Microgrids

White paper

1. Introduction

Distributed generation located close to demand delivers electricity with minimal losses. This power may therefore have a higher value than power coming from large, central conventional generators through the traditional utility transmission and distribution infrastructure. With the use of renewable distributed generation, the dependency on fossil fuels and on their price can be minimized. This step will also lead to a significant reduction of carbon dioxide emissions, which is required in several government programs. If, in addition, distributed generation and consumption in a certain area are integrated into one system, reliability of the power supply may be increased significantly, as shown in figure 1. The importance and quantification of these benefits has been recognized, although these are yet to be incorporated within the technical, commercial, and regulatory framework [11].

However, under today's grid codes, all distributed generation, whether renewable or fossil-fueled, must shut down during times of utility grid power outages [IEEE 1547]. This is precisely when these on-site sources could offer the greatest value to both generation owners and society.

A microgrid is a regionally limited energy system of distributed energy resources, consumers and optionally storage. It optimizes one or many of the following: Power quality and reliability, sustainability and economic benefits and it may continuously run in off-grid- or on-grid mode, as well as in dual mode by changing the grid connection status.

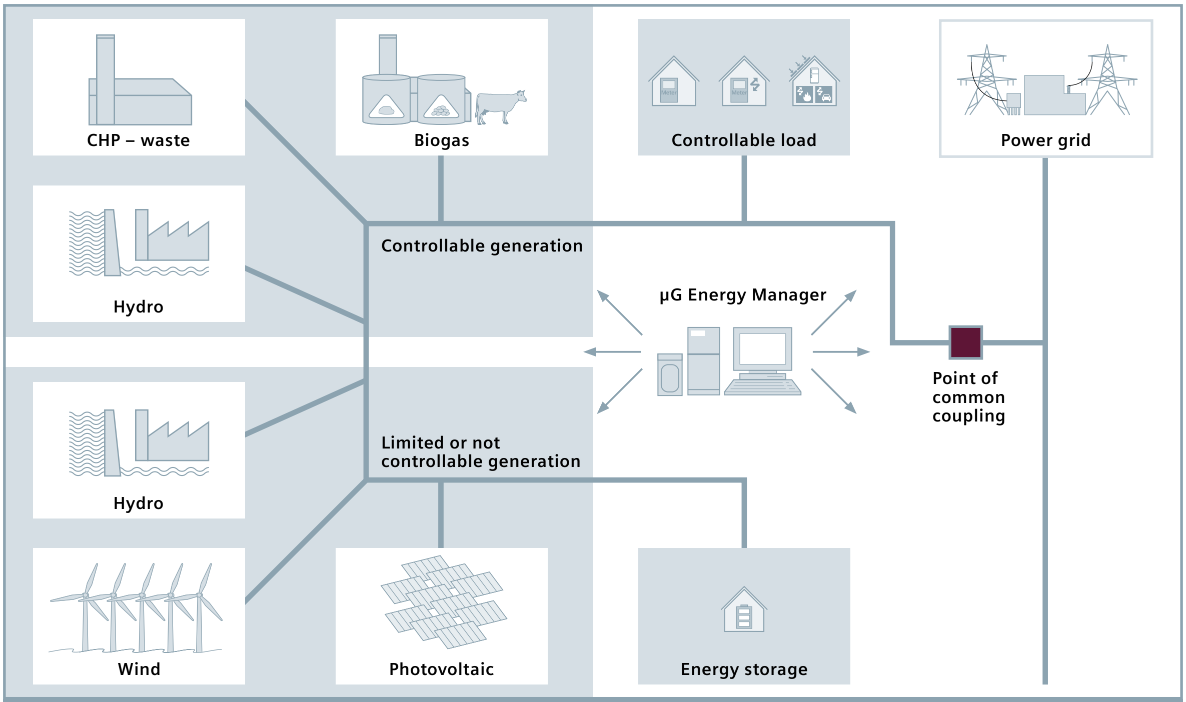

Figure 1: Microgrid with one common point of coupling to the utility grid

According to this definition, a microgrid maximizes the benefits of distributed generators and solves the above-mentioned disadvantage, also utilizing distributed generation during utility power system outages.

In grid-connected mode, the microgrid operator can take economic decisions – such as to sell or buy energy depending on on-site generation capability, its cost, and the current prices on the energy market. In case of a utility power system outage, the point-of-common-coupling breaker will automatically open, and own generators will continue to supply power to loads within the microgrid.

The idea of microgrids is not new. In the very beginning of rural electrification, several microgrid structures had been installed. Later, the economical benefits of an interconnected utility grid with large power plants led to today's power system structures.

Today, there are several industrial sites worldwide with on-site generation and islanding capability. The main reason for these constellations usually is the requirement for process optimization in a certain industrial site. For example, huge amounts of steam are required for chemical processes. In this case the process owner can decide to install its own steam turbine-based generation, which will increase power supply reliability and reduce the cost of energy. The generators in such an industrial sites usually cover exactly the demands of the site, generally to avoid possible generation and demand imbalance in case of islanding. This "classical microgrid" will be separated from the utility grid in case of a disturbance outside the microgrid, and its own generators will continue to supply the process load. The grid connection is a backup solution for the case that one or more on-site generators have to be disconnected, for example due to a fault or for maintenance purposes. The related investments can be justified through the calculation of economical losses caused by utility power system outages and energy cost reduction by the use of the steam, which is created for the chemical process anyway. Other on-site generation systems can achieve a high degree of efficiency through the application of combined heat and power (CHP) or combined cooling and heating power (CCHP) systems, if the heating and cooling can be reasonably used for own processes.

At the same time, there are other on-site generation installations with a different focus. In countries with a weak power grid infrastructure, the main driver of on-site generation is the frequent loss of electrical power, which leads to significant manufacturing losses. Also, there are on-site generator installations in answer to relatively high energy prices. Thus, on-site generation enables energy cost reduction and offers the possibility to sell energy during peak demand time intervals.

However, expectations on today's microgrid structures significantly exceed the capabilities of the systems described above, especially in terms of physical characteristics, and the number and size of distributed generators within the microgrid. A modern microgrid will include renewable and fossil-fueled generation, energy storage facilities, and load control. And this new system will be scalable, which means that growing load may require the installation of additional generators without any negative effect on the stable and reliable operation of the existing microgrid. Typical distributed energy resources for microgrids are wind and solar-powered generators, combined heat and power systems (CHP), and biogas and biomass systems.

A microgrid energy manager (MEM) as shown in figure 1 is a monitoring and control software, which usually includes functions like SCADA (Supervisory Control and Data Acquisition), energy management, generator and load management, system reconfiguration and black start after a fault, system efficiency monitoring, carbon dioxide contribution analysis, system health monitoring and other functions. The microgrid energy manager generally has a communication link to all major generators and loads within the system. In addition, it may receive precise weather forecast data from a professional weather service for all locations of renewable power generators inside the microgrid. Merging this information with the physical characteristics of the generators, the microgrid energy manager can predict the available amount of renewable power generation for the near future. This information helps plan the utilization rate of the fossil-fueled generators within the microgrid.

In grid connected mode, distributed generators and battery systems within the microgrid will synchronize the frequency and magnitude of the voltage at the own terminals to the grid voltage and will optimize the energy supply, as required by the energy manager. Grid voltage and frequency stability is maintained by large rotating generators connected to the utility grid. In islanded mode, however, steady state and dynamic power balance between load, generation, and electrical energy storage, such as batteries, inside the microgrid system must be achieved without any dependency on a central component or on a communication infrastructure. This important requirement has been expressed and proven in successful research projects worldwide [5].The implementation of this feature is possible with intelligent local controllers for generators, battery systems, and load management units in a decentralized and autonomous infrastructure, for example using the classical "frequency droop control", "voltage droop control" and "frequency dependent load control" principles.

In summary, the microgrid energy manager with its variety of functions described above helps operate a microgrid in a very efficient way, while local controllers of distributed generators, batteries and loads care for stable voltage and frequency within the microgrid, in grid connected as well as islanded mode.

Microgrids can be considered the building blocks of a Smart Grid or an alternative path to the "super grid." The most important feature of a microgrid is its ability to separate and isolate itself from a utility's distribution system during power system disturbances and blackouts. This is referred to as "islanding."

Increased expectations on the availability and quality of electrical power have shown the limits of today's power grids, especially in large countries with low population density in remote areas. The transmission and distribution infrastructure in these regions is usually weak for economic reasons, and power availability and quality generally is a serious challenge. The shortcomings of today's utility grids and future challenges on electrical power supply will be discussed in the next chapter.

2. Utility grid shortcomings and microgrid value propositions

Actual and expected utility grid challenges were first published in [3] and have been analyzed by various authors. The following paragraphs summarize the related power supply challenges and the benefits of microgrid installations.

2.1. Power quality challenges

The term "power quality" refers to the quality of the supply voltage in a certain area, which strongly depends on the characteristics of the loads and the transmission and distribution grid infrastructure in this area. Long distribution lines with asymmetric loads, for example, may lead to significant low voltage quality, eventually resulting in effects such as low and unbalanced voltage, voltage harmonics, and flicker in certain load locations.

Power quality challenges are mainly caused by a lack of investment in the grid. In several countries, demand for electricity is growing so fast that the construction of generation plants as well as transmission and distribution lines cannot keep pace. This situation leads to power outages in certain areas when demand exceeds actual generation, or the thermal limits of the power system equipment endanger the integrity of the power systems. Deregulation and tough competition forces utilities in some other countries to economize on investments – a situation that ultimately leads to low power supply quality.

A microgrid with an option to disconnect from the utility grid in case of power quality problems may benefit the loads inside its borders significantly. Depending on the field of application (military, industrial, commercial, or residential, for instance), power quality requirements of the loads inside the microgrid may be different. In highly sensitive industrial areas with semiconductor or chemical manufacturing facilities, for example, reliable power at a high power quality level is required. This may be achieved with the installation of reliable fossil-fueled generators within the microgrid. Additional power-conditioning equipment may be an option if there are nonlinear loads.

In off-grid areas in some developing countries, where residents have no option other than a microgrid solution, most of them will be satisfied with somewhat poorer power quality.

2.2. Natural disasters

In some areas of the world, the Americas or the Indian subcontinent, for instance, natural disasters such as tornados, hurricanes, and earthquakes followed by tsunamis may completely annihilate parts of the transmission and distribution infrastructure. Even if a certain area is not directly affected by the disaster, its power supply may be interrupted for weeks or even months if its connection to the utility grid has been interrupted by such an event.

Due to the fact that a microgrid does not depend on the power supply of the utility grid, the immediate construction of microgrids appears feasible in some areas, especially those that have been repeatedly struck by natural disasters, such as some southern parts of the USA. On the other hand, a microgrid can be planned and assembled in a comparatively short time. It could turn out to be more beneficial to decide for the immediate construction of a microgrid instead of waiting for the reparation and reinstallation of the common transmission and distribution infrastructure after a natural disaster.

2.3. Vulnerability to power system disturbances, terrorist attacks, and human errors and related reliability and security requirements

Power systems face hundreds of disturbances every day, mainly caused by natural incidents such as lightning and arc flashes on rainy days. The majority of disturbances is usually eliminated by protection devices that only separate the affected power system component for a limited period of time – for example a transmission line segment until an arc has disappeared. If a power system meets certain reliability and security requirements, nearly none of these disturbances will lead to significant power outages.

Reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period.

Security of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances.

[The definitions above have been published in “Definition and Classification of Power System Stability,” by IEEE/CIGRE Joint Task Force on Stability Terms and Definitions in 2004.]

In every country of the world, today’s customers expect a reliable and secure power supply. However, an interconnected power system with long transmission and distribution lines will always be prone to disturbances. Unfortunately, there are always some exceptional situations, in which a single disturbance causes cascading outages, eventually leading to blackouts. It is generally expensive and requires a rather long time scale to increase the reliability and security of a large power system.

As mentioned above, a power system is subject to several disturbances every day, and it can cope with these disturbances without any power supply interruption on the customer’s side. In addition to natural disturbances, there are – intentionally or unintentionally – man-made disturbances. This includes physical damage to power system components such as transmission towers or transformers, which may lead to large outages. In today’s digital world, cyber attacks such as intentionally wrong remote switching operations can also cause damage if sensitive communication channels do not meet cyber security requirements. An example of man-made, unintentional damage is an outage due to wrong operational decisions in a power system control center, taken by operators with limited experience and a lack of training.

Irrespective of its nature and source, any power system disturbance can trigger a cascading outage. This happens, for instance, when protection and automation devices in close proximity to the disturbance do not react appropriately to an exceptional situation, which can be the case with inadequately parameterized or faulty devices.

By contrast, a power system consisting of several microgrids is virtually not affected by large outages due to the fact that each microgrid can disconnect from the rest of the system in case of a disturbance.

A microgrid is located in a geographically limited area. Its generation and load, as well as load balance, are controlled by reliable electronic components, and it can disconnect from the utility grid and run in “island” mode if required. The probability that a microgrid will be shut down due to natural disaster, a terrorist attack, or human error is very low. In a power system consisting of several microgrids, a very few of them may be shut down due to disturbances, but most of them will continue operation, either in grid-connected mode or in island mode.

2.4. Growing demand, grid extensions, and social resistance

Everybody wants a reliable power supply. The demand for electrical power is growing in many areas of the world, and people expect appropriate enhancements of the power system, such as new power plants and new transmission and distribution lines.

However, reality shows that everyone opposes the construction of a power plant or a power line in their own neighborhood. This “not in my backyard” attitude makes investments difficult, so building permissions may take ten years, or even longer.

In an area with microgrid structures, a growing demand for electrical energy can be satisfied by the installation of new distributed generators, preferably based on pollution-free generation from renewable sources. This way, microgrids can help defer investments in transmission and distribution systems and solve related social problems such as demonstrations against the installation of transmission lines close to residential areas.

2.5. Optimal utilization of distributed generators

According to today’s grid codes, all distributed generation, renewable or fossil-fueled, must shut down during power outages. But it is exactly in such “emergency situations” that distributed generators offer the greatest benefit to both generation owners and society: microgrids can provide power services to consumers, when the larger grid system fails.

2.6. Peak load limitations

From the utilization point of view, there are three major types of power plants. A base-load power plant produces base-load supply. Base-load plants are the power generation facilities used to meet some or all of a given region’s continuous power demand. They produce power at a constant rate, usually at comparatively low cost as compared to other production facilities available to the system. Examples of base-load power plants include nuclear and coal-fired plants.

Peak-load power plants are ”power plants that generally run only when there is a high demand for electricity, so-called peak demand. In many countries of the world, this often occurs in the afternoon, especially during the summer months when the air-conditioning load is high” (Wikipedia). Natural-gas-fired turbines are the typical prime movers in peak-load power plants.

A load-following power plant is a power plant that adjusts its power output to the actual demand for electricity, which fluctuates throughout the day. Load-following plants are typically in-between base load and peaking power plants in terms of efficiency, ramp times, construction costs, cost of electricity, and capacity.

Due to economical limitations, the capacity of load-following power plants and peak-load power plants is limited. Also, the load on transmission and distribution systems must not exceed certain thermal limits, especially during hot summer days that are characterized by a high demand for electrical energy. Utilities need to shed load in such cases when actual demand exceeds given generation and grid capacities.

A microgrid, however, can manage its own generation and load balance. The system can always shed load if necessary and avoid peak load. If a certain amount of peak load becomes “regular,” the generation capacity of the microgrid can be enhanced with the installation of additional distributed generators.

2.7. Transmission and distribution losses

Average transmission and distribution losses of a power system amount to six to eight percent of total generation. A solution that can reduce this figure will help save significant amounts of money and will also support the reduction of CO_2 emissions.

If the generation capacity of a microgrid covers its own demand, and generation costs are within an acceptable range, energy import from the utility grid will only be necessary in exceptional situations. This means that energy transport losses will be less than one percent under normal circumstances, which is a significant contribution to the reduction of CO_2 emissions. A microgrid will only import energy from the power grid if its own demand exceeds its given generation capacity.

In addition to offering adequate solutions for the elimination of utility-grid shortcomings, microgrids promise these benefits:

- **Reduced energy costs**
  This topic strongly depends on the long-term development of fossil-fuel prices and on installation costs for microgrids. Military bases in remote locations, for example, may have significantly lower energy costs with microgrids based on renewable power generation, as compared to power supply solutions based on the continuous transportation of oil and gas.
- **Reduced price volatility**
  If a microgrid is made up of highly efficient fossil-fuel-based generators (combined heat and power systems) and renewable energy-based generators, the dependence on fossil-fuel prices will be very low.
- **Utilization of highly efficient fossil-fuel-based distributed generation**
  Use of low-emissions fuel (natural gas) systems and highly efficient power supply solutions (combined heat and power, CHP) increases overall fuel efficiency.
- **Job creation**
  In the long term, microgrid structures will be attractive for (small) businesses, which will eventually bring about local jobs, not only in microgrid maintenance.

It must be considered that standards and grid codes must be adapted for the installation and operation of microgrids of the type shown in Figure 1. The IEEE 1547 standard, which provides all rules and requirements for the connection of distributed generators, is therefore being revised, and the requirements for microgrid applications are being adapted.

If microgrids gain wide acceptance in future, however, regulations governing energy-trade practices as well as related laws will also need to be adapted. This may change established utility structures significantly.

3. Microgrid market segments

According to today's experience and publications, there are five major microgrid market segments:

3.1. Institutional and campus microgrids

Institutional and campus microgrids consist of a certain number of buildings in a limited geographical area. The requirements on the quality of power supply may differ, depending on the type of the institution. A moderate degree of power supply reliability will suit most government or college buildings, while research institutes may require a power supply that provides better supply quality.

Usually, all buildings and participants in this type of microgrid belong to a single organization, and there is a single decision maker. This structure makes fast decisions possible, and in case of obvious benefits, the real estate owner can initiate necessary action.

3.2. Commercial and industrial microgrids

In case of single ownership, this microgrid type is similar to the one described above. The matter becomes more complex if a microgrid is to be established in an existing commercial or industrial area and comprises several participants. When a "commercial-industrial park" is a greenfield project with premium and normal power supply capability, the investor can decide for a microgrid structure to meet all customers' expectations.

3.3. Military microgrids

Although this is the smallest microgrid market segment, it is being developed with high effort, because there are tangible, quantifiable customer benefits. Distributed generators based on renewables are being used to secure power supply and reduce fuel costs.

3.4. Community and utility microgrids

"Community and utility" microgrids will mainly comprise private end-customers in predominantly residential areas, but sometimes commercial and industrial customers in that area as well. They may include urban areas, neighborhoods, and rural feeders. Such microgrids can provide power to urban or rural communities that are connected to the larger utility grid. There can be a wide variety of renewable or fossil-fueled distributed energy resources within this type of microgrid. Widespread commercial acceptance of this class of microgrids will strongly depend on national and international standards and regulations. Due to the high number of participants, decisions will be lengthy as compared to other microgrid structures.

3.5. Island and remote "off-grid" microgrids

An island microgrid is usually very similar to a community or utility microgrid. The main difference is that in most cases there will be no connection to the utility grid. In very few cases there may be a cable connection to the utility grid on the mainland if the distance from the island to the mainland makes this feasible. On the other hand, the decision making process may be very short, depending on the actual power supply infrastructure on the island.

"Off-grid" microgrids for geographically remote communities and developing countries focus on distributed and diverse power sources. As regions in the developing world continue to expand their electricity infrastructure, many remote microgrids are being designed to eventually interconnect to a larger grid system. Other remote microgrids are built to remain autonomous in order to maintain energy independence.

4. Microgrid examples

Microgrids may be very different depending on market segment, size, and location. Some microgrid examples are discussed below.

4.1. Institutional/campus microgrids

This example shows an institutional/campus microgrid, which is continuously operated in island mode. Connection to the utility grid is a backup option. The biogas and CHP units are necessary for continuous energy supply, and also for heat for cold winter days. However, fluctuating energy of renewable resources like wind and solar systems can be stored, for example with an electrolysis system. This stored energy can then be used with the application of a fuel cell.

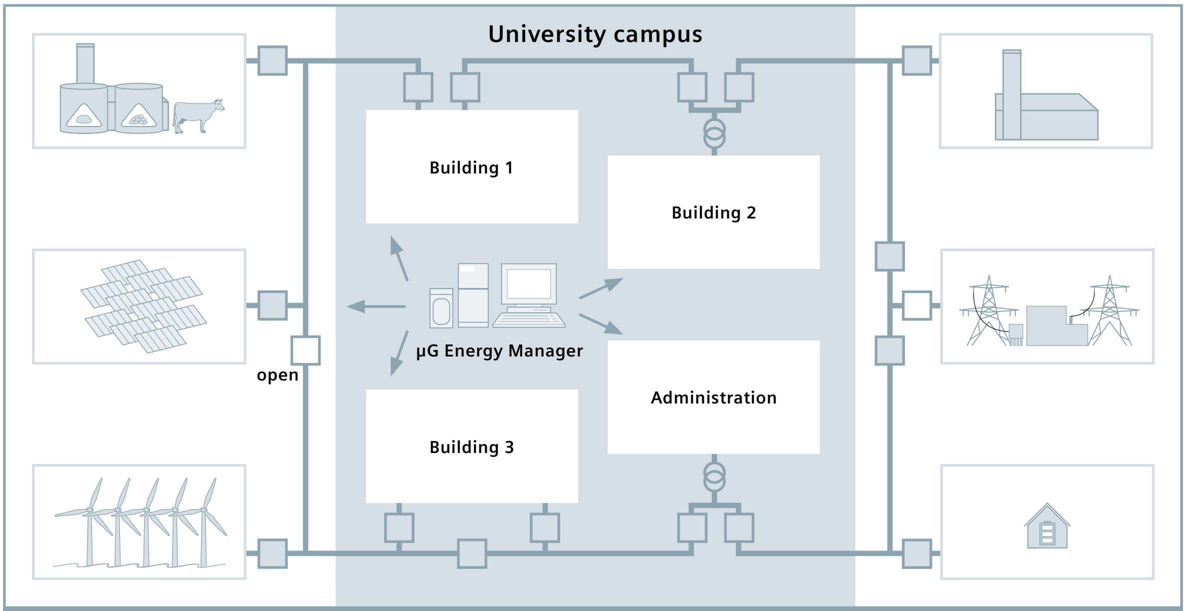

Figure 4.1: Institutional/campus microgrid

4.2. Industrial microgrid

Main reasons for the installation of an industrial microgrid are power supply security and its reliability. There are many manufacturing processes in which an interruption of the power supply may cause high revenue losses and long start-up times.

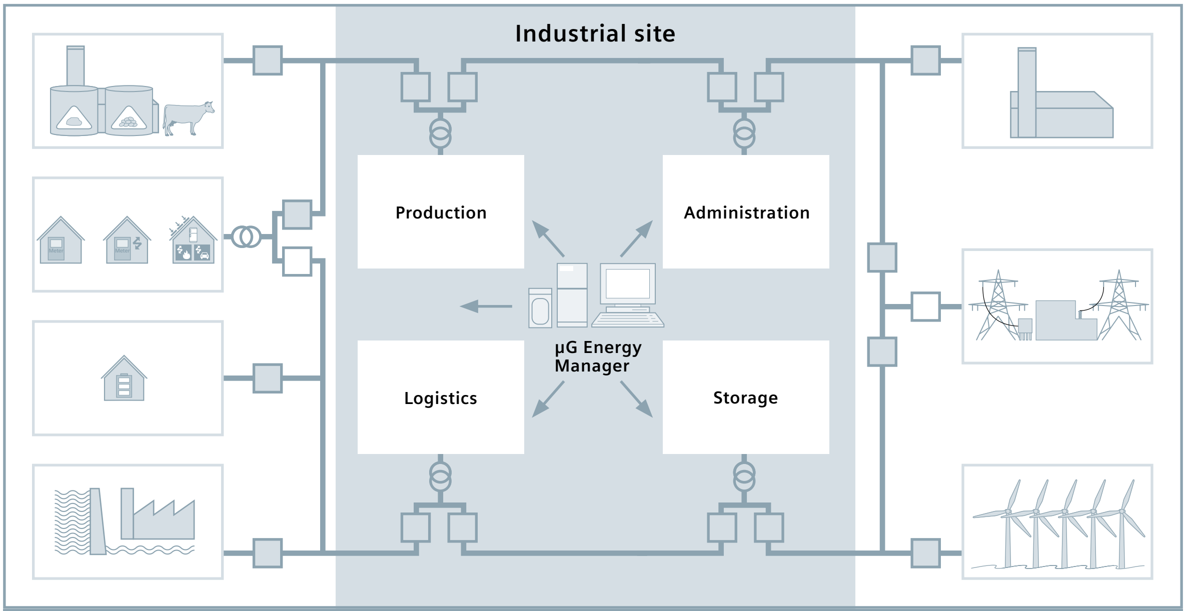

Figure 4.2: Industrial microgrid

Typical examples are chip manufacturing, the chemical industry, and the paper and foodstuff industries, for instance. Today, some industrial sites are installing uninterruptable power supplies if their utilization is economically justified. Microgrid structures may bring additional advantages, for example the combination of secure power supply with high energy efficiency and the utilization of renewable generation.

4.3. Off-grid and island microgrid

An “off-grid” microgrid as shown in Figure 4.3 is usually built in areas that are far distant from any transmission and distribution infrastructure and, therefore, have no connection to the utility grid. Due to this, such a microgrid must have black start capability.

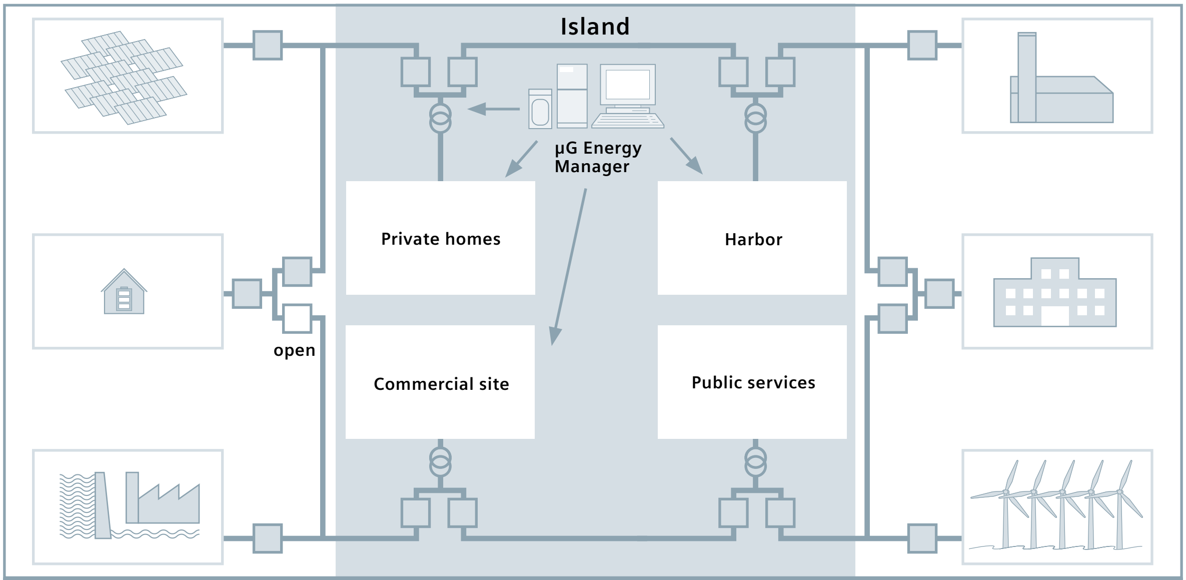

Figure 4.3: “Off-grid” microgrid

4.4. Utility microgrid

A utility microgrid may include a distribution feeder, a complete medium voltage distribution substation (Figure 4.4) or even several distribution substations in a large area. In the latter case, the energy flow from

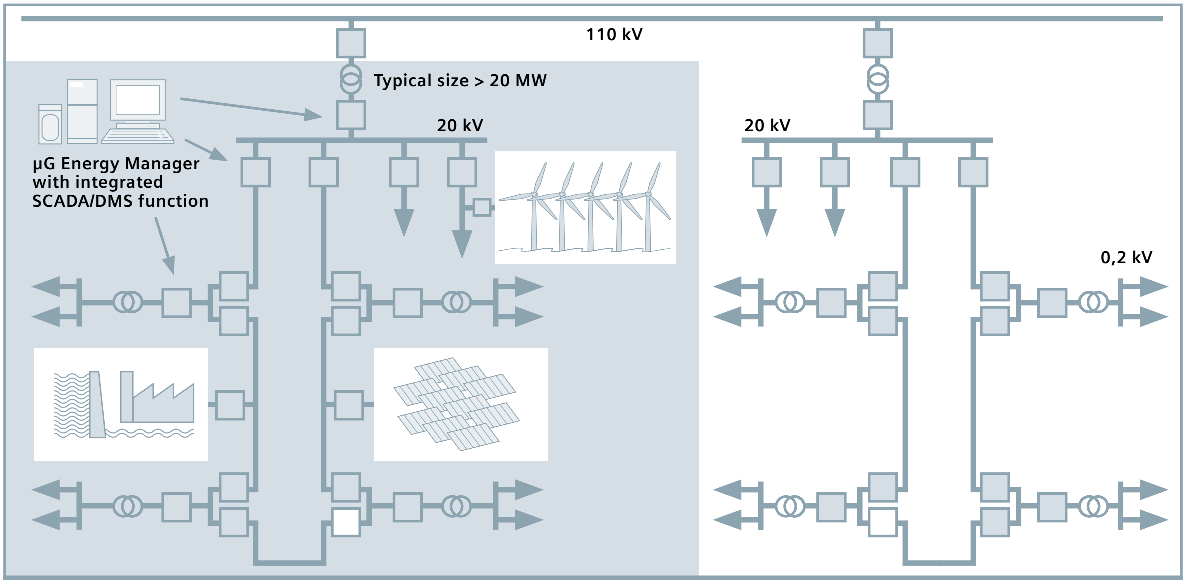

Figure 4.4: Utility microgrid

various generators within the microgrid to the loads and the energy exchange between different segments may become difficult to handle. Thus, the microgrid operation may require the installation of a distribution SCADA and a distribution management system (DMS), including distribution state estimation and power flow calculation. Additional operation, control, and automation systems such as an outage management system (OMS) and distribution substation and feeder automation may be required to keep the outage time short in case of a disturbance within the microgrid.

5. Expected microgrid features

Microgrid components such as renewable or fossil-fueled generators, point-of-common-coupling breaker and its control, loads, energy storage systems, and others must meet several requirements to enable seamless operation. Appropriate microgrid standards will be laid down, others will be revised. To support these activities, Lawrence Berkeley National Laboratory has identified some important top-level microgrid features [1, 10] that should be considered in all research, development, prototyping, and standardization projects:

- **Autonomy:** Microgrids include generation, storage, and loads, and can operate autonomously in grid-connected and islanded mode. In the first case, a microgrid can independently optimize its own power production and consumption under the consideration of system economics such as buy or sell decisions. In both operation modes, the system can minimize CO_2 emissions by maximizing renewable energy consumption and minimizing fossil-based generation. In islanded mode the system is capable of balancing generation and load and can keep system voltage and frequency in defined limits with adequate controls.
- **Stability:** Independent local control of generators, batteries, and loads of microgrids are based on frequency droops and voltage levels at the terminal of each device. This means that a microgrid can operate in a stable manner during nominal operating conditions and during transient events, no matter whether the larger grid is up or down. (Additional research is required, however, to achieve a high level of stability, for example to eliminate unnecessary reactive power exchange between rotating or inverter-based generators.)
- **Compatibility:** Microgrids are completely compatible with the existing utility grid. They may be considered as functional units that support the growth of the existing system in an economical and environmentally friendly way.
- **Flexibility:** The expansion and growth rate of microgrids does not need to follow any precise forecasts. The lead times of corresponding components (fossil-fueled and renewable generators, storage systems, and others) are short, and a microgrid can grow incrementally. Microgrids are also technology-neutral and able to cope with a diverse mixture of renewable and fossil-fueled generators.
- **Scalability:** Microgrids can simply grow through the additional installation of generators, storage, and loads. Such an extension usually requires an incremental new planning of the microgrid and can be performed in a parallel and modular manner in order to scale up to higher power production and consumption levels.
- **Efficiency:** Centralized as well as distributed microgrid supervisory controller structures can optimize the utilization of generators, manage charging and discharging energy storage units, and manage consumption. In this way energy management goals can be profoundly optimized, for example in economic as well as environmental respects.
- **Economics:** According to market research studies, economics of heat recovery and its application by CHP systems is very important to the evaluation of microgrids. In addition, the utilization of renewable energy resources will help reduce fuel costs and CO_2 emissions.
- **Peer-to-peer model:** Microgrids can support a true peer-to-peer model for operation, control, and energy trade. In addition, interactive energy transactions with the centralized utility grid are also possible with this model. The proposed concept does not dictate the size, scale, and number of peers and the growth rate of the microgrid.

  This means that no central entity, such as a central computer with appropriate software and communication capability to all microgrid components, will be required.

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