ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

INGENIERO ELECTROMECÁNICO

MICROGRIDS

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Madrid

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MICROGRIDS

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RESUMEN DEL PROYECTO

1. INTRODUCCIÓN

En los últimos años Estados Unidos ha experimentado un incremento en su población y una gran expansión económica que ha dado lugar a líneas, que forman parte de la red de distribución eléctrica, de las más largas del mundo. Encuentra el problema de las caídas de tensión provocadas tanto por esas largas distancias que recorren las líneas eléctricas como los frecuentes desastres naturales. Años atrás, la red eléctrica del país se vio congestionada durante horas punta y a la vez se ha visto gravemente perjudicada por frecuentes apagones que dieron lugar a repercusiones sociales y económicos. Como resultado, las fuentes de energía distribuida entran a jugar un importante papel ya que, no solo ayudan a aliviar la congestión en las líneas produciendo energía, también hacen que la red sea menos vulnerable cuando se produce una falta.

Por otro lado, estas fuentes de energía distribuida crea tantos problemas como los que resuelven, ya que los operadores desconocen cuantas unidades de generación hay activas y cuanta potencia generan, desconociendo entonces cuánta potencia deben suministrar. Se genera pues la necesidad de controlar estas fuentes de energía distribuida. Los sistemas controlados que dan respuesta a esta necesidad son las microredes.

2. QUÉ ES UNA MICRORED?

El Departamento de Energía de Estados Unidos define a una microred como una red de energía local que integra estas fuentes de energía además de otras cargas eléctricas que pueden operar tanto conectadas a la red en paralelo u operar en modo independiente a ella y proporcionando así, mayor fiabilidad y resistencia ante perturbaciones. Diseñadas para ser implementadas en aquellos lugares donde el abastecimiento de energía es tedioso, como aquellos lugares remotos y para proteger aquellas zonas que manejan altas cargas eléctricas además de suponer un desarrollo económico importante.

Las microredes pueden entenderse como subsistemas que son capaces de autoabastecerse, pero también es importante mencionar, que no se pueden ser vistos como un sustituto de la red eléctrica. Normalmente, las microredes operan conectadas a la red a baja tensión, manteniendo abastecimiento constante de sus cargas. Cabe mencionar, cuando alguna falta tiene lugar, la microred comienza a operar de modo independiente y manteniendo el abastecimiento constante. Además, ofrece el control necesario sobre las fuentes de energía distribuida, informando a los proveedores cuanta energía estos generan y por tanto ofreciendo una noción de cuantos MW deben ser suministrados. Estas fuentes de energía distribuida incluyen: generadores (como paneles solares, turbinas de viento o CHP entre otros), unidades de almacenaje de energía (como baterías, supercondensadores o flywheels) además de las cargas que son las encargadas de consumir la energía.

3. VENTAJAS Y DESVENTAJAS

Las microredes ofrecen un gran número de beneficios, pero desde que son sistemas que aún siguen en desarrollo, no existen muchas políticas reguladoras por lo que genera también un importante número de desventajas.

a. Ventajas

La implantación de las microredes genera importantes ahorros económicos para sus usuarios, ya que al producir energía gracias a los generadores, no se precisa tanta energía importada de la red principal. También supone ahorros para la red, ya que no precisa generar, transmitir y distribuir esta energía. Durante una falta de suministro, la microred operará de manera aislada, de este modo operará de una manera más eficiente y resistente, produciendo la energía necesaria y reduciendo las caídas de tensión y frecuencia que se producen cuando ocurre un apagón o caída de tensión. Finalmente, además también presenta beneficios medioambientales ya que confía en fuentes de energía renovable para producir la energía como son la solar y el viento, reduciendo así la contaminación medioambiental.

b. Desventajas

Las microredes solo son rentables cuando están ubicadas en aquellos lugares donde existen fuertes motivaciones para invertir en ellas, como por ejemplo: aquellas áreas que precisan abastecimiento constante de energía como hospitales o bases militares; o aquellas áreas donde los beneficios favorecen a un gran numero de usuarios. Por otro lado, desde que no existen políticas reguladoras y la relación que mantienen la red eléctrica y las microredes no está definida, existen conflictos para establecer criterios de operación, de financiación o de mercado. Aparte, existen unas normas impuestas por la red eléctrica, como por ejemplo: en algunos estados está prohibido que las microredes tengan sus cables de alimentación sobre la calle pública para abastecer a sus usuarios. Con ello se requiere un aumento de costes en la infraestructura para enterrar la micro-red eléctrica.

4. POSIBLE CARACTERIZACIÓN

Este trabajo ofrece una clasificación basada en la aplicación de las microredes, y con ejemplos reales de las mismas ofrecer una clasificación que exprese características comunes y no comunes entre las categorías. Las categorías se describen a continuación:

Microredes en Campus universitarios presentan un perfil de potencia diaria contante y necesitan abastecimiento constante de la misma sobretodo en aquellos edificios con laboratorios. La implementación de microredes implican potencias que varían desde los 4 los 40MW. Los generadores utilizados para producir esta potencia suelen ser paneles solares, turbinas y CHP systems. Para el almacenaje de la misma, utilizan bancos de almacenaje de energía. Con la implantación de microredes podrán reducir emisiones contaminantes además de otros beneficios como la reducción de las facturas eléctricas ya que implementan medidas rentables y eficientes. Uno de los problemas que presentan las microredes en los campus universitarios es que la propiedad de los mismos muchas veces no depende de una única organización…. Los ejemplos estudiados fueron UCSD, NYU e IIT.

Zonas residenciales presentan también una curva de potencia bastante uniforme con dos picos durante el día. Estas microredes presentarán potencias de una media de 15kW por hogar, y los generadores utilizados para producir esta energía serán paneles solares y CHP. Para el almacenaje de la misma, las microredes utilizan bancos de energía además de unidades de energía térmica de almacenaje. Los ejemplos estudiados para la clasificación fueron las urbanizaciones Mesa del Sol y Mannheim-Wallstadt.

Lugares remotos, estas áreas también presentan un curva de potencia diaria bastante uniforme con dos picos a lo largo del día. Las potencias que presentarán estas microredes variarán de 4 a 10MW y para generar esta energía confiará en generadores como paneles solares y generadores diesel. Además, para el almacenamiento de la misma cuenta con unidades de almacenaje y flywheels. La peculiaridad que presentan estas microredes sobre las demás, es que sólo presentan una única línea de transmisión. Los ejemplos estudiados para la clasificación fueron Borrego Springs, la isla de Kythnos y Hartley Bay.

"Critical loads" en este grupo se incluyen los hospitales, bases militares y otras áreas que precisan abastecimiento constante y altas potencias. La curva de potencia consumida que presentan todas es bastante similar. Para producir la energía utilizan generadores como paneles solares, pilas de combustible y generadores diesel. Para el almacenamiento de la misma, utilizan baterías y supercondensadores. Los ejemplos estudiados son únicamente bases militares, ya que aún no existen ejemplos de microredes que estén operativas para hospitales, aunque se prevé que en un futuro cercano sean implantadas. Estos ejemplos son: Santa Rita Jail y Department of Defense grid-tied microgrid, Fort Bliss, Texas.

Edificios comerciales son el último grupo que estudiaremos. Estos presentan una curva de potencia diaria con un alto valor durante las horas que los comercios se encuentran en funcionamiento y un valor muy bajo cuando los mismos están fuera de servicio.

Actualmente, este tipo de microredes se encuentran en el mismo lugar que las microredes residenciales aunque en un futuro estarán situados por separado implementando medidas mucho más eficientes.

Las potencias de estas microredes variaran desde 4 a 40MW. Además, los generadores para producir energía eléctrica serán paneles solares, pilas de combustible y CHP. Para el almacenamiento de la misma, confiarán en bancos de energía y unidades de energía térmica de almacenaje. Los ejemplos estudiados fueron: Borrego Springs and Mesa del Sol que son también microredes residenciales.

5. RESULTADOS

Los datos recogidos de los ejemplos de microredes ayudaron a desarrollar una serie de conclusiones donde quedan reflejadas las características entre las distintas categorías.

Características comunes: los resultados de las características comunes quedan reflejados en distintas tablas que incluyen como generan las microredes la energía, como la almacenan o quien tiene la propiedad de la misma. Los resultados reflejan que todas suelen utilizar paneles solares para producir energía y baterías para almacenarla. La propiedad de la microred, es algo más complejo aunque todas coinciden que un usuario privado puede poseerla.

Características no comunes: la diferencia más clara entre ellas es la cantidad de energía que producen y la cantidad que consumen, esta potencia variará en función del las necesidades proyectadas por arquitectos e ingenieros. En este estudio Las microredes que más potencia consumen y generan son los campus universitarios, las microredes en edificios comerciales y las microredes de alta potencia. Aunque las microredes residenciales y en lugares remotos, también pueden ser de mayor potencia en función del tamaño de la microredes, según las necesidades. Además, dependiendo de los generadores para producir la potencia serán más o menos ecológicos. Esta no es una diferencia entre categorías, sino dentro de la misma categoría una microred puede ser más ecológica que otra. Las microredes serán más o menos ecológicas en función del número y potencia de las energías renovables proyectadas.

CONCLUSIÓN

Las microredes pueden clasificarse de muchas maneras, según infinitas áreas y campos para su estudio. Es importante mencionar, que este trabajo, refleja una posible clasificación de las microredes, pero no es la única posible. Sólo pretende conocer algo más y mejor el funcionamiento de las redes de transporte y redes de distribución local de energía eléctrica. La aparición masiva de redes de Generación Distribuida en EEUU también conduce a tener en cuenta el “balance” global de las redes eléctricas, especialmente en cuestiones de evitar las caídas de tensión o la sobre tensión. Las Microredes podrían ser una de las soluciones técnicas más pertinentes para la evolución de los modos de generación, hoy por hoy muy centralizados en (hidroeléctrica, térmicas, nucleares...), pero que en un futuro cercano podrían llegar a ser mucho más descentralizados (energía eólica, energía solar, fotovoltaica, etc.).

EXECUTIVE SUMMARY OF THE PROJECT

1. INTRODUCTION

The U.S. has experienced an increase in demand due to high population growth and economic expansion. These factors resulted in longer distribution lines, which would result in services drops and damages due to natural weather disasters. In the last few years, the U.S. grid has been stressed during peak hours and badly damaged, resulting in many financial and social impacts. As a result of these impacts, distributed energy resources play a key role providing energy supply and helping to relieve the congestion in the distribution grid apart from making the grid less vulnerable during a large scale event. Otherwise, distributed energy resources may create as many problems as they solve, since the utility and operators do not know how many of them are installed and how many power they supply, creating the need of better control over these distributed energy resources. The controlled system, that provides a solution to the problem stated is a microgrid.

2. WHAT IS A MICROGRID?

Microgrids are defined by the U.S. Department of energy as “a local energy network, that offers integration of distributed energy resources (DER) with local elastic loads, which can operate in parallel with the grid or in an intentional island mode to provide a customized level of high reliability and resilience to grid disturbances. This advanced, integrated distribution system addresses the need for application in locations with electric supply and/or delivery constraints, in remote sites, and for protection of critical loads and economically sensitive development”.

Microgrids can be seen as subsystems that are capable of self-balancing; however, they are not a substitute for the main grid. Virtually, microgrids work connected to the grid connected via low-voltage, maintaining continuous supply to their loads. Furthermore, when a fault occurs, the circuit breaker is opened allowing the subsystem work in islanded mode providing constant supply to their loads. Thus, microgrids provide control over distributed energy resources, informing to the operators how much power they generate and how much they are going to purchase. Distributed energy systems that a microgrid encompass include: distributed generators (such as solar PV panels, wind turbines, CHP, etc. that provide energy supply), energy storage systems (such as flywheels, batteries and supercapacitors that maintain balance among demand and generation) and loads (that consume energy).

3. ADVANTAGES AND DISADVANTAGES

Microgrids offer a tremendous number of benefits, but since they are relatively new they still present an important number of disadvantages.

a. Advantages

Microgrids mean cost savings since there is no need to purchase that amount of energy from the main grid, and will result in savings for the grid by reducing generation, transmission and distribution. In case of a fault, the microgrid will operate islanded from the grid, providing the needed power increasing the reliability of the system with reductions in the frequency and voltage drops, increasing power quality. Lastly, microgrids offer environmental benefits, since microgrids rely on renewable sources such solar or wind to produce energy, reducing pollutant emissions.

b. Disadvantages

Microgrids are only cost-effective in places where there are strong motivations that justify the inversion, or when benefits accrue to a large number of users. Otherwise, since there are not many policies for microgrids, they have to be catalogued under the Public Utility Regulatory Policies and categorized as Qualifying Facilities. There are some economic issues. Since microgrids are categorized as Qualifying Facilities, they have the right to sell power back to the local utility but their relationship is undefined and there are no policies to regulate it, among other issues, such as fuel supply management, market penetration or financing costs. Thus, there are some utility franchise rules that must be followed by microgrids; for example, in some states it is forbidden using wires across the streets to serve costumers.

4. POSSIBLE CHARACTERIZATION

This work suggests a classification based on microgrids application. Results are based on real microgrids in order to bring out some common characteristics among microgrids and also the main difference among them. The categorization will be as follows: Campus Microgrids, Residential Microgrids, Commercial Microgrids, Isolated

Microgrids and “Critical Loads” Microgrids. All of these categories are very suitable for the implementation of microgrids, since all of them need constant supply so the inversion will be cost-effective.

Universities Campuspresent a load profile constant, but need constant supply, especially in those buildings with laboratories. So the implementation of microgrids will vary from 4 to 40 MW relying on distributed generators such as CHP systems, PV solar panels and gas/steam turbines to generate electricity. Hence, they rely on energy storage banks to store their energy. Campus microgrids will reduce local emissions and pollutants among other benefits including reducing the electricity bill, since microgrids implement cost-effective and energy-efficiency measures. The only issue that campus microgrids experience, are ownership issues, since universities can be owned by many different organizations. The examples of campus microgrids used in the report are UCSD, NYU and IIT.

Residential houses present a fairly uniform load profile with two peak hours during the day. The implementation of microgrids will be 15kW corresponding to a standard house relying on distributed generators such as PV panels, natural gas and CHP systems to generate their electricity. Hence, they rely on energy storage banks and hot and cold thermal storage to store their energy. The examples of residential microgrids used in the report are Mesa del Sol and Mannheim-Wallstadt.

Isolated areas also present a load profile with two peak hours during the day. The implementation of microgrids will vary from 4 to 10MW to generate its electricity relying on distributed generators such as solar PV panels and diesel generators. Hence, they rely on energy storage units and flywheels to storage their energy. This kind of microgrid presents a peculiarity among the rest of microgrids, they use just a single transmission line. The examples used in the report are Borrego Springs, The Kythnos Island Microgrid and Hartley Bay.

Critical loads may include hospitals, army bases and other areas apart from constant supply and need a large amount of power. The value of the load profile will vary on the application, but the profile is pretty similar among them since it is uniform during the day. To generate its energy they rely on distributed generators such as fuel cells, solar PV panels and diesel generators to generate their electricity and batteries and capacitors for storage. The examples used in the report are just army bases since there are no hospital microgrids developed, but it is important to mention that many hospitals are interested in investing in microgrids. The examples are Santa Rita Jail and Department of Defense grid-tied microgrid, Fort Bliss, Texas.

Commercial buildings are the last group of the categorization. The load profile that they present during the day is high and constant during the open hours of the building and pretty low when they are close. Moreover, this kind of microgrid is located within residential microgrids however in the near future they will be built separately from them and efficiency measures will be also implemented. To generate its electricity, commercial microgrids rely on distributed generators such as natural gas, solar PV panels, fuel cells and CHP unit systems producing an average power from 4 to 40MW. Hence, they rely on energy storage banks and hot and cold thermal storage to store their energy. The examples used in the report are Borrego Springs and Mesa del Sol that are also residential microgrids.

5. RESULTS

With all the information taken from the examples, the purpose of the report is to find similarities and dissimilarities among categories.

Similarities: the results are shown in the report, using different tables that include the way microgrids produce their electricity, how their storage their energy and finally, who owns the microgrid.

Dissimilarities: the clearest difference is the amount of power they consume and they generate, depending on the project they will generate more or less. The ones that consume and generate more power are campus, commercial and critical load microgrids; otherwise, depending on where they are located isolated and residential microgrids and also have high power rates. The projects vary in power, mainly because of their size.

Moreover, depending on the distributed generators that microgrids have implemented, they could be more or less environmentally friendly. This is not only a difference among categories; it is also a difference among microgrids in the same category. Microgrids, reduce their pollutant emissions depending on how many renewable resources they have.

6. CONCLUSION

Microgrids can be classified in many different ways, but since there are an infinite number of areas to classify them, sometimes the classification can be very difficult. Even in the same category, microgrids can be incredibly different, not only in how they produce or store their energy but in infrastructure, among other things. It is important to mention that this report depicts a possible categorization among microgrids; otherwise, this categorization may vary in the near future because of developments or future policies that will help to better classify all microgrids.

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1. INTRODUCTION

For several years, we have been concerned about some issues on the electric grid such as reliability and efficiency, while considering improvements such as smart grids. Nowadays, microgrids are being considered as smart systems that can solve many of these problems. This paper offers a small introduction to the concept of microgrids and further classification in terms of application of microgrids, explaining some microgrid examples that are now working.

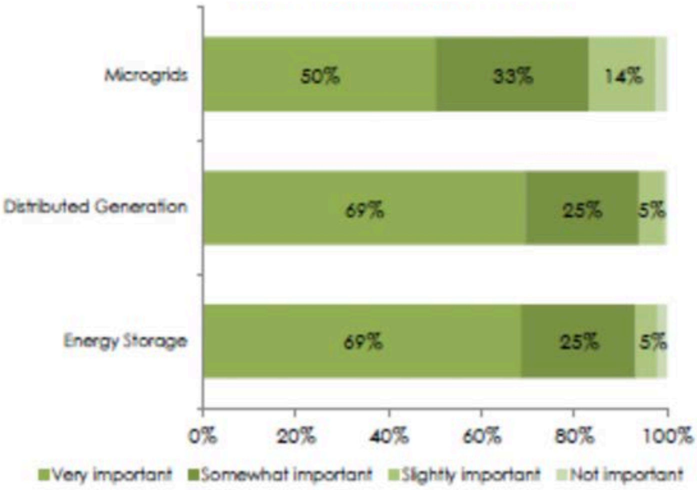


Figure 1. Survey Results

According to a survey, summarized in Figure 1, made by Zpryme Research and Consulting and sponsored by the International Society of Electrical and Electronics Engineers (IEEE), microgrids are going to be more and more important every day and will increase smart grid deployment. Furthermore, microgrids are going to be essential in order to meet local electricity demands, to ensure local control of electric supply and to enhance grid reliability. Hence, they will be an important area of study in terms of evaluating design and deployment of the Smart Grid, will be used to produce its electricity distributed energy resources, and will bring reliability improvements into the main grid.

1.1 State of Art

Over the past few years, we have experimented with changes in production, delivery and consumption of electricity not only due to the concern about climate change but also for the benefits of using renewable energy sources instead of the conventional energy sources (such as oil, natural gas, and coal). New ways to produce electricity are enabled by advances in technology, including software, solar panel production, battery storage units and systems capable of autonomously responding to signals. These technologies, when they are organized, could mean advantages for consumers, the environment and the economy, because they can operate without the oversight of the local utility.

At the beginning of the century, most customers received their power from plants under 10MW in capacity; these kinds of plants were not very reliable because the grid was supplied from a single plant (in some occasions from two plants).

The enormous capital that we have to invest in order to build the infrastructure (generation, transmission and substation infrastructure) has increased. The increase in demand owing to high population growth and economic expansion would imply long distribution lines and service drops for the more remote customers. Losses and cost are increased because of long distribution lines, increasing the probability of damage in lines due to natural weather disasters. The US grid has been badly damaged, causing grave social and financial impact. Besides, today's transmission system is heavily stressed during peak hours with extensive grid congestion.

To relieve the congestion in the distribution grid and maximize its load-carrying capability, distributed energy resources play an important role connected at sub-transmission and distribution voltage levels, since they can provide many of the needed energy services, and they are located closer to loads, making them less vulnerable to grid component failures during a large scale event.

Distributed energy resources (DERs) can be classified as follows:

- Distributed generation (DG): such as PV, wind turbines, micro-turbines and fuel cells.
- Distributed storage (DS): such as batteries, flywheels and energy capacitors.
- Distributed loads (DRR)

Furthermore, the use of individual distributed generators can cause as many problems as it may solve. The problem is how to manage so many DG sources. There is a need to inform the distribution company as to how many MW it may buy. Companies do not know how many DG are installed and how many MW they produce, creating the necessity of more control over these DG.

As a result of combining DER and interconnected loads, we now define the concept of microgrids.

1.2 What is a Microgrid?

A microgrid is defined as a cluster of interconnected loads and microsources, called distributed energy resources (DER), that operates as a single controllable system within defined electrical boundaries and is able to connect and disconnect from the grid.

The main structure of a microgrid consists of a group of radial and interconnected feeders, which could be part of a distribution system or could be part of a building's electrical system. On a smaller scale than a traditional grid, the microgrid is nevertheless able to operate as a grid, generating, distributing and regulating the supply of electricity to customers.

1.3 Microgrid Concept

A microgrid can be seen as a subsystem and hence can provide a solution to the concern stated above, which is how to manage so many DG sources. There is a need to inform the distribution company as to how many MW it may buy, and microgrids can provide the information needed by the operators, as well as providing better control over DER. The electrical loads and distributed energy resources of a microgrid are connected via low-voltage. Microgrids are an alternative reconfiguration of power systems acting as a single entity capable of self-balancing when necessary; nevertheless, they are not a substitute for the distribution infrastructure.

Microgrid's systems are connected and placed close to each other to reduce losses during energy transmission. In normal conditions, the microgrid operates connected to the grid, making full use of the advantages such as exporting and importing energy, and maintaining continuous supply to its loads. However, microgrids are designed to operate semiconnected to a macrogrid but islanded from it, and when a fault occurs the circuit breaker is opened allowing to the microgrid to operate in islanded mode, which is like a backup or emergency operation mode (making use of local generation).

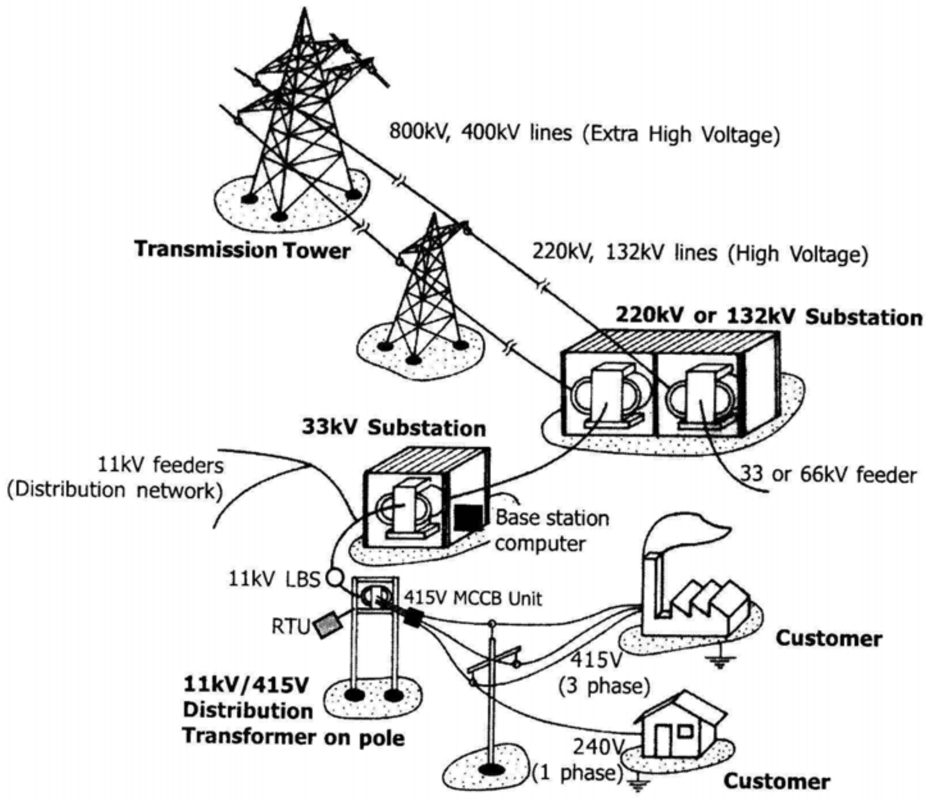


Figure 2. Electricity Transmission Diagram

1.4 Salient Features

Edison and other pioneers originally designed the microgrid as a reformulation of power systems. A microgrid is designed to be located near a building or buildings, like a hospital or recently built neighborhood, near an industrial area like a farm or industry with special requirements for quality of supply, and also can be implemented in underdeveloped countries without electrification (or very weak network).

The microgrid has two steady states of operation: the islanded mode and grid connected mode. Beside these states of operation exist two transient states corresponding to the transition-states. It is important to note that the microgrid must remain stable during all conditions.

The implementation of microgrids has resulted in many different projects that vary in a wide range of power from kW to MW depending on the project, but the microsources of special interest for microgrids are small units (<100kW) with power electronic interfaces into low-voltage electricity systems. A microgrid encompasses a wide variety of distributed generators (DG), distributed storages (DS) and variety of customer loads.

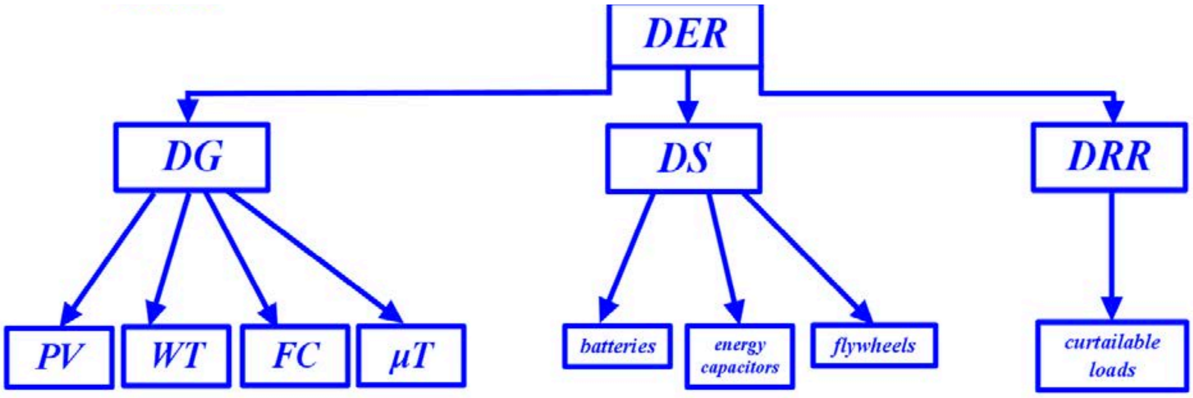


Figure 3. The different kind of Distributed Energy Resources

Distributed generators are the base components of microgrids, which provide the power to meet the consumer’s need. Distributed generators are units of renewable or non-renewable resources such as PV, micro-turbines, fuel cells, and wind turbines, which provide cleaner power generation, and internal combustions engines, diesel generators and CHP (combined heat and power) under 50MW, which are the conventional options. Furthermore, these sources are low voltage, low cost, and highly reliable with low emissions. To coordinate distributed generation, microgrids rely on integrated control systems. To manage the resources there is a single connection point which connects the distribution system with the resources.

To meet customers’ and utilities’ needs, microgrids use three important components in their system architecture: local microsource controller, systems optimizer and distributed protection. The most important component is the microsource controller that uses local information to control the microsource during all events. A key element is that communications among microsources are unnecessary for basic operation. This means that, without requiring data from loads or other resources, each inverter must be able to respond effectively to system changes. Their basic inputs are steady state set points for output power and local bus voltage. Moreover, the control functions of the controller must regulate the power flowing on feeders, and the voltage at the interface of each feeder, and make the island process smooth.

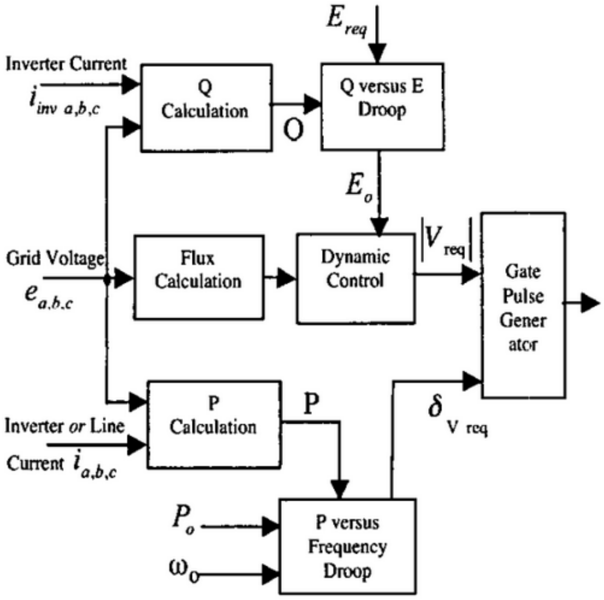


Figure 4. Microsources controller.

As we can see in the block diagram in Figure 4, the main components are the voltage versus reactive power droop and power versus frequency droop.

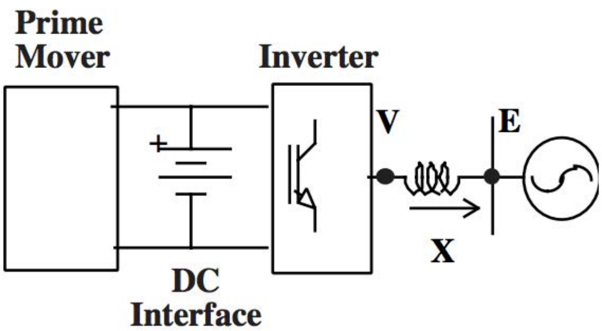
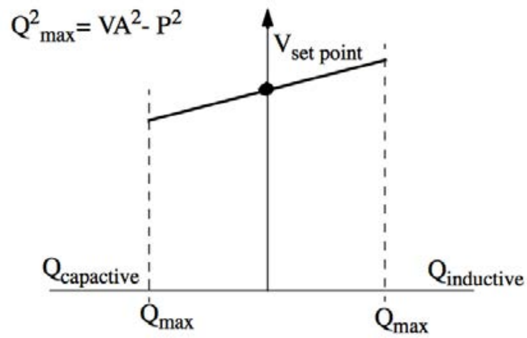


Figure 5. DC interface and Inerter

Since in the microgrid we can find a large number of DERs, the basic P-Q control is impossible. The reactive power is dependent on the magnitude of the converter's voltage while the real power is dependent on the power angle.

Voltage vs. Q droop: this is necessary, since the DERs experience voltage and/or reactive power oscillations, to ensure stability and that there are not high currents circulating among sources. To control the situation we need a voltage versus reactive current droop controller, because the local voltage set point decreases as the reactive power generated becomes more capacitive (and vice versa).



$$Q = \frac{3}{2}\frac{V}{X}(V - E\cos\delta_p)$$

$$\delta_p = \delta_V - \delta_E$$

Figure 6. V-Q Diagram

Power vs. Frequency Droop: Using control techniques, microgrids can island smoothly and are able to reconnect automatically to the grid.

The main function of *Energy Storage Devices* is to maintain the balance among the power and energy demand with generation. The most suitable energy storage technologies for microgrids are flywheels, rechargeable batteries and super capacitors. Also, electric vehicles are also seen as an alternative option in order to store power when demand and cost of electricity are low, which occurs at night.

Most of the emerging DER technologies, in order to control and operate distributed generators with distributed storage and loads, require control capabilities that integrate communication among all components. Specialized software and hardware are required by which a fault can be repaired quickly and the system islanded when a fault occurs. In order to convert the energy into grid-compatible ac power, an inverter interface is needed. This interfacing may either consist of inverter and converter, or just an inverter. Table 1 summarizes a distributed energy resources classification.

Primary Energy Source Type		Typical Interface	Power Flow Control
DG	CHP	Synchronous generator	AVR and Governor (+P,+/-Q)
	Internal combustion engine	Synchronous or induction generator	
	Small hydro	Synchronous or induction generator	
	Fixed speed wind turbine	Induction generator	Stall or pitch control of turbine (+P, -Q)
	Variable speed wind turbine	Power electronic converter (AC-DC-AC)	Turbine speed and DC link voltage controls (+P, +/-Q)
	Micro-turbine	Power electronic converter (AC-DC-AC)	
	Photovoltaic (PV)	Power electronic converter (DC-DC-AC)	Maximum power point tracking and DC link voltage controls (+P, +/-Q)
	Fuel Cell	Power electronic converter (DC-DC-AC)	
DS	Battery	Power electronic converter (DC-DC-AC)	State of charge & output voltage/frequency control (+/-P, +/-Q)
	Fly wheel	Power electronic converter (AC-DC-AC)	Speed control (+/-P, +/-Q)
	Super capacitor	Power electronic converter (DC-DC-AC)	State of charge(+/-P, +/-Q)

Table 1. Distributed Energy Resources Classification

Microgrids loads are those components that consume electricity such as air conditioners, water heaters, coolers, etc. These components use electricity during the day at different points depending on usage. The principle that emphasizes the importance of making choices is the third principle of capacity planning which explains the importance of matching demand to supply. In order to achieve this, it is very important to use these loads with some discretionary ability. Furthermore, microgrids could be divided in groups depending on the variety of customers they serve: residential, industrial and commercial. In general, commercial and industrial are defined as critical/sensitive loads, which require a high degree of power quality and reliability. This classification has to:

1. Stabilize voltage and frequency in island mode and meet net import and export power in grid-connected mode.
2. Improve power resilience and reliability of critical loads, generally known as commercial and industrial loads.
3. Optimize the DER ratings by reducing the peak load.

To connect all the essential parts, a physical network is required, which distributes the power among the DERs and the main grid being the base of the power system. To supply the loads, wires are required, which connect the DERs to customers and the main grid at low voltage from a low voltage distribution feeder. Finally, these feeders are connected to a central distribution substation via the point of common coupling, which is an interconnection switch connected at medium voltage. The last main components are the intelligent electronic devices, and the main function is to prevent injuries and damage from happening in the first place. In this group are included circuit breakers, digital protective relays, remotely operated switches, current and voltage sensors and condition monitoring units for switch transformers and gear, and when a fault occurs prevent personal and equipment. The microgrid has an Interconnection Point, which connects the microgrid with the electricity grid, also has protections, powers of short circuit for fault detection, switches, etc. There are two possibilities to connect the local generation with loads: the first is to use microgrid wires and the second is to use the utility distribution network.

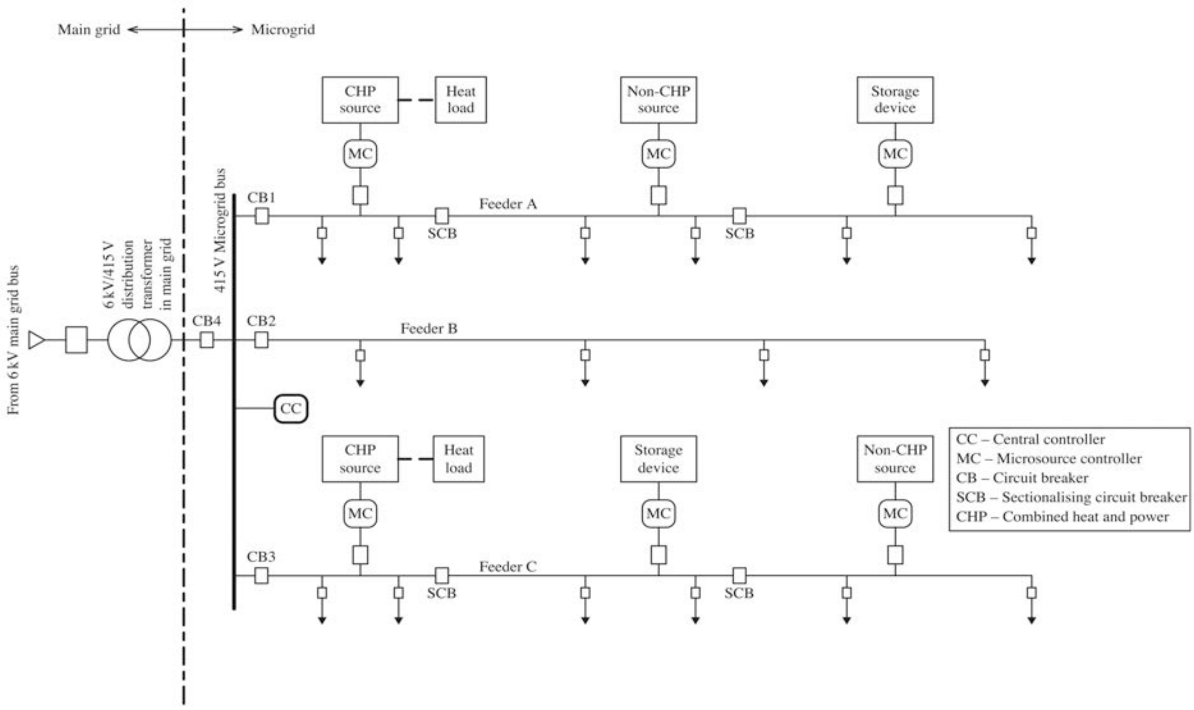


Figure 7. Microgrid Configuration

The Figure 7 illustrates two basic microgrid types. At the point of common connection or at the site of the load, the microgrid is measured.

1.5 Most common distributed generators and energy storage devices

This section briefly describes the most common DERs used in microgrids.

1.5.1 Distributed Generators

1.5.1.1 Solar Panels

Solar photovoltaics are electricity systems that use photovoltaic cells to capture the sun's energy. They capture the sun's electricity and generate cheap and green electricity even during a cloudy day, so they do not require direct sunlight. The sunlight is converted into electricity by using the cells.

1.5.1.1.1 Benefits

Following are some benefits when using solar panels to generate electricity.

- Since sunlight is free, the only cost is to install the solar panels, and using them will reduce the electricity bills.
- Some countries, such as the UK, pay for the electricity that solar panels generate, even if the user consumes that electricity.
- Through Feed-in Tariffs, owners can sell to the grid the electricity they do not need if their solar panels produce more electricity.
- Since using solar panels produces renewable energy, they reduce the carbon dioxide and other pollutant emissions. Using solar PV panels can reduce more than a tonne of emissions per year.

1.5.1.1.2 How do they work?

Solar panels are produced from a semiconductor material, typically silicon, and they are placed in layers. Across these layers an electric field is created when the light shines on the panel. There is also a second generation of solar cells called thin-film solar cells and they are made of amorphous silicon or cadmium or telluride. Since they are more flexible they can be building facades, grazing skylights or can be placed on rooftops. And finally, there is a third-generation of solar panels, which are made from a variety of materials such as solar inks, solar dyes and conductive plastics. This kind of PV panel is more expensive but more effective, especially for industry and utilities, but on the other hand, they are limited to the sunniest parts of the country.

The amount of energy that solar panels produce depends directly to the strength of the light. A group of cells together constitute a panel or a module and all together they can be placed on a roof or on the ground. PV panels can be found in many different shapes and sizes, in tiles and in slates.

The power that a solar panel generates is measured in kWp, which is the maximum energy generated in full direct sunlight during the summer.

1.5.1.1.3 Solar tiles and slates

These PV panels are designed to substitute the common roof tiles. But this kind of panel will cost double the equivalent panel system. Moreover, they are not cost-effective and they are only used for planning reasons or when they are not considered suitable for aesthetic.

1.5.1.1.4 Other installation costs

- The cost will rise if the system is capable of producing a lot of energy, but at the same time the more they produce, the more they can save.
- Small systems (up to 4kWp) are less cost-effective than the larger ones.
- PV tiles cost much more than a typical system, but PV panels per kWp cost more or less the same.
- Panels placed on top are cheaper than panels built into a roof.

1.5.1.1.5 Financial support and Savings

Through Feed-in Tariffs, owners can sell to the grid the electricity they do not need if their solar panels produce more electricity; therefore, for each kWh exported from PV panels, owners earn a tariff. In the UK there is a technology, which is a financing mechanism owned by the UK government's Green Deal, which consists mainly in helping people with energy-efficiency improvements that will reduce their energy bills.

1.5.1.1.6 Maintenance

Solar panels not only produce green energy and reduce pollutant emissions; they also need little maintenance beyond just keeping them clean. Commonly they are tilted 15º or more ensuring optimal performance and getting additional benefits of being cleaned by rainfall. If panels are placed on the ground, they are more likely to accumulate waste materials on the panels and they must be cleaned. Otherwise, each solar panel needs special maintenance depending on where they are placed or how tilted they are to ensure solar panels work as they should. In each solar panel must be included information with all the details (for example, how much power they might generate) or further details such as the main inverter fault signals and key trouble-shooting guidance.

Solar panels should have a lifetime of more than 25 years, but during this period the owner will have to replace some of them at a current cost of 1228$.

1.5.1.2 Wind Turbines

Another form of solar energy, which is a result of the unequal heating by the sun, some irregularities on the surface and the rotation of the earth, is the wind. Wind flow is used to generate electricity. The kinetic energy in the wind is converted into mechanical power or electricity by using wind turbines.

1.5.1.2.1 Benefits of wind turbines

Following are some benefits when using wind turbines to generate electricity:

- Since the wind is free, the only cost is to install the wind turbines, and using them will reduce the electricity bills.

- Some countries, such as the UK, pay for the electricity that wind turbines generate, even if the user consumes that electricity. Through Feed-in Tariffs, owners can sell to the grid the electricity they do not need if their wind turbines produce more electricity.
- Since solar panels produce renewable energy, they reduce the emission of carbon dioxide and other pollutants. Using solar PV panels can reduce more than a tonne of emissions per year.
- Even if the owner is not connected to the main grid, the excess electricity can be stored in batteries and use that electricity when there is no wind.

1.5.1.2.2 How does wind turbine work?

Wind turbines use the wind to produce electricity. When the wind blows, the wind turbines have the blades that are forced round, spinning a shaft; the shaft is connected to a generator and that is how it makes electricity. The amount of electricity produced depends directly on the force of the wind.

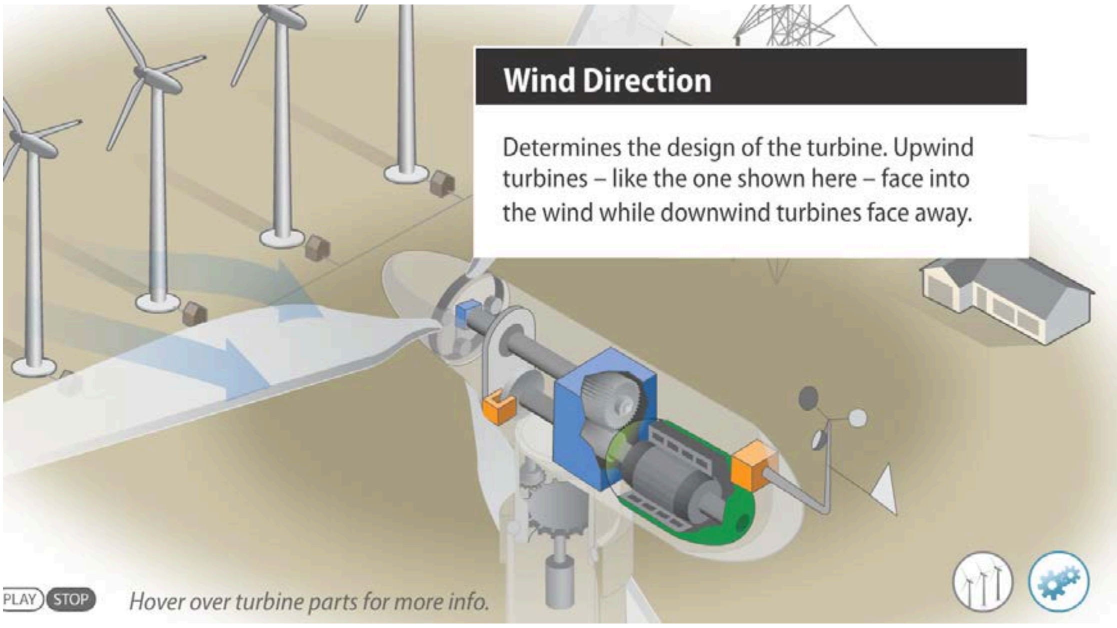


Figure 8. How a wind turbine works

Wind Turbines can be classified as horizontal-axis and vertical-axis.

Horizontal-axis wind turbines commonly have two or three blades and they work “upwind”, and the blades are facing into the wind.

Vertical-axis wind turbines, following Darrieus-style, have aerodynamic blades and rotate around a shaft with their aerodynamic blades flying through the wind.

Moreover, wind turbines can be built on land or offshore. Actually, the U.S. does not have offshore wind turbines but is very interested in making this technology available.

1.5.1.2.3 Different sizes

Wind turbines can be classified in different sizes; the most common are utility-scale turbines and single smart turbines, which include domestic-sized wind turbines.

The utility-scale turbines are from 100kW to wind turbines of mW. The larger they are, the more cost effective they will be and all grouped together constitute wind farms providing bulk power to the main grid.

Single small turbines are below 100kW and their main purpose is for water pumping, telecommunications dishes or for homes. Sometimes they are connected to diesel generators, batteries and solar PV panels and they are called hybrid wind systems. This type is located commonly in remote areas where the connection to the main grid is very difficult. In this group of small turbines, domestic-sized wind turbines can be found also in this group. There are two types:

- Pole mounted: commonly from 5 to 6kW and they are placed erected and freestanding position.
- Building mounted: this type is smaller and commonly from 1 to 2kW and they are installed on the roof of a home.

1.5.1.2.4 Costs

The cost of a wind turbine will depend directly on its size and the mounting method. Building-mounted turbines are cheaper to install than pole-mounted turbines but on the other hand since they are smaller they are less efficient. The price of a vertical-axis turbine could vary from 4500$ for a roof-mounted turbine of 1kW to 45000$ for a pole-mounted turbine of 6kW.

1.5.1.2.5 Maintenance

Every few years, wind turbines must be checked and prices could vary from 150$ to 300$ per year, but the price will depend on the size of the turbine. The lifetime of a wind turbine is more than 20 years, but at some point of its lifetime, the inverter must be replaced and the price could vary from 1500$ to 3000$ for a large system. If the wind turbine is part of an off-grid system, the batteries must be all replaced every 6 to 10 years, and the price will vary depending on the design and scale of the system.

1.5.1.2.6 Savings and financial support

Through Feed-in Tariffs, owners can sell to the grid the electricity they do not need if their wind turbines produce more electricity; therefore, for each kWh exported from wind turbines, owners earn a tariff. In the UK there is a technology, which is a financing mechanism owned by the UK government's Green Deal, which consists mainly in helping people with energy-efficiency improvements that will reduce their energy bills.

For example, pole-mounted turbines produce much more electricity per kW than the building-mounted ones. If a turbine is well placed, it can produce 10000kWh, the equivalent of 5.2 tonnes of carbon dioxide a year.

1.5.1.3 Fuel Cells

To produce electricity cleanly and efficiently the fuel cell uses a chemical fuel such as hydrogen. If the fuel cell uses hydrogen the only products that they use are water, heat and electricity. Fuel cells are very important for their potential applications; for example, they can supply systems in a wide range of power such as a utility power station or a laptop.

1.5.1.3.1 Benefits

Following are some benefits of using fuel cells to generate electricity:

- They can be used in a wide range of applications, such as emergency backup power applications, transportation, material handling, stationary and portable applications.
- They present more advantages than common combustion-based technologies used in power plants or passenger vehicles.
- Fuel cells can operate at higher efficiencies, transforming the chemical energy into electricity at higher efficiency than, for example, combustion engines of up to 60%.
- Fuel cells produce lower emissions than combustion engines. The ones that consume less are the hydrogen fuel cells emitting only water; therefore there are no carbon dioxide emissions and other air pollutants.
- Since fuel cells have not many moving parts, they are quieter during operation.

1.5.1.3.2 How do fuel cells work?

Unlike batteries, fuel cells do not need recharging but they work like them. As long as fuel is supplied, fuel cells work and can produce electricity. Two electrodes compose fuel cells, the positive is the cathode and the negative is the anode. The anode is fed with fuel such as hydrogen, and the cathode is fed with cathode. In this kind of fuel cells there is a catalyst in the anode, which has the function of separating hydrogen moles into electrons and protons taking different paths in their way to the cathode.

Through an external circuit, the electrons go through creating a flow of electricity. When the protons get to the cathode they mix with oxygen and the electrons in order to produce water and heat.

1.5.1.3.3 Costs

One of the largest cost components of the fuel cells is the platinum. Since it is the largest cost, the U.S. Department of Energy is making much progress in order to reduce costs. For example, in automotive fuel cells cost is reduce by 50% since 2006 and by 30% since 2008 reflecting numerous advances including the development of durable membrane electrode assemblies with low platinum content. Fuel cells can be manufactured at high volumes and low volumes. They are also developing manufactured methods and materials that will reduce the cost of gas diffusion layers by 50% since 2008.

1.5.1.3.4 Maintenance

Fuel cells are designed to meet application expectations since one of their key performance factors is durability. The Department of Energy has established for stationary cells a lifetime of 40.000 hours and for transportation fuel cells a lifetime of 5.000 hours under real operating conditions. These conditions may include impurities in the fuel and air among factors such as humidity, freezing and thawing, starting and stopping that could result in stresses on both mechanical and chemical stability of their components and other materials. The Research and Development department is developing some strategies and materials such as ion-membrane electrolytes that can mitigate the degradation of mechanisms and enhance their efficiency.

1.5.1.3.5 Financial support

In some states, fuel cells can be very competitive even with grid electricity rates. Prices can be from 8 to 15 cents/kWh, which can be cost competitive in states where the price of electricity is very high for industrial or commercial applications, such California, Connecticut, Massachusetts, New Jersey, and Alaska among other states.

To make fuel cell projects viable it is necessary to apply incentives creatively since these projects carry a high cost. Furthermore, there are many federal and state incentives that will help to develop these projects. Otherwise, these incentives are in constant change as legislatures pass new programs, rules must be applied and there are some budget cuts that will make these incentives ineffective.

1.5.1.4 CHP

CHP is combined heat and power, but it is also known as cogeneration. From a single source of energy, electricity and useful thermal energy (such as heating or cooling) can be obtained. It is a type of distribution generation located close to the point of consumption. To generate electricity, CHP systems use a variety of fuels that during the power generation will allow heat be lost and be recovered in order to provide heating and cooling.

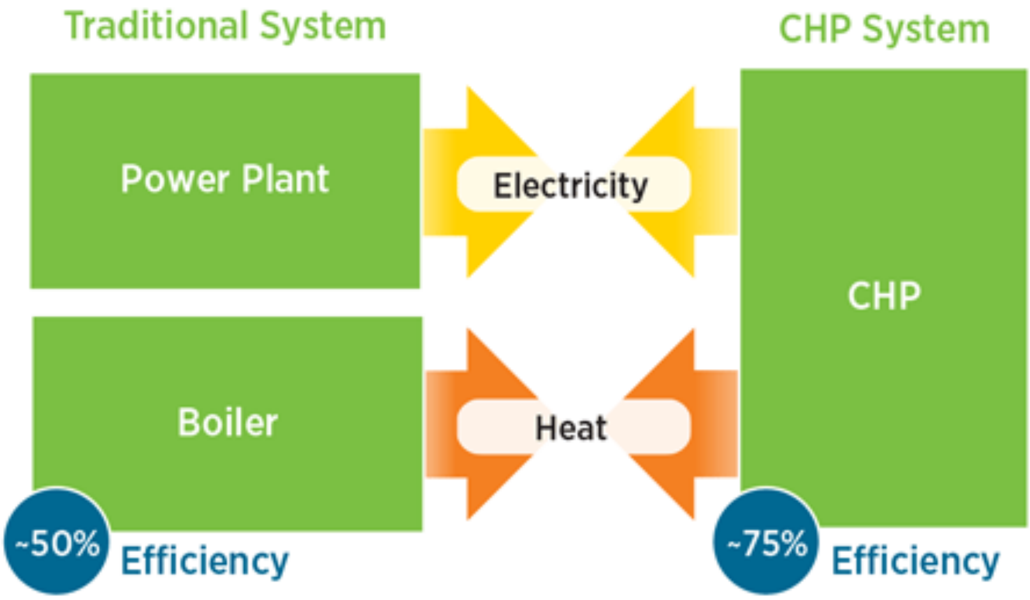


Figure 9. Traditional system vs. CHP system

1.5.1.4.1 Benefits

One of the most important benefits is that CHP can support national policy goals in many different ways such as:

- By reducing the U.S. energy requirements, CHP enhance their energy security.
- CHP reduce CO_2 emissions and other pollutant emissions in order to help save the environment.
- CHP will increase enterprise competitiveness by improving managing costs and increasing energy efficiency.
- Since there are no transmission losses and the infrastructure limits congestion, one of the most important benefits is increased resiliency.

- CHP systems capture heat that commonly is wasted, improving energy efficiency.
- Integrate domestically produced and other renewable fuels that diversify energy supply.
- With very few geographic limitations, CHP technology can operate very quickly and is cost-effective.
- To produce electricity, CHP systems can use a wide variety of fuels, renewable-based and fossil-based.
- CHP systems can be used in a wide range of applications, such as industrial, commercial, institutional and utility circles.

1.5.1.4.2 How does a CHP plant work?

To produce electricity and thermal energy, a Combined Heat and Power system uses the wasted thermal energy. The configuration can be topping or bottoming cycle.

In a topping cycle system, in a prime mover such a gas turbine or an engine the fuel is combusted to produce electricity. The energy lost in the first prime mover is recovered in hot exhaust and cooling systems to produce heat for industrial processes, hot water, heating, cooling, etc.

In a bottoming cycle system, in order to produce the thermal input for example to an industrial process, the fuel is combusted and the heat that has been rejected is used to produce electricity.

1.5.1.4.3 Costs

The cost of a CHP plant is directly proportional to its size, so as the plant increases, capital and installation costs increase. Other factors must be taken into account such as operating and maintenance costs, especially for reciprocating-engine-based systems. Otherwise, if the plant is sized accordingly to meet the maximum demand then it will produce more savings in purchased electricity, and therefore it will be more efficient and economical.

1.5.1.4.4 Maintenance

The components of a CHP system are: a generator, cooling, ventilation systems, controls, electrical and thermal distribution, a heat recovery system, and absorption chillies (which will convert excess heat into chilled water for cooling) among others. Since there are no specific standards, it is difficult to estimate the durability of the components.

For example, the internal combustion engines use a marine motor, which has a long life. Approximately, their lifetimes are 10-20 years and the electrical energy output is from 50kW to 5MW. Gas turbines must run under full load conditions to maximize their efficiency. The larger ones are more efficient and commonly used for commercial and industrial applications with electrical outputs of more than 1MW, but the most important components that require maintenance are the bearings and the blades.

1.5.1.4.5 Savings

The Department of Energy is seeking partners that could increase CHP's share of U.S. electricity generating capacity; meanwhile, they are also doing research in order to develop CHP systems with the aim of achieving 40GW of new cost effective systems by 2020. Following are the expectations:

- CHP applications operate at 70% efficiency.
- In less than a decade, CHP systems would increase total CHP capacity in the U.S. by 50%.
- It would save 1 Quad of Energy, which means around 1% of the energy use in the country.
- It would reduce pollutant emissions by 150 million metric tons of CO_2.

1.5.1.5 Internal combustion engines

More than 250 million transportation vehicles rely on internal combustion engines in the U.S. for their outstanding drivability and durability. Apart from diesel and gasoline, they can work using other alternative and renewable fuels such as propane and natural gas. With the aim to be more economical, they can be combined with hybrid electric powertrains, and to extend the range of plug-in EV they can be combined with plug-in hybrid electric systems.

1.5.1.5.1 Benefits

The advantages of using an internal engine over an external one are:

- An internal combustion engine is lighter and the external ones are heavier and bulkier. Since they are lighter and smaller, motorbikes and vehicles can use a petrol engine.
- It is quite safe because there is no high-pressurized steam present in the boiler.
- The internal combustion engine can start working immediately and does not need a long time to start.
- Finally, this kind of engine is more efficient, up to 40%, than the external combustion engine, which is only about 20%.

1.5.1.5.2 How does an internal combustion engine work?

It can be know as burning apart from combustion, and is the result of a chemical process that produces energy from a fuel and air mixture. In the engine occurs both, the ignition and combustion of the fuel, converting this energy into work. A moving piston and a fixed cylinder compose the engine. Gases push the piston, which rotates the crankshaft and through a system of gears drives the vehicle’s wheels. Internal combustion engines can be classified as “the spark ignition gasoline engine” and “the compression ignition diesel engine” and most of them are 4-stroke cycle engines, and the main difference is how they supply and ignite the fuel.

In the first one, the fuel and the air are mixed together and introduced during the “intake” process into the cylinder. In diesel engines, only air is introduced and then compressed into the engine.

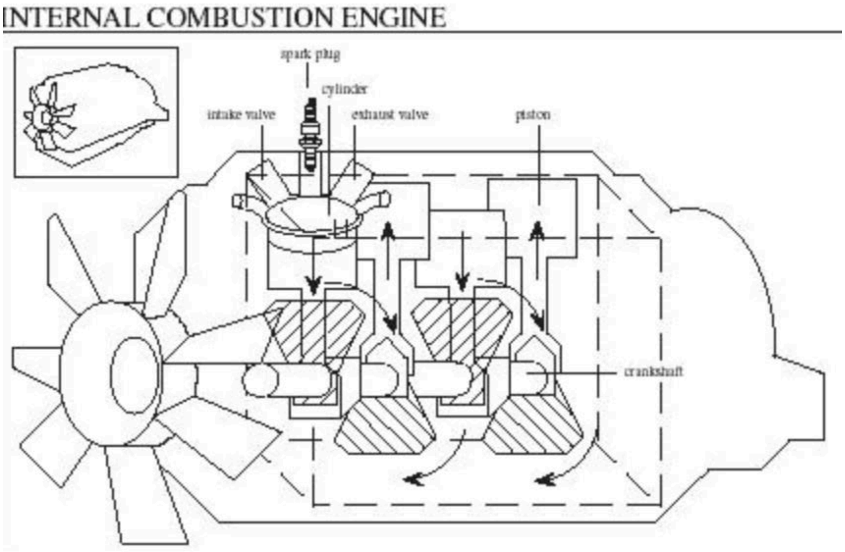


Figure 10. Internal Combustion Engine

1.5.1.5.3 Costs

The advantage of using an internal combustion engine is its lower cost. They cost 50$ per kW instead of 3.000$ to 5.000$ per kW of a fuel cell, which is much higher. Furthermore, fuel cells are seeking for developments in order to reduce their costs, which seem to be a real challenge.

Over the years, research has led to improvements and efficiency in internal combustion engines that will help manufacturers increase fuel economy.

1.5.1.5.4 Maintenance

While maintenance work is being performed or when the system is connected, such maintenance work exposes the employee to possible injury.

The air that is compressed must be avoided when maintenance work is being performed, because the air can cause movement in the engine or turn it over. To prevent this, first the starting air-line union must be disconnected. Second, there must be an open tee between the two closed valves having a discharge capacity.

1.5.1.5.5 Savings

Improving the efficiency of internal combustion engines will increase highway vehicles' fuel economy (being one of the most important cost-effective approaches). There are some barriers to commercializing higher efficiency and low emissions for internal combustion engines in vehicles.

Internal combustion engines already have the potential to exceed 50% efficiency, and some simulation models indicate more than 75%. To produce the energy, advanced combustion engines can use renewable fuels and can yield further reductions in fuel consumption when it combined with hybrid electric powertrains. It is expected that by 2035 99% of light-vehicles and heavy-vehicles will have internal combustion engines with tremendous potential, according to the EIA.

1.5.1.6 Micro-turbines

Micro-turbines can be classified in the group of distributed generation technology and they are used to produces stationary energy. On a small scale, they produce both electricity and heat; they are like jet engines that produce electricity rather than thrust.

Microturbine Overview	
Commercially Available	Yes (Limited)
Size Range	25-500 kW
Fuel	Natural gas, hydrogen, propane, diesel
Efficiency	20-30% (Recuperated)
Environmental	Low (<9-50 ppm) NOx
Other Features	Cogeneration (50-80°C water)
Commercial Status	Small volume production, commercial prototypes now.

Figure 11. Micro-turbine Overview

1.5.1.6.1 Benefits

Following are some benefits when using micro-turbines to generate electricity:

- Micro-turbines do not have very many moving parts.
- They are very compact and lightweight.

- They reduce the carbon dioxide and other pollutant emissions. Using solar micro-turbines can reduce more than a tonne of emissions per year. Micro-turbines also offer a great opportunity to produce electricity from waste fuels.
- They present greater efficiency and lower electricity costs. To produce electricity, waste heat can be used achieving efficiencies greater than 80%.

1.5.1.6.2 How does a micro-turbine work?

Micro-turbines are normally fuelled by natural gas, but there are some of them that are fuels using renewable fuel sources such as bio-fuels. The fuel powers the turbine turning a generator that produces the electricity. The process also produces hot exhaust air that is used to produce hot water that can be used for many different applications.

Micro-turbines can be found in many different sizes depending on the size of the refrigerator and the outputs are from 25kW to 500kW. They can be used in many different applications such as auxiliary power units used in airplanes, automotive and truck turbochargers or small jet engines.

The elements that comprise a micro-turbine are a combustor, a compressor, a turbine, an alternator, a recuperator (the main function of which is to compute the waste heat to make the compressor stage more efficient) and a generator.

1.5.1.6.3 Costs

Due to its size, the capital costs are very low, from 700$ to 1.100$ per kW including hardware, software and initial training. The cost can increase up to 75$ to 350$ per kW when adding heat recovery. Depending on the location of the micro-turbine, the installation adds 30 to 50% of the price, increasing the total cost.

It is expected to have low maintenance costs and low operations. It is also expected that micro-turbines will capture an important share of the market for distributed generation.

In the future, it is expected that the cost of micro-turbines can fall below $650/kW if the market expands and sales volumes increase.

1.5.1.6.4 Maintenance

Since micro-turbines do not have a lot of moving parts, units can provide high reliability. Moreover, the initial units are expected to need more maintenance, requiring it at least once a year. Manufacturers consider maintenance intervals from 5.000 to 8.000 hours. Maintenance costs range from 0,005$ to 0,016$ per kWh. It is important to note that micro-turbines are very efficient and very clean and can be used in mechanical drive markets, for example in air-conditioning and compression.

1.5.1.6.5 Characteristics

Micro-turbines can be used to produce electricity since they are distributed generators, perfect for areas that are not very close to power grids.

Since there are not many frequency variations, disruptions and voltage transients, they offer high reliability and high quality of power. They also can be used as a backup when a fault occurs and also when demand charges are high. It is a way to produce electricity much more cheaply than purchasing it from the utility grid. Finally, since they use waste heat to generate electricity, the process is more efficient.

1.5.2 Energy Storage Devices

1.5.2.1 Flywheels

Flywheels can be considered energy storage units that appear to compliment solar PV panels and wind turbines' limitations, when they do not produce electricity or when they produce more power than power demand.

As an energy storage system, flywheels are mechanical batteries and their function is to convert and the energy in kinetic energy and store it until is needed. In order to supply the electrical grid, and when distributed generators cannot generate for some reason, in a matter of seconds, flywheels can create electricity from the spinning.

1.5.2.1.1 Benefits

Following are some benefits of using flywheels to storage energy:

- Since not demanded electricity can be stored, there is a reduction in generation capacity. When generators are not able to produce electricity, flywheels will supply the system with the stored energy.
- There is no need to use more fuel for generation, since there is a reduction in generation capacity.
- Therefore, if there is no need to use fuel to generate and no need for generation, this means pollutant emissions are reduced. In California flywheels reduce emissions by 26% to 60% in carbon dioxide and by 20% to 50% in nitrogen oxide.
- Reduced generation equipment wear and tear.

1.5.2.1.2 How does a flywheel work?

A flywheel has a heavy shaft and rotating disc, which is mounted on it, and when the electrical energy is applied then the flywheel speeds up. When energy is needed, the flywheel slows down and then the kinetic energy is converted again into electrical energy, then the electricity is transported where is needed.

The mathematic equation to obtain the energy that a flywheel contains is: the moment of inertia multiplied by the spinning; therefore this equation is a function of the speed. It is important to note that in the moment of inertia, when an object is spinning, its effective mass is independent on how much mass the object contains. Otherwise, it is dependent on where the mass is located and where is the central point that is rotating around.

1.5.2.1.3 Costs

The main costs are: the cost of the plant, taxes and the cost of financing. Another costs are: the cost for "make-up" energy needed due to the losses related to the process of charging and discharging storage.

The cost of purchasing a flywheel vary from 100$ to 300$ per kW. The lower range would imply lower rpm models, but on the other hand, smaller or higher rpm models would imply higher costs per kW. The installation of a flywheel is not expensive and prices vary from 20$ to 40$ per kW.

1.5.2.1.4 Maintenance

Maintenance costs and operating costs are not very expensive but will vary depending on the type of the flywheel. Commonly, the process of maintenance is very simple, which consist in changing cabinet air filters and checking vacuum pump oil level that must be checked every few months, so costs are few $/kW per year. It must be mentioned, that the vacuum pump oil must be replaced every year.

Flywheels with mechanical bearings, used in lower rpm flywheels, no quire maintenance but must be replaced every 3 to 10 years and will vary from 5$ to 15$ per kW depending on the type of the flywheel.

Standby power consumption will also carry some costs that will be about 5$ per kW per year, for lower rpm flywheels.

1.5.2.2 Rechargeable batteries

Batteries are energy storage devices composed of one or more cells, which are electro-mechanical devices that are a result of an internal chemical reaction producing an external electric circuit capable of supplying energy. If the battery is composed by more than one cell, cells can be placed in series or parallel depending on how much current or voltage the circuit needs. For the most common batteries, cells are connected in series. Moreover, the result of the series or the parallel is known as the equivalent series/parallel resistance, which is the internal resistance in the cell that limits the delivered peak current.

1.5.2.2.1 Benefits

Following are some benefits of using rechargeable batteries to store energy

- With a simple battery charger, batteries can be changed and come in many different designs that are constantly being developed in order to be more reliable, easier to use and extend their lifetimes. Moreover, there are a lot of ways to charge a battery, such as a computer USB, and wall outlet among others.
- There are two kinds of batteries, rechargeable and disposable. Rechargeable batteries use the same voltage during the time they are in use, which is 1.2V. Peak performance is reached at all times by using rechargeable batteries even when the battery does not have “much battery left”. Moreover, there are some rechargers that create a “refresh mode”, which consists mainly in draining the batteries before fully charging them, getting the optimum performance from them.
- Rechargeable batteries can be made of many types of materials, but batteries made of nickel metal hydride (NiMH) are less pollutant than nickel cadmium (NiCd). Thus, all kind of rechargeable batteries are better and less pollutant than disposable batteries, since they can be used a million of times producing less waste. Rechargeable batteries

use less energy and are also more energy efficient than disposable batteries since it is cheaper not having to produce new ones.

- To charge a battery only takes 15 minutes to fully charge batteries again, which is less time than going to the store to buy disposable batteries.
- The most important benefit is that rechargeable batteries can be used around 500 times, so it makes it worth it spending the initial cost, which is a little higher than disposable batteries, but in the future, will help customers save a lot of money.

1.5.2.2.2 How do rechargeable batteries work?

When an electric current is applied to the battery, rechargeable batteries fully restore their energy capacity. The electromechanical cells mentioned above, produce an amount of energy, which is finite, and can be recharged again when runs out of battery by reversing the chemical reaction, result of the charging current supplied by the battery charger. The most common rechargeable batteries are: (NiMH) Nickel Metal Hydride, (Li-ion) Lithium Ion, (Ni-Cd) Nickel Cadmium, and (Li-ion polymer) Lithium ion polymer, (Lead-acid) Combination of lead and Sulfuric Acid.

Among their advantages we must highlight the high power delivered in short periods of time; for low power applications, batteries have a longer battery life and do not need too much time to recharge the battery… among other characteristics. Designers should pick the most appropriate technology for the application.

1.5.2.2.3 Costs

Among all the many types of rechargeable batteries, the ones made of Ni-Cd are cheaper and offer a better performance value among all the other types. Many manufacturers produce this kind of batteries in large volumes and are also constantly being developed. A new different kind of batteries is now being developed, which is foamed nickel substrate or the "new Ni-Cd" and offers volumetric energy density that doubles properties of the Ni-Cd.

For example, "AA" can be found rated at 600 MA/hr, but now can also be found in 900mA/hr or more capacity, which means 10% or 20% more of capacity and higher density. Otherwise, it is less environmentally friendly than Ni-MH, but both need the same discharge voltage, which means that we can use Ni-Cd in many different applications. The Lion-battery is the most expensive and is commonly used in high end products where performance is the key point.

1.5.2.3 Supercapacitors

These electronic devices are designed to store large amounts of electrical energy. They do not use conventional dielectric as common capacitors; they use a double-layer capacitance and pseudo-capacitance. The first mechanism is the electrostatic while the second one is the electrochemical, which is a mix of common capacitors and ordinary batteries.

1.5.2.3.1 Benefits

Following are the benefits of using supercapacitors to store energy:

- Practically can be recycled unlimited times.
- Since capacitors, therefore also supercapacitors have low resistances; by all means the circuit reaches high currents.
- Does not take to long to reach full charge as well as they do not need end-of-charge termination.
- High specific power
- Supercapacitors are known for their discharge performance and also for their excellent temperature when charging, which is very low.

1.5.2.3.2 Disadvantages

- Supercapacitors present low specific energy.
- The full energy spectrum cannot be reached due to linear discharge voltage.
- As most batteries they self-discharge, but the key point is that supercapacitors have the highest self-discharge.
- Due to the low cell voltage, they require several important connections with voltage balancing.
- The cost is very high per watt.

1.5.2.3.3 How do supercapacitors work?

These devices are polar devices and must be connected to the circuit right way. Opposed to an electrochemical reaction static charge is possible. This is achieved by applying a differential of voltage on both plates of the capacitor. The supercapacitor does not operate as a stand-alone energy storage device, supercapacitors work bridging short power interruptions with low maintenance memory backup. Another characteristic is that supercapacitors charge incredibly fast and deliver high currents, which can be used as a peak-load enhancer for hybrid vehicles, among other applications. The time that a supercapacitor takes to charge is 10 seconds and the charger limits the maximum current. The first time that a supercapacitor is charged, the time to charge takes a little longer but it is important to mention that provision must be made to limit the first initial current.

1.5.2.3.4 Costs

Disadvantages listed above, the prices appears as one of the most important disadvantages since supercapacitors are very expensive in terms of $/W. Some engineers prefer to spend the money on a larger battery instead of on a supercapacitor, when it is important to realize that each of them serves for unique applications. Costs vary from 2.400$ to 6.000$ per kWh of energy storage.

1.5.2.3.5 Maintenance

Practically, supercapacitors can be charged unlimited number of times.

Commonly, after 10 years supercapactiors' capacity is reduced from 100% to 80%. When high voltages are applied, the lifetime of the capacitor is reduced but can handle hot and cold temperatures. Moreover, the stored energy decreases the first month from 100% to 50%. Common rechargeable batteries only discharge from 5% to 15% per month, which is why many engineers prefer to invest in larger batteries than in supercapacitors.

1.6 Benefits and Costs

Microgrids offer at the same time, a tremendous number of benefits. Following are some benefits: energy, reliability, power quality, environmental, public safety, health, and security benefits. Moreover there are many regulatory and economic challenges. Following are some challenges: the capital investment, project planning, administration, maintenance costs, environmental costs and operation costs.

Usually, it is difficult to explain how benefits and costs interact, and sometimes can be very complex. First, we have to take into account stakeholders, who have direct financial interest in microgrids, in direct or indirect way, and can be classified as follows:

1. The improvements in reliability and resiliency will benefit microgrid customers from reductions in energy cost coming from the reduction in peak charges or cost per energy consumed.
2. The reliability and resiliency also can benefit grid consumers.
3. Microgrid developers could benefit from energy sales profits coming from agreements, providing different services or coming from participation in other markets.

4. The distribution network operator will find savings in maintenance costs and will possibly avoid energy services purchases.
5. Society in general, since microgrids help in the reduction of pollutant emissions and can increase the employment.

Benefits:

1. Energy Benefits mean a reduction in the energy costs derived from CHP (combined heat and power) and/or electricity production. Other cost savings come from the upgrading of energy distribution, transmission and generation systems. If operational services are provided then the utility will benefit because there is no need to procure the services elsewhere. Furthermore, the additional generation capacity installed in the microgrid will generate benefits to the main grid by reducing generation, transmission and distribution capacity constraints.
2. Reliability Benefits are related to power outages. Since microgrids can operate isolated from the grid during a fault. Microgrids can provide energy generation and/or storage capacity. Therefore, customers will benefit from the increased reliability, which also means monetary savings.
3. Power Benefits are related to consumption. Nowadays power quality is becoming more important, because of highly sensitive devices that can be damaged during a fault. Those benefits include reductions in the frequency of voltage drops.
4. Environmental Benefits can be achieved by installing microgrids, due to reduction in pollutant emissions. This is possible because microgrids use renewable sources of energy such solar and/or wind or CHP systems (more efficient fossil-fueled generation) that not only imply less pollution, the use of CHP also imply higher efficiency. Environmental benefits not only affect consumers they also help the environment with reductions in pollutant emissions. The benefit from emissions reduction can be found as:

$$E_{\epsilon} = E_{\epsilon\ BC} - E_{\epsilon\ \mu G}$$

$$= \sum_{t}^{T} P(t)_{GP} E_{\in\ G} \Bigg| BC - \sum_{t}^{T} \overrightarrow{P(t)_{DG}} * \overrightarrow{E_{\in\ DG}} + (P(t)_{GP} - P(t)_{GS}) * E_{\in\ G} \Bigg| \mu G$$

Where $E_{\epsilon\ BC}$ and $E_{\epsilon\ \mu G}$ are the emissions reduction of the base case and the microgrid case, $E_{\in\ G}$ is the average rate of emissions from the grid per kWh, “t” is the time step (in hours), "P" is the power purchased and sold from the grid in the base case and microgrid case, $\vec{P}$ is the vector of the power produced by each distributed generator and $\vec{E}$ is the vector that contains the emissions rate of each distributed generator.

Cost issues:

The most economical challenge is the generation equipment for microgrids that can be very expensive. Microgrids are only cost-effectives when benefits accrue to a number of users; this means that only it is worth to invest that amount of money in places where there are strong motivations that can justify the inversion. Ownership of the wires and generation equipment is relatively easy and cost-effective when microgrids are able to provide power to their own area (for example to a hospital, a university, a farm, an industrial area…). On the other hand, if it is made by more than one entity, the ownership rights and how costs affect to microgrids are very complex. However, microgrids have to be catalogued under the Public Utility Regulatory Policies Act and they must be categorized as Qualifying Facilities; which means that generation must come from renewable energies and power must be less than 80MW. Hence, they must generate, both electrical and useful thermal energy being a cogeneration plant. Furthermore, some economical issues can be solved since Qualifying Facilities have the right of selling and buying power at competitive rates to the local utility.

It is expected that utilities provide a reliable service and at certain level of energy and so do microgrids. Otherwise, due to conventional kWh charges, microgrids are not going to recover the full value of their service Nevertheless, in terms of balancing and reliability, we might take into account that the grid also provides substantial value to self-generating customers.

The energy prices are always increasing due to energy demands, which are increasing too, and therefore, the possibility of failures and blackouts also increase. If demand increases, the loads have to increase and also do the deformation of components on the network, increasing voltage drops. The peak load causes deformations on the wires and this means that when a component reaches its capacity limit, it must be replaced. Because of the presence of DERs, the peak load is reduced and this will allow the components extend their lifetimes. Owning a microgrid would imply that consumers have to pay less for the reduced peak load than other consumers in the base case (without one). The network upgrade timeline can be determined in both cases, with the reduction and without the reduction coming from the microgrid. It can be predicted with the following equation:

$$PV = \frac{C_i}{(1+d)^{Y_i}}$$

Where "d" is the interest rate, "C_i" is the present value for an investment and "Y_i" is the year. If we have the presence of a microgrid then the benefit will be the difference from the present value of the base case and the present value of the microgrid.

$$B = PV_{BC} - PV_{\mu G} = C_i * (\frac{1}{(1+d)^{Y_{BC}}} - \frac{1}{(1+d)^{Y_{\mu G}}})$$

Therefore if we have a number of affected network components the deferral can be calculated as:

$$Defferral = \left(\sum_{t=1}^{x} \sum_{i=1}^{n} \frac{C_{i,t}}{(1+d)^t} \middle| BC \right) - \left(\sum_{t=1}^{x} \sum_{i=1}^{n} \frac{C_{i,t}}{(1+d)^t} \middle| \mu G \right)$$

Where "x" is the time of the end of the planning horizon, and "n" the number of investments required in time step, which is "t." It is important to mention that not all the distributed generators contribute to the peak load reduction, but microgrids typically content some means of dispatch, whether that can be though generators, storage systems or dispatchable loads.

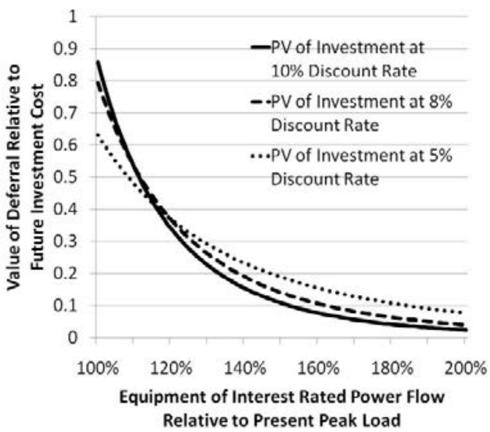


Figure 12. Future investment cost of equipment relative to present peak load

Not only there are issues in terms of ownership, there are also in terms of regulation. Under most regulatory bodies, microgrids are not considered legal. As of 2012, there are no policies that describe a legal and viable market for utility distribution. There are complex regulations in terms of generation and distribution in electric power, across developing countries. Therefore in terms of microgrid development we can define six policy issues:

1. Ownership Rate Structure, if the microgrid meets some standards established by a given country, the microgrid can be exempt from federal/state regulations, or exempt from most of them depending on the size, structure, or ownership model of the microgrid. Otherwise, if the microgrid meets the standards, this implies that some regulations regarding finances, construction, operation or rate setting, can be avoided.
2. Ownership: There are no existing policies about who owns the wires for linking loads or the equipment because it can be shared among customers or not, as a non-profit association (or corporation).
3. Franchise rights: Lawsuits can be triggered when wires are built over public streets. Microgrid's infrastructure must not infringe franchise rights but we do not have to forget that we should avoid going through lengthy and expensive lawsuits. To avoid this, microgrids' owners must contract to the utility and pay some fees to build and use wires across public streets.
4. Size of generation installations should be beneficial when some regulations are avoided in terms of avoiding some regulation rates on steam corporations.
5. Customer rights: when microgrid is shared by residential customers owning all the facilities, all customers should pay all the standby fees. Customers, while they remain connected to the main grid standby charges are applied, whether or not they receive power from the utility. When customer's generator is not working, by law the utility must supply delivering energy automatically and that is why customers have to pay these fees. Obviously, the amount of money required depend on the size of the generator, but even if the microgrid can supply most of its own electricity needs, microgrids must remain connected to the main grid, and therefore, fees and charges are applied.
6. Interconnection: Especially if we talk about renewables energies, there are some rules for small generators. To build an accurate project, these rules and requirements must be stay up to date and will mean significant savings among other benefits.

1.7 Growth and economics of microgrid

The next step is the commercialization of microgrids, according to Navigant we could characterize microgrids in two different groups: grid-tied and direct current. The future of microgrids over the next several years will depend on two factors, the industry and government. According to Navigant and I quote “The key to future growth in microgrid now rests with greater creativity in both the public policy and business model arenas.”

The company Frost & Sullivan sees the US as the main pioneer and leader in microgrids since there are many microgrids around the country and many suitable areas to develop them. After the research was concluded, the company concluded that there would be a rapid microgrid growth in the next 5 years. Another factor that will affect microgrids deployment is the utilities, such as municipal utilities, institutions, governments, health care, solar and energy storage developers, engineering firms, etc.

The firm also warns that introducing microgrids into the market can be expensive, emphasizing that the most expensive microgrids are going to be the ones that integrate into a central grid. The high cost of microgrids is due to a lack of their standardization and the slow propagation of user interfaces. Since this is a problem, European companies are trying to overcome the problem by building microgrid networks for field tests and analysis.

Other experts are also doing research and they made a report called “The advanced microgrid integration and interoperability” made by Ward Bower, Dan Ton, Ross Guttromson, Steve Glover, Jason Stamp, Dhruv Bhatnagar and Jim Reilly.

The following table shows the capacity in MW and the revenue in dollars of the different kind of areas that are suitable for microgrids: commercial, education, government, healthcare, industrial, and research. Finally, it is important to note that military and remote areas are also suitable for microgrids but are not included in this table. The data is taken from Navigant (Pike research) Q1 2012 and credit from Schneider Electric.

North America	Capacity (MW)			Revenue ($)		
	2011	2017	CAGR%	2011	2017	GAGR%
TOTAL	603	1572	17.3	59.73	735.65	52.0
By segment						
Commercial	71	179	16.6	8.95	80.91	44.3
Education	488	1281	17.5	45.48	603.71	53.9
Government	34	73	13.8	4.28	28.56	37.2
Healthcare	10	31	20.4	0.85	16.73	64.3
Industrial		4		-	3.06	N/A
Research	0	4	64.5	0.18	2.68	56.6

Table 2. Average market growth projection by capacity and revenue.

The institutions that have implemented microgrids and have a great experience optimizing and operating with microgrids are campus universities and colleges. The main purpose was to focus on delivering highly reliable energy services. Hence, over many years of integration, many mission critical end-users, such as research centers, data centers and laboratories have experimented the advantages of integrating microgrids. Campus microgrids are designed to deliver these highly resilient energy services. Some research projects hosted by US institutions demand precise and constant temperature and humidity settings, which means that they are not a solution for the commercial electricity grid.

This means that microgrids growth is subject to regulatory policies, as well as reducing interface costs and developing the technology. Some conservatives do not see microgrids as a revolutionary development, but other pioneers describe a future grid comprised of a central grid and microgrids.

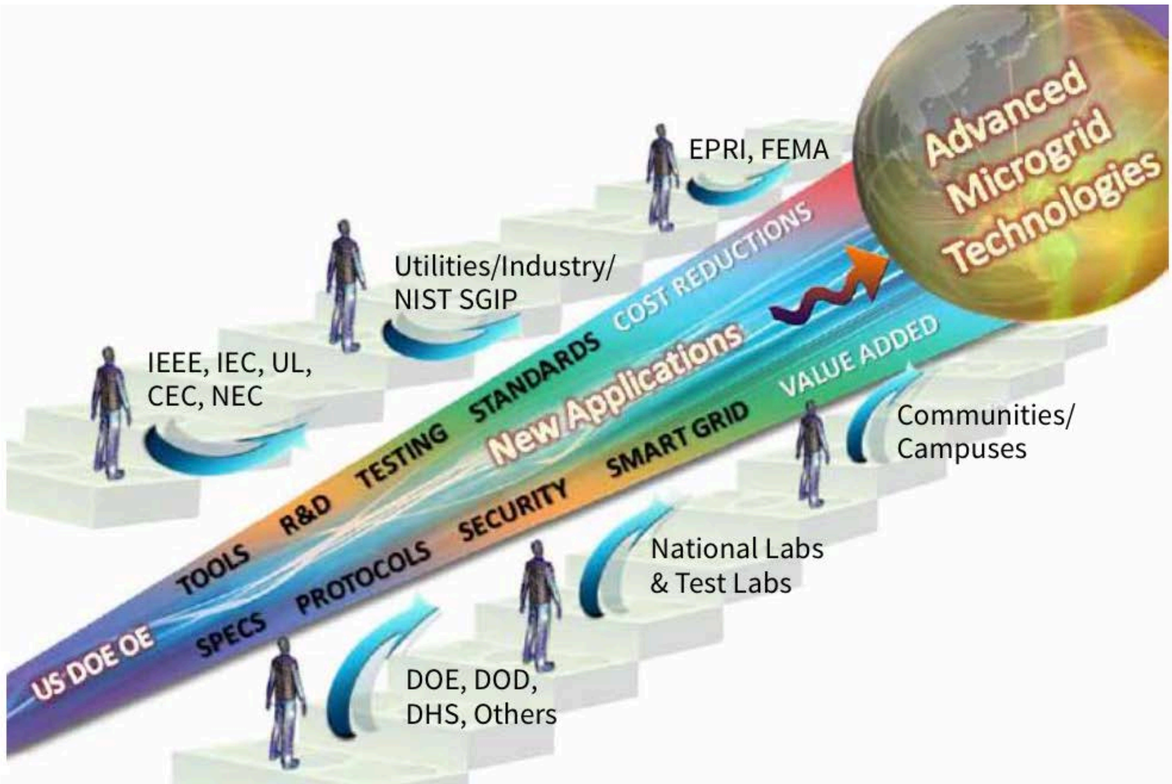


Figure 13. Advanced microgrid growth chart

As it is mentioned above, the future of microgrids growth will depend on economics and how effective the policies, grid operators and regulations are, will allow microgrids to monetize. Microgrid developers could end up having to navigate 50 different sets of rules that govern their major permissions and relationships with utilities, because regulation and power plant siting rules are set at the state level in the U.S.

Moreover, the different grid operators set rules for buying and selling power into wholesale markets. US electricity consumers, two-thirds of which receive their energy from regional transmission operators (RTO) and 10 independent system operators (ISO). In the U.S. rules, markets and policies could vary by location. Since microgrids are designed for specific areas where electricity prices are high, or high load exists or need to be supplied 24-7 (such us campus universities, hospitals, commercial or industrial and military), microgrids take advantaged of their efficiencies offering a cost-effective product.

One factor that will predetermine microgrid's return on investment is the geography. Other factors that play an important role into microgrid economics, such as local electricity process, fuel prices, timing of construction, equipment costs, financing costs and government incentives; this information can be found in a paper published in August 2013 and it is called "Microgrids for fun and profit".

Moreover, microgrid's revenue will depend on its host. Depending on who owns the microgrid, it may collect retail energy rates from the energy users it serves. By maximizing power and thermal outputs microgrids can improve their savings and their revenue. To generate a competitive rate of return for investors, a microgrid will require high load factors and utilization.

In order to manage operating risks, reduce their costs and earn revenue, operators show their interest in many different ways, such as market transactions and hedging strategies. Microgrids are designed for avoiding peak energy costs when they use the stored energy and also to manage their onsite energy. Another thing that makes microgrids a revolution is that microgrids can sell power back to the grid when it is necessary, and makes the served area more economical. By participating in demand response programs and some secondary service markets microgrids can reduce costs and earn revenue. Moreover, in order to meet state portfolio standards, microgrids have to provide utilities with renewable energy coming from distributed generators and may sell that energy into carbon credit markets.

Microgrid operators are confident when they are offered fair compensation for services and can operate successfully in these markets. On the other hand, there are some economical problems that will make microgrid's growth slower, and affecting mostly operators. Some of the economical benefits offered by microgrids are unrecognized, for example, there exists an issue of avoided costs. A microgrid owned by a private user in some strategic area may avoid the need for a utility or a specific infrastructure for transmission and distribution. Nowadays, private investors pay for the microgrid but the ones who benefit from it are the operators and ratepayers. So here is the big issue, there are no policies that compensate microgrids for reducing grid congestion, being an area subject to discussion since the business model of the current utility does not incentive, reliability and the optimization of system integration (factors that microgrids take into account) just rewards investment in assets. Microgrids play the important role of determining the future of the electric industry but at the same time they are not easily managed, therefore facing some development risk.

Some other energy projects have the same risk, such as market penetration, fuel supply management, permitting issues or financing. But the most alarming risk nowadays is the relationship with the local utility, which is also undefined. Since there are undefined and non-existent policies to regulate the relationship it is impossible to know, if microgrids will compete with the utility or will complement it. As originally planned, microgrids are designed to complete the utility instead of replace it but utilities have financial and technical concerns about how will microgrids affect their business model and mode of operation.

Some technical concerns are that utilities do not know how microgrids are going to damage the main grid if there is a fault during the reconnection or when they are in islanded mode.

In order to find a solution, private developers find it difficult to deal with the utility's legacy system or to follow some interconnection procedures.

The financial concerns for example focus on the cost of proving back-up power for microgrids. It is important to mention that some utilities have accepted microgrids or plan to develop them. Otherwise, the main concern is that there are more customers each day that are planning to own a microgrid, which means that customers will flee the system for distributed generation and will leave the utility with a rate base too limited.

Moreover, there are some utility franchise rules that microgrids have to follow, for example, in some locations it is forbidden that microgrids use string wires across a public street in order to sever customers.

An article published in March 2013 by Sara Brown and Paul McCary called "Peaceful co-existence" pointed out that those policies and laws vary widely in all the different states throughout United States. Moreover, the same happens with microgrid development. For example, it is allowed in Connecticut to sell power across public streets. On the opposite extreme, in South Carolina, it is forbidden the sale of power from rooftop solar panels to a host. It is said that a campus microgrid with no intervening public streets, can operate in South Carolina without concern about franchise rules since a campus microgrid is a simple microgrid. For more complex ones, with multiple pieces of property and with end users there are more issues. Microgrid owners depend on utility's willingness to sign an agreement or to form a financial partnership. Another question that comes up is if utilities are allowed to own microgrids, and if so, if they are allowed to charge a premium rate or apply a special tariff.

Moreover, apart from economical factors, microgrids must be recognized for their environmental value. Environment Northeast pointed out that it is as important as the benefit and cost analysis as the value of greenhouse gas emissions reductions. Many microgrids to produce their energy they use as distributed generators PV solar panels, and wind turbines, CHP systems that will reduce greenhouse gases. It was proved by ACEEE in April 2014 in its study called "Change is in the air: how states can harness energy efficiency to strengthen the economy and reduce pollution", which are explained the key efficiency strategies to reduce gas emissions.

1.7.1 States in the lead

Many states in the U.S. have begun to tackle these issues. Below are explained some of the key incentive programs and reports among other key proceedings that states are following when implementing microgrids.

- California

  The California Public Utilities Commission Policy & Planning Division issued a paper in April 2014 called "Microgrids: a regulatory perspective" by C. Villareal, D. Erickson and M. Zafar, which points out some policy and regulatory issues that must be considered. The paper also points out the importance of microgrids and the wide range of benefits that microgrids offer. Since microgrids are going to change the conventional utility model, regulators and policymakers must consider a new role for the utility. Moreover, the paper discusses some issues such as problems with interconnection and net metering that microgrids installed in California have to face. Since there are no policies established, the microgrids working must fit into a slot. The report says and I quote: " *Distribution interconnection rules that have been established by the Commission only recognize three types of generation interconnection: net metering, self-generation (non-export), and wholesale* *distribution access tariff (WDAT). Net metering is on the customer side of the meter and involves a bill credit for exported energy. It is not visible to the California ISO, and is connected at distribution-level voltage. There is a limit of 1 megawatt (MW) of nameplate capacity. Self- generation interconnect is effectively wheeled to the customer via the distribution grid, but is not intended for net production. Wholesale distribution access interconnect is visible to the CAISO and is interconnected on the utility side at distribution level voltage. There is a limit of 3 MW at the 12 kV PCC and 5 MW at the 60 kV PCC.*"

It is important to mention that these techniques require the approval of the utility. Moreover, the paper also discusses some other regulatory issues that need to be faced such as how the interconnection tariff will affect microgrids when they are acting as a consumer or as a producer of electricity in short periods of time. Another important issue in the state is that California does not support islanding, which means that the state negates one of the most important benefits of microgrids that is the ability to provide electricity during a fault.

In this paper there are explained some suggestions that regulators must follow including development of standards for microgrids that ensure safely interconnection and interaction with the main grid. Finally, it is described the most suitable areas in California to place microgrids and suggests setting up a locational pricing system for those areas.

- Connecticut

The stated suffered some power outages due to weather conditions; the most damage case was after the Superstorm Sandy in October 2012. The state was considering microgrids as a solution even before Sandy, and nowadays has been supporting them through incentives and policy changes.

In 2013 the stated issued one solicitation resulting in 9 projects and granted $18 million. The microgrids include distributed generators such as micro gas turbines, solar PV panels, CHP, diesel, fuel cells, natural gas reciprocating engines and as a distributed storage they use batteries. The microgrids are hosted by critical facilities such as hospitals, fire departments, shelters, university campus, and police stations among others.

In 2014 the state issued the second solicitation offering $15 million seeking for projects in order to promote geographic diversity. The purpose is to seek not only in one type of microgrids; they are seeking a variety of projects with different sizes, scales and technical configurations. Also the state is planning a third solicitation.

Moreover, the state established some incentives published the Public Act 12-148 that became law in 2012. Another incentives that Connecticut established were modifying some utility franchise rules. In 2013 the Public Act No. 13-298 became law and it allows to site microgrids crossing public streets without franchise infringement. G. Sherman one of the managers at the Clean Energy Finance and Investment Authority said and I quote, "*Utility franchise rights in Connecticut are now essentially erased for municipal microgrids. So if you have a microgrid in Connecticut that is serving what is considered a municipal critical facility, you can string wires wherever you want, and the utility is not allowed to sue you — although that could still be challenged in court*."

- Maryland

Abigail Hopper, one of the energy advisors to Governor Martin O'Malley is leading a The Resiliency Through the Microgrids Task Force that was originally created to study microgrids including all the regulatory, financial and technical barriers that affect microgrids. In 2012 a report was published and includes some recommendations and includes the suitable areas where pilot projects may be built because of high electric demand. O'Malley said and I quote, "*Marylanders expect and deserve an electric grid they can count on, especially during unpredictable severe weather events. Developing microgrids is critical to a sustainable future*".

- Massachusetts

As a result of Governor Deval Patrick's aggressive approach to renewable energy, the state has several regulatory policies for microgrids, instituting goals and supporting initiatives with the purpose to increase by 45% by 2020 the use of green electric energy.

These proceedings include:

- D.P.U. 12-76-A Order on grid modernization
- 13-182 Order electric vehicles and charging
- 14-04 Investigation into time-varying rates

- New Jersey

With the purpose of improving the state's energy resiliency and developing some microgrids projects, the Governor Chris Christie invested $25 million in 146 government agencies. The first intention is to develop the existing distributed generators, such as fuel cells and CHP systems in order to improve resiliency and increase capacity. The money is also used in engineering studies, such as buying solar, natural gas-powered generators, dynamic inverters and storage (for existing solar panels).

Moreover, $1 million federal grant in one project called NJ TRANSIT where the U.S. Department of Energy, the New Jersey Board of Public Utilities and Sandia National Laboratories collaborate on the project. The project is nowadays the third largest transportation system and this project includes:

- For self-generation power facilities is required the design, construction and operation.
- A new power grid requires the design, construction and operation.
- Catenary wire network for distribution.
- Distribution of power to the project's facilities.

It is needed transportation between Newark and Jersey city and Hoboken among other critical stations and facilities. About 20 military bases are now operating and the project will also use the Energy Surety Design Methodology to evaluate energy needs in order to make microgrids more reliable and improve resiliency among other cost-effective strategies for system upgrades.

- New York

A proceeding was opened in 2014 by the New York Public Service Commission in order to influence microgrid development in the state called Reforming the Energy Vision.

The idea consists in creating a grid operator that not only manages the distributed energy resources; it also manages the bulk power markets in the U.S. By creating a new kind of market platform called a Distributed System Platform Provider and it is a platform where power can be sold or bought by competitive distributed energy players. The operator may also provide tariffs, handle payments and transactions and create markets and systems to monetize important factors such as: demand response, distributed generation, energy efficiency, microgrids, energy storage, CHP, among other forms of distributed energy.

The state also pays a lot of attention on how microgrids will affect and requires policy attention, the report recommends that utilities play an important role. The Governor Andrew Cuomo, one of the most eminent persons in favour of microgrids and distributed energy resources agrees with Reforming the Energy Vision. Nevertheless, the proposal is under review now and will possibly be changed. The commission wants to begin with new policies this year. Moreover, the Governor invested $40 million in order to jump-start 10 community-based microgrids, which supports many customers in some area even if they are businesses or residents. NYPA sees itself one of the leaders of the new grid since it is know NY as one of the largest hydroelectric resource. With 16 power plants and 1400 circuit-miles of transmission, the non-profit energy corporation is one of the most important power suppliers.

Meanwhile, one of the oldest utilities called Consolidated Edison agreed to consider microgrids as a new grid resilience measure, since microgrids can reduce peak load, they can act in islanded mode during a fault islanding from the main grid.

1.7.2 U. S. Government

In 2014, the Department of Energy began to subsidize microgrids research, design and development. Grants were specially, for microgrid controllers for microgrids projects between 1 to 10MW. The money will be given to projects of microgrids capable to provide enough power for a small community or critical infrastructure such as hospitals. However, the Federal Energy Regulatory Commission tries to solve some issues related to the payment to microgrids for grid services. Another important question that must be considered is if microgrids can act as qualifying facilities, such small CHP projects under 80MW, allowing microgrids to sell electricity at competitive rates to utilities. It is still under discussion if microgrids can be except from federal or state policies governing utilities.

Finally, there are several agencies that are studying microgrids issuing reports. Among them it is important to mention: Microgrids Group at Berkeley Lab, The Department of Energy, EPRI and Sandia National Laboratories.

1.8 The nature of the problem

Several studies have described and characterized some microgrids' proposing hypothetical analysis or developments. Several studies have been done to date on microgrid concept, technology and operation. Many papers suggest a case study, which could mean a revolution in some areas of microgrids, but they are just hypothetical studies based on mathematical equations, such as "Application and Positioning Analysis of a Resistive Type Superconducting Fault Current Limiter in AC and DC Microgrids using Simulink and SimPowerSystem" [34] or "Optimal Switch Placement by Alliance Algorithm for Improving Microgrids Reliability" [35]. Other papers tried to classify microgrids in groups based on theoretical research but they are not developed. Finally, a few studies have explored policy barriers, costs and benefits; such as "Economic Coalition Strategies for Cost Reductions in Microgrids Distribution Networks" [37] or "Evaluation of the Costs and Benefits of Microgrids with Consideration of Services beyond Energy Supply" [38].

1.9 Contribution of the thesis

This work reviews what has been done ranging from definition, concept and salient features of a microgrid to a possible characterization. This paper suggests a classification based on application, and to bring out some characteristics, each category is based on real examples of microgrids actually running.

Finally, the purpose of this paper is to compare and contrast these categories in order to bring out a final conclusion.

1.10 Description of the report

In this work we are going to build the classes for the characterization of the microgrids on the basis of the applications.

1. Campus Microgrids

   The main goal is to aggregate existing on-site generation with multiple loads, and these loads are located in an industrial park or campus. Some studies shown that Campus microgrids have achieved this boom in the market because there is just a single owner for both generation and multiple loads located all together in a reduced area. For the owner, this is very easy to manage and to avoid many of the regulatory obstacles. Campus microgrids are able to supply energy from 4MW to 40MW.
2. Remote Microgrids

   This kind of microgrid operates in an islanded mode, and a single transmission line to the main grid generally connects them. Islanded microgrids represent, nowadays, the largest number of current deployments.
3. Critical Loads Microgrids

   This kind of loads needs constant supply 24-7. Microgrids are very suitable for these loads because during an outage the microgrid is going to supply the installation.
4. Commercial Microgrids

   There is lack of well-known standards for this type of microgrid. Since there are existing boundaries that limit them, we can say that they are a “type” of microgrid but without clear characteristics; on the other hand, they were quickly developed in America and some places in Asia.

5. Residential Microgrids

   This kind of microgrid provides in a more reliable, economical and environmental service than the existing centralized electricity grid. Residential microgrids bring together energy efficiency improvements, renewable energy, and distributed generation with lower energy costs, lower emissions and boost resilience and reliability.

2. Possible Characterization

Unexpected weather events and increased electricity needs have raised several questions over the capability of the grid to provide electricity. A practical solution is the widespread implementation of the microgrid concept.

Several authors have described microgrids in great detail specific to a particular application but there is no existing work that attempts to categorize all the microgrids. Since we now understand the concept of microgrids and we have extracted the salient characteristics, hence in this work, we are going to build the classes for the characterization of the microgrids on the basis of the applications.

We are going to classify microgrids as follows: Campus Microgrids, Residential Microgrids, Commercial Microgrids, Isolated Microgrids and “Critical Loads” Microgrids. To extract the most important characteristics we are going to focus on real examples of microgrids around the world in order to extract conclusions.

2.1 Campus Microgrids

A university campus presents a fairly uniform daily load. According to the University of Massachusetts, a university campus with 60 homes uses an average of 30kWh/home of electricity. Lighting, ventilation, and cooling are the largest consumers of electricity.

The most suitable areas for microgrid implementation are university campuses since they are able to reduce their energy bills by 30% by implementing cost-effective and energy-efficiency measures. A survey made by 50 campus universities showed that the home campus, private partners, private investors, the local government or educational partners could own campuses.

The following picture represents the load profile for a typical university campus. The profile exhibits a fairly uniform load with no peak hours.

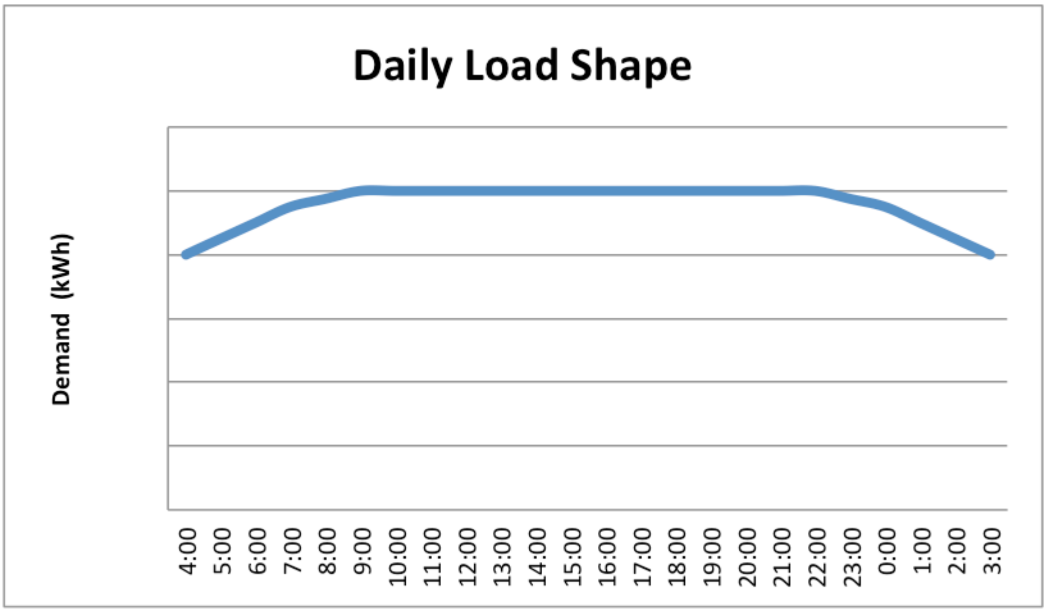


Figure 14. Campus University Daily Load Curve

When it is necessary, for example, during a utility outage, campus microgrids are able to operate as a single controllable entity with respect to the grid**.** As microgrids, they operate at some level of service isolated from the grid during a utility outage. In normal conditions, they are fully interconnected with the grid.

Furthermore, not all US campuses are located in the most suitable areas for investing in a campus microgrid. The main reason is that not all areas are threatened by the risk of blackouts caused by natural disasters such as hurricanes, earthquakes, and wildfires among others resulting in a blackout that could last a long time.

For example, in coastal areas where blackouts occur very often, there is a need to invest in microgrids. On the other hand, in the Midwest there is no need to invest in microgrids since the probability of a blackout is almost zero.

Nowadays, green energy has become a major priority and there is a growing concern about the electric grid reliability. Therefore, every day more and more universities in the Midwest are considering investing in microgrids as they seek for greater control over their energy use.

Campus microgrids use an average of 2 to 40MW, and most of them rely on DERs such as CHP systems, PV panels and gas/steam turbines to generate electricity. Hence, they rely on energy storage banks to store energy.

Now we are going to study different university campuses that have already invested in microgrids; today these are the most important examples of campus microgrids.

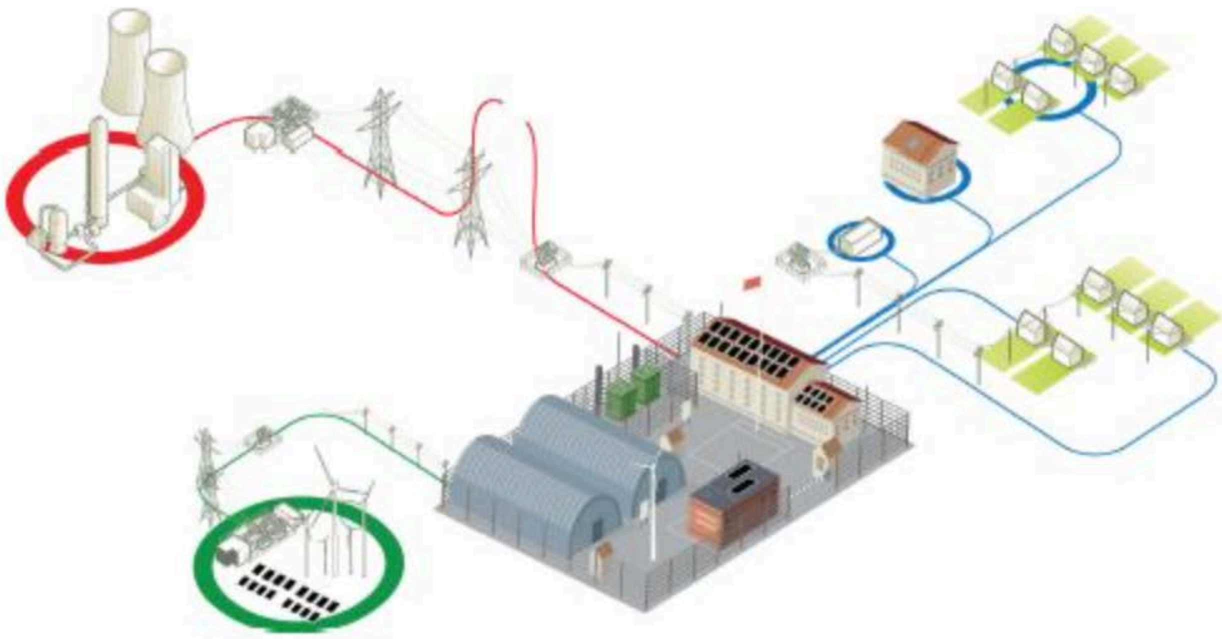


Figure 15. Campus Microgrid

2.1.1 New York University

New York University (NYU) is one of the largest universities in the United States. Since 1960 the university has produced power onsite, and in 1980 it installed a large oil-fired cogeneration plant. Years ago, NYU made a transition away from oil-fired technology towards a natural-gas fired combined heat and power facility, seeking new ways to produce energy. A Few years ago the university was looking toward better reliability and control of its energy and considered microgrid capabilities.

The university invested \$126 million in the new infrastructure. In order to help to provide low-cost financing sources, tax-exempt bonds were arranged through the Dormitory Authority of the State of New York and also through NYU fees.

NYU has a CHP system with an output capacity of 13.4MW, which means double capacity compared to the old plant. The CHP system has been fully operational since 2011. On campus, it is able to provide electricity to 22 buildings and heat to 37 buildings. The microgrid has two gas turbines with an output of 5.5MW, and they are coupled with heat recovery steam generators that produce electricity, and a steam turbine with an output of 2.4MW.

The distribution grid is Con Edison and the NYU microgrid is connected to it. With the microgrid they replaced the existing 5-kV electrical underground service feeders with a 10MVA 27:13.8-kV substation. For enhanced reliability the substation utilizes three parallel primary utility feeders.

When demand is greater than the on-site generating capacity, the microgrid purchases electricity. As a microgrid, it is able to island from the main grid, and it was tested during Hurricane Sandy, when the NYU microgrid islanded successfully from the distribution grid and provided reliable power to much of the university campus.

Impressive results, both environmental and economical, happened with the modernization of the plant, and the microgrid has proven its benefits. Per year, NYU has rated savings on total energy costs that vary from $5 to 8$ million. The new infrastructure not only saved money, it also contributed to the reduction of local emissions with an approximate 68% decrease in EPA criteria pollutants (NO_x, SO_2, and CO_2 emissions) and an estimated 23% contributing to the reduction of the greenhouse effect emissions.

With this reduction of the local emissions, the university microgrid also made the city of New York decrease its pollution (and greenhouse gas emissions).

2.1.2 Illinois Institute Of Technology

Approximately three blackouts per year occur in the area where the Illinois Institute of Technology is located. Since a lot of power outages have happened, the IIT decided to invest in infrastructure in order to build the perfect power prototype. To reduce consumption, improve energy efficiency and accommodate its growth the new infrastructure take an important role.

To demonstrate intelligent grid applications, validate new smart grid technologies, and create innovative policies to better serve consumers, IIT is working in collaboration with the Galvin

Electricity Initiative (GEI) and other partners that play an important role in order to develop the innovative infrastructure.

The campus is located near Comiskey Park, located close to the Chicago White Sox stadium, and during baseball games the ITT is involved in load reduction. For this, they receive significant payments, so IIT invested $3 million in order to record how much load is needed and is being used in various buildings; to achieve this, they invested in smart meters to record it.

To build the microgrid, IIT counts on $5 million of industrial funds and $7 million of federal funds (DOE) together for five years. The main objective and purpose is to create a smart grid capable of self-healing, learning and self-awareness, that is capable of identifying and islanding in case of fault, redirects power to accommodate generation and load changes and, since it is able to self-balance when necessary, then reduces demand and reduces grind blackouts that last a long time because of weather forecasts.

Based on PJM/ComEd market signals, the IIT microgrid is the first prototype of an integrated microgrid system that is able to operate islanded from the grid while providing the power needed for the entire campus.

The innovative technology applications mentioned above could include: high reliability distribution system, intelligent perfect power system controller, advanced ZigBee wireless technology, advanced distribution recovery systems, buried cable fault detection and mitigation.

The highest power needed is around 10MW. To provide this power, ITT relies on DER including two 4MW combined cycle gas units and a small turbine, and the institute plans to include in this infrastructure rooftop solar PV panels and a 500kWh battery. In total, the power produced is around 9MW, so most of the time the campus is able to operate in an islanded mode, and not having to import power from the grid. IIT is able to operate with full islanding and it has already been tested.

In order to reduce peak demand load by up to 50%, around 20% of the load can be shed, achieving a high reduction in carbon emissions.

In a few years, ITT can be considered a sustainable urban campus because, in quantity or potency, the materials leaving campus do not exceed what the ecosystem can handle. By 2020, the institute plans to reduce carbon emissions by 50% compared with a baseline of fiscal year 2008.

Three 12.47kV circuit feeders supply the IIT's demand. The distribution grid is ComEd and the IIT microgrid is connected to the Fisk substation (owned too by ComEd). The distribution system consists of supply/feeder breakers, building transformers and 12.47/4.16 kV transformers. The peak load is approximately 10MW. Buildings at 120V (in each building) are fed through the primary feeder and with a secondary redundant feeder, which is a backup that incorporates an automatic switch.

2.1.3 UCSD (University of California, San Diego)

The UCSD microgrid project supplies electricity, heating, and cooling for a 450-hectare campus with a daily population of 45,000. The microgrid has two gas turbines with an output of 13.5MW and one steam turbine with an output of 3MW. It also has a solar-cell installation with an output of 1.2MW. Hence, the microgrid is able to supply 85% of campus electricity needs, 95% of its cooling and the same for heating. The new infrastructure not only implied savings, it also contributed to the reduction of the local emissions. The turbines produce 75% less emissions of criteria pollutants than a conventional gas power plant. The infrastructure also includes a 14,385 m3 capacity thermal energy storage bank and a molten carbonate fuel cell with an output of 2.8MW running on waste methane.

The microgrid is sponsored by California's self-generation incentive program and a 30% federal investment tax credit. The distribution grid is SDG&E and a single 69kV substation connects the campus to it. The infrastructure has been installed with power meters through the main electrical lines and at the circuit breakers. A high-end controller/Paladin has been installed, and it will control generation, storage and loads in order to optimize operating conditions. The Paladin is supported by a software installation, which processes market-price signals, availability of resources and weather forecasts.

2.2 Residential Microgrids

A residential house presents a fairly uniform daily load. The electrical load profile of a residential house shows two distinct peaks. The first, smaller one occurs in the early morning and tops out around 9:00 a.m. The second one is much higher, lasting until about 8:00 p.m. Finally, we can appreciate low loads throughout the day.

Figure 10 shows the load profile for a typical residential house, which monthly uses 903kWh per household.

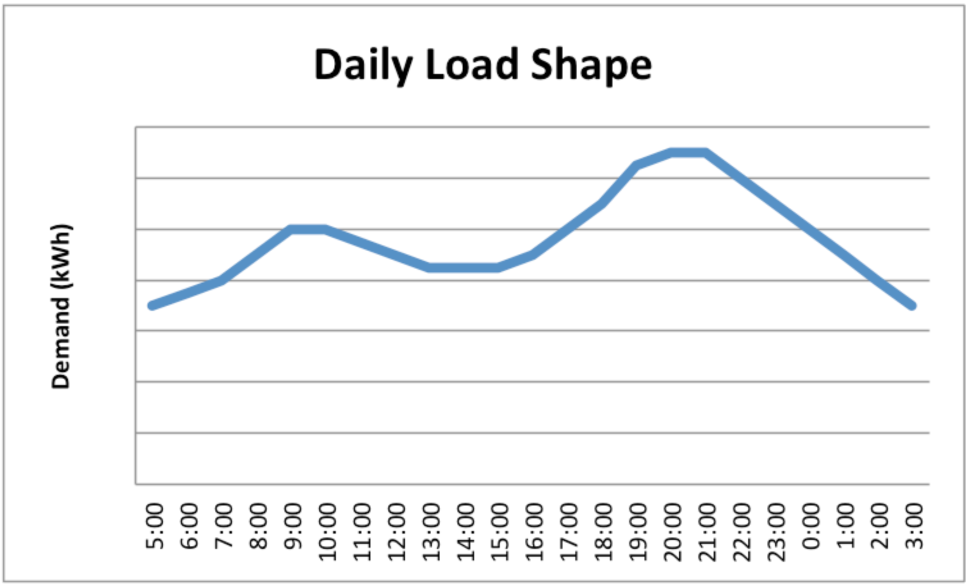


Figure 16. Residential Daily Load Curve

Residential microgrids use an average of 15kW, which corresponds to a middle class house, and most of them rely on DERs such as natural gas, PV panels and fuel cells and CHP units to generate electricity. Hence, they rely on a battery bank and hot and cold thermal storage of energy. Furthermore, a customer, the utility, a developer or an investment trust can own a residential microgrid.

Now we are going to study different residential houses that have already invested in microgrids; today these are the most important examples of residential microgrids.

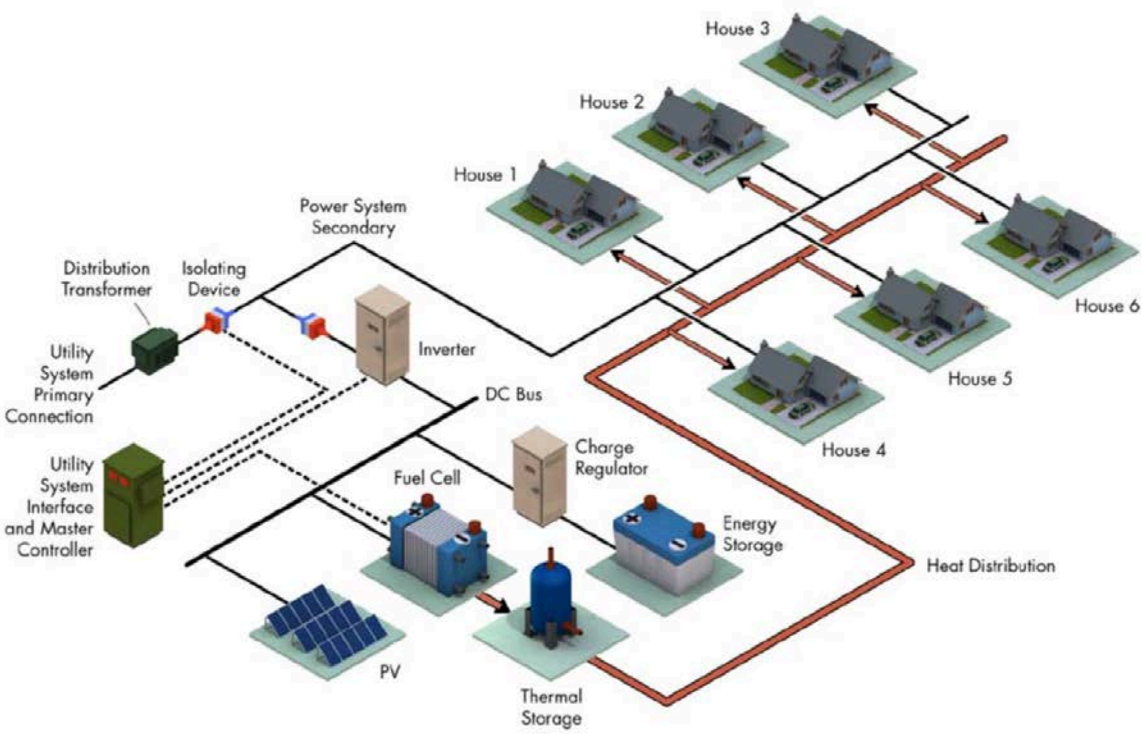


Figure 17. Residential Microgrid

2.2.1Mesa del Sol

Mesa del Sol is located in Albuquerque, New Mexico. Japan’s New Energy and Industrial Technology Development Organization (NEDO) alongside the Public Service Company of New Mexico, Sandia National Laboratory, and a number of Japanese companies including Shimizu, Toshiba, Tokyo Gas, Mitsubishi, Fuji Electric, Furukawa Battery, among others, developed the microgrid project.

The microgrid has a solar PV system with an output of 50kW, a fuel cell with an output of 80kW and a natural gas-powered generator with an output of 240kW. Hence, the microgrid has a lead-acid battery bank and hot and cold thermal storage. A method for estimating the carbon emissions has been developed by The World Building Council relying on the US Environmental Protection Agency’s eGrid database, which determines the emissions on a tonperMWh basis local generation. The results revealed a carbon factor of 1.992 lbs/kWh. The purpose is to eliminate more than 30MW of demand and reduce the 50000 tons of annual carbon emissions.

Input	Size	Business as Usual	Carbon Emissions, tons
Mixed Use	11,000,000 sq-ft	200,000 MWh	200,000
Residence	12,455 units	125,000 MWh	125,000
		Total	**325,000**

Table 3. Mesa del Sol, Carbon Emissions

2.2.2 Mannheim-Wallstadt

The microgrid project in Mannheim-Wallstadt, Germany, was made in order to transform an inhabitant ecological estate into a residential and commercial area, which has been undertaken and developed by MVV (the state utility company since 2006).

The project was supported by a lot of private investors and the European FP6. As a microgrid, the project's main goal is to smoothly and swiftly switch from connected to the grid mode to island mode.

The microgrid uses an average load of 80kW to 230kW, and every building needs 60 kW for ventilation and 48kW for boiler loads. The microgrid relies on several distributed generators such as fuel cells with an output of 4.7kW, a solar PV system with an output of 3.8kW and two CHP units with an output of 9kW and 5.5kW respectively. The infrastructure also has a flywheel storage unit with an output of 1.2kW. Private investors also installed one more CHP and five solar PV systems with a total output of 30kW.

The microgrid was tested by MVV and when switching from grid-connected mode to islanded mode the frequency only increases 2Hz given the reduction of connected loads when it is islanding. When the microgrid is connected again to the main grid, it returns instantly to its normal frequency. The project has demonstrated how renewable energy helps improve energy supply and could be adopted by a community.

2.3 Isolated Microgrids

Isolated areas are mainly rural areas and farms. Rural areas, depending on the state, could use an average of 531kWh to 1245kWh a month and the load curve presents two distinct peaks. The first one is smaller and occurs in the early morning and tops out around 9:00 a.m. The second one is much higher, lasting until about 8:00 p.m. and in case of a dairy farm the peaks are coincident with the milking periods, one in the morning and one in the night, and the peaks are much higher. Finally we can expect low loads throughout the day.

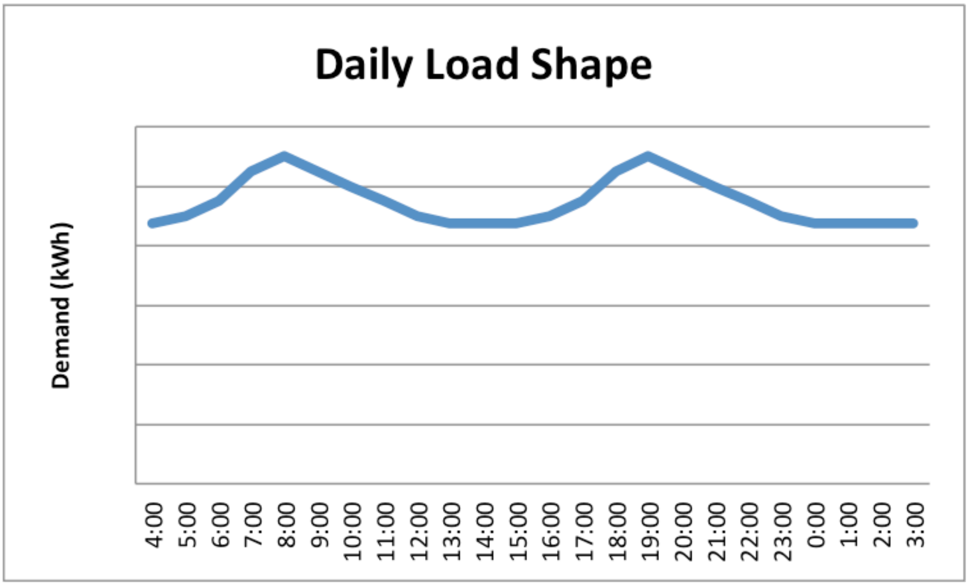


Figure 18. Isolated areas Daily Load Curve

Those isolated microgrids load is 4MW to 10MW, but depending on the size this kind of microgrid load could vary. Most of them rely on DERs such as diesel generators and PV panels to generate their electricity. A single transmission line to the main grid generally connects isolated microgrids. Hence, they rely on flywheels and energy storage units to storage their energy. Moreover, the utility and investment trust can own isolated microgrids.

Now we are going to study different rural areas that have already invested in microgrids; these are nowadays the most important examples of rural microgrids.

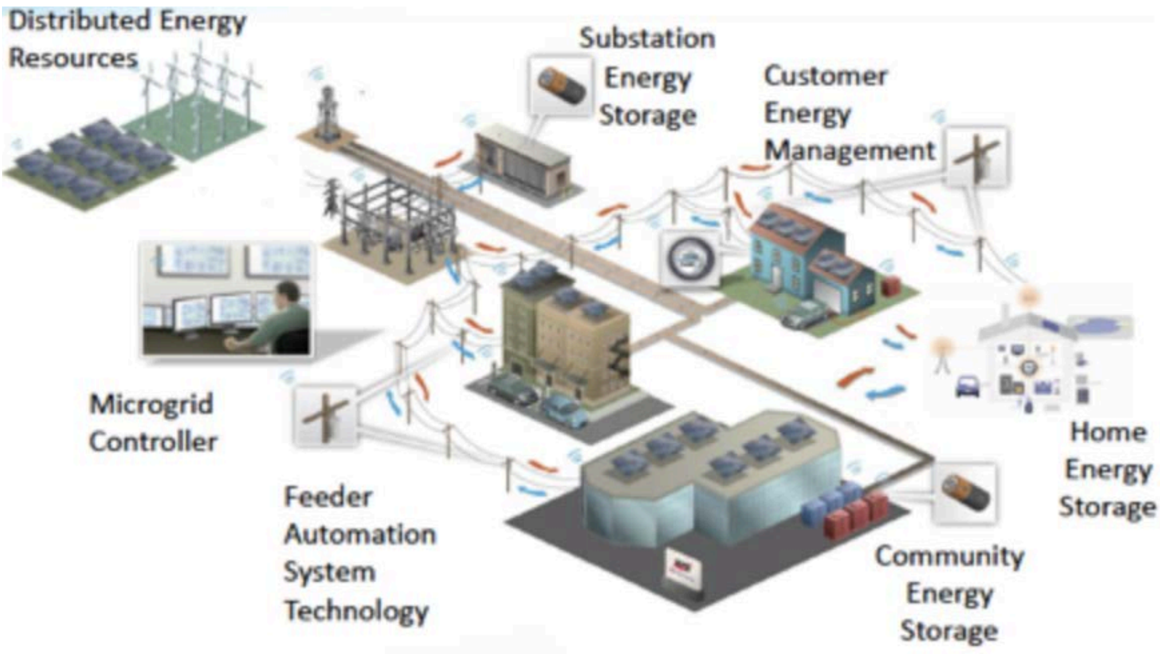


Figure 19. Isolated Microgrid

2.3.1 Borrego Springs

The microgrid is located in the residential community of Borrego Springs in California and it is a clear example of an “unbundled utility microgrid” where some of the DERs are owned by customers but most of the distribution assets are owned by the utility, San Diego Gas and Electric Company’s (SDG&E).

The main purpose of the microgrid is to increase utility asset utilization and reliability provided by DERs and new technologies.

The project’s partners include Lockheed Martin, IBM, Advanced Energy Storage, Horizon Energy, Oracle, Motorola, Pacific Northwest National Laboratories, and University of California San Diego. The US DOE supported the project with $7.5 million of federal funding; other funds came from the utility company (SDG&E) with $4.1 million, CEC with $2.8 million and other companies and partners with $0.8 million.

As a rural area, it is isolated and that is why, a single sub-transmission line feeds it. The microgrid is capable of completely islanding the entire substation area and, if demonstrated to be reliable could be an alternative to building additional transmission capacity.

Before installing the microgrid in the rural area, the community already had installed many rooftop solar PV systems. SDG&E is exploring the possibilities of price driven demand response, via interaction with in-home storage, electric vehicles, and smart appliances using the areas installed smart meters and home area network devices.

The infrastructure has a total capacity of 4MW and the microgrid relies on several distributed generators such as two diesel generators with an output of 1.8MW, rooftop solar PV with an output of 700kW and has 125 residential home area network systems. For storage, the microgrid relies on a large battery of 500kW/1500kWh at the substation, three smaller batteries of 50kWh and six 4 kW/8 kWh home energy storage units.

2.3.2 Greece: The Kythnos Island Microgrid

The rural area comprises 12 houses and it is located in a small valley on Kythnos, an island in the Cyclades Archipelago of the Aegean Sea.

The microgrid relies on several distributed generators such as a solar PV system with an output of 10kW, a diesel generator with an output of 5kW and a second solar PV system with an output of 2kW placed on the roof of the control system building.

For storage, the microgrid relies on a battery bank of 53 kWh, and another battery bank of 32 kWh and is located on the roof close to the solar PV system; there is also a SMA inverter to provide power for monitoring and communication.

Three SMA battery inverters (with an output of 3.6 kW) are connected in parallel master-slave configuration, forming a strong single-phase circuit. When consumers demand more power, more than one of these battery inverters is used. They can operate in frequency droop mode limiting the power output of the PV inverters when the battery bank is full and allowing information to switching load controllers if the battery state of charge is low.

2.3.3 Hartley Bay

Hartley Bay is located in British Columbia in Canada, and it is a remote coastal village accessible only by air or water. The area has a community of 170 members where the microgrid is located and providing power. Thanks to new technologies and improvements, places like Hartley Bay can improve their energy management and save money.

The microgrid relies on several distributed generators, including three diesel generators with an output of 420kW providing electricity to 62 homes and there is another one with an output of 210 kW providing electricity to more than 20 commercial buildings.

Since 2008, the community has undertaken the full optimization of it energy network, with smart meters across the village; energy use is monitored in-real time and they installed flow sensors are installed on the generators to evaluate their efficiency.

In commercial buildings they deployed the demand response system, composed of 20 variable thermostats and 12 load controllers able to reduce the maximum demand by 15% (which means 61.3kW).

This project saves around 77000L of diesel fuel per year and now the community is planning to introduce new innovations such as DR programs that could help save an additional 5% of annual fuel costs.

2.4 Critical Loads

A “critical load area” presents a fairly uniform daily load with the requirement of continuous electricity supply throughout. The electrical load profile of these buildings shows no distinct peaks.

Figure 14 represents the load profile for a typical example of a “critical load” building, in which the average power depends on the purpose of the building, but the curve is almost the same for all of them.

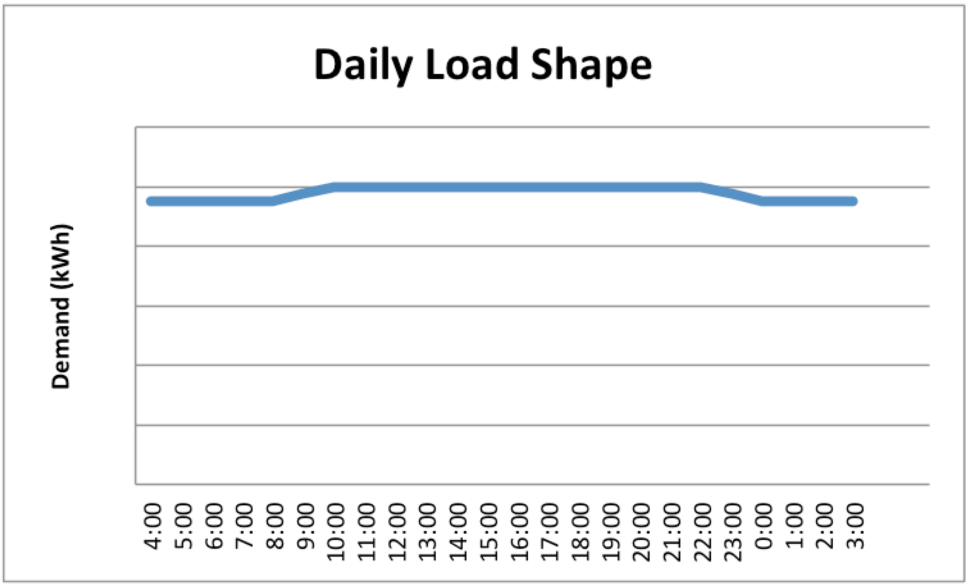


Figure 20. “Critical Loads” Daily Load Curve

These “critical load” microgrids use an average of 15kW, which corresponds to a middle class house, and most of them rely on DERs such as fuel cells, PV panels and diesel generators to generate their electricity. The storage for these microgrids is composed mainly batteries (including lithium batteries and energy battery units) and capacitors. Thus, the state, local government entities, a customer or a company can own this kind of microgrid.

In this section, we have classified as “critical loads” Army Bases and hospitals. Hospitals in the U.S. use an average of 27.5 kWh annually. Hospitals use 72% of their energy for lighting, heating and hot water, making those systems the best targets for energy savings. Microgrids are very suitable for these buildings because they need constant electricity supply even during an outage, but there are not real examples of hospital microgrids.

Now we are going to study different “critical loads” areas that have already invested in microgrids; these are nowadays the most important examples of this kind of microgrids.

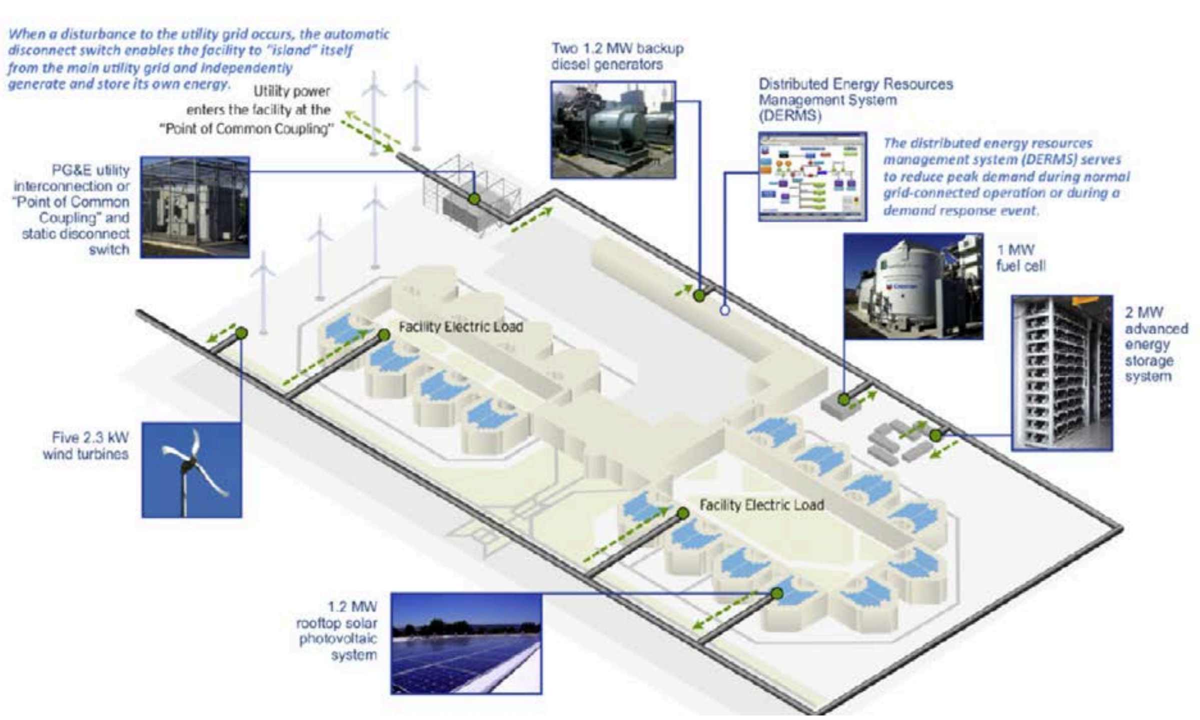


Figure 21. "Critical Loads" Microgrid

2.4.1 Santa Rita Jail

Santa Rita is located in Dublin, California. The jail operates in Alameda Country and has installed distributed energy resources to reduce energy consumption.

Peak demand is approximately 3MW. Santa Rita Jail is one of the best examples of a microgrid in the world today. The infrastructure takes its energy from solar PV panels with an output of 1.5MW and carbonate fuel cell with an output of 1MW; the jail also has back-up of diesel generators that can operate in grid-connected or islanded mode using a lithium iron battery of 2MW-4MWh as a balancing resource. Hence, the battery and the switch allow the microgrid to operate in islanded mode, disconnecting from the main grid and reconnecting to it again.

On the other hand, to reduce the peak load in the local feeder by 15% the jail must contract with the utility company PG&E, but reliability is a major concern. When a blackout occurs takes a few minutes to diesel generators begin, but the jail needs a constantly supply that is why it is a real concern.

Jail specifications: Over 2.4 million kWh of annual electricity is no longer purchased from the power grid.

System Specifications

System size:	1.18 MW
Annual Power Generated:	1,460 MWh
PowerLight Photovoltaic Roof Tiles:	9,726
Solar Array Size (square feet):	130,000
Solar Array Size (acres):	3 aprox.

2.4.2 Department of Defense grid-tied microgrid, Fort Bliss, Texas

This Army Base is located in Texas and the microgrid project started in 2010. To produce its electricity the microgrid relies on renewable energy such as solar arrays with an output of 120kW and relies on back-up generators. For storage, the infrastructure has a battery system of 300kW. The Army is investing in more solar arrays and other renewable energy projects and has invested in partnership with local utility El Paso Electric $120 million in a solar PV plant with an output of 20MW. The back-up generators installed for energy storage are too small, which means low cost and low cost maintenance.

2.5 Commercial Microgrids

In most commercial buildings, demand for electricity varies significantly. The load profile exhibits variations in demand over days, and demand in commercial buildings is higher on weekdays than on weekends.

In most commercial buildings there are a cafeteria, social meeting rooms, high-end multimedia, audiovisual systems and an auditorium for a number of congregants besides offices and stores. By managing the spaces in the area, some efficiency measures can be implemented.

Another important factor is the size of the commercial area; from data taken over a 24-hour period we can say that commercial buildings use an average of 4.5kWh annually per ft^2 and the load curve presents a high peak during the day and tops out around 1:00 pm.

Commercial buildings consume approximately 19% of all energy in the U.S. and contribute 18% of all CO_2 emissions. By 2035 the space for commercial areas is expected to increase by 28%; that is why, nowadays, the concern about sustainability is increasing. Hence, energy management is important in order to achieve energy conservation and to reduce environmental impact.

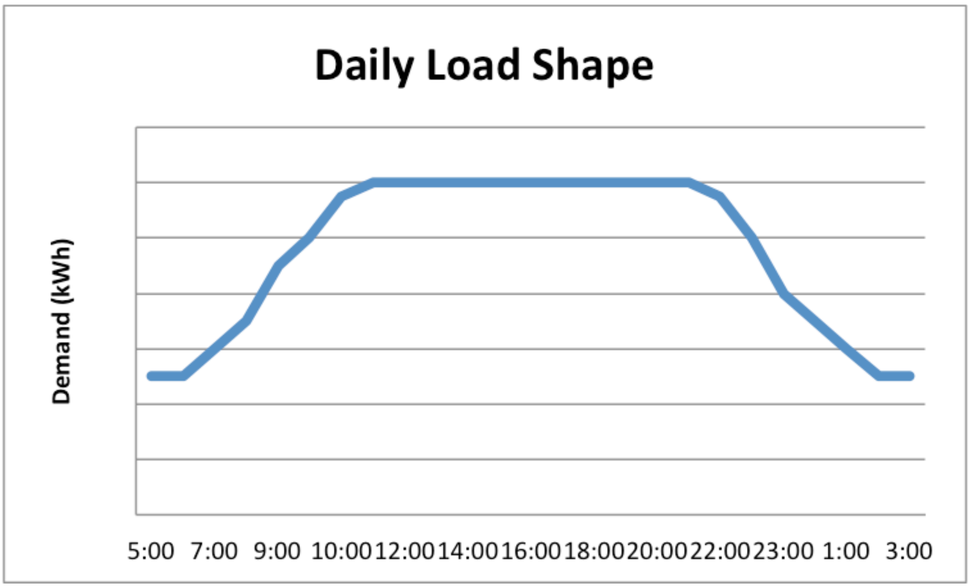


Figure 22. Commercial Daily Load Curve

Those commercial microgrids load is 4MW to 40MW but depending on the size this kind of microgrid load could vary. Most of them rely on DERs such as natural gas, PV panels and fuel cells and CHP units to generate their electricity. Hence, they rely on a battery bank and hot and cold thermal storage to store their energy. Like residential microgrids, customers, utilities, developers or investment can own commercial microgrids trusts.

A commercial microgrid should interact with the smart grid, where Demand Response (DR) plays an important role minimizing peak demand.

Nowadays, there are many commercial areas that have already invested in microgrids. The most important commercial microgrid examples have been explained in section 2.2, "residential microgrids", these examples are Borego Springs and Mesa del Sol.

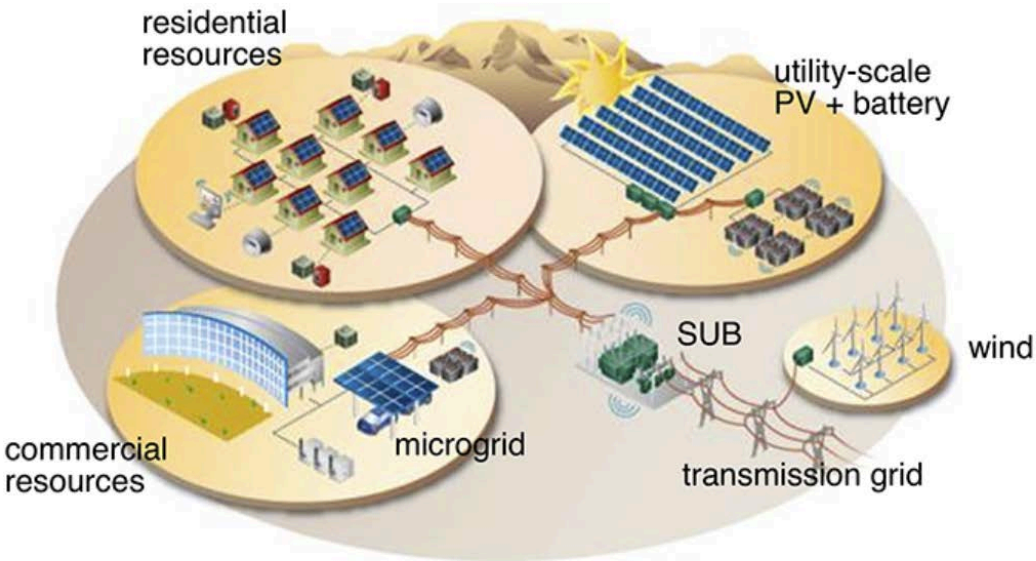


Figure 23. Commercial Microgrid

3. Description of Research Results

Now that we have explained our characterization in detail, based on real examples of microgrids we are going to find similarities and dissimilarities among these categories.

First of all, we are going to study common characteristics since it is more difficult to find them in all of categories, and then we are going to study dissimilarities among them since there are a lot of differences among these categories.

3.1 Common Characteristics

Since there are a lot of differences among the categories, even a lot of differences among different microgrids in the same group, it would be easier to begin with common characteristics among them.

Table 4 examines the different kind of microgrids and how they produce its electricity nexus. The results are that all of them could generate its electricity using solar PV panels, residential and commercial microgrids generate its electricity in the same way.

	University C.	Residential	Commercial	Isolated areas	Critical Loads
CHP systems	✗	✗	✗		
Solar PV Panels	✗	✗	✗	✗	✗
Gas Turbines	✗				
Steam Turbines	✗				
Fuel Cells			✗		✗
Natural Gas		✗	✗		
Diesel generators				✗	✗

Table 4. How Microgrids generate its electricity

Table 5 examines the different kind of microgrids and how they manage their storage nexus. All of them use batteries to store its energy, and flywheels, capacitors and hot and thermal storage are not very common.

	University C.	Residential	Commercial	Isolated areas	Critical Loads
Batteries	✗	✗	✗	✗	✗
Capacitors					✗
Flywheels				✗	
Hot/Cold Thermal Storage		✗	✗		

Table 5. Storage Management

Table 5 examines our groups of microgrids and ownership of microgrids, in which energy is produced, nexus. The table shows that private customers could own all the different kind of infrastructures; residential, commercial are almost always owned under the same ownership:

	University C.	Residential	Commercial	Isolated areas	Critical Loads
Private Customer/s	✗	✗	✗	✗	✗
Developer		✗	✗		
Utility		✗	✗	✗	
Investment Trust		✗	✗	✗	
State or Local Government entities	✗				✗
Company			✗		✗

Table 6. Microgrids ownership

3.2 Uncommon Characteristics

The main difference is the amount of electricity they consume and the amount of electricity they generate. Depending on the project, they produce and consume more or less power. The ones with higher average are Campus Microgrids, Commercial Microgrids and "Critical Loads" Microgrids. The ones with lower average are Isolated and Residential Microgrids. Many different projects vary in a wide range of power from kW to MW because of the size of the project, the bigger they are, the more power they need.

We have defined a microgrid, as a cluster of interconnected loads and DERs. Most of these DERs generate electricity coming from renewable resources, which means lower emissions and pollutants. This is another difference among the categories (and even among the microgrids in the same group): they reduce their pollutant emissions in by different amounts depending on how many renewable resources they have.

4. Conclusion

During this research, we have presented microgrids as a group of interconnected loads and DERs able to connect and disconnect from the main grid within electrical boundaries. Microgrids appear because they solve the problem that we have with all the distributed generators, since the distribution company does not know how many distributed generators are installed and how many MW they produce. Here, microgrids play an important role because they provide more control over these distributed generators. Microgrids encompass not only distributed generators; they also have distributed storage and customer loads. The main characteristic is that a microgrids has two modes of operation, the connected mode and the islanded mode, and two transient states, and in all of them, it has to remain stable.

Microgrids have been implemented in a wide variety of projects that vary from kW to MW depending on the magnitude of the project and they are connected to the grid at low voltage. We have explained that microgrids are able to supply the energy needed, but they also require control and reliability over their DERs since most of these microgrids are located in areas that require constant supply.

After introducing microgrids and their salient features we stated why is this paper interesting, since there are many studies and published papers introducing revolutionary ideas in order to improve microgrids or future architectures that are not developed yet. Other studies have focused on the benefits and problems that microgrids have in order to be implemented, such as costs.

This paper offered a possible characterization of microgrids based on application. We have classified them as campus, residential, islanded, commercial and "critical loads" microgrids.

Campus microgrids are one of the most suitable areas for the implementation of microgrids since they require constant supply almost all day long. By implementing microgrids, campusses reduced the local emissions and pollutants by 40% on average and they also reduced their bills by implementing cost-effective and energy-efficiency measures. Campus microgrids use an average of 4 to 40MW and they mainly rely on CHP systems, PV solar panels and gas/steam turbines to generate electricity. Hence, they rely on energy storage banks to store their energy. The home campus, government partners, private investors or academic partners can own University campuses.

Residential microgrids use an average of 15kW corresponding to a standard house. These microgrids might be able to supply a house's electricity needs even during the two peak hours that the daily load profile shows that occur around 9:00 am and around 8:00pm. They also rely on PV panels, natural gas and CHP systems to generate their electricity. Hence, they rely on energy storage banks and hot and cold thermal storage to store their energy. Furthermore, a customer, the utility, a developer or an investment trust can own a residential microgrid.

Isolated areas are mainly rural areas and farms. The peculiarity of this kind of microgrids is that it is connected to the grid with a single transmission line. Depending on the size of the area and their application isolated microgrids use an average of 4MW to 10MW to generate its electricity. They also rely on PV panels to generate their electricity but they also rely on diesel generators. Hence, they rely on energy storage units and flywheels to store their energy. Moreover, the utility and investment trust can own an isolated microgrids.

We have defined the next group as "Critical Loads" because they need constant supply even during an outage. We have included in this group hospitals and army bases. The average daily load varies depending on the application, but the daily load curve is pretty similar since it is very uniform since they need constant supply. No hospital exists yet, but it would be a suitable building for a microgrid. This kind of microgrids relies on fuel cells, solar PV panels and diesel generators to generate their electricity and batteries and capacitors for storage. Hence, they rely on batteries (such as lithium battery) and capacitors to store their energy. Thus, the state, local government entities, a customer or a company can own this kind of Microgrids.

Finally the last group that we have studied is commercial microgrids. All of these microgrids are nowadays located within residential buildings, but in the near future, commercial microgrids will be built separately from residential buildings and some efficiency measures are going to be implemented. This kind of microgrid uses an average of 4 to 40MW annually relying on natural gas, solar PV panels, fuel cells and CHP unit systems to generate their electricity. Hence, they rely on energy storage banks and hot and cold thermal storage to store their energy. Commercial buildings consume 19% of the energy in the U.S. and it is planned to increase; that is why energy management so important. Like residential microgrids, can be owned by customer, utilities, developers or investment trusts.

References

[1] "Advanced combustion engines", *U.S. Department of Energy*. Available at: http://energy.gov/eere/vehicles/vehicle-technologies-office-advanced-combustion-engines

[2] Arghandeh, M. Brown, A. Del Rosso, G. Ghatikar, E. Stewart, A. Vojdani and A. von Meier, "The Local Team, Leveraging distributed resources to improve resilience", *IEEE Power & Energy Magazine*, pp. 76-83, September-October 2014.

[3] M. Barnes, J. Kondoh, H. Asano, J. Oyarzabal, G. Ventakaramanan, R. Lasseter, N. Hatziargyriou and T. Green, "Real-World Microgrids-An Overview", *IEEE International Conference System of Systems Engineering*, 2007. SoSE '07, pp. 1-8, April 2007.

[4] "Battery chargers and the benefits of rechargeable batteries", *Top Ten Reviews*. Available at: http://battery-charger-review.toptenreviews.com/battery-chargers-and-the-benefits-of-rechargeable-batteries.html

[5] "Benefits of combined heat and power", *U.S. Department of Energy*. Available at: http://energy.gov/eere/amo/benefits-combined-heat-and-power

[6] "BU-209: How does a supercapacitor work?", *Battery University*. Available at: http://batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor

[7] N. Brown, "Cheaper ultracapacitors for electric vehicles", *Clean Technica*, May 2011.

[8] V. Calderaro, V. Lattarulo, A. Piccolo and P. Siano, "Optimal Switch Placement by Alliance Algorithm for Improving Microgrids Reliability", *IEEE Transactions on Industrial Informatics*, vol.8, no. 4, pp. 925-934, November 2012.

[9] B. L. Capehart, "Microturbines", *Whole Building Design Guide, National Institute of Building Sciences*, April 2014.

[10] W. Chae, H. Lee, S. Hwang, I. Song and J. Kim, "Isolated MicroGrid's Voltage and Frequency Characteristic with Induction Generator Based Wind Turbine", *Scientific Research, Smart Grid and Renewable Energy*, pp. 180-192, 2014.

[11] "Characteristics of rechargeable batteries", *Texas Instruments*, Literature number SNVA533.

[12] "CHP Finance", *U.K. Department of Energy and Climate Change*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/345190/Part_5_CHP__Finance.pdf

[13] "Combined heat and power basics, *U.S. Department of Energy*. Available at: http://energy.gov/eere/amo/combined-heat-and-power-basics

[14] "Combined heat and power: frequently asked questions", *EPA CHP partnership*. Available at: http://www.epa.gov/chp/documents/faq.pdf

[15] S. Curtin and J. Gangi, "The business case for fuel cells 2013 reliability, resiliency and savings", *Fuel Cells 2000*, December 2013.

[16] R. C. Davison, "How do rechargeable batteries work?", *Bright Hub Engineering*, May 2010.

[17] F. J. R. Ducoy, "Implantación de energías renovables en una planta de producción de Amoniaco". Available at: http://bibing.us.es/proyectos/abreproy/5145/fichero/3.+%BFQu%E9+es+una+microrred.pdf

[18] Electricity 101, Frequent questions, *U.S. Department of Energy*. Available at: http://energy.gov/oe/information-center/educational-resources/electricity-101

[19] J. Eyer, "Benefits from flywheel energy storage for area regulation in California-demonstration results, a study for the DOE Energy Storage Systems Program", *Sandia Corporation*, October 2009.

[20] B. Falber and N. Feller, "The top 6 legal factors holding back Microgrids", July 2013. Available at: http://www.greentechmedia.com/articles/read/the-top-6-factors-holding-back-microgrids

[21] "Flywheel Energy Storage", *the green age*. Available at: http://www.thegreenage.co.uk/tech/flywheel-energy-storage/

[22] “Flywheels energy storage”, *U.S. Department of Energy*. Available at: http://smartenergy.illinois.edu/pdf/Archive/FlywheelEnergyStorage.pdf

[23] “Fuel cells”, *U.S. Department of Energy*. Available at: http://energy.gov/eere/fuelcells/fuel-cells

[24] M. Hadinezhad and M. Gandomkar, Voltage Control of Microgrid Systems Connected to Power Network System in Fault Condition, in *International Electrical Engineering Journal (IEEJ)*, vol. 4 (2013) No. 3, pp. 1087-1097

[25] N. Hatziargyriou, H. Asano, R. Iravani, C. Marnay, “Microgrids”, *IEEE Power & Energy Magazine*, pp. 78-94, July-August 2007.

[26] E. Hayden, “Introduction to Microgrids”, *Securicon*, 2013.

[27] “How do wind turbines work?”, *U.S. Department of Energy*. Available at: http://energy.gov/eere/wind/how-do-wind-turbines-work

[28] “Internal combustion engines”, *U.S. Department of Energy*. Available at: http://energy.gov/eere/energybasics/articles/internal-combustion-engine-basics

[29] J. Kelly, M. Meiners and G. Rouse, “Mesa del Sol. A path to perfect Power”, *Galvin Electricity Initiative*, December 2007.

[30] J. Kelly and G. Rouse, “Electricity reliability, problems, progress and policy solutions”, February 2011. Available at: http://www.galvinpower.org/sites/default/files/Electricity_Reliability_031611.pdf

[31] U. A. Khan, J. Hwang, J. Seong and B. Leel , “Application and Positioning Analysis of a Resistive Type Superconducting Fault Current Limiter in AC and DC Microgrids using Simulink and SimPowerSystem”, *IEEE Electric Power Equipment*, pp. 348-351, October 2011.

[32] J. E. Lane and K. Kinser, “Five Models of International Branch Campus Ownership”, *International Higher Education*, 2012. Available at: http://www.academia.edu/2395628/Five_Models_of_International_Branch_Campus_Ownership

[33] R. Lasseter, "Microgrids", *IEEE Power Engineering Society Winter Meeting*, Vol. 1, pp. 305-308, 2002.

[34] R. Lasseter and P. Paigi, "Microgrid: A Conceptual Solution", *IEEE Power Electronics Specialists Conference*, vol. 6,pp. 4285 – 4290, June 2004.

[35] C. Legere, "Baker appointments may signal change in policy", *Cape Cod Times*, January 2015.

[36] H. Liang and W. Zhuang, "Stochastic Modeling and Optimization in a Microgrid: A Survey", March 2014. Available at: http://www.mdpi.com/1996-1073/7/4/2027/htm

[37] N. W. A. Lidula and A. D. Rajapakse, "Microgrids research: A review of experimental microgrids and test systems", September2010. Available at: http://www.academia.edu/7273103/Microgrids_research_A_review_of_experimental_microgrids_and_test_systems_A_R_T_I_C_L_E_I_N_F_O

[38] A. Maitra, B. York, H. Kamath, T. Key and V. Singhvi, "Microgrids: A Premier", *EPRI Electric Power Research Institute*, September 2013.

[39] P. Mayer, "What it cost: Combined heat and power systems", *Building.co.uk*, August 2007.

[40] C. Marnay and G. Venkararamanan, "Microgrids in the Evolving Electricity Generation and Delivery Infrastructure", February 2006. Available at: http://emp.lbl.gov/sites/all/files/REPORT%20lbnl%20-%2059544.pdf

[41] C. Marnay, G. Venkataramanan, M. Stadler, A. Siddiqui, R. Firestone, and B. Chandran, "Optimal Technology Selection and Operation of Microgrids in Commercial Buildings", *IEEE Transactions on Power Systems*, vol. 23, n. 3, August 2008.

[42] P. Mason, J. McGervey, E. Yuzugullu, "An Evaluation guide for fuel cell deployments at EPA superfund sites", *SRA International, Inc*. Contract EP-W-07-023, Assignment 306, January 2012.

[43] "Massachusetts Microgrids: Overcoming Legal Obstacles", *Harvard Law School*, September 2014. Available at: https://hlsenvironmentallaw.files.wordpress.com/2014/09/masschusetts-microgrids_overcoming-legal-obstacles_final12.pdf

[45] L. Martirano, S. Fornari, A. di Giorgio, F. Liberati, "A case study of a commercial/residential microgrid integrating cogeneration and electrical local users", *IEEE Environment and Electrical Engineering*, pp. 363-368, May 2013.

[46] "Microturbine demonstration project", *Hennepin*. Available at: http://www.naco.org/programs/csd/Green%20Government%20Database/Hennepin%20County%20MN%20Microturbine%20Demonstration%20Project.pdf

[47] T. Mohn, "Microgrid Workshop", *CEO, General Microgrids Chairman, Microgrid Alliance*, May 2014.

[48] G. Y. Morris, C. Abbey, S. Wong and G. Joós, "Evaluation of the Costs and Benefits of Microgrids with Consideration of Services beyond Energy Supply", *IEEE Power and Energy Society General Meeting*, pp. 1-9, July 2012.

[49] A.F. Muerza, "Microrredes, una posible revolución energética para los consumidores", March 2009. Available at: http://www.consumer.es/web/es/medio_ambiente/energia_y_ciencia/2009/03/12/183966.php

[50] G. Neagu and A. Stanice, "Grid Infrastructure Development as Support for e-Science Services", *WSEAS TRANSACTIONS on COMPUTERS*, Issue 10, vol. 9, October 2010.

[51] M. Y. Nguyen and Y. T. Yoon, "A Comparison of Microgrid Topologies Considering Both Market Operations and Reliability", in *Electric Power Components & Systems*, March 2014, pp. 585-594.

[52] O. Onodera, "Microgrid activities related to Japan", *The New Energy and Industrial Technology Development Organization (NEDO)*, March 2013.

[53] "Smart grid", U.S. Department of Energy. Available at: http://energy.gov/oe/services/technology-development/smart-grid

[54] M. Soshinskaya, W. Graus, J. Guerrero, J.C. Vasquez Quintero, "Microgrids", *Renewable & Sustainable Energy Reviews*, 2014.

[55] "Solar panels", *Energy saving trust*. Available at: http://www.energysavingtrust.org.uk/domestic/content/solar-panels

[56] "Solar photovoltaic technology basics", *National Renewable Energy Laboratory*, July 2014. Available at: http://www.nrel.gov/learning/re_photovoltaics.html

[57] *The U.S. Department of Energy (DOE).* Available at: http://www.powerislandenergy.com/files/85581241.pdf

[58] "Think microgrid: a discussion guide for policymakers, regulators and end users", *International district energy association, Schneider electric and Microgram knowledge*. Available at: http://blog.schneider-electric.com/wp-content/uploads/2014/06/Think-Microgrid-Special-Report.pdf

[59] S. B. Van Broekhoven, N. Judson, S. V. T. Nguyen, W. D. Ross, "Microgrid Study: Energy Security for DoD Installations", *Lincoln Laboratory MIT*, Technical Report 1164, June 2012.

[60] C. Villarreal, D. Erickson and M. Zafar, "Microgrids: A regulatory Perspective", *California Public Utilities Commission*, April 2014.

[61] B. Washom, J. Dilliot, D. Weil, J. Kleissl, N. Balac, W. Torre and C. Richter, "Ivory Tower of Power", *IEEE Power & Energy Magazine*, pp. 28-32, July-August 2013.

[62] "Wind turbines", Energy saving trust. Available at: http://www.energysavingtrust.org.uk/domestic/content/wind-turbines

[63] B. Winergarden, "Principle 3rd of capacity planning: Matching supply and demand", *Agile, Business agility, Capacity planning*. Available at: https://www.rallydev.com/blog/agile/principle-3-capacity-planning-matching-supply-demand

[64] Y. Xu, E. Hou and N. Ansari, “Economic Coalition Strategies for Cost Reductions in Microgrids Distribution Networks”, *IEEE Global Communications Conference*, pp. 2703-2708, December 2014.

[65] Z. Ye, R. Walling, N. Miller, P. Du and K. Nelson, “Facility Microgrids”, *National Renewable Energy Laboratory, General Electric Global Research Center NY*, NREL/SR-560-38019, May 2005.