larger industrial, commercial and campus facilities where a single facility can cause thermal and reverse power flow constraints. Additional context and information is located in the report.

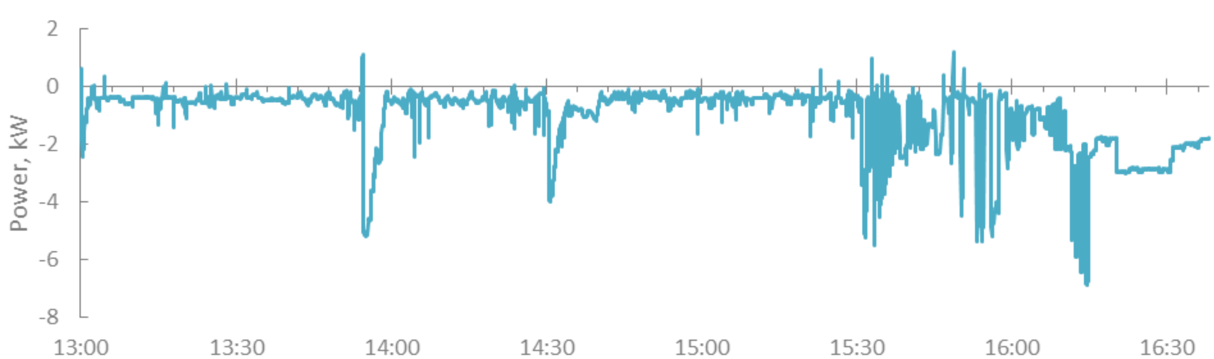

Figure 15: Net Power Flow at PCC for a Home Load with Controlled DER including EV, ESS and PV.

- The three simulation test runs demonstrated scenarios which, although not common for residential constraints on grids at present, are highly likely to occur in the future as DER penetration increases:
    - The constrained reverse power flow test demonstrated that it is possible to utilize controllable EV and ESS to allow PV generation to be connected to a grid that is unable to support additional generation export.
    - The voltage rise constraint simulation test demonstrated how controllable EV and ESS can be used to maximize PV generation on a grid which is subject to voltage rise constraints.
    - The import constraint simulation test demonstrated how DER's within the home can be utilized to provide demand response from a smart home.

6.1.1.Smart Home Principles of Access

The order by which curtailment is allocated to DERs is determined by the configurable Principles of Access (POA) priority stack. The priority stack employed for each test scenario is shown in Figure 16. The DER at the top of the priority stack are first to gain access to available network capacity. The DER at the bottom of the priority stack are last to gain access to available network capacity.

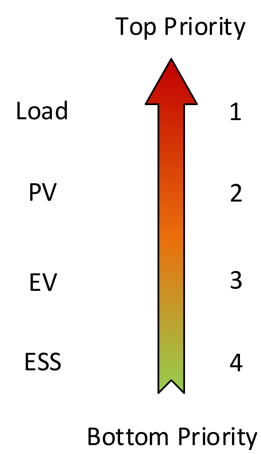

Figure 16: ANM Priority Stack of DERs for the Smart Home

The load is at the top of the priority stack. This is the uncontrolled domestic load and is at the top of the priority stack as it is not used by ANM for demand response. The DER at the bottom of the priority stack, the ESS, is the first device to be curtailed during a trim event and the last device to be released following a release event. The highest controllable DER in the priority stack, the PV, is the last DER to be curtailed during a trim event and the first device to be released following a release event.

6.1.2.Smart Home Test Setup

Figure 17 shows the configuration of the Smart Home use case devices connected within the Smart Power Lab (SPL) and the ANM control system.

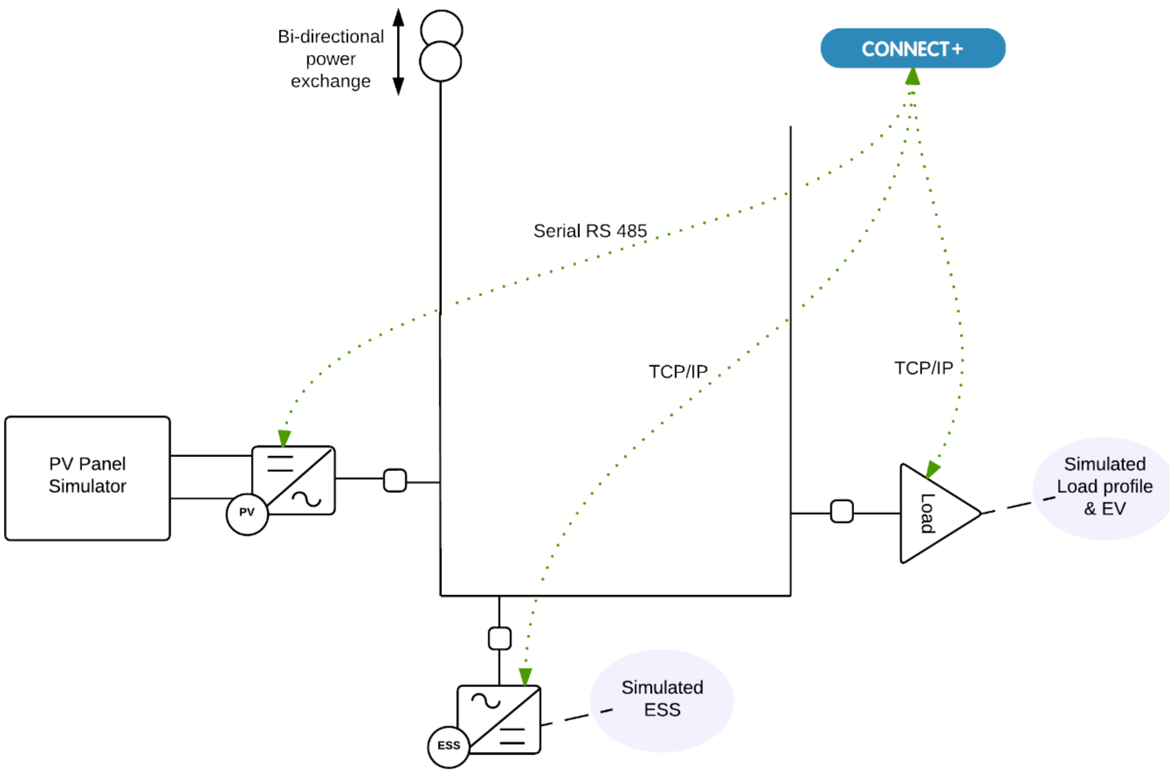

Figure 17: Smart Home Use Case Overview

The Smart home use case uses the following Devices:

- Simulated ESS: Simulated data model for home scale 3kW, 3.4kWh ESS. Control signals are transferred via TCP/IP.
- PV Panel Simulator and inverter: Fronius 3kW PV Inverter and TerraSAS PV Simulator – a PV panel Simulator and PV Inverter. Control signals are transferred via a Modbus RTU link.
- Load profile and simulated EV: Simplex Powerstar 50 Load Bank – A load bank used to represent uncontrolled home load and EV. Control signals are transferred via TCP/IP.

Each device is individually metered and measured real power values were sent to the ANM using 0-10VDC signals. Measurements for each DER were collected from the SPL National Instruments DAQ unit and communicated to the SGS CONNECT+.

6.1.3. Smart Home Simulation Test Runs

Three Smart Home simulation test runs were conducted to test three different grid constraint scenarios. These are:

1) A *Reverse Power Flow Constraint* where wider grid constraints mean that the Smart home is not permitted to export power to the local grid. ANM coordinates the energy consumption and/or production of the PV inverter, battery ESS and EV charging to prevent power export from the home.

2) A *Voltage Rise Constraint* where power export from the home can cause the grid voltage to exceed limits. The ANM system coordinates the energy consumption and/or production of the PV inverter, battery ESS and EV charging to prevent over voltage on the grid.
3) An *Import Constraint* where the smart home is part of a wider demand side management system, which can instruct the home to limit import power when required to resolve grid issues. The ANM system coordinates the energy consumption of the battery ESS and EV charging to maintain demand within limits.

Please note the power flow sign convention for all tests: negative power (-kW) indicates loads are consuming power from the grid, positive power (+kW) represents excess generation exported to the grid, and zero power (0kW) represents zero real power flow (e.g. all generation consumed and matches instantaneous load).

For brevity of this report, only the results of the constrained reverse power flow testing are shown below. See [5] for the full set of test results.

6.1.4. Constrained Reverse Power flow

6.1.4.1. Scenario & Industry Context

In the reverse power flow simulation test runs, ANM thresholds are configured to prohibit power export by the Smart Home to the grid. Thresholds are configured as real power limits that if breached initiate a control action - either curtailment or tripping of DER outputs. SGS CONNECT+ receives real-time measurement of power flows and calculates the necessary action. SGS CONNECT+ then assesses DER availability and using a priority stack assigns curtailment to DERs, bringing power flows below a target threshold value.

In this scenario, grid conditions mean that the home is unable to export power to the grid. In order to allow the home to utilize a PV installation, an ANM system along with a controllable EV battery and ESS is used to ensure that reverse power flow does not occur.

6.1.4.2. Data Profiles

The data used in this simulation run contains a selection from Pecan Street's domestic home data sets acquired for the project.

1) **Domestic Load –** the uncontrolled load profile used in the simulation run is taken directly from 1 minute resolution 2015 data of a real home in Boulder, Colorado.
2) **Solar PV –** the solar PV output is taken from 1 minute generation data from an example home within Pecan Street's database; the solar generation power output is scaled to a percentage of peak inverter power and then multiplied by the peak irradiance of 1100 W/m^2 to get the irradiance profile required for the TerraSAS solar PV simulator.
3) **Electric Vehicle (EV) Charging -** the EV does not follow a recorded profile. The EV load demand is instead generated by an EV charging simulator. The EV simulator is configured to allow the driver to select a time to be fully charged, and delays charging as long as possible to ensure it is available for ANM for the greatest amount of time.
4) **Energy Storage System (ESS) -** The ESS selected to be used for the use case was not available for testing at the time and instead an ESS simulator was used. The ESS simulator in this use case will target

minimum state of charge and export power whenever capacity is available. This ensures the ESS is available to consume power and avoid PV curtailment for the greatest amount of time.

6.1.4.3. Operational Results without ANM

As a baseline without ANM, Figure 18 shows the net power flow of a home installed with 3kW of uncontrolled solar PV. It demonstrates how the home is perceived as both a generator and a load depending on the collective instantaneous load demand and PV output. For the reverse power flow scenario where the power export threshold is 0kW, all positive values are above the permitted operational grid limit. Operational limits are used by utilities in planning studies to determine the interconnection capacity. In this case, using static hosting capacity under traditional planning, the deployment of PV would be prevented or grid asset upgrades would be required to ensure operational limits are not breached. Although a situation like this is unlikely with a single home it is common in areas with high PV penetration where the collective impact of many homes cause issues, as is seen in some states already. Additionally, as will be seen later in this project, this example is directly applicable to larger industrial, commercial and campus facilities where a single facility can cause thermal and reverse power flow constraints.

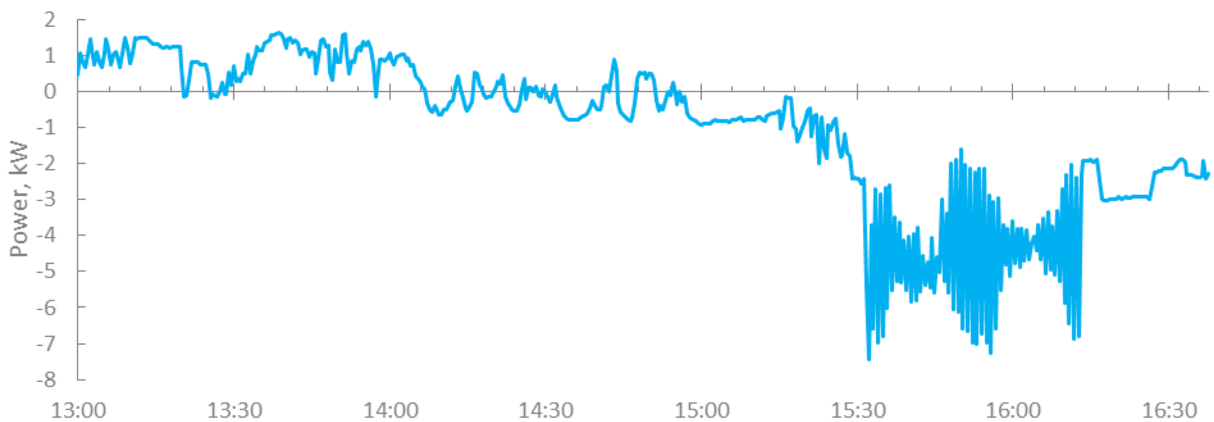

Figure 18: Smart Home Net Power at PCC without ANM

6.1.4.4. Operational Results with ANM

Figure 19 shows how ANM maintains the net power flow of the home below 0kW. This is in comparison to Figure 18 where the net power flow frequently exceeds 0kW between the time of 13:00:00 and 17:00:00. Short duration excursions above 0kW in Figure 19 are caused by step increases in the uncontrolled load. These are quickly addressed by the ANM system, which reduces power flow to below 0kW within 2 seconds on each occasion.

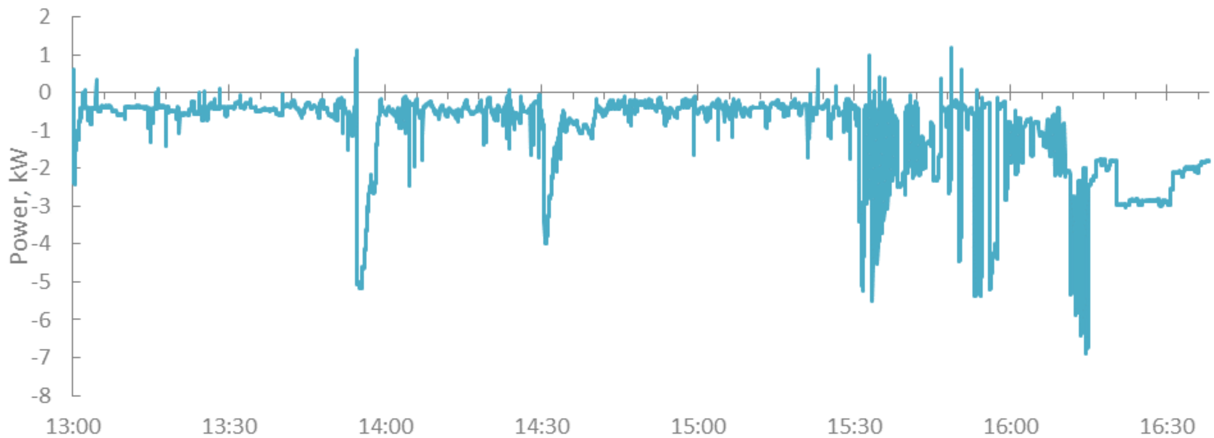

Figure 19: Net Power Flow at PCC for a Home Load with Controlled DER including EV, ESS and PV

The priority stack of DER is configured within ANM such that solar PV curtailment is minimized. Utilizing the storage capacity of the ESS battery is prioritized as a method to provide the necessary curtailment. Subsequently, if the ESS battery is unable to resolve the constraint issue, time shifting EV charging for a given state of charge and charge completion time can be used. This ensures the PV owner receives the maximum return on investment from the PV system and maximizes clean energy generation.

Figure 20 shows the uncontrolled PV output versus controlled PV output. Point 1 shows an example of a curtailment event where the controlled PV output is reduced by a set amount and then released back up to a value where the net power flow is still below 0kW. The other spikes on the Controlled PV trace are short duration reduction of PV output, lasting around 1 second. These reductions were not requested by ANM and the cause was not determined during testing at NREL. It is assumed that the spikes indicate a control logic and/or power electronics issue internal to the solar PV inverter[7] or PV simulator. The solar PV output was the only power hardware device subject to the spikes, which took place independent of ANM curtailment control action. While the team did not have sufficient time to further troubleshoot this issue, the need to do so is consistent with the on-going advancement of industry smart inverter functionality for controllable power as well as supporting grid power quality.

The highly variable nature of the uncontrolled load at approximately 1500hrs is caused by the clothes drier within the home. Fast acting control such as that provided by ANM is essential to be able to work in conjunction with variable load devices and maintain power flows within limits.

[7] After testing was complete and while analyzing the results, NREL's ESIF team mentioned that they have noticed this on other Fronius inverters. This is potentially caused by the inverter disconnecting from the PV panel periodically to perform an isolation test, as mentioned in the user manual.

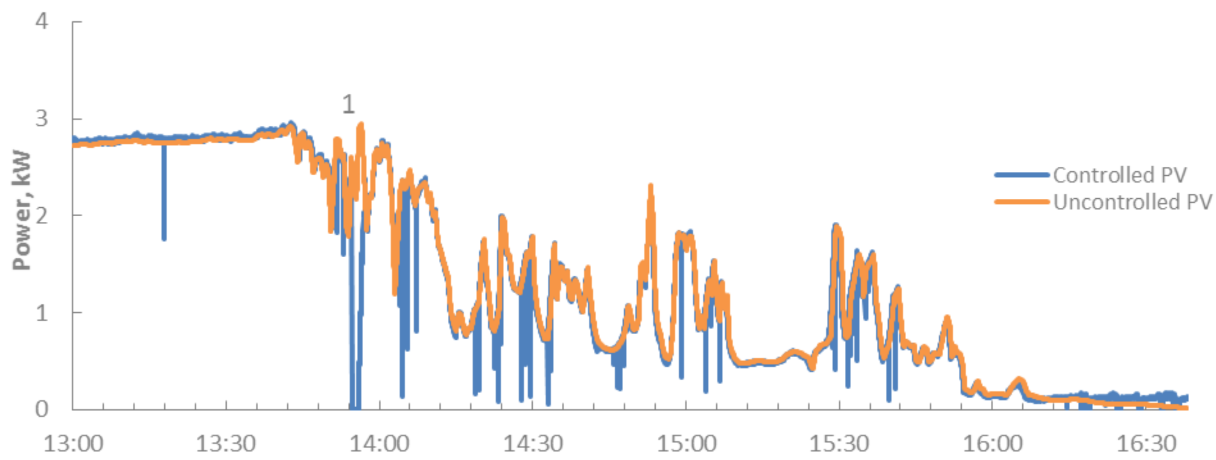

Figure 20: Smart Home Uncontrolled PV and Controlled PV

ANM control of each DER is shown in the upper graph in Figure 21. At the start of the test, high PV export caused the ANM to instruct the ESS to charge in order to prevent reverse power flow, and when it neared full capacity excess generation began charging the EV at 13:40. At 13:54, the ESS became fully charged and stops charging. The EV is then instructed to charge in order to maintain the power flow below 0kW as per the constrained reverse power flow scenario. Beginning at 14:30, the EV begins maximum charging in order to ensure full charge by the driver requested time of 15:00 hours. EV charging was supplied by ESS discharging as well as by excess PV when available (hence the non-uniform changes in ESS discharge rate). At 15:00 the EV was fully charged and excess PV (beyond the uncontrolled home load) charged the battery for a short time before the large uncontrolled home electric dryer load turned on. The battery and PV then supplied as much of that cycling electric load as possible within the second-to-second control of the SGS CONNECT+. After 16:12, the ESS was discharged to its minimum SOC level and remained in that state until the end of the test because there was not any excess PV generation. The overall combined effect of the DER are shown on the lower graph in Figure 21. The combined controlled DER response is shown, and for further clarity, the whole home net power is shown (as per Figure 19 above), reflecting the net controlled home at the PCC.

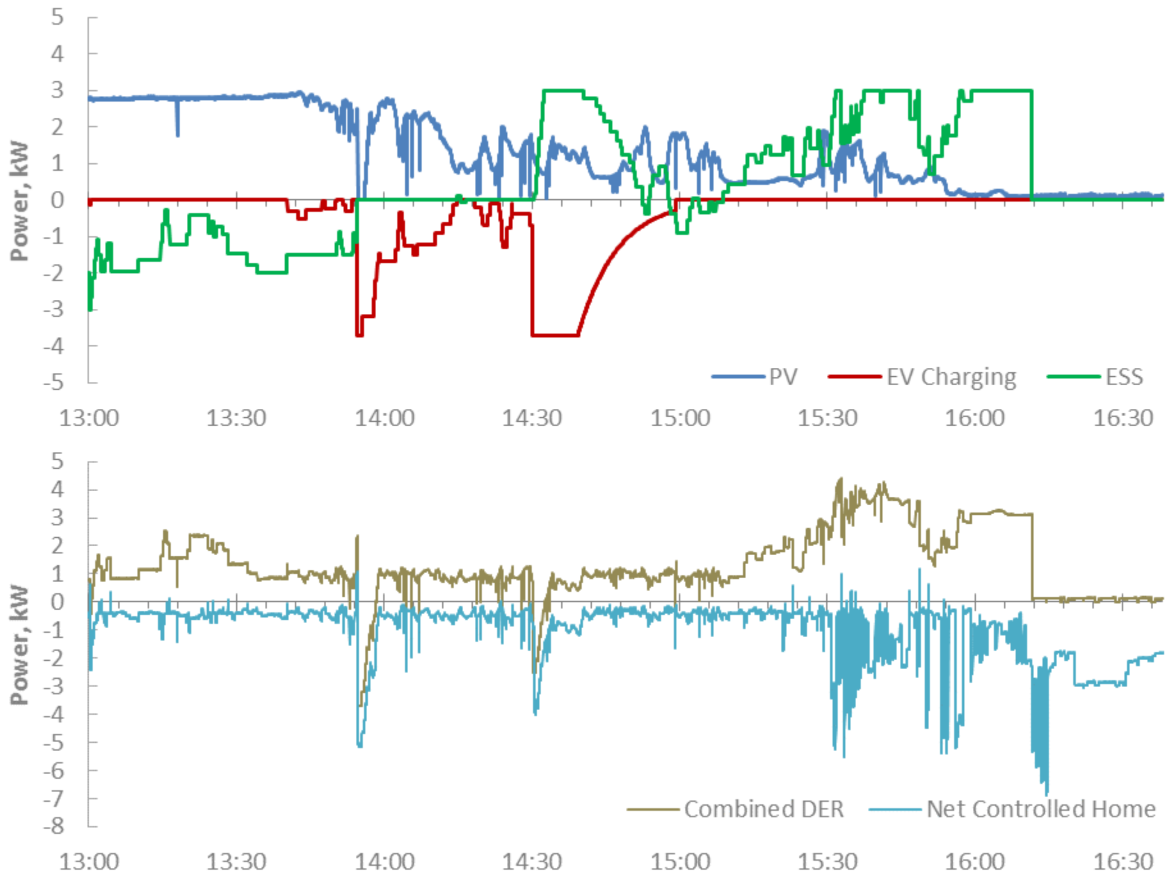

Figure 21: Smart Home DER Import / Export and Combined DER

Figure 22 shows the state of charge of the ESS and EV batteries. At point 1 in Figure 22 the ESS begins charging to consume the output of the PV system that would otherwise be curtailed due to restricted export. The ESS maximum state of charge is 90%, representing the manufacturer's charging instructions for battery longevity. When the ESS reached 90% state of charge at point 3 it was no longer available to the ANM system. At point 2, the EV began charging because the ESS was unable to accept the total curtailment value required by ANM. At point 3, when the ESS was full, the EV received an even larger curtailment value required to avoid curtailing the PV. Note that when not being used by the ANM system the EV began charging at full power as late as possible to be fully charged by a configured time. This phase of EV charging began at point 4 until it completed charge at point 5. When the ESS was not being used by ANM it was configured to discharge when capacity existed to export power. This functionality ensured that the ESS was available as much as possible for PV curtailment avoidance and can be seen between points 4 and 6. Between points 4 and 5 the ESS was supporting charging the EV, and between points 5 and 6 the ESS charged for approximately 10 minutes to negate PV curtailment and then discharged to its minimum state of charge to support uncontrolled load, thereby maximizing availability for ANM control under this constrained home export use case.

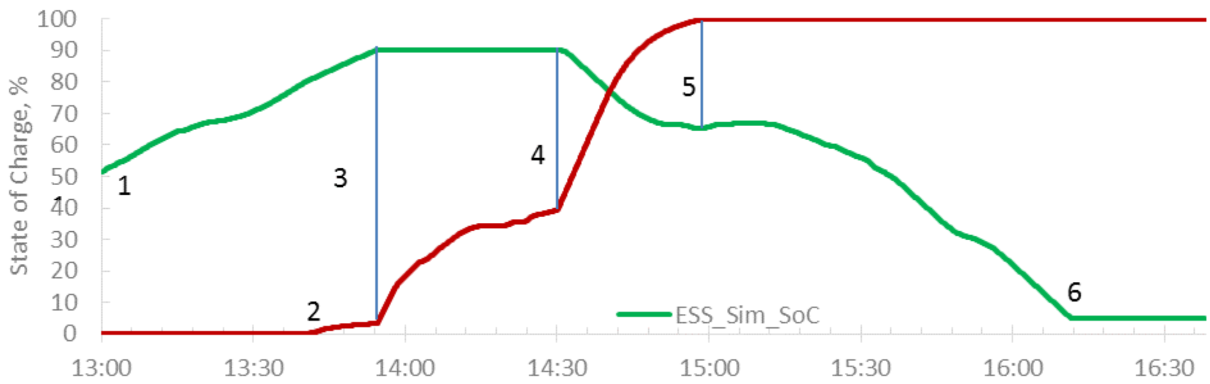

Figure 22: Smart Home ESS & EV State of Charge Over Time; used as ANM Resources

6.1.4.5. Failsafe Response

The ANM system manages DERs to maintain constraint locations within design limits. This requires a real-time measurement of constraints and control of DERs. ANM monitors all the communication links required to provide this control and monitoring, and implements a failsafe response in the event of a link failure. The example below shows the ANM system response to a loss of communications link to the measurement point. The configuration of the ANM system will determine how sensitive the smart home is to a loss of communications, based on a timer set by the operator. The significance of this functionality will only increase as DER penetration increases.

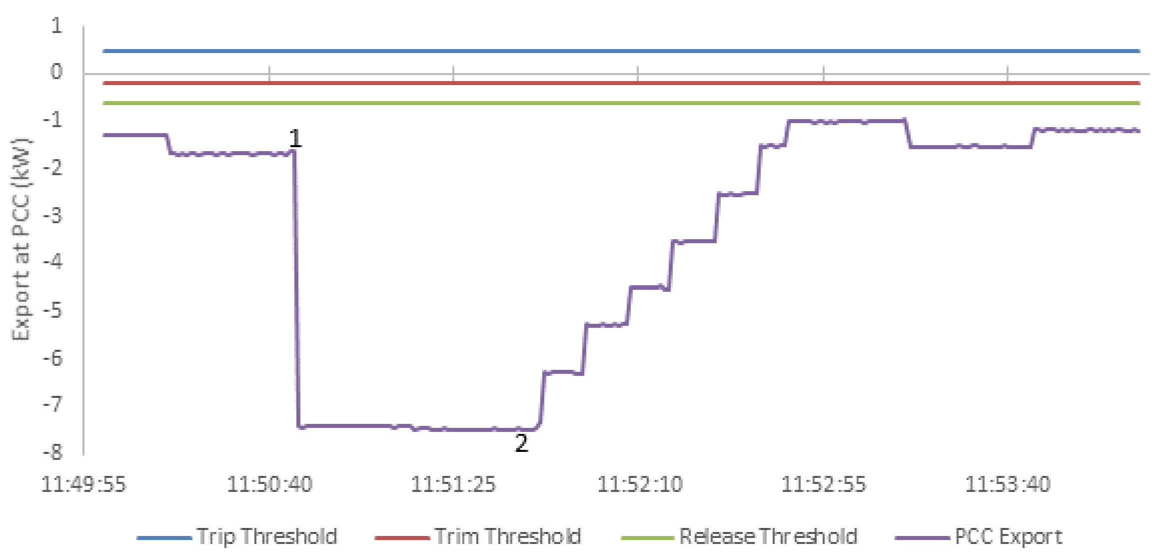

Figure 23: Smart Home Export at PCC during MP Communications Error

At Point 1 in Figure 23 the loss of communications is detected by the ANM system. As the measurement is not available, the ANM must assume that there is no capacity for PV export and it instructs the DERs to their minimum set-points and awaits the restoration of the communications link. At Point 2 in Figure 23 the communication link is restored and the ANM system manages the controlled release of DER devices to use the available capacity. After point 2, the step change in the data reflects the corresponding controlled release of the PV as per its configurable ramp settings.

6.1.4.6. Findings

It is evident from Figure 20 that the ESS and EV are able to consume much of the curtailment that would otherwise be given to the PV system. In terms of hosting capacity of the circuit, this degree of DER monitoring and real-time control would enable continued PV interconnection on circuits with constrained capacity. This ANM enabled Smart Home could therefore interconnect on circuits where for instance the total sum of whole circuit generation output is approaching/higher than circuit minimum load – a common worst case traditional static circuit planning criteria that restricts further generation interconnection (due to the prohibitively high circuit reinforcement cost burden for new interconnecting DER). This Smart Home use case focused on demonstrating ANM technology for residential scale DER and thus simulated network conditions upstream from the PCC. Future use cases will aggregate such ANM enabled Smart Homes control responses in order to include their control within whole circuit testing, thus will quantify how for a small amount of curtailment additional PV systems would be permitted to interconnect.

6.2. Smart Campus Use Case Outcomes

The following sub-sections present results and outcomes from the Smart Campus use case. See [6] for the complete set of outcomes and final report.

Summary:

- The Smart Campus use case is designed to demonstrate how ANM's real-time monitoring, automation and control can be used to manage constraints associated with high penetrations of DER at a single point of common coupling on a radial distribution circuit. As a result of constraint mitigation, it is shown that dynamic DER control can allow for higher penetrations of PV than would otherwise be permitted using traditional static grid planning and operations processes. ANM is demonstrated to safely and reliably manage the PV system only, and then manage the coordination of PV, battery ESS, aggregated EV charging, and controllable load for optimized behind the meter energy resources.
- For the megawatt (MW) scale DER flexibly interconnected to the Smart Campus, ANM has been proven in the past to be a cost effective alternative compared to traditional T&D reinforcement.
- The Smart Campus control system architecture is an ANM 100 system with a central controller (incorporating sgs core and sgs comms hub) and DER device controllers (sgs connect) along with monitoring points at constraint locations. This ANM architecture then allows the smart DER devices to behave as a coordinated and managed resource that is scalable and extendable into a larger smart distribution control system, as will be considered in the subsequent smart distribution INTEGRATE use case.
- As seen in the following table, the results of the Smart Campus testing showcase the ANM control approach can safely and reliably integrate campus DER to increase grid hosting capacity and minimize clean energy curtailment.

Table 2: Smart Campus Static vs Dynamic Grid Summary

Constraint Type	Location	Static Design Factor	Static Generation Capacity Limit	ANM Dynamic Design Factor	ANM Dynamic Generation Capacity Limit	% Difference
Thermal Export	SC service conductor	75% of thermal rating (185 kVA) + Min Coincident Load (28 kVA)	213 kVA	90% of thermal rating: 222kVA, actively managed	500 kVA	135%
Over-Voltage	SC PCC	1.05 p.u. voltage; worst case scenario	295 KVA	1.05 p.u. voltage; actively managed	500 kVA	69%

- There were four elements to the Smart Campus demonstration. The first three focused on the use of ANM to allow the installation of a solar PV generator on a smart campus connected to a distribution grid with a reverse power flow constraint at the point of common coupling (PCC). The last focused on voltage rise management at the smart campus interface to the distribution grid. The demonstration was as follows:
  - **Annual offline assessment of flexible interconnection:** An analysis of the flexible management of PV generators by the ANM system, along with the estimated annual curtailment levels.
  - **PHIL testing of worst-case grid operation scenario - reverse power flow of PV only:** a 3-hour duration demonstration of the PV system managed by the ANM system using a physical PV inverter for a PHIL simulation run in the ESIF at NREL. This testing showcased ANM's functionality and basic value to the grid at its most fundamental level: demonstrating a massive deployment of clean energy that is actively managed by ANM that otherwise would have been uneconomic[8] for the PV developer to deploy at that scale.
  - **PHIL testing of coordinated DER for maximum clean energy:** a 5-hour duration demonstration showing how additional DERs (ESS, EV and controllable load) can be used by ANM to coordinate and manage all DER in real-time to maximize clean energy generation, thereby reducing curtailment levels experienced by the PV in the previous demonstration. This testing showcased ANM's innovative ability to manage multiple DER in real-time to ensure the grid is operated in a secure and dependable manner under massive clean energy deployment levels.
  - **PHIL testing of coordinated DER for resolving a voltage constraint:** a 5-hour demonstration run showing the campus with a voltage rise constraint at the PCC caused by generation export.

[8] "Insufficient capacity" due to how traditional static grid limits would have required the PV customer to pay for uneconomic distribution equipment upgrades (e.g. reconductoring cables that would make the solar PV deployment uneconomic). ANM enabled distribution circuits allows DER developers to choose the most economic interconnection by comparing firm "fit and forget" interconnection versus flexible "managed" interconnection.

For brevity of this report, the following subsections below present the results of the PHIL testing of coordinated DER for maximum clean energy. See [6] for the complete set of outcomes and final report.

6.2.1. Coordinated DER Demonstration

The Smart Campus Coordinated DER Demonstration shows that ANM can be used to control multiple DER types in order to minimize constraints and maximize the use of renewable energy sources. For this test, various controllable devices within the campus:

- Physical EV and charger,
- Simulated aggregated EV charging load,
- A load bank representing a controllable load within the campus,
- Battery energy storage system (ESS).

6.2.1.1. Circuit Characterization and Static Grid Capacity Limits

A modified IEEE 13-Node test feeder was used as the grid simulation Test Circuit for evaluating the ANM technology at NREL. Adaptations to this circuit were necessary in order to meet the requirements of this study and moreover utilize a realistic circuit model.

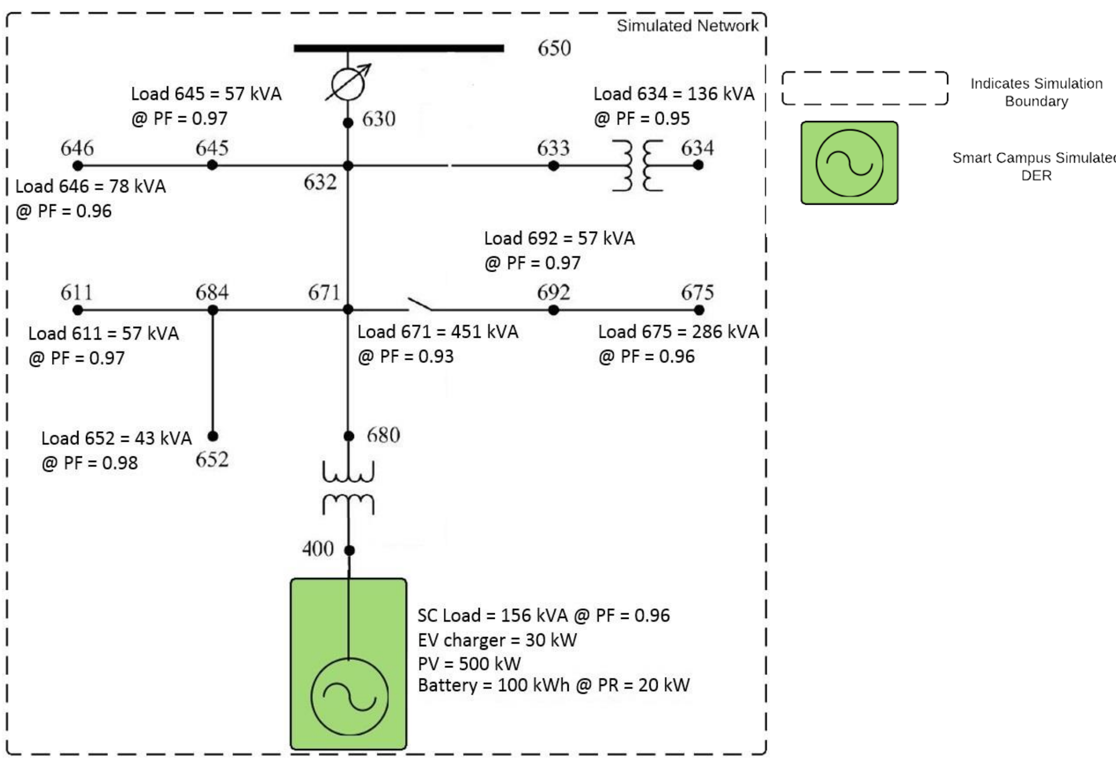

Figure 24: Modified IEEE 13-Node Test Feeder Including the Smart Campus

6.2.1.2. Smart Campus Static Constrained Grid Definition

Using the test circuit and employing the conceptual static versus dynamic hosting capacity framework, the sub-sections below define the static grid interconnection capacity of the Smart Campus. These were compared to and tested against the ANM enabled dynamic hosting capacity limits.

6.2.1.3. Circuit Power Export Thermal Capacity for Unmanaged DG

In order to assess the limits of the static grid thermal capacity when adding unmanaged DG to a distribution circuit, a limit of 75% of the thermal capacity[3] of utility assets is utilized. For the modified circuit this equates to a 75% thermal capacity limit of 185 kVA.

For this phase of the project, there was no other generation on the circuit and there are no other conductors in the model with a thermal capacity less than that of the Smart Campus service conductor, therefore the only possibility for a thermal constraint is within the Smart Campus service conductor. The minimum coincident load therefore also only relates to the Smart Campus load profile.

Consistent with static grid limits, the worst case scenario is evaluated against the peak output of the generator in conjunction with a coincident minimum load condition. For typical PV in much of North America, this coincident minimum load condition can be generalized as the minimum load experienced between 11:00 and 15:00 between April and September. If interval metered data is available at the circuit substation, this can provide the minimum load condition directly. Otherwise, local utility engineers are consulted in order to provide a reasonable conservative estimate of the minimum daytime load relative to the peak load of the circuit.

The minimum coincident load demand of the Smart Campus with the PV system was found to be 28 kVA occurring May 14 at 14:00. Adding the minimum coincident load of the Smart Campus to the 75% design rating threshold of the service conductor produces a static grid interconnection limit of 213 kVA relative to power export thermal capacity for the Smart Campus distributed generation.

For ANM managed DER interconnection, the grid can be operated closer to its engineering limits due to the real-time deterministic, autonomous, and failsafe ANM control characteristics. Therefore, the threshold for ANM managed thermal export is increased to the 90% design rating, resulting in a dynamic grid thermal export limit of 222 kVA.

6.2.1.4. Summary of Key Static Grid Smart Campus Constraints

The summary of the Smart Campus static grid thermal and voltage constraints are shown in the table below. At 213 kVA, thermal export is the limiting constraint for DER interconnection. It is assumed that sizing generation beyond the limits below would incur uneconomic distribution reinforcement costs. The sections below assess how an ANM enabled grid can manage DER interconnection beyond these limits – with on-site testing data to demonstrate these results.

To compare against the static grid limits presented here as well as to test the ANM control system, the sections below present the annual power flow curtailment results of the uncontrolled and then ANM-controlled DER for the high penetration ANM-enabled dynamic grid. Gathered DER data was collected and presented below for managing DER under reverse power flow thermal export as well as voltage rise constraints.

Table 3: Smart Campus Static Grid Constraint Summary

Constraint Type	Location	Design Factor	Generation Capacity Limit
Thermal Export	SC service conductor	75% of thermal rating (185 kVA) + Min Coincident Load (28 kVA)	213 kVA (Generator)
Over-Voltage	SC PCC	1.05 p.u. voltage	295 KVA (Generator)

6.2.1.5. Smart Campus Test Setup

The Smart Campus Coordinated DER Demonstration includes grid simulation with ANM & PHIL, as shown in Figure 25.

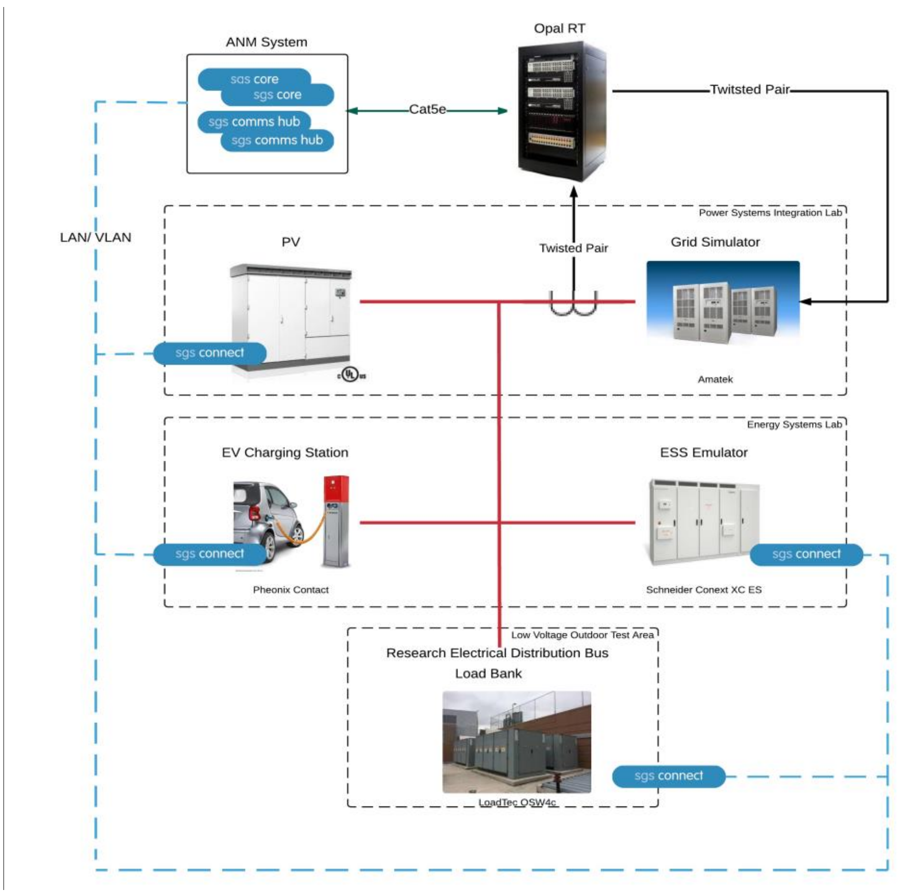

Figure 25: Smart Campus Test Setup[9]

[9] Note that the diesel generator was unavailable during the on-site activities. Its contribution is therefore not included in the use case curtailment analysis and likewise testing scenarios.

The additional DER devices are used in this demonstration to provide a controllable demand, which is used to consume the PV generation locally to maintain the export to the grid below the reverse power flow limit.

The ANM system is configured to control the DERs according to a Principles of Access (POA) framework. The POA governs which order the DERs are used to resolve the constraints and which DERs are permitted access to grid capacity as it becomes available. The Coordinated DER Demonstration uses the POA order shown in the following figure.

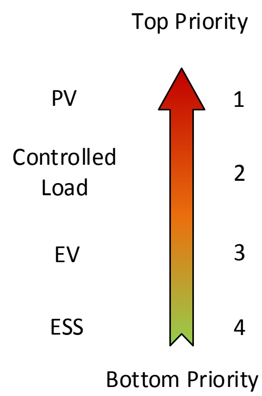

Figure 26: Smart Campus POA Order for Coordinated DER Demonstration

Within the POA framework solar PV is at the top of the priority stack. This means that it is the last device to get used by the ANM for managing grid constraints (i.e. minimizing curtailment) and the first device to have excess grid capacity released to it.

Due to the physical size of the ESS relative to the circuit and grid simulation scaling, the ESS is configured with a limited storage capacity of 125 kWh. Under POA when that storage capacity is exhausted and an additional curtailment is required, the ANM system automatically allocates curtailment to additional DER higher up the POA priority stack until the constraint is resolved.

6.2.1.6. Annual Load and PV Generator Profiles with ANM

The hourly Smart Campus load profile and the uncontrolled output of the 500 kW PV generator are presented in the following two figures respectively. The peak of the Smart Campus load is 150 kW with a total consumption of 582.5 MWh. The peak output of the PV generator is 500 kW with a total uncontrolled generation of 820.4 MWh.

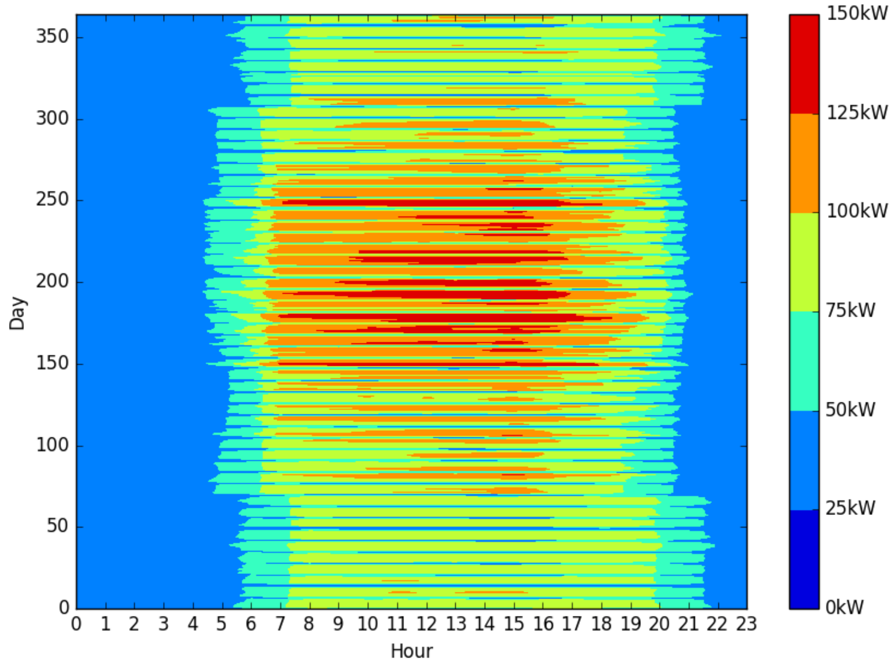

Figure 27: Annual Smart Campus Load Profile (note scale shading)

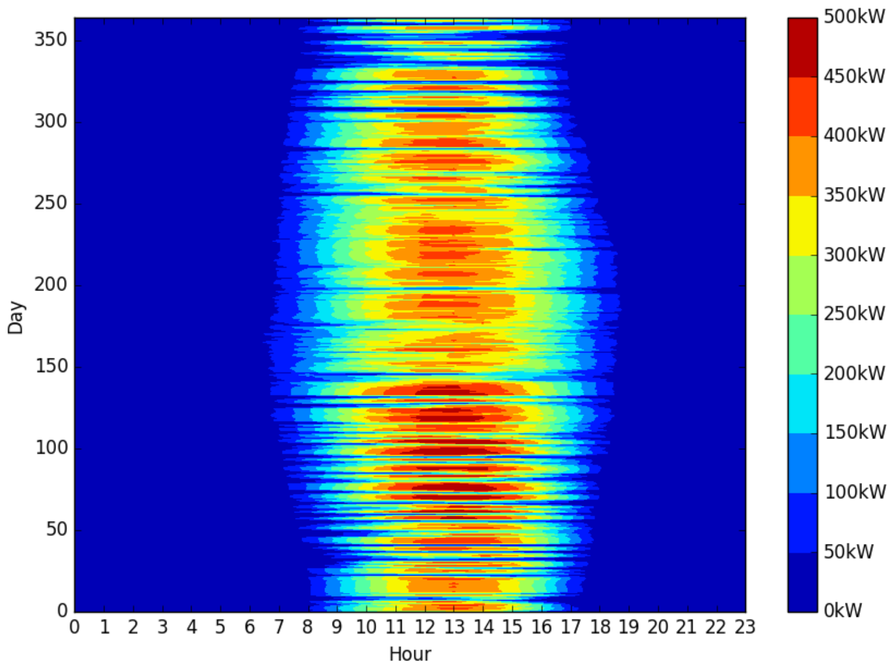

Figure 28: Smart Campus Annual Uncontrolled PV Generation Profile

6.2.1.7. Curtailment Analysis Results and Discussion

The ANM managed curtailment profile of the PV generator – to respect the service conductor's 90% thermal design limit of 222 kVA under ANM management, is presented below in Figure 29. The total annual generation post-curtailment represented in this figure is 732.5 MWh, which corresponds to 10.7%

curtailment. Please note that this is the estimated generation of the 500 kW PV system alone – thus representing a conservative assumed curtailment level for an actively managed DER on the circuit. For additional information and background, see the static vs dynamic grid conceptual framework and curtailment assessment assumptions, and see also [6].

As generally seen in the uncontrolled PV generation, the decreased production related to power output correlates to generation greater than 350 kW. Given the predominance of the campus load demand to be in the 75 to 125 kW range, this is in alignment with the ANM managed net power export being limited to 222 kVA.

As described previously, it is assumed that curtailment levels much greater than 10% would render a given generator interconnection unprofitable. Thus for the smart campus historical load, its location on the distribution circuit, and considering the historical loading on the circuit, this curtailment estimate correlates to the conservative worst case curtailment scenario. A PV-only evaluation therefore demonstrates ANM's fundamental value proposition – maximizing grid connected clean energy that can be safely and reliably operated had massive deployment levels in a cost effective manner. Compared to the static grid thermal export limits, the hosting capacity increased 135%. The subsections below showcase the incorporation of battery energy storage and EV charging with the PV in order to demonstrate their coordinated real-time control to minimize curtailment and maximize ANM integration of clean energy.

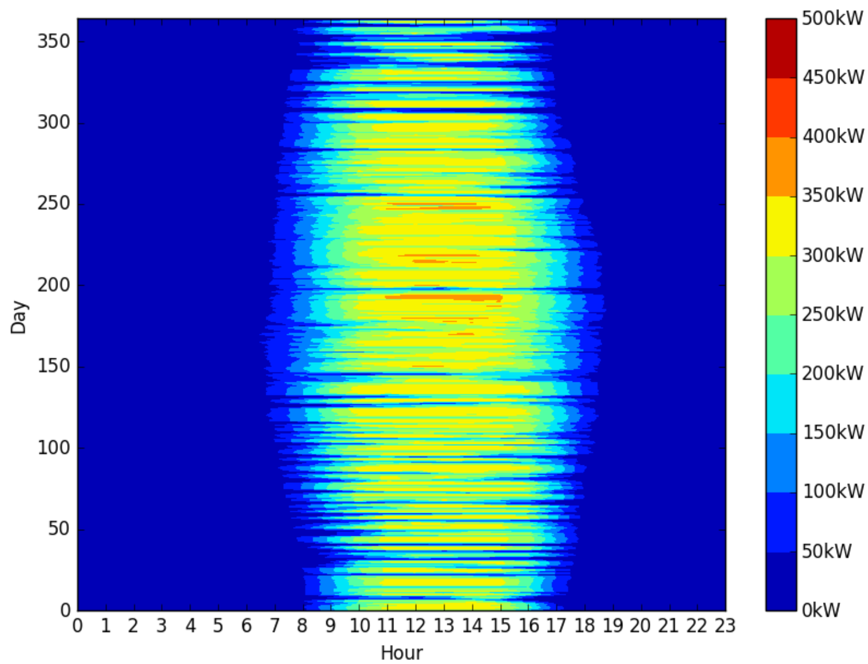

Figure 29: Smart Campus Annual Post-Curtailment PV Generation Profile

6.2.1.8. Coordinated DER Testing Results

The graphs below show the results of the demonstration. The data shown is an extract from the historian database with runs on the sgs comms hub server and logs all ANM activity.

The first figure below shows the campus PCC current being actively managed against the thermal export constraint limit, and the second figure shows the individual DER coordinated according to the POA framework. Compared to the PV Only Demonstration, the PV export under the Coordinated DER

Demonstration is not issued with any curtailment and so is allowed to produce 100% of its potential output during the demonstration period. This is achieved using the various DERs to produce demand to offset the PV export.

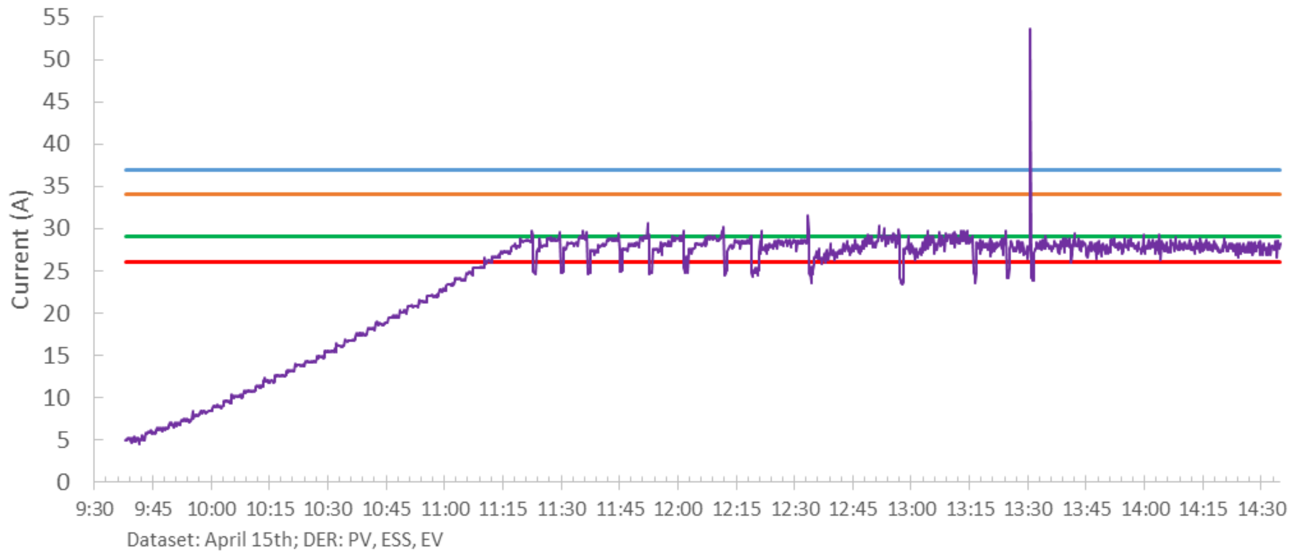

Figure 30: Smart Campus Full DER – Measured Current at the PCC

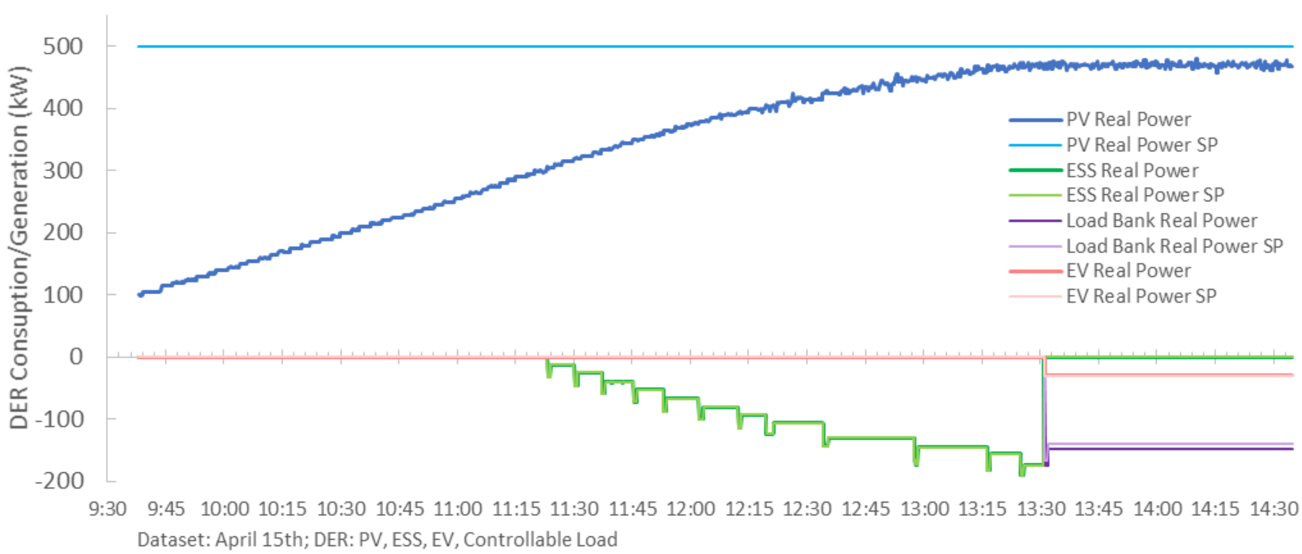

Figure 31: Smart Campus Full DER – DER Export and Set-points

Relative to the export thermal constraint, Figure 30 shows export gradually increasing as the PV output increases. At 11:22am, the export current breaches the trim threshold. ANM then calculates the reduction in real power required to bring the export current below the reset threshold. In this case, the ANM system calculated that a 32 kW reduction was required and this was allocated to the ESS, being the lowest active DER on the POA priority stack. This resulted in the ESS being issued with a 32 kW import set-point. This is reduced to a 13 kW import set-point when the reset threshold is breached and the ANM maximizes export.

As the PV export continues to increase, successive trim events cause the ESS import set-point to increase to 174 kW import.

At 13:30 the ESS becomes fully charged and is no longer able to consume any power. This results in the load dropping from 174 kW to 0 kW. This causes an increase in the current at the campus PCC to 53.6 A. Although this breaches the sequential trip and global trip thresholds, the observation timers which trigger the event are set such that the trim operation will occur before either of the trip events.

As the ANM system was no longer able to use the ESS to reduce the campus export it moved up the priority stack and issued constraint management requests to the next DER, in this case, the aggregated EV charging load. The ANM instructed the EVs to start charging at their maximum charge rate of 30 kW. As additional curtailment was still required to bring the measured current below the reset threshold, the ANM system also requested that the load bank provide a load of 166 kW. The load of these two DERs caused the export current to fall below the reset threshold within 5 seconds.

For the remainder of the demonstration, the PV export did not increase further and the campus uncontrolled load did not vary such that further constraint management actions were necessary.

The use of the additional DER’s in this demonstration had the advantage over the PV-Only demonstration of reducing PV curtailment to zero – showcasing the coordinated control of the systems to increase grid hosting capacity and minimize clean energy curtailment. The ANM system is configured such that the energy stored in the ESS would be discharged to support campus load and/or grid export when there is sufficient grid capacity to do so, e.g. overnight. This therefore demonstrates that ESS, co-located with a renewable generator can be used to reduce curtailment on a constrained circuit with the use of ANM.

Compared to the annual curtailment analysis, these Coordinated DER results highlight that DER developers with too much curtailment have an ANM enabled smart grid extension available by incorporating energy storage or synchronizing RE curtailment with controllable load. If for instance the DER developer wanted to limit PV curtailment to 5%, a battery ESS with 260 kWh of storage capacity and a 60 kW power rating would be required.

6.3. Smart Distribution Use Case

6.3.1. Circuit Characterization and Static Grid Capacity

The Smart Distribution use case provided an integrative perspective of ANM across all distribution grid DER device scales (incorporating aggregated Smart Homes and the Smart Campus) in order to showcase how these devices can support smart grid services to manage DER penetration constraints in a safe and reliable manner, and likewise also extend and scale for future grid modernization schemes. See [1], [2], [5], and [6] for more information.

A modified IEEE 13-Node test feeder was used as the grid simulation Test Circuit for evaluating SGS’ ANM technology at NREL. Adaptations to this circuit were necessary in order to meet the requirements of this study. Each change is documented below. An overview of this circuit that includes the addition of the Smart Distribution DER is presented in Figure 32 below. Pre-existing firm interconnection generation are shown in black, ANM enabled flexible interconnection PHIL generation are shown in red, and simulated[10] ANM enabled flexible interconnection generation are shown in purple.

[10] Note: SGS assumed that small generators like the Smart Home PV systems would be interconnected through aggregator control schemes – as such they are not included in the increased grid hosting capacity calculations.

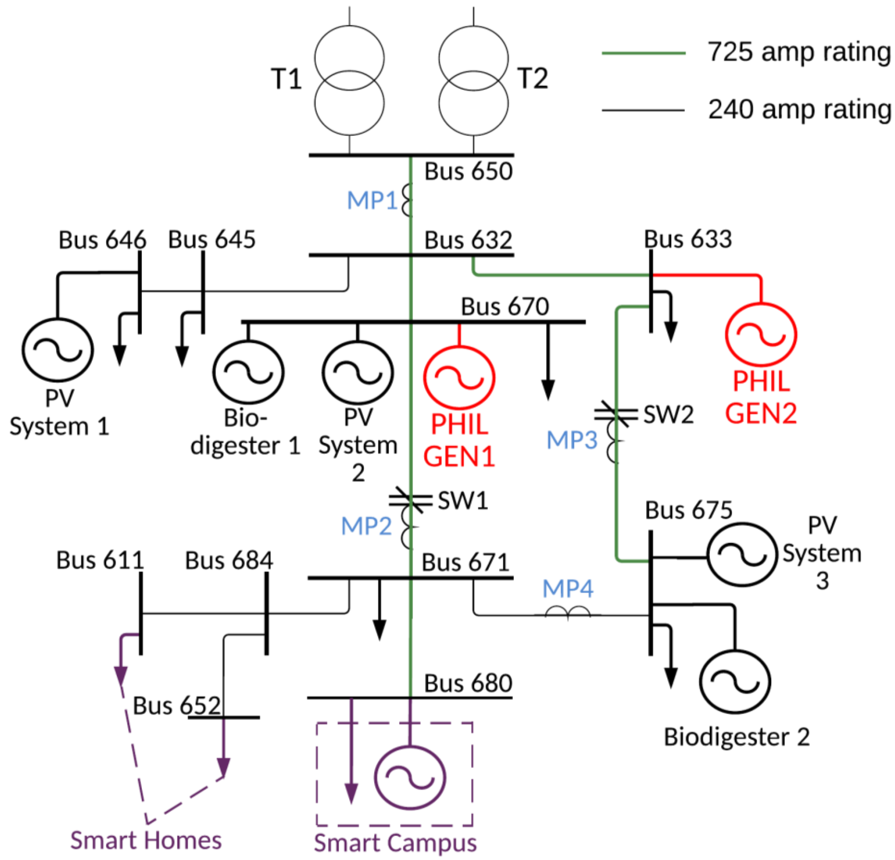

Figure 32: Smart Distribution Test Feeder

Grid simulation of the test feeder was performed by hosting the circuit model in OPAL-RT, with the DER and the Amatek Grid Simulators connected to the Research Electrical Distribution Bus (REDB). Figure 33 displays the PHIL setup. The REDB network is a balanced 3 phase network, with a line to line voltage of 480V. The grid simulator acted as a sink and source to the network.

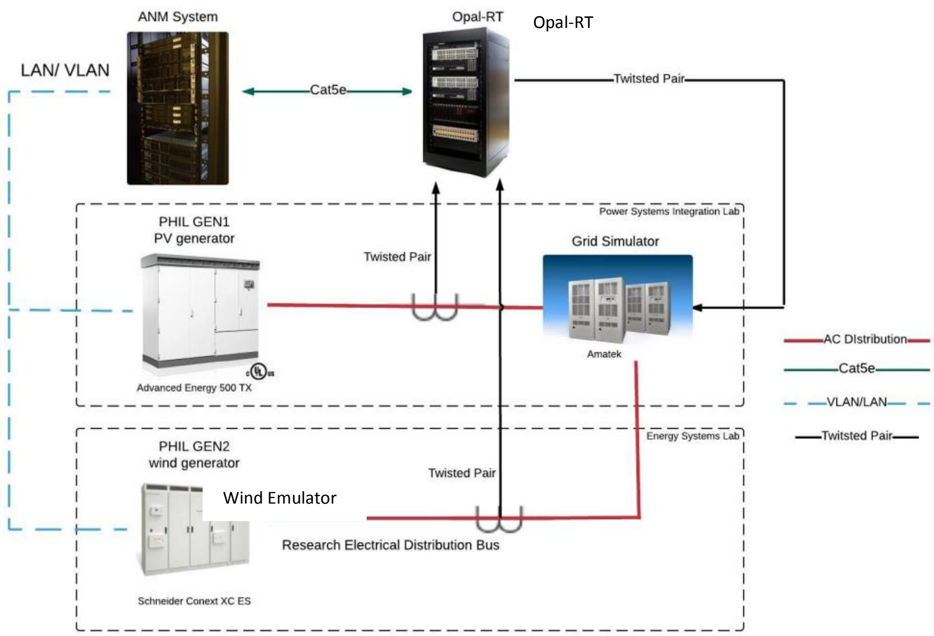

Figure 33 REDB Configuration for Smart Distribution

6.3.2. Creating a Realistic Circuit Model

For the offline annual power flow analysis, the circuit was modeled using OpenDSS. Standard distribution engineering assumptions have been followed for specifying the circuit model and correlating the OpenDSS version with the Simulink/OPAL-RT version. These modifications were done to ensure a realistic representation of a medium voltage distribution circuit that moreover could be simulated using NREL's ESIF equipment. The circuit was modified as follows:

- Conversion to a balanced symmetrical model: the IEEE 13-Node feeder was originally designed to test the limits of 3-phase control and load-flow solvers through severe phase imbalance. Control systems to address a high degree of phase imbalance are not currently a short-term utility request for ANM, as such they were outside the scope of this project. An equivalent balanced 3-phase circuit model was used instead, as is typical for circuits targeted for high clean energy deployment. This conversion is based on the standard procedure of averaging the self and mutual complex impedance[11] of the three phases. The zero sequence and positive sequence impedances are then calculated based on the following formula:

  $Z_0 = Z_{self,avg} + 2*Z_{mutual,avg}$

  $Z_1 = Z_{self,avg} – Z_{mutual,avg}$

- Circuit transformers have been removed to simplify the real-time simulation model. As such, bus 650, which acts as the source bus, is assigned a voltage of 1.025 per unit and is linked directly to bus 632. Also, the load on bus 634 was moved to bus 633 and the pre-existing transformer between these nodes was removed.

[11] I.e. resistance is the real component and reactance is the imaginary component.

- The switch located between nodes 671 and 692 was removed and the loads on each of these nodes was combined.
- The shunt capacitors originally positioned at Bus 611 and Bus 675 have been removed. These components add additional grid simulation complexity that is not required for this project.
- Line and switch addition: in order to satisfy the Smart Distribution use case requirements ("200285 34A Smart Distribution Requirement Specification"), which include alternate topologies, an additional line was added between Bus 633 and Bus 675 that included a switch. A switch was also added to the line between Bus 670 and Bus 671 in order to provide the alternate topology functionality.
- Simplified line specifications[12]: a variety of line types and associated properties were specified in the original model. To simplify the testing configuration, only two types of line specifications were used in the OpenDSS circuit model and the NREL simulation environment. The original specification for the overhead line feeder from the substation, the ACSR 'Dove' conductor that has a 725 amp rating, was used on the same line segments[13] as well as line segments 632 to 633 and 633 to 675. The remaining line segments were assigned the ACSR 'Raven' conductor that has a 240 amp rating. The line segments assigned the 'Dove' conductor have been highlighted green in Figure 32 and all of the line segments assigned the 'Raven' conductor are black. The amp ratings correspond to a thermal rating of 5.2 MVA and 1.7 MVA at the 4.2 kV voltage level of the Test Circuit for the 'Dove' and 'Raven' conductor, respectively.
- As per Figure 32, a number of DER devices have been added to the circuit. Conceptual static grid hosting capacity considerations were included in the design, such that:
    - Prior DER deployment takes place without triggering ANM (i.e. firm interconnections due to existing circuit headroom capacity). Therefore existing DG on the circuit that is within static hosting capacity limits, and thus outside the ANM control scheme, have been placed at Bus 670 and 675 in the form of a biodigester and at Bus 646, 670 and 675 in the form of a PV system.
    - The Smart Homes have been added as a portion of the load on Bus 652 and Bus 611 – as a percentage of total residential homes. There will be no PHIL elements associated with the Smart Homes, but instead all DER at each location will be treated as aggregate prosumers integrated via an aggregator. Integration with the ANM scheme is with the sgs connect element to the aggregator. Given the simulated DER, the sgs connect will interact with the net data profile of the controllable aggregated smart homes. The amount of management allowed will be dictated by the number of Smart Homes included in these load profiles as well as the available resources assumed to be associated with the Smart Homes.

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[12] Line configuration data for the IEEE 13-node test feeder is available on the IEEE website (http://ewh.ieee.org/soc/pes/dsacom/testfeeders/).

[13] This includes the line segment between Bus 671 and Bus 680, which acts as the Smart Campus service conductor and was assigned the ACSR 'Raven' conductor in the Smart Campus use case.

- The DG added to Bus 680 within the Smart Campus boundaries corresponds to later DER deployment that is beyond static grid limits and would trigger the ANM deployment. Similar to the simulated Smart Homes, there will be no PHIL elements, but instead all DER within its boundary will be treated as a whole with the sgs connect element interacting with the net data profile of the Smart Campus.
- Power hardware in the loop (PHIL) elements for the demonstration, 'PHIL GEN1' and 'PHIL GEN2', have been added to Bus 670 and Bus 633. These will be a PV and wind generator, respectively, with the inverters being the PHIL interface.

In keeping with traditional distribution planning, with these modifications it was ensured that voltages and power flows across the circuit were within operational limits considering load alone (loss of all generation) prior to deployment of DG. Similar precautions were taken when adding the pre-existing DG to the circuit as well as the Smart Home PV systems. This is elaborated further in Section 6.3.4.

6.3.3. Circuit Load Characterization

The circuit load characteristics are presented in Table 4. The peak value was specified first based upon the pre-defined load values in the IEEE 13-Node Test Feeder model and according to the static capacity limits associated with the circuit when load needed to be added. The annual consumption and minimum load was then derived using a number of characteristic load profiles. These profiles were derived using high resolution Pecan Street datasets and from public data sources[14] as necessary. The annual offline modeling and simulation of flexible interconnection used the same load and DER profiles as the data profiles used in the real-time PHIL simulation testing environment to provide direct correlation between the curtailment analysis and the results of the real-time testing.

The load profiles included a number of homes aggregated together to represent a community: a quick service restaurant, a secondary school, an office building, a warehouse, an outpatient medical office, a small hotel, and a strip mall. At each node the particular composition of profiles were aggregated, normalized and multiplied to match the peak demand. A power factor was then assigned where it was assumed that a pure industrial customer would have a power factor of 0.92 and a strictly residential load a power factor of 0.98.

These high resolution data sets are averaged to hourly profiles for the purposes of the curtailment analysis. Hourly profiles have been chosen because this is quite often the resolution of data provided by utilities from circuit metering.

[14] EERE Commercial Reference Building profiles were used (http://energy.gov/eere/buildings/commercial-reference-buildings) and modeled via EnergyPlus (http://apps1.eere.energy.gov/buildings/energyplus/).

Table 4: Circuit Load Characteristics

Load Bus	Peak Load [kW]	Minimum Load [kW]	Annual Consumption [MWh]	Power Factor
645	163	26	486	0.97
646	222	56	715	0.96
633	389	45	1161	0.95
670	191	36	617	0.97
671	1111	137	3807	0.93
652	123	17	345	0.98
611	164	31	495	0.97
675	824	137	2895	0.96
680	230	48	988	0.96

6.3.4. Static Constrained Grid Definition

As mentioned in Section 6.3.2, a series of changes were applied to the IEEE 13-Node Test Feeder in order to accommodate the requirements of the study. Using this modified IEEE 13-node feeder, the sub-sections below define the static grid hosting capacity of the Smart Distribution use case. These will be compared to and tested against the ANM enabled dynamic hosting capacity limits described in Section 8.3.

6.3.5. Circuit Capacity for Load

In order to ensure that the concept model circuit used within the testing correlated with typical distribution planning and was a sufficient representation of reality, it was ensured that voltages and power flows across the circuit were within operational limits considering load alone. This means adhering to a voltage range of 0.95 to 1.05 p.u. and respecting the thermal capacity of all assets. The peak load conditions presented in Table 4 sum to load demand of 3595 kVA. The substation transformer capacity of 5000 kVA as specified in the original IEEE 13-Node Test Feeder model was maintained as a suitable capacity to accommodate this level of demand.

Running a loadflow on the test circuit model under this peak load scenario, the lowest voltage experienced was 0.968 p.u. at Bus 675, and line segment 650 to 632 experienced the greatest thermal loading at 70% of the 725 amp current carrying capacity. Also, the power flow through the substation transformer was 3746 kVA, or 75% of the substation transformer capacity. This represents a circuit with a realistic basis for operation.

6.3.6. Unmanaged DG Interconnections

In order to assess the limits of the static grid thermal capacity, a certain measure of unmanaged DG has been added to the distribution circuit. Under static hosting capacity requirements, a limit of 75% of the thermal capacity[15] of utility assets is utilized. The voltage range on the circuit must also be held within the range of 0.95 to 1.05 p.u.

All generators outside of ANM control[16] are presented in Table 5 along with the corresponding effect on the circuit characteristics. Due to the fact that all generators are outside of ANM control, the traditional FERC SGIP and utility limits of the circuit must be respected with all generators operating simultaneously at peak output under minimum circuit load conditions; this is the scenario used to quantify the voltage and service conductor loading.

Table 5: DG Interconnections Outside of ANM Scheme (Peak Load with Minimum Generation)

Name	Capacity [kVA]	PF	Annual MWh	PCC	Voltage at PCC [p.u.]		Service Conductor Loading [%]	
					Normal Topology	Alt. Topology	Normal Topology	Alt. Topology
'Smart Homes' PV[16]	25	1	41	Bus 611	1.046	1.044	1	1
'Smart Homes' PV[16]	40	1	66	Bus 652	1.046	1.044	1	1
'PV System 1'	1400	1	2297	Bus 646	1.046	1.046	74	74
'PV System 2'	550	1	902	Bus 670	1.043	1.042	34	19
'Bio-digester 1'	556	0.9	4380	Bus 670				
'PV System 3'	750	1	1231	Bus 675	1.05	1.045	56	15
'Bio-digester 2'	444	0.9	3504	Bus 675				

The total of the capacity listed in Table 5 sums to 3761 kVA. Under the minimum load scenario and the normal topology, this results in a real power export of 3068 kW through the substation, or a total power flow of 3070 kVA. This corresponds to 61% of the substation transformer capacity, which is below the 75% limit of 3750 kVA. These substation power export results also hold for the alternative topology with very minor differences due to a small increase in losses.

To compare against the static grid limits presented here as well as to test the ANM control system, the sections below present the annual power flow curtailment results of the uncontrolled and then ANM-controlled DER for the high penetration ANM enabled dynamic grid.

[15] Utilities have been known to apply a limit of 20% of the thermal capacity. SGS has advised utilities and regulators that this is very conservative, and in one instance the utility changed its standards to allow 75% loading (without ANM). ANM enabled circuits have in the UK, and can for US utilities allow loading much closer to the design limit and even exceed it at times due to seasonal variations (e.g. summer thermal limits lower than winter).

[16] Smart Home PV systems included from the perspective of high residential rooftop PV deployment being assessed against traditional distribution planning criteria due to how integration via aggregators is not end-to-end control typical of larger ANM controlled commercial/community scale/utility DER. As per the body text, these are controllable via the aggregator controlling a combined solar PV + ESS prosumer.

6.3.7. On-site Demonstration Results

The demonstration day primarily centered on the functional aspects of the ANM system. The demonstration started by showing the fundamental features of ANM; the ability of the ANM system to resolve a constraint in a real-time, deterministic manner. Upon a breach of a threshold at a measurement point, the ANM system correctly instructed devices to reduce their output, thus alleviating the constraint. This was shown for multiple measurement points. Another fundamental feature of the ANM system exhibited was the ability to fail safe. During the loss of communications, simulated by removal of the cable which connected sgs comms hub to sgs connect, the sgs connect recognized that it no longer was part of the wider ANM system and instructed the device to reduce is output to its failsafe value of 0kW.

Following this, more advanced features were shown. The ability to detect a different topology and change the measurement point to generator relationship for that topology was shown. Switch positions, read from the simulated network in OPAL-RT, were read and processed to determine the topology. The final advanced functional element of the ANM system exhibited was dynamically changing thresholds at run-time. Deterministic state-driven logic was shown to reduce the output of generators to a pre-defined *safe* zone, ensuring that the network was in a state ready to accept the new thresholds to prevent unnecessary breaches of thresholds.

It should be noted that artificial loads and generation were introduced to the simulated network to demonstrate the actions and therefore the numerical results may appear to show significant load shifts atypical of a distribution network, and were therefore not the focus of the demonstration day. Figure 34 to Figure 38 are from the actual day of demonstration and show the ANM system demonstrating its various functionalities to the advisory board.

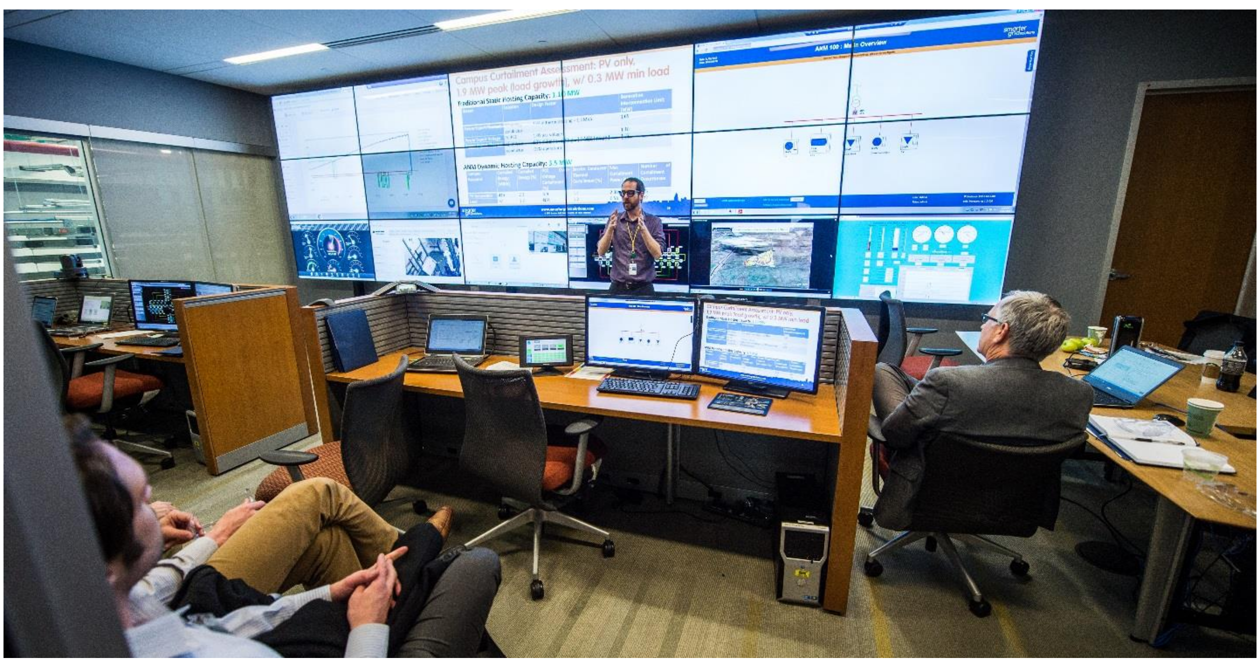

Figure 34: Demonstration of ANM Functionality to Advisory Board

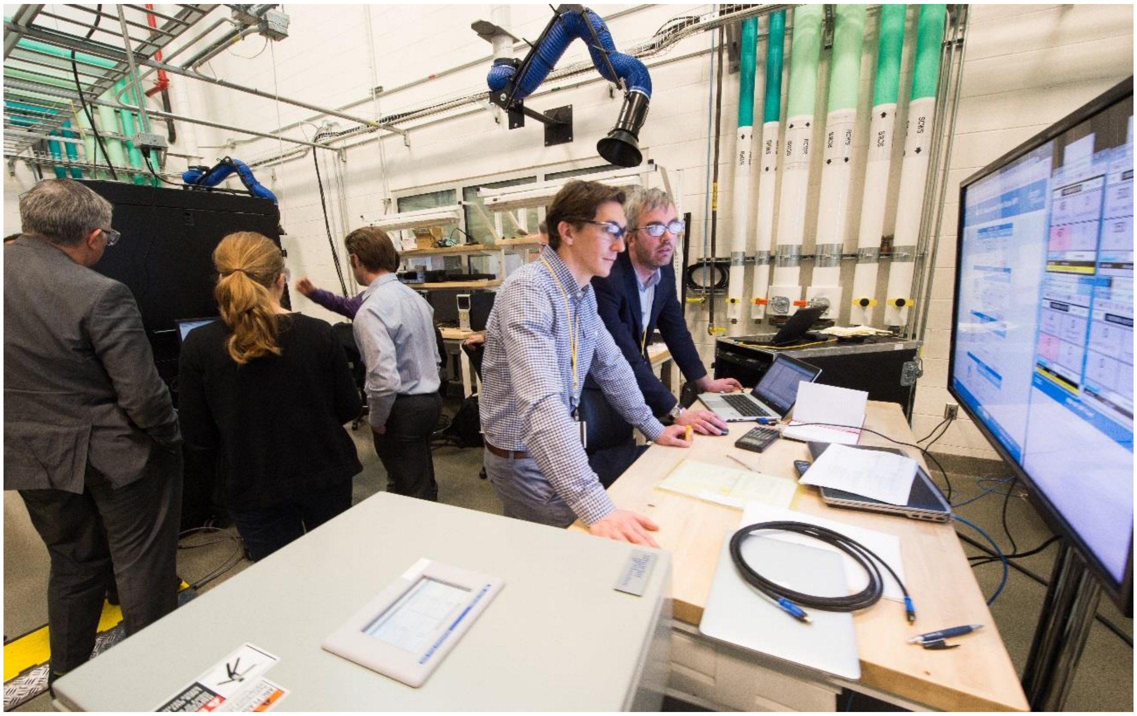

Figure 35: Engineers R. Sims and F. Watson Demonstrating Live Control of ANM System

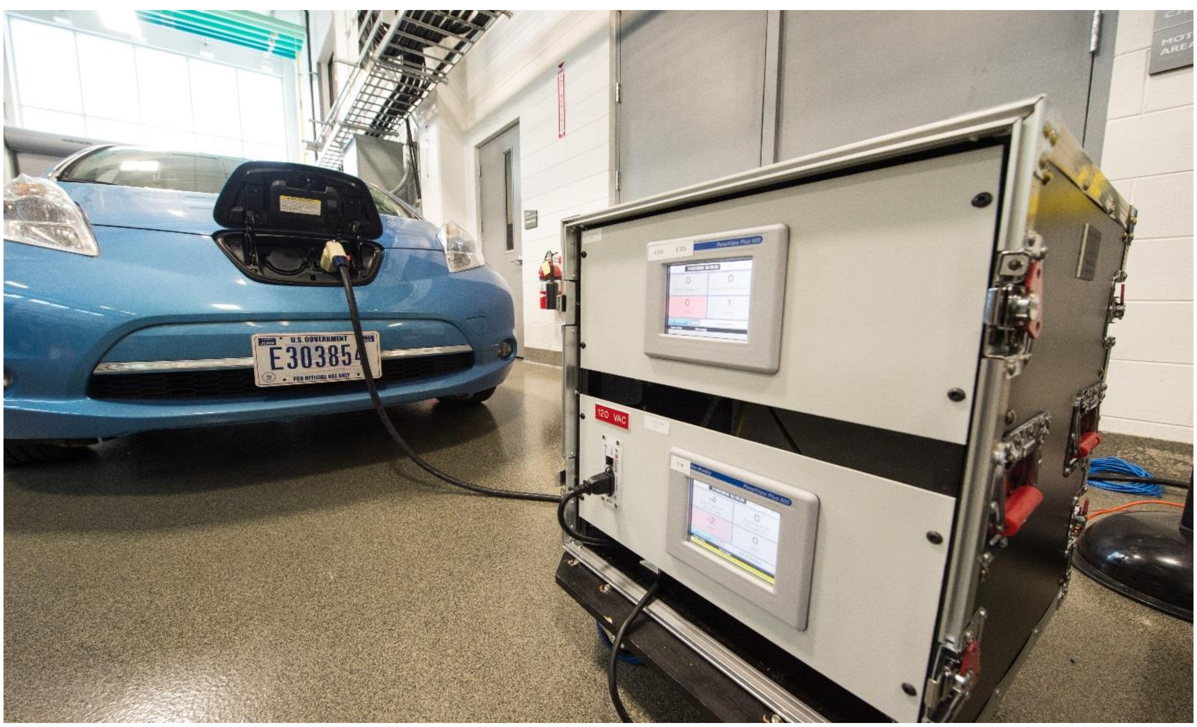

Figure 36: ANM Demonstration of EV Charging Control Capabilities

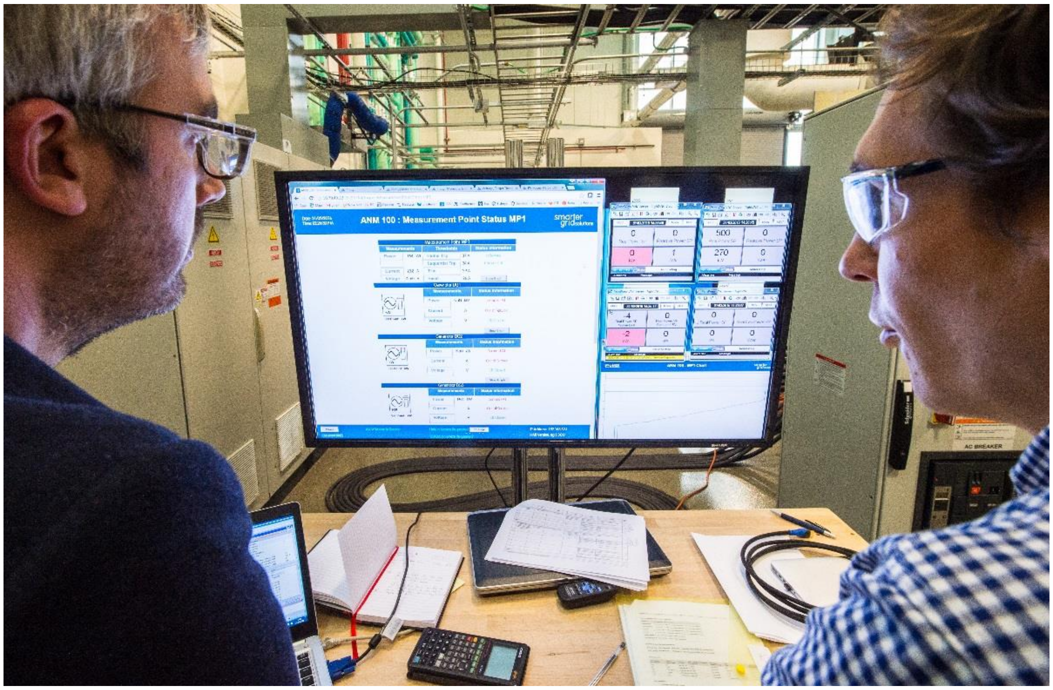

Figure 37: F. Watson and R. Sims Demonstrating ANM Functionality

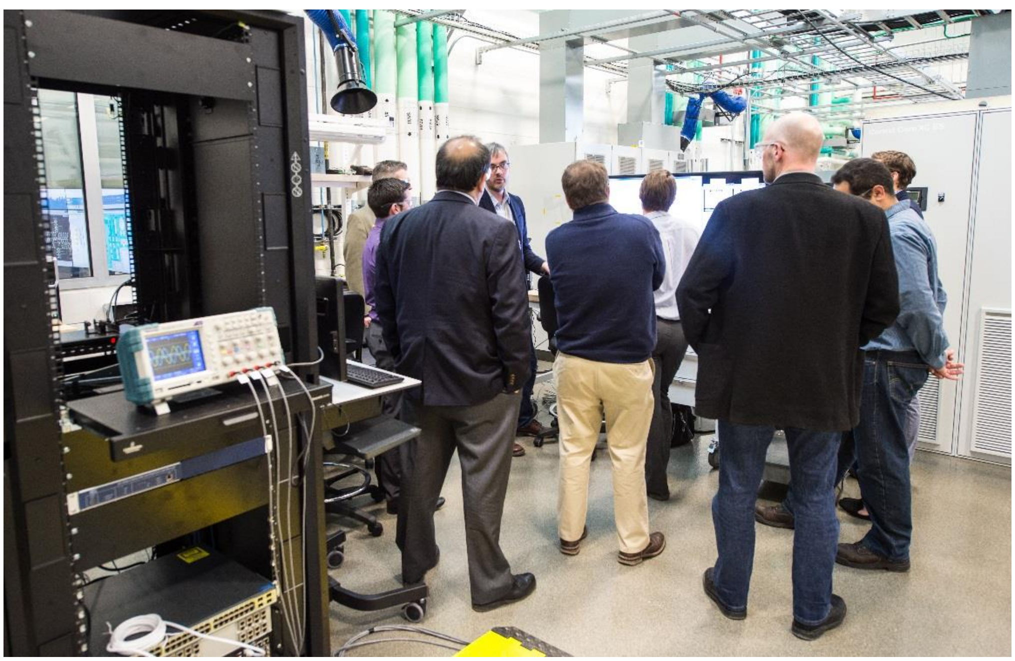

Figure 38: F. Watson Explaining the ANM Functionality to the Board

6.3.7.1. Demonstration of effective grid-edge control of DER through ANM technologies

As part of the on-site testing, the ANM system was evaluated through end-to-end and systems testing (see [5]) to ensure the control architecture and functionality allows distribution feeders to flexibly interconnect DER on constrained grids. The ANM controls thereby increase grid hosting capacity by enabling DER developers to interconnect via a flexible interconnection. This approach has been shown to be significantly more cost effective compared to firm interconnection via traditional T&D reinforcements.

A suite of site acceptance and commissioning tests were performed to verify the ANM design meets functional and performance requirements. ANM escalating actions and failsafe operation represent two critical functionalities due to the Utility's need to ensure grid safety and reliability, performance requirements traditionally guaranteed using T&D reinforcements.

6.3.7.1.1. Escalating actions

ANM escalating actions are carried out relative to the trim, trip, sequential trip, and global trip threshold definitions as seen in Figure 9 and Figure 10. Successful tests were carried out on-site where the current went above the trip threshold and the PHIL solar and wind DER were tripped according to priority order until the measured current fell below the Sequential Trip threshold, as seen in Figure 39.

Figure 40 shows results from the day of demonstration when the trim threshold was breached at 10:41 and the Sequential Trip threshold was breached at approximately 10:45. In both instances we see that the current was curtailed almost instantaneously by tripping the Wind Generator as the first line of curtailment in the escalating actions, and then tripping the Smart Campus as the second line of curtailment in the escalating actions. In Figure 40 we see the Wind Generator curtailed at 10:41 and subsequently at 10:45. Figure 41 demonstrates the Smart Campus being tripped to initially resolve the trim threshold breach and subsequently resolve the sequential trip breach. This test was repeated for the global trip scenario as well.

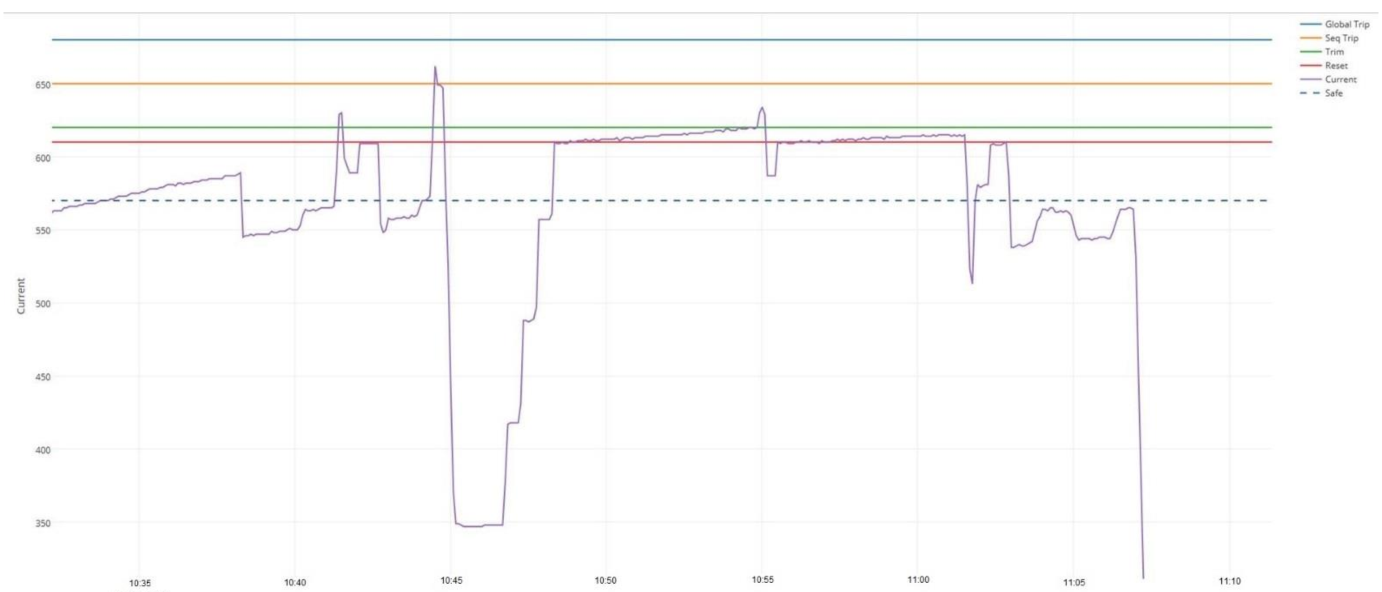

Figure 39: Breach of Sequential Trip Threshold & Resulting Curtailment

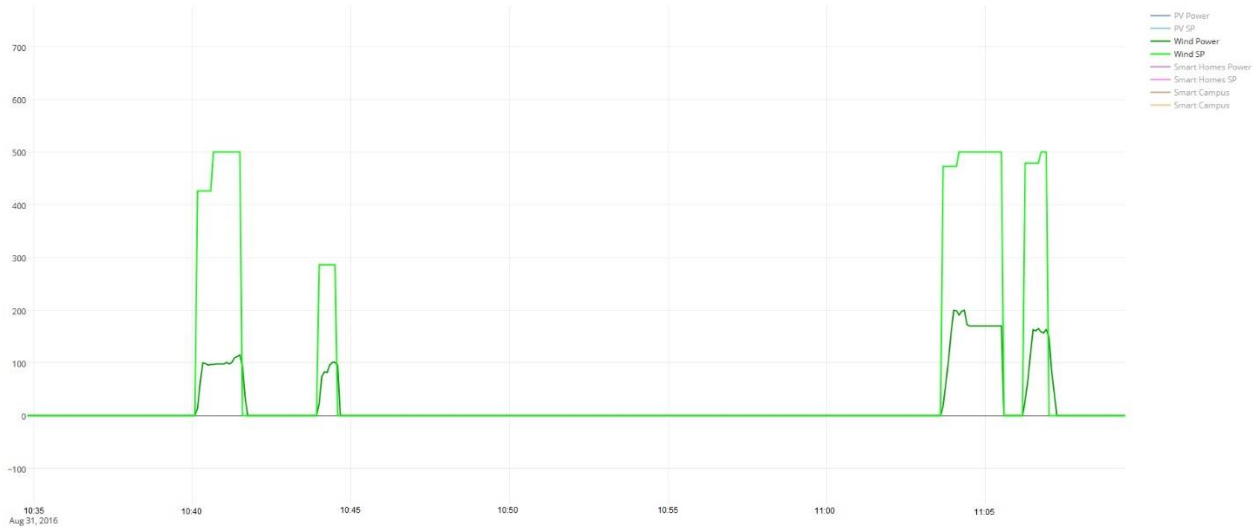

Figure 40: Breach of Sequential Trip Threshold & Resulting Wind Generation Curtailment

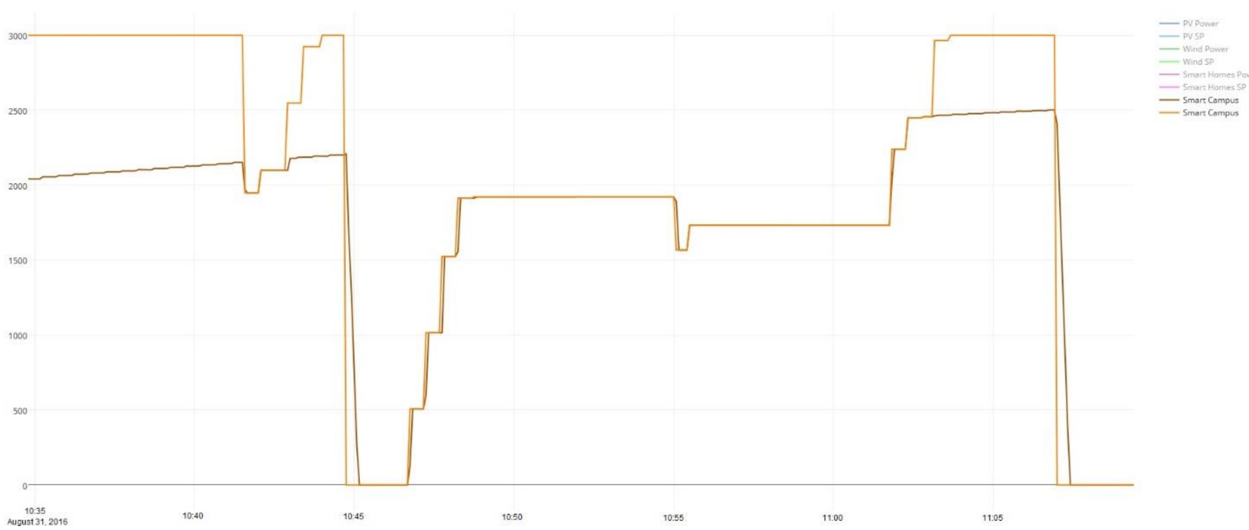

Figure 41: Breach of Sequential Trip Threshold & Resulting Smart Campus Curtailment

Figure 42 demonstrates ANM's functionality of the Response Timer, which communicates to the system that if the first generator curtailment does not bring the current below the safe threshold within a pre-determined timeframe, the next sequential trip will occur autonomously. In Figure 42 we see that curtailing the Wind Generator did not bring the total current below the sequential trip threshold, and within a matter of seconds the ANM system autonomously responded by tripping the Smart Campus generation as well. This also illustrates the Principles of Access (POA) in that the Wind Generator falls at the bottom of the merit order followed by Smart Campus generation. It should be noted that the global trip threshold is set just below an Upper Limit threshold corresponding to physical limitations on the operation of the grid equipment corresponding to the protection settings for that asset. In this way, the

Global Trip should take action to avoid any nuisance tripping of the protection system, ensuring the asset remains in service.

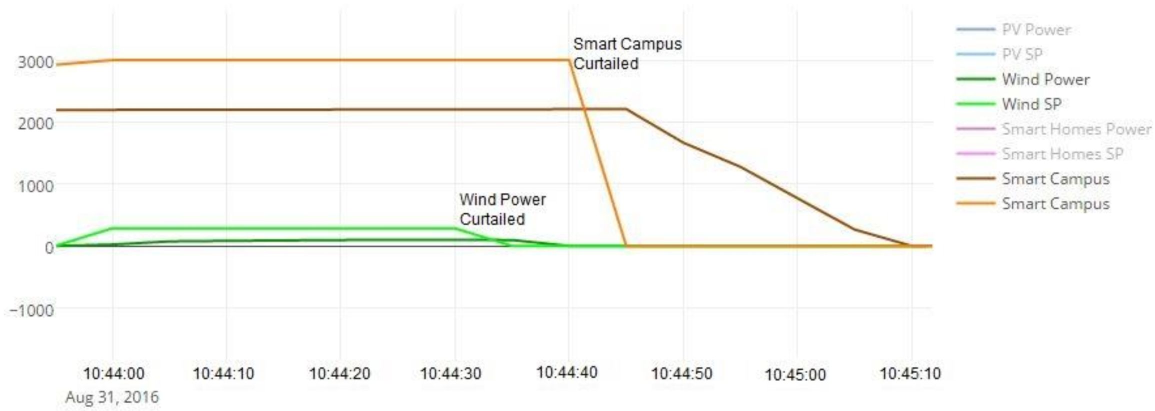

Figure 42: Curtailment of DER According to Principles of Access Merit Order

6.3.7.1.2. Threshold group changes

As referenced in Section 5.2.3, Figure 43 demonstrates the change of the Safe Threshold to a new threshold set. On the day of demonstration the new threshold set was initiated around 9:49:00, which resulted in the current being curtailed to below the newly defined Safe Threshold, at which point the new threshold set was accepted and put into service.

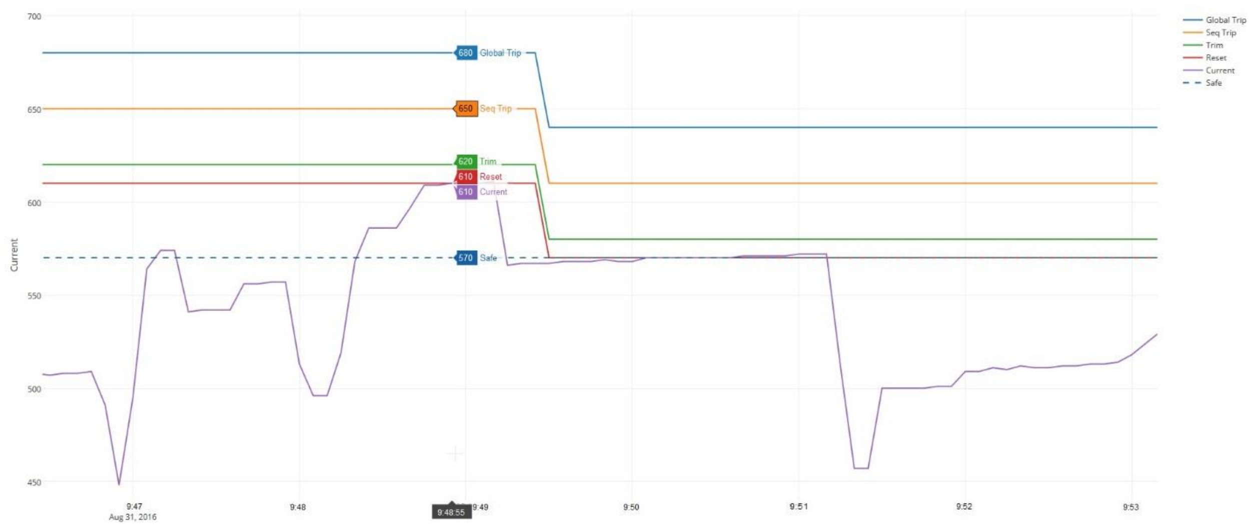

Figure 43: Demonstration of New Safe Threshold Set

6.3.7.1.3. Fail-to-safe control

The sgs connect and sgs core conjointly implement a number of fail-to-safe responses to system events. These failsafe responses are used to ensure that there is no possibility of overloading any network component in the event of failure of some or all ANM subsystems. The following functionality was demonstrated, along with advisory board member feedback from the demo:

- Loss of communications to sgs comms hub: in the event of a loss of communications between sgs connect and sgs comms hub, sgs connect was configured to implement a failsafe response[17] to ensure there is no possibility of network overloads from the respective DER. Following restoration of communications, the generator is automatically released by sgs connect in a stepwise manner to ensure safe grid operation during release. Stakeholder affirmed that this failsafe functionality is critical for grid safety, and on the other hand, automated restoration supports optimizing DER cost-benefits.
- Setpoint monitoring and non-compliance: This failsafe response is designed to prevent issues associated with a generator failing to respond to setpoints issued by sgs connect. sgs connect can be configured to trip the DER following a period of non-compliance.
- Stakeholder discussion moreover included instances of where fail-to-safe did not necessarily require tripping off generation. This agrees with how ANM was implemented for the Smart Campus, where for instance if communications are lost between the campus solar PV sgs connect and the sgs comms hub, then failsafe entailed reduction of the PV power setpoint to prevent export (i.e. load following and diversion to the battery energy storage).

Overall these functionality perspectives and stakeholder discussions align with ANM's critical systems control design principles: grid-edge distributed control technologies that are guaranteed to be predictable and repeatable in a time-bounded manner for deterministic operation based on available data.

[17] Please note that a circuit breaker (CB) was not available at the time of ANM testing at ESIF. Fail-to-safe operation was therefore demonstrated by confirming zero setpoint functionality (i.e. no generation), which in some cases may be acceptable as well for the utility.

7. SUMMARY OF KEY OVERALL PROJECT OUTCOMES

By achieving very high penetrations of variable renewable energy on a representative distribution circuit, this *ANM Integration* project demonstrated that distributed autonomous controls can effectively increase grid hosting capacity using Active Network Management (ANM) technologies. ANM's autonomous distributed control doubled the capacity of interconnected wind and solar systems by managing the thermal and voltage constraints in real-time. These generators flexibly interconnected to the grid via ANM's end-to-end control architecture, and were managed and coordinated with other smart distributed energy resources (DER; e.g. EVs, battery ESS, controllable load) to unlock the latent capacity of the system. As a smart grid technology for standardizing the grid integration of variable generation sources, ANM provides a cost effective alternative to traditional transmission and distribution (T&D) reinforcements. The testing utilized full grid simulation with DER power-hardware-in-the-loop and likewise ANM's distributed central and grid-edge controls deployed in NREL's Energy Systems Integration Facility (ESIF) on the Research Electrical Distribution Bus (REDB).

The Smart Distribution use case provided an integrative perspective of ANM across all distribution grid DER device scales (incorporating aggregated Smart Homes and the Smart Campus) in order to showcase how these devices can support smart grid services to manage DER penetration constraints in a safe and reliable manner. Furthermore, this shows how the system can extend and scale under future grid modernization schemes.

A project industry advisory board attended a one-day demonstration and set of workshops to assess project outcomes and evaluate the relevance of ANM for increasing the grid hosting capacity for clean energy. Their comments were captured and are embedded in the summaries that follow.

The results from the three use cases, the set of project outcomes and suggested field deployment recommendations that emerged from this demonstration project are summarized in this final section of the report. We include an assessment of opportunities to deploy ANM in the field today to address existing interconnection challenges, as well as project advisor suggestions for investment in these smart grid techniques, including possible future pilots for advanced schemes. The following subsections reflect the overall project outcomes, lessons learned, and recommendations.

7.1. Summary of Increase in Grid Hosting Capacity:

For the Smart Distribution test circuit, that integrates elements of the two prior use cases, ANM enabled a doubling of interconnected generation. This presupposes the existence of commercial arrangements for flexible interconnection and comparable economics that have proven successful in the UK. The following calculations and descriptions apply:

- **3.665 MWs 'firm' generation interconnected** (solar PVs, bio-digesters) – these generators utilize the static grid hosting capacity which does not require active control of these energy resources.
- **4.0 MWs 'flexible' generation interconnected** (solar, wind) – these generators utilized the dynamic grid hosting capacity enabled through ANM end-to-end control that resolves the thermal and voltage constraints caused by these generators.
    - Note: there were also battery ESSs, and EVs (both campus and aggregated smart homes), but these are not accounted for in hosting capacity calculations so as to reflect worst-case curtailment risk consistent with the financial impact evaluation these DER developers

would undertake. Including them within this calculation would further increase the hosting capacity value due to the coordinated management of all the DER.

- **109% increase in generation interconnected:** (4.0 MW) / 3.665 MW = 1.09, or 109% increase in generation interconnected. This increase in generation is relative to the thermal rating of the substation transformer, as well as minimum and maximum load.
    - **Generation interconnected at 2.765 MVA above transformer thermal ratings:** 3.765 MVA + 4.0 MVA - 5 MVA = 2.765 MVA over the thermal rating of the substation transformer of 5 MVA.
    - **116% over peak load:** ([3.765 MVA + 4.0 MVA] - 3.595 MVA)/ 3.595 MVA = 116% over the peak load of 3.595 MVA.
    - **1289% above minimum load:** ([3.765 MVA + 4.0 MVA] - 0.559 MVA)/ 0.559 MVA = 1289% above minimum load of 559 kVA.
- **Hosting capacity is set by the market:** By offering DER developers the choice of firm or flexible interconnection, utilities allow hosting capacity to be set by the market (i.e. will the next 5 MW of DER accept the implied level of curtailment risk?).
    - ANM enabled circuits always allow DER developers the choice of firm versus flexible interconnection – DER developers can choose the most economic arrangement for their given site. This choice can be made by an individual DER developer, or in coordination with multiple DER developers seeking to interconnect at the same time. Under joint DER constrained interconnection scenarios, flexible interconnection is therefore not required if the developers can mutually agree on the allocated costs and benefits of firm interconnection reinforcements – again ultimately aligning with a market definition of hosting capacity characterized by DER developers determining the most economic grid integration relationship for their site location on the distribution grid.
- **Summary of major outcomes:**
    - Flexible interconnection can support hosting capacity increases beyond >50% of peak load. Typically this represents a doubling of hosting capacity but will be dependent on specific project economics.
    - Hosting capacity shifts from being utility defined to being market defined.

7.2. Enabling Active Distribution Circuits

As detailed in Section 3.3 for conceptualizing grid hosting capacity, there is a need to consider static grid limits that constrain DER pentation based on worst case constraint scenarios and require full T&D reinforcement for increases in grid hosting capacity, and compare this with actively network management (ANM) schemes that unlock these grid assets to enable the dynamic grid hosting capacity through distributed automation controls. Key outcomes include:

- **There is a need to move from passively managed distribution grids to actively managed distribution grids:** smart grid investments to enable DER grid services correspond with rising penetrations of solar, wind, and other clean energy DER. Yet, single large DG projects (e.g. greater than 500 kW) can have prohibitively high interconnection costs under the traditional passive grid integration scenarios.

- **The ANM enabled dynamic grid hosting capacity allows for much higher penetrations of solar and wind energy:** grid edge ANM controls can support variable renewable generation interconnection at greater than 50% of peak load through flexible interconnection arrangements.
    - As calculated in the prior subsection, for the Smart Distribution test circuit the ANM was capable of managing the DER at 116% above peak load and 1289% above minimum load.
- **ANM's real-time grid edge controls are cost-effective smart grid investments to "unlock" latent grid capacity/assets**: dynamic hosting capacity is set by the market, whereby DER developers choose firm interconnection with traditional T&D reinforcements, or flexible interconnection via grid edge autonomous control. Under flexible interconnection, these DER utilize the real-time hosting capacity of the circuit based on the existing grid assets that have been modernized by deploying ANM's distributed control platform.
    - A shift to market defined hosting capacity assessments supports utilities and their DER customers to evaluate the better of traditional T&D reinforcement versus smart grid upgrades, thereby mutually determining the most economic scenario to meet grid modernization goals.
    - The ANM control architecture is designed to be extendable and scalable for future DER flexible interconnection. New generators can join ANM schemes through Principles of Access (POA) arrangements that extend control schemes to zones and nested zones for coordinated multiple DER and multiple constraint management. As DER penetration continues, ANM schemes can scale to include multiple instances of distributed controllers and also can be installed at central locations to ensure ANM coordination with system-wide bulk management requirements.
- **ANM modeling and simulation of distribution circuits can be performed based on small and incremental improvements to current feeder models:** system wide distribution circuit models are not required for short-term ANM schemes, and small and incremental investments in better models coincide with DER developer interconnection needs on constrained circuits. Flexible interconnection arrangements can be deployed on circuits with very limited historical data. DERs have successfully flexibly interconnected to the grid in the UK under limited historical data, and the NY REV ANM demonstration project[18] is employing similar techniques. ANM modeling and simulation, and likewise, curtailment evaluation process for the Smart Distribution use case are detailed in the appendices, see also [8], [10], and [11]. Based on the project testing and stakeholder engagement, the following scenarios apply:
    - ANM modeling and simulation are carried out offline and are used to determine curtailment risk relative to defining ANM control system configuration settings. These settings are pre-configured on the ANM controllers and confirmed via on-site testing and DER commissioning.
    - ANM modeling and simulation typically only uses, and requires, 8760 hourly data profiles (load & generation) for the local distribution circuit where interconnection is taking place.

[18] http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7B06E123A8-0151-4456-93BB-CCC9E87280F8%7D

- Higher resolution data sets are helpful but not required – they support curtailment risk sensitivity evaluations. For this project for instance, 1-min load and generation profiles[19] were compared with 1-hour profiles: finding on the order of 0.5% annual curtailment variance between the two simulations. This variation is of the same magnitude as other factors (e.g. loss of comms, variation of intermittent generation from year to year, etc.) such that hourly data profiles are sufficient for near-term flexible interconnection opportunities.
- Online firm and flexible circuit capacity models can be created that allow DER developers to receive fully automated preliminary interconnection studies. One such system has been deployed with success in the UK, and it is anticipated such systems will be effective in North America.

  - Reduced circuit models can be appropriate, and generally are all that is required, for ANM modeling & simulation given that the constraints caused by the flexibly interconnected generation are generally restricted to one or two locations.
  - ANM schemes can successfully be modelled and simulated for circuits without full historical data – in these scenarios a Monte Carlo simulation with typical load/generation profiles can be used.
    - Unknown circuit parameters (e.g. cable types/distances/impedance) can be addressed within the model by configuring the ANM control thresholds more conservatively. After one or two years of ANM operation, the analysis of actual operational data can determine if additional capacity is available (i.e. determine if thresholds can be increased for example by extrapolating the rate of change of ramp rates/etc.).

- **Summary of major outcomes:**
  - There is a need to shift from passive/static grid integration of variable renewable energy to active/dynamic grid integration of clean energy. Through flexible interconnection, ANM techniques incorporate wind, solar, biogas, and other DERs into the distributed control operations of the grid.
  - ANM schemes can be deployed today on circuits whose circuit models lack historical data at the individual customer level and without the need for high resolution datasets (e.g. 8760 hourly data profiles of interval metered data at the substation level).

7.3. Robust Distributed Smart Grid Controls

- **ANM's deterministic control manages constraints safely and reliably:** ANM manages DER through an end-to-end critical control systems approach that is time-bounded and guaranteed repeatable. As demonstrated through the INTEGRATE use cases can be done without the need for forecasting or energy storage. Although not required for initial ANM flexible interconnection schemes, very high penetration scenarios present forecasting, energy storage, and demand response with additional revenue opportunities.

[19] High resolution profiles were required for the real-time grid simulation, but were down-sampled to hourly profiles for the ANM modeling, simulation and configuration tasks of this project.

- As part of the on-site testing, the ANM system was assessed through end-to-end and systems testing via grid simulation with PHIL (see [10]) to ensure the control architecture and functionality allows distribution feeders to flexibly interconnect DER on constrained grids. ANM is a distributed control architecture and deterministic controls scheme that is separate and complementary to ADMS/SCADA – see Section 8.8 for more information.
- Key demonstrated ANM functionality included:
  - **Real-time**: second-to-second control to manage multiple DERs and multiple constraints in real-time. Modern grids need to handle fast-changing volumes of data. That is why the ANM control platform uses critical systems industrial controls technology, which include time-bounded control responses.
  - **Autonomous**: The need to respond rapidly to large volumes of data and under a second-to-second basis make operator-in-the-loop control impractical, thus ANM operates autonomously.
  - **Deterministic**: Control decisions must be predictable, reliable, safe, secure and repeatable. The tested ANM scheme applied feed forward control within finite state machines that operate via time bounded response windows, thus yielding guaranteed repeatable, deterministic control responses. DER response characteristics are pre-configured for their respective constraint contribution sensitivity factors.
- Critical to achieving dynamic grid hosting capacity are ANM escalating actions and failsafe operation due to the Utility need to ensure grid safety and reliability through ANM smart grid techniques compared to traditional T&D reinforcements under such massive DER penetration levels. The following critical systems functionality included:
  - **Escalating Actions:** ANM escalating actions are carried out relative to trim, trip, sequential trip, and global trip thresholds. ANM control actions are furthermore taken based on the information available at that time – hence control actions and escalating actions ensure grid safety and reliability even under loss of communication scenarios. Several scenarios comport with the need for escalating actions:
    - Escalating actions are required given how ANM enables DER interconnection and grid equipment operation closer to the actual physical limits of the distribution grid. Upper limits reflect equipment ratings versus protection ratings, such that protection schemes should only operate when the ANM control actions are not implemented within a reasonable time-frame for the constraint event.
    - ANM's second-to-second operations align with the needs for control during high-rate-of-change events (e.g. intermittent cloud cover; e.g. a strong wind gust). Distributed control escalating actions again ensure grid safety given that the duration of these events are fast enough in many instances to not even be registered by traditional SCADA/ADMS central controller response times. For example, a high rate of change ramp rate could necessitate a trip event given the very high DER penetration levels.

- As a part of escalating actions, there is a need for alarms and potentially operator action for higher-level system needs. Bulk power operator notifications might be necessary in order for them to assess if the changes in distribution power flow necessitate schedule changes for bulk generation.
- Engagement with Utility and DER developer stakeholders are therefore critical during the ANM modeling & simulation and ANM design configuration phases in order to ensure control actions meet grid safety requirements while still maximizing DER interconnection economics.
- There is an ongoing need for discussion and evaluation as ANM schemes expand, especially for outage and fault conditions. Will for instance pre-fault or post-fault limits be observed in cases where constraints occur during outage or fault conditions?

- **Fail-to-safe control:** the sgs connect DER device controller implements a number of fail-to-safe responses to system events. These failsafe responses are used to ensure that there is no possibility of overloading any grid component in the event of failure of some or all ANM subsystems. The following functionality was demonstrated:
  - Loss of communications to sgs comms hub: in the event of a loss of communications between sgs connect and sgs comms hub, sgs connect was configured to implement a failsafe response[20] to ensure there is no possibility of network overloads from the respective DER. Following restoration of communications, the generator is automatically released by sgs connect in a stepwise manner to ensure safe grid operation during release. Stakeholders affirmed that this failsafe functionality is critical for grid safety, and on the other hand, automated restoration supports optimizing DER cost-benefits.
  - Setpoint monitoring and non-compliance: This failsafe response is designed to prevent issues associated with a generator failing to respond to setpoints issued by sgs connect. sgs connect can be configured to trip the DER following a period of non-compliance.
  - Consider failsafe modes that do not trip off generation: Failsafe commonly requires generators to trip off, but ANM schemes can be configured to restrict any export when sited with load. This aligns with how ANM was implemented for the Smart Campus, where if communications are lost between the campus solar PV sgs connect and the sgs comms hub, then ANM is equipped with failsafe functionality to reduce the PV power setpoint so the PV system will autonomously curtail export (i.e. load following and diversion to the battery energy storage).

[20] Please note that a circuit breaker (CB) was not available at the time of ANM testing at ESIF. Fail-to-safe operation was therefore demonstrated by confirming zero setpoint functionality (i.e. no generation).

- **Enhanced ANM features:**
  - **Alternative circuit topologies:** SGS demonstrated ANM deployment on a test circuit that included an alternative topology configuration. DER can therefore flexibly interconnect to distribution circuits that have alternative configurations (e.g. for fault isolation schemes to restore service to the other customers). With topology detection ANM can manage the DER to safely transition from one configuration to the next.
    - ANM has also been deployed in the UK for a scenario where there were no constraints under the normal topology, but were constrained under the alternative configurations. Again, allowing flexible interconnection in a scenario that historically would have been uneconomic (or not allowed) for those generators to connect to the grid.
    - This can also be applied to address constraints that only occur under N-1 or N-2 scenarios.
  - **Dynamic threshold configuration:** SGS demonstrated that thresholds could be dynamically altered by the grid operations engineer in a manner that safely transitioned the DER to the new thresholds. This feature makes it easier to change thermal thresholds to incorporate seasonal/weather related changes to equipment ratings.
- **Protection systems are still required:** As indicated in Figure 2, ANM technologies bridge the control and time response needs of protection (local, <1s) and SCADA/ADMS (central, minute+). As such, ANM does not replace protection systems, which are designed consistent with the level of DER penetration.
    - Additional modeling may be required. Changes in settings to existing protection may be required. Additional protection may be required.
    - The deterministic and local control attributes of ANM device controllers might support adaptive protection schemes and FLISR: on-going studies and pilots are necessary.

7.4. Flexible Interconnection is Relevant to DER Sites Today

- **High DER penetration grid constraint periods coincide with when the DERs are available to be controlled:** ANM monitors the constraints and controls DER when constraints occur. Constraints are mostly all local: circuit-by-circuit, substation-by-substation, with voltage, power flow, backfeeding, etc., managed autonomously to ensure grid limits are not breached by the ANM-enabled DER.
  - DER interconnection constraints are mostly all local: circuit by circuit, substation by substation. And while many DERs might be non-dispatchable resources, the problems they cause coincide with when they are available to be controlled: voltage, power flow, and backfeeding. ANM enables DERs to be controllable, even if they are not dispatchable[21]. As demonstrated in this project, significant increases in hosting capacity

[21] ANM autonomous and real-time control of variable renewable generation necessitates the need to define "controllable" as distinct from "dispatchable." Controllability of a given DER is a function of constraint contribution,

can be achieved for various grid configurations without also requiring dispatchable generation.

- **Flexible interconnection is relevant today:** DER interconnection limits can be breached by individual projects and are not a symptom of large-scale solar and wind penetration, these limits just become more frequent at higher DER penetration levels. Flexible interconnection curtailment solutions are already proven to provide economic solutions for developers that can significantly increase hosting capacity. Curtailment risk for a few ten to a few hundred hours of the year can be much more economic for some developers compared to traditional T&D upgrades for a firm interconnection.
  - Static hosting capacity limits reduce the size of DER projects or result in projects being moved to other locations due to uneconomic grid integration costs. This results in less interconnection and encourages the idea that there are no interconnection or constraint issues (i.e. these sites are not tracked).
  - Given that traditional static hosting capacity assessments limit DER interconnection based on rare worst case scenarios (and very rare coincident scenarios), ANM technologies offer an opportunity to increase the utilization of existing grid assets when they align with DER developer grid integration needs.
  - A small amount of curtailment risk could be more cost effective compared to T&D reinforcement costs, and such approaches align with ANM flexible interconnection schemes based on similar efforts in Europe.[22] Hence ANM commercial arrangements cannot be separated from the technical control system functionality, and utilities will need to consider how to balance traditional system reinforcements with smart grid investments. ANM offers an example of a small, marginal smart grid investment that supports DER developers needs today to help inform wider grid modernization investment analysis.
- **ANM allows for faster interconnection to constrained grids:** DER developers value optimal sites with locational value for clean energy, but also value speed to interconnect and overall grid integration costs. New flexible interconnection solutions can therefore provide significant and timely increases in hosting capacity that are aligned with developers' interests when distribution feeders are constrained. ANM schemes can be deployed in a matter of months to meet flexible interconnection requirements, as compared to traditional T&D reinforcements for firm interconnection that can sometimes take years.

current generation level, and ANM control response, whereas dispatchablity includes these characteristics and also incorporates rated capacity availability (i.e. fuel/storage availability that is not dependent on intermittent resources).

[22] See for instance IEA, 2016. "Re-powering Markets: Market design and regulation during the transition to low-carbon power systems", and also see:
http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/Studien/verteilernetzstudie-englisch,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf

- **Summary of major outcomes:**
    - Hosting capacity constraints happen today (e.g. with a single large solar/wind site on a "weak" grid), and flexible interconnection would offer an alternative grid integration pathway for constrained generators.
    - ANM allows faster interconnection to meet DER developer commissioning timeframes and goals as compared to lengthy construction times for T&D reinforcement.

7.5. Deployment Opportunities for ANM Today

Flexible interconnection has proven effective in the UK for certain use cases where firm interconnection is cost prohibitive (e.g. 276 MW in operation with a few hundred more already under contract) – it is anticipated that ANM opportunities will be similar for the US. Given the degree of utility and DER developer learning required for ANM adoption, pilot projects are encouraged that include public dissemination of results and lessons learned. As the market matures best practice guides would need to be developed similar to the UK.[23]

- **General ANM adoption characteristics:**
    - **Large commercial/community/utility scale DER: 50kW+:** Today's ANM hardware requirements (e.g. sgs connect: RTU controller) are typically only cost effective for DER above 50kW, with a few hundred kW to MW sites being the most common in the UK.
        - ANM hardware cost reductions or hosting of ANM software on other DER equipment would be needed to cost effectively apply ANM to smaller DER – noting that there is a risk of potentially reducing hardware reliability and/or performance that would need to be considered within the controls configuration.
    - **DER nameplate capacity causes constraints beyond FERC SGIP screens:** The proposed DER name plate capacity is large enough that potential constraints are triggered due to going above FERC SGIP screens.
        - As mentioned in the prior section, these triggers can happen for large individual DER systems seeking to interconnect (e.g. 2MW solar array on a rural feeder) – thus high penetration challenges are present even for single DER deployments.
- **Short-term ANM deployment criteria that are applicable for field trial today:**
    - DER flexible interconnection sites will be those with export power constraints that may also coincide with further upstream reverse power flow constraints.
        - Scenario feasibility will need to assess allowable reverse power flow use cases (e.g. changes to protection settings/sensitivity to allow reverse power flow). Examples include: N-1/etc. conditions and alternative topology configurations.
        - ANM is typically deployed today on balanced 3-phase circuits.
    - Mitigating constraints via real power (P) setpoint control of DER, typically inverter based interconnection, is the most simple control scenario: direct curtailment of DER.

[23] http://www.energynetworks.org/modx/assets/files/news/publications/1500205_ENA_ANM_report_AW_online.pdf

        - While P control is more simple for Utility adoption of ANM schemes (i.e. less risk to grid operations control), real-power curtailment directly impacts DER revenue.
        - For thermal constraints, P control schemes are easy to adopt within LIFO Principles of Access (POA) frameworks.
    - sgs connect (e.g. RTU) devices may replace the need for a separate Direct Transfer Trip (DTT) relay.
        - Beyond DTT expense, extensive use of DTT schemes has scalability issues when the DER trip scenarios start interfering with each other. These issues can be circumvented by providing DTT functionality as part of the ANM system. Among other criteria, ANM was originally developed in the UK to address this lack of scalability of intertripping, which has similar performance requirements to DTT.
    - Interconnection causing voltage rise issues are likely to be the most common constraint[24] to trigger ANM adoption in North America.
        - Early field deployments are likely to be limited to voltage rise management at the point of common coupling (PCC) for single large DER (i.e. multiple DER coordinated volt/VAR management is a longer-term use case as mentioned below).
            - Initial deployments may coordinate with grid tap changer/voltage regulation equipment control schemes. Inverter control be configured so as to minimize extensive tap changes (i.e. minimize costly replacement due to shortened life from repeated tap changes).
            - Coordination with tap changers, capacitor banks, and/or line drop compensation schemes might be required, hence DER provision of Volt/VAR use cases in the short-term are likely to use single/a few DER so as to fully test the scheme before expanding to multiple DER.
            - Short-term deployment scenarios will be limited to ensure operational grid reliability goals are met.
        - For voltage constraints, a pro rata/shared Principles of Access (POA) framework might be the most appropriate for expanding the scheme for future generators. This is due to how future ANM generators can disproportionally affect the original ANM generator's relationship to the voltage constraint.
        - Reactive power (Q) control may be more effective at managing voltage rise constraints compared to P control, yet not all DER have this capability.
            - Initial field trials may only use stepped power factor (PF) control due to its simplicity, ease to plan for, and ease to understand.
            - Dynamic P & Q setpoint control is more flexible and powerful for a wider variety of situations.

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[24] See for instance: Reno, M.J. and Broderick, R.J., (2016). "Statistical Analysis of Feeder and Locational PV Hosting Capacity for 216 Feeders." No. SAND2016-6874C. Sandia National Laboratories (SNL-NM), Albuquerque, NM.

- Utilities might require controls and HIL grid simulation to validate factory assessment testing.
- Early field deployments should push for this functionality to ensure operational performance before wide deployment.
- Oversizing the inverter to make full use of the Q control needs might be necessary depending on the nature of the voltage constraint.
- Incentivizing Volt/VAR support from DER may be required to support creating ancillary markets – early pilots could test some of these market functions. The economics of Q control are less clear.

- **Long-term ANM deployment criteria that will require more simulation and lab testing with more restrictive field testing:** more advanced ANM schemes will require more modeling/simulation, more controls & HIL grid simulation for factory acceptance testing, and thus more targeted pilot projects to mature these approaches before wider field deployment. These include:
    - Schemes that address observability and controllability for underdetermined distribution circuits such as Distribution State Estimator, may enhance the performance of ANM or limit the monitoring and communication requirements. We should investigate conditions under which this a DSE should be leveraged.
    - Examples of long-term ANM deployment scenarios include:
        - Multiple DER providing dynamic volt/VAR in coordination with grid voltage regulation equipment (and possibly line drop compensation), with higher complexity when some DER are absorbing and some are injecting VARs. Stable reactive power flow schemes will need to be developed.
            - More advanced scenarios will include substation configurations where the tap changer controls voltage on multiple feeders, but DERs providing volt/VAR are only on one feeder.
        - Volt-Var Optimization (VVO) or Conservation Voltage Optimization (CVO) for underdetermined distribution circuits to support minimizing losses or energy consumption, with higher complexity when DER providing volt/VAR are included in the scheme.
        - Use of ANM to mitigate voltage flicker on long rural feeder.
        - Deploying ANM schemes on underdetermined unbalanced distribution circuits: incorporating, for instance microPMUs with an ANM scheme. Investigate developing ANM schemes to aid in phase balancing through control of DER.
        - Role of ANM in multiple points of common coupling (MPCC) utility / community microgrids, with higher level complexity for synchronized macrogrid disconnection (i.e. transitioning) and also island mode operation for weak grids, and under fault conditions (N-1, etc.)
        - ANM interfacing for adaptive protection and distribution automation schemes, For instance, new network protector schemes for DER reverse power flow scenarios on secondary mesh grids would need to be piloted. Adaptive

configurations as well as coordination among zonal protection equipment will be required, and ANM's distributed finite state machine control architecture aligns well with the deterministic needs for effective protection.

- Piloting this functionality on secondary mesh grids today aligns with how adaptive projection will be needed in the future for radial grids with very high DER penetrations.
- Application of ANM to manage DER during fault location, isolation and system restoration (FLSIR) schemes.

- Very high DER penetrations will start disrupting transmission systems markets and in some scenarios real-time operations, for instance balancing and ancillary services – thus requiring T&D coupled forecasting and potentially coordinated control. Modeling and simulation of TSO-Distribution interfacing should be investigated and lab tested today to consider effective coordination and systems design characteristics, especially if a Distribution System Operator (DSO) emerges (i.e. the TSO-DSO interface)
- ANM applications for utilities of the future: as a second-to-second data and control layer within grid systems, ANM can support grid modernization use cases today. The following key scenarios apply:
  - DER-to-DER markets test DSO implementation and operation that support transactive distribution grid schemes. It should be noted that early ANM schemes exemplify DER-to-DER market situations, where matching load/storage with generation curtailment would increase the value for all DER while utilizing smart grid techniques valuable to all ratepayers. Given flexible interconnection inherently includes curtailment risk, this property reflects one of the highest value propositions for testing DER-to-DER market animation – as anticipated for example in NY REV's Flexible Interconnection Capacity Solution (FICS)[18] demonstration project.
  - ANM's existing control architecture supports import constraint management (i.e. demand response; peak shaving; demand side management)[25] in addition to export, reverse power flow, and voltage constraints.
    - Beyond allowing operation closer to equipment ratings due to ANM's autonomous, deterministic, real-time control framework, ANM enhances demand response schemes by mitigating oversubscription and fully incorporating flexibly interconnected variable renewable generation within peak demand operational scenarios. It is anticipated that this might also thereby reduce the use of high emissions peaking plants.

[25] Note: this functionality was tested in factory simulation during the Smart Campus use case, but was unable to be site tested on the ESIF grid simulator due to time constraints.

7.6. Other Considerations

- **ANM platforms support grid modernization today:** ANM deployments align with grid modernization efforts to actively manage distribution resources, and such approaches augment the ongoing work on LMP+D+E and transactive grid initiatives[26], moreover they support efforts for utilities to develop alternative revenue streams in light of changing regulatory structures.
    - Given that traditional static hosting capacity assessments limit DER interconnections based on rare worst case scenarios (and very rare coincident scenarios), ANM technologies offer an opportunity to increase the utilization of existing grid assets when they align with DER developer constrained grid integration needs. These smart grid ANM investments deploy a real-time controls and data platform that can be extended to include DER-to-DER markets and other transactive grid and nodal pricing DSO market schemes.
    - ANM systems should be deployed utilizing existing infrastructure where available and cost effective. Investments for ANM should be targeted to meet specific DER deployment needs with interoperability, cybersecurity, extendibility, and scalability in mind.
    - Coordinated distributed and centralized data management – typical ANM controllers allow local data logging up to 1 month, with data consolidation to necessary distilled data required for transmission to a central repository. Central/remote database synchronization is available upon restoration of communications.
- **Commercial arrangements for flexible interconnection cannot be considered independent of the technical control requirements:** beyond a DER developer choosing between a firm and flexible interconnection, commercial arrangements for DER access to the grid need to be contractually defined at the time of interconnection and through a framework that extends to future generators with clear grid access rights defined. The following key attributes apply:
    - Firm interconnection DERs are given full access to the grid.
    - Flexibly-interconnected DERs are given access to the grid based on a Principle of Access[6] (POA) scheme. POA frameworks relate the risk of curtailment to the control priority ordering for resolving constraints from multiple DERs. Example POA schemes include: Last-In-First-Off (LIFO), Shared Percentage, Generator Size, Greatest Carbon Benefit, Market Based, Technical Best, Most Convenient, Combined/Hybrid Approach.
        - The technical portion of the POA specifies the POA scheme and maps directly to the control priority stack pre-configured in the ANM system.
        - The commercial portion of the POA specifies where the DER developer resides within the control priority stack and the associated annual curtailment risk (percent reduction of estimated generation).
        - Curtailment estimates are given to the DER developer as part of their evaluation to accept a flexible interconnection contract. Assumptions, analysis methodology, and model characteristics are all included in the estimate. DER

[26] See for instance NY DPS effort here:
http://documents.dps.ny.gov/public/MatterManagement/CaseMaster.aspx?MatterCaseNo=15-E-0751&submit=Search+by+Case+Number

developers have the right to request the full model (data sets, load/generation profiles, distribution grid model) for independent 3rd party due diligence evaluation of curtailment risk, including performing sensitivity and scenario analysis.

- Additional information for the POA scheme and curtailment estimate approach used for the Smart Distribution use case can be found in Section 6.3 and Section 8.1.
- In terms of the initial investments and annual costs for ANM schemes, it should be noted that a variety of shared versus separate cost frameworks have been utilized in the UK and there is on-going evaluation. There will be a need for similar considerations in the US that reflect the mutual interests of all stakeholders (utility, DER developers, ratepayers, society).

- **Cybersecurity requirements and mitigation techniques need to be addressed throughout the ANM design, deployment, and operation processes:** The foundations of achieving a secure, stable ANM platform are anchored in the culture and business practices adopted by both SGS and the Utility – see [9] for more information.
  - SGS has committed to operating a formal, documented integrated management system. SGS's management system is certified to ISO 9001, this provides the framework upon which to establish, verify and continually improve business procedures that ensure the intended cybersecurity outcomes and objectives of SGS technology are met.
  - As part of the integrated management system, SGS has established an Information Security Management System (ISMS). The ISMS is focused on establishing and meeting the security objectives of SGS and its stakeholders. SGS has used the ISO27001 standard to build its ISMS and the system also draws heavily from the NIST 800 series of guidelines and NERC-CIP. SGS was awarded ISO 27001 in August 2016.
- **Incremental and diverse communications investments triggered and aligned with DER developer needs and ANM deployments:** ANM schemes have been applied successfully across a myriad of communication systems with loss of communications representing one of several curtailment uncertainty variables. Two things to consider for communications quality are (1) the marginal reduction in curtailment from improved communications availability, and the (2) varied ownership options that can exist within an ANM scheme.
  - Extensive high speed fiber communications are not required for ANM. Instead communications investments to each ANM component should be considered for the value that improved communications brings to the ANM scheme. Improved communications can support:
    - Faster and more reliable communications to grid constraint locations on the utility side of the meter ensure DER devices maximize their access to the grid: further unlocking grid equipment operation margins for increased dynamic hosting capacity levels.
    - Quicker DER release times after a constraint has been cleared.
    - More marginal economic value might be realized when fiber or other high speed/high reliability communications are used for constraint measurement points. However, if these communication media are required to meet DTT requirements, then obviously they can be leveraged for ANM.

        - Communication investments might only be required/economic local to the ANM integrated equipment, but this approach aligns with how the constraints that need managed are local and ANM is a distributed control approach.
    - The Utility and DER customer should decide if mixed communications ownership models mutually address each other's risk.
        - Having the DER developer own the communications to their DER site controller might for example align risk better: a flexibly interconnected DER site would have the responsibility for, and thus the incentive to improve communications to their site when loss of comms to the site increases curtailment to an uneconomic level.
- **Systems integration and continuing to support interoperability at each control domain layer:** there is an on-going need to have interoperability communications and controls signals industry wide, and at all layers: DER device, distributed controls, and central controls. There is moreover a need to consider ANM integration across utility systems. Additional information can be found in [4] and [7], with the following key considerations:
    - ANM's distributed control architecture aligns with recent developments around OpenFMB and other industry efforts to ensure field and enterprise systems integration interoperability across all DER and grid equipment devices.
    - Systems configuration needs to be approached from a management of complexity perspective, as well as utilizing risk identification and mitigation strategies. ANM deployments need to be considered from a systems of systems approach that includes hierarchical control requirements. Systems integration requirement at a minimum needs to consider ANM interfacing with regard to:
        - *Systems integration:* SCADA/DMS/EMS | Measurement Points |Field message bus | Local Control Systems
        - *Teams involved:* Commissioning | Real-time systems | IT | Network Planning
        - *Systems involved:* Up and downstream communications | Cybersecurity | Firewalls | Databases | Data protection & privacy | Standards and protocols
    - Enterprise integration and architecture should be considered early within the ANM scheme. Figure 44 provides an example of the systems to consider.

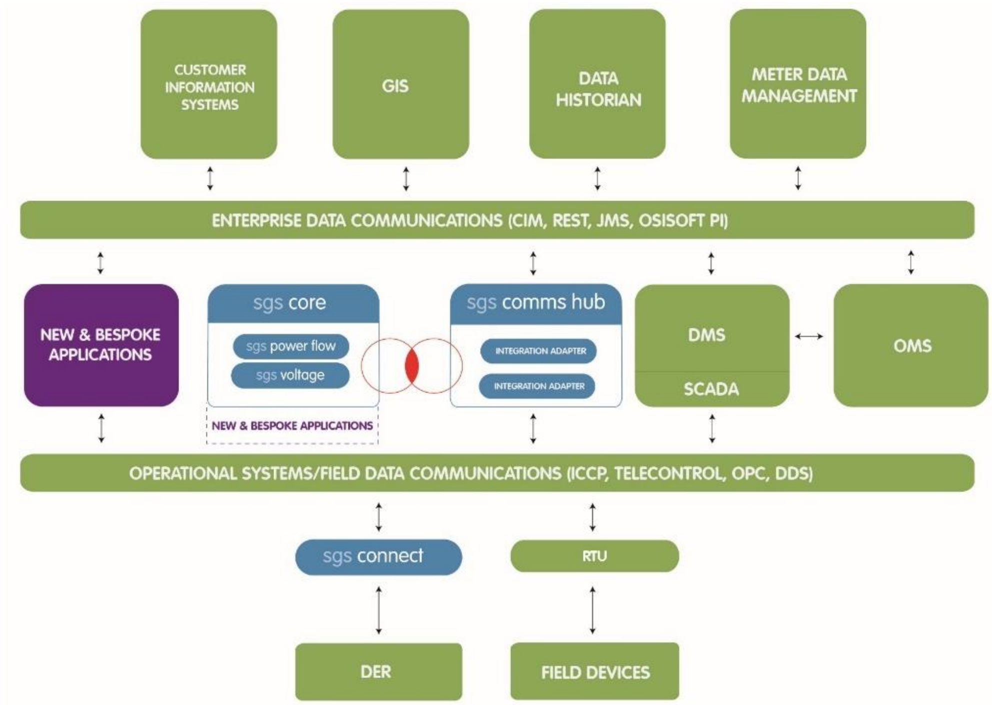

Figure 44: Enterprise Integration of ANM

- For the Smart Distribution use case, integration options included:
  - Serial and IP-based: ModBus | DNP3
  - IP-based only: ICCP/TASE.2 | IEC 61850 | OSIsoft PI | OPC | DDS
  - Gateway adapters: Apache Camel | MQTT | AMQP | XMPP | JMS
  - The following adapters are under development: CIM/XML | CIM/RDF

- **Prevalent flexible interconnection will impact transmission systems operations:** regions with extensive ANM-enabled DER will export power. This exported power will need to be considered in TSO balance and reserve margin markets.
  - While outside the scope of this project, future coupled transmission-distribution systems modeling is suggested to characterize impacts on markets as well as support integrated systems planning for balancing smart grid investments with traditional T&D reinforcements.
- **Cost-Benefits of flexible interconnection are site specific and relative to the DER developer's risk profile.** When connecting to constrained grids, flexible interconnection is generally 60-90% more cost effective compared to traditional T&D reinforcements[27]. When extrapolating these results system-wide for grid modernization over the coming decades, a 30% savings is estimated.[28] The following table includes key ANM cost-benefit categories:

[27] See for instance the deliverable reports from the Flexible Plug & Play (FPP) project from UKPN, available here: http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Plug-and-Play-(FPP)/

[28] See TRANSFORM model from Ofgem's Smart Grid Forum: Workstream three (WS3): Developing networks for low-carbon. See also footnote 22.

Table 6: Cost and Benefits of ANM Enabled Flexible Interconnection of DER

	Category	**Description**
Investments / costs	Operational IT & Telecoms	Data monitoring and acquisition, including communications; if not already available
	Operational IT & Telecoms	ANM/smart grid technology CAPEX
	Operational IT & Telecoms	DER host site ANM communications
	Network Design & Engineering	Data gathering & verification labor
	Network Design & Engineering	Data integration for system modeling labor
	Network Design & Engineering	ANM/smart grid technique modeling and simulation labor
	Reinforcement	New/increased O&M costs (distribution equipment)
	Technical losses and other environmental	Higher system loss due to reverse power flow
	Engineering Mgt & Clerical Support	Design, testing, integration, commissioning
	Engineering Mgt & Clerical Support	On-going support & service
	Project Management	PM throughout
Benefits	Interconnections	ANM system fees, where relevant
	Reinforcement	Deferred/mitigated traditional distribution system reinforcement costs
	Operations	Additional DER contributing to security of supply
	Existing assets	Higher asset utilization
Society	Losses	Net losses
	Environmental	Environmental benefits (e.g. CO_2 etc.)
	GDP / jobs	Additional DER developer business; faster interconnection; highly skilled technicians and engineers employment

8. APPENDIX

8.1. Background Information on the Curtailment Assessment

Overall ANM unlocks the dynamic grid hosting capacity for DER – see Section 3.3 for background information on conceptualizing grid hosting capacity under static “fit and forget” perspectives compared to ANM enabled dynamic “managed” perspectives.

Having established the circuit definition as well as the constraints present due to the addition of DER and load demand restriction, an annual estimate of the ANM actions associated with a given installed DER capacity can be derived. To do so requires that at each time step, all required actions to relieve constraint breaches are recorded to provide an estimate of the actions that the ANM system might incur in reality over the entire year.

8.1.1. Curtailment Assessment Methodology

Curtailment assessments use time-series historical circuit data, representative of the expected range of demand and generation conditions, to approximate the power system conditions at constraint locations on the circuit. This allows the identification of cases where constraints will arise and thereby simulate the control actions required to manage those constraints. This involves performing a large number of calculations to represent a sufficiently broad range of circuit conditions, reflecting the frequency of such conditions occurring. In terms of constraint impact locations, interconnecting DER to a constrained circuit generally causes thermal and voltage issues local to the DER location, as such vast and complex circuit models can typically be simplified to those zones sensitive to the DER’s constraints. The curtailment assessment methodology applied for a specific case will depend upon the availability of input data, power system circuit models, and the complexity of constraints that are to be studied.

8.1.1.1. General Approach

At a minimum, the historical time-series profiles of aggregated power flows at the constraint location(s) and time-series profiles of ANM generator export are required. Sensitivity factors can then be used to approximate worst-case power flows, prior to ANM control actions, at each constraint location. A simple spreadsheet analysis can then be applied to estimate overall curtailment. The following figure conceptually presents the simulation layers for performing a curtailment analysis.

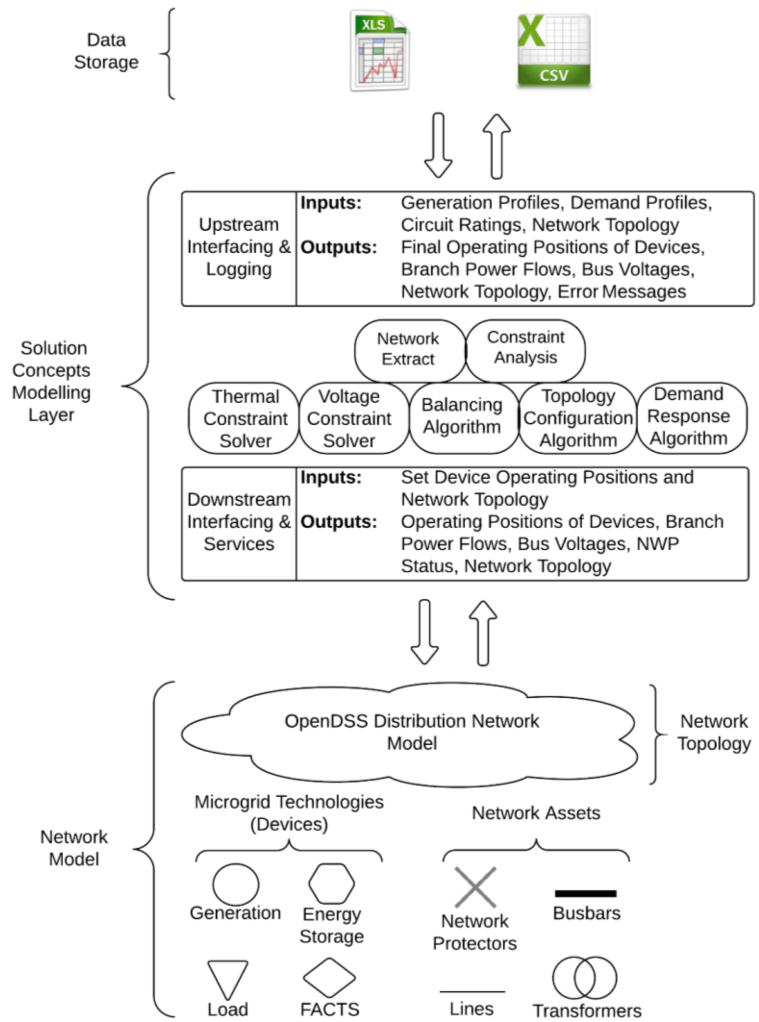

Figure 45: Simulation Layers for Curtailment Assessment Modeling

In the event that a circuit model is available as well as historical time series information for vital elements, such as loads and existing generation, an iterative approach can be employed. This entails integrating the historical data into a power simulation software and performing load flow simulations across each time step under study. A more accurate estimate of the required curtailment is provided through this approach. Given the large number of simulations to be run, the aid of computer scripts is required to produce the results. SGS has developed in-house modeling tools designed specifically for this purpose.

8.1.1.2. Calculation of ANM Actions

Initial power flow estimates at the constraint location(s) are compared with asset operational limits for each time step; in cases where the constraint threshold is exceeded, a high-level simulation of ANM control actions is performed, modelling the curtailment of ANM generators with reference to ANM scheme operational characteristics. The constraint threshold is typically set at a defined design factor below the actual operational limit of the constraint. Summing the ANM actions over all time steps for each DER reveals an estimate of the amount of action required.

8.1.2. Curtailment Analysis Assumptions

A number of discrepancies exist between the modeling associated with a curtailment analysis and the operation of an ANM system in the field. These discrepancies often require that an assumption be made or corrective measurement applied. Such actions are performed in a fashion that intends to capture a conservative estimate of the number and magnitude of control actions that the ANM system is likely to incur over the course of a year.

Below is a list of the discrepancies that exist as well as a description of the relevance toward this demonstration project and any associated corrective measure that is applied as a result.

- Operating margins: In practice, the ANM system performs increasing control actions based on the level to which the constraint breach occurs. This is done to ensure the ANM system respects protection limits when bringing circuit operating conditions a safe distance away from the constraint threshold. The ANM system then also incrementally releases export capacity back to the DG over specified time intervals. This is done to prevent cycling of the DG. In order to account for the operational nature of the ANM system within the curtailment analysis, a safety factor is added to a given constraint's threshold instead of controlling DER directly to the constraint threshold.
- Sensitivity factors: A DER element under the control of an ANM scheme is assigned a sensitivity factor toward each of the constraints it is being used to manage. Due to the time constraints associated with the real-time control aspect of ANM and to ensure that it operates in a deterministic fashion, it is currently not feasible to calculate this sensitivity factor in operation based upon the circuit conditions at the time of a constraint breach. A curtailment analysis that runs a load-flow based upon current conditions is able to determine the exact level of control required. In operation, power export capacity is decreased in iterations through ANM until the targeted limit is achieved. This can have the effect of extending the amount of time required for the ANM system to limit the export capacity to an appropriate level. This however would be balanced with a delayed start to the release of export capacity and no corrective measure is taken within the curtailment analysis.
- Load profile derivation[29]: metered data is typically not available for each load on a given circuit. Instead, characteristic load profiles are derived to the extent possible using historical information from existing metered data sources on the circuit (e.g. substation transformer) and the load qualities available (e.g. peak demand, annual consumption, customer type, etc.). The more historical data being used to form the basis of the curtailment analysis the better. The loading on the circuit can vary between years. At minimum one calendar year should be considered. To ensure that a conservative curtailment estimate is being used, caution is always taken toward incorporating a low estimate of the load on a given circuit to provide a worst case curtailment estimate. It is also assumed that the nature of the load on the circuit does not change over the

[29] The annual profiles being used for the curtailment analysis being performed for the Smart Distribution are derived directly from the high resolution data being used within the real time simulation environment. Therefore, measures to ensure that a conservative profile is derived for circuit elements need not be applied to the profiles being used for the curtailment analyses performed for this study.

project lifetime. This of course may not be the case (e.g. relocation of industrial customer) and can affect future curtailment results. Sensitivity analyses can be run to try to predict such effects.

- DG profile derivation: A best estimate can be made based upon historical conditions, but there is a certain measure of uncertainty inherent to predicting the output of a resource dependent DG. To compound this uncertainty, the historical data attributed to a given project site is often derived through the correlation of data from an existing nearby installation. This is accommodated by adding an additional measure to the safety factor associated within the operating margins above. This has the same effect as assuming higher power export during constraint conditions, without increasing the overall magnitude of power export. Similar to the loading on the circuit, the more historical data being used to form the basis of the curtailment analysis the better, since the resource supporting the generation can vary year to year. At minimum, one calendar year should be considered so as to capture seasonal variations in generation.
- Data cleansing/ profile averaging: Data profiles provided by the utility are often incomplete and/ or contain errors within the data. These must be removed and assumptions made to correct these inconsistencies. Furthermore, a certain level of error is inherently associated with the averaging of data, where constraint breaches within an interval are masked. This is compensated for by both taking conservative assumptions toward filling in data as well as further adding to the safety factor associated with the operating margins.
- Communications availability: The reliability of the communication channels between sgs connect and sgs comms hub depend upon the communication technology available for an ANM deployment scheme. When this communication link is lost, logic is contained within sgs connect that places the DER into a fail-safe mode, which in some instances can mean full shut down. Depending upon the reliability factor of the communication channel and fail-safe settings of the DER, a loss factor can be applied to the final output of the curtailment analysis.
- ANM maintenance: The ANM system itself requires maintenance. As the nature of the conditions on a given circuit change, the parameters that ANM uses to dictate control of DER may need updating. This means that the ANM system is put offline periodically to update these parameters, but more importantly, increased levels of curtailment could be the result prior to updating the parameters. A small correction factor is applied to the result of the curtailment analysis to account for this fact.
- Microgeneration presence: The initial curtailment analysis takes into account all loads and generators present on a circuit at the present time. The uptake of microgeneration on a circuit that is outside the purview of ANM can erode the generation capacity available over time as compared to the curtailment analysis. This scale of DG currently does not need to contract under a flexible connection scheme, and will not for the foreseeable future, but it does remove capacity on the circuit. If enough microgeneration connects, curtailment levels for existing ANM contracted generation could experience an increase. Uptake scenarios can be implemented to predict this influence.

- Principles of Access (POA): the order in which DER are utilized toward the relief of a given constraint must be established. If this includes DER from different owners, this priority stack is typically governed by the principles of access, which could be Last In First Off (LIFO).

8.2. Curtailment Assessment Application

8.2.1. Annual Load and Generator Profiles

The hourly load and generation profiles for the Smart Distribution ANM scheme are presented below. This includes the aggregate load on the circuit as well as the output profile for the 500 kW 'PHIL GEN1' PV generator, and a normalized output profile that represents the uncontrolled output from all firm interconnection generators (PV and biodigesters).

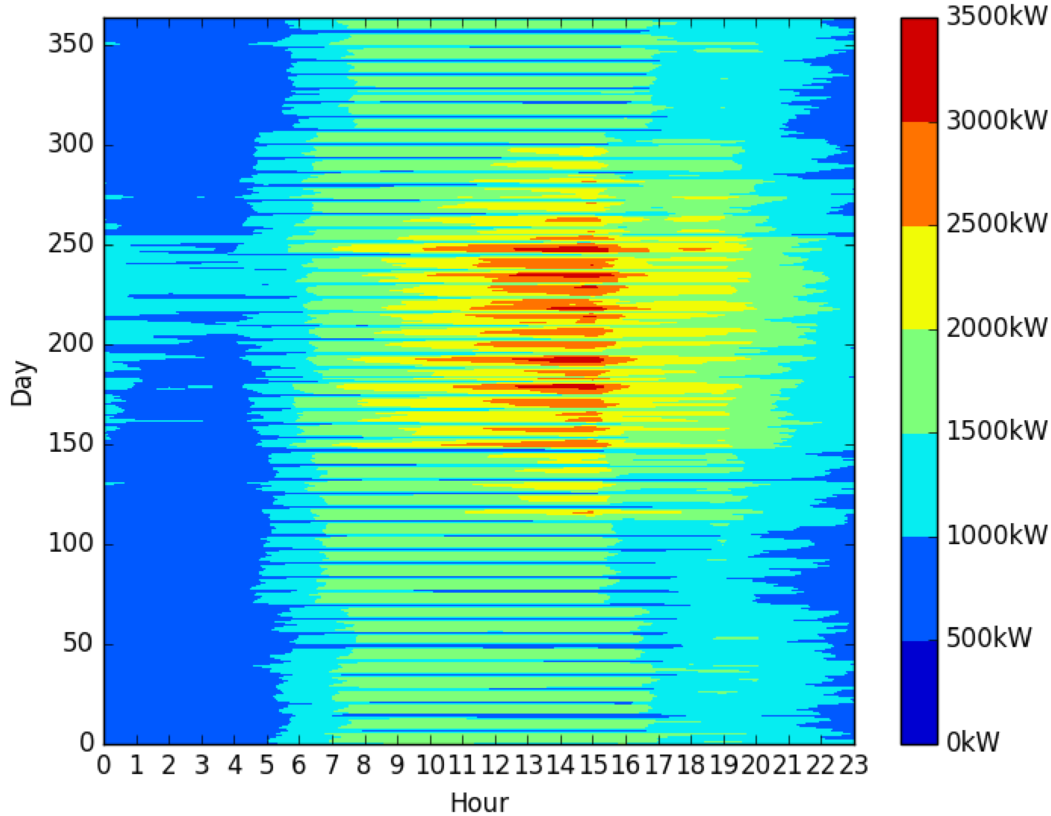

Figure 46: Annual Smart Distribution Circuit Load Profile (note scale shading)

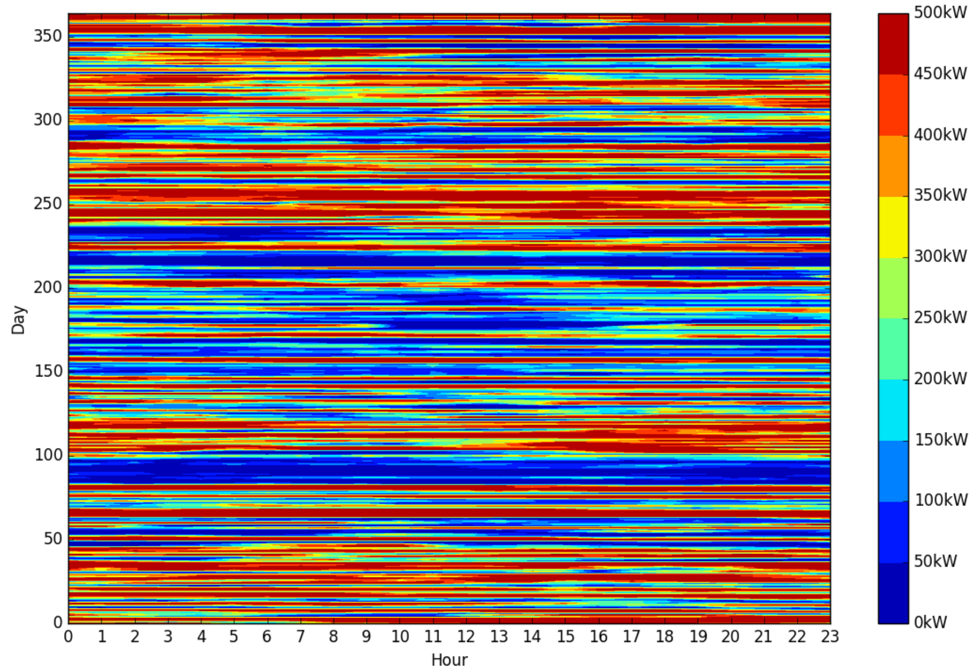

Figure 47: Annual Uncontrolled 500 kW Wind Generation Profile (note scale shading)

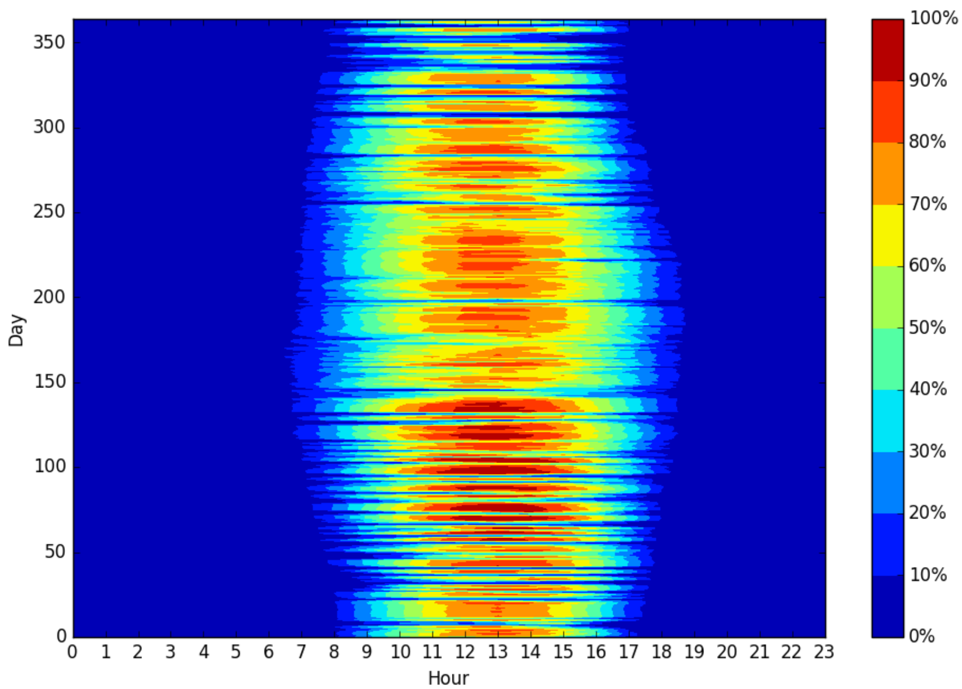

Figure 48: Annual Uncontrolled Normalized PV Generation Profile (note scale shading)

These annual profiles are processed on a coincident per interval basis through the OpenDSS power simulation software to reveal resultant power flows and voltages across the network. ANM actions on distributed energy resources are then simulated within each interval as required to resolve any breaches of the constraint zones identified in Section 8.5. The predicted actions of the ANM system on each of the distributed energy resources is known as the curtailment assessment and is described in further detail in the Appendix.

8.3. Curtailment Assessment Results

The curtailment results pertaining to each of the four zones identified as being part of the ANM control scheme in Section 8.5 are presented below. The results of this curtailment assessment are subsequently discussed and the appropriate time intervals selected to realize the objectives of the Smart Distribution use case through testing in the OPAL-RT system.

For those applicable constraints, the curtailment assessment is presented for both the normal topology case as well as the alternate topology separately across the entire year. In practice, an estimate toward the duration of time that the alternate topology will be present is required to properly estimate the expected curtailment of a particular generator, or utilization of a particular resource.

8.3.1.Substation Thermal Export Constraint

The net power flow through the substation transformer constraint prior to ANM controlling any resources in response to the 4.5 MVA power export limit, as defined in Section 8.5, is presented below in Figure 49.

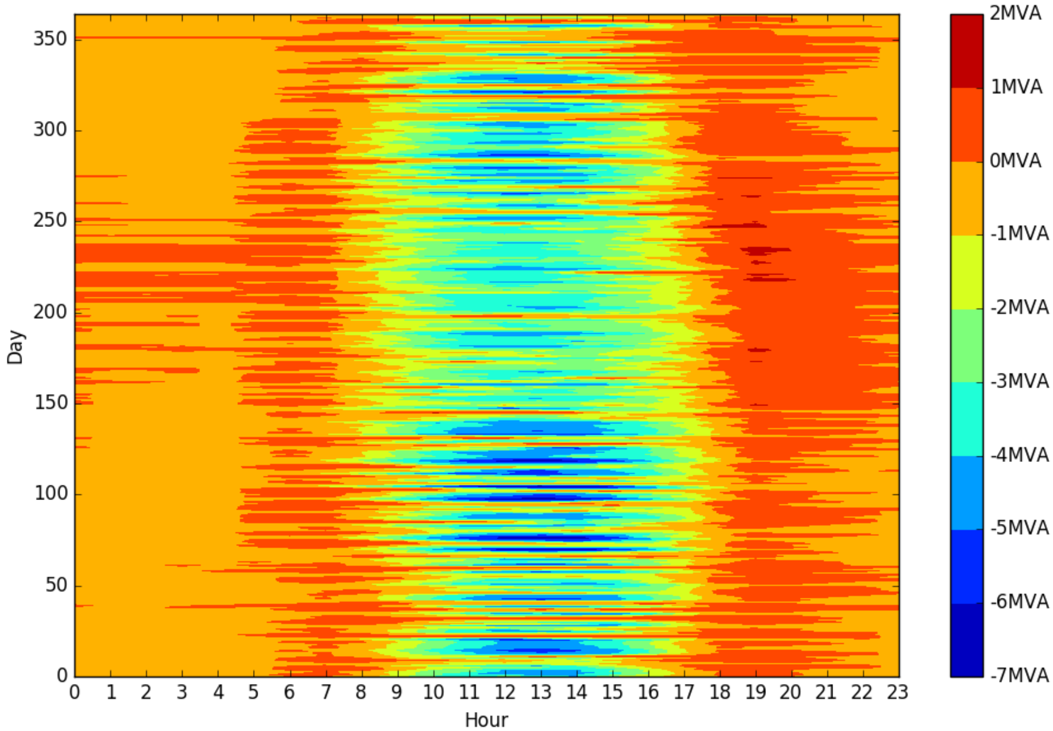

Figure 49: Net Power Import through the Substation Transformer Prior to ANM Control (note scale shading)

The net power flow through the substation transformer constraint under the alternate topology is nearly identical to the normal topology case prior to applying the ANM Smart Distribution control scheme. It is therefore also represented by this figure.

In order to limit the power export on the circuit to 4.5 MVA, Table 7 presents statistics describing the control actions applied by the Smart Distribution ANM control scheme to each of the 10 dedicated resources as presented in Table 13.

The thermal export constraint at Line 671 to 675 is present under the alternate topology and this constraint is nested within the substation thermal export constraint. Being nested within the substation thermal constraint, it is assessed first. This changes the net flow at the substation when assessed by the ANM control scheme and also the required control actions as compared to the normal topology case. The updated statistics describing the control actions on the dedicated resources for the alternate topology is therefore presented separately in Table 7.

Table 7: Substation Thermal Export Constraint Control Action Summary

Resource	Total Number of Control Actions		Total Annual Energy Adjustment via Control Actions [MWh]	
	Normal Topology	Alternate Topology	Normal Topology	Alternate Topology
Smart Campus PV	71	27	-35.0	-2.6
Smart Campus Flexible Load	76	0	3.7	0
Smart Campus ESS	96	0	9.6	0
Smart Campus EV	116	0	6.4	0
PHIL GEN1	221	136	-71.1	-30.4
PHIL GEN2	311	263	-68.6	-56.3
Smart Homes Prosumer Bus 611	320	41	6.3	0.7
Smart Homes Prosumer Bus 652	329	35	10.4	0.9
Smart Homes EV Bus 611	338	28	8.0	0.6
Smart Homes EV Bus 652	356	30	12.5	0.8

8.3.2. Line 671 to 675 Thermal Export Constraint

The net power flow through the line segment from Bus 671 to bus 675 prior to ANM controlling any resources in response to the 1.56 MVA power export limit, is presented below in Figure 50. This constraint only exists under the alternate topology and is the first constraint to be addressed when the alternate topology is present.

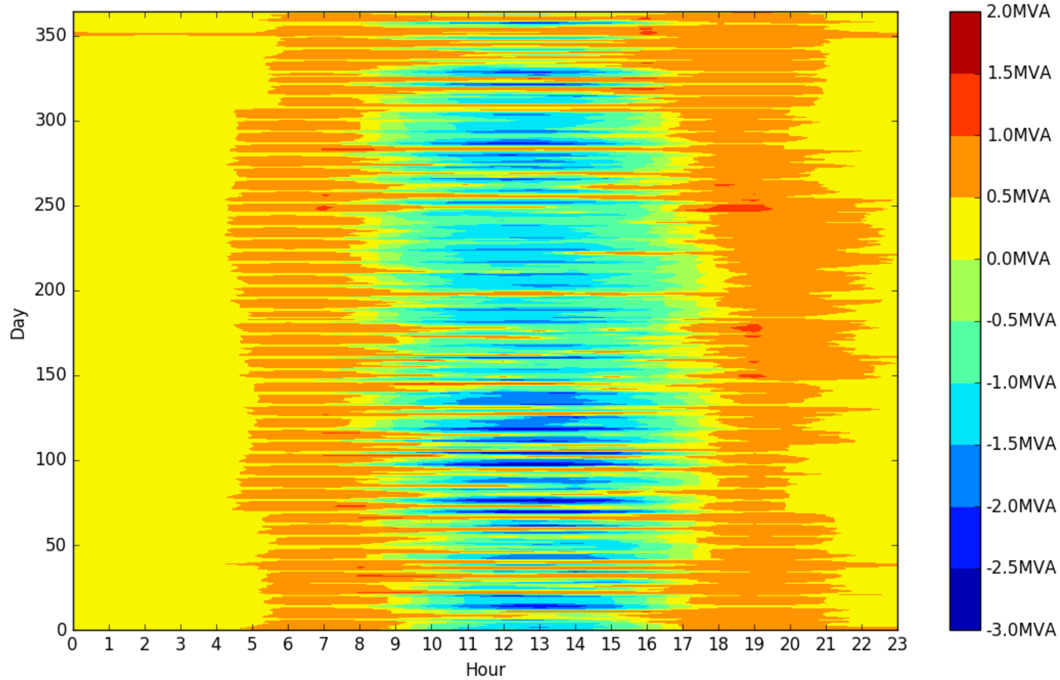

Figure 50: Net Power Flow through Line 671 to 675 Prior to ANM Control (note scale shading)

In order to limit the power export through this conductor to 1.56 MVA, Table 8 presents statistics describing the control actions applied by the Smart Distribution ANM control scheme to each of the 9 dedicated resources as presented in Table 13.

Table 8: Line 671 to 675 Thermal Export Constraint Control Action Summary

Resource	Total Number of Control Actions	Total Annual Energy Adjustment via Control Actions [MWh]
Smart Campus PV	197	-58.7
Smart Campus Flexible Load	220	10.4
Smart Campus ESS	281	27.7
Smart Campus EV	340	18.8
Smart Homes Prosumer Bus 611	360	7.0
Smart Homes Prosumer Bus 652	398	12.1
Smart Homes EV Bus 611	412	9.6
Smart Homes EV Bus 652	445	15.5

8.3.3. Line 632 to 670 Thermal Export Constraint

As was initially predicted, there were no control actions initiated during the curtailment assessment specifically toward the thermal constraint through line segment 632 to 670. As was previously mentioned, future additional ANM generation could cause constraints at this location depending on future load and generation on the circuit. However, it will not be required for set up within the NREL testing environment.

8.3.4.Smart Campus PCC Over-Voltage Constraint

The annual voltage profile at the Smart Campus point of common coupling, Bus 680, prior to ANM controlling any resources in response to the 1.05 p.u. upper voltage limit, as defined in Section 8.7, is presented below for the normal and alternative topology in Figure 51 and Figure 52, respectively.

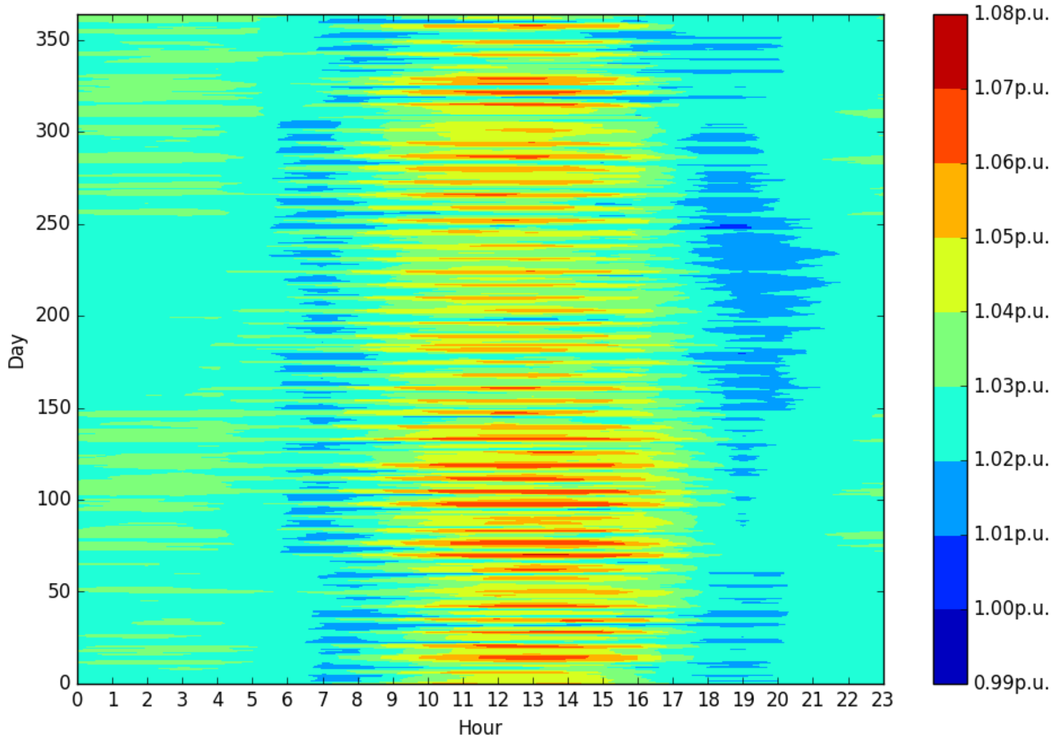

Figure 51: Voltage Profile at the Smart Campus PCC Prior to ANM Control – Normal Topology (note scale shading)

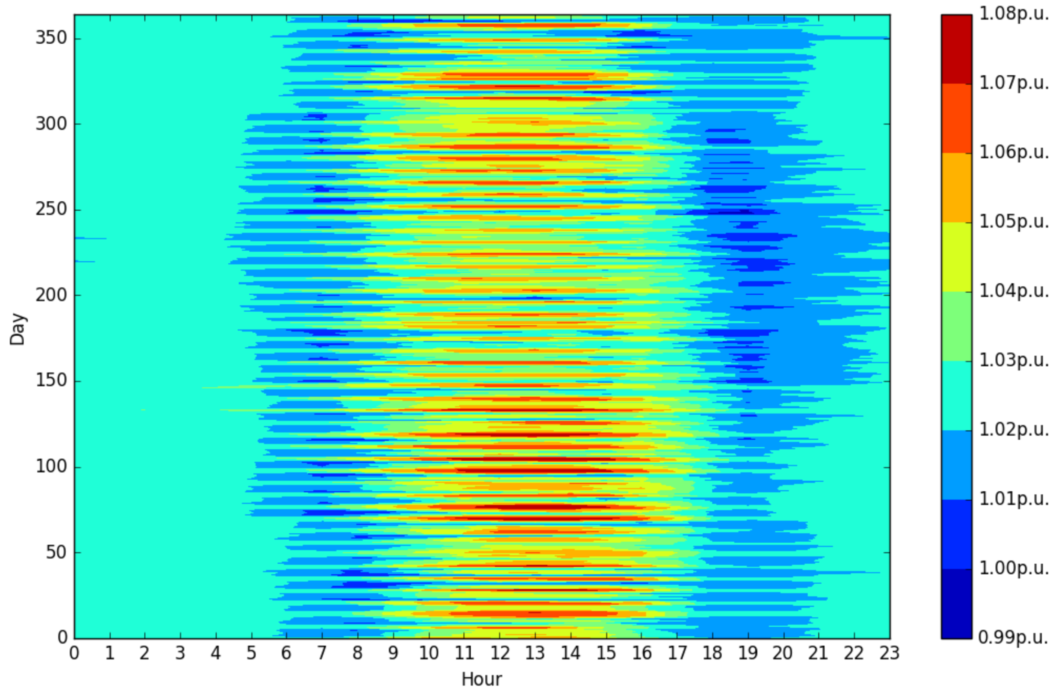

Figure 52: Voltage Profile at the Smart Campus PCC Prior to ANM Control – Alternative Topology (note scale shading)

In order to limit the voltage at this node to the 1.05 p.u. upper limit, Table 9 presents statistics describing the control actions applied by the Smart Distribution ANM control scheme to each of the 4 dedicated Smart Campus resources presented in Table 13.

Table 9: Smart Campus PCC Overvoltage Constraint Control Action Summary

Resource	Total Number of Control Actions		Total Annual Energy Adjustment through Control Actions [MWh]	
	Normal Topology	Alternate Topology	Normal Topology	Alternate Topology
Smart Campus PV	344	414	-171.8	-215.8
Smart Campus Flexible Load	310	256	14.7	12.0
Smart Campus ESS	318	264	32.8	23.8
Smart Campus EV	328	256	18.8	14.0

8.4. Curtailment Assessment Discussion

Under the normal topology, the Smart Campus PV experiences a total of 207 MWh of curtailment by summing the values in Table 7 and Table 9. From the 4923 MWh of uncurtailed production listed in Table 10, this equates to 4.2% curtailment. The 'PHIL GEN1' and 'PHIL GEN2' managed connections experience a total of 71 MWh and 69 MWh of curtailment respectively, as listed in Table 7. From the 820 MWh and 2047 MWh of uncurtailed production listed in Table 10, this equates to 8.7% and 3.4% of respective curtailment. The following figure shows the aggregated curtailment level (all ANM enabled flexible interconnection generation) for the full annual period by hourly impact.

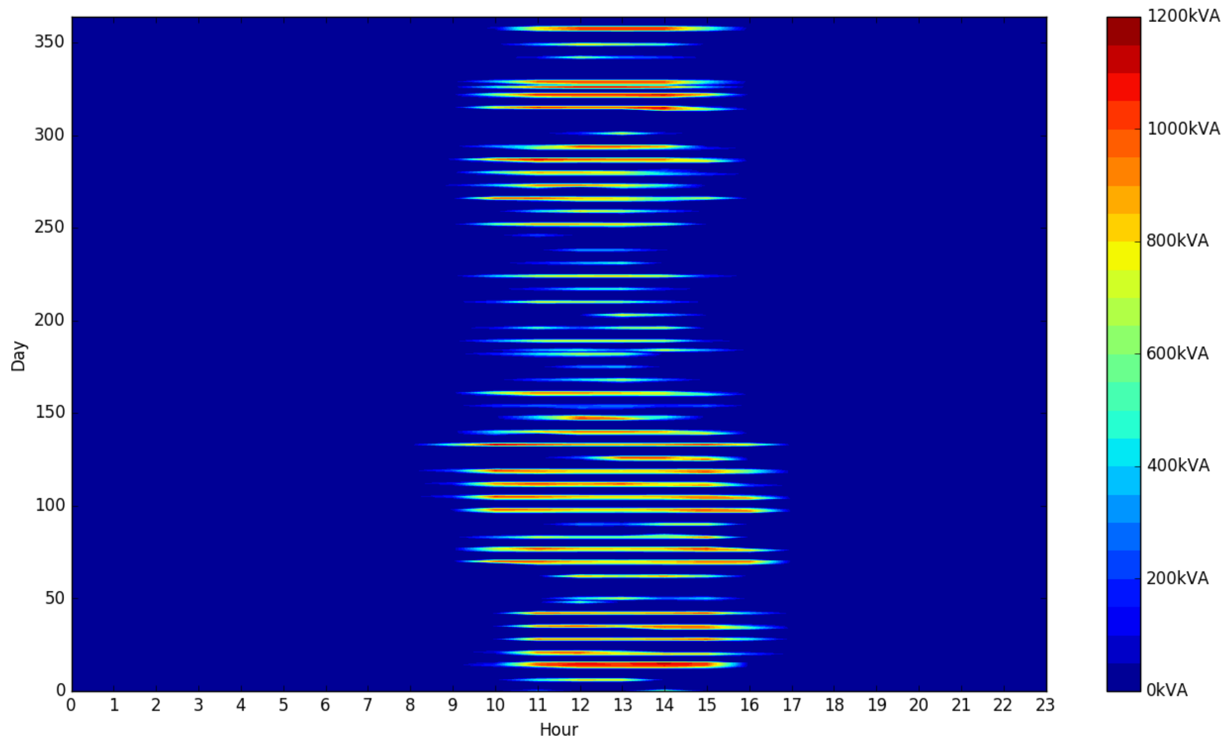

Figure 53: Estimated ANM Curtailment (note unique scale shading)

This level of curtailment corresponds to a 109% increase in generation interconnected: (4.0 MW flexible) / 3.665 MW firm = 1.09, or 109% increase in flexible interconnected generation above the firm generation. The following figure visually displays this increase in capacity relative to the substation thermal constraints. The effect of the ANM enabled solar PV (i.e. the 3 MW Smart Campus PV array and the 0.5 MW community/utility scale PV array) is seen in the mid-day maximum generation. The effect of the ANM enabled wind energy (i.e. the 0.5 MW community/utility scale wind turbine) is seen primarily in the ~500 kVA generation during the overnight hours.

From reviewing these curtailment and capacity diagrams, SGS noted that additional flexible interconnection generation could have connected onto the circuit to further take advantage of the nighttime capacity. It was estimated for instance that up to 2 MWs of additional wind energy could flexibly interconnect under the same ANM curtailment and economics assumptions.

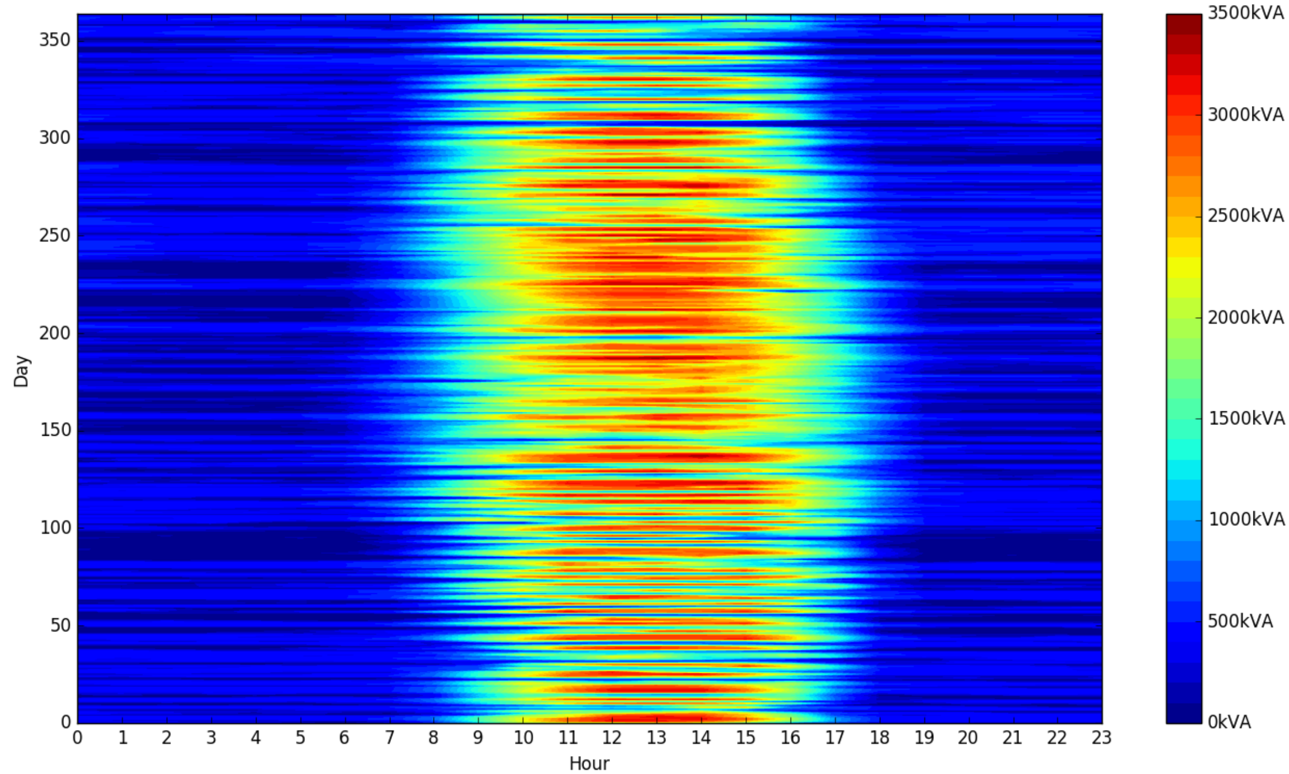

Figure 54: ANM enable dynamic capacity at the substation transformer (note unique scale shading)

When multiple topologies are possible on a circuit, the effect of each topology should be considered toward the total curtailment estimate. This requires an estimate toward the amount of time spent in each arrangement as well as when the switching actions are likely to occur. For the Smart Distribution test circuit, the alternate topology provides back-up to the customers downstream of Bus 670 in the case of an outage along line segment 670 to 671. The probability of an outage along this section of the feeder would drive this narrative.

Under the alternate topology, the Smart Campus PV experiences a total of 5.6% curtailment, the 'PHIL GEN1' PV generator 3.7% and the 'PHIL GEN2' wind generator 2.8% curtailment due to the three constraint zones (i.e. sum of results for each presented in Table 7, Table 8 and Table 9). The Smart Campus PV generator has greater curtailment under this topology due to the nested constraint of the thermal export through line segment 671 to 675 acting as a bottle-neck to limit the export of PV. This subsequently reduces the amount that the 'PHIL GEN1' and 'PHIL GEN2' generators must be curtailed to respect the thermal export limit of the substation.

In order to gauge whether these generator capacities are economically viable, a curtailment assessment was run on the three generators under the normal topology without any of the additional demand response and prosumer resources from the Smart Homes. The Smart Campus demand response load and energy storage are not included so as to ensure economic viability under conservative assumptions. In order to satisfy the substation thermal export constraint and maintain an acceptable voltage at the Smart

Campus PCC, the resulting curtailment numbers were 10.3% for the 'PHIL GEN1' 500 kW PV generator, 3.9% for the 'PHIL GEN2' wind generator and 6.6% for the 3000 kW Smart Campus PV generator.

The effects of the alternate topology on the curtailment estimates have been assumed to be negligible. The curtailment numbers presented for the alternate topology do not deviate widely from the associated numbers quoted for the normal topology. Furthermore, a greater presence of the alternate topology would effectively act to balance the curtailment numbers between the two generators.

The 10.3% curtailment listed for the 'PHIL GEN1' PV generator is at the threshold for project economic viability in many cases. However, in this case, the capacity factor for the PV generation is high at 0.187. As such, it is likely that this level of curtailment is economically viable and demonstrates the combination of multiple variables that affect DER economics – enforcing the view of the market need to assess hosting capacity of the dynamic grid.

The Smart Campus PV experiencing 6.6% curtailment and 'PHIL GEN2' 3.9% curtailment are within the range that SGS has seen DER developers consider economically. Furthermore, the capacity factor being used for the wind generation is also high at 0.47. As such, it could likely endure even greater amounts of curtailment.

These curtailment results demonstrate the hosting capacity of the Smart Distribution circuit to have increased from the 4310 kVA traditional limit, based upon the substation thermal export rating, to at least 7765 kVA as the total generation capacity presented here under the ANM control scheme.

8.5. Managed DG Interconnections Description

8.5.1. Smart Campus PV Generator

The first ANM managed DG interconnection was placed within the Smart Campus (i.e. Bus 680), where a 3 MW PV generator was included. Accompanying this PV generator was a 600 kWh capacity lithium-ion storage system with a 120 kW power rating and 110 kWs of flexible load (aggregated EV's and facility controllable load). These resources together form the Smart Campus that is actively managed by ANM.

For static grid hosting capacity scenarios, worst case conditions must be assumed. In this case, it means that the storage and demand response through flexible load are not available to assist with any issues caused by excess generation from the PV system. Therefore, the PV system alone will be considered with the other existing DG on the circuit and minimum circuit load conditions for the static design case.

In order to trigger the implementation of a circuit-wide ANM control scheme, the avoided T&D reinforcement costs must be cost prohibitive and the DG project must still be economically viable relative to curtailment risk under ANM. Three conditions must be satisfied for this to be true: (1) the cost of implementing a new or updating an existing ANM scheme must be less than the traditional upgrades being triggered by the interconnection screens, (2) the cost of implementing or being adopted within an existing ANM scheme must be economical to the generation developer, (3) the amount of energy lost due to generator curtailment in response to ANM constraint management must not render the generation project uneconomical. Additional assumptions and information on curtailment analysis is described in "200285 26A - Smart Campus AMM Modeling and Simulation", and overall Smart Campus hosting capacity assumptions in "200285 29A - Smart Campus Acceptance Test Specification & Final Test Plan".

For interconnecting the campus solar PV, the power export limit through the substation transformer of 3750 kVA, or 75% of its thermal rating, was breached with a power export of 6557 kVA. The cost to upgrade the substation transformer would be in the order of millions of dollars, which is well above the threshold required to adopt an ANM control scheme. Also, given the large nature of a 3 MW PV project, it is more than likely that the cost of the ANM system could be accommodated within the DG project's economic budget.

To ensure the substation thermal capacity is not breached, measurement point 1 (MP1) is shown in Figure 32 to monitor real-time power flow. The Smart Campus 3 MW PV generator also produced an over-voltage at its PCC of 1.071 p.u. as well as a breach of the 75% thermal capacity threshold of line segment 632 to 670 at 89% under the typical topology arrangement. While under the alternate topology (i.e. Switch 1 (SW1) normal open and Switch 2 (SW2) normal closed), line segment 671 to 675 is overloaded at 189%.

In practice, each of these constraints would also need to be managed within the ANM scheme. As such, MP4 in Figure 32 is included for the management of the constraint at line segment 671 to 675. The ANM control system monitors the status of the switches on the circuit (MP2 and MP3) to identify the current topology of the circuit. Under the alternate topology this constraint zone also becomes active.

Given that the breach of line segment 632 to 670 was not greater than the 90% threshold for thermal capacity under ANM, this constraint could be excluded at this point, but would need to be re-considered with the inclusion of future generation.

8.5.2. PHIL GEN1 PV + PHIL GEN2 Wind Generation

Following the interconnection of the Smart Campus, an additional 500 kW PV generator was interconnected at Bus 670 (i.e. 'PHIL GEN1' in Figure 32) followed by a 500 kW wind generator at Bus 633 (i.e. 'PHIL GEN2' in Figure 32). Given that the static design case must consider all existing interconnected generators, including the Smart Campus PV, these interconnections further exacerbated the thermal export breach through the substation transformer and line segment 632 to 670 as well as the overvoltage at the Smart Campus PCC (i.e. Bus 680).

The inclusion of 'PHIL GEN1' caused the loading on line segment 632 to 670 to reach 99%, which is now above the 90% threshold permissible under ANM. However, this constraint is not expected to incur any control actions even though it is possible, given that the ANM system will already be managed against the lower capacity constraint at the Substation (i.e. MP1). Similar to the overvoltage at Bus 680, the constraint on this line segment was still included in the preceding curtailment assessment to produce a comprehensive curtailment assessment and to quantify the rarity of its occurrence.

Under the alternate topology, the service conductor for 'PHIL GEN2' identified with the potential to be overloaded. This overload can be ignored due to the fact that the downstream line segment 671 to 675 is the ACSR 'Raven' type conductor with much less capacity than the ACSR 'Dove' type conductor servicing this generator. This lower capacity line segment is already included as a constraint zone for the Smart Campus PV. The ANM control system would resolve the breach of the downstream constraint prior to this potential constraint surfacing.

These generators were therefore only associated with the thermal export through the substation transformer, MP1, for both the real-time testing and curtailment assessment.

8.5.3. ANM Managed Generator Interconnection Summary

A summary of the ANM-managed generator interconnections is presented in Table 10. It should be noted that the results presented are also reflective of the interconnection order. The 'PHIL GEN1' PV generator was interconnected after the Smart Campus and this was followed by 'PHIL GEN2'. The effects of each generator therefore included the peak generation of the preceding generators, as well as itself, on the circuit when analyzing the minimum load static design case scenario.

Table 10: ANM Managed Generator Interconnections

Name	Capacity [kW]	Uncontrolled Annual Production [MWh]	PCC	Voltage at PCC [p.u.]		Service Conductor Loading [%]	
				Normal Topology	Alternate Topology	Normal Topology	Alternate Topology
Smart Campus PV	3000	4923	Bus 680	1.071	1.081	64	65
'PHIL GEN1' PV	500	820	Bus 670	1.056	1.05	99	18
'PHIL GEN2' Wind	500	2047	Bus 633	1.05	1.052	8	90

8.6. ANM Managed Loads & Smart Home Prosumers

In addition to the generators listed in Table 10 that are under ANM control, additional resources within the Smart Homes and Smart Campus were also added to the resources accessible by ANM. A summary of these managed load and prosumer objects is presented in Table 11, below. Smart Homes control is via the single sgs connect at the aggregator. Through the aggregator, Smart Home control includes EV charging as well as a combined solar PV + ESS prosumer. Thus aggregator integration with the ANM scheme is consistent with the industry today: control of key loads like EV chargers, and control generically of generation and/or storage for the stochastic prosumer availability of responding to grid constraint signals and/or pricing to maximize clean energy generation.

Table 11: ANM Managed Load Connections

Name	PCC	Flexible Power Capacity [kW][30]	Max Load [kW]	Min Load [kW]
Smart Campus Load	680	50	265	46
Smart Campus EV	680	60	60	0
Smart Campus ESS	680	120	120	-120
Smart Homes 611 Prosumer	611	20	165	19
Smart Homes 611 EV	611	24	24	0
Smart Homes 652 Prosumer	652	32	125	13
Smart Homes 652 EV	652	36	36	0

[30] The flexible capacity would be limited by the maximum load in the case of supporting an export constraint, and the minimum load in the case of supporting an import constraint.

8.7. Principles of Access ANM Control Scheme

As described in the curtailment assumptions detailed in Section 8.1.1, a Last In First Off (LIFO) Principles of Access approach has been taken toward controlling generators – in correlation with their order of interconnection. This means that the 'PHIL GEN2' 500 kW PV generator would be the first generator to be curtailed followed by 'PHIL GEN1' wind, and lastly, the Smart Campus in order to try to remedy a breach of the substation transformer thermal export capacity. But given that Smart Homes with controllable PV, storage and EV charging exist on the circuit that is controlled by ANM via the aggregator, for the purposes of the demonstration these resources will be targeted first in order to avoid clean energy curtailment (i.e. enabling coincident load or storage to minimize clean energy curtailment). This could be the case in the event that a utility is trying to meet carbon reduction targets, or some other metric that promotes renewable power production. This principles of access curtailment order will demonstrate functionality sufficient for the use case, while also initiating discussion from the project Advisory Board consistent with how establishing LIFO, shared, or hybrid curtailment regimes is fundamental to each DER's economic considerations – fitting of the market assessment of hosting capacity needed for ANM enabled dynamic grids.

For the case of the Smart Campus, its supporting energy storage and controllable load resources will be utilized to the extent possible prior to curtailing the 3000 kW PV generator.

The summary of the static grid thermal and voltage constraints are shown in Table 12 below. As described in Section 8.5, it is the breach of the substation transformer thermal export capacity that triggers the deployment of the circuit's ANM control scheme.

Table 12: Smart Distribution Static Grid Constraint Summary

Constraint Type	Constraint Location	Topology	ANM Control Threshold	Traditional Design Factor	Traditional Generation Capacity Limit	Contributing Generator Location
Thermal Export	Substation Transformer	Normal and Alternate	90% of thermal rating (4500 kVA)	75% of thermal rating (3750 kVA) + Min Load (560 kVA)	4310 kVA (Generation)	Anywhere on circuit
Thermal Export	Line Segment 632 to 670	Normal	90% of thermal rating (4700 kVA)	75% of thermal rating (3920 kVA) + Min Load Downstream (427 kVA)	4347 kVA (Generation)	Downstream of Bus 670 (inclusive of Bus 670)
Thermal Export	Line Segment 671 to 675	Alternate	90% of thermal rating (1560 kVA)	75% of thermal rating (1300 kVA) + Min Load Downstream (252 kVA)	1552 kVA (Generation)	Downstream of Bus 671 (inclusive of Bus 671)
Over-Voltage	SC PCC	Normal and Alternate	1.05 p.u. voltage	1.05 p.u. voltage	2000 KVA (Generation)	Smart Campus (Bus 680)

An overview of the ANM control scheme is presented below in Table 13. The ANM constraint zones are assessed from lowest priority (Zone Priority #4) to highest priority (Zone Priority #1). Similarly, the resources are accessed from lowest priority (Resource Priority #10) to highest priority (Resource Priority #1) when attempting to relieve the breach of the corresponding ANM constraint zone. Highest priority DERs are curtailed last as per the principles of access LIFO regime described above.

Table 13: Smart Distribution ANM Control Scheme Overview

	Zone Priority #1	Zone Priority #2	Zone Priority #3	Zone Priority #4
ANM Constraint Zone	Smart Campus PCC Over-Voltage	Line 632 to 670 Thermal Export Capacity	Substation Transformer Thermal Export Capacity	Line 671 to 675 Thermal Export Capacity[31]
Resource Priority #1	Smart Campus PV	PHIL GEN1	Smart Campus PV	Smart Campus PV
Resource Priority #2	Smart Campus Flexible Load	Smart Homes Prosumer Bus 611	Smart Campus Flexible Load	Smart Campus Flexible Load
Resource Priority #3	Smart Campus ESS	Smart Homes Prosumer Bus 652	Smart Campus ESS	Smart Campus ESS
Resource Priority #4	Smart Campus Flexible Load	Smart Homes EV Bus 611	Smart Campus Flexible Load	Smart Campus Flexible Load
Resource Priority #5	--	Smart Homes EV Bus 652	PHIL GEN1	Smart Homes Prosumer Bus 611
Resource Priority #6	--	--	PHIL GEN2	Smart Homes Prosumer Bus 652
Resource Priority #7	--	--	Smart Homes Prosumer Bus 611	Smart Homes EV Bus 611
Resource Priority #8	--	--	Smart Homes Prosumer Bus 652	Smart Homes EV Bus 652
Resource Priority #9	--	--	Smart Homes EV Bus 611	--
Resource Priority #10	--	--	Smart Homes EV Bus 652	--

The fourth priority constraint zone, 'Line 671 to 675 Thermal Export Capacity', is only present under the alternate topology and is a nested constraint relative to the substation transformer thermal export capacity when active.

The overvoltage at the Smart Campus PCC and thermal export constraint through line 632 to 670 are resolved last.

[31] The thermal export capacity breach of line segment 671 to 675 only occurs under the alternate topology scenario. The ANM system is able to identify the current topology and activate this constraint zone when required.

8.8. Background Information for ADMS versus ANM Systems

ADMS and ANM are complementary technology solutions for managing today's grid resources and supporting grid modernization for tomorrow's smart grid. The following summarize their typical applications and key functionality:

- Advanced Distribution Management System (ADMS)
    - Evolution of SCADA/DMS/OMS control and asset management systems
    - For central area power system management
    - Rely on operator in the loop and power model in the loop approaches for grid monitoring and control
    - Ensure safe and reliable bulk power delivered to customers
- Active Network Management (ANM)
    - Recent critical industrial controls applied to distribution grids
    - Deterministic, real-time, autonomous control
    - Distributed and localized monitoring
    - Allows for better (and real-time) utilization of grid assets to meet customer needs
    - ANM is most commonly associated with the creation of hosting capacity for new Distributed Generation (DG) connections

The following table compares ADMS versus ANM in more detail.

Table 14: ADMS vs ANM Comparison

Functionality	ADMS	ANM
Overall Description	• Whole distribution system control and asset management • Bulk transfer of power (minutes-to-hours) • Control center visibility and situational awareness • Enterprise deployment to support bulk distribution automation for all customers.	• Local and autonomous control system • Actively manageme grid constraints in real-time (second-to-second) • Incremental deployment to support specific customer needs.
Architecture; Operation	• Central and hierarchical • Platform hosts many non-critical applications • Limits to scalability due to increasing complexity in control actions • Operator-in-the-loop operation	• Part-central & part-distributed • Dedicated platform, hierarchical and next generation is networked p2p • Architecture allows for high rate of change applications across larger areas and devices • Autonomous operation
Timescale	• Minutes-to-hours • Some synchronous and many asynchronous communications and responses to control	• Second-to-second • Real-time synchronous communications with responses in sub-seconds • Based on the capability of the underlying communication
Control applications framework	• Event driven • Load flow modeling-in-the-loop and iterative objective seeking control applications • Require operator intervention • Speed of logic interpretation dependent on the other (not critical) activities of the system at the time	• Local time-bounded (deterministic) • Repeatable control of multiple constraints (thermal, voltage) & multiple DERs (grid assets and DG/load/ESS) • Includes failsafe and escalating actions control.
Deployment scale; Costs	• Whole network, enterprise wide • Millions to 10's of millions to 100's of millions	• From single constrained DER to multiple constrained circuits • Tens of thousands to a few million
Links to Guides / Best Practices	https://www.smartgrid.gov/files/ADMS-Guide_2-11.2015.pdf	http://www.energynetworks.org/modx/assets/files/news/publications/1500205_ENA_ANM_report_AW_online.pdf