E. S. Cornwall Memorial Scholarship

Fourth Quarterly Report

Commonwealth Edison

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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 do not relate to any person or organisation associated with the author. Any reproduction or referencing of this report should reflect this.

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1 Glossary, Abbreviations & Definitions

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

Terminology / Acronym / Abbreviation	Definition
BGE	Baltimore Gas and Electric (Company)
CDF	Cumulative Density Function
CF	Confidence Factor
COM	Component Object Model *A Windows-native interfacing standard that enables cross-process control and automation between independent processes*
ComEd	Commonwealth Edison (Company)
DNO	Distribution Network Operator
EIMA	Energy Infrastructure Modernisation Act
EPRI	Electric Power Research Institute
ERC	Energy Research Centre *As used in reference to the E.ON Energy Research Centre in Aachen, Germany*
FERC	Federal Energy Regulatory Commission *A USA Federal Government organisation that regulates interstate energy markets (including electricity)*
HiL	Hardware in the Loop
HV	High Voltage
HVDC	High Voltage Direct Current (DC)
ICC	Illinois Commerce Commission *The state government appointed tribunal that is responsible for regulating utilities in the state of Illinois*
IFHT	Institute for High Voltage Technology *One of the Electrical Engineering Institutes as the RWTH Aachen University, also known in German as the Institut für Hochspannungstechnik (hence the acronym IFHT)*
ISO	Independent System Operator
KDE	Kernel Density Estimation *A non-parametric method for estimating probability and cumulative density functions of a finite sample set of data*
MSE	Mean Squared Error
MV	Medium Voltage
MVDC	Medium Voltage Direct Current (DC)
NERC	North American Electricity Reliability Corporation *A not-for-profit regulatory organisation based in the USA that is responsible for monitoring and ensuring the reliability of the North American interconnected network*
PDF	Probability Density Function
PECO	PECO Energy (Company) (formerly Philadelphia Electric Company)
RTO	Regional Transmission Organisation
SNS	Smarter Network Storage
TNO	Transmission Network Operator
UKPN	UK Power Networks
USA	United States of America
USD	United States Dollars

2 Executive Summary

The influx of distributed generation (specifically roof-top solar) on Australia's electricity distribution networks, buoyed initially by generous incentive schemes and feed-in tariffs, has been swift with wide-ranging challenges. Even with substantial revisions to these incentives schemes and tariffs, the high price of electricity, increased consumer interest, and the desire for environmentally sustainable generation has seen growth in this area continue. As the penetration of distributed generation increases, network operators have seen and will continue to see these technologies impact network performance. Quantifying the ability of the network to accommodate distributed generation at a feeder, substation, regional, and whole-of-network level would provide a valuable tool to network operators, regulators, and state and federal governments in ensuring that distributed generation is utilised in a sustainable manner, both for the electricity distribution network and the economy.

This report is focused on this challenge and provides an overview of my work within the Smart Grid and Technology team at Commonwealth Edison. During the past three months I have been responsible for implementing and refining one such method to analyse Commonwealth Edison's distribution network. The method which was implemented utilises a stochastic approach to model a large number of distributed generation locations and levels of penetration, producing a hosting capacity cumulative and probability density function. With this statistical approach and a defined confidence factor the hosting capacity of a feeder can be quantified. This technique also enables more detailed analysis like understanding the locational sensitivity of a feeder to distributed generation. By combining this approach with clustering techniques widely used in big data analysis, it is possible to scale this hosting capacity analysis across the wider network. The output of this analysis will be used to:

- Expedite the screening of connection requests, as an alternative to the current heuristic approach;
- Understand the ability of the network to accommodate distributed generation at various levels; and
- Drive the development of sustainable incentive and subsidy schemes.

This report outlines each of the components of this analysis in more detail and provides representative results.

Over the coming months I hope to refine this methodology, particularly the clustering component, which has shown mixed results thus far. I am also in the progress of writing a technical paper with my colleagues. This paper documents a technique for quantifying the locational sensitivity of feeders to distributed generation and describes the application of this analysis to a real ComEd feeder. It is my intention that this paper be published at a reputable conference.

Outside of the Smart Grid and Technology team I will work to gain exposure to some of the traditional asset management challenges that Commonwealth Edison are facing, including 10 "smart substation" upgrades as a part of the Electric Infrastructure Modernisation Act that was passed in Illinois.

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 [1]

During the same period advances in distributed generation 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 fourth of six quarterly reports that will be compiled throughout my placements on the scholarship. It covers the first 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. Since starting with this team I have been given the responsibility of developing a tool that can quantify the ability of ComEd's network to accommodate distributed generation (also known as hosting capacity). To date this work has involved:

- A literature review of relevant publications to develop an understanding of existing research and methodology in this area;
- Development of a stochastic modelling tool that, coupled with ComEd's chosen distribution modelling software – CYME, is capable of calculating a network's distributed generation hosting capacity; and
- Using big data analysis techniques to improve the scalability of the modelling tool, allowing for regional or whole-of-network analysis.

This report will cover these works in more detail, while also providing an overview of the electricity sector in the United States of America (USA) and setting the scene for my placement with ComEd.

4 Background

This section covers background material important to the content of my placement. It consists of five subsections that discuss: the electricity industry in the USA and Illinois, the Exelon Corporation (the holding company that owns ComEd), ComEd, the Energy Infrastructure Modernisation Act within Illinois, and the Smart Grid and Technology team that I am based within.

4.1 Overview of the USA's and Illinois' Electricity Industry

Historically, the development of USA's electricity network was driven by the need to supply load centres and growing communities, with little consideration for interstate or USA-wide planning and operation. Although this is no longer the case, this fragmented approach is evident in the electricity network of today, which consists of a complex web of regulatory bodies, generators, transmission, and distribution network operators, all of which operate within seemingly different industry structures. The convoluted nature of the electricity industry in the USA is highlighted in a publication by the Regulatory Assistance Project[1], which states that [2]:

> *"The U.S. electric industry comprises over 3,000 public, private, and cooperative utilities, more than 1,000 independent power generators, three regional synchronized power grids, eight electric reliability councils, about 150 control-area operators, and thousands of separate engineering, economic, environmental, and land-use regulatory authorities."*

At its highest level the USA's electricity network consists of three separate network areas interconnected by high voltage direct current (HVDC) lines. These geographical regions, known as interconnections, all operate at 60Hz average frequency but are not directly synchronised with each other. This allows for slight frequency and phase angle variations during normal network operation and provides some isolation from system-wide frequency oscillations during major events. These interconnections are[2]:

- Western Interconnection;
- Eastern Interconnection; and
- Texas Interconnection.

The largest two of these interconnections, the Western and Eastern Interconnections, extend beyond the USA into large parts of Canada as shown in Figure 1.

[1] The Regulatory Assistance Project is a not-for-profit group who provides technical guidance and input to policymakers in relation to the gas and electricity sectors.
[2] A fourth interconnection, the Québec Interconnection covers the province of Québec, Canada. This interconnection is not discussed in this report as it is wholly outside of the USA.

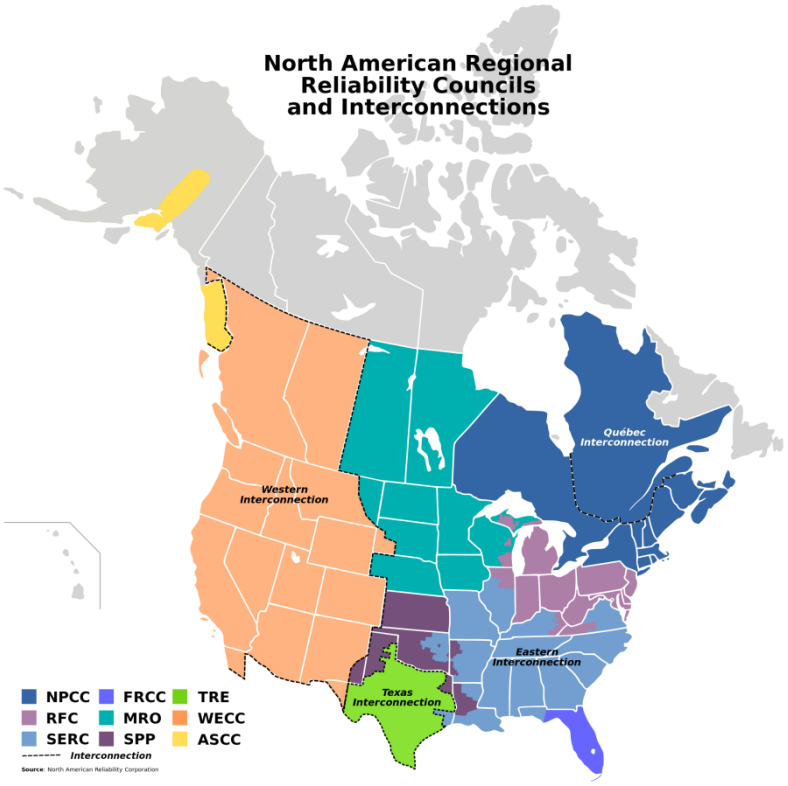


Figure 1: Map of USA's and Canada's Interconnections (dotted outline) and NERC Regional Reliability Councils (colour coded) [3]

These interconnections evolved from geographically localised interconnections through the early 20th century, achieving majority coverage of the USA and parts of Canada by the mid-20th Century. Although the increased level of interconnection helped to improve network flexibility and reliability, planning and operating of the interconnected network lacked nation-wide oversight. This was emphasised on the 9th November 1965 during the Northeast Blackout[3], which saw approximately 30 million customers across the north-eastern USA and into south-eastern Ontario, Canada lose power for up to 13 hours [4]. These events resulted in the establishment of the North American Electric Reliability Council three years later in 1968 (now the North American Electric Reliability Corporation (NERC)). The NERC is responsible for ensuring the stability and reliability of the USA's vast electricity network, which it does via enforcement of reliability standards, monitoring of the transmission power system, and through long-term planning and forecasting. Figure 1 shows the nine Regional Reliability Councils that make up NERC.

Other regulatory functions are split across two predominant levels:

- Federal-level regulation, which is imposed by the Federal Energy Regulation Commission (FERC), who regulates the electricity, gas, and oil industry. The FERC's core roles relating to the electricity industry include regulating the interstate transmission and wholesale of electricity, the development of mandatory reliability standards for the interstate transmission network (via the NERC), guidance of the NERC, and policing energy markets [5]. It is important to note that FERC is not responsible for the regulation of publicly-owned, cooperative, or federal utilities as discussed later in this section.
- State-level regulation, which is imposed by various state-level organisations (generally commissions) across the USA. Within Illinois this role is fulfilled by the Illinois Commerce Commission (ICC), which is primarily responsible for setting allowed retail rates and service charges for the electricity (and other industry) utilities. In addition, the ICC has various departments and bureaus responsible for:

[3] For more information see http://observer.com/2015/11/lights-out-the-great-northeastern-blackout-of-1965/

- Representing and protecting consumer interests;
- Encouraging retail competition, consumer awareness , and education;
- Monitoring the reliability performance of the two major electricity utilities (and incentivising these utilities to maintain a reliable network); and
- Reviewing electrical incidents and events.

For more information on the USA's industry and regulatory model I recommend [2].

Mirroring the complex regulatory model, the USA's electricity industry incorporates a mixture of utility business models, including [2, 6]:

- Investor-owned utilities, like ComEd, which make up the largest utility group by population served, are given monopolised access to defined regions (generally within a state). Historically, investor owned utilities existed as vertically integrated organisations; however deregulation of generation and retail in some states during the 1990s and early 2000s saw companies (like ComEd) divest their generation business and assets. In today's industry there is still a mixture of states with vertically integrated investor owned utilities, deregulated industries, or partially deregulated industries.
- Publicly owned utilities that are generally defined at state or local level (e.g. municipalities and utility districts). Unlike investor owned utilities, publicly owned utilities are not-for-profit and thus aim to return surplus income to their customers.
- Cooperative utilities, which are customer-owned businesses that generally provide service to areas deemed to be financially unviable for investor-owned utilities; for example, sparsely populated rural communities.
- Federal utilities who leverage public facilities like dams for use in generation.

At the generation and transmission level, regional transmission organisations (RTOs) and independent system operators (ISOs) are not-for-profit, federally regulated, neutral third parties who do not own electricity assets. Their role is to work generation and transmission utilities across a region (often encompassing multiple states) to coordinate and manage the wholesale electricity market while providing nonpartisan access to and operation of the transmission network. PJM Interconnection is the RTO that services the state of Illinois[4]. As one of the states to undergo deregulation, Illinois has a competitive electricity generation and retail sector, with ComEd and Ameren as the monopolistic providers of electricity transmission and distribution services. ComEd and Ameren have both maintained a presence in the electricity retail market.

Figure 2 and Figure 3 attempt to provide a simple summary of the relationships and roles that these organisations play in the electricity industry (specifically within Illinois). Figure 2 captures core inter-organisational relationships and hierarchy, showing the flow from international, federal, and state regulation and their involvement with the Illinois RTO (PJM Interconnection) and Illinois' two main electricity utilities (ComEd and Ameren). It is worth noting that there are a number of relationships not shown in Figure 2 for the sake of simplicity. For example: as an international organisation, NERC takes guidance from Canadian and Mexican government organisations in addition guidance provided by FERC. Similarly, as the wholesale market operator, the RTO is responsible for collating market bids from a large number of generation organisations and service providers not shown in this figure. Figure 3 visualises the involvement of these organisations across the various electricity industry functions (generation, electricity wholesale, transmission, distribution, and retail). Shaded areas shown in Figure 3 are competitive functions and are serviced by multiple organisations (e.g. generators or retailers).

[4] As a RTO PJM Interconnections also provide services for Delaware, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia.

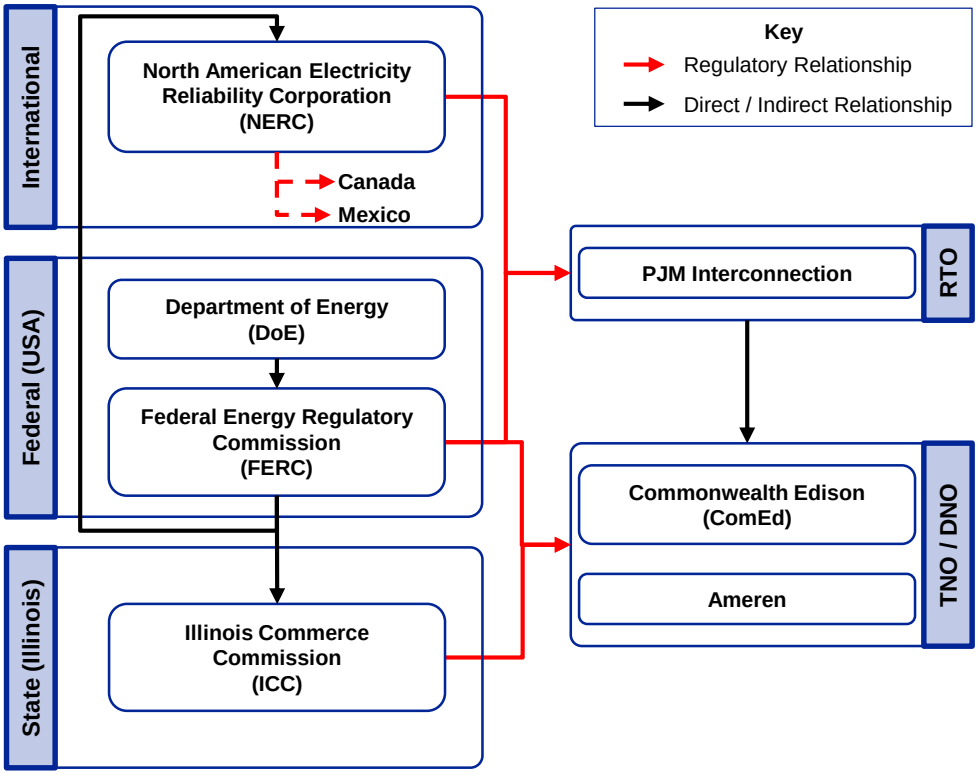


Figure 2: Electricity industry regulatory hierarchy and relationships for the USA and Illinois[5]

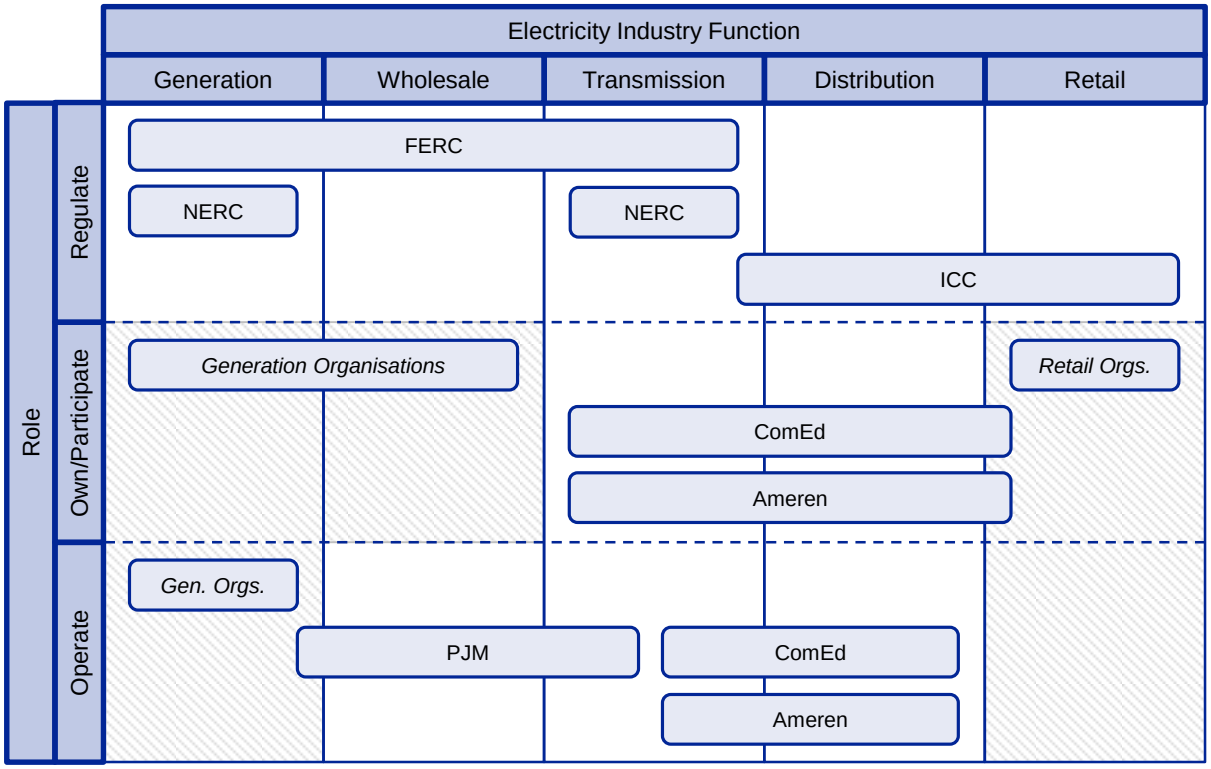


Figure 3: Electricity industry role and functions for the USA and Illinois

[5] It is important to note that certain states and utilities operate under different regulatory hierarchies to that shown in this figure. This figure is intended to represent the regulatory environment as it applies to Illinois.

The long and often pioneering history of the USA's electricity industry, coupled with diverse interstate dynamics have shaped many of the idiosyncrasies of the modern day industry and regulatory model. Compared to my transition to working within the UK electricity industry, which shares a number of commonalities with the structure and regulatory model of the Australian electricity industry, I have found grasping the USA's industry structure more challenging but nonetheless interesting. I look forward to continuing to learning about the USA's electricity industry and providing clarifications and additional information during my time with ComEd.

4.2 Exelon Corporation

Exelon Corporation is a holding company that was established in 2000 with the merger of PECO Energy Company (formerly Philadelphia Electric Company) in Philadelphia, Pennsylvania and Unicom Corporation, the then owner of ComEd in Illinois. Since then Exelon Corporation has acquired a number of businesses spanning the gas and electricity energy sector, growing its operations across the USA and Canada. Exelon Corporation's holdings fall within three predominant areas of the energy sector: generation, transmission and distribution (for gas and electricity), and competitive energy sales (wholesale and retail). Figure 4 shows the structure of Exelon Corporation and its subsidiary companies.

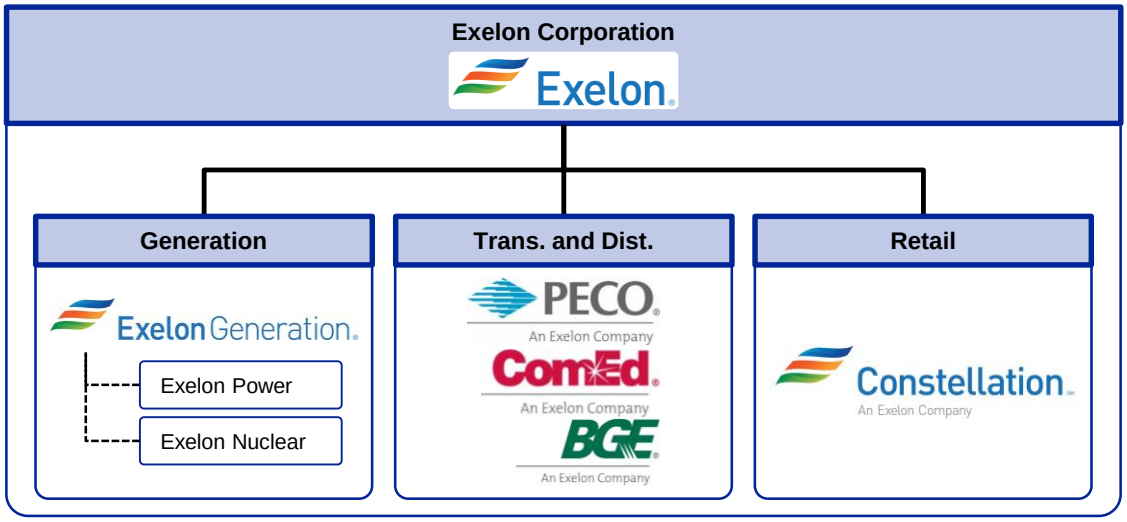


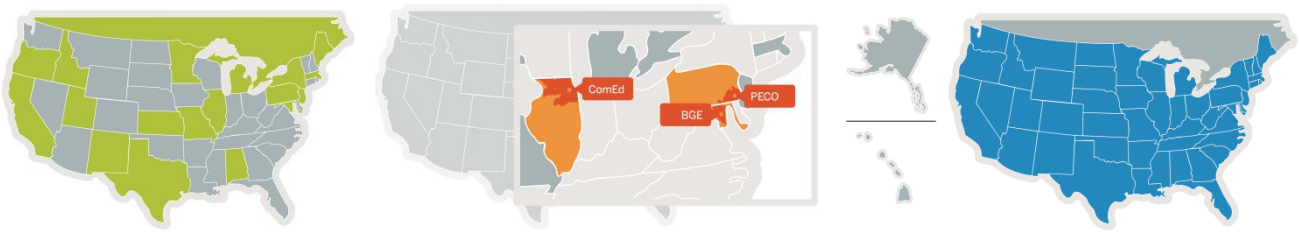
Figure 4: Exelon Corporation and its subsidiary companies

Through its subsidiaries Exelon Corporation boasts an impressive company portfolio; for example, Exelon Generation (specifically the Exelon Nuclear division of Exelon Generation) is the largest owner of nuclear generation in the USA; Constellation, Exelon Corporation's competitive energy retail business, services one of the largest customer portfolios in the USA including more than two thirds of the Fortune 100 companies. In total Exelon Corporation and its subsidiaries are active in 48 states of the USA, the District of Columbia (DC), and Canada with an asset holdings valued at $86 billion (USD), and employing circa 29,000 people [7]. Table 2 provides a brief overview of each of the Exelon Corporation subsidiaries.

Table 2: Overview of Exelon Corporation's subsidiaries [8, 9, 10]

Exelon Corporation Subsidiaries Statistics (2014)				
Exelon Generation[6]	An electricity generation business, which consists of two divisions: • **Exelon Nuclear**, who own and operate Exelon Corporation's nuclear generation fleet; and • **Exelon Power**, who own and operate Exelon Corporation's fossil fuel, landfill gas, hydro, wind and solar generation fleet.			
	Headquarters:	Baltimore, Maryland		
	Operating States:	18 states of the USA and Canada (see Figure 5 (a))		
	Generating Capacity:	35,137 MW (2013)		
	Generation Mix:	54.8% Exelon Nuclear, 45.2% Exelon Power (see [9] for detail)		
	Operating Revenue:	*$17.4 billion (USD)*	% Exelon Total	*62%*
	Net Income:	*$1.02 billion (USD)*		*51%*
	Total Asset Value:	*$45.3 billion (USD)*		*51%*
	Prop., Plant & Equip.:	*$22.9 billion (USD)*		*44%*
PECO	A utility business that provides electricity and gas transmission and distribution service to consumers in south-eastern Pennsylvania, particularly focused on the city of Philadelphia and surrounding counties.			
	Headquarters:	Philadelphia, Pennsylvania		
	Employees:	2,400		
	Service Area:	5,400 km^2 (2,100 mi^2) in south-eastern Pennsylvania		
	Customers:	1,600,000 electric, 506,000 gas		
	Operating Revenue:	$3.09 billion (USD)	% Exelon Total	11%
	Net Income:	$0.211 billion (USD)		18%
	Asset Value:	$9.94 billion (USD)		11%
	Prop., Plant & Equip.:	$6.80 billion (USD)		13%
ComEd	A utility business that provides electricity transmission and distribution service to customers in northern Illinois, including the city of Chicago.			
	Headquarters:	Chicago, Illinois		
	Employees:	5,400		
	Service Area:	29,500 km^2 (11,400 mi^2)		
	Customers:	3,800,000		
	Operating Revenue:	$4.56 billion (USD)	% Exelon Total	16%
	Net Income:	$0.408 billion (USD)		20%
	Asset Value:	$25.4 billion (USD)		29%
	Prop., Plant & Equip.:	$15.8 billion (USD)		31%
BGE	A utility business that provides electricity and gas transmission and distribution service to customers in central Maryland, including the city of Baltimore.			
	Headquarters:	Baltimore, Maryland		
	Employees:	3,400		
	Service Area:	6,000 km^2 (2,300 mi^2)		
	Customers:	1,200,000 electric, 655,000 gas		
	Operating Revenue:	$3.17 billion (USD)	% Exelon Total	11%
	Net Income:	$0.211 billion (USD)		11%
	Asset Value:	$8.08 billion (USD)		9%
	Prop., Plant & Equip.:	$6.20 billion (USD)		12%
Constellation[7]	A competitive energy retail business which sells electricity, natural gas, and energy services (e.g. energy efficiency, load response, building energy management) for wholesale and retail customers.			
	Headquarters:	Baltimore, Maryland		
	Employees:	≈10,000		
	Service Area:	48 states of the USA and the District of Columbia (DC)		
	Customers:	2,500,000 across all sectors		

[6] Exelon Generation's financial figures include that of Constellation (Exelon Corporation's retail subsidiary)
[7] For the United States Securities and Exchange Commission Form 10K [10], reporting of Constellation's financial performance is incorporated in those of Exelon Generation.



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

Figure 5: Maps of Exelon Corporation's Operating Areas [8]
(a) States with Exelon Generation (Power and Nuclear) assets
(b) Exelon Corporation's utility (gas and electricity transmission and distribution) utilities
(c) Exelon Corporation's (Constellation's) energy retail service states

Given Exelon Corporation's interests that traverse the electricity sector (i.e. generation, transmission, distribution, and retail), it is in a unique position to understand and, where possible, optimise the value chain from generation to end user, something that was lost as a part of the dissolution of vertically integrated companies. For this reason Exelon Corporation provides a guiding vision that drives each of its subsidiaries and, within legal limitations[8], utilises partnerships and collaboration across its business to ensure the best value outcome.

4.3 Commonwealth Edison (ComEd)

Commonwealth Edison (commonly known as ComEd) is one of three utility companies owned by the Exelon Corporation and was one of the two founding utilities of the Exelon Corporation (the other being PECO Energy Company). ComEd was founded in its current form in 1907, but traces its roots back to the Western Edison Lighting Company, which was established in 1882 by Thomas Edison. In 1887 the Western Edison Lighting Company was absorbed by the Chicago Edison Company, which came under the leadership of Samuel Insull (a long-time Edison employee and past Vice President of General Electric) in 1892. Insull lead the company to a merger with Commonwealth Electric Light and Power Company in 1907, which saw the creation of Commonwealth Edison [11, 12].

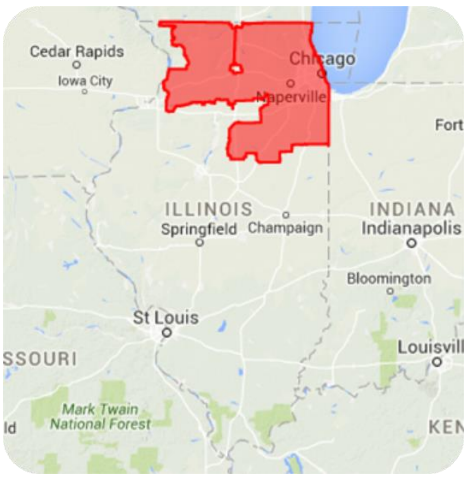


Figure 6: Map of Illinois showing ComEd's service territory [13][9]

In its modern form ComEd has grown beyond its Chicago-beginnings and is now the transmission and distribution network owner for Chicago and northern Illinois (with the other major network operator for

[8] Legislation and regulatory requirements like the Federal Energy Regulatory Commission's (FERC's) Standards of Conduct, which sets legal boundaries within companies like Exelon Corporation, have been put in place to avoid collusion and anti-competitive behaviour within companies that have interests spanning the electricity sector (e.g. generation and transmission).

[9] The small region in central north Illinois that is not included in ComEd's service territory is the city of Rochelle, Ogle County. Rochelle has its own municipal utility (Rochelle Municipal Utility) that is responsible for providing electricity, water, waste water treatment, and communications services.

southern Illinois being Ameren). ComEd now services a network that supplies approximately 3.8 million customers (70% of Illinois population) and covers a territory of 29,500 km^2 (11,400 mi^2). Figure 6 shows a map of the extents of ComEd's service territory. In 2014 ComEd's property, plant, and equipment asset value was estimated to be $15.8 billion (USD) (2014 depreciated asset value), of which the electricity and transmission and distribution network makes up circa 98% [10].

4.4 Energy Infrastructure Modernisation Act (EIMA)

ComEd is currently undergoing a significant period of grid renewal, investment, and innovation that has been made possible largely as a part of the Energy Infrastructure Modernisation Act (EIMA). Prior to the passing of the EIMA, ComEd faced a challenging regulatory and financial environment with little surety of return on investment (figures show the return on investment varied significantly, from a high of 82% return on investment to a low of 17% [14]). This uncertainty and variability resulted in a period of underinvestment in the network, which became evident in the years preceding and during 2011 where storms and tornados resulted in wide-spread network outages to hundreds of thousands of customers [15, 16, 17].

The introduction of EIMA, which was passed in October 2011 and runs until 2017, provides a predictable and stable performance-based formula for use in calculating the cost of equity and return on investment of Illinois' electricity utilities. It has also provided $2.6 billion (USD) of funding for ComEd to invest in infrastructure modernisation and developing smart grids. Of the $2.6 billion (USD):

- $1.3 billion (USD) has been allocated to infrastructure renewal and upgrades, including:
  - Underground cable refurbishment and replacement;
  - Pole inspections, maintenance, and replacement;
  - Work to improve storm resilience of network; and
  - Construction of training facilities.
- With the remaining $1.3 billion (USD) to be allocated to "smart grid" related works including:
  - Integration of 2,600 distribution automation systems (for automated switching and outage recovery);
  - Developing 10 smart substations (providing detailed remote monitoring and automation functionality (e.g. condition monitoring)); and
  - The rollout of 4 million smart meters.

ComEd was also required to establish the Illinois Science and Energy Innovation Foundation trust[10], to foster Illinois-based innovation in the energy and technology sector; as well as the Smart Grid Test Bed[11] to provide businesses access to ComEd's network for testing and demonstration of new services and technologies.

To ensure delivery and benefit from this investment ComEd must report their performance against defined network reliability and consumer benefits to the Illinois Commerce Commission annually. Failing to deliver against these performance targets will result in financial penalties.

Given the level of investment in innovation and smart grid development, ComEd has established a Smart Grid and Technology team lead by Shay Bahramirad (Director of Smart Grid and Technology, Commonwealth Edison), which has grown substantially over the past year. The Smart Grid and Technology team are responsible for identifying, trialling, and implementing smart grid technologies throughout ComEd's network. It is within this team that I will spend the majority of my nine months with ComEd.

[10] For more information on the Illinois Science and Energy Innovation Foundation see http://www.iseif.org/
[11] For more information on the Smart Grid Test Bed see https://www.comed.com/technology/test-bed/Pages/default.aspx

4.5 Smart Grid and Technology Team

The Smart Grid and Technology team, which is based in the Technical Services business unit at ComEd, is responsible for developing and overseeing ComEd's strategy on smart grids and new technologies. As discussed in Section 4.4, the Smart Grid and Technology team has grown substantially in the past year, thanks in part to funding from the EIMA to fund smart grid related works. The team, which was founded as a small group of engineers and project managers has grown to approximately 20 people (both engineering and project management) in the past year. Internally the Smart Grid and Technology team is divided into three sub-teams, each responsible for managing part of the innovation lifecycle. These sub-teams are:

- **Emerging Technologies** that are responsible for identifying and researching emerging technologies that provide value to or have an impact on ComEd's network;
- **Grid Modernisation Projects** that are responsible for developing and implementing trials of these technologies; and
- **Smart Grid Programs** that are responsible for transitioning viable technologies past the trial stage and embedding them within the business.

Within these three sub-teams the Smart Grid and Technology team is responsible for developing and managing a diverse set of projects, which includes (but is not limited to):

- Establishing partnerships with innovative start-up companies to trial technologies within ComEd's Test Bed (see Section 4.4);
- Working with industry and research partners to develop a microgrid controller [18];
- Establishing a number of trial microgrids as a means of improving network resiliency [19];
- Trialling small-scale battery storage to improve network reliability;
- Trialling Smart LED lights to improve energy efficiency and leverage available capacity of the Silver Spring Networks[12] meshed network [20]; and
- Using innovative modelling techniques to understand and quantify the impact of distributed generation on ComEd's network, the project that I have been predominantly focused on.

[12] Silver Spring Networks are a multinational organisation who specialise in the development, construction, and management communication network equipment predominantly for use in the energy sector. ComEd utilise their meshed network for communication as a part of their advance metering infrastructure (smart meters) and for distribution automation.

5 Placement Experience

This section provides an overview of work that I have completed, including lessons learnt from my experience. It consists of one subsection that discusses the concept of distributed generation hosting capacity, outlining two common methods for quantifying hosting capacity, the application of these techniques within ComEd and my lessons learned in undertaking this work. Where possible, I have drawn comparisons as to how my experience may be of value to the Australian electricity supply industry.

5.1 Distributed Generation Hosting Capacity

Distributed generation systems, particularly renewables (solar and wind), are proliferating within Australia and internationally as a result of reducing costs, attractive incentive schemes, and legislative mandates. Understanding and quantifying the impact of these technologies on networks, which have traditionally not been designed to accommodate such technology, is a complex and time consuming problem. In many instances it is not viable to undertake detailed manual case-by-case studies of high volume, low capacity connection requests (like those for small rooftop solar systems); however, as the penetration of these smaller systems increases, their cumulative impact can negatively affect the performance of the network.

To expedite the interconnection assessment process, while minimising the impact of distributed generation on the network, utilities, industry groups, and regulators have worked to develop connection standards that provide the ability for expediting connection assessments. Within Illinois the Joint Committee on Administrative Rules have published Illinois' Administrative Code for Electricity Utilities (Title 83, Chapter I, Subchapter C) Part 466: *"Electric Interconnection of Distributed Generation Facilities*" [21] that builds upon "*FERC Order 2006: Standardization of Small Generation Interconnection Agreements and Procedures*" [22]. These documents provide well-constructed set of requirements for screening and assessing distributed generation connection requests on a case-by-case basis. In particular, Part 466 utilises a four tiered approach to assessing interconnection requests based on: the size of the system, its specifications, the penetration of distributed generation on the target feeder, and how distributed generation impacts the feeder's performance. One component of this assessment (that originated in FERC Order 2006) is a heuristic screen known within the USA's electricity industry as "the 15% rule". Under the 15% rule, interconnection requests on feeders where the total capacity of distributed generation (including the proposed distributed generation facility) does not exceed 15% of the feeder maximum load may be eligible to be approved through an accelerated assessment.

Although heuristic screens like the 15% rule and the 100% minimum daytime load rule (that has become a de facto standard [23]) are necessary as a part of an expedited assessment process, they fail to take account of all feeder dynamics and often impose conservative limits. As such, it is important to provide a more realistic estimate of a network's capability to accommodate distributed generation.

It is this topic that has received substantial interest from industry organisations like the Electric Power Research Institute (EPRI). EPRI has worked extensively on developing techniques for quantifying distributed generation hosting capacity [24, 25, 26]. Distributed generation hosting capacity, often referred to by the more general term "hosting capacity", is the amount (by kVA or MVA capacity) of distributed generation that a feeder can accommodate without negatively impacting its performance. This research and subsequent studies have shown the relationship between network dynamics and hosting capacity to be complex and, in the case of [26], reason for updating existing screening processes when assessing distributed generation connection requests.

5.1.1 Application within Commonwealth Edison

To date ComEd and the state of Illinois has received little interest in distributed generation (including renewables), thanks in large to the low price of electricity[13] and lack of significant subsidy programs. As a result, ComEd is in the fortunate position of looking to other utilities within the USA and internationally to observe and learn from the challenges that others have experienced and to adapt and prepare their business for the eventual uptake of these technologies, better managing and minimising the impact of distributed generation on their network.

Since starting with the Smart Grid and Technology team my core focus has been to develop a tool to automatically calculate the hosting capacity of feeders within ComEd's network. Quantifying hosting capacity on a feeder-by-feeder basis would:

- Provide an analytical measure to use in expediting application screening process (in comparison to the current heuristic method);
- Provide a detailed understanding of feeder limitations;
- Identify the optimal distribution of distributed generation (capacity and location) that allows for maximum penetration with minimal network impact; and
- Inform other works like the development of incentives to encourage installation of distributed generation in a sustainable way.

Within literature there are two common approaches to calculating the hosting capacity:

Method 1 - The stochastic and simulation-based approach discussed in [24], which uses a network simulation tool (CYME in the case of ComEd) to model a large number of distributed generation scenarios (i.e. different locations of distributed generation on the network). In each scenario the penetration of distributed generation is iteratively increased until a network constraint is reached.

Method 2 - The streamlined approached discussed in [25], which builds on the analysis utilised in [24] to develop a set of correlations and equations that can be used to quickly estimate the hosting capacity of a feeder based on a feeder load flow and short circuit analysis.

Both of these methodologies provide a means for estimating the minimum and maximum hosting capacity (as they are commonly referred to in literature). The minimum hosting capacity is the amount of distributed generation that can be accommodated on a network without negatively impacting its performance, regardless of installed location. The maximum hosting capacity is the maximum amount of distributed generation that can be accommodated without negatively impacting network performance, requiring optimal location of distributed generation. These values are demonstrated graphically in Figure 7, which shows the distributed generation penetration against maximum phase voltage on an example ComEd network. This figure was created using the stochastic, simulation-based approach outlined in the Method 1. The line between Region A and Region B is the minimum hosting capacity, this is the level of distributed generation penetration at which the first overvoltage constraint occurs. Similarly, the line between Region B and Region C is the maximum hosting capacity, the penetration at which distributed generation must be optimally located to avoid an overvoltage constraint. Beyond the maximum hosting capacity (i.e. within Region C) all possible distributions of distributed generation will cause a network constraint violation.

Although either scenario is unlikely to eventuate as a result of random customer uptake of distributed generation, it is this region near the minimum hosting capacity that is of most interest to ComEd (and other utilities utilising the same analysis) as it identifies the level of penetration below which distributed generation will not likely have a negative impact the performance of the network regardless of location. Such a limit could be used to more accurately assess when to fast track connection requests when compared with the existing requirements of FERC Order 2006 [22]. For the purpose of this report and from this point forward, the term "hosting capacity" will be used to refer to the single value at which the network will not likely experience a network constraint. This value can be

[13] The average retail price of electricity in Illinois is 8.40 cents / kWh [49].

determined by the combining the desired level of organisational risk and probabilistic nature of network constraints occurring. This principle is discussed in more detail in the following subsection.

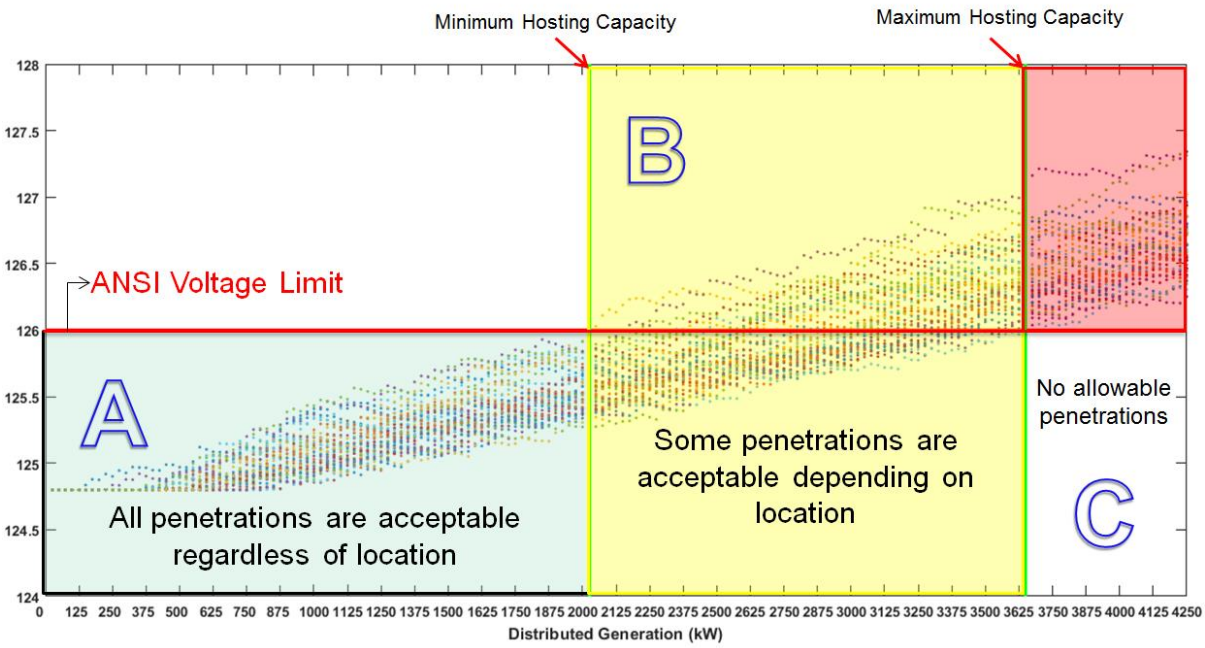


Figure 7: Comparison of distributed generation penetration (in kW) and maximum network phase voltage (at LV[14]) for a range of scenarios on an example ComEd feeder [27]

5.1.1.1 Analysis Algorithm

After reviewing both of the aforementioned methodologies for estimating hosting capacity it was decided that the first methodology would be implemented as the preferred means for estimating the hosting capacity of ComEd's network. This method has been shown to provide a more accurate assessment of hosting capacity at the expense of being slower and more computationally complex [25]. Moreover, by utilising this method it was possible to build on other work already undertaken by -members of the Smart Grid and Technology team [27, 28, 29]. To this end I started by re-working the existing Matlab-based prototype to improve efficiency, robustness, and scalability of the algorithm.

The algorithm that I implemented is outlined in Figure 8 and was re-coded in VB.NET to reduce reliance on expensive Matlab licenses and for speed improvements. It utilises CYME's[15] component object model[16] (COM) interface to automate the iterative adding of distributed generation to network model and running of load flows inherent in the stochastic method. In more detail, the modelling process applies and object-oriented programming approach and consists of two key components: a Feeder Study, and Feeder Scenario. A Feeder Study is the structure that drives the hosting capacity analysis for one feeder; in this way one Feeder Study is created for each feeder to be studied. The Feeder Scenario is the structure that analyses different stochastic distributions and levels of penetration of distributed generation by running iterative simulations within CYME. With each simulation additional distributed generation is added at a random customer node until a network constraint is reached. This relationship is demonstrated in Figure 9, showing how these core components of the stochastic modelling process are built up. Using the Feeder Study structure to

[14] Nominal household service voltage (low voltage, line to neutral) within Illinois is 120V. ANSI C84.1 requires that, during normal network operation (i.e. non-fault or contingency conditions), voltage is regulated ±5% of nominal (i.e. 126V-114V).
[15] CYME is a power system modelling and analysis software developed by Cooper Power Systems.
[16] The component object model (COM) is a standard interface for Windows native applications that is used for communication and automation between otherwise independent applications and processes.

model many different Feeder Scenarios it is possible to build the stochastic modelling technique outline in Method 1.

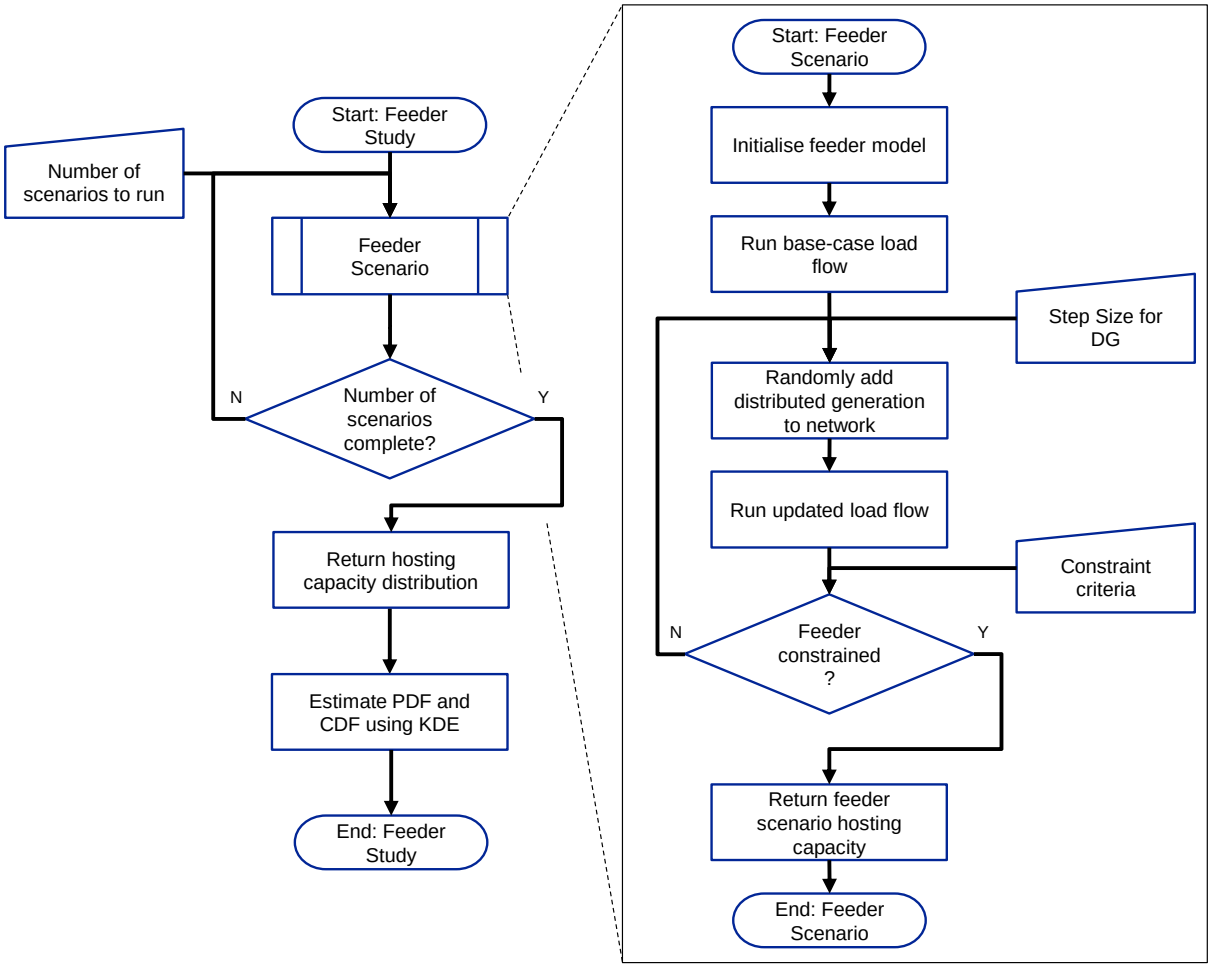


Figure 8: High-level overview of stochastic hosting capacity estimation process

Practically, when implementing such an algorithm there are a number of considerations that should be taken into account. These considerations are vast and varied; covering each in detail within this report would not be appropriate. However, I have highlighted four core areas that I believe, from my experience, can significantly impact the accuracy, validity, and speed of the modelling process:

- **Model accuracy versus speed** – as with most stochastic modelling algorithms there is a compromise between computational complexity and level of accuracy or confidence. As such, it is important to consider the number of scenarios to be modelled to ensure statistical validity of the outcome. Failing to consider a sufficient number of scenarios could result in feeder hosting capacity being overestimated, while incorporating too many scenarios would substantially extend modelling time, particularly when taking into account the compounding relationships shown in Figure 9. From experience I found that at least a few hundred scenarios were required to provide an accurate estimate of hosting capacity.
- **Network constraints to considered** – high penetrations of distributed generation can cause a wide-variety of network issues and constraints; for example:
    - Voltage-related (overvoltage, voltage imbalance, voltage swing);
    - Capacity-related (overloading, phase current imbalance);
    - Protection-related (reduction of reach, mal-coordination, reverse power flow);
    - Harmonics-related (total harmonic distortion)

  Some of these constraints lend themselves to being more easily identified as a part of basic network analysis (e.g. overvoltage, voltage imbalance, and overloading), while others require more detailed and complex analysis (e.g. protection-related and harmonics-related

constraints). As a result, it may not be possible to consider every type of network constraint in calculating the hosting capacity. For the most part, literature tends to identify voltage-, capacity-, and protection-related constraints as being the predominant limiting factors [25, 30]; therefore, these constraints should be considered wherever possible to ensure validity of the calculated hosting capacity.

- **Dynamic feeder elements and characteristics** – within a feeder there are a number of dynamic or controllable elements and characteristics that can significantly impact the hosting capacity. For example: tap changer set point voltage (at the substation and, if applicable, on line regulators), feeder loading (minimum and maximum), phase loading imbalance (under normal operation), and the presence and operation of switched capacitors. It is important that these characteristics are well captured and accounted for as a part of the modelling process as variations in feeder load, set point voltage, or other controlled elements can significantly impact feeder hosting capacity.
- **Model and data accuracy** – as with all big datasets (like one that comprises a utility's network and asset data), there exist data errors that occur as a result of incorrect, outdated, or missing data. Implementing a large-scale modelling algorithm like this one is reliant on having good data readily at hand (i.e. requiring no manual updates or modification). Although data errors are normally readily identifiable and feeders with data errors can be excluded from the algorithm, instances were these errors are not identified may reduce the accuracy of any analysis undertaken.
- **Statistical limitations** – although the stochastic nature of this modelling technique attempts to account for the diversity in distributed generation uptake, both in size and location, the number of possible permutations (or Feeder Scenarios) is so large that modelling each scenario is not viable. As a demonstration, even for a relatively simple feeder with 100 secondary transformers[17], assuming average incremental distributed generation step sizes of 5kW, where the feeder hosting capacity is approximately 500kW, the number of permutations can be calculated as shown in Equation (1). The resultant network would have approximately 10^{200} different possible scenarios, without taking into account the possibility for different phasing of single phase connections. Although considering practical network limitations, such as constraining the maximum amount of distributed generation connected on any one distribution transformer to the rating of that transformer would reduce the possible permutations, this number would still be substantial.
  Considering this, it is unlikely, given the finite (and comparably small) number of simulations conducted that this stochastic method will capture the single worst or single best case scenario for location of distributed generation. However, giving a large enough number of scenarios and resultant hosting capacity calculations, a representative probabilistic distribution can be approximated. Using this statistical approach it is possible to understand the hosting capacity of a feeder without having to model every possible permutation.

$$Permutations = Customers^{\frac{Hosting\ Capacity}{Step\ Size}} \quad (1)$$

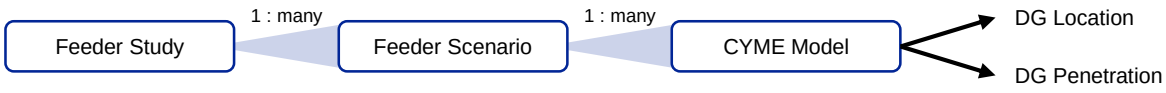


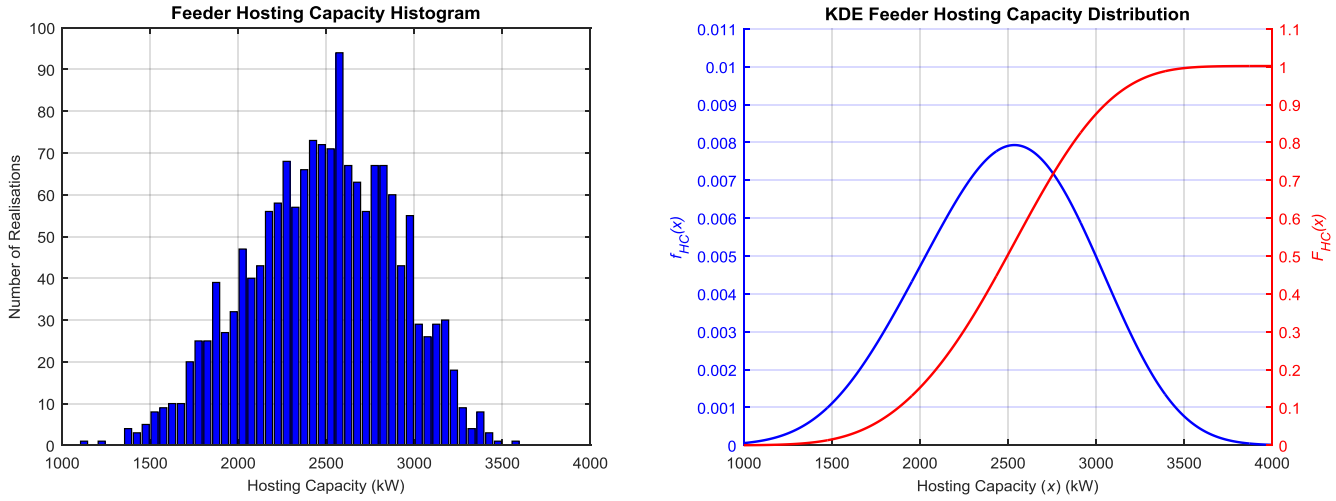
Figure 9: Relationships within stochastic hosting capacity estimation process

In light of the considerations, I was able to successfully implement a stochastic hosting capacity algorithm that was capable of automatically estimating the hosting capacity for a large number of feeders (tens to hundreds of feeders). The resultant algorithm produces a hosting capacity distribution, which can be utilised to calculate a single value hosting capacity (depending on the requirement). Figure 10 (a) shows the hosting capacity distribution histogram for a representative feeder in ComEd's network, generated from simulation of 1200 scenarios. Figure 10 (b) shows the feeder's hosting capacity probability density function (PDF) (in blue) and cumulative density function

[17] This assumes that the network model only considers to the HV terminal of the secondary substation and does not model the LV network. Considering the impact of distributed generation on the LV network would further increase the computational complexity of this task.

(CDF) (in red). These curves were calculated using the kernel density estimation[18] (KDE) method on the simulated data (shown in Figure 10 (a)). With this information it was possible to calculate a single value hosting capacity for the feeder using the hosting capacity CDF and related confidence factor. Confidence factor (shortened to CF in equation notation) is described in Equation (2) where x is the related feeder hosting capacity (in kW).

By setting the confidence factor and solving for the related hosting capacity it was possible to quantify the likelihood that the penetration of distributed generation cold be accommodated within the network without causing network constraint(s). For example, setting a confidence factor of 0.5 ($F_{HC}(x) = 0.5$) it can be said that the feeder will accommodate approximately 2,500kVA of distributed generation with a 50% likelihood that there will be no constraint (see Figure 10 (b)). Similarly, for a confidence factor of 0.9 ($F_{HC}(x) = 0.1$) the feeder will accommodate approximately 1,900kVA of distributed generation with a 90% likelihood that there will be no constraint. This probabilistic approach provides a means of directly relating an organisation's "appetite for risk" to a value for feeder hosting capacity. Given the traditionally risk adverse nature of the electricity industry, and the potential use of hosting capacity in fast-tracking applications it is expected that the confidence should be high (i.e. between 0.85 and 0.95), however this is organisation specific.



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

Figure 10: Hosting capacity for representative ComEd feeder
(a) Histogram of stochastic hosting capacity simulation results for 1600 scenarios
(b) Hosting capacity PDF (blue) and CDF (red) calculated using kernel density estimation (KDE)

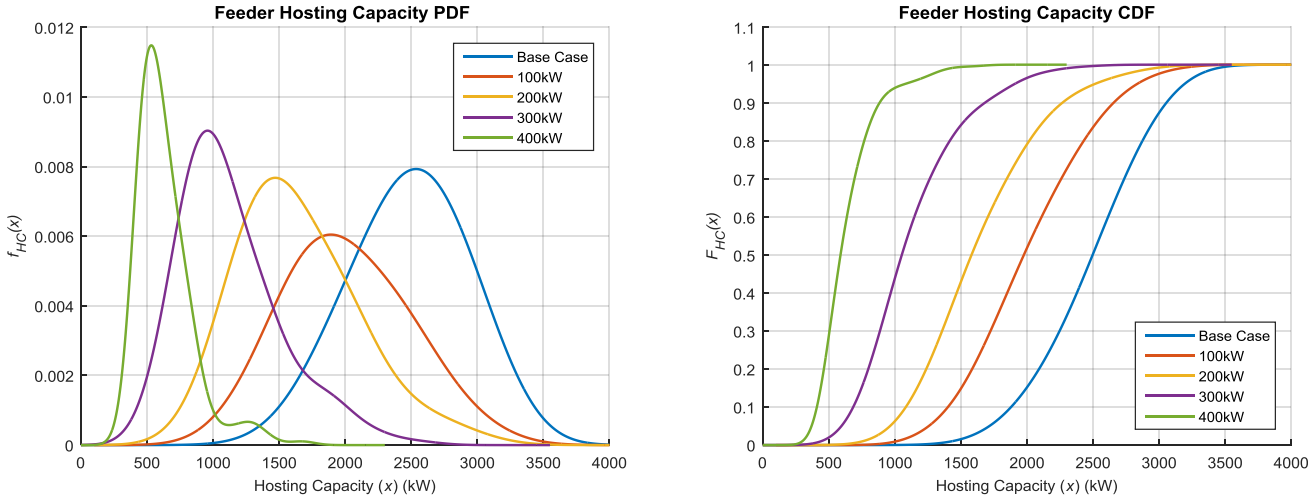
$$CF(x) = 1 - F_{HC}(x) \quad (2)$$

As a part of my work, this analysis was further extended to understand the locational sensitivity of a feeder in accommodating distributed generation. By fixing a set amount of distributed generation to a location on the feeder and recalculating the feeder hosting capacity it was possible to analyse how installing distributed generation at that location impacted the overall feeder hosting capacity. Furthermore, by iteratively increasing the amount of distributed generation fixed to the predefined location it may be possible to quantify the locational sensitivity (i.e. $\Delta P_{HC}/\Delta P_{DG}$ at a set location). Such analysis could be used to optimally locate and size distributed generation or to develop incentive programs to encourage installation and uptake of distributed generation in a way that would have minimal impact on the network (e.g. via targeted incentive programs).

An example of this analysis is shown in Figure 11 (a) and (b), demonstrating the overall feeder hosting capacity with increasing levels of distributed generation installed at a single node on the far

[18] Kernel density estimation is a non-parametric method for estimating the probability density function (and hence the cumulative density function) of a finite set of samples.

end of a radial feeder. As is evident by these figures, installing distributed generation at this location has a substantial impact on the hosting capacity PDF and CDF, causing a shift in the hosting capacity distribution to lower overall feeder hosting capacity (i.e. from right to left on all three charts). This is somewhat intuitive, as the far end of a radial feeder is likely to be constructed with smaller conductors that would have lower current carrying capacity and higher impedance, leading to issues like poor voltage regulation. Installing large amounts of distributed generation in these areas would almost certainly create overvoltage and capacity constraint issues.



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

Figure 11: Locational sensitivity to distributed generation for representative radial ComEd feeder
(a) Hosting capacity PDF with increasing levels of distributed generation installed at the far end of the feeder
(b) Hosting capacity CDF with increasing levels of distributed generation installed at the far end of the feeder

Even with these interesting and promising results, it was evident that, owing to the computational complexity of this modelling technique, it would not be feasible to conduct this level of analysis for each of the feeders in ComEd's network. To this end, I investigated the use of clustering techniques to simplify and characterise ComEd's network.

5.1.1.2 Feeder Classification

ComEd's distribution network consists of circa 5,000 feeders, even allowing for significant speed improvements and substantial computational power, a system-wide network analysis would be difficult (although not impossible) with the current algorithm. This is a common challenge in "big data" analysis where the sheer quantity of data often calls for techniques to compress or simplify the data to make analysis possible. To this end I investigated the use of big data analysis techniques, namely clustering algorithms to identify a characteristic set of feeders within ComEd's network. Indeed, this is a technique that has already found application in a number of network analysis problems within the electricity industry [31, 32] (to name a few).

By identifying a smaller and unique set of characteristic feeders it is possible to undertake detailed hosting capacity studies on this subset of feeders and extend the findings to the larger population. The clustering algorithm selected for this application is a common partitioning method known as k-means clustering. K-means clustering works by iteratively locating centroids (or means) in a way that minimizes the Euclidian distance (error) between the centroid and its associated data points (feeders)[19]. Figure 12 provides an overview of the clustering process that was utilised in this application. Each of these steps is discussed in more detail below.

[19] For an overview of the k-means clustering algorithm see http://mnemstudio.org/clustering-k-means-introduction.htm

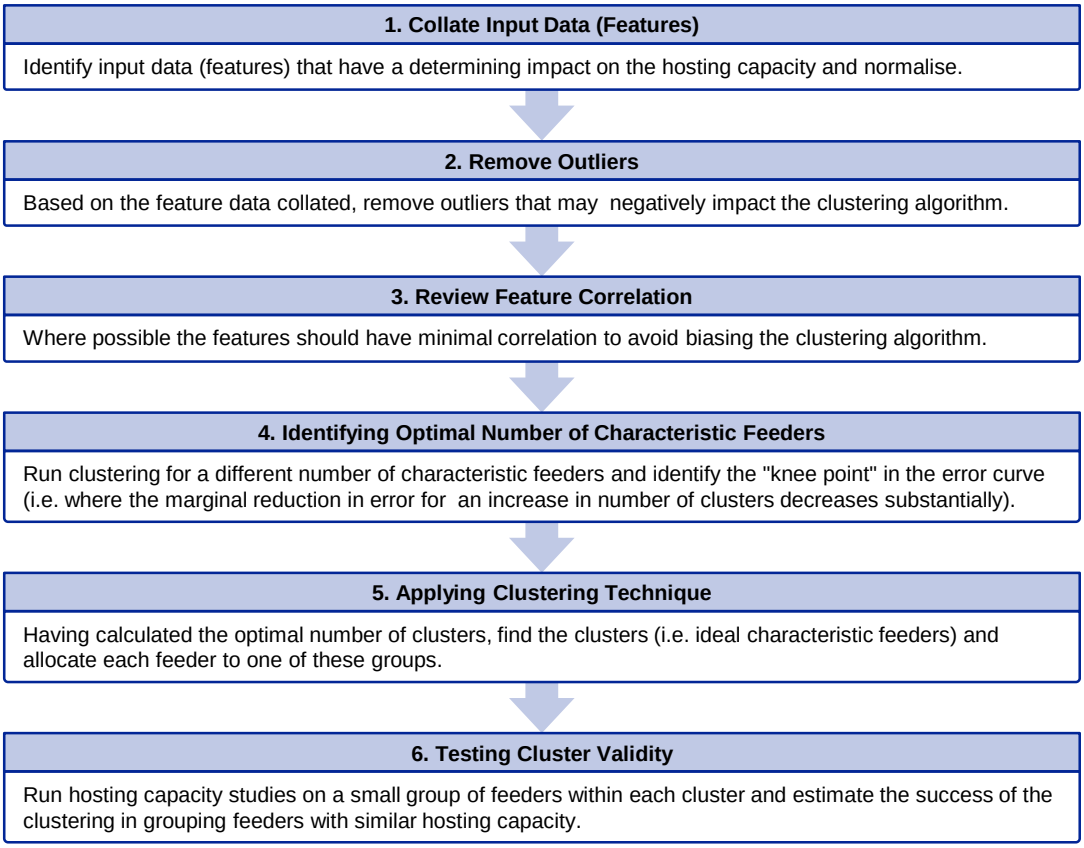


Figure 12: Overview of clustering methodology

Input Data (Features)

The underlying assumption in this process is that the clustering methodology successfully groups feeders of similar hosting capacity. To ensure this holds true it is important that the inputs (referred to as features) in some way describe a feeder's ability to host DG. Feeder characteristics which impact hosting capacity are discussed in Section 2 of [33]. For this application I investigated the following features for use in feeder characterisation:

- Total line length
  - One phase
  - Two phase
  - Three phase
- Number regulators
- Reactive compensation (kVAR)
- Number tee points
- Total secondary transformer connected capacity (kVA)
- Minimum Demand (kVA)
- Maximum demand (kVA)
- Customer Count
  - % Residential
  - % Commercial
  - % Unknown
- Average pos. sequence resistance (Ω / mi)
- Average pos. sequence reactance (Ω / mi)
- Voltage regulation
  - Source voltage to highest
  - Source voltage to lowest

Once selected, these features are normalised to a similar range and order of magnitude. This avoids biasing of the clustering algorithm by features with comparably large magnitude or range. In this instance a simple normalisation function was used, as set out in Equation (3), where D is the $m \times n$ matrix of feeder data with m feeders and n features describing each feeder. It follows that d_i is the i^{th} feeder feature vector, d_{ij} is the element relating to the j^{th} feature of the i^{th} feeder, and $\widehat{D}$ is the normalised feeder data matrix. Using this normalisation transformation in this way ensures that each feature covers the same magnitude and range (0 to 1).

$$\widehat{D_j} = \frac{[d_{1j}, d_{2j}, d_{3j}, \dots, d_{mj}] - \min([d_{1j}, d_{2j}, d_{3j}, \dots, d_{mj}])}{\max([d_{1j}, d_{2j}, d_{3j}, \dots, d_{mj}]) - \min([d_{1j}, d_{2j}, d_{3j}, \dots, d_{mj}])} \quad \text{for } j = 1, \dots, n \tag{3}$$

Outliers

Given the size and diverse nature of ComEd's network and unavoidable data errors it is inevitable that the dataset will contain outlier feeders that are not generally representative of ComEd's network. Including these feeders in the clustering algorithm may act to bias the algorithm and generally degrade the quality of the resultant characteristic feeders. To minimize the impact of outlier feeders, two methods are applied to identify and remove them from the dataset, they are:

1. By identifying obvious outliers and data errors by inspection. For example, feeders with no customers were removed from the study dataset. While it is entirely feasible that ComEd would have feeders with no customers (e.g. an interconnecting feeder), it is unlikely that these feeders will have DG connected and therefore need an estimate of hosting capacity[20].
2. By measuring the Euclidian distance of any feeder to its nearest neighbour (or in this case the average distance to the 10 closest neighbours). This provides a more analytical means for identifying feeders that are on the "fringe" of the dataset. Although these feeders should still be subject to hosting capacity studies, they're unlikely to be good fits to the estimated hosting capacity calculated on a characteristic feeder (as they themselves would be significantly dissimilar to the characteristic feeder).

   This process is outlined in Equations (4) and (5), where V is the $m \times x$ matrix that holds the x smallest Euclidian distances between each feeder (i) and the other $m-1$ feeders in $\widehat{D}$ (termed the neighbor distance). It follows that $\overline{V}$ is the vector of length m that holds the mean of the x smallest neighbor distances for all feeders in $\widehat{D}$. An example of the outcome of this is shown in Figure 13, where the threshold distance for outliers was selected by visual inspection and set at 0.25.

$$V_i = \min_x([\|\hat{d}_i - \hat{d}_1\|, \|\hat{d}_i - \hat{d}_2\|, \dots, \|\hat{d}_i - \hat{d}_m\|]) \quad \text{for } i = 1, \dots, m \tag{4}$$

$$\overline{V_i} = \frac{1}{x}\sum_{k=1}^{x} V_{i,k} \tag{5}$$

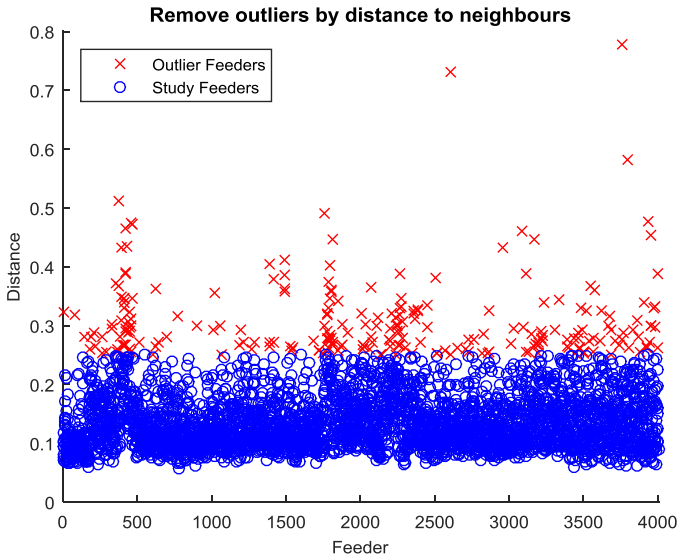


Figure 13: Example of removing outliers by their Euclidian distance to neighbouring feeders' features

[20] In the instance of interconnecting feeders, ideally they should be considered as a part of the wider network as they may still impact the final hosting capacity (e.g. through overvoltage or capacity constraints).

Feature Correlation

Once outliers have been removed it is important to test for correlations between features in the dataset. Strong correlation (either positive or negative) between features is undesirable as it will bias the resultant clusters locations. To avoid correlation in outputs, two possible solutions are:

- To remove features with a high level of correlation, as shown in Figure 14
- To use transformations like principal component analysis (PCA) that takes the initial features as inputs and generates a new set of features that are uncorrelated

Both of these methods will help to improve the quality of the final clusters.

Figure 14 (a) shows a correlation heat map for a set of example features, while Figure 14 (b) identifies features that have a positive or negative correlation above a defined threshold (in this case 0.7). In this instance the features identified in Figure 14 (b) could be considered for exclusion from the clustering data set.

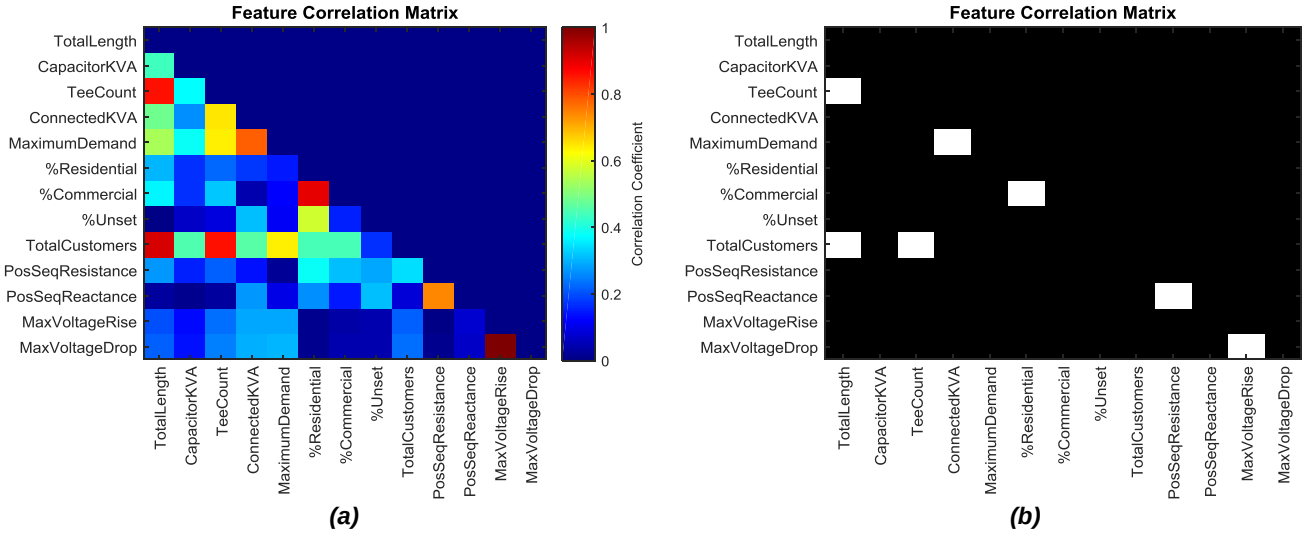


Figure 14: Example of feature correlation
(a) Showing correlation across all features
(b) Showing features with a correlation magnitude greater than 0.7

Optimal Number of Characteristic Feeders

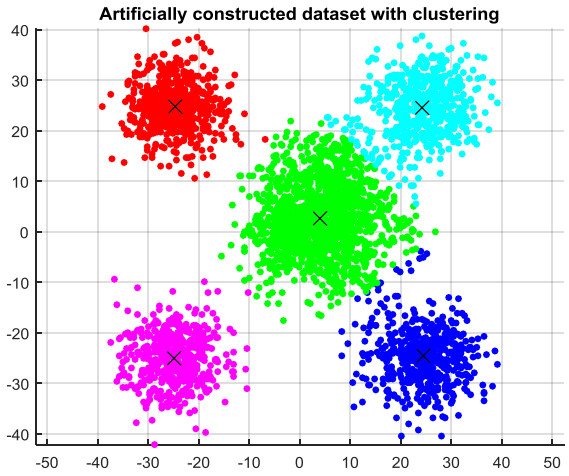
K-means clustering, like many clustering techniques, requires that the user nominate the desired number of clusters to be allocated. Although this may sound somewhat counter intuitive, it is possible to estimate the optimal number of clusters via a number of means, for example the mean squared error (MSE) or cubic clustering criterion. For this application the MSE was utilized.

Both methodologies work using a similar principle whereby the k-means clustering algorithm is run for a range of different cluster numbers (or values of k)[21]. From the resultant clusters the desired metric (i.e. MSE) is calculated and compared graphically across the range of cluster numbers. In the case of MSE the rule of thumb is to pick the "knee point" in the error curve; that is where the marginal reduction in error for an increase in number of clusters decreases substantially. This is demonstrated on a two dimensional artificially constructed set of data in Figure 15 (a) and (b).

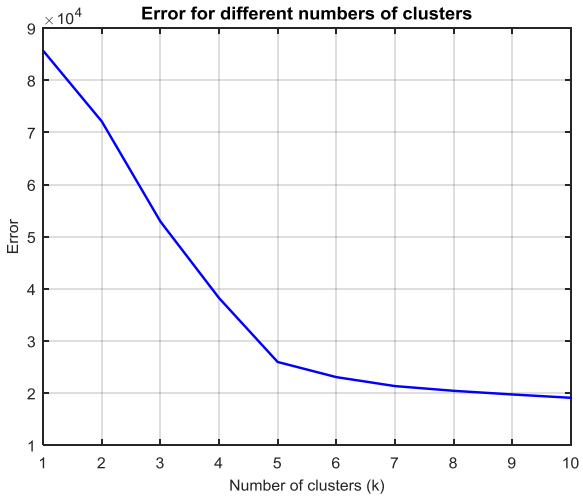
From Figure 15 (a) using a simple visual inspection it can be deduced that there are five natural clusters within the data. However for complex higher-dimensional datasets, like the one used in this

[21] It is important to note that the k-means clustering algorithm does not guarantee convergence to a global minimum. Therefore it is important to run the algorithm multiple times for each cluster number using different starting conditions. The global minimum would be identified by selecting the best error performance across the multiple iterations.

application, visual inspection is not an option. By calculating the cluster MSE for a number of numbers of clusters and finding the knee point in the MSE curve (see Figure 15 (b)) it is also possible to identify the optimal number of clusters. In a more complex example, like the application of k-means clustering to characterizing feeders, the knee point is likely to be less prevalent, as shown in Figure 15 (c). Given the decrease in marginal reduction in error between 4 and 8 clusters it is possible to conclude that the ideal number of clusters falls somewhere in this region.



(a)



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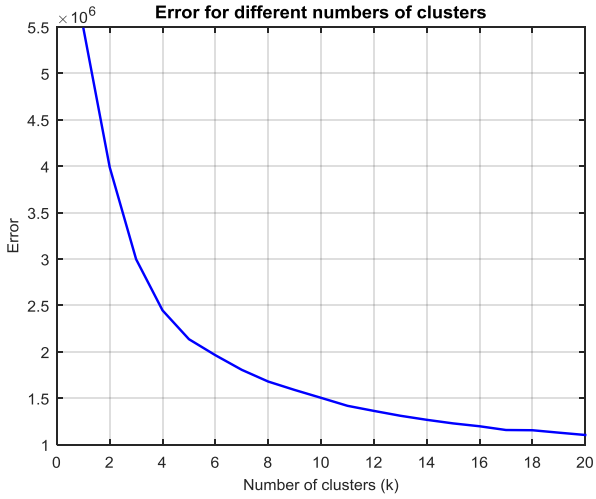


(c)

Figure 15: Demonstration of selecting the optimal number of clusters
(a) An artificially constructed test dataset with clustering (coloured) and means
(b) The error curve for different numbers of clusters using the k-means algorithm on the test data
(c) The error curve for different numbers of clusters using the k-means algorithm on the actual feeder dataset

Clustering

The final step in identifying the characteristic feeders is to utilize the optimal number of clusters (identified in the previous step) and re-run the k-means clustering algorithm to solve for the characteristic feeders. As mentioned previously, it is important that the clustering algorithm is run a number of times with different initialisation, as k-means clustering does not guarantee convergence to a global minimum. Figure 16 shows an example of cluster centroids calculated using eight clusters. Using these cluster centroids and associated feeder classifications, a set of real feeders can be identified by selecting those closest to their respective cluster centroid.

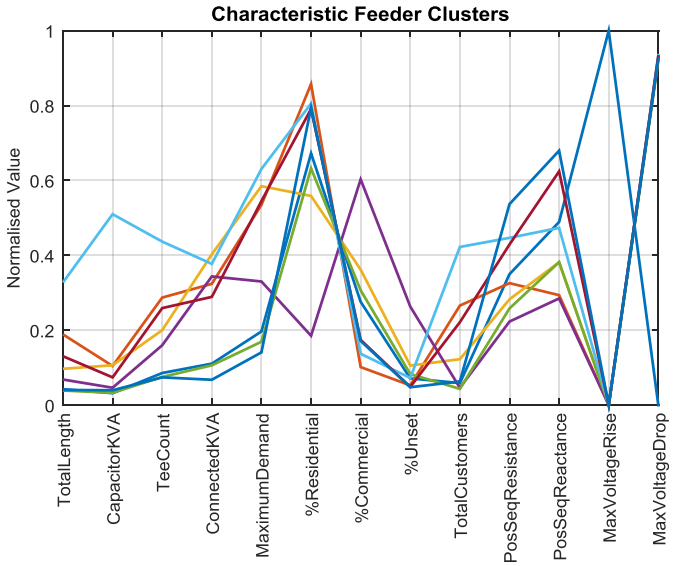


Figure 16: Example characteristic feeder clusters for eight clusters

Cluster Validity

Once feeders have been clustered it is important to test the validity of the resultant groupings. To do so the hosting capacity for a subset of feeders is calculated. If the k-means clustering has achieved its desired goal it should group feeders with similar hosting capacity. By comparing the hosting capacity for the subset of feeders the validity of the resultant clusters can be tested.

5.1.2 Lessons Learned

The algorithms discussed in Section 5.1.1 provide one method for quantifying the hosting capacity of a feeder. By combining this analysis with clustering techniques it is hoped that this analysis can be scaled to provide a regional or whole-of-network estimate of hosting capacity. This analysis could then be used to:

- Providing an analytical guideline for expediting the screening of distributed generation connection requests;
- Target the optimal location of distributed generation on the network; and
- Inform targeted incentive schemes for the installation of distributed generation.

Illinois and its constituent electricity utilities are in the fortunate position of having had little interest in distributed generation to date. Although this will almost certainly change in coming years, the ICC, ComEd, and Ameren have the advantage of looking to other utilities to see the challenges that they have faced and to better plan for them. Quantifying hosting capacity will enable a proactive and considered approach to the eventual ramp up in distributed generation connection requests.

Within Australia, electricity utilities (specifically DNOs) were less well prepared for the influx of distributed generation initiated by incentives like the Solar Bonus Scheme. As a result, utilities worked reactively to deal with the administrative and technical challenges that these technologies presented. Although the opportunity for Australian electricity utilities to proactively plan for distributed generation may, to a large extent, have lapsed, analysis like that presented still provides benefit. Armed with information like feeder hosting capacity, DNOs can better understand the impact of distributed generation on their networks and more confidently expedite distributed generation connection requests.

Personally, my review of literature on this topic and implementation of these analysis techniques has greatly developed my understanding of the challenges that distributed generation poses to electricity networks and DNOs. I have also learned about some of the challenges of using such techniques. For

example, when undertaking initial testing of the clustering technique discussed in Section 5.1.1.2, I identified large intra-cluster variations in feeder hosting capacity. Such large variations may limit the accuracy and ultimately the ability of such a technique to be applied to a whole-of-network analysis. This is one portion of the analysis that I look forward to improving in the coming weeks and months.

6 Future Works

My first three months with ComEd have been interesting, exciting, and challenging. Over the coming three months I look forward to building upon my existing work to develop a tool than can be incorporated into "business-as-usual" use. As a part of these refinements I will be working with my colleagues to investigate:

- Possible speed improvements for the stochastic analysis technique;
- The use of the streamlined approach to calculating hosting capacity (discussed in Section 5.1.1); and
- Improvements to the clustering methodology.

I am also in the process of working with my colleagues to develop a publication for the 2016 IEEE Power and Energy Society General Meeting. Over the coming months this paper will be submitted and if accepted, will be presented in Boston, Massachusetts in July 2016. As the analysis technique is refined and further developed I hope that additional publications may be possible.

While undertaking this work I have been able to network with ComEd colleagues across the business. It is my desire that, through these networks, I can learn more about some of the regulatory and more traditional asset management challenges that ComEd is facing. In particular, I am eager to learn more about:

- The 10 "smart substation" upgrades that ComEd is working on as a part of their EIMA funding proposal;
- How changing technologies and business model at a distribution level is impacting the transmission part of ComEd's business; and
- ComEd's long term plan (post-EIMA) to continue development of their network in a way that is sustainable and affordable for their customers.

Outside of work, I have been fortunate enough to attend a number of visits to institutions in Europe and the USA. During the period between finishing my placement with UK Power Networks and starting with ComEd I was able to visit:

- UK Power Network's 6MW / 10MWh Li-ion battery Smarter Network Storage facility in Leighton Buzzard, England;
- The E.ON Energy Research Centre in Aachen, Germany; and
- The RWTH Aachen University in Aachen, Germany.

Each visit is documented in more detail in Section 7. During my first three months with ComEd I have also been able to visit Schweitzer and Conrad (S&C) Electric's main manufacturing plant in Chicago, Illinois, as well as their Power Quality Products factory in Franklin, Wisconsin. I will document these two S&C Electric site visits in my next quarterly report. Over the coming months I hope to attend more conferences and site visits, particularly when considering my proximity to the many major conferences and presentations that are held within the USA.

In my personal endeavours, I have spent the past three months exploring the city of Chicago and its surrounding suburbs. I have also been able to undertake an impromptu trip to Toronto in Ontario, Canada and the Niagara Falls. Over the coming months I am hoping to take advantage of ComEd's numerous community outreach programs to spend time volunteering within the community, while fitting in the occasional weekend road trip.

7 Other Works

This section covers other work or experience undertaken during my time abroad that is of interest but not directly related to my area of research on the E. S. Cornwall Memorial Scholarship.

In my third quarterly report I had discussed my intention to attend the Energy Thought Summit at Chicago, Illinois on the 22nd and 23rd July. Owing to possible issues with transferring between the tourist and working non-immigrant (E3) visa I chose to not fly to the USA before starting my working visa. As a result I was unable to attend the Energy Thought Summit at Chicago and forfeited my registration to this event. For those interested in learning more about the Energy Thought Summit at Chicago, a selection of presentations from the 2014 and 2015 event are available online (http://ets-chicago.com/ets-highlights/).

7.1 UK Power Networks' Smarter Network Storage Facility

UK Power Networks' (UKPN's) Smarter Network Storage (SNS) project, which was partially funded as a Tier 2 (major) project under the Low Carbon Networks Fund[22], facilitated the construction of a 6MW / 10MWh lithium-ion energy storage facility, the largest battery storage facility in Europe at the time of its construction. During my last week with UK Power Networks (UKPN) I was able to visit the energy storage facility at Leighton Buzzard and was given a detailed tour by Ian Cooper (Technology Transfer Engineer and Lead on the Smarter Network Storage project, UK Power Networks).

During the tour of the site I was shown around the SNS compound and adjacent 33/11kV Leighton Buzzard substation (the point of connection for the storage facility). The SNS compound consists largely of an elevated structure[23], which houses the control and communications room, battery room, transformer and inverter room, and HV (11kV) switchboard (see Figure 20 for an existing building layout). Although the initial capacity of the storage system is 6MW / 10MWh, the site has been designed to be easily expandable to a capacity of 8MW/17MWh in future, as shown in Appendix 5 of [34]. Figure 18 shows a high-level single line diagram of the Leighton Buzzard energy storage site and the point of connection to the adjacent primary substation.

(a)

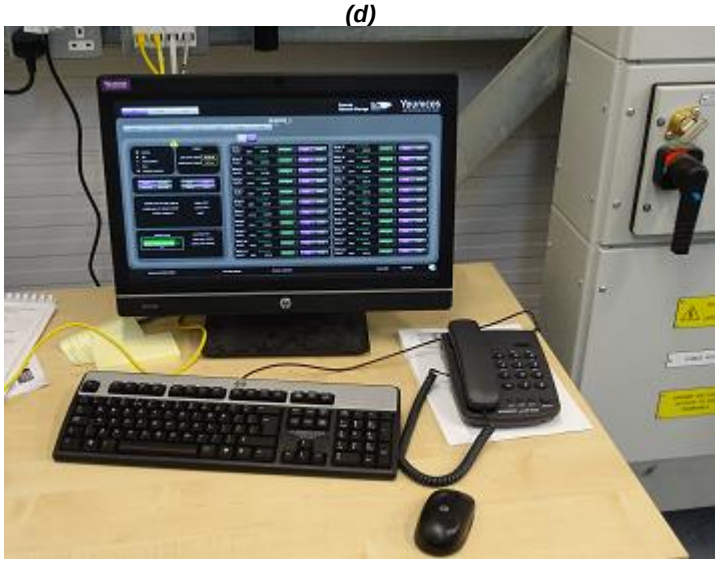
(b)

[22] The Low Carbon Networks Fund has been superseded by the Network Innovation Competition as a part of the transition to the RIIO regulatory model.
[23] The building was constructed on an elevated platform to mitigate the risk of flooding.

(c)

(d)

(e)



(f)

Figure 17: Leighton Buzzard Smarter Network Storage Photos
(a) Overview of the Leighton Buzzard energy storage building
(b) Battery room showing the four-by-three layout of battery arrays, two arrays feed one half of a power conversion (inverter) system
(c) One of the Samsung 60Ah Li-ion battery cells that make up the energy storage capacity
(d) One of the three existing S&C Electric PureWave® power conversion (inverter) systems, consisting of two inverters (left and right) that provide the full 2MVA capacity per power conversion system, and six circuit breakers
(e) An overview of the transformer and inverter room showing 2.5MVA Transformer 3 (foreground) and the back-side of the power conversion system
(f) Control PC (in the control room) showing the Battery Storage System Manager interface

While on site, Ian completed testing on the Battery Energy Storage System Manager application to ensure correct mapping and function of the 12 battery arrays, each of which is made up of 22 independent strings of battery cells. Being present while this testing occurred allowed me to gain a good overview of the system and its operation, particularly relating to control and monitoring of the system through the Battery Energy Storage System Manager Human Machine Interface. Ian also provided me with an overview of some of the challenges that had been incurred during construction, commissioning, and the early stages of operation. In particular, I was interested to hear about an issue that had been identified during early operation of the storage system whereby a voltage resonance was occurring between the two halves of the power conversion (inverter) systems, which was causing voltage swings in the battery circuit and resulting in intermittent tripping of batteries and

system instability[24]. As a temporary work around, one half of the power conversion system is isolated, therefore halving the capacity of the three installed systems and temporarily limiting the maximum power transfer of the whole system to 3MW. It is these kinds of issues, which are difficult to anticipate that make the Smarter Network Storage project and the lessons learned from this project very valuable.

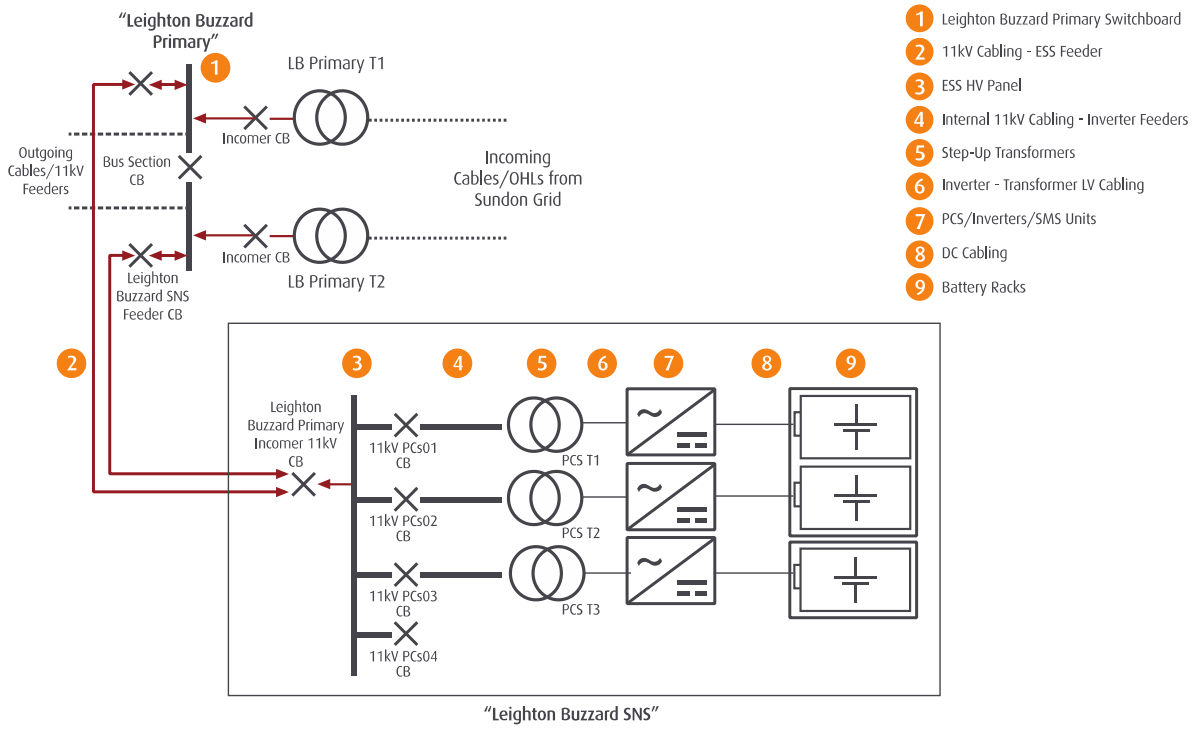


Figure 18: Single line diagram of Leighton Buzzard storage facility and connection to Leighton Buzzard primary [34]

I also found it interesting to learn during the tour (and subsequently from reading project documentation) about the core focus and testing schedule for the SNS project. Although the Leighton Buzzard storage facility provides obvious benefits to the network including: improving quality of supply, network reliability, and alleviating network constraints; I was particularly interested to learn that this is not the core focus of the SNS project. While this is one of the benefits of the storage device, the SNS project is aimed at investigating the different operating models with the goal of understanding optimising the value of energy storage. For this reason the energy storage facility at Leighton Buzzard is operated as though it were an independent business, cognisant of but not limited by the perceived network value of UKPN. Some of the operating modes being investigated for the storage facility include:

- Services specific to the **distribution network**, such as:
  - Peak shaving, to alleviate capacity constraints on the local network
  - Reactive power support, to alleviate capacity constraints on the network (caused by poor power factor) and to minimise losses
- Services specific to the **wholesale electricity market**, such as:
  - Long-term market optimisation, whereby energy suppliers may contract the services of the energy storage facility for use in optimising the operation of over long periods.
  - Short-term market operation, whereby energy suppliers may contract the services of the energy storage facility for use in the spot market.
- Services specific to the **transmission network**, such as:

[24] This issue is discussed in more detail in [46] and [47].

- Dynamic firm frequency response, static firm frequency response, and frequency controlled demand management, all of which are services available to National Grid (the UK's transmission network operator) to ensure frequency regulation and stability of the transmission network.
- Short-time operating reserve, for use in short-time matching of generation and demand on the wider network.

For more information on how the SNS's control and optimisation system, termed Smart Optimisation and Control System, was designed to cater for each of these applications see Section 3 of [35].

By developing a system that is capable of providing services across a number of industries the SNS project hopes to understand the ideal mix of services so that the storage system is optimally utilised. Figure 19 highlights how this is done through the role of an independent Battery Manager, who is responsible for consolidating information pertinent to all modes of operation and, with the assistance of dedicated forecasting software, termed the Forecasting, Optimisation and Scheduling System (FOSS).

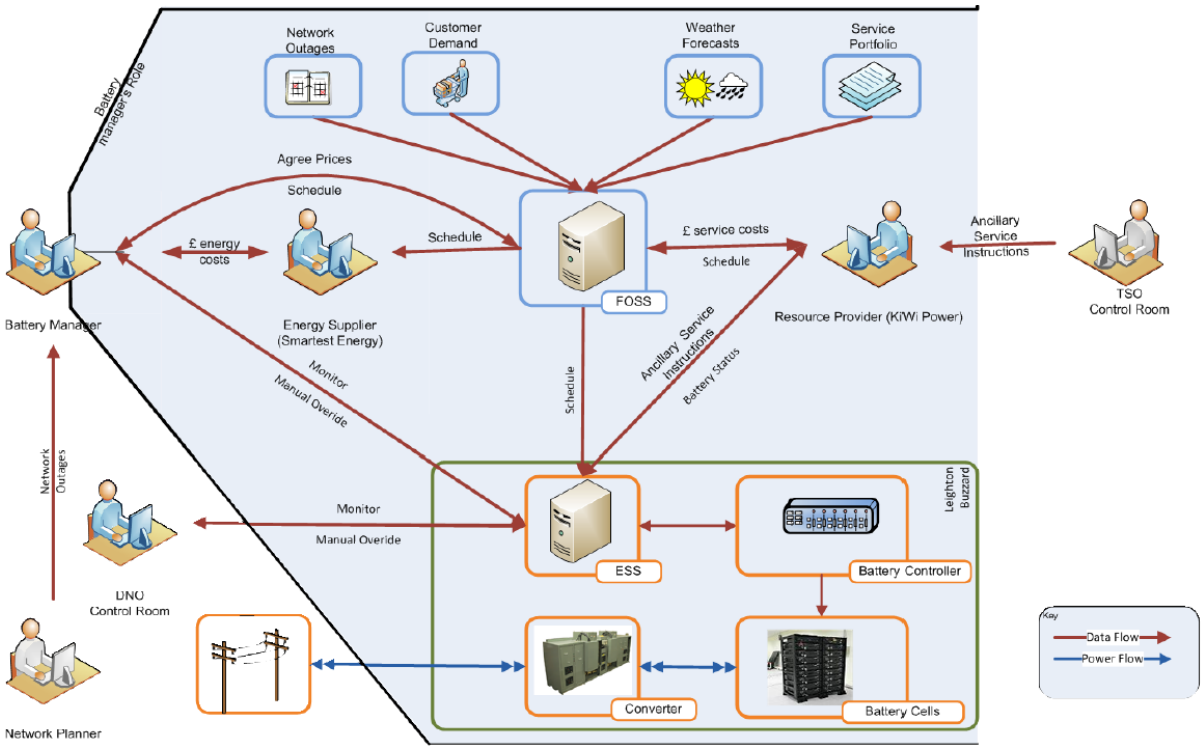


Figure 19: Smart Optimisation and Control System overview [35]

Over the approximately two year testing period of the SNS project, the different roles and value streams of energy storage will be trialled and evaluated. This will provide an understanding of the optimal mix of services and operating model to improve the financial and economic viability of energy storage.

I would like to thank Ian Cooper for taking me on a tour of the Leighton Buzzard energy storage facility and for his time spent explaining the challenges, opportunities, and lessons learned from the SNS project thus far. For more information on the SNS project and supporting documentation see http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Smarter-Network-Storage-(SNS)/.

7.1.1 Lessons Learned

Although this project is only in the primary stages of testing there have already been a vast number of lessons learned during the construction, commissioning, and early operation. Future energy storage

projects (including those in Australia) have the opportunity to learn from these experiences in a way that should allow more seamless integration of large-scale energy storage into electrical networks.

Personally, I am interested to see the outcome of the economic and business model evaluation that is one of the SNS project deliverables. The SNS project will undoubtedly put forward an interesting operating model that sees a single asset being used for multiple purposes and by multiple parties. This model will challenge accepted norms and operational boundaries to achieve the greatest return on investment. If such a model can be implemented in practice it will aid in the proliferation of energy storage, adding resilience and flexibility to distribution and transmission networks.

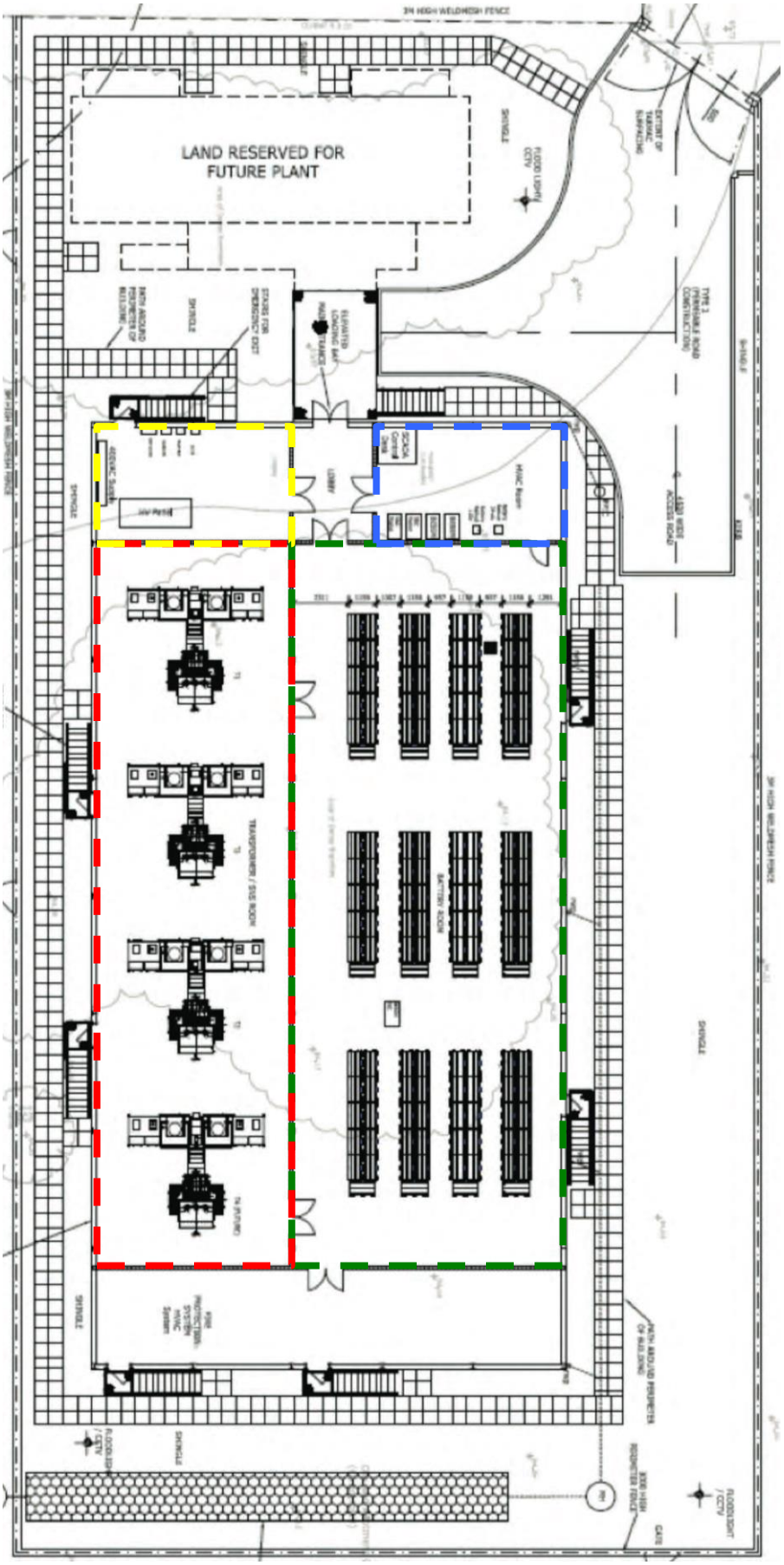


Figure 20: Building layout of Leighton Buzzard storage facility [34], showing control room (blue), battery room (green), transformer and inverter room (red), and 11kV switchroom (yellow)

7.2 E.ON Energy Research Centre and RWTH Aachen University

During the period between finishing with UKPN in the UK and starting with ComEd in the USA I was fortunate enough to spend some time travelling through central Europe. In addition to learning about the arts, culture, and history of the various countries, I was able to undertake tours of the E.ON Energy Research Centre (ERC) and RWTH Aachen University, both located in Aachen, Germany.

Aachen is a relatively large town (population circa 240,000) situated in far West Germany, a short distance from Germany's borders with Belgium and the Netherlands. Although the town has a number of historical claims to fame, modern-day Aachen is predominantly known for its innovation and research, which is led by the RWTH Aachen University and associated facilities. On Tuesday 30th June I toured the E.ON ERC under the guidance of Nils Soltau (Research Engineer in Institute for Power Generation and Storage Systems group, E.ON Energy Research Centre) and Alexander Helmedag (Head of Division for Grid Dynamics in the Institute for Automation of Complex Power Systems, E.ON Energy Research Centre).

The E.ON ERC is a partnership between the RWTH Aachen University and E.ON[25] established with the aim of researching the fields of:

- Network automation, control, and information communication technology for energy applications within the **Institute for Automation of Complex Power Systems**;
- Energy efficient buildings and thermal behaviour within the **Institute for Energy Efficient Buildings and Indoor Climate**;
- Customer behaviour and dynamics, energy markets and economics, and policy within the **Institute for Future Energy Consumer Needs and Behaviour**;
- Geothermal generation and energy storage within the **Institute for Applied Geophysics and Geothermal Energy**; and
- Power electronics, electrical drives, energy storage, and energy conversion systems (particularly focused on medium voltage) within the **Institute for Power Generation and Storage Systems**.

Given the diverse nature of these research topics and institutes, the E.ON ERC is a multi-disciplinary faculty that incorporates electrical engineers, information and communication engineers, computer scientists, mechanical engineers, geologists, materials scientists, and economists who work in close collaboration on the research projects. This provides the E.ON ERC with the unique capability to research issues in a holistic manner, rather than considering specific aspects of each topic in isolation.

During my visit to the research centre I was provided with an overview of the five institutes and the research being undertaken in each area as well as a tour of the E.ON ERC facilities including the newly constructed Centre for Wind Power Drives. Through this tour I learned about:

- The recently commissioned 4MW wind turbine test bench at the Centre for Wind Power Drives, which is destined for use in hardware in the loop (HiL) research into and certification of wind turbines (see Figure 21 (b)). The test bench is able to replicate torque up to 3300kNm, but is also able to apply three dimensional linear forces to the drive shaft via the load unit. Moreover the test bench is able to fully control the electrical characteristics at the point of connection of the wind turbine allowing for tests like fault ride through, over voltage performance, and performance of power electronics during adverse electrical conditions.
- The high-power (5MW) test bench, which similar to the wind turbine test bench, is a HiL system that is capable of replicating a wide range of mechanical and electrical conditions for

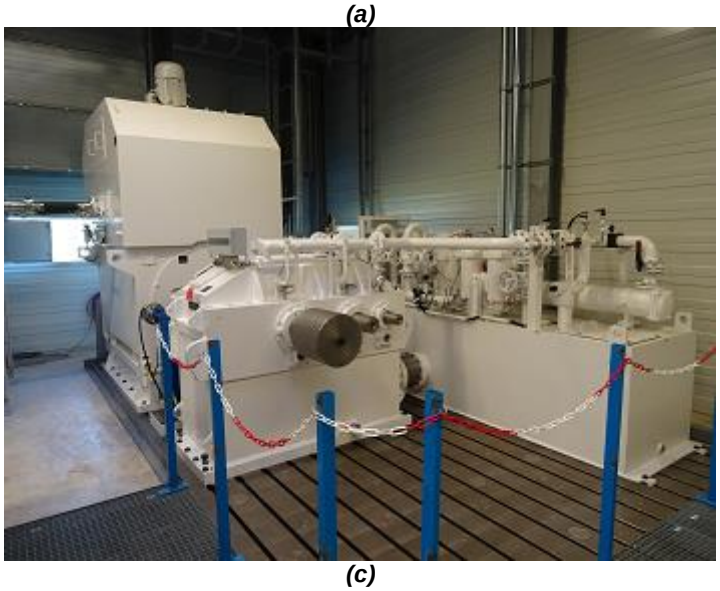
[25] E.ON is a European Union registered company which operates predominantly within the energy sector. Headquartered in Düsseldorf, Germany, E.ON historically handled services across electricity generation, distribution, and retail, as well as natural gas exploration, production, and distribution. However, E.ON is currently undergoing a transformation that will see the electricity generation, energy trading, and gas exploration and production arms of the business transitioned to Uniper, a newly established company that will come into operation at the start of 2016.

use in testing of power converter devices and electrical drives or motors (see Figure 21 (c)). I found it interesting to learn about the design of the test bench which recycles energy during tests to minimise losses.

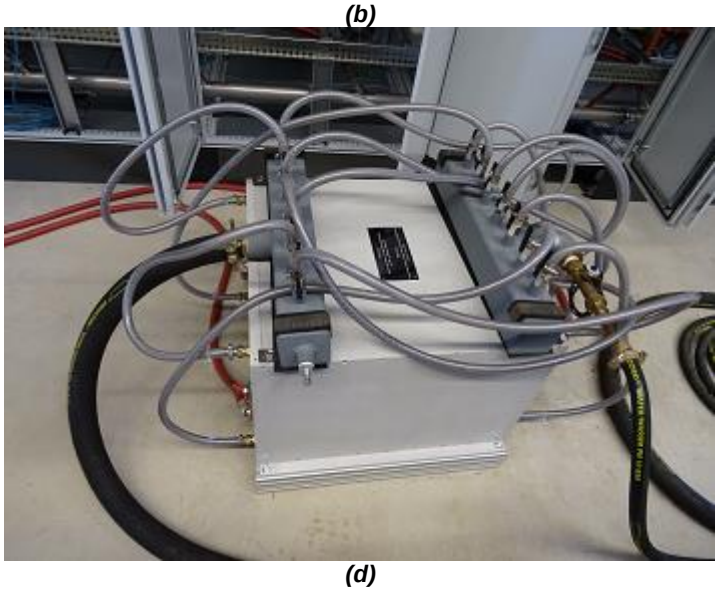
- The design and development of a 2MVA DC-DC converter, and the development of higher power equivalents. I found this particularly interesting as the development of feasible high-power DC-DC converter is a key enabler for the establishment of DC grids, a topic that is gaining a lot of traction in Germany and much of central and western Europe, driven by the proliferation of DC (generally renewable) generation. Nils explained some of the challenges that they were experiencing developing a transformer core that is able to withstand and operate efficiently under the high frequency switching (1kHz) and high-power conditions (see Figure 21 (d)).
- The Institute for Automation of Complex Power System's test laboratory that hosts a wide array of real-time simulators for use in the development and testing of control elements, such as relays and controllers using HiL simulation.

(a)

(b)



(c)



(d)

Figure 21: Facilities and research at the E.ON Energy Research Centre
(a) E.ON ERC main building (right foreground) and one of the research buildings (left mid-ground) [36]
(b) Centre for Wind Power Drives 4MW wind turbine test bench with 4MW drive motor (left background), load application unity (centre mid-ground), and wind turbine motor (nacelle) under test (right foreground)
(c) 5MW high power test bench with gearbox and three motor drive shafts to provide different drive speeds(left foreground) and motor / generator (left background) with power electronics not shown
(d) Prototype high frequency (1kHz) transformer for use in 2MVA DC-DC converter (foreground), cabinets housing power electronic (background)

Overall my visit to the E.ON ERC provided and interesting insight into future developments within the German (and likely international) electricity networks. For more information on the E.ON ERC, its facilities, their research occurring, and associated publications see http://www.eonerc.rwth-aachen.de/.

Following my tour of the E.ON ERC, on Wednesday 1st July I visited the Institute for High Voltage Technology (Institut für Hochspannungstechnik (IFHT)) at RWTH Aachen University. While at the university I was provided with an overview of each of the four key departments within the IFHT, their research projects, and in many instances given a tour of the research facilities themselves. The four departments that make up the IFHT are:

- **The Department for Electrical Equipment and Diagnostics** that is responsible for research into new insulation materials, monitoring and diagnostic equipment, and operation and maintenance of equipment;
- **The Department Switchgear and DC Technology** that is responsible for research into SF_6 free switchgear, fault arcs, circuit breaker diagnostics, protection for DC systems, and integrating DC systems with existing AC network;
- **The Department for Sustainable Transmission Systems** that is responsible for research into grid expansion and optimisation, system assessment, transient stability and the impact of renewables, new transmission network technologies; and
- **The Department for Sustainable Distribution Systems** that is responsible for research into planning and operation of smart grids, market models for distributed energy systems, combined generation and energy storage.

As the research projects that I was presented with during my tour were diverse and numerous it is not feasible to cover all of them in this short overview; rather, I will highlight work that I found particularly interesting. This included:

- The Syntactic Foam for Outdoor Insulation project (within the Department for Electrical Equipment and Diagnostics), which was developing a silicon-based insulating material impregnated with “micro-spheres.” By including minute voids in the insulating medium the material cost and overall weight can be reduced, ideally without substantially impacting the insulating properties. I found this application particularly interesting as the presence of voids in insulation is to some extent counter intuitive and undesirable. The presence of voids in insulating medium can create inconsistencies and weak points in the dielectric strength of the medium, potentially resulting in partial discharge and over time full electrical breakdown. However, from my discussions with researchers at the university, they were not seeing substantial degradation of insulating properties by the addition of these micro-spheres. Although the insulating material was still in the developmental stages they had received promising test results and were investigating different applications for the use of the material (e.g. suspended insulation like tower insulators). It was also interesting to hear about a possible secondary benefit if the material was used in low temperature superconductors. In this application the micro-spheres increased the thermal insulating properties of the material, which could aid in more efficiently cooling superconductors. Figure 22 (a) shows a test bench that is measuring changes in hydrophobicity[26] of the syntactic foam during accelerated ageing under a concentrated electric field.
- Research into integrating HVDC within existing AC transmission infrastructure (within the Department Switchgear and DC Technology). Given the drive toward establishing wide-spread HVDC networks within Germany, particularly for long distance transmission of renewable energy, the university is working to understand how existing AC infrastructure may be transitioned to an AC and DC hybrid (e.g. sharing of transmission towers for AC and DC transmission). To this end the university is researching the impact of DC electric fields on AC networks (and vice versa) to identify any possible concerns. Within the same department

[26] Hydrophobicity is a measure of a material’s (or molecule’s) ability to repel water, which is generally observable through the beading and formation of water droplets on a surface. Polymeric insulators are renowned for being highly hydrophobic, a property that is advantageous particularly in weather exposed insulation, such as tower insulating stings.

there are a number of other projects studying DC arcing, arc quenching, and the development of DC protection schemes, all of which pose interesting challenges.

- Research into development and planning for smart grids (within the Department for Sustainable Distribution Systems). The RWTH Aachen University had developed their own miniature smart grid test network, which allows them to test a number of the dynamics of different generation, storage, and inverter systems alongside a range of control technologies. During my tour of the smart grid test network I learned about some of the trials that they were running using the test network, as well as some of the interesting research into developing models for market participation of decentralised generation and storage systems.

For a detailed overview of the IFHT's research topics and publications see http://www.ifht.rwth-aachen.de/en/forschung/.

(a) *(b)*

Figure 22: Research at the RWTH Aachen University
(a) Test bench for measuring the hydrophobicity of insulating materials over time while subject to an electric field, pictured testing syntactic foam subjects (top shelf)
(b) Weil-Dobke circuit used to generate high voltage and high current impulses (maximum voltage 140kV, maximum current 30kA) to test circuit breaker and switch performance

I would like to sincerely thank Simon Bartlett (Australian Chair in Electricity Transmission, University of Queensland) and Blake Harvey (Manager of Network Strategy and Policy, Ergon Energy) for their assistance in arranging these tours, Nils Soltau and Alexander Helmedag for their time spent showing me around the E.ON ERC and their detailed explanations of the research being undertaken at this facility, and Regina Oertel (Deputy Director of the Institute for High Voltage Technology, RWTH Aachen University) and the faculty at the Institute for High Voltage Technology who are too many to name, for their hospitality and extensive tour of the university's research facilities.

7.2.1 Lessons Learned

During my tours of the E.ON ERC and RWTH Aachen University it was evident that the German electricity network is undergoing a period of substantial change, largely as a result of the German Energiewende (or energy transition). The Energiewende is a policy put in place by the German government to reduce reliance on nuclear and fossil fuel-based generation in favour of renewables[27]. Most notably, the Energiewende sets the target of phasing out all nuclear generation by 2022, a plan that was initially put in place in 2000 but that was reinforced following the nuclear meltdown at the Fukushima Daiichi nuclear power plant in March 2011. The plan to remove such a substantial portion of base load generation in favour of intermittent renewable generation will put significant strain on the operation and stability of Germany's electricity network. Indeed figures from as recent as 2014 show that, although wind and solar were the first and second largest forms of generation by capacity, each

[27] For more information on the German Energiewende see http://energytransition.de/.

produced approximately half the amount of energy as nuclear generation and substantially less than that sourced from coal. These figures alone demonstrate that there is still a large reliance on nuclear and fossil fuel generation for providing reliable energy [37].

Even at this early stage of the Energiewende (which sets targets for efficiency, renewable generation, and energy efficiency out to 2050), the German electricity network and energy markets have been significantly impacted. The requirement for priority access of renewables coupled with the large PV and wind generation capacity has seen negative spot prices within the electricity market become a common occurrence [38, 39, 40]. The resultant distortion of the electricity market is impacting the profitability of base load generation plants, which are less responsive and thus more exposed to large swings in electricity prices. This was highlighted by the announcement of E.ON in March 2015 that it would look to cease operation of the Irsching 4 and 5 combined-cycle gas turbines (which were commissioned in 2011 and 2010 respectively) due to poor profitability [41], despite the turbines being amongst the most efficient of their kind in Germany [42]. As the operation of existing and construction of new base load generation plants slows and ceases, the German electricity network will have to deal with the volatility of renewable generation while maintaining a reliable and stable network.

This issue of grid stability and operation is further exacerbated by the geographical disparity between the location of renewable generation resources (particularly wind) in the north and load centres in the south, exposing the lack of north-south interconnection within the German transmission network. To address this issue Germany is investing in major transmission network augmentations (1,700km of AC and 2,100km of DC) [43]. It is this application of HV and MV DC that I found particularly interesting. My discussions with those at the E.ON ERC emphasised that, although there is still research and development required, MVDC networks may become prevalent as a means to minimise losses between renewable generation (e.g. in offshore windfarms) and end use, which is increasingly becoming dominated by DC-powered electronics.

Ultimately, the challenges of the Energiewende are numerous and complex. It was apparent from these tours and my discussions with researchers at both institutes that the German people and government are serious about dealing with these challenges. The level of funding for research and development from government, as well as the strength of university and industry partnerships bodes well for the future of Germany's electricity network. Only through partnerships like the E.ON ERC and the research occurring within departments like the Departments for Sustainable Transmission and Distribution Systems will Germany's electricity network be able to adapt and achieve the ambitious targets set out by the Energiewende. As the Energiewende unfolds the world will look to Germany as an example to how similar generation and network transformations might occur.

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