The feasibility of microgrids for large facilities

by

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Abstract

Typical building power supplied from power plants has significantly evolved over the last century. After power is generated and transferred from the power plant, it is distributed to the customer. The concept of Microgrid was introduced to address increasing concerns with power reliability requirements for some facilities. The Microgrid is a localized electric grid that can operate autonomously from the traditional electric grid (Macrogrid). Compared with generator sets, a Microgrid provides a faster system response and recovery to either whole or part of the electric load for a facility. The Microgrid can operate under two operation conditions: grid-tied mode and island mode. When it is working individually like an “island”, the system is not providing or receiving disturbance to or from the Macrogrid. The purpose of this paper is to give a detailed introduction of Microgrid and present research and conclusion about its feasibility.

This report references previously published research to explain what a Microgrid is. Also, two detailed case studies provide a discussion about the feasibility of the Microgrid in terms of its reliability, economics and environmental impact - air quality. Although there are many challenges that Microgrids are facing, there are quite a number of reasons to consider them. The goal is to balance the benefits and challenges of Microgrids depend on each case. No doubt, the existing power grid will still provide the majority of power supply for global population. However, many companies and government-funded laboratories are investing time and money into research and development of Microgrids. With the advancement of the Microgrids, it is likely that Microgrids will be playing a larger role in providing secure, reliable energy to the building industry.

Table of Contents

List of Figures

List of Tables

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Chapter 1 - Introduction

Electricity plays a significant role in human lives. Some common uses of electricity would be for lighting, HVAC equipment, food refrigeration and mobile devices. Humans tend to take electricity for granted, but there is no doubt how important it is in daily operation and function.

There are many ways to generate power, but the most widely used source is from a centralized power plant. From the power plant, the electricity is transmited to the end user according to their demands via a distribution system. Electricity has been available for more than a century and will continue to be used because of its convenience. However, people have encountered many problems with electricity. Since Superstorm Sandy in 2012 damaged parts of New York and New Jersey, business owners have never been more aware of utility grid reliability and the unpredicted cost of outages. Other problems include the increasing demand for power with limited electricity generation capacity, the environmental pollution caused by burning coal, and the huge amount of wastewater resulting from power generation. Recently, people in the electrical industry are looking for an alternative way to produce power that will provide a more stable electrical power supply and not harm the environment. To prevent power outages, generators are sometimes used to provide the backup power supply for buildings. However, generators may fail during power outages. A report published in August 2013 by the President's Council of Economic Advisers puts the average annual cost for U.S. weather-related outages between 2003 and 2012 at an inflation-adjusted $18 billion to $33 billion (The President’s Council of Economic Advisers and the U.S. Department of Energy’s Office of Electricity Delivery and Energy Reliability, n.d.).

Recently, the concept of a Microgrid was introduced. A Microgrid is a localized electric grid that allows the use to disconnect from the traditional electric grid (Macrogrid). It provides faster system response and recovery to either the whole or part of the electric load for a building. When it is working individually, like an “island,” the system is not providing and getting the disturbance to and from the traditional grid. Microgrids generally involve generators, storage devices and controlled loads (U.S. Department of Energy, n.d.).

A Microgrid offers several benefits in terms of electricity efficiency, economic and environment benefits. First, a Microgrid helps increase the efficiency of the electric delivery system by reducing the energy losses from transmission and distribution. Since generators are on site, the customer has more control over the power supply, which increases the reliability of the electrical system inside a building. Since the energy source for generators can be renewable sources such as solar and wind, a Microgrid can help counter global climate change. By using a Microgrid, the building owner can save money and generate revenue, which provides the opportunity to pay back the cost of a Microgrid. (Whitlock, 2015)

The main purpose of the report is to analyze the feasibility of a Microgrid. The size and power demand of a building is not the limiting factor. Some applications are small based on the size and load demand. Also, there are some large facilities with more load demand such as a hospital, a data center, or an industrial manufacturer. This paper will start with a brief history of electricity, the current power system, and an explanation of a Microgrid. Following this introduction, this report will discuss the feasibility of Microgrids through the case studies: the Microgrid technology and Microgrid life cycle cost analysis. Finally, the report will present conclusions on the feasibility of Microgrids.

Chapter 2 - Electricity Evolution

History of Electricity

In order to have a better understanding of the Microgrid, it is good to know the background of electricity. Since the mid-18th century, the study of electricity has flourished. Each of its major findings has led to a wide range of practical research, thus promoting the rapid development of science and technology. Today, human life, science, technology activities and physical production activities are inseparable from electricity. With the development of science and technology, researchers contributed to the formation of specialized disciplines, such as electronics and electrical engineering. Knowledge of electricity is from many contributors who gave of their time, money and even their lives.

The electrical record can trace back to the 6th century BC. The word "electricity" was changed from the Greek word “amber.” As early as 585 BC, the Greek philosopher Thales recorded that the friction between pieces of amber can attract pieces of small objects. Later, many materials were found that, after rubbing, also can attract small objects. The phenomenon is treated as a nature of matter, just like magnets at that time. No other significant developments related to electricity were found in the next 2,000 years (Baigrie, 2006).

Benjamin Franklin

In 1752, Benjamin Franklin, by using a famous experiment of tying a key to a kite string and flying the kite in a storm, established that static electricity and lighting were the same. The experiment inspired many people. Some people tried to replicate the test to understand the theory, but died during the experiment. For example, Georg Wilhelm Richmann was killed when he was attempting to replicate the experiment in Saint Petersburg in August 1753. Later, Franklin invented the lightning rod, which is considered to be the first practical application of electricity.

Alessandro Volta

Before 1800, scientists were able to produce only nearly instantaneous current flow. These, high-voltage, low-current, short duration bursts of electricity were not functionally usable as a source of power (Blasi, 2013). In 1800, Alessandro Volta invented the first electrical battery called the voltaic cell. He also created battery cells by placing pieces of brine-soaked cardboard in between two metal disks. The battery cell generates electricity with relatively low voltage, high current, and long duration. This kind of electricity is considered to be direct current (DC). Since a constant electric potential creates the DC, the current is relative constant for a short time. Volta's battery provides scientists an easy way to study electricity.

The invention of the battery was a big step for the evolution of electricity. However, the limitation of the battery was apparent. The amount of electricity from the battery was very small. Volta's batteries, despite their limitations, remained the only reliable source of electricity for more than 30 years until Michael Faraday introduced his dynamo in 1831 (Baigrie, 2006).

Michael Faraday

As an English scientist, Michael Faraday was the first person to realize that electric current could be generated when passing a copper wire by a magnet. He introduced the concept of the electric field. As Figure 2-1 shows, the field lines are the paths that a point positive charge would seek to make as it was forced to move within the field and the field permeates all the intervening space between the lines. The field lines are however an imaginary concept with no physical existence (Morley, 1994). The relationship between magnetic fields and currents was paramount because it led to Michael Faraday's invention of the electric motor in 1821. This discovery allowed him to invent the first electrical generator in 1831. The electrical generator converted the mechanical energy of a rotating copper disc to electrical energy, which showed the potential of generating electric power using magnetism. Faraday made a great contribution to the people who would continue the study of electricity.

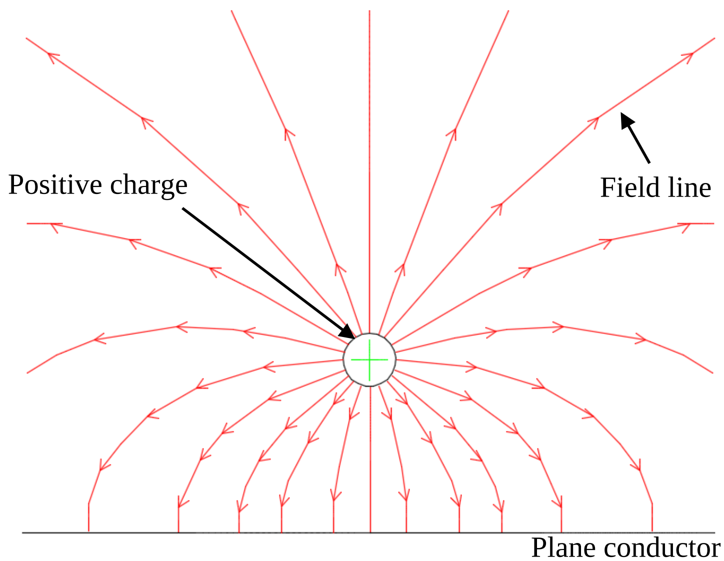

Figure 2-1 Field Lines for a Positive Charge Above a Plane Conductor

Reproduced from (Morley, 1994)

Thomas Edison

In 1879, Thomas Edison devoted himself to inventing the practical light bulb. The problem was finding a sturdy material for the filament, the small wire inside the light bulb that conducts electricity. Edison tried many materials for the invention of incandescent lamp.

The next challenge was developing an electrical system that could provide a useful energy source to deliver power to the new light bulbs. Edison intended to make electricity both practical and economical. Therefore, he designed and built the first power plant to generate electricity and deliver it to homes.

In 1882, with J.P. Morgan funding, Edison launched the business, later known as General Electric. In September of that year, Edison's Pearl Street Power Station started up its generator in New York City. Approximately 85 customers in lower Manhattan got enough power to light 5,000 lamps. In today's dollars, the electricity cost $5 a kilowatt-hour substantially greater than today electricity costs 12.5 cents a kilowatt-hour for residential, 11 cents for commercial, and 7 cents a kilowatt-hour for industrial customers (The NEED Project).

Nikola Tesla

As a Croatian scientist, Nikola Tesla created the alternating current(AC) electrical system, which is considered the turning point of the electrical age. Tesla discovered the rotating magnetic field in 1882 and came to the United States to work with Thomas Edison in 1884. Tesla first introduced the AC induction motor in May 1888. Then Tesla teamed up with engineer and businessman George Westinghouse to patent the AC system and install the alternating current generator system at Niagara Falls. Edison's DC plant could carry electricity only within a square mile of his Pearl Street Power Station, where as the Niagara Falls plant was able to transport electricity over 200 miles (The NEED Project). Electric services at this time were single phase, 133 hertz (Hz) power, which was not practical for use with electric motors due to the high rate of speed the motors would turn. Tesla and Westinghouse put in effort to replace 133 Hz infrastructures with 60 Hz, three phase services. 60 Hz AC has been used as the standard since then in USA (Blasi, 2013).

War of AC and DC

The actions that Tesla took were in direct competition with Edison's DC system. What came next was the "War of AC and DC," with Tesla and Westinghouse vs. Edison and J.P. Morgan. The "war" was referring to a series of scare tactics by Edison trying to show the danger of the high-voltage alternating current.

Harold Brown, who worked for Edison, performed an exhibition to show how lethal AC was. In one of Brown's first exhibitions, he chained down a dog in front of a crowd and proceeded to electrocute it. He first started by electrocuting it several times by increasing the voltage of direct current up to 1000VDC. He then switched over to AC and killed the dog with a mere 300VAC. The actual reason for the death of the dog is still debatable (Blasi, 2013).

Then, Brown was hired as an expert on the electrical execution of man, named Kemmler. In Brown's mind, he wanted to prove that AC can kill people. However, the reality is that the man was still alive after the first try of electrocution. Then, the executioner turned the power back on until the man died. After an examination, it was determined by a doctor that the man was cooked alive rather than swiftly executed. The failure of electrocution proved to be a blow for DC and Edison on the grounds that the AC was no longer thought to be an instant killer (Jonnes, 2003). AC continued to grow and when Westinghouse received the contract to light the 1893 World's Fair in Chicago. That finally showed AC as a safe source to the masses, and the growth of AC power exploded (Blasi, 2013).

The competition between AC and DC is not about how one is better than the other. Because voltage can be stepped up and down, AC has become the standard for electric distribution in society. This does not mean that the use of DC is gone. Both AC and DC contributed to have their own development over the past century.

DC distribution systems are very rare today, but many applications for DC power still exist. For example, batteries supply DC (it is a DC device that converts the AC power for storage), and many of our electronic devices such as mobile phones and computers run on DC power. Since there is a difference between AC and DC, an AC adapter is needed for converting AC power to DC on its way to devices. The adapter converts 120V, 60 Hz current into direct current, typically 12V or less. Most electronic devices use DC power for many reasons. Microprocessors use direct current power to operate and send signals, because a practical AC microprocessor has not been made yet. (Blasi, 2013)

Summary

As history shows, electricity did not have a smooth start. Although many people were excited about the new inventions when electricity came about, some were afraid of electricity and concerned about the safety of bringing it into their homes. Many people in today's society would argue that electricity has provided light and convenience to our lives. No matter how people might criticize electricity, electricity plays a significant role in human lives.

Today's Power System

How power is generated, transmitted and distributed today? Figure 2-2 shows a basic relationship of all three components. Electricity is commonly generated at a power plant; then it is sent on high-voltage lines. Finally, electricity is then distributed to our homes and businesses by local power distribution lines. A detailed illustration is included in the following.

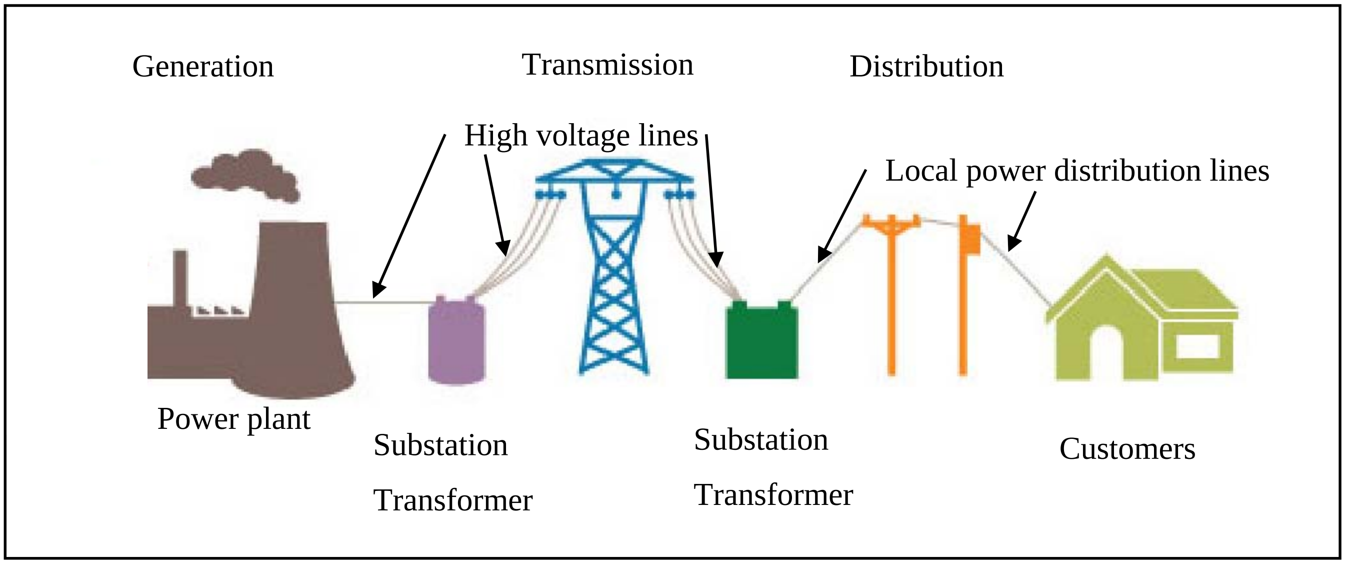

Figure 2-2 The Basic Relationship of Generation, Transmission and Distribution

Reproduced from (IER, History of Electricity, 2014)

Generation

As noted, Edison opened the United States' first central power plant — the Pearl Street Station in lower Manhattan, New York. Edison created a network of buried copper to connect a large bank of generators to homes and businesses (including the New York Times). At that time, there was no such term as "electric grid." If customers wanted to power a lamp or motor, they needed to rely on the generators on-site, usually located in a basement. Pearl Street's "central" power plant design was an important shift from small-scale, on-site generation to industrial-scale power, and soon became the model for the entire power generation industry (IER, History of Electricity, 2014).

When it comes to electricity, it is necessary to mention that there is a great variety of generation sources, using such fossil fuels as coal, petroleum and natural gas, in addition to nuclear, hydroelectric, wind and solar power. However, due to the limitation of resources and technology, the most common fuel source is coal, petroleum, natural gas, nuclear power and hydroelectric power.

More fuel is being devoted to the production of power. The use of oil, natural gas and coal in electrical generation is constantly growing, as opposed to the direct use of such fuel for heating and transportation. For example, in 1900, less than 2 percent of natural gas, oil, and coal were used to make electricity. A century later, 30 percent of our use of natural gas, oil, and coal was devoted to electric power (IER, History of Electricity, 2014).

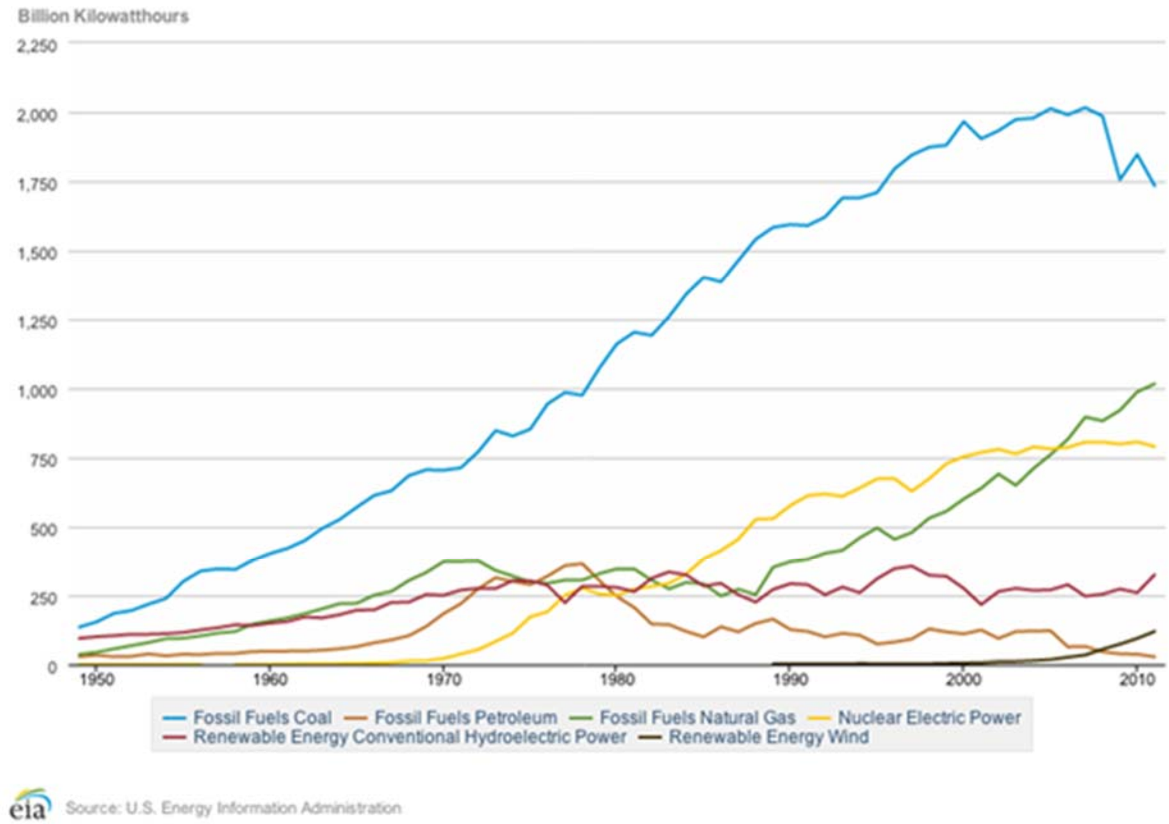

Figure 2-3 Electricity generation mix by fuel type (1949-2011)

From U.S Energy Information Administration (U.S. Energy Information Administration, n.d.)

The fuel used to generate power is changing with time. From Figure 2-3, coal has always been used in modern power plants to generate electricity more than all another fuel sources in the U.S. The consumption of coal is increasing from 250 Billion KWh in the 1950s to 2,000 Billion KWh in the 2000s. In recent decades, other sources were competing for second place: first hydroelectric in the 1950s, then natural gas in the 1970s, nuclear power in 1990s, and natural gas again in 2010 (U.S. Energy Information Administration, n.d.).

Transmission

Today, AC power is the most common way of power transmission around the world. That is because it is easy to convert voltage into high- or low-based on use. The transmission lines usually have very high voltages in order to reduce the power loss, because higher voltages lose less energy than lower voltages during transmission. Because of the electromagnetic field produced around the wire, transmission lines are either suspended above the ground at a required height or buried below the ground at a required depth. The higher the voltage, the stronger the electromagnetic field that will be generated.

For example, in a straightforward AC distribution system, the power is stepped up from a transformer to 345kV after coming out of the power plant. After a long, high-voltage transmission, the power is step down at 69kV before it comes to distribution level at 7.2kV. That way a house can get power at 220 volts. During the step-up and step-down process, transformers change the voltage while capacitors and inductors keep the waveform in sync. Effects of inductance and the changing loads can put the AC waveform out of sync, which ends up in loss of efficient transmission (Edison Tech Center, n.d.).

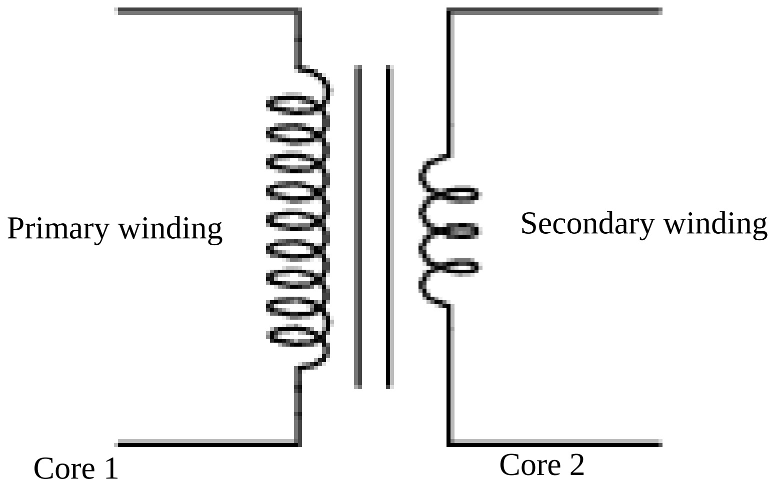

Figure 2-4 Step Down tranformer

Reproduced from (IER, Electricity Distribution, 2014)

The process used to change the voltage of electricity by a tranformer is defined as follows. The transformer has two cores wrapped in copper wiring. An electromagnetic field passes between two cores to make a workable transformer. For example of Figure 2-4, in order to step down voltage, power enters the transformer through the core 1 with many windings of copper wires around it. As it leaves the transformer, it travels through the core 2 with many fewer windings, causing the power to have a much lower voltage. When it is stepped up, the windings of the cores will be opposite. The concept sounds easy, but high-voltage transformers are a significant investment —they each cost millions of dollars and weigh hundreds of tons (IER, Electricity Distribution, 2014).

Distribution

After electricity is generated and travels along the high-voltage transmission system, it comes off the transmission grid and arrives at local distribution substations. The distinction between transmission and distribution lines is that distribution lines tend to have voltages below 50,000V. Also, because of the electromagnetic field produced around the wire, distribution lines are either suspended above or buried below the ground. The voltage varies for different end users. For some industrial customers, the voltage may be relatively high as it reaches its destination, usually between 4,000 and 13,000V (IER, Electricity Distribution, 2014). As was mentioned in the transmission section, 120 or 240 V is typically the voltage for house and business.

Before power enters a customer's building, a meter is applied. It measures the quantity of electricity flow for the utility company to charge the customer. With the advance of the technology, the meter is evolving the function day by day. For example, a two-way meter can measure the electricity flow both into and out of a building. In this case, the meter detects whether a building is contributing electricity to the power grid. For over a century, utility companies had to send workers to collect the data from meters. Computerized meters have two-way digital communication technology, which can automatically send data to the utility company. This is important because it allows the building to generate more power than it needs and sell it back to the utility company (Litos Strategic Communication).

Chapter 3 - What is a Microgrid

How to make a more reliable power supply has been an issue of constant research and study. Looking for an alternative way to generate and distribute power, which provides a more stable electrical power supply without being a detriment to the environment is the goal of many in the industry. A concept to address this concern is the Microgrid.

The Microgrid has a long history, though its name is relatively new. Edison’s Manhattan Pearl Street Station, constructed in 1882, was essentially a Microgrid, since a centralized grid was not yet established (Asmus, Microgrids, 2009). Of course, Edison’s first Microgrid as well as many to follow were DC Microgrids. However, the interests of getting more electricity to the consumer and the financial benefits accelerated the evolution of the central power grids delaying the evolution of Microgrid. Today, because of the use of the AC and DC equipment, Microgrids have AC and DC involved.

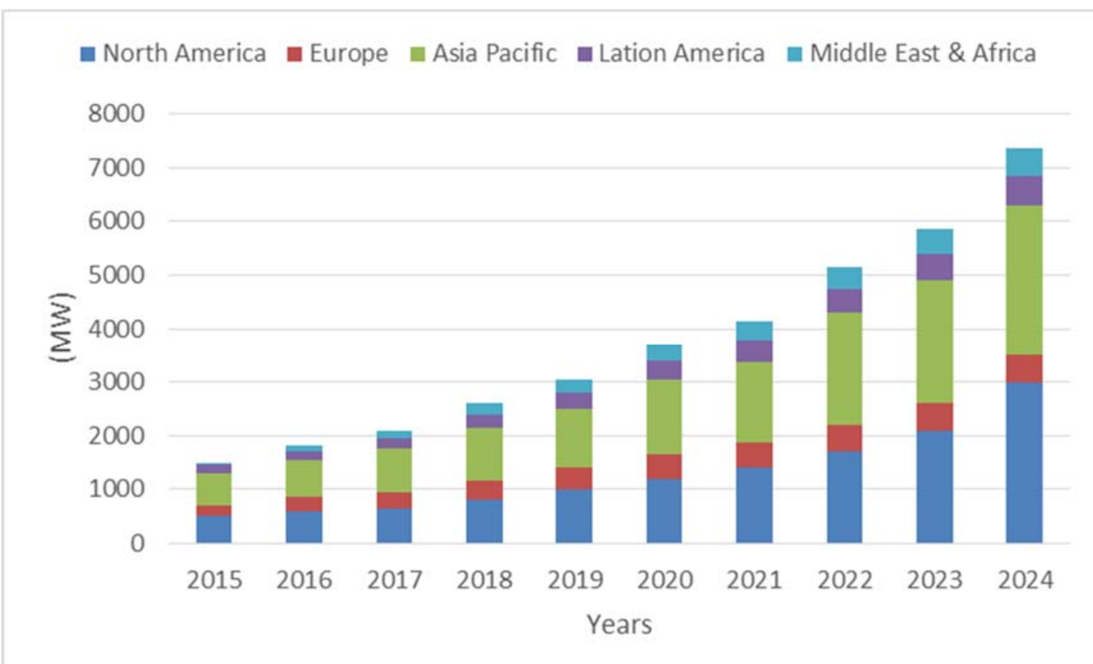

Figure 3-1 Projected Annual Total World Microgrid Market Capacity: 2015-2024

Reproduced from (Navigant Consulting Inc., 2016)

Recently, the Microgrid market has been booming. The Navigant Research shows that the largest Microgrid market as of 2015 is Asia Pacific, displacing North America for the first time. Estimated total Microgrid capacity in Asia Pacific in 2015 was 581.9 MW, compared to 490.7 MW in North America, the second largest market. Figure 3-1 shows the Projected Annual Total Microgrid Market Capacity by Region in World Markets from 2015 to 2024. By the end of the 10-year forecast, Asia Pacific and North America are expected to switch places again, with North America forecast to bring online 3.0 GW capacity. In contrast, Asia-Pacific is expected to reach an annual capacity of 2.8 GW by that time (Navigant Consulting Inc., 2016). Also, academics from the University of Wisconsin- Madison — an institution often credited with the birthing of the Microgrid concept (at least in engineering terms) — predict it could take 30 years for the Microgrid to become ubiquitous (Asmus, Microgrids, Virtual Power Plants and Our Distributed Energy Future, 2010). Appendix A is a roadmap found from a report done by Christine Schwaegerl (Schwaegerl, 2009). It generally shows the whole trend of Microgrids.

It is easy to see that the worldwide market of Microgrid is constantly evolving. This report is focusing on an analysis of the feasibility of Microgrids for large power demand facilities.

A Microgrid is more than just generation and distribution. More pieces and parts are involved in the Microgrid management. Because the personal computer (PC) was first released in the 1980s, the computer-based management system is a reason why Microgrid was slow to develop after Edison’s Microgrids. Edison’s Microgrids are essentially basic and simple Microgrids. With the technology and power system development, Microgrids have evolved to be a more sophisticated system.

Definition of a Microgrid

It is beneficial to come to the understanding of the definition of Microgrid. There are more definitions than it is feasible to list, but following are some examples of definitions found from Berkeley Lab (Berkeley Lab, n.d.).

> U.S. Department of Energy Microgrid Exchange Group:
> *A Microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A Microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.*
>
> CIGRÉ C6.22 Working Group, Microgrid Evolution Roadmap:
> *Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while is islanded.*

Both definitions are helpful to give a general idea about a Microgrid. From the definitions, there are three messages are worth pointing to. First, a Microgrid comprises both supply-side and demand-side resources in a defined boundary. Supply-side resource include micro generators (microturbines, fuel cells, PV, etc.) together with storage devices (flywheels, energy capacitors, batteries, etc.). The demand side resources are all the loads within the building needing power (lighting, HVAC, PC, etc). All the components will be explained in later in this chapter. A defined electrical boundary infers that the Microgrid itself does not have a clear, specified boundary, and the size varies. The defined boundary is set by the Microgrid owner and Microgrid designer. The name Microgrid is used in contrast with the traditional power distribution system-Macrogrid.

Secondly, the Microgrid can operate under two operation conditions: grid-tied mode and island mode. Grid-tied mode means the Microgrid is running connected to the utility grids a majority of the time. Island mode means that the Microgrid is operating autonomously without a power supply from the utility grid. Island mode serves as backup power, which is helpful during brownouts or blackouts of the utility's distribution system. Also, the electricity storage size of a Microgrid will vary related to the Island Mode. This is what Siemens AG published in Advanced Architectures and Control Concepts for More Microgrids: "Long-term islanded operation of an entire Microgrid poses high requirements on storage size and capacity ratings of micro-generators" (Schwaegerl, 2009).

Finally, a Microgrid is a single controllable entity that is operated in a coordinated way. The method of management and coordination of available resources is the main difference between a Microgrid and Distributed Energy Resources(DER). Distributed Energy Resources (DER) are autonomous generating, storage, and load control technologies that are typically located at customer premises and operated for the customer's benefit. They include microturbines, fuel cells, photovoltaic systems, and traditional internal combustion engines DER's impact on the grid's reliability. Specific areas that must be addressed include: control and dispatch strategies for DER; strategies to ensure the safety and protection of the grid; and the role of power electronic interfaces in connecting DER to the grid (CERTS, n.d.). A Microgrid is more than an aggregator of small generators— it intends to solve the problems DERs have and performs more functionalities like a network service provider, or a load controller, or an emission regulator, and serves multiple economic, technical, and environmental aims (Schwaegerl, 2009).

Many other organizations have defined Microgrids with very similar definitions. Common between all definitions a system consisting of multiple loads and generation sources, with the availability of islanding from the macrogrid. Although, a Microgrid is not dedicated by its physical size, a precise definition is expected to be released in the near future by researchers. This report will look into the structure, technology availability and economics of Microgrid to see the feasibility of it.

The Structure of Microgrids

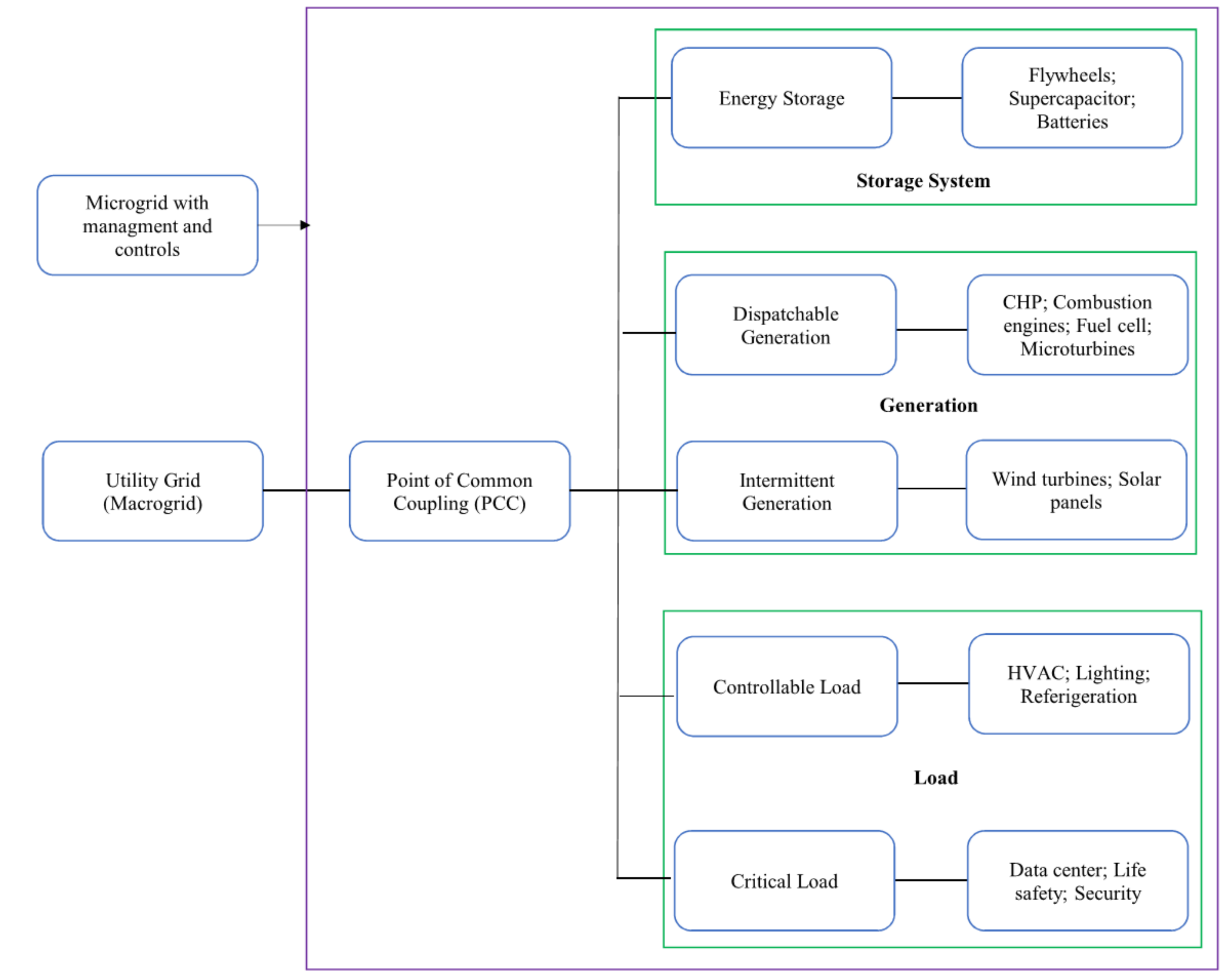

Figure 3-2 Main Components in Microgrids

Reproduced from (Su, 2012)

The structure of Microgrid is introduced in this section. The most common Microgrid components are illustrated in Figure 3-2. Microgrids consist of the power generation resources, power storage system, system loads and energy management system. The connection between Microgrid and utility grid is through a Point of Common Coupling (PCC). The Microgrid has the ability to provide both power and heat to a building through the use of Combined Heat and Power (CHP). Cable and protection devices are also used in a Microgrid system. The following is a discussion of the most common elements of a Microgrid.

Generation

A Microgrid can use many different methods to create power with the most common manners being combustion engines, solar photovoltaic arrays, wind turbines, fuel cells and microturbines. All these devices are sometimes referred to as distributed generators. The following is a detailed list of these components:

1. Combustion Engines

   Combustion engines are a well-known way to provide power for buildings. Mainly, it is because the emergency generators in the form of combustion engines are commonly used to provide backup power for buildings. There are many different types of combustion engines to choose from, due to a variety of fuel sources. Combustion engines produce AC power, and emissions are the main concern when installing the engines. Due to combustion engines lack of power electronics, take time to come on for power supply and have unstable frequency compared with the grid, designers tend to minimize their role in a Microgrid. However, reciprocating engines will remain competitive in many applications due to their familiarity.

2. Solar Photovoltaic arrays

   Solar energy has been used for a long time as a renewable energy source and is becoming more popular. As solar arrays relate to buildings, they can be installed on a roof, wall or on the ground. Solar power generation depends on weather conditions such as snow, clouds and fog. These conditions can significantly affect efficiency by blocking the sunlight. The solar panel generates DC power. In order to capture the power, inverters are installed to convert DC power to AC power for load use.

3. Wind Turbine

The wind turbine is another type of renewable energy resource that has been generating electricity for a long time. Big turbines are widely used in offshore and wind farms for power generation. The average size of onshore turbines ranges from 2.5 to 3 MW (European Wind Energy Association, n.d.). For a Microgrid application, smaller wind turbines are most likely to be installed depend on the facility size. Because the site geography will have a big influence on the wind turbine, wind maps are used to determine ideal sites. The wind turbine initially generates unstable AC power. After an AC to AC rectifier, the generated electricity is ready for use.

4. Fuel Cells

Fuel cells work similar to a battery. The DC power is derived from the chemical reaction that generates an electrical potential. However, fuel cells are a bigger energy conversion device that convert the chemical energy of fuel into electrical energy. These devices use only the energy from the chemical reaction. Since the voltage output from the cell is typically less than 0.7 volts, fuel cells are placed in a series to produce a higher voltage before entering into inverters (Blasi, 2013). Limitations of the fuel cell involve slow start-up times, low power output, sluggish response on power demand, poor loading capabilities, narrow power bandwidth, short service life and high cost (Cadex Electronics Inc., n.d.).

5. Microturbines

   Microturbines are different from the traditional means of generating electricity via combustion engines, mainly because of the construction elements. They are a type of combustion turbine that produces both heat and electricity on a relatively small scale There are essentially two types of Microturbines. One is a high-speed, single-shaft unit with the compressor and turbine mounted on the same shaft as the electrical alternator. Turbine speeds mainly range from 50,000 to 120,000 rpm. The other type of Microturbines is a split-shaft design that uses a power turbine rotating at 3,600 rpm and a conventional generator connected via a gearbox. Their primary fuel is natural gas, although sometimes a clean-combustion fuel such as propane is used. The split shaft is necessary for machine drive applications, which does not require an inverter to change the frequency of the AC power (Capehart, n.d.).

In order to know which generation option is best for an application, a balance of site constraints, fuel availability, and environmental impact need to be considered. A on-site generator is likely to move NOx(nitrogen oxide) emissions closer to population centers. Environmentally, fuel cells and most renewable sources are a major improvement over conventional combustion engines (Lasseter et al., 2002).

Storage

Storage is likely to be integral with Microgrid applications. Storage is the key to regulating the system voltage and frequency. Storage typically refers to the backup supply of the Microgrid system. It is necessary to have a storage system in order to have a more reliable power supply for a Microgrid system both in grid-tied and island mode. The following are three types of the storage system, and all are based on different working theories.

1. Flywheels

   Flywheels store energy in the form of kinetic energy. The mechanical flywheel is connected to the drive system through an axle. The electrical flywheel requires an electrical input to a built-in motor for accelerating its rotor. The same motor can be a generator to supply energy by reversing the process. The most challenging factor for flywheel design is the material used for the flywheel rim. A flywheel rim needs to be made of a material with high tensile-strength-to-density ratio to maximize the stored kinetic energy. Flywheels can become an excellent high power density storage device. An optimistic estimate for specific power ranges between 2000 W/kg (short-term) and 8000 W/kg (long-term). The corresponding specific energy ranges from 4 to 50Wh/kg (Mierlo et., 2003).

2. Energy Capacitors

   Energy capacitors also refer to super or ultracapacitors. Those capacitors behave like very high-power and low-capacity batteries. Ultracapacitors store electric energy by physically accumulating and separating opposite charges. The capacitor chemically stores energy in a reversible chemical reaction, opposed to batteries. The high expected life is an important benefit of supercapacitors. Supercapacitors can be cycled very quickly, while most chemical batteries do not have the same capability. Supercapacitors also have high cycle efficiencies compared to chemical cells. Ultracapacitors have a unique feature in that their voltage is directly proportional to their state-of-charge. Therefore, either their operating range must be limited to high state-of-charge regions, or control electronics must be used to compensate for the widely varying voltage. The primary obstacles with ultracapacitors are their low specific energy, which is in the range 5–10Wh/kg. Power densities of 2,000–4,000 W/kg have been demonstrated by ultracapacitors in the laboratory (Mierlo et., 2003).

3. Batteries

Though a battery cannot be cycled very quickly like a supercapacitor, it is still preferred in some applications. Batteries are characterised by their life cycle, energy, power density and energy efficiency. The life cycle refers to the number of charging and discharging cycles before a battery loses its ability to hold a useful charge. A useful charge is typically when the available capacity drops less than 80% of the initial capacity(Mierlo et., 2003). Life cycle typically depends on the depth of discharge and charge. When charging and discharging a battery, the percentage of discharge and charge should be based on the manufacture specification in order to maximize the battery life.

In reference to a Microgrid, the storage is referring to the distributed energy storage. All methods store excess energy at the off-peak time and operate as supplement generators at the peak. They are applied to regulate the voltage and frequency of the Microgrid, which is critical on the control of a Microgrid. In terms of the choice of storage system, models may be needed to compare the different storage system.

System Loads

The load is essentially where the electricity and useful heat goes. Based on consumption type, the load is made up of many things. For a Microgrid, it can be separated into two general categories: controllable loads and critical loads.

1. Controllable Loads

   Controllable loads refer to any devices that plugs in or requires power for operation such as lighting, heating, ventilation, and air conditioning and personal computers (PC). Large facilities such as data centers, hospitals and industrial manufacturing usually use a large amount of power because of their size and their constant use. Nowadays, with technology increases, mobile electrical storage, plug-in hybrid electric vehicle (PHEV) and plug-in electric vehicle (PEV) also play a significant role. Furthermore, there is a voltage difference between commercial and industrial buildings that will need to be considered when designing a Microgrid (Su, 2012).

2. Critical Loads

   Critical loads is usually determined by the islanding mode of the Microgrid. During islanding mode, some loads need an uninteruptable power supply. For example, the data center needs power for its critical equipment to secure data; there are minimum requirements of light needed for life safety; critical loads related to security, such as in a jail, could be another example. Any controllable loads can be critical load based on code requirements or owner preference. In order to improve the availability and reliability of power supply for critical loads, the size of Microgrid need to be increased. Also, some noncritical loads or controllable loads might have to be disconnected or shed if the microgrid size is set (Su, 2012).

Point of Common Coupling

The Point of Common Coupling (PCC) is a switch used for islanding from or interconnecting with the utility grid. It is usually located on the primary side of the utility transformer before electricity enters the building. It is critical that the PCC function appropriately when blackouts happen or during any other situation when islanding of a Microgrid is needed. Under today's grid protocols, all distributed generation, whether renewable or fossil-fueled, must shut down during times of macrogrid outages, unless it can control voltage and not feed power back to the larger utility grid. (Asmus, 2010). The protocol disappointed many Microgrid advocates at the beginning until the invention of PCC, because PCC can help the Microgrid islanding so that the Microgrid can still operating during outage.

Controller

A Microgrid needs to be operated in a controlled, coordinated way to allow it to be a semiautonomous power system. The key feature of a functioning Microgrid is the capabilities of the power electronics to properly control electricity quality. All the Microgrid power supply devices need electronic devices to operate well and provide a stable power supply. Electronic devices are mostly referred to as controllers. A controller near each generator is called a local controller. The controller has the ability to filter the power from the generator. This capability also demonstrates the feature of a Microgrid to add more power resources or ban the resource if fault current occurs. A Microgrid can have many local controllers. In another scenario, the controller manges the whole Microgrid system without local controllers. This controller is referred to as a master controller. Overall, Microgrid development is tied to the development of technologies.

What a Microgrid is Not

The term Microgrid is commonly misused. All Microgrids have three components: 1) Load, 2) Generation, 3) Management. Any system missing any of these components should be labeled something other than a Microgrid. In order to further understand the Microgrid concept, example comparisons between Microgrid and some common misused terms will be introduced in the following sections.

Smart Grid

The utility grid refers to the traditional power networks that carry electricity from the power plants to consumers. To make the utility grid smart is similar to the way a smartphone works. Smartphones using a computer in the phone to make it smarter. Similarly, Smart Grid means computerizing the electric utility grid. Smart Grid is well illustrated by an introduction found from Energy.gov:

"Smart grid" generally refers to a class of technology people are using to bring utility electricity delivery systems into the 21st century by using computer-based remote control and automation. These systems are made possible by two-way communication technology and computer processing that has been used for decades in other industries. They are beginning to be used on electricity networks, from the power plants and wind farms all the way to the consumers of electricity in homes and businesses. They offer many benefits to utilities and consumers -- mostly seen in big improvements in energy efficiency on the electricity grid and in the energy users' homes and offices (Ton, 2014).

Smart Grid is a term that is used to describe the process of modernizing the nation's electricity delivery system. A key feature of the smart grid is automation technology that lets the utility adjust and control each individual device or millions of devices from a central location (ENERGY.GOV, 2017). A detailed introduction about smart grids can be found in The Smart Grid: An Introduction, a publication sponsored by DOE's Office of Electricity Delivery and Energy Reliability (Litos Strategic Communication).

On the utility side, the application of Microgrids can improve power reliability and quality, increase system energy efficiency, and provide security by islanding from the grid to individual end-user sites. On the customer side, a Microgrid gives the bulk power grid a chance to move from traditional grid towards to a smart grid.

A Microgrid is relatively close to a Smart Grid. Most of the time, Microgrids are getting power from the uility grid. With the use of two-way meter, Microgrids can communicate with the utility grid. If a Microgrid is smarter in terms of technology, the utility grid is smarter because it consists many Microgrids. The smart functionalities of a Microgrid makes a great contribution to the formation of smart grid.

A Smart Grid is different from a Microgrid when it comes to funding. At present, energy regulations do not keep pace with emerging Microgrid technology, which did not help with the progress of Microgrids. So far, very little funding is given to the development of the Microgrid technologies because the money invested from the public and private is flowing to electrical grids. A study shows that "Of the $4.5 billion allocated from federal American Recovery and Reinvestment Act (ARRA) stimulus spending on Smart Grid-related spending, only $55 million — 1.2 percent — flowed to projects that advanced Microgrid technologies." (Asmus, 2010)

However, Microgrids have been regarded as a most important component of the Smart Grid. The DOE Smart Grid research and development (R&D) Program considers Microgrids as a key building block for a Smart Grid and has established Microgrid R&D as a key focus area

(Dan T. Ton, Merrill A. Smith, 2012). It is optimistic to see that the Microgrid may have more funding with the developement of Smart Grid.

Virtual Power Plant

As mentioned earlier, a Microgrid has the ability to aggregate, manage, and deploy distribute energy resources, especially when the grid outage happens. Virtual Power Plant (VPP) is another option to do the aggregation. Both Microgrid and VPP are aggregation platforms that are meeting the market need for reliability, reduced capitals costs of power plants, and demand response (DR) resources.

The concept of VPP in this report is focusing on the USA. In Europe, a VPP refers to the supply side resources aggregation, mainly on the wholesale renewable energy source, while a VPP might not involve sources for generation. Instead, the VPPs mentioned in this report relate to utility demand response (DR) and critical peak pricing (CPP) programs in the USA. The concept of VPP provides the opportunity of not upgrading large-scale, existing infrastructure through existing power generators and utility demand reduction programs. As Peter Asmus, a senior analyst with Pike Research, states: “The beauty of the VPP is that it can optimize the entire system without the need for large capital investments in infrastructure” (Asmus, 2010).

VPP is putting the potential resources, owned by DR customers, to a “Virtual” Facility. The VPP concept is an emphasis on smart meters, real-time pricing and DR. VPP is helping utilities move toward the Smart Grid by using software and management. In short, VPPs represent an ‘‘Internet of energy,’’ tapping existing grid networks to tailor electricity supply and demand services for a customer, maximizing value for both end-user and distribution utility through software innovations (Asmus, 2010).

Microgrid and VPP share some critical features, such as the ability to aggregate generation and storage resources at the distribution level. The difference between Microgrid and VPP is summarized below (Asmus, 2010):

1. *Microgrids can be grid-tied or off-grid remote systems (VPPs are always grid-tied);*
2. *Microgrids can ‘‘island’’ themselves from the larger utility grid (VPPs do not offer this contingency);*
3. *Microgrids typically require some level of storage (whereas VPPs may or may not feature storage);*
4. *Microgrids are dependent upon hardware innovations such as inverters and smart switches (whereas VPPs are heavily dependent upon smart meters and IT);*

Net Zero

Net Zero is a term popular in the building market. A Zero Energy Building can generate enough renewable energy on site to equal or exceed its annual total energy consumption. There is a common definition for Zero Energy Buildings (ZEB) from the Energy Department: *A Zero Energy Building is "an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy."* (The National Institute of Building Sciences, 2015).

The key features of Net Zero is focusing on the quantity of the total energy consumption is net zero. However, the main focus of a Microgrid is providing building with a stable energy supply. Table 3-1 shows the ZEB Renewable Energy Supply Options Hierarchy. The table shows the ZEB supply-side options, which consist of the use of technology and renewable energy to reduce the building energy consumption. However, Microgrid will use renewable sources as DER to produce energy for building use in order to meet the power demand for a building. Net Zero are more concentrated on the energy saving, while the Microgrid use many types of energy in order to make a building self-sustained.

Table 3-1 ZEB Renewable Energy Supply Options Hierarchy

Reproduced from (P. Torcellini, S. Pless, M. Deru, D. Crawley, 2006)

Option Number	ZEB Supply-Side Options	Examples
0	Reduce site energy use through low-energy building technologies	Daylighting, high-efficiency HVAC equipment, natural ventilation, evaporative cooling, etc.
	On-Site Supply Options	
1	Use renewable energy sources available within the building's footprint	PV, solar hot water, and wind located on the building.
2	Use renewable energy sources available at the site	PV, solar hot water, low-impact hydro, and wind located on-site, but not on the building.
	Off-Site Supply Options	
3	Use renewable energy sources available off site to generate energy on site	Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or waste streams from on-site processes that can be used on-site to generate electricity and heat.
4	Purchase off-site renewable energy sources	Utility-based wind, PV, emissions credits, or other "green" purchasing options. Hydroelectric is sometimes considered.

Most Net Zero Energy Buildings are also connected to the electric grid, because it is designed for times when renewable energy generation is not meeting the building's energy load.

In this case, zero net energy buildings will get part of their energy from the utility company, and return the same amount of electricity at other times.

Overall, the big difference between the Net Zero and Microgrid depends on the goals building owners are trying to accomplish. Microgrid would use any methods to provide power supply to the user without too much concentration on energy saving. Since the similarity between Net Zero and Microgrid, a building can be net zero tied to the Microgrid.

Reasons to Consider Microgrids

Why are we considering Microgrids? It is a frequently asked question when people are not quite sure of the benefits of a Microgrid. To answer the question, it is good to look at the Microgrid in three aspects: reliability, economics, and air quality.

Reliability

Power outages are still problems people face. According to a grid resilience report found from the DOE, weather-related outages have cost the U.S. economy an inflation-adjusted annual average of $18 billion to $33 billion between 2003 and 2012 (The President's Council of Economic Advisers and the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability, n.d.). There are a number of reasons for power outages. For instance, peak demand overloads the feeder and can cause the circuit breaker to trip; the failure of the electronic devices either from operation or protection; any disconnections of the transmission line; a natural disaster such as hurricane, tornado or earthquake. Any failures of the utility will cause a blackout to an individual end user.

The current reliability system involves Uninterruptible Power Supply (UPS) and backup generator sets. It is designed under normal situations, to provide power for a couple hours to couple days, depending on the application. Some facilities have a requirement of high-reliability power. For example, a data center, hospital or manufacturing facility. An example of this would be the Santa Rita Jail (SRJ) in Dublin, California. The San Ramon feeder that serves the jail has had an increasing amount of reliability issues. From 2002–2006, there were total 458 minutes that the jail was out of service because of power interruptions. For the jail, reliable power is essential so that inmates and staff will have a safe, secure, and humane environment (Alegria, 2014.).For a long time, SRJ was aiming to find a solution to deliver uninterrupted power to its facility. The power outage problems got resolved after an installation of a Microgrid. Problems can happen to the utility power supply, even though it functions most of the time. Some facilities need a far more reliable power supply to operate. The Microgrid is a reliable power supply system meeting customer's needs.

Economics

How much does a Microgrid cost? In short, a lot. However, Microgrid costs vary for each application, based on the design size. Before the installation of any system, a thorough life cycle cost analysis should be conducted and verified. By finding all the potential incentives, selling the extra energy to the utility, using heat from CHP and balancing the peak and normal electricity price with the storage system, it is possible to get all the money back after a certain amount of years. There is a NY Prize community Microgrid feasibility study (a further discussion of life-cycle cost analysis (LCCA) illustrated in the LCCA section under chapter 4). This Microgrid project has an estimated total cost of $32,500,000 with a 20-year operating period. With an annually benefit of $7,266,521 from the Microgrid. The project has a payback time in less than 10 years.

Air Quality

Air quality recently has become a hot topic especially in China. For example, CBS News, American television and radio networks, report that the U.S. Embassy in Beijing recorded PM2.5 measurements of 291 μg/m3 on January 14, 2013 (Johnson, 2013). PM2.5 is the abbreviation for fine particulate matter with a diameter smaller than 2.5 microns, it is frequently used for Air

Quality Index. The National Ambient Air Quality Standards (NAAQS) for the 24-hour average and annual average have been set at 35 and 15 µg/m3, respectively. (Department of Environmental Conservation, n.d.).

Air quality issues are not confined to small particles but also concern that air contains poisonous material such as sulfur dioxide(SOx), nitrogen oxides(NOx), PM10 and volatile organic compounds. These particles are also found in fossil coal. As mentioned earlier, a large amount of energy is still being created from fossil coal. The coal-dominated energy structure is one of the major causes of air pollution in Beijing. It is estimated that Beijing's power plants emitted 49% of the total SO2 emissions, as well as NOx and PM10 contribute at a rate of 27% and 11%, respectively (Hao, J.M. Wang,L.T. Shen,M.J. Li,L Hu,J.H., 2006). Beijing is not the only city to have air pollution issues. The poisonous air also happens in Bangladesh, Iran, Afghanistan, Nepal, and even in the US near the coasts (The US Embassies in China, n.d.). Poisonous air is now the fastest-growing cause of death in urban populations (Vidal, 2013). Air pollution causes lung ailments and heart attacks. Dr. Maria Neira, the Director of Public Health and Environment in World Health Organization (WHO), says 3.3 million deaths every year are caused by outdoor air pollution (UN News Center, 2013). The environmental effects of power plant emissions are substantial. Microgrids are more efficient on generating electricity than power plant. Therefore, Microgrid applications are intend to improve the air quality of our living environment.

Chapter 4 - Microgrids Design

Many countries, including United States, Japan, China and countries in Europe have shown interest in Microgrids. Each country has its own focus and goals related to the development of Microgrids. The United States is investing in the development of Microgrids because of the issues of reliability and quality relating to electricity. This chapter will cover the types of Microgrids and some Microgrid examples. Also, the report gave a more detailed explaination about the Santa Rita Jail Microgrid project and The NY Prize Community Microgrid feasibility study. These projects intended to show the feasibility of the Microgrid in terms of reliability and economics.

The Types of Microgrid

The types of Microgrid generally can be listed as below (Berkeley Lab, n.d.):

1. Customer Microgrids

   Customer Microgrids is more related to the ownership of the Microgrids, which is the customer. Many of the most popular examples are this type. They are particularly easy to imagine because they fit neatly into our current technology and regulatory structure.

2. Utility or community Microgrids

   It involves a segment of the regulated grid. They are not technically different from Customer Microgrids in that they have all the same components. However, they are fundamentally different because they incorporate traditional utility infrastructure. Utility regulation comes much more significantly into play. Also, the financing structure is different with Customer Microgrids.

3. Virtual Microgrids

Similar to the virtual power plants (VPP), DER at multiple sites are connected but to differentiate this as a Microgrid they are coordinated. Very few demonstrations of virtual Microgrids exist, but they have been proposed in the literature. Note: To be consistent with the definition, the system must be able to operate as a controlled island or coordinate multiple islands.

4. Remote power systems
   This is for a facility not able to operate grid-connected; Remote power systems involve similar technology. They are in island mode constantly compared to the other types of Microgrids.

The original goal of the feasibility study of Microgrids is to cover all types of Microgrids since the size and power demand of a facility is not the limiting factor based on the definition of a Microgrid. However, with the limitation of Microgrid projects, detail Microgrid case studies are not available for each type of Microgrids. There are some examples of Microgrids application found during research like data centers, healthcare and industrial manufacturers. These facilities are large on size sometimes. Large facilities have a lot of equipment and devices in operation with many electricity usages.

Data Center

There are companies whose business model is to provide clients cloud services for data storage. It is important to keep the electricity available in order to provide Cloud services. Many companies, such as Google, Amazon, Microsoft, Alibaba, IBM and Rackspace, have their own data centers to keep their data safe. Google's market share was 2.5 percent in 2015, while Amazon Web Services controlled 70.1 percent of the market; Microsoft Azure's share was 10.8 percent of what was then an $11 billion market. The market is still growing. Google said in

March 2017 it would add 10 new cloud data center locations by the end of this year. (Sverdlik, n.d.).

An emergency generator is one of the conventional backup solutions for data centers. However, failures could still happen. Craigslist and Yelp housed their servers in a San Francisco data center that relied on 10 backup generators for emergencies. However, a brief blackout in San Francisco in 2007 took down there several and other websites because three of the generators failed to start. The data center's operator, 365 Main, said after an investigation that sites affected by the outage took anywhere from an hour to 12 hours to get back online (Kopytoff, 2012).

As mission-critical enterprises, data centers have a requirement for reliable power. An Uninterruptible Power Supply (UPS) was provided to a data center**.** UPS provides power conditioning and backup power when utility power fails, either long enough for critical equipment (computers, data centers, telecommunication equipment) to shut down gracefully so that no data is lost, or long enough to keep required loads operational until a secondary AC source, like a generator, comes online (Loeffler, 2015). However, the capacity of a UPS system is limited. The advanced Microgrid technology is an ideal solution to the data center platform. Data centers and Microgrids are considered a natural pairing because of the large amount of energy consumed by data centers and their need for high-quality, reliable power (Wood, 2016). Also, the more reliable a data center is the more likely it is to have a better reputation to market.

So far, no demonstration of Microgrids was found for a Data center. However, there are some ongoing Microgrid projects for a data center. In March 2016, Arizona's largest utility, Arizona Public Service (APS) was developing a large data center Microgrid with partner Aligned Data Centers, a subsidiary of Aligned Energy. The Microgrid is rated at 63 MW. Some larger

Microgrids are also in development. The Niobrara Energy Park in Colorado is planning to serve multiple data centers with a 200-MW gas-fired plant, a 50-MW solar farm, 50 MW of fuel cells, and other energy resources (Wood, 2016). Both of the Microgrids are Utility or community Microgrids

Healthcare

Emergency generators are also a most popular way to provide back-up power for healthcare facilities since power outage is catastrophic results in loss of life. For instance, Hurricane Sandy had a strong effect on the Northeast in October 2012. Even though three New York hospitals wisely installed their backup generators above street level to keep them from being flooded, backup generators failed because their fuel tanks and pumps were placed in basements. During the power outage, vital hospital equipment such as medical monitors and ventilators no longer operated. Hundreds of patients had to be evacuated during the height of the storm. A similar scenario played out in New Orleans hospitals in the wake of Hurricane Katrina in 2005, leading to a number of patient deaths (Kopytoff, 2012). Building a Microgrid for a hospital is to prevent a power outage in order to save lives.

Under a multiyear contract since 2009, NRG Energy Inc. has provided The University Medical Center of Princeton with electricity and heat from a Microgrid. The Microgrid consists of a 4.6 MW gas turbine-powered CHP; a 1 million-gallon chilled water thermal-energy storage tank, which is a thermal “battery” that can be charged during off-peak hours and discharged during peak-demand periods and a 200 kW solar array with panels. This Microgrid solution enhances the hospital’s energy reliability at a cost that is lower than that required to provide several energy sources individually. It also provides the institution with the flexibility to export power to the local grid when rates are high, or to quickly draw power from the grid when rates are low or when additional energy is needed (NRG). This is also an utility or community Microgrids

Industrial Manufacturers

Like data centers and hospitals, the industrial manufacturer also faces challenges from a power outage. ABB installed an integrated solar-diesel Microgrid at its Longmeadow premises in Johannesburg, South Africa, in 2016. This would belong to a customer Microgrid. ABB's facility houses the company's country headquarters, as well as its medium-voltage switchgear manufacturing and protection panel assembly facilities. The Microgrid solution includes a 750-kW rooftop solar photovoltaic (PV) array and 1 MVA/380 kWh battery-based grid stabilizer, which helped to maximize the use of clean solar energy and ensure an uninterrupted power supply to keep the factories running even in the event of a power outage on the utility supply. A battery-based grid stabilizing system can address frequency and voltage fluctuations. A Microgrid-distributed control system manages the supply of power and balances the fossil-fuel and renewable energy sources in accordance with loads, in a coordinated manner, enabling access to utility.

The Microgrid application for a manufacturer is optimal for couple reasons. First, a Microgrid ensures the facility continuously operating when a power outage happens. Secondly, a Microgrid can provide the opportunity to get the Microgrid investment back by selling extra power to the utility.

Microgrid Technology

Serving as the “brain,” control and management are some of the most important parts of a Microgrid. A Microgrid is a sophisticated system that integrates many resources and equipment, which requires technology for properly control. There are many organizations getting involved with Microgrid development. Each Microgrid researcher has its own laboratory to do the research.

Siemens, ABB, SEL are some companies offer Microgrid business models and advanced control and optimization software to maximize the value of the onsite generation and energy storage in coordination with local utility rates. They all commitment to making electric power safer, more reliable, and more economical. provide high-performance Microgrid control. They sale Microgrid controllers that is able to respond to external data, such as real-time pricing signals and fast-changing system dynamics.

There is organization called the Consortium for Electric Reliability Technology Solutions (CERTS) also provides Microgrid technology support. CERTS was formed in 1999 to research, develop, and disseminate electric reliability technology solutions in order to protect and enhance the reliability of the U.S. electric power system under the emerging competitive electricity market structure. The founding members include four DOE National Labs: Lawrence Berkeley National Laboratory (LBNL), Sandia National Laboratory (SNL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL); National Science Foundation’s Power Systems Engineering Research Center; and the Electric Power Group. Currently, CERTS is conducting public interest research for the DOE Office of Electricity

Delivery and Energy Reliability and the California Energy Commission (CEC) Public Interest Energy Research program (Alegria, 2014.).

All the company and organization listed above are capable of designing controllers and continuously studying and testing Microgrid devices. Following a case study about SRJ, which is a Microgrid project conducted by CERTS. The case study is the work of Chevron Energy Solutions (CES) to prove the feasibility of a Microgrid.

Case Study

The SRJ project, in the San Francisco Bay Area, is a Microgrid demonstration project from the CERTS. This CERTS Microgrid project was the first of its type and scale. Most of the Microgrid components were custom designed to meet specific site and utility requirements. The Microgrid project is led by CES. A team of researchers and contractors worked together to design, construct, and commission the Microgrid. By following the CERTS protocol, the Santa Rita Jail Microgrid project serves as proof of the feasibility, operability, and benefits of a CERTS Microgrid in a real-world application (Alegria, 2014).

The Santa Rita Jail experienced a total 458 minutes of power interruptions between the years 2002 to 2006. For the Santa Rita Jail, it is essential to maintain the power so that the inmates and staff will have a safe, secure, and humane environment. SRJ was aiming to find a solution to deliver uninterrupted power to its facility. Before the Microgrid project, SRJ had two 1.2-MW diesel generators. During a power outage, the jail still needed to experience about 15 seconds of due to the delay of generator startup. Also, installed were a 1.2-MW photovoltaic (PV) system and 1-MW ultra-clean fuel cell as DER. These had not consistently reduced peak load nor are they available as backup power sources (Alegria, 2014.).

Partner	Role	Capabilities
Chevron Energy Solutions	Team Lead and General Contractor	35 years of experience in the energy services industry providing clients a variety of services from energy audits to bill aggregation and payment
Alameda County (Santa Rita Jail)	End Customer and Microgrid Owner	Housing over 4,000 inmates, is the fifth largest county detention facility in the nation and Alameda County's largest energy-consuming facility; national leadership role in sustainable local government operations
Pacific Gas & Electric	LSE Interconnection & Communication	One of the largest combination natural gas and electric utilities in the United States
California Independent System Operator	System Operator: Grid Interoperability Testing & Market Design	Improved the ease of interconnection and enabled market acceptance of Microgrids and advanced energy storage
University of Wisconsin, The Wisconsin Alumni Research Foundation	CERTS License Provider and Technical Oversight	Has one of the world's top power electronics and distributed energy centers
National Renewable Energy Laboratory	Measurement & Verification	The nation's primary laboratory for renewable energy and energy efficiency research & development (R&D)
Lawrence Berkeley National Lab	Storage Scheduling Optimization	Analyzing on-site generation potential of commercial buildings; led to the development of the DER-CAM

Table 4-1 Project Partner Roles and Capabilities

Reproduced from (Alegria, 2014)

A Microgrid system was introduced to SRJ as a solution to their power issues. Table 4-1 shows the partners of the project with the roles and capabilities.

The Microgrid project started on September 30, 2008, and finished on October 31, 2013. It consists of a 1.2 MW photovoltaic system; 1 MW molten carbonate CHP fuel cell; 2 MW energy-storage system; a 12 kV sub-cycle static disconnect switch; and two 1.2 MW backup diesel generators. (Alegria, 2014).

Three key enabling technologies:

1. CERTS Microgrid
2. Advanced Large-scale Energy Storage
3. Advanced Communication and Control Systems

1. CERTS Microgrid

Reduced Microgrid system cost and increased reliability were two of the objectives of the CERTS Microgrid concept. CERTS concept included four critical components: the static disconnect switch, the microsources, the storage and loads. CERTS Microgrid includes “plug-and-play” functionality. Plug-and-play can reduce the chance for engineering errors because a unit can be placed at any point on the Microgrid system without re-engineering the controls. Analysis indicates that at the American Electric Power (AEP) Microgrid test site that the Microgrid’s stability is not dependent on the number of CERTS devices in a Microgrid. Therefore, it can be expected that the system would remain stable with an infinite number of CERTS units (Alegria, 2014.).

2. Advanced Large-scale Energy Storage

Batteries were used for increasing Microgrid power quality and reliability. When a Microgrid is grid connected, the batteries charge or discharge are controlled by the DERMS to maximize the economic benefit of the battery. During an island mode because of a grid disturbance or outage, the energy in the battery is used to continuously supply power to the on-site loads. The battery provides enough energy to maintain the system until the diesel generators come on line, if required. Moreover, the battery has limitations on upper and lower state-of-charge with 90% and 10%, respectively, when connected to the grid. During island mode, a load and generation management system is installed to control the shedding and adding of load and generation sources in order to let the batteries charge or discharge as needed.

3. Advanced Communication and Control Systems

In terms technology between the utility and Microgrid, a static disconnect switch (SDS) was installed to island the Microgrid. Voltage and current transformers help the SDS to constantly detect the voltage and frequency on either side of the utility and Microgrid systems. Any power quality events will cause the SDS to disconnect and island from the utility within 4 to 10 milliseconds. The process is fast enough that sources in the Microgrid will not detect any utility events. The SDS, rated 12.47kV, 60Hz, three-phase, is acting like a disconnecting means for the CCP. It operates as N+2 redundancy with an overall efficiency of 99% or greater. Also, CERTS Microgrid controls do not rely on a master controller. Instead, each source is connected to a local controller. The coordination among sources and loads is through the control of the Microgrid frequency. This arrangement increases the reliability of the system compared to having a centralized control scheme.

The main 12-kV utility breaker prevents current from flowing towards the utility. Overvoltage, undervoltage, overfrequency, underfrequency and directional overcurrent of the power could trigger islanding operation. The fuel cell inverters and PV inverters are ensured to detect and revise the situations above to ensure all renewable generation stays on line.

As part of the Microgrid, the generators are now integrated to charge the batteries, if needed. One of the advantages of using CERTS is that it reduces the operation time of the diesel generators by integrating renewable or large-scale energy storage equipment with conventional generation. As a result, the energy storage system can support the facility during island mode. When the facility is grid-tied under normal operation, the battery can save money by buying and storing electricity at off-peak hours and using the electricity during peak. Furthermore, the battery helps relieve the strain on the utility's distribution feeder.

Since the SRJ microgrid has been installed and commissioned, there have been no outages due to grid instability. Table 4-2 shows that by avoiding power outage issues, the Microgrid will have a payback time of 109 years. This is a simple payback without interest rate and does not include the cost savings from incurred due to the power outage. Even though the microgrid project has a prolonged payback period, it should be remembered that the Santa Rita Jail site is a high security location. keeping the lights on via island mode of Micrgird has precedence over energy cost savings. The dollar value of Seamless Islanding is not quantifiable within the scope of this project.

Table 4-2 SRJ Microgrid Project Payback Period

Reproduced from (Alegria, Eduardo, Anthony Ma, Osama Idrees, 2014.)

Item considered	Cost and savings
Capital Cost of Microgrid Design R&D, Equipment, and Installation	$12MM
DERMS Estimated Annual Demand and Energy Cost Savings (Using the battery to shift the load from peak periods to off-peak periods)	$ 110M
Facility Benefit of Seamless Islanding and Restoration	Not Quantifiable
Simple Payback Period	109 Years

Overall, the Santa Rita Jail Microgrid project demonstrates the reliability of a Microgrid. It utilized plug-and- play concepts to reduce engineering cost and errors; resolved power quality problems; and united all the applications to work properly as a whole using advanced communication and control systems. The Microgrid has reduced peak load and improves power reliability for the Santa Rita Jail.

Life Cycle Cost Analysis

To see if a Microgrid is feasible or worth installing, a Life Cycle Cost Analysis (LCCA) is needed. A cost comparison for this scenario is impossible to forecast without building a computer model. The model includes the consideration of utility, maintenance and operation costs; component prices. Also, the model needs to include any incentives provided as a result of using a Microgrid by using renewable resources. The incentives need to be confirmed with the local or federal governments or organizations. The following is an example of a Life Cycle Cost Analysis, it is a feasibility studies for NY Prize Community Microgrid Competition proposed by Central New York Regional Planning and Development Board (CNY RPDB) (Prize, n.d.).

Case Study

The Microgrid project is intended to enhance the resiliency of electric service for almost 2,300 residential, commercial, and industrial customers in Onondaga County. The Microgrid includes a new, 2 MW natural gas-fired combined heat and power (CHP) generator located at the State University of New York (SUNY) Upstate University Hospital; an existing 75 kW solar photovoltaic array located at Onondaga Community College, and an existing 40 MW waste-to-energy plant owned by the Onondaga County Resource Recovery Agency (OCRRA). All these resources would produce electricity for the community grid both under normal operation and island mode. In addition, nine existing natural gas and diesel backup generators will operate when called upon to provide peak load support. Since the waste-to-energy plant and solar array are already installed and operating, the energy they generate and the capacity they provide are not treated as benefits of the Microgrid. The LCCA considers only those costs and benefits that are incremental to the baseline, which are existing equipment like CHP. Over a 20-year operating period, LCCA calculates the present value of costs and benefits, employing an annual discount rate at 7 percent, which was specified by the user. The model also calculated the project's internal rate of return, which indicates the discount rate at which the project's costs and benefits would be equal. All monetized results were adjusted because of inflation associated with the year 2014 (CNY RPDB, 2016).

The project considered scenarios that No major power outages over the assumed 20-year operating period (i.e., normal operating conditions only). Table 4-1 illustrates the detailed results of the Scenario 1 analysis.

Table 4-3 Detailed LCCA Results

(No Major Power Outages; 7 Percent Discount Rate)

Reproduced from (CNY RPDB, 2016)

COST OR BENEFIT CATEGORY	PRESENT VALUE OVER 20 YEARS (2014$)	ANNUALIZED VALUE (2014$)
Costs		
Initial Design and Planning	$840,000	$74,100
Capital Investments	$6,180,000	$545,000
Fixed O&M	$1,700,000	$150,000
Variable O&M (Grid-Connected Mode)	$3,350,000	$296,000
Fuel (Grid-Connected Mode)	$11,500,000	$1,010,000
Emission Control	$17,000	$1,500
Emissions Allowances	$0	$0
Emissions Damages (Grid-Connected Mode)	$8,880,000	$579,000
Total Costs	**$32,500,000**	
Benefits		
Reduction in Generating Costs	$10,700,000	$948,000
Fuel Savings from CHP	$4,310,000	$380,000
Generation Capacity Cost Savings	$5,160,000	$456,000
Distribution Capacity Cost Savings	$828,000	$73,000
Reliability Improvements	$9,980,000	$881,000
Power Quality Improvements	$42,200,000	$3,720,000
Avoided Emissions Allowance Costs	$5,900	$521
Avoided Emissions Damages	$12,400,000	$808,000
Total Benefits	**$85,600,000**	$7,266,521
Net Benefits	**$53,200,000**	
Benefit/Cost Ratio	**2.6**	
Internal Rate of Return	**222%**	

As the table above shows, the LCCA looked at the fixed cost, variable cost, avoided cost, reliability benefits and power quality benefits. The fixed cost included the initial design and planning, capital cost, fixed operations and maintenance (O&M) costs and emission control. The present value of those cost is approximately $840,000, $6,180,000, $1,700,000 and $17,000 respectively. The values in the last column are the cost annually.

Besides the fixed cost, the variable costs also had to be taken into account. The most significant variable cost was the cost of fuel consumption from the CHP generator. The fuel cost is estimated with a 20-year operating period and at a total cost of around $11.5 million. The present value of the variable O&M is estimated at approximately $3.35 million. In addition, the analysis of variable costs considers the environmental damages associated with pollutant emissions from the Microgrid. None of the system's generators would have emissions allowance requirements, based on the information from project team. In this case, the damages attributable to emissions from the Microgrid were estimated at approximately $579,000 annually. The majority of these damages are attributable to the emission of CO_2. Over a 20-year operating period, the present value of emissions damages is estimated at approximately $8.88 million.

A Microgrid has benefits related to the reduction of electricity demand from utility, fuel saving from the new CHP system with approximately at $10.7 million, $4.31 million respectively. The reduction in demand for electricity from utility and for heating fuel would also avoid emissions, which yield emissions allowance cost savings with a present value of approximately $5,900 and avoided emissions damages with a present value of approximately $12.4 million. Moreover, the present value of generating capacity benefits is approximately $5.16 million, and the project's potential distribution capacity benefits is estimated at $828,000.

In addition to the savings noted above, Reliability benefits is reflected by the feature of a Microgrid, which can transit from grid-tied mode to island mode to prevent outage. Reliability benefits is estimated a present value of $9.98 million. With assumes that establishment of a Microgrid would reduce the rate of failure to near zero, this estimate is developed using the U.S. Department of Energy's Interruption Cost Estimate (ICE) Calculator, and is based on the following indicators of the likelihood and average duration of outages in the service area: System Average Interruption Frequency Index (SAIFI) – 0.96 events per year; Customer Average Interruption Duration Index (CAIDI) – 116.4 minutes (Nexant, n.d.).

Furthermore, the power quality benefits of a Microgrid may include reductions in the frequency of momentary outages (More than five minutes). The analysis of power quality benefits relies on the project team's best estimate of the number of power quality events that development of the microgrid would avoid each year. With seven of such events annually, the Syracuse team estimates that the facilities served by the Microgrid would avoid an of approximately $42.2 million over a 20-year operating period. Finally, the analysis shows the benefit over cost ratio is 2.6, which means the project financial savings are more than twice of the project cost over the 20-year time frame. The payback for this project is less than 10 years, which shows the commercial feasibility of a Microgrid

Overall, it is difficult to have an overview show whether a Microgrid project will make profits without a LCCA, because a Microgrid has many things involved. Though a Microgrid is costly to install and operate, a clear financial analysis will help a business owner to invest in Microgrids. Because each site is different, the costs analysis is worth doing before each Microgrid application. It is expected that the cost will continue to decrease with the advance of technology.

Chapter 5 - The Challenges of Microgrids

Though the Microgrid is a great concept, it faces challenges. Those include the limitation of technology, lack of standards and incentives, high initial cost, emission and recycling issues. Each of these limitations will be discussed below.

Limitation of Technology

It is challenging to maintain proper Microgrid system voltage and frequency. There are technical difficulties related to the control of a large number of distributed energy resources within the Microgrid. Currently, the focus is on the development of fast sensors and complex controls from a central point. However, the development could still provide a potential for failures. The fundamental problem with a complex control system is that failure of a control component or a software error will bring down the entire system.

A safety issue relates to Microgrid is that unintentional Microgrid islanding can put utility workers in danger, because they might not be aware that a Microgrid circuit still has power. Also, existing grid protocols dictate that all distributed power generation must shut down during power outages. Microgrid islanding may automatically reconnect to the grid if there is a failure of PCC. When the failures happen, utilities are not pleased, which is why utilities have been reluctant to endorse Microgrids.

Lack of Standards

When it comes to the Microgrid application, the reality is that Microgrids lack established standards. However, there have been some positive steps made by the Institute of Electrical and Electronics Engineers (IEEE). The 2011 adoption of the IEEE Standard P1547.4, “Guide for

Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems." The standard provides best-practice guidelines for implementing different ways a Microgrid can island and reconnect, all while seamlessly providing power to users. Standards and protocols like the IEEE 1547 and IEEE 2003 provide overarching constructs for the Microgrid design process. Microgrids must meet certain specifications before they can interconnect with the local utility's distribution grid (Siemens, Deep Dive on Microgrid Technologies, 2015).

Lack of Incentives

So far, there are not many incentives available to encourage owners to make the quick transition to Microgrids. One good news is that Public Act 13 - 239, which is under Substitute Senate Bill No. 23 in the state of Connecticut. Connecticut created a Microgrid Program to help support local distributed energy generation for critical facilities. This act required the Department of Energy and Environmental Protection (DEEP) to establish a pilot of the Microgrid Program (DEEP, n.d.).

Also, individual applications, such as renewable energy, have been receiving incentives from both the federal and state governments. Based on the type of resources and the location of the project, it is beneficial to look through Database of State Incentives for Renewables & Efficiency (DSIRE) to find some possible incentives for the renewable generator component of the Microgrid. The DSIRE is the most comprehensive source of information on incentives and policies that support renewable energy and energy efficiency in the United States. Established in 1995, DSIRE is operated by the North Carolina Clean Energy Technology Center at North

Carolina State University and is funded by the U.S. Department of Energy (North Carolina Clean Energy Technology, n.d.).

Initial Cost

The key factor for the adoption of Microgrids may still come down to cost. From case studies, most of the cost will appear at the beginning of the project, and they are not insignificant. The initial cost will vary based on the size of the Microgrid in terms of the loads that the Microgrid is covering. Also, since the Microgrid is a relatively new idea, people might lack knowledge of it. When it comes to the installation side, the construction cost also has the potential to go higher due to unfamiliarity (Blasi, 2013).

It is most likely that a life cycle cost analysis will be applied to a Microgrid before installation. Depending on the owner's requirements, the return on investment will have a clear forecast. Furthermore, with the decreasing cost for the main Microgrid elements such as renewable energy sources, energy storage, Microgrid costs will continue to decline. In the future, compared to traditional power sources, the economics for Microgrids for specific applications may become cost-competitive.

Emission

Though Microgrid is efficient compared to power plant. There are multiple source of emission relating to Microgrids like generator sets and microtubines. For axample, SRJ's two large 1.2-MW diesel generators can emit significant amounts of toxic air contaminants, pollutants, and greenhouse gasses. People on site could be exposed to pollutants during power outages. SRJ has had to accept these environmental risks because of its critical need for backup power, which until now could be supplied only by polluting diesel generators. Since it is the backup for the Microgrid, it will have less chance to contribute (Alegria, Eduardo, Anthony Ma, Osama Idrees, 2014.). As for other gas- or fuel-based resources such as natural gas, they will have the same kind of issues. One solution is that Microgrid generation sources can move toward more renewable energy, such as hydrogen. Also, there are cost involved for the emission.

Recycling

All components of a Microgrid will have to be replaced at some point. For example, photovoltaic panels are designed for 25 years of use, and the Federal Resource Conservation and Recovery Act (RCRA) governs the disposal of solar panels (Solar Energy Industries Association, n.d.). Batteries are meant to be recycled. Battery acid is typically sulfuric acid that has been diluted with water to attain a 37 percent concentration level. The acid can be extremely dangerous to humans because of its corrosive nature. If acid encounters soil, the soil will be contaminated for a period of time, which is dependent on the concentration of the acid (Battery world, n.d.). Though the chemicals inside the batteries are very dangerous, if properly handled, there will be minimal potential for harm to humans and the environment. There are some costs involved in recycling.

Summary

Many factors affect a Microgrid. What we need to do is evaluate the situation to see if Microgrid is beneficial to apply. It is necessary to take all challenges into consideration before applying the Microgrid. Installing a Microgrid is a balance between reliability of the system, challenges, investment and return.

Chapter 6 - Conclusion

The history of electricity was introduced in Chapter 2. Those who contributed to the evolution of electricity include Benjamin Franklin, Alessandria Volta, Michael Faraday, Thomas Edison and Nikola Tesla. The widespread implementation of electricity includes a competition between Tesla and Westinghouse vs. Edison and J.P. Morgan in the War of AC and DC. The competition ended up showing AC is a safe source to the masses like DC. AC has become the standard for electric distribution since then. Also, the current electrical system was introduced. Electricity is generated at a power plant, transmitted on high-voltage lines and distributed to homes and businesses by local distribution lines. DC distribution systems are very rare today, but many applications for DC power still exist like most electronic devices. Microgrids usually involve both AC and DC power.

In Chapter 3, Microgrids were introduced. The current market of Microgrids show the popularity and growth of Microgrids. The illustration of the structure of the Microgrid includes the generation, storage, system load, point of common coupling and controller. To further understand the Microgrid concept, some comparisons were shown to illustrate the difference between Microgrids and smart grids, between Microgrids and virtual power plants and between Microgrids and Net Zero. The reasons of considering Microgrids include the reliability, economics and air quality.

A Microgrid is reliable because it allows a facility operate autonomously from the grid while serving as a reliable backup power supply. Some examples were shown to illustrate that large facilities with high power demand can have power outages even with generators sets as backup. The application of a Microgrid prevents power outages and keep facilities continuously operate, provide data service, and even save lives. Many companies and orgnization like

Siemens, ABB, SEL and CERTS are dedicated to the development of Microgrid technology. The SRJ Microgrid project is a demonstration by the CERTS to show the reliability of a Microgrid. Before the installation of the Microgrid, the SRJ experienced a total of 458 minutes of power interruptions between the years 2002 to 2006. Since the SRJ Microgrid has been installed and commissioned, there have been no outages due to grid instability.

A Microgrid is economical because it can save money by storing low-price, off-peak-hour electricity and using it during peak. It also can generate revenue by selling the excess power to the utility. The benefits also include preventing blackouts for a facility. The SRJ Microgrid has a total initial cost at $12,000,000 with an estimated annual demand and energy cost savings of $ 110,000. The Microgrid will have a payback period of 109 years. Although the Microgrid project has a prolonged payback period, the Santa Rita Jail site is a high security location, which means reliability takes precedence over energy cost savings. For the NY Prize Community Microgrid feasibility studies, it serves as an example of a life cycle cost analysis. The NY Prize Community Microgrid proves that a Microgrid is capable of paying back its cost in a short period of time. The total cost is estimated at $32,500,000 over a 20-year period. With annual cost savings of $7,266,521, the payback period is less than 10 years. Both projects show the feasibility of Microgrids in terms of economics and benefits.

A Microgrid intend to improve air quality. For the NY Prize Community Microgrid study, the damages attributed to emissions from the Microgrid were estimated at approximately $579,000 annually, whereas the Microgrid could avoid emissions damages with a present value of approximately $12.4 million. Therefore, Microgrids can improve air quality by producing fewer emissions than power plants. Also, Microgrids use more renewable resources like wind and solar to provide power for facilities, which is an environmentally friendly way to generate power compared to traditional power plants. Therefore, Microgrid applications are intended to improve the air quality of the environment.

Finally, the challenges that Microgrids face was mentioned. The challenges include the technology limitation, lack of standards and incentives, high initial cost, emission and recycling issues. Technology is constantly improving and reduces the failures of Microgrids. In regards to the lack of standards, a positive step has been made by IEEE is Standard P1547.4. Also, DEEP established a pilot of the Microgrid Program to encourage the growth of Microgrids. DSIRE is also providing a comprehensive source of information on incentives and policies that support DER in the Microgrid. In addition, Microgrids may still come down in cost. It is possible to pay back the cost with the expected benefits. For environmental impact, the emission and recycling have to be considered in order to have a sustainable design for Microgrid system. By using more renewables, the on-site emission could be reduced. In addition, the benefits of Microgrid may overcome the emission and recycling cost.

Althought there are many challenges, there are quite a few reasons to consider a Microgrid. The goal is to balance of the reliability, challenges and cost of a Microgrid. No doubt the existing power grid will still provide the majority of power to society. However, it is encouraging to consider the larger role that Microgrids will play in providing reliable, economical and environmentally friendly energy to the market. The research has shown the feasibility of Microgrids especially for large facilities. However, the research has not shown enough evidence for the feasibility of Microgrids for individual business. With advances in development, it is possible to apply Microgrids to small facilities.

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Appendix A - Roadmap for Microgrid Development

Reproduced from (Schwaegerl, 2009)