E. S. Cornwall Memorial Scholarship

Fifth Quarterly Report

Commonwealth Edison

1st November 2015 – 31st January 2016

Matthew Zillmann
07/03/2016

Disclaimer

This report provides a candid assessment of the author's experiences, drawing comparisons to the Australian electricity supply industry. Statements and material contained within this report (except where explicitly referenced) are the expressed opinion of the author and not that of any person or organisation associated with the author. Any reproduction or referencing of this report should reflect this.

Acknowledgements

The author of this report acknowledges the support of Commonwealth Edison and its employees. Without their assistance and willingness to share knowledge this report would not have been possible. In particular, the author would like to thank: Daniel Gabel (Manager of Interconnection and System Studies, Commonwealth Edison), Joe Svachula (Vice President of Smart Grid and Technology, Commonwealth Edison), Shay Bahramirad (Director of Smart Grid and Technology, Commonwealth Edison), Manuel Avendano (Manager of Emerging Technologies, Commonwealth Edison), all members of the Smart Grid and Technology team (who are too many to name), and Prof. Simon Bartlett (Australian Chair in Electricity Transmission, University of Queensland).

The author would also like to thank: the E. S. Cornwall Memorial Scholarship and its Board for the personal, professional, and technical development opportunity that this scholarship affords; his family (Heather, Allan and Hayley) for their ongoing support and encouragement; and his friends and colleagues, both old and new.

Table of Contents

1 Glossary, Abbreviations & Definitions 1

2 Executive Summary 2

3 Introduction 3

3.1 Motivation 3

3.2 Area of Research 3

4 Background 4

4.1 Microgrids 4

4.1.1 What is a Microgrid? 4

4.1.2 Why Microgrids? 5

5 Placement Experience 7

5.1 Microgrids 7

5.1.1 Microgrids at ComEd 7

5.1.2 The Bronzeville Community Microgrid 9

5.1.3 Lessons Learned 12

5.2 Distributed Generation Hosting Capacity 14

5.2.1 Analysis Algorithm 14

5.2.2 Feeder Classification 16

5.2.3 Lessons Learned 21

6 Future Works 24

7 Other Works 26

7.1 S&C Electric Site Visits 26

7.2 Braidwood Nuclear Generating Station Site Visit 29

8 Bibliography 34

1 Glossary, Abbreviations & Definitions

Table 1: List of acronyms, abbreviations, and technical terminology

Terminology / Acronym / Abbreviation	Definition
BCM	Bronzeville Community Microgrid
BWR	Boiling Water Reactor *Referring specifically to a type of nuclear reactor design*
CDF	Cumulative Density Function
COM	Component Object Model *A Windows-native interfacing standard that enables cross-process control and automation between independent processes*
ComEd	Commonwealth Edison (Company)
DER	Distributed Energy Resource
DG	Distributed Generation
DNO	Distribution Network Operator
DoD	Department of Defence
DoE	Department of Energy
EIMA	Energy Infrastructure Modernisation Act
EPRI	Electric Power Research Institute *A not-for-profit research organisation largely funded through investments from organisation in the electricity industry*
FOA	Funding Opportunity Announcement
HiL	Hardware in the Loop
IIT	Illinois Institute of Technology
MMC	Microgrid Master Controller
PDF	Probability Density Function
PWR	Pressurised Water Reactor *Referring specifically to a type of nuclear reactor design*
S&C	Schweitzer and Conrad (Electric)
SAIDI	System Average Interruption Duration Index
USA	United States of America
USD	United States Dollars

2 Executive Summary

The increasing penetration of distributed generation and, more generally, distributed energy resources within the electricity grid presents a number of well documented technical and operational challenges. However, if adequately planned for and managed, these technologies and services may also provide a number of opportunities across the energy sector. One such opportunity is the ability to island (or temporarily disconnect) parts of the network from the traditional distribution and transmission grid. To date this capability has been considered a significant safety and operational concern and thus been precluded through the anti-islanding requirements of standards like AS/NZS 4777 (within Australia and New Zealand), IEEE 1547 (predominantly with the USA), and VDE-AR-N 4105 (within Germany). For the most part, these concerns stem from the lack of control that distribution network operators have over the operation of these devices, particularly during contingency events; however, developments in DER technologies have greatly advanced the control and monitoring capability of these systems. Connecting these "smart" devices to a communication and control network capable of facilitating inter-device and centralised control opens up the possibility for the development of microgrids within the distribution network.

Microgrids are areas within the distribution grid that can seamlessly disconnect (island), run islanded, and reconnect in response to pricing, contingency, power quality, or other signals. As such they provide greater reliability, grid resiliency, and power quality for customers, while also allowing for increased penetration of distributed energy resources through the granular control of said devices. By definition microgrids may challenge the traditional business model of generators, transmission utilities, and distribution utilities. In the same way that distributed generation has provided customers with greater freedom and choice around how they source electricity, microgrids may provide customers and utilities with more flexibility in how they connect and operate. The impact that microgrids have on transmission and distribution businesses will largely depend on the approach, mindset, agility, and flexibility of these businesses in adapting to this changing environment. Within Commonwealth Edison (ComEd), microgrids are seen as an opportunity to improve the electrical service provided to customers while also bolstering the resiliency of the system. As such, ComEd is working to develop six microgrids within its service territory to supply a range of customers and critical public infrastructure.

This report introduces the concept of a microgrid, delving into the work that is being undertaken by ComEd to:

- Identify locations within ComEd's service territory where microgrid development will provide greatest value;
- Deploy a microgrid in the South Chicago community of Bronzeville that is capable of interfacing and sharing resources with the Illinois Institute of Technology's (IIT's) microgrid (known as a microgrid cluster); and
- Develop, test, and implement a master microgrid controller that is capable of operating the clustered microgrid.

It also discusses my contribution to the latter two components of this work.

Separate to this, the latter sections of this report discuss my progress on the distributed generation hosting capacity assessment of ComEd's network that was introduced in my Fourth Quarterly Report [1]. This tool provides an estimate of the ability of each feeder to accommodate distributed generation without negatively impacting feeder performance. The development of this tool has provided a number of interesting learning opportunities and unearthed challenges with the use of clustering algorithms that are applied to make the analysis technique scalable.

Over the coming months I will be working to finalise the development, documentation, and handover of this tool and its code to my colleagues. I will also be exploring opportunities to network and learn from other groups within ComEd.

3 Introduction

This report builds on my previous quarterly reports undertaken on the E. S. Cornwall Memorial Scholarship. For more information on past and future reports see http://escornwall.com.au/index.php/category/study-topics/optimise-expenditure-on-asset-management/.

3.1 Motivation

Australian Transmission and Distribution Network Operators (TNOs and DNOs) are under continual pressure to provide a more economical, efficient network while ensuring the reliability and security of supply to consumers. Recent years have seen the prevailing perception of electricity network service providers as over investing, building "gold-plated" networks. This has been compounded by a circa 70% increase in the average cost of residential electricity from 2008 to 2012, with 51% of this price being made up of network charges [2].

During the same period advances in distributed generation (DG) and its affordability (through incentives and economies of scale) have placed significant pressure on the traditional operating model of TNOs and DNOs. If TNOs and DNOs are to remain relevant players in the electricity supply chain they will have to adapt to the changing network environment and increasingly competitive market in all facets of their business. One area that will be heavily impacted by this drive for efficiency and change will be asset management, the focus of my placement on the E. S. Cornwall Memorial Scholarship.

3.2 Area of Research

During my tenure on the E. S. Cornwall Memorial Scholarship I will explore ways of optimising capital and operational expenditure in asset management. In particular, I am interested in understanding how:

- International best-practice asset management techniques, such as the Publicly Available Specification (PAS) 55 (PAS55:2008) and the recently published International Standards Organisation (ISO) 55000 (ISO55000:2014), can be used to drive efficiency in asset management.
- Improvements in data availability and analysis can be used to better understand network and asset performance, subsequently driving more informed and better value investment in assets.
- New technologies can be utilised within the network to improve network performance as an alternative to, or means of deferring expensive network augmentations.

I will also gain exposure to leading business practices, systems, technologies, and research that may fall outside of these core areas. Where this occurs I will provide information as an appendix to my scholarship reports.

To achieve this body of research I am undertaking two, nine-month placements within:

- **UK Power Networks (UKPN)** – a DNO servicing the south eastern region of England in the United Kingdom; and
- **Commonwealth Edison (ComEd)** – a transmission and distribution network operator servicing the northern Illinois area in the USA.

This document is the fifth of six quarterly reports that will be compiled throughout my placements on the scholarship. It covers the second three (of a total nine) months that I will spend at ComEd based in Oakbrook Terrace, Illinois. During this period, and for the majority of my placement with ComEd, I will be working within the Smart Grid and Technology team. In the last three months I have had two predominant focuses:

- Continuing my work developing ComEd's DG hosting capacity assessment tool, specifically focusing on further improvements to the modelling algorithm and feeder classification analysis; and
- Working intermittently on ComEd's microgrid efforts, around the Bronzeville Community Microgrid (BCM) and Microgrid Master Controller project.

This report will cover this work in more detail, while also providing an introduction to microgrids and the benefits they provide.

4 Background

This section covers background material important to the content of my placement. It consists of one subsection that provides an introduction to microgrids, the components of a microgrid, and the benefits that they provide. For an overview of the electricity industry in the USA and Illinois, ComEd, its parent holding company Exelon Corporation, and the Smart Grid and Technology team that I am currently working within, see Section 4 of my Fourth Quarterly Report [1].

4.1 Microgrids

4.1.1 What is a Microgrid?

The concept of "microgrids" has received growing attention within the electricity industry in recent years. Although the term is generally used to encapsulate the theme of DG and islandable network, it can have varying meanings. The concept of utilising DG to provide the capability to disconnect from the electrical network is not inherently new. Indeed, it has already been employed in key infrastructure (like hospitals, other emergency services, major office buildings, and data centres) to ensure reliable power supply during short outages or network disturbances. For clarity, the USA's Department of Energy[1] (DoE) Microgrid Exchange Group defines a microgrid as [3]*:*

> "*…a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.*"

The DoE further characterises microgrids into four categories, determined by the level of complexity and defining boundaries. They are (in order of complexity):

1. **Single customer microgrid**, the most common form of existing microgrid, that allows a customer (normally a major customer or critical infrastructure) to isolate from the distribution network using an embedded generation.
2. **Partial-feeder microgrid**, for example housing estates, small communities, or facilities (e.g. military bases or the Illinois Institute of Technology) that can isolate (e.g. at a line recloser or automated switch) and maintain supply to a portion of the distribution network.
3. **Full-feeder microgrid**, that allows a whole feeder to isolate at the substation circuit breaker while maintaining supply to most (if not all) customers on the feeder.
4. **Substation microgrid**, that allows the primary substation to isolate at the incoming HV feeder while maintaining supply to multiple outgoing distribution feeders.

For the purpose of this report the term "microgrid" will be used to refer to a full-feeder application. It follows that, under this definition a microgrid consists of four core components:

1. **Distributed energy resources** (DERs), including dispatchable generation (e.g. combined heat and power, gas micro-turbines), intermittent generation (e.g. solar PV and wind), and energy storage systems (e.g. battery storage). These systems provide power to customers

[1] The US Department of Energy (DoE) is a department of the United Sates Government that is responsible for federal direction on energy and nuclear-related policy.

within the microgrid and should be available in adequate capacity to sustain the microgrid when running in islanded mode.

2. **A controller**, that is capable of managing the various resources within the microgrid to ensure safe operation, stability, power quality, and (ideally) to optimise the economic utilisation of generation and demand management during grid connected and islanded operation.
3. **Customers**, who form the load component of the microgrid (both flexible and inflexible). While the majority of customers will be traditional residential or commercial and industrial customers, microgrids will ideally supply a number of critical customers (e.g. hospitals, disaster response and recovery facilities, police facilities, communication infrastructure, etc.).
4. **Distribution network and associated infrastructure**, that defines the electrical boundary of the microgrid and provides its foundation (i.e. electrical connectivity, heat-transfer infrastructure, automated switches and protection devices, and communication), as well as the flexibility to accommodate operation of the microgrid.

These four components are shown in Figure 1, which provides a simple representation of a microgrid.

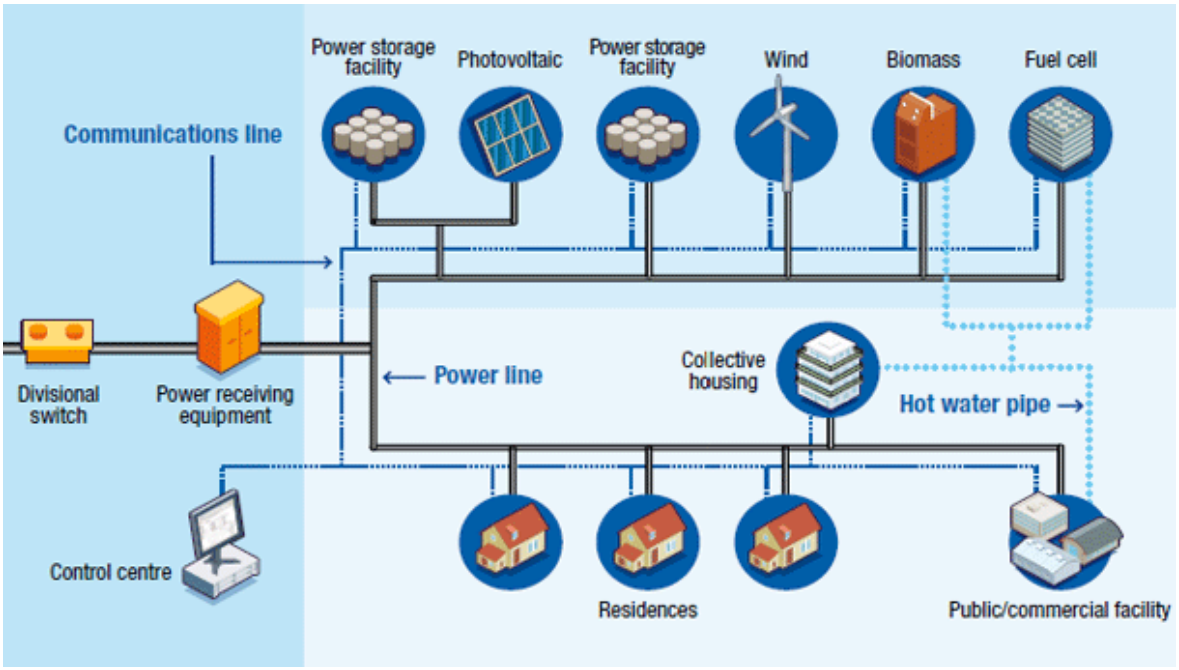


Figure 1: The microgrid and its components [4]

4.1.2 Why Microgrids?

Electricity networks in the developed world are facing three considerable challenges:

1. **Society's growing expectations for reliability and power quality**. The community, businesses, and industry have grown reliant on electricity to power many aspects of their daily lives and businesses. Issues like: momentary outages, voltage sags, swells, and harmonics can compromise industrial processes, damage equipment, and destabilise sensitive electronics, the cost of which is often counted in the tens to hundreds of thousands of dollars per event.
2. **The need for improved system resilience**. Electricity networks must be able to withstand the increasing severity and frequency of extreme weather events, as well as the threat of physical and cyber-attacks.
3. **The proliferation of distributed (particularly renewable) generation.** Attractive incentive programs, coupled with ambitious targets around renewable energy generation and reductions in CO_2 emissions have seen DG proliferate in recent years. At high penetrations, these technologies may negatively affect the grid's performance and operation.

Addressing these challenges through traditional network augmentation is costly and not economically viable. One possible solution that is gaining traction with the federal government, regulators, and utilities in the USA is the development of microgrid-enabled networks. In particular, Microgrids allow:

- Improved system resilience through islanding;
- Improved reliability and power quality through localised control and monitoring;
- Reduced transmission losses;
- The development of "smart grids" (and the additional benefits that accompany their realisation);
- Higher penetrations of distributed renewable generation, through improve control and device management; and
- Reduced CO_2 emissions.

To date, microgrids have been constructed in a number of locations around the world [5, 6, 7], generally to supply remote communities, military facilities, or for the purpose of research and development. Figure 2 provides a snapshot of the current deployment of microgrids within the USA and their application. It highlights a number of hotspots for microgrid activity, particularly on the east coast of the USA where microgrids are being utilised to reinforce population centres, and sensitive political and Department of Defence (DoD) infrastructure.

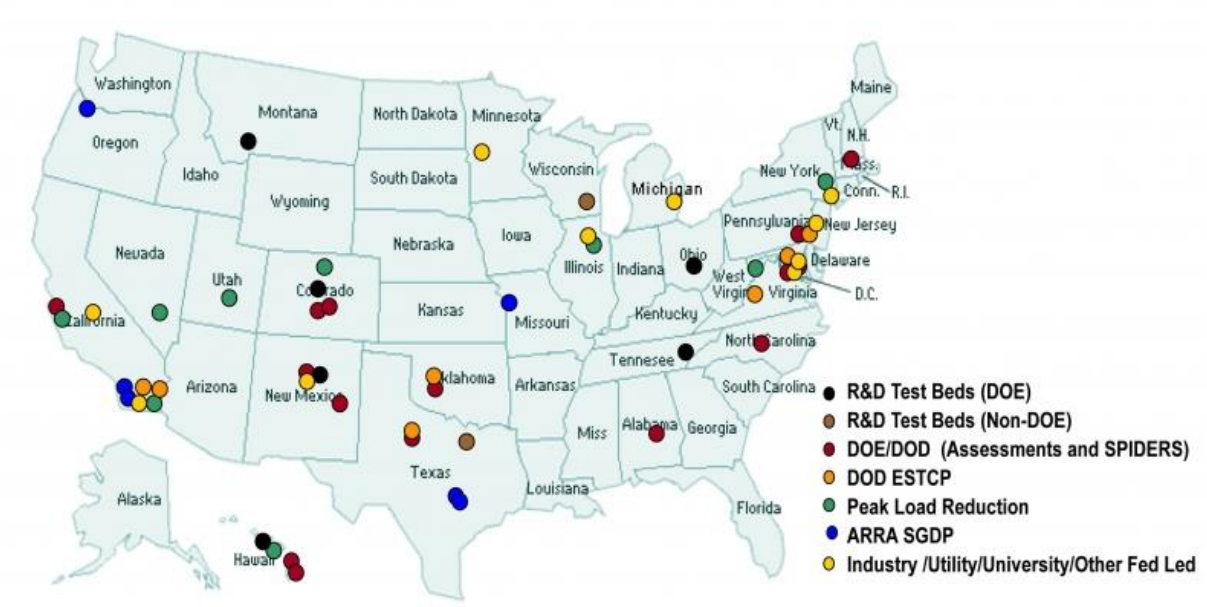


Figure 2: Current deployment of microgrids within the USA [7]

In an attempt to further encourage research into, and the deployment of "commercial scale" microgrids the DoE's Office of Electricity Delivery and Energy Reliability issued Funding Opportunity Announcement (FOA), DE-FOA-0000997 titled, "Microgrid Research, Development, and System Design" [8]. Although this FOA is specifically targeted at the development of a robust and scalable microgrid controller, it sets a number of requirements and operational targets that highlight the benefits that should be achievable through the application of microgrids. The FOA requires that the funded microgrid and its controller [8]:

- Reduces outage time of critical loads by >98% (as measured by the system average interruption duration index (SAIDI)) at a cost that is comparable to alternate solutions (e.g. uninterrupted power supplies (UPSs) and backup generators);
- Reduces CO_2 emissions by >20%; and
- Improves overall system energy (i.e. electrical and heat) efficiency by >20%.

These values provide some measure of the expected performance improvement achievable through the deployment of microgrids.

5 Placement Experience

This section provides an overview of work that I have completed, including lessons learned from my experience. It consists of two subsections that discuss: my continued work on estimating the DG hosting capacity of ComEd's network, and the Bronzeville Community Microgrid, including my involvement on this project. Where possible, I have drawn comparisons as to how my experience may be of value to the Australian electricity supply industry.

5.1 Microgrids

5.1.1 Microgrids at ComEd

ComEd's Future Energy Plan [9], which was introduced to the Illinois General Assembly[2] as a part of amendments to the Public Utilities Act in the spring of 2015 (HB3328 / SB1879), seeks to construct a number of microgrids at different locations around Northern Illinois. If approved, the program will be one of the largest demonstrations of its kind, costing an estimated (USD) $300 million over five years. These microgrids will strengthen supply to a number of key community services and critical infrastructure, while also allowing ComEd and their project partners to explore a number of research and development opportunities.

Locations to be targeted for microgrid deployment were selected using an internally developed network resiliency metric [10]. This metric divided ComEd's service territory into 0.5 mile by 0.5 mile squares within Chicago city and 1 mile by 1 mile squares in suburban and rural areas. Each of these areas was then given a ranking between one and 10 (one being low, 10 being high) depending on the need for grid resilience within the area. An area with a resiliency metric score of seven or above was identified as a possible location for microgrid development. In calculating this rating, each area was assessed against four criteria, namely: the number of critical customers and their importance, reliability performance, system loading, and outage risk. These metrics are described in more detail in Table 2. Each of these metrics were given a weighted contribution (β_n) to the overall resiliency rating of the area, as highlighted in Figure 3.

Table 2: ComEd resiliency metric components

Metric	Description
Critical Customers	A list of critical customers within ComEd's service territory was developed through the engagement of key emergency management and national security organisations. This metric allocated critical customers into one of three categories depending on their level of significance: national, regional, or local. Critical customers included: hospitals, fire stations, public services (e.g. water pumping stations), and data centres.
Reliability Performance	Is calculated from the system average interruption duration index (SAIDI), which is estimated at a feeder section level. These SAIDI values are converted to a reliability ranking score.
System Loading	Highlights load-related issues across three levels: where feeder rating is exceeded with forecast (three years) load growth, where substation rating is exceeded with forecast (three years) load growth, and the amount of energy at risk where distribution infrastructure exceeds N-1 rating. These three rankings are combined, with energy at risk having the highest weighting in the final system loading metric.

[2] The Illinois General Assembly is the state legislative body that is formed by the combination of the Illinois House of Representatives (lower house) and the Illinois Senate (upper house).

Metric	Description
Outage Risk	Each substation was ranked based on the probability of an outage occurring (e.g. through transformer failure, circuit breaker failure, or circuit breaker lockout) and consequence of an outage occurring (i.e. the number of customers impacted taking into account the ability to restore through network reconfiguration).

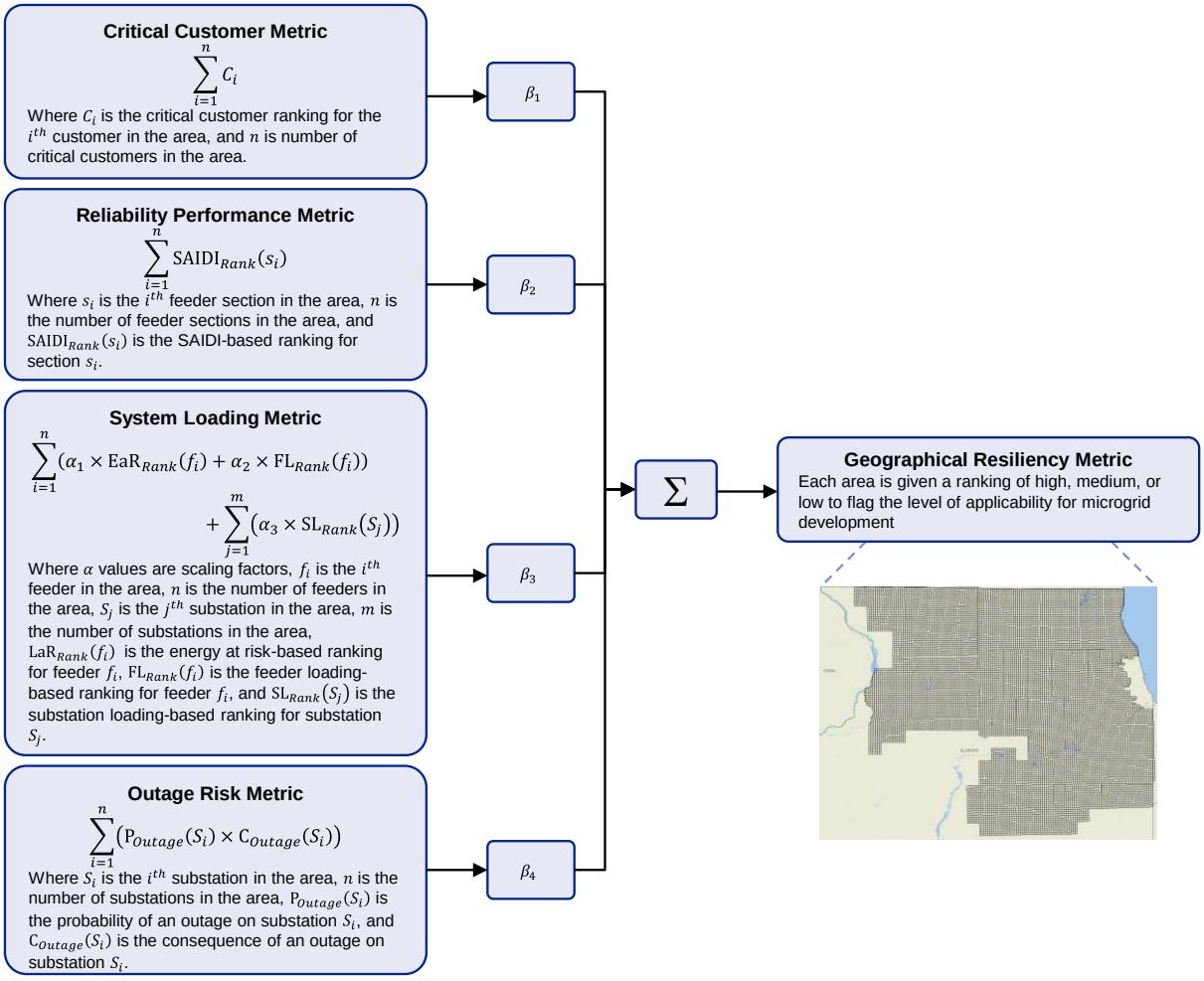


Figure 3: Calculation of the ComEd network resiliency metric

From the approximately 13,000 unique areas that make up the ComEd's service territory, it was found that approximately 30 areas scored highly (seven or above) on the resiliency metric. As such, this metric was successful in identifying a small number of regions that could be studied in more detail to understand the suitability for microgrid development. With this information, six specific areas were selected as ideal locations for microgrid deployment; they were:

1. Bronzeville, a community located in the South Side of Chicago.
2. The Illinois Medical District, located around the University of Illinois' medical school in West Chicago.
3. Rockford International Airport, located on the outskirts of Rockford in northern Illinois
4. Du Page County Government Complex, located in the suburbs west of Chicago.
5. The Federal Aviation Administration (FAA) facilities in Aurora.
6. Chicago Heights Water Department's pumping and treatment facility.

While funding for these microgrids is somewhat reliant on amendments to the Illinois Public Utilities Act being passed[3], ComEd is working to progress the construction of a microgrid in Bronzeville as the first of these six. The following section provides more detail around the Bronzeville microgrid and the work that is being undertaken in planning for its development.

5.1.2 The Bronzeville Community Microgrid

The Bronzeville community, located south of "The Loop" (Chicago's city centre), is an area predominantly known for its African-American heritage that was forged during the early-1900s. It is the home to a number of key academic facilities (most notably the Illinois Institute of Technology (IIT)) and the Chicago Police Headquarters. The diversity of customers within Bronzeville, along with the number of critical services and key infrastructure made it an ideal location for the development of Chicago's first microgrid. Over the past three months I have been working with members of the Smart Grid and Technology team (and a number of other groups within ComEd) on the planning and proposal for the Bronzeville Community Microgrid (BCM).

Given the sensitive and confidential nature of this work I am not at liberty to discuss my contribution in detail; however, I have attempted to provide an overview of the microgrid, my work, and detail of some of the challenges encountered thus far.

Although ComEd's proposed amendments to the Public Utility Act (discussed in Section 5.1.1) are seeking funding specifically for the development of six microgrids, ComEd is working to incorporate two additional projects within the development of the BCM. These projects are targeted at:

1. The development of a microgrid master controller (MMC) (under DE-FOA-0000997[4]), for which ComEd was awarded (USD) $1.2 million by the DoE [11]; and
2. Deploying a combined solar PV and energy storage system (under DE-FOA-0001108[5]), for which ComEd was awarded (USD) $4 million by the DoE [12].

The amalgamation of these projects with the BCM will reinforce the benefits of the microgrid while providing additional learning opportunities. It follows that the BCM project as a whole consists of these three inter-related projects as shown in Figure 4.

If successful, the BCM would become part of one of the first "clustered" microgrids in the world through its interconnection with IIT. The IIT campus, which has a peak demand of approximately 10MW, is wholly encapsulated within its own, privately owned microgrid. The IIT microgrid can be supplied from a number of distributed energy resources (DERs) including: two 4MW combined cycle gas units, an 8kW wind turbine, rooftop solar, and a 500kWh flow battery. With the addition of controllable loads, IIT has the capability to island its campus from ComEd's network during major events and contingencies, or in response to signals from PJM Interconnection[6] (e.g. electricity pricing) or ComEd.

The clustering of the BCM microgrid with the IIT microgrid will:

- Further improve the resilience of both networks;
- Allow for more rigorous testing of microgrid and MMC; and
- Enable resource sharing between the two facilities.

[3] At the time of publication ComEd were still engaged with the Illinois General Assembly on these amendments.
[4] DE-FOA-0000997, titled "*Microgrid Research, Development, and System Design*" is focused on the development of a microgrid master controller that is capable of controlling and operating microgrid systems of between 1 and 10MW of load.
[5] DE-FOA-0001108, titled "Sustainable and Holistic Integration of Energy Storage and Solar PV" (SHINES) is focused on the demonstration of solar PV generation coupled with energy storage to mitigate the impact of intermittent solar generation on the network and better match energy dispatch with customer demand.
[6] PJM Interconnection is the regional transmission organisation that manages the electricity wholesale market and transmission network operation in ComEd's service territory (as well as a number of other eastern states in the USA.

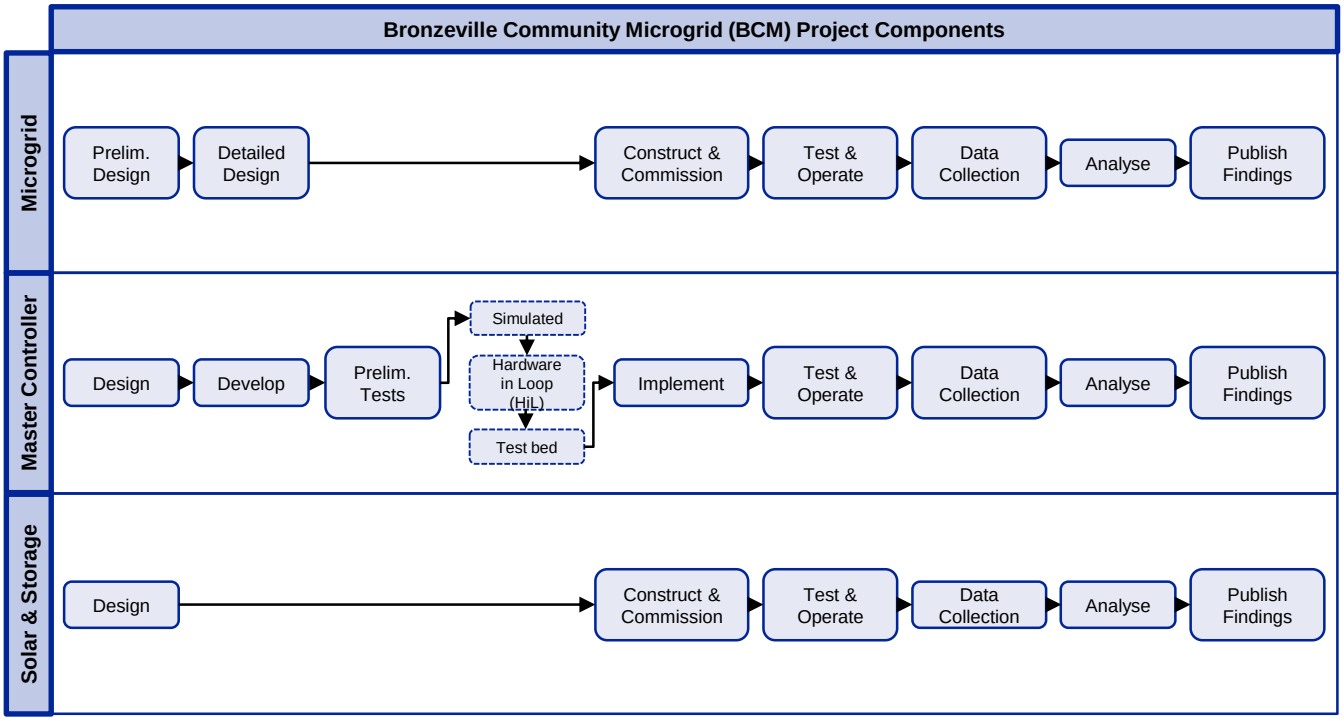


Figure 4: Bronzeville Community Microgrid project components and timeline

The research goals for these three constituent projects are outlined in Table 3.

Table 3: Research goals for Bronzeville Community Microgrid projects

Proj.	Research Goals
Microgrid	• Understand the optimal sizing, customer composition, mixture and sizing of DERs, and network design for future microgrid implementations. • Explore the challenges of operating and successfully implementing a clustered microgrid between a utility and privately owned infrastructure. • Achieve marked improvements in grid power quality, reliability, and resilience, while reducing system losses, and CO_2 emissions and increasing overall renewable penetration. • Quantitatively measure the benefit provided by the microgrid using actual performance figures (i.e. CO_2 emissions saved, voltage regulation improvement, power quality improvement, reliability improvement (SAIDI and SAIFI), and financial savings through avoided outages.
Master Controller	• Develop a versatile microgrid controller architecture that is capable of managing DERs, controllable loads, and network operation in a clustered microgrid environment while grid connected and islanded. As a part of this operation the microgrid controller should be capable of: ○ Reliably and accurately controlling the voltage and frequency of the microgrid in grid connected and islanded mode within defined limits. ○ Controlling the real and reactive power output of DERs to meet customer demand. ○ Seamless grid disconnection (transition to islanded mode) and grid resynchronisation. ○ Recovering from black start of the microgrid. ○ Achieving defined levels of emergency (expedited) demand response. ○ Isolation and continued operation following an internal grid fault. ○ Handling coordination of third-party-owned and utility-owned assets. • Develop control algorithms to perform: economic dispatch optimisation, CO_2 emission reduction, demand reduction. • Create a controller agnostic test plan (including performance metrics) that can be used to assess and compare microgrid performance.

Proj.	Research Goals
Solar and Storage	• Develop and demonstrate integrated, scalable, and cost-effective solar generation that incorporates energy storage and works seamlessly to meet both consumer needs and the needs of the electricity grid. • Evaluate the required sizing and effectiveness of energy in mitigating the impact of solar PV on the grid owing to its intermittency and high ramp rates. • Understand the role of solar generation and energy storage within the microgrid environment. • Explore business models for the economically sustainable uptake of energy storage-backed solar generation. • Quantitatively quantify the benefit provided by coupling solar PV and energy storage.

Given that the funding for each of these projects is sourced through independent streams, although they are interrelated, they have different timeframes for completion. The BCM, which is still progressing through legislation, is in the preliminary design phase. As a part of ComEd's engagement with the Illinois General Assembly, the team that are working on this project are considering a number of different network designs and generation scenarios. These scenarios compare four different cost-benefit structures for the microgrid deployment. My role on the project has been to develop CYME[7] network models for the proposed microgrid design to emulate minimum and maximum network loading conditions. Other work that I have been involved in as a part of the BCM project includes:

- Compiling estimated maximum and minimum demand load profiles for the feeders in the BCM based on available SCADA (PI Historian) network loading data;
- Reviewing and providing high-level input on the MMC test plan;
- Provided an initial proposal for siting of DER throughout the BCM; and
- Developed a number of presentations outlining BCM design scenarios and the benefits of the microgrid for dissemination to key stakeholders.

The Microgrid controller project, which received funding in September 2014, is due for completion in August 2016, with the final test plan due at the end of January 2016. During the past quarter I have provided my input to the test plan as it progresses through the final stages of review, which is being developed with project partners Quanta Technology[8]. Moreover, the models that I developed for the BCM will be used for validation in simulation and testing of the MMC. Each CYME model will be converted into RSCAD[9] models that will be used for real-time digital simulations of the microgrid and the MMC operation.

Following the completion of the test plan and implementation of the MMC, the operation of the MMC will be tested in three phases:

1. Real-time simulation-based testing, where the operation of the IIT microgrid, proposed BCM, and MMC will be simulated in a computer-based environment;
2. Real-time hardware in the loop (HiL) simulation-based testing, which will extend the real-time simulation-based testing to include primary hardware; and
3. Test bed testing, where the MMC will be trialled on a real-world microgrid environment (likely the IIT microgrid) to verify operation and functionality.

This testing will explore the behaviour and operation of the MMC under different operating conditions and scenarios; and how the three different levels of MMC control interact to ensure operational stability. These three levels of control are defined as:

[7] CYME, or more specifically CYMDIST, is the distribution network modelling tool (developed by Cooper Power Systems) that ComEd use to model their sub-transmission and distribution network.
[8] Quanta Technology is a subsidiary of Quanta Services, a consulting business that provides a broad range of services across generation, transmission, distribution, and regulation within the electricity industry.
[9] RSCAD is a simulation and analysis environment developed by RTDS Technologies for use with their real-time digital simulation systems. These

1. **Primary control** – implemented at a local level (i.e. distributed control) that operates on the timescale of fractions of a second to a couple of seconds. The primary control algorithm will implement droop control [13] on the DERs, utilising this technique for the initial sharing of load and calculation of voltage set point to prevent circulating currents amongst the microgrid DERs.
2. **Secondary control** – that will operate on the timescale of seconds and use centralised or peer-to-peer control to provide an integral control component, removing steady state error from the voltage and frequency operating point achieved by the primary (droop) control
3. **Tertiary control** – that will operate on the timescale of minutes to perform the economic optimisation of generation dispatch.

Finally, the solar and storage project (known also as the SHINEs project due to the name of the DoE FOA) has predominantly been focused on developing the project proposal and supporting documentation. Now that this project has received funding from the DoE (January 2016) work on this project is expected to pick up as the project moves toward detailed design phase. It is expected that the final solar PV and energy storage system installation will be located within the footprint of the BCM, to allow for it to be incorporated into the BCM's distribution network.

I look forward to continuing my involvement and gaining more exposure to these projects over the coming quarter.

5.1.3 Lessons Learned

The development of microgrids presents a significant paradigm shift from the centralised model that the electricity industry has built upon over the past 50 to 60 years. It is this centralized model that has provided the necessary economies of scale, availability of electricity, and generation efficiency to allow the rapid growth of many of the world's leading economies. As such, a transition toward a more distributed model may seem somewhat unfounded; however, given the increasing availability of DERs and the need for grid resiliency microgrids provide a logical "next step" to compliment the centralised network of today. A microgrid-enable system will have greater flexibility and control, while also enabling the optimisation of generation economics, reductions in CO_2 emissions, reductions in transmission losses, and improved power quality.

It is important to note however, that the additional cost and operational complexity inherent in a microgrid will mean that such topologies are not suitable for every application. As with all new technologies, microgrids should compete with other applicable traditional augmentations as part of an impartial cost-benefit analysis. This analysis should consider all value streams available to microgrids, including: deferred investment across all areas (e.g. generation, and capacity-related, reliability-related, power quality-related deferral of investment), reductions in outage and power quality-related losses, customer metrics like the value of lost load (VoLL) or value of customer reliability (VCR) [14], productivity increases, savings through loss reduction, energy efficiency, and environmental (CO_2 emission) savings.

Before the use of microgrids can be realised on a large scale there are a number of issues that will need to be resolved. These include:

- **The requirement for additional investment in DERs**. Although DG has proliferated in recent years, this has largely been in the form of solar PV or wind that, due to its intermittent nature, is not sufficient in its own right to sustain a microgrid. Therefore, it will be necessary to invest in dispatchable DERs that add inertia to the system and maintain the stability of the microgrid during islanded operation.
- **The technical complexity of managing DERs, including controllable loads**. In a truly distributed scenario, managing DERs is likely to require communication to hundreds, if not thousands, of embedded components (e.g. behind-the-meter inverters, controllable cooling or heating, building management systems). Developing a communication network and control system that is capable of managing such an embedded system is non-trivial.

- **The market complexity of managing DERs, including controllable loads**. As the number of DERs and need for controllable load increases, it will be necessary to develop an aggregator or distribution system operator function that can manage these resources and how they participate in energy markets.
- **Ownership of DERs**. During the early stages of microgrid development it is likely that utilities (particularly distribution utilities) may be required to invest in DERs. In areas with partially deregulated industries (i.e. where generation and retail operate under a deregulated, market environment) this will present regulatory challenges, as transmission and distribution utilities, that continue to remain regulated entities, are often precluded from owning generation assets due to the inherent conflict of interest.

In the Australian electricity industry, microgrids will likely find applications in capital or major cities where the need for grid resiliency justifies the cost of investment. Outside of major cities, microgrids may provide reliability and resiliency to remote and isolated communities, particularly where the cost of providing this reliability through traditional network augmentation (e.g. parallel feeders) is comparable to the cost of microgrid development.

In future, if the cost of electricity continues to increase, communities or new developments may look to invest in a microgrid-capable electricity grid in a bid to become self-sufficient and ultimately to move “off grid”. Realization of such a scenario would present a significant challenge for distribution and transmission utilities and may ultimately make much of the service that they provide redundant. As such, utilities within Australia need to maintain an agile and flexible approach to this changing environment, positioning themselves to respond quickly to changing customer needs. Indeed, the utility of the future may look to provide services developing community microgrids as a way of better serving their customers and remaining relevant in the changing industry environment.

5.2 Distributed Generation Hosting Capacity

In Section 5.1 of my Fourth Quarterly Report [1], I presented the concept of DG hosting capacity, discussed two common methods for quantifying hosting capacity, and outlined how I was working to apply one of these techniques to ComEd's network. In this quarterly report I will outline my continued work on this project and some of the issues that I have experienced over the last quarter.

5.2.1 Analysis Algorithm

Over the past three months I have been working on the analysis algorithm in three key areas:

1. Speed and efficiency improvements;
2. Attempting to take into account additional constraint considerations; and
3. Standardisation and interfacing of code to enable GUI development.

Although my focus has not been primarily on reviewing the code and analysis algorithm with the goal of making speed improvements, as I have become more experienced with the analysis technique and with CYME, I have been able to identify a number of minor code tweaks or process improvements. In addition, I identified some parts of the algorithm (namely the identification of network constraints) that can be completed within CYME as an embedded functionality. By using the "abnormal condition" functionality made available through CYME's component object model (COM) interface it is possible to identify when a network constraint (e.g. voltage constraints, thermal rating overload, protection mal-coordination, or short circuit current overload) occurs. This significantly reduces the amount of data that is transferred between CYME and the program that I have code to managing the Monte Carlo simulation, in turn speeding up the algorithm. Through these changes I have been able to achieve a 5-10% improvement in modelling time.

Initial analysis conducted with the hosting capacity algorithm returned relatively high values for feeder hosting capacity (in the order of thousands of kW per feeder), particularly on "strong[10]", well regulated feeders. In these cases, feeders, which were modelled at their 10th percentile loading[11], were frequently found to have hosting capacities that would result in reverse power flow at the primary substation circuit. While this scenario was entirely feasible while maintaining acceptable voltage and thermal loading, allowing reverse power flow to a substation level may create issues with:

- Protection, particularly transformer or feeder protection where directional elements are used;
- Line and transformer voltage regulation control, particularly in older devices that do not have reverse power flow control capability; and
- Short circuit fault current, increasing fault current on equipment beyond their rating.

In the hope of providing a more realistic estimate of hosting capacity, and as a part of the stakeholder engagement process for the project I sought input from two internal ComEd departments:

- Relay and Protection Engineering, who (among other things) are responsible for issuing protection settings, undertaking fault studies, and studying protection-related issues for DG interconnection requests; and
- Distribution Capacity Planning, who (among other things) are responsible for undertaking system area studies, developing capacity-related augmentation plans, and studying capacity and voltage-related issues for DG interconnection requests.

During these sessions I worked with my colleague from Smart Grid and Technology, Dimitra Apostolopoulou (Engineer, Commonwealth Edison), to explore the interconnection assessment process undertaken by the respective departments. This discussion provided a more detailed

[10] A "strong" feeder in this application is one that has low source (primary substation) Thevenin equivalent impedance and is constructed with low impedance conductors.
[11] Unfortunately, feeder minimum load during normal operation was not recorded in any available data source; therefore, the 10th percentile loading was used as a simple, easily calculable estimate for minimum feeder demand.

understanding of the assessment process, beyond the high-level assessment requirements documented in Illinois' Administrative Code for Electricity Utilities (Title 83, Chapter I, Subchapter C) Part 466 [15]. In doing so, Dimitra and I were able to identify possible additional constraints that could be incorporated into the hosting capacity assessment algorithm and how these constraints might reasonably be assessed. Some of the findings from these sessions are documented in Table 4.

Table 4: Additional network constraints for consideration as a part of hosting capacity algorithm

Session	Constraint Consideration
Relay and Protection Engineering	• Failure of anti-islanding protection (due to high penetration of DG) • Conductor fault current overload • Recloser fault current overload • Protection grading • Loss of reach
Distribution Capacity Planning	• Load (and voltage) imbalance • Distribution transformer overload • Increased operation of tap changers • Total harmonic distortion limitations (THD)

Our discussions with Relay and Protection Engineering also highlighted that inverter-based DG has limited contribution to short-circuit fault current. The industry rule of thumb estimates the peak fault contribution of inverter systems as twice the inverter rating. Although industry testing has shown that slightly higher fault contributions can occur, in the order of two to three times rated current, this testing also identified that the fault contribution was generally sustained for between 1ms to 4ms [16]. This time scale (less than a quarter of a cycle at 60Hz) is much less than the sub-transient fault current duration of most generators. Therefore it is expected that inverter connected systems, which represents most renewable forms DG, are unlikely to have a significant impact on overcurrent protection operation.

Over the past few weeks (and in coming weeks) I have been investigating how to incorporate these modelling considerations into the stochastic modelling algorithm without significantly impacting efficiency. In some instances my ability to account for constraints has been limited by data availability. For example, the Relay and Protection Engineering group use an alternate modelling system (Computer-aided Protection Engineering (CAPE)[12]) for protection studies, so, although CYME is capable of conducting protection grading and reach studies, some of the data required to complete these studies (e.g. protection settings) are not embedded within the CYME models. In cases like these, where I cannot adequately account for constraint considerations due to modelling, data, or time constraints I will document them for future development.

As more of these constraints are added, it is expected that the hosting capacity calculation will reduce, reflecting the possibility that other network constraints may occur at lower DG penetration than for the overvoltage and capacity constraints currently being considered. Ultimately this will improve the accuracy and confidence of the resultant DG hosting capacity assessments.

Over the past three months I have also reviewed the application of the Electric Power Research Institute's (EPRI's) "streamlined method". This technique, which was introduced briefly in my Fourth Quarterly Report [1], utilises a number of correlations and resultant formulations identified from stochastic hosting capacity studies to estimate the feeder hosting capacity with a single load flow, short-circuit analysis, and feeder data. After investigating this technique with my colleagues I recommended that, at the present time, the streamlined method not be progress further because:

[12] CAPE is a modelling environment developed by Electrocon International that is specifically targeted at protection system modelling and fault analysis for distribution and transmission systems.

- On a feeder-by-feeder comparison, the stochastic approach provides a more accurate assessment[13], better capturing the probabilistic nature of hosting capacity; and
- Applying the streamlined approach on a whole-of-network hosting capacity assessment (as done by other utilities [17, 18]) requires modelling each feeder and, as a result, has far greater implications for data completeness and accuracy.

In addition, EPRI is currently working with Cooper Power Systems (the company that produces CYME) to develop an add-on for CYME. This add-on would implement the streamlined approach within CYME's modelling environment. As such, ComEd may be able to investigate the streamlined approach in more detail once this add-on has been released.

5.2.2 Feeder Classification

In my Fourth Quarterly Report [1], I discussed the use of K-means clustering to classify all feeders in ComEd's network and identify a representative subset of characteristic feeders. As a brief recap, K-means clustering takes a matrix of input data that represents a group of items (i.e. distribution feeders) and characteristics that describe those items (also known as features). With this information the clustering algorithm divides the items into a specified number of clusters based on similarities within the feeder characteristics.

The goal of clustering in this application is to group feeders with similar hosting capacities. If this can be achieved, it follows that one feeder in each group (the characteristic feeder) can be analysed for its DG hosting capacity, providing an estimate of the hosting capacity of all other feeders in that group. However, as was discussed briefly in my last report, initial results from the feeder classification showed large intra-cluster variations in hosting capacity. Over the past quarter I have been working with my colleagues to improve this clustering technique with the hope of reducing intra-cluster variation and improving the overall accuracy of the feeder classification technique.

As a part of this process, I have attempted to run detailed hosting capacity studies on approximately 1,000 feeders, approximately 500 of which were successfully modelled[14] (close to 10% of ComEd's 5,000 distribution feeders). This information has been used twofold:

1. As a means to understand and measure the accuracy of the feeder classification technique; and
2. To investigate the correlation between feeder characteristics and hosting capacity.

In the second instance, by calculating the correlation between hosting capacity (for the modelled feeders) and each of the feeder characteristics, it is possible to identify features that should have a stronger link with hosting capacity. Moreover, using features that demonstrate a higher correlation with hosting capacity as input to the K-means clustering algorithm should improve the likelihood that feeders with similar hosting capacities will be allocated to the same cluster. In calculating the correlation we considered two values: the correlation coefficient (r) and the statistical significance (p) value. The correlation coefficient (r) defines how well variation in one variable (e.g. hosting capacity) can be described by a variation in a second variable (e.g. feeder length). Values for r range between $|r| = 1$ denoting a perfect correlation (i.e. one variable perfectly describes another), to $|r| = 0$ denoting no correlation (i.e. the two variables have no relationship). Alternatively, the statistical significance (p) value describes the likelihood that a correlation may occur by chance (i.e. random sampling). Values for p range between $0 \leq p \leq 1$, with lower values for p denoting a greater statistical significance or confidence of the observed correlation. Traditionally, a statistical significance threshold (denoted as α) is utilised to set the level at which a correlation is considered statistically significant.

[13] This speed / accuracy tradeoff is an inherent decision in the development of the streamlined approach.
[14] Although ComEd has feeder models for its approximately 5,000 distribution feeders, some of these feeders cannot be successfully modelled using the hosting capacity algorithm for a variety of reasons. Common reasons include: abnormally high values for hosting capacity, data errors, incomplete data, or models failing to converge.

Typical values for α are 0.1, 0.05, or 0.01, depending on the application. For this application, the statistical significance threshold was set to 0.05.

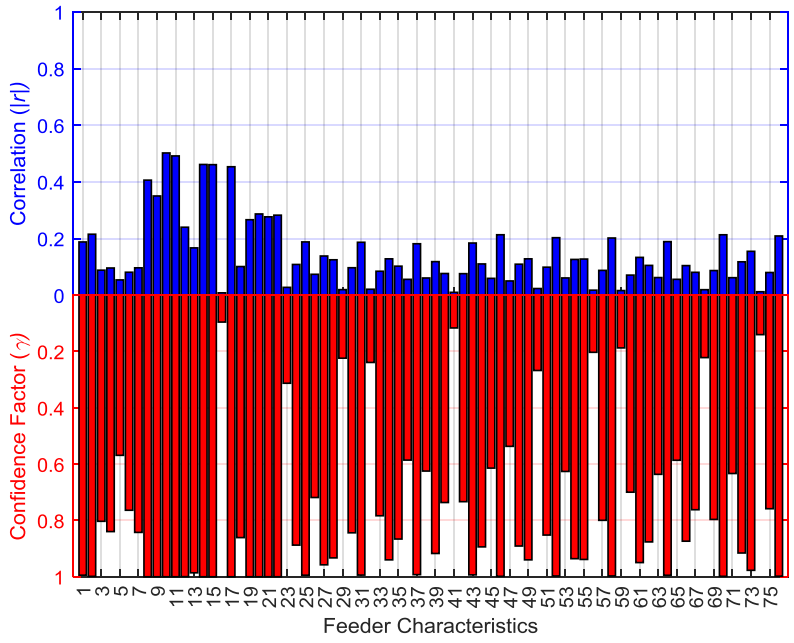
Figure 5 provides graphical representations of the results obtained from the correlation analysis that compared a range of feeder characteristics to hosting capacity. Both graphics in this figure show correlation ($|r|$) in blue and confidence factor (γ) in red, with the confidence factor plot inverted and stacked below the correlation for ease of comparison.

Given the probabilistic nature of hosting capacity (discussed in Section 5.1.1.1 of my Fourth Quarterly Report [1]), it was necessary to provide a single value for hosting capacity for each feeder analysed. To this end, the 5th percentile hosting capacity ($F_{HC}^{-1}(0.05)$) was utilised; where $F_{HC}(x)$ is the cumulative density function (CDF) that describes the hosting capacity distribution and probability density function (PDF) ($f_{HC}(x)$). It is also important to note that, to more clearly highlight correlation values with a favourable statistical significance, an analogous metric called confidence factor (γ) was employed. Calculation of the confidence factor is defined in Equation (1). It follows that high values of γ (i.e. $\gamma \geq 0.95$) denotes a low probability that the correlation was observed by random sampling.

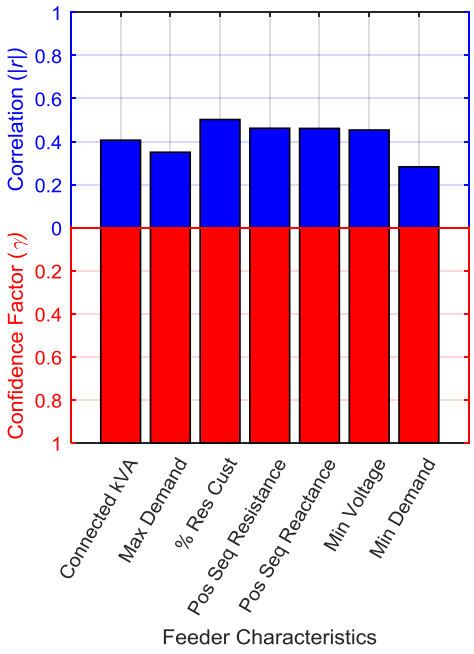
Figure 5 (a) shows the correlation coefficient for all of the 77 different feeder characteristics considered (each of which are documented in Table 5). In particular, it highlights the low correlation ($r < 0.2$) that was observed for most feeder characteristics. While it is reasonable to expect that not all characteristics would have a strong correlation with hosting capacity, by intuition, it was anticipated that a number of fundamental electrical characteristics, like the nodal Thevenin equivalent impedance values would show a high correlation. Given the counter intuitive nature of this result, the analysis technique and characteristic data were thoroughly reviewed to ensure that these low correlations were not the result of a calculation or data error; however no plausible explanation was identified. Those characteristics that did display a reasonable correlation ($r > 0.3$) were selected for use in the revised clustering algorithm, as shown in Figure 5 (b)[15].

$$\gamma = 1 - p \tag{1}$$

[15] To avoid biasing the K-means clustering algorithm, characteristics that are highly correlated with each other should be avoided. For this reason not all characteristics with a hosting capacity correlation greater than 0.3 were included in the final algorithm.



(a)



(b)

Figure 5: Correlation coefficient (r) and confidence factor (γ) for various features with hosting capacity
(a) Showing all feeder characteristics considered
(b) Showing feeder characteristics that were selected for use in the clustering algorithm

Table 5: Feeder characteristics by reference number

#	Description	#	Description
1	Σ(1 phase length)	39	X_{ab} max
2	Σ(2 phase length)	40	X_{ab} min
3	Σ(3 phase length)	41	$\|Z_{ac}\|$ mean
4	Σ(conductor length)	42	$\|Z_{ac}\|$ max
5	Count(regulators)	43	$\|Z_{ac}\|$ min
6	Σ(capacitor rating)	44	R_{ac} mean
7	Count(tee points)	45	R_{ac} max
8	Σ(distribution transformer rating)	46	R_{ac} min
9	Max demand	47	X_{ac} mean
10	% Residential cust.	48	X_{ac} max
11	% Commercial cust.	49	X_{ac} min
12	% Unspecified cust.	50	$\|Z_{bb}\|$ mean
13	Σ(customers)	51	$\|Z_{bb}\|$ max
14	Pos. sequence resistance / mile	52	$\|Z_{bb}\|$ min
15	Pos. sequence reactance / mile	53	R_{bb} mean
16	Source voltage	54	R_{bb} max
17	Min node voltage	55	R_{bb} min
18	Max node voltage	56	X_{bb} mean
19	A phase min current	57	X_{bb} max
20	B phase min current	58	X_{bb} min
21	C phase min current	59	$\|Z_{bc}\|$ mean
22	Min demand	60	$\|Z_{bc}\|$ max
23	$\|Z_{aa}\|$ mean	61	$\|Z_{bc}\|$ min
24	$\|Z_{aa}\|$ max	62	R_{bc} mean
25	$\|Z_{aa}\|$ min	63	R_{bc} max
26	R_{aa} mean	64	R_{bc} min
27	R_{aa} max	65	X_{bc} mean
28	R_{aa} min	66	X_{bc} max
29	X_{aa} mean	67	X_{bc} min
30	X_{aa} max	68	$\|Z_{cc}\|$ mean
31	X_{aa} min	69	$\|Z_{cc}\|$ max
32	$\|Z_{ab}\|$ mean	70	$\|Z_{cc}\|$ min
33	$\|Z_{ab}\|$ max	71	R_{cc} mean
34	$\|Z_{ab}\|$ min	72	R_{cc} max
35	R_{ab} mean	73	R_{cc} min
36	R_{ab} max	74	X_{cc} mean
37	R_{ab} min	75	X_{cc} max
38	X_{ab} mean	76	X_{cc} min

Nodal Thevenin Equivalent Impedance (rows 23–38)

Nodal Thevenin Equivalent Impedance (rows 39–76)

With these revised characteristics and the K-means clustering methodology outlined in Section 5.1.1.2 of my Fourth Quarterly Report [1], I was able to identify characteristic feeders and clusters for ComEd's distribution network. In an attempt to improve the accuracy of the clustering and to provide greater granularity, ComEd's distribution feeders were split into two groups based on their nominal voltage (i.e. 4kV and 12kV), and a total of 40 feeder clusters were identified (20 in each group). From these feeder clusters a representative group of 40 feeders was selected by finding the feeders closest to the cluster centroid (i.e. with the smallest Euclidian distance). These characteristic feeders were then analysed to find their hosting capacity, with the resultant values used to represent the hosting capacity of all feeders in the same cluster. The following figures and tables provide a summary of the findings from this analysis and some of the limitations.

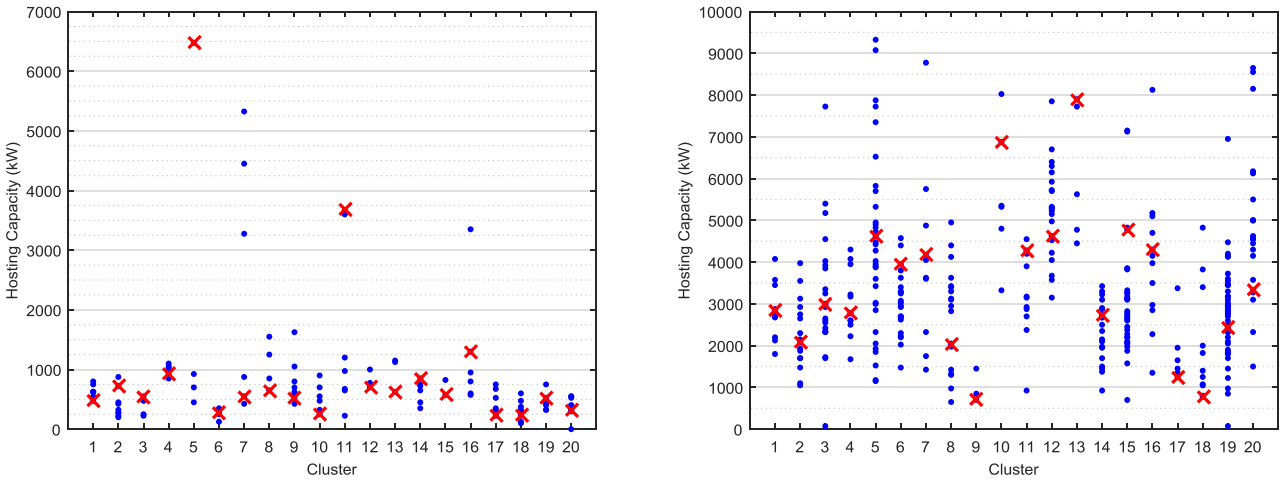
Table 6 provides a breakdown of ComEd's 4kV and 12kV distribution feeders, and the final number of feeders that were input to the clustering algorithm. The discrepancy between these values is representative of the number of outlier feeders that were identified as a part of data pre-processing. Outlier feeders are those with anomalous feeder characteristics that may negatively impact the performance of the clustering algorithm. From these figures it is evident that 70.1% of ComEd's distribution feeders (i.e. 5385 feeders) were included in the clustering algorithm. While this may seem like a low conversion rate, this could be increased by increasing tolerance to variation in feeder characteristics.

Table 6: Summary of ComEd's distribution feeders by nominal voltage

Voltage	Number of Feeders	Clustered Feeders	Percentage
4kV	1113	661	59.39%
12kV	4272	3114	72.89%
Total	**5385**	**3775**	70.10**%**

These 3,775 feeders were clustered into two sets of 20 groups (split by nominal voltage). Figure 6 shows the hosting capacity values for a subset of feeders in each cluster where the hosting capacity of the feeder has been calculated. These hosting capacities (shown as blue dots), were compiled over a number of weeks of modelling runtime, and give an estimate of the distribution of within-cluster hosting capacity. Also shown on these plots are the hosting capacities of the characteristic feeders (shown as red crosses), providing an indication of how the characteristic feeder fits within the cluster. From these figures it is evident that the hosting capacity values for some clusters exhibit a close relationship (i.e. they are tightly grouped), while others range widely. It is also interesting to note that some clusters contain seemingly anomalous feeders that have hosting capacities widely divergent from the remainder of the group. Moreover, in a couple of instances, these anomalous feeders were actually the characteristic feeder that was identified by the clustering algorithm to be the most representative of the cluster.

To summarise these values, Table 7 details the breakdown of each cluster identifying the number of feeders analysed in comparison to the total number of feeders within a cluster. This provides an understanding of the "size" of each cluster and the percentage of feeders represented in Figure 6 and Figure 7.



(a) ***(b)***

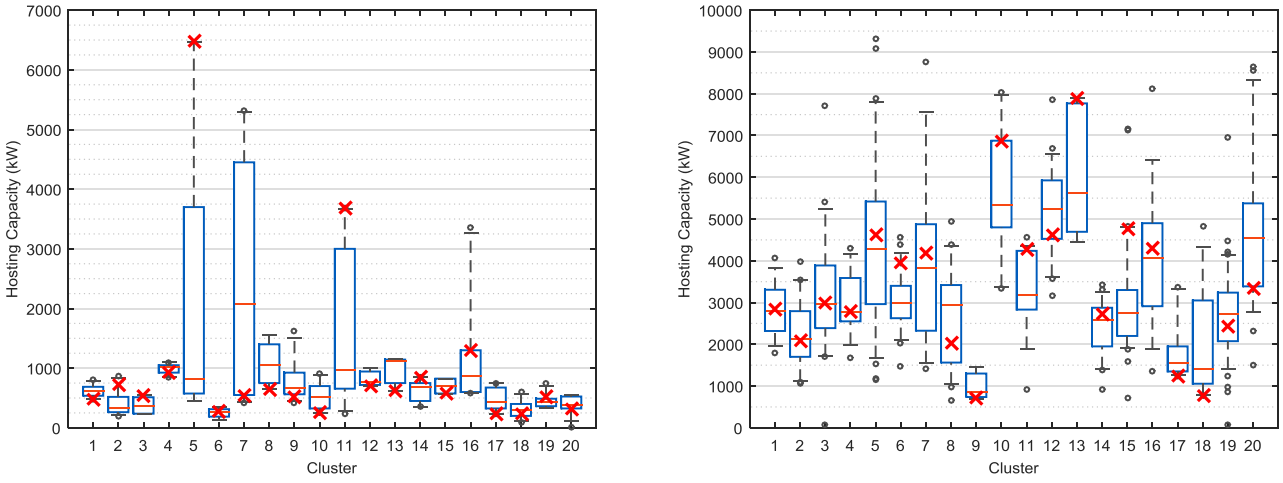
Figure 6: Scatter plots of modelled hosting capacity (blue points) and characteristic feeders (red cross)
(a) For 4kV feeders
(b) For 12kV feeders

Table 7: Summary of feeder clusters

		Cluster																				
	Feeders	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Σ**
4kV	**Analysed**	8	9	4	6	4	4	6	4	8	6	7	3	3	6	2	6	6	9	8	10	**119**
	Within-Cluster	43	36	31	41	35	31	24	44	21	16	38	20	20	26	30	46	42	35	48	34	**661**
	Percentage	19%	25%	13%	15%	11%	13%	25%	9%	38%	38%	18%	15%	15%	23%	7%	13%	14%	26%	17%	29%	**18%**
12kV	**Analysed**	11	17	24	12	33	22	10	19	3	6	13	22	5	22	32	12	6	11	48	23	**351**
	Within-Cluster	133	220	140	174	182	185	118	242	52	139	159	142	89	224	154	138	113	128	229	153	**3114**
	Percentage	8%	8%	17%	7%	18%	12%	8%	8%	6%	4%	8%	15%	6%	10%	21%	9%	5%	9%	21%	15%	**11%**

Figure 7 uses box plots[16] to provide a clear statistical comparison of the data presented in Figure 6, in this form the accuracy of the clustering algorithm can be visually assessed. In particular, there are two predominant findings to consider:

1. The spread of hosting capacity values within a cluster. In an ideal situation the clustering algorithm should group feeders with similar hosting capacities, so it follows that each cluster should only have a small spread.
2. How representative the characteristic feeder is of the group. If the characteristic feeder is representative of the group it should have a hosting capacity that is close to the group median (red line on the box plot) and well within the 25th and 75th percentiles (upper and lower blue lines).



(a) ***(b)***

Figure 7: Box plots of modelled hosting capacity and characteristic feeders (red cross)
(a) For 4kV feeders
(b) For 12kV feeders

As was identified from Figure 6 and is clearly apparent from Figure 7, the clustering algorithm achieved mixed results. In some instances clusters contain a small range of hosting capacity values, particularly for 4kV feeders (e.g. 4kV clusters 1 through 4), and have representative feeders with hosting capacities that closely match the group median (e.g. 12kV clusters 1 through 4). However, there are also a large number of clusters with widely varying hosting capacities, particularly for 12kV feeders (e.g. 12kV clusters 5 and 7), and poorly represented characteristic feeders (e.g. 4kV clusters 5 and 11). Given that one of the key applications of this analysis is to improve on the accuracy of existing DG interconnection screening methods, a low level of accuracy resulting from the clustering algorithm may heavily limit the applicability and value of results produced using this approach. It follows, considering the performance observed at this stage, that although this feeder classification

[16] Box plots (also known as box and whisker plots) provide a visual representation of five key statistical values (from top to bottom) the: maximum value, 75th percentile, median (or 50th percentile), 25th percentile, and minimum value. Statistical outliers, which are points that are 1.5 times the inter-quartile range above or below the 75th or 25th quartile (respectively), are also shown on these boxplots (represented as circular points).

algorithm can be used to undertake a system-wide hosting capacity assessment, any outcome of this analysis should be treated with great caution.

It is important to note that the data for actual feeder hosting capacities shown in these figures represents only a small subset of the total number of feeders within each cluster and within ComEd's network (as shown in Table 7). If a greater percentage of feeders were analysed, the more complete distribution of hosting capacity values may show the characteristic feeders to be more representative of the cluster median; however, I would not expect significant deviations from these initial distributions.

5.2.3 Lessons Learned

Six months ago I set out to develop a tool that combined stochastic Monte-Carlo simulations with clustering techniques to analyse the hosting capacity of ComEd's entire distribution system. To date there have been a number of success and challenges, all of which have produced interesting learnings and greatly developed my understanding in this field. Although the resultant tool has opportunities for future development, it was successful in employing stochastic modelling techniques to estimate hosting capacity of feeders, and using clustering to group and characterise ComEd's network. However, it is the accuracy of the latter, the clustering algorithm, that has provided the greatest number of challenges and learnings.

Despite K-means clustering being used in a range of applications relating to characterising the distribution network [19, 20, 21, 22], and, more specifically, to characterising distribution networks for quantifying hosting capacity [23, 24, 25], it would appear that the accuracy of the clustering algorithm is often assumed and not measured. This is in part because a true measure of accuracy requires calculation of the metric that is attempting to be scaled through clustering (e.g. hosting capacity). If these values are available on a large scale then applying clustering techniques provides no additional value, other than for understanding the accuracy of clustering techniques.

In my Fourth Quarterly Report [1] I alluded to some of my early findings from clustering; in particular, I noted the large intra-cluster variations in hosting capacity. As additional results from detailed hosting capacity studies have become available, it has also become evident that the characteristic feeders (identified from the clustering algorithm) were often not a good representation of other feeders in the same cluster (i.e. they were largely divergent from the cluster median). Since writing my last quarterly report the Electric Power Research Institute (EPRI)[17] has published a summary of their concerns relating to the accuracy of using K-means clustering as a part of a large-scale hosting capacity assessment [26]. Although EPRI employed a slightly different methodology in their clustering technique, such as analysing the performance of clustering by topological and electrical feeder characteristics separately, they observed similar challenges with large intra-cluster variations and misleading characteristic feeders.

In an attempt to improve the accuracy of the clustering algorithm, and using the results of hundreds of detailed hosting capacity studies, I calculated the correlation between hosting capacity and large number of feeder characteristics. This analysis highlighted the complex nature of hosting capacity, as only a small number of characteristics were shown to have some (albeit not particularly strong) correlation with hosting capacity. Even characteristics that are intuitively and intrinsically linked to the feeder constraints being assessed (like Thevenin equivalent impedance) showed limited, almost insignificant correlation with hosting capacity.

It is this area, namely feeder clustering techniques and characteristics for hosting capacity assessments that warrants further research. Although some published findings [26] have cast doubt

[17] The Electric Power Research Institute (EPRI) is a not-for-profit organization based in the USA that conducts research on a broad range of issues to the electric power industry (from generation through delivery and end customer use). It is funded largely through the membership and participation of electricity utilities and other industry partners.

over the accuracy of this method (including the findings in this report), the performance of this algorithm is predominantly limited by the characteristics that are used in the clustering technique. For this reason, I believe that additional characteristics, be they topological, electrical, sociological, or a mathematical blend of a number of these, will unlock vastly improved accuracy in clustering feeders with similar hosting capacity.

Given the existence of alternate techniques for quantifying hosting capacity, like EPRI's "streamlined method" [27], it could be argued that there is limited value in refining the application of clustering techniques for system-wide hosting capacity assessments. However, clustering has an inherent and non-trivial advantage over the streamlined method in that it has a substantially lower requirement on data completeness and accuracy. Figure 8 provides a representative visualisation of this trade-off, showing the direct compromise between speed and accuracy with the added dimension of data requirements. It demonstrates the step change in data requirements that comes as a part of the streamlined method, which requires an accurate model for each feeder in the network. Comparably, analysis using clustering techniques requires accurate feeder models only for the characteristic feeders, reducing the amount of feeder models required from hundreds or (more likely) thousands to only a handful.

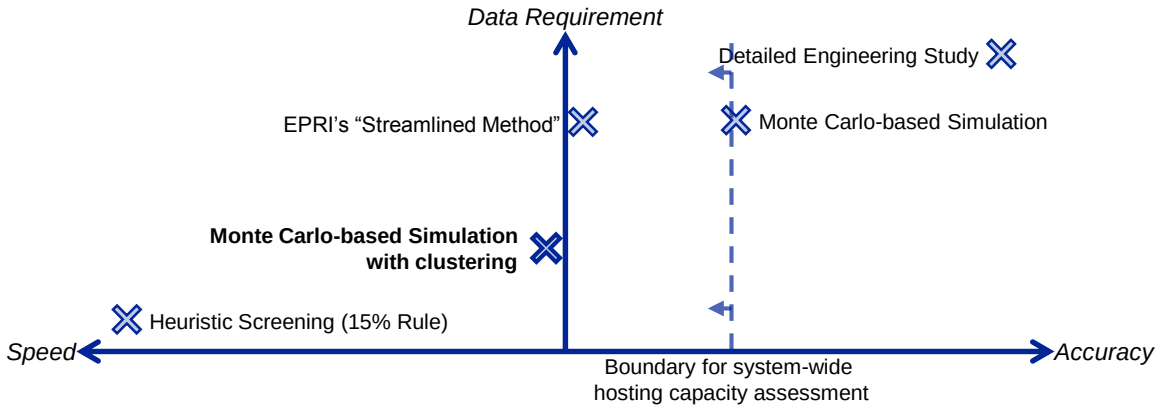


Figure 8: Comparison of tree-way trade-off (speed, accuracy, and data requirements) for hosting capacity assessment techniques

One additional point of learning that has become apparent over the past quarter, that I feel is important to note relates to the aggregation of feeder hosting capacities to a substation, regional, or system-wide level. It has been suggested in some publications [18, 26] that the sum of feeder hosting capacities can be used to calculate the hosting capacity at higher levels within the system. Given the probabilistic nature of hosting capacity, summing these values inherently implies that the hosting capacities of distribution feeders are independent – this is not the case. Consider, for example, the calculation of a substation hosting capacity, as the penetration of DG on one feeder increases approaching that feeder's hosting capacity, the substation loading, upstream voltage profile, harmonic distortion, and short-circuit currents will all change. While the substation transformer tap changer may effectively regulate the secondary bus voltage, maintaining it at the same set voltage, at a minimum the short-circuit current would have increased on other feeders owing to the reduced Thevenin equivalent circuit impedance owing to the increased level of DG. This in turn may change the hosting capacity of feeders connected to that substation. In a similar way that installing DG on a weak node of the feeder will impact hosting capacity of the feeder as a whole differently to installing DG on a strong node, installing DG on one feeder in an interconnected system will impact other feeders on that same system. Performing a true and accurate assessment of the whole-of-network DG hosting capacity would require development of a single system-wide network model that could be applied to the same stochastic modelling algorithm discussed in this report. Such a model would simulate all distribution feeders at one time, taking account of the inter-feeder and inter-substation impacts of DG.

In summary, the analysis that I have performed with my colleagues has provided an initial estimate for the hosting capacity of feeders within ComEd's network. Given the current level of variability and inaccuracy in the clustering algorithm I would recommend taking significant caution when using the results of this or similar types of analysis, particularly when informing decisions that could have long lasting technical, financial, or safety impacts. Considering this I see the primary value of these figures in providing a relative scale for the ability of one feeder to accommodate DG in comparison to another. Over the coming months and years, it is inevitable that further research and development will improve the accuracy of these algorithms and their resultant values, allowing them to be applied with greater confidence and across a broader number of applications.

6 Future Works

The past quarter at ComEd has continued to be interesting and technically challenging, while providing a number of opportunities for learning. Over this period I have continued work on developing and refining the hosting capacity and clustering algorithms, building on my work of the last quarter. I have also had the opportunity to provide input to the initial proposal and design for the Bronzeville Community Microgrid and the microgrid master controller test plan that has developed my understanding of the microgrid controller operational requirements and inherent challenges. Over the coming quarter, my last on the E.S. Cornwall Memorial Scholarship, I will be working to:

- Complete the system-wide hosting capacity assessment, document my findings, and present these findings to management;
- Presenting my work on hosting capacity at ComEd's Engineering Day[18];
- Finalising the documentation of my code, the design of the hosting capacity algorithm, and supporting material;
- Running a handover training session to brief my colleagues on the hosting capacity tool code and its structure so that they may further develop the tool following my departure.
- Assisting ongoing work relating to the Bronzeville Community Microgrid.

I had mentioned in my past quarterly report that I was working with my colleague Dimitra Apostolopoulou (Engineer, Commonwealth Edison) to develop a paper for publication at a reputable conference. After presenting the first draft of this paper, which is titled "*Locational Impact of Distributed Generation on Feeders*" to Shay Bahramirad (Director of Smart Grid and Technology, Commonwealth Edison) it was suggested that we work to further develop this paper and submit it to a journal (most likely IEEE Transactions on Smart Grid). It is my strong desire that, over the coming months, I am able to work with Dimitra to finalise and submit this paper.

During the last quarter I was able to visit the Braidwood Nuclear Generation site, a large nuclear generation facility based in Illinois that is owned by Exelon Generation, a subsidiary of ComEd's parent company Exelon. This visit is documented in Section 7 of this report, along with the details of my visit to S&C Electric's Headquarters in Chicago, Illinois and Power Quality facility in Franklin, Wisconsin.

In my personal endeavours, I was able to spend the Christmas period with my partner and her family in County Meath, Ireland; while there I experienced much of the beautiful landscape and cold, wet winter weather that the region has to offer. I have also been able to volunteer at a number of community events including:

- The Chicago Children's Advocacy Center (CAC) 2015 Kid's Holiday Party, which provides children involved with the CAC, their siblings, and family the opportunity to enjoy a morning of Christmas festivities.
- The Special Olympics Illinois 2015 Athletes Banquet, a gala event held for the athletes and their coaches.
- Food repackaging at the Chicago Food Bank. The Chicago Food Bank provides meals to the Illinois community who otherwise may not be able to afford to eat.
- The Black History Month Solar Spotlight, an interactive event targeted at teaching African American children from the south and west communities of Chicago about solar PV generation and careers in the fields of science, technology, engineering, and maths (STEM).

Over the coming quarter I hope to continue to network within ComEd, taking the opportunity to learn from others about innovative work being undertaken at ComEd. I also intend to continue my involvement with volunteer organisations, as it is something that I have found particularly rewarding

[18] ComEd's Engineering Day is a day-long exhibition of interesting and innovative engineering-based projects currently taking place at ComEd. It is scheduled to be held on Thursday 3rd March and will be attended by members of the Illinois Commerce Commission, and ComEd's sister utilities Philadelphia Electric Company (PECO) and Baltimore Gas and Electric (BG&E).

and enjoyable. I will also be participating in the Respiratory Health Association's "Hustle up the Hancock," a 91 story stair climb to the observation deck at the Hancock Tower, and the "Polar Plunge," where I will wade into the freezing waters of Lake Michigan to raise money for Special Olympics Illinois.

7 Other Works

7.1 S&C Electric Site Visits

S&C Electric[19] is a Chicago-based company that was founded in 1911 by two ComEd employees (Edmond O. Schweitzer and Nicholas J. Conrad) initially specialising in designing and manufacturing fuses. From this simple foundation the company has grown and diversified. S&C Electric is now a multi-national company that manufactures a wide range of power systems equipment including: indoor, outdoor, and underground switchgear, automated switching devices, and inverter systems (predominantly used for energy storage and power quality applications). S&C Electric also offer a number of services including: design, construction, asset management and monitoring, lifecycle optimisation. During my first month in the USA I attended site visits to S&C Electric's Headquarters in Chicago, Illinois and Power Quality Production facility in Franklin, Wisconsin.

While at the Headquarters in Chicago I was able to meet briefly with Wanda Reder (Chief Strategy Officer, S&C Electric) who, in addition to her role with S&C Electric, is very active in the Institute of Electrical and Electronics Engineers (IEEE) Power and Energy Society (PES). I took this opportunity to ask Wanda's about her career thus far, which has included a number of diverse and challenging projects, and understanding the lessons she has learned that may be applicable to my career. I also spent some time discussing Wanda's new role as the Chief Strategy Officer to understand her vision of S&C Electric's role within the changing power industry. It was interesting to hear about her vision for the company and its expansion from a switchgear and fuse-based company into distribution automation devices, commercial-scale uninterrupted power supplies, and inverter systems, which is expected to grow in coming years.

After meeting with Wanda I was given a tour of the S&C Electric Headquarters facility by Jason Lander (Director of Power System Solutions: Asia Pacific, S&C Electric). During the tour I was able to see most of the approximately 42.5 acre complex, which houses (among other things) the company's:

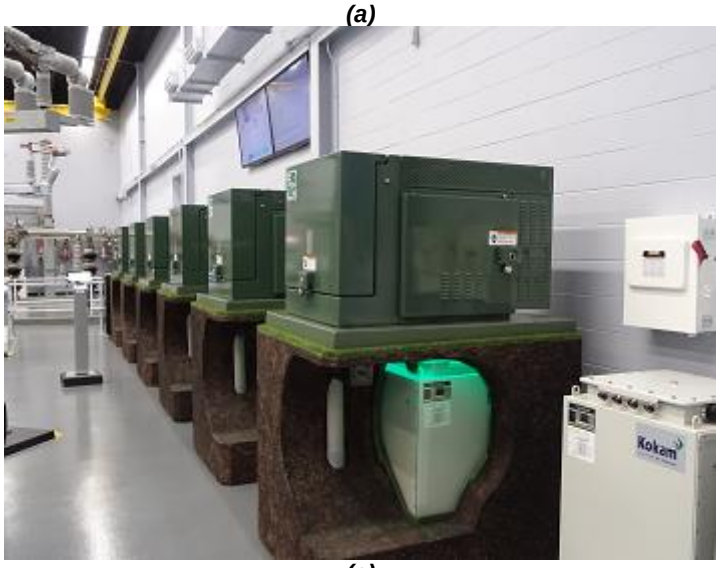
- Product demonstration and showroom;
- Central offices for many US and international design and construction teams, including one of their asset management and monitoring control centres;
- Manufacturing lines for a large number of products including: power fuses, distribution automation devices, and switchgear;
- Metalwork, fabrication, and painting facilities;
- Nicholas Conrad Laboratory, one of the leading power engineering test facilities in North America; and
- Storage and warehouses.

Figure 9 provides a selection of photos taken during my tour, highlighting some of the facilities that I toured. Overall, the tour provided an impressive overview of the in-house manufacturing and testing capability and also allowed me to closely observe the various stages of construction of a number of different S&C Electric products.

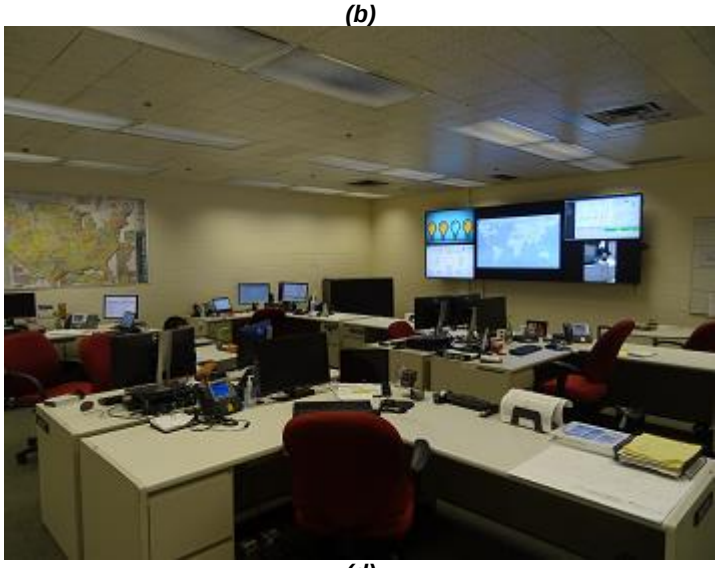
[19] For more information on S&C Electric see http://www.sandc.com

(a)

(b)



(c)



(d)

Figure 9: Facilities at the S&C Electric Headquarters in Chicago, Illinois
(a) The distribution automation demonstration floor with Vista® switchgear (rear right, ground mounted) and IntelliRupter® recloser (rear left, tower mounted)
(b) Product showroom with more IntelliRupter® reclosers (left) and six PureWave® community energy storage systems
(c) Six PureWave® community energy storage systems with 25kW inverter systems (green enclosure, shown as above ground) and 25kWh Li-ion batteries (white enclosure, shown as below ground)
(d) Asset Management and Monitoring Control Centre

The second site visit to S&C Electric's Power Quality facility in Franklin, Wisconsin was as a part of a ComEd project investigation the use of S&C Electric's small-scale (25kW) community energy storage systems to help reduce customer outages. This tour started with a short presentation that provided an overview of S&C Electric's storage management system range. S&C Electric have targeted their products for three specific sizes[20]:

- Community energy storage (25kW), which is designed to be connected at the LV side of the distribution transformer and supply a small number of residential customers.
- Medium-scale energy storage (250kW), which is targeted at commercial or small-utility scale (e.g. microgrid) applications.
- Large-scale energy storage (≥1MW), which is targeted at large-utility scale applications (e.g. UK Power Networks Smarter Network Storage system discussed in my Fourth Quarterly Report [1])

[20] With each of these solutions storage capacity (kWh / MWh) can be sized to suit the desired application.

Following this presentation we were given a tour of the manufacturing facility and were able to see:

- Engineering and design offices;
- Assembly lines for the inverter systems (for the respective energy storage systems), as well as their uninterrupted power supply (UPS) and static compensation (STATCOM) devices;
- A demonstration of the operation of the community energy storage system;
- Testing facilities for type and stress testing of the storage systems;
- Product warehousing.

As with the Chicago facility tour, this tour highlighted the substantial manufacturing and testing capability that S&C Electric possesses. Moreover, it was evident there exists a somewhat symbiotic relationship between S&C Electric and ComEd (and other utilities within the USA). Both organisations are able to work closely together in trialling and refining technologies and products. Unfortunately, this is not always a possibility in Australia due to its geographical isolation from many major manufacturers and the added cost and complexity that ensues.

I would like to thank Simon Bartlett (Australian Chair in Electricity Transmission, University of Queensland), and Stephen Sproul (Technology Innovation Engineer, Ergon Energy) for their help in arranging the site visit of the Chicago S&C Electric Headquarters; as well as Wanda Reder, Jason Lander, and the staff at S&C Electric's Franklin facility who gave their time to provide a tour of the two facilities.

7.2 Braidwood Nuclear Generating Station Site Visit

The Braidwood Nuclear Generating Station is a 2,330MW, two reactor facility located in Will County, Illinois, approximately 80km (50mi) from the city of Chicago. It is the largest (by generating capacity) of six nuclear power stations within the state of Illinois, all of which are operated by a subsidiary of ComEd's holding company, Exelon Generation. In early December I was able to attend a site visit to the Braidwood facility as a part of a tour arranged for young ComEd professionals.

The site visit commenced with a presentation overview of the facility, its history, some general information pertaining to the operation and environmental impact of the facility, particularly in comparison with other forms of electrical generation, and safety precautions important to our visit to the facility. This presentation gave an appreciation of the design, construction, and operation of a nuclear facility, while outlining a number of related facts and statistics. A selection of these points is provided in Table 8, which groups them into three categories: general, operational, and safety and environmental information.

Table 8: Overview of point of interest from Braidwood Nuclear Generation site tour

General	• Exelon Generation is the largest owner and operator of nuclear facilities in the USA, and the third largest in the world. • Construction of the reactors began in 1976, with the first reactor (Unit 1) being commissioned in 1987, and the second (Unit 2) following in 1988. These reactors were initially licensed for an operating life of 40 years (i.e. until 2026 and 2027 respectively), but both reactors have recently had their licenses extended allowing them to operate for an additional 20 years (i.e. until 2046 and 2047 respectively), providing a more than 70 year lifespan from construction through conceived operation (excluding decommissioning). • The two reactor units at Braidwood are Westinghouse pressurised water reactors (PWRs), the most common type of reactor used in nuclear generation. The PWR technology works by circulating high pressure, heated water, which maintains liquid form due to pressurisation, from the reactor core to a heat exchange system (or steam generator) that boils a second isolated body of water turning it into steam for use in a steam turbine. This pressurised water is then cycled back into the reactor core for reheating. This differs from another common design of nuclear reactor known as the boiling water reactor (BWR) that boils water directly within the reactor core, generating steam to turn the steam turbine. • The Braidwood facility does not have the distinctive hyperbolic cooling towers that are commonly associated with nuclear generation plants. Instead Braidwood uses water from the Braidwood Lake to cool water from the turbines in a condenser.
Operational	• In recent years the Braidwood facility has achieved a capacity factor[21] of 97.3%, an impressive value for a nuclear generation plant, but also substantially higher than other generation sources, including dispatchable generation like coal, hydro, or natural gas [28]. • After almost 28 years of operation, the Braidwood facility has accumulated a total of 16 dry casks22 of spent fuel, all of which are wholly contained and monitored on site. It is expected that these dry casks will be transitioned to a national repository for permanent storage and management; however, the development of such a complex is still in planning. • When full, each reactor holds 193 fuel assemblies. The location of each fuel rod is carefully planned and managed to ensure uniform dispersion of heat throughout the reactor, and avoiding uneven expenditure of the rods. • The reactor is refuelled approximately every 18 months with one third to one half of the fuel rods cycled from the reactor into the spent fuel pool. Each rod assembly will be cycled through the reactor a total of three times before it is "spent". Once a fuel rod is spent it will spend a period of approximately 10 years in the fuel pool to cool before it is transitioned to a dry cask for semi-permanent storage.

[21] Capacity factor is the ratio of actual generation to possible generation or $C = E_{Actual}/(P_{Rated} \times t)$, where E_{Actual} is the energy generated in Wh, P_{Rated} is the power rating of the facility in W, and t is the time duration of measured energy generation in hours.

[22] Dry casks are passively cooled containers that are used to safely store spent nuclear fuel after it has been removed from the reactor and been allowed to sufficiently cool in a spent fuel pool.

Safety and Environmental

- Vital systems and equipment can have up to four levels of redundancy.
- The main structures at Braidwood are manufactured to survive earthquakes, tornados, and flooding far more extreme than anything observed historically in the Braidwood area. Large portions of the facility were constructed with 1.2 meter (4ft) thick, steel reinforced walls. In addition to natural disasters, all structures housing primary equipment (i.e. that contain the reactor and generator) are designed and frequently tested to ensure that they are capable of withstanding an internal failure, like a rapid depressurisation of the steam system.
- Areas of the facility that may be prone to flooding are fully contained and sealable to ensure no water ingress.
- The dry casks used to store spent fuel are designed to withstand the impact of a full speed train collision.
- The lifecycle CO_2 equivalent greenhouse gas emissions from nuclear-based generation is, by most estimates, lower than solar generation and comparable to wind and hydro-electric generation, as shown in Figure 10.

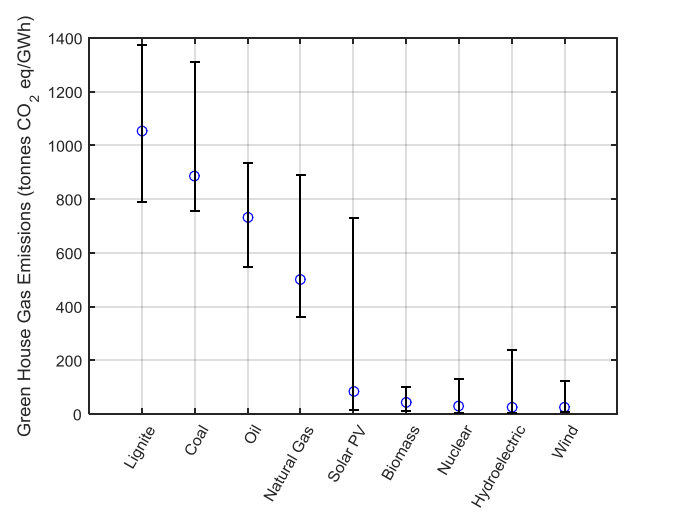


Figure 10: Summary of lifecycle greenhouse gas emissions by generation type and showing the mean, upper, and lower bounds from a range of literary estimates (modified from [29])

Following the completion of the opening presentation we were provided with a safety brief on the risks of exposure to radiation, the use of dosage monitoring equipment that we would be required to wear throughout our tour, and an understanding of safe levels of radiation exposure (measured in roentgen equivalent man or rem[23]). We were then able to enter the Braidwood facility, which, following the events of September 11th 2001, had understandably extensive and strict security requirements[24]. Once onsite we were escorted by our designated tour guide to the office component of the facility where all visitors were provided with their radiation monitoring device.

The tour that followed incorporated:

- The generator floor, that held the steam turbines used to generate electricity from the PWR.
- The condenser floor, located below the generator, which used water pumped from the Braidwood Lake to cool the steam after it had passed through the turbines.
- The spent fuel pool that is located in a building between the two reactor structures. The spent fuel pool, as the name suggests, is the storage location for fuel rod assemblies during and for approximately 10 years after their use in the reactors. Fuel assemblies are loaded into the pool upon arrival on site, where they are managed for the duration of their “active” life, being transferred to and from the reactor via two channels that connect to each reactor (one channel for each). Once expended, and following the 10 year cool-down time, the fuel

[23] Roentgen equivalent man is a “dosage equivalent” measure of radiation (of which there are three other common means of measuring radiation). It quantifies the amount of radiation absorbed by a person and the medical effect of this radiation.
[24] Even before attending the tour we were required to submit for a background screening.

assemblies are loaded into submerged dry casks before being transferred to the storage yard.
The spent fuel pool is more than 12m (40ft) deep, with approximately 9m (30ft) of coverage between the surface and the top of the fuel rods. This body of water serves two purposes: it cools the fuel assemblies, maintaining them at a safe temperature as they dissipate decay heat, and contains any radiation emanating from the rods. At full capacity, Braidwood's spent fuel pool is capable of holding 2984 fuel rod assemblies (each reactor can hold 193 assemblies at any one time).
During our time in the spent fuel pool area we were given an overview of how the fuel rod assemblies are managed throughout their active life and the strict safety precautions that are applied with each "handling".

- The control room, which is laid out in a mirrored horseshoe configuration, with each side being dedicated to one reactor and every aspect of its operation. During this time, we were given a more detailed overview of the operation of the reactors using some of the real-time monitoring and SCADA displays. We were able to talk with some of the operators who were on duty to understand what is involved in the methodical day-to-day operation of the plant, as well as the significant amount of training and qualification required in becoming a nuclear operator. I was especially surprised to find out that, as a part of their qualifications, an operator is only licensed to operate at a specific facility. Transferring to a different nuclear facility requires the operator to re-sit and be re-licensed to operate at the new facility.
- One of the backup generator rooms that houses a 5.5MW locomotive engine, diesel generator. At any one time each generator has approximately 190,000L (50,000US gal) of diesel available, enough to run the generator for 7 days of continuous operation.
  Like all of the systems within the nuclear facility, these generators undergo frequent and strict testing to ensure they are operating correctly and to specification. One of the most stressful tests for the backup diesel generator is the requirement for the system to be generating within 10 seconds of being called online. To meet this performance requirement, the pistons of the generator are "primed" by firing highly compressed air into the combustion chamber, bringing the pistons quickly up to speed before diesel is introduced to start combustion.
- A view of the dry cask storage yard, located on the east of the site that is used as the temporary holding place for the spent fuel until a national repository is established.

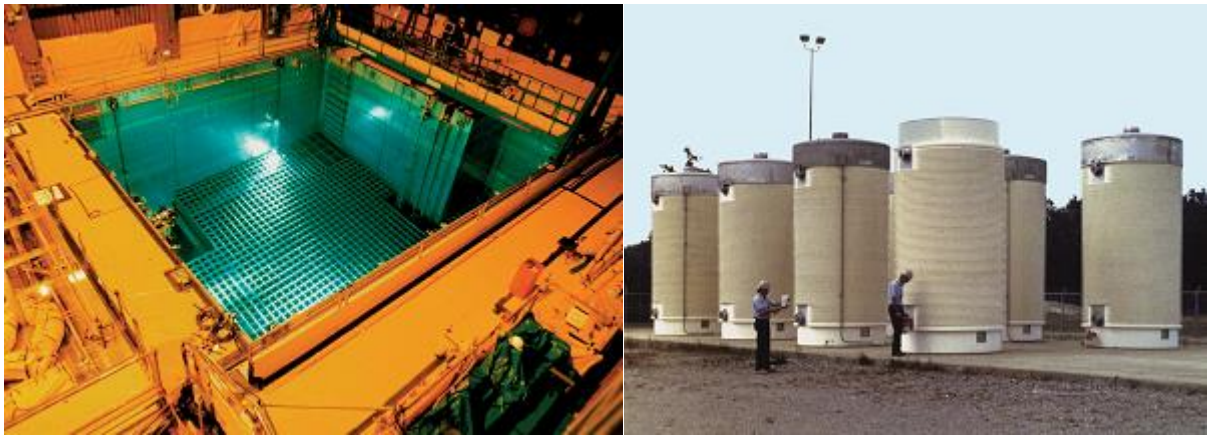
Unfortunately, due to security concerns I was not able to take photographs during the tour of the facility; however, I have collated a number of photos below to demonstrate some of the particularly unique aspects of the tour.

Figure 11 shows a life-size replica of a Westinghouse Vantage 5 fuel rod assembly, the same type that is utilised in the Braidwood and other PWR reactors. Actual fuel rods are made of zircaloy (zirconium alloy), owing to zirconium's low neutron absorption properties, and can hold U_{235} that is enriched to approximately 4.85%. The pins that hold the fuel pellets are laid out in a 17 by 17 configuration and are 3.9m (12.75ft) long. Each pin holds more than 100 pellets, each of which is approximately 1.5cm (0.6in) long and 1cm (0.4in) in diameter and has the same energy density as 900kg (2,000lb) of coal.

Figure 12 (a) shows an empty spent fuel pool at a nuclear generation site in California, USA that is somewhat similar to that used at the Braidwood facility; while Figure 12 (b) shows the dry cask storage cylinder, similar to those used to store expended fuel at the Braidwood facility. These dry casks have an expected life of approximately 100 years, within this time it is hoped that a permanent storage repository will be developed to allow the permanent storage of this the spent fuel.

Figure 13 shows part of the control room and control and annunciation panels associated with the Unit 2 reactor at Braidwood. The control and annunciation panels for Unit 1 follow the same layout but mirrored in the opposite direction to that which the photo was taken.

Figure 11: Fuel rod assembly display at the Braidwood Visitors Centre showing fuel pins and lifting assembly (left, foreground)



(a) ***(b)***

Figure 12: Spent fuel storage [30]
(a) The spent fuel pool at the San Onofre Nuclear Generating Station (California) pool, similar to that used at Braidwood
(b) Dry casks containing spent nuclear fuel for semi-permanent storage

Figure 13: Unit 2 side of the Braidwood Nuclear Generation control room [31]

I would like to finish this section by thanking ComEd's graduate and young professional resource group, GrADS, for making this tour a possibility. I would also like to thank the engineers at Braidwood Nuclear Generation site, whose names unfortunately escape me, but who took time from their daily roles to provide this extremely interesting and informative tour. As an engineer from Australia, a country with no nuclear generation, this was a once-in-a-lifetime opportunity that will add to the many others I am thankful and humbled to have been afforded since embarking on my E.S. Cornwall Memorial Scholarship.

8 Bibliography

[1] M. Zillmann, “E.S. Cornwall Memorial Scholarship: Fourth Quarterly Report,” 15 January 2016. [Online]. Available: http://escornwall.com.au/reports/Q4-report-matthew-zillmann.pdf. [Accessed 3 February 2016].

[2] Australian Government: Department of Industry, “The fact sheet on electricity prices,” February 2013. [Online]. Available: http://www.industry.gov.au/Energy/EnergyMarkets/Documents/ELECTRICITY-PRICES-FACTSHEET.pdf. [Accessed 12 October 2014].

[3] Department of Energy, “Summary Report: 2012 DoE Microgrid Workshop,” 30 July 2012. [Online]. Available: http://energy.gov/sites/prod/files/2012%20Microgrid%20Workshop%20Report%2009102012.pdf. [Accessed 9 January 2016].

[4] Alstom Grid, “The challenge of protecting microgrids,” Think Grid, pp. 28-29, 2011.

[5] Berkeley Lab, “Examples of Microgrids,” 2015. [Online]. Available: https://building-microgrid.lbl.gov/examples-microgrids. [Accessed 10 January 2016].

[6] J. Romankiewicz, N. Zhou, M. Qu and C. Marnay, “International Microgrid Assessment: Governance, Incentives, and Experience,” in ECEEE Summer Study Proceedings, Toulon, France, 2013.

[7] Office of Electricity Delivery and Energy Reliability, “Microgrid Activities,” 2015. [Online]. Available: http://energy.gov/oe/services/technology-development/smart-grid/role-microgrids-helping-advance-nation-s-energy-syst-0. [Accessed 10 January 2016].

[8] Office of Electricity Delivery and Energy Reliability, “DE-FOA-0000997: Microgrid Research, Development, and System Design,” 31 January 2014. [Online]. Available: http://nyssmartgrid.com/wp-content/uploads/DOE-Microgrid-FOA.pdf. [Accessed 10 January 2016].

[9] Commonwealth Edison, “ComEd's Future Energy Plan,” 2015. [Online]. Available: https://www.comed.com/newsroom/energy-plan/Pages/energy-plan.aspx. [Accessed 10 January 2016].

[10] Commonwealth Edison, “ComEd Grid Modernization,” 15 March 2015. [Online]. Available: http://www.cookcountyil.gov/wp-content/uploads/2015/03/Cook-County-SunShot-SAG-Meeting__150325_Final.pdf. [Accessed 10 January 2016].

[11] Department of Energy, “Energy Department Announces $8 Million to Improve Resiliency of the Grid,” 8 September 2014. [Online]. Available: http://www.energy.gov/articles/energy-department-announces-8-million-improve-resiliency-grid. [Accessed 17 January 2016].

[12] Department of Energy, “Energy Department Announces $18 Million to Develop Solar Energy Storage Solutions, Boost Grid Resiliency,” 19 January 2016. [Online]. Available: http://energy.gov/articles/energy-department-announces-18-million-develop-solar-energy-storage-solutions-boost-grid-0. [Accessed 19 January 2016].

[13] H. R. Pota, M. J. Hossain, M. A. Mahmud and R. Gadh, “Control for Microgrids with Inverter Connected Renewable Energy Resources,” in IEEE Power and Energy Society General Meeting, Washington DC, 2014.

[14] Australian Energy Market Operator, “Value of Customer Reliability Review,” September 2014. [Online]. Available: http://www.aemo.com.au/Electricity/Planning/~/media/Files/Other/planning/SAAF/VCR%20final%20report%20%20PDF%20update%2027%20Nov%2014.ashx. [Accessed 24 January 2016].

[15] Illinois Commerce Commission, “Part 466: Electric Interconnection of Distributed Generation Facilities,” Chicago, 2008.

[16] J. Keller and B. Kroposki, “Understanding Fault Characteristics of Inverter-Based Distributed Energy Resources,” National Renewable Energy Laboritory, January 2010. [Online]. Available: http://www.nrel.gov/docs/fy10osti/46698.pdf. [Accessed 27 January 2016].

[17] J. Smith and M. Rylander, “Distribution Planning with DER: Distribution System-Wide Impact Assessment Methods,” 22 October 2015. [Online]. Available: http://www.nrel.gov/esi/pdfs/highpenworkshop_smith.pdf. [Accessed 31 January 2016].

[18] M. Rylander, J. Smith, W. Sunderman, D. Smith and J. Glass, “Application of New Method for Distribution-wide Assessment of Distributed Energy Resources,” in IEEE Power and Energy Society Transmission and Distribution, Dallas, 2016.

[19] L. Dow, M. Marshall, L. Xu, J. R. Agüero and H. L. Willis, “A Novel Approach for Evaluating the Impact of Electric Vehicles on the Power Distribution System,” in IEEE Power and Energy Society General Meeting, Minneapolis, 2010.

[20] R. J. Broderick and J. R. Williams, “Clustering methodology for classifying distribution feeders,” in 39th Photovoltaic Specialists Conference, Tampa, 2013.

[21] G. Grigoras, G. Cartina, M. Istrate and F. Rotaru, “The Efficiency of the Clustering Techniques in the Energy Losses Evaluation from Distribution Networks,” International Journal of Mathematical Models and Methods in Applied Sciences, vol. 5, no. 1, pp. 133-140, 2011.

[22] K. P. Schneider, Y. Chen, D. P. Chassin, R. Pratt, D. Engel and S. Thompson, “Distribution Taxonomy Final Report,” Pacific Northwest National Laboritory, 2008.

[23] Electric Power Research Institute (EPRI), “Clustering Methods and Feeder Selection for PV System Impact Analysis,” 26 March 2014. [Online]. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?productId=000000003002002562. [Accessed 7 December 2015].

[24] Electric Power Research Institute (EPRI), “Alternatives to the 15% Rule: Modeling and Hosting Capacity Analysis of 16 Feeders,” 29 April 2015. [Online]. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?productId=000000003002005812. [Accessed 7 December 2015].

[25] V. Rigoni, L. F. Ochoa, G. Chicco, A. Navarro-Espinosa and T. Gozel, “Representative Residential LV Feeders: A Case Study for the North West of England,” IEEE Transactions on Power Systems, vol. 31, no. 1, pp. 348-360, 27 February 2015.

[26] Electric Power Research Institute (EPRI), “Determining the Effectiveness of Feeder Clustering Techniques for Identifying Hosting Capacity for DER,” 18 December 2015. [Online]. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002005795. [Accessed 5 January 2016].

[27] Electric Power Research Institute (EPRI), “A New Method for Characterizing Distribution System Hosting Capacity for Distributed Energy Resources: A Streamlined Approach for Solar,” 20 December 2014. [Online]. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?productId=000000003002003278. [Accessed 24 October 2015].

[28] Energy Information Administration (EIA), “Electric Power Monthly with Data for November 2015,” January 2016. [Online]. Available: http://www.eia.gov/electricity/monthly/pdf/epm.pdf. [Accessed 1 Febrary 2016].

[29] World Nuclear Association, “Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources,” July 2011. [Online]. Available: http://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/comparison_of_lifecycle.pdf. [Accessed 1 February 2016].

[30] Nuclear Regulatory Comission, “Nuclear Regulatory Commission Photo Gallery,” 2016. [Online]. Available: https://www.flickr.com/photos/nrcgov. [Accessed 1 February 2016].

[31] “Illinois plan would aid Exelon nuclear plants,” 2 March 2015. [Online]. Available: http://www.daily-journal.com/news/local/illinois-plan-would-aid-exelon-nuclear-plants/article_d0328eb5-f16b-567c-8f06-ed5cfca61749.html. [Accessed 1 February 2016].