CABA™ Continental Automated Buildings Association

The Role of Hybrid AC/DC Building Microgrids in Creating a 21st Century Enernet

Part I: Doing for Electricity What the Internet did for Communications

A CABA WHITE PAPER

Brian T. Patterson
EMerge Alliance & B. L. Coliker Associates

CABA Intelligent & Integrated Buildings Council

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Part I: Doing for Electricity What the Internet did for Communications

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ABOUT CABA

The Continental Automated Buildings Association (CABA) is an international not-for-profit industry association, founded in 1988, and dedicated to the advancement of intelligent home and intelligent building technologies. The organization is supported by an international membership of over 330 organizations involved in the design, manufacture, installation and retailing of products relating to “Internet of Things, M2M, home automation and intelligent buildings”. Public organizations, including utilities and government are also members. CABA's mandate includes providing its members with networking and market research opportunities. CABA also encourages the development of industry standards and protocols, and leads cross-industry initiatives. CABA's collaborative research scope evolved and expanded into the CABA Research Program, which is directed by the CABA Board of Directors. The CABA Research Program's scope includes white papers and multi-client market research in both the Intelligent Buildings and Connected Home sectors. www.caba.org

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The CABA Intelligent & Integrated Buildings Council works to strengthen the large building automation industry through innovative technology-driven research projects. The Council was established in 2001 by CABA to specifically review opportunities, take strategic action and monitor initiatives that relate to integrated systems and automation in the large building sector. The Council's projects promote the next generation of intelligent building technologies and incorporate a holistic approach that optimizes building performance and savings. www.caba.org/iibc

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1. EXECUTIVE SUMMARY

Renewable energy sources and storage generate power for buildings as direct current (DC). An inverter is required to produce alternating current (AC) from DC in order to inject the power into a conventional AC-based distribution grid. However, many electronic devices used in buildings convert AC to DC. These conversions to and from AC are inefficient, causing useful power to be converted into waste heat.

This white paper examines the alternative of maintaining power in its native DC form from distributed generation and storage sources in a simplified, more flexible, efficient and resilient configuration in the building. This DC power could be aggregated with AC power from the public grid and distributed in the building via a hybrid AC/DC microgrid.

The paper also explores the eventual interconnection of building-level microgrids within and between buildings and the public grid to create an energy network. The paper refers to this energy network as the “Enernet,” analogous to the network of computers that constitute the Internet. A tiered configuration of private microgrids and public grids in domains akin to the physical network topology of the Internet is proposed. Also discussed are the motivation, need, and status of new standards to support the implementation of such buildings with wide-scale use of private microgrids that would be increasingly based on low voltage (under 1500 Volts (V)DC) direct current.

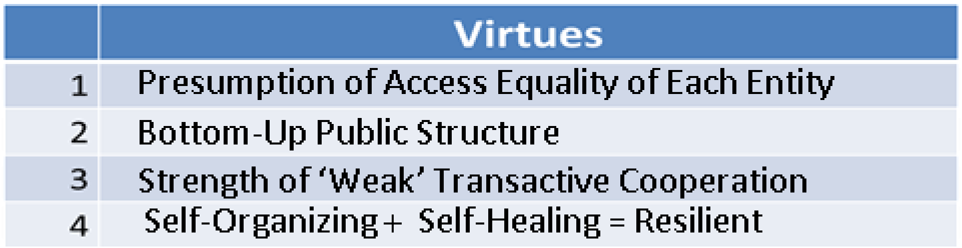
2. ENERNET, MICROGRIDS AND THE SMART GRID

The prospect of massively distributed clean renewable power generation in buildings becoming a reality is more certain today than ever before. The leading renewable source is solar, where a combination of technology improvements and market-scale developments is soon to be followed by a second wave of more capable and lower cost storage solutions. Many former cynics and reluctant financiers now believe we are on a fairly rapid path to a new electric power paradigm. Coincident with this is an increasing use of electronic devices within buildings in more productive and efficient ways. Key to the success of this transformation lies two critical cornerstones: the new role of buildings as power providers and the increased use of non-synchronous DC in hybrid AC/DC power microgrids.

While the forecasted increase in use of clean renewable energy by buildings may be music to the ears of most environmentalists, net zero energy building advocates and many electronic device manufacturers, it strikes a dissonant and concerning note for facility managers and utility professionals alike. Both groups are concerned such a rapid and significant change will be highly disruptive and problematic. Facility managers well versed in the deployment and use of traditional electric power systems are not as skilled in these new systems. Utility executives and regulators are beginning to grapple with the grid implications of massively distributed privately-owned, non-dispatchable generation, looking to be connected to the public grid; constituting a significant portion of distributed power.

But innovators and early adopters see this situation as a giant window of opportunity. They see it as similar in scope, scale, and character to the data/telecommunication industry's disruptive migration to solid state computers, microprocessor-based electronics, and the Internet. Conceptually, many believe a similar migration is past due in the power domain; that is, they believe what's needed is an electrical energy network of power that can deliver the same systemic virtues to power systems that the Internet produced for communications. They are calling this new configuration of power infrastructure the Enernet, or electric energy network.

In both cases the Internet and the Enernet are built on the concept of interconnected domains of smaller, more self-reliant, grids. They are not point-to-point hard-connected wiring distribution systems like the old telephone systems or like the present power grids systems that are essentially one way. They are true mesh networks, where the traffic (data or power) can be passively and/or actively routed. The Internet, is equally capable of distributing data created by large central computers as it is of collecting and redistributing data that are created by widely deployed personal computers, tablets or smartphones. A similar capability should be available from today's so-called "Smart Grid," but it is not. That is, the grid should be equally capable of distributing both centrally and widely deployed distributed electricity generation, but it cannot. It is believed that a properly configured Enernet will transcend the limitations of current grids and more easily allow the generation, storage, distribution and use of electricity to achieve the same virtues we enjoy from the Internet:



	Virtues
1	Presumption of Access Equality of Each Entity
2	Bottom-Up Public Structure
3	Strength of 'Weak' Transactive Cooperation
4	Self-Organizing + Self-Healing = Resilient

Table 1 Virtues

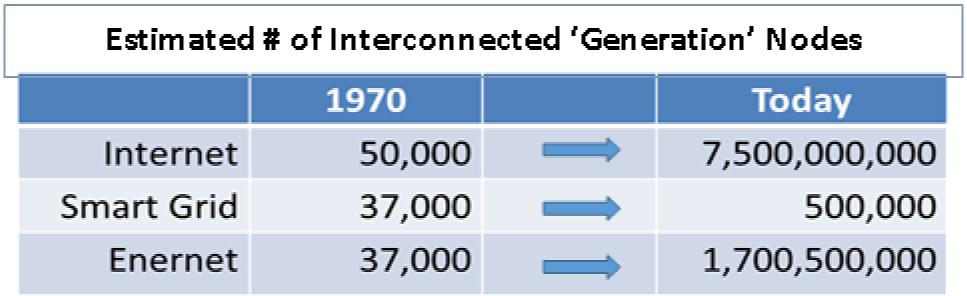
Electric power infrastructure around the world has not progressed like the global data infrastructure. From the late 1970s, when computer networking was first developed, to 2013, with computer based networking in high gear, the Internet went from being 100 percent central data production on large mainframes, to 68 percent distributed data production on small devices, starting with personal computers and now laptops, tablets, and smartphones. The Internet turned data production, storage distribution, and use disruptively upside down in less than 40 years. The success of the Internet is based on:

- An evolved set of open standards.
- A non-synchronous means for many sources of data to be combined on the same carrier.

- The innovative development of small data creation devices (generally called personal computing including tablets, smartphones, and similar devices) to complement the existing central data processing devices.

Even the latest buzz around Big Data, is really more a collection of aggregated "little data," including texting, Tweets, selfies, temperature readings, occupancy sensors, light switches, E-Z Passes, etc. And it will not stop there, the much talked about Internet of Things is really the same Internet simply expanded to include billions more distributed data creation and use devices, most of which will be embedded in the building and mobile environments.

While the Internet has flourished, the electric power infrastructure has hardly changed. The present power grids do not get power from distributed sources; they are still highly centralized with little storage capability. Engineering marvels that they are, they have essentially been designed to distribute power generated at large central generation stations (power plants) in one direction to loads (mostly buildings) where it is consumed. Despite all the investment in Smart Grids, these grids will likely be incapable of handling much more than 15 percent of their total power coming from distributed sources (like commercial buildings and homes) without significant difficulty and cost.



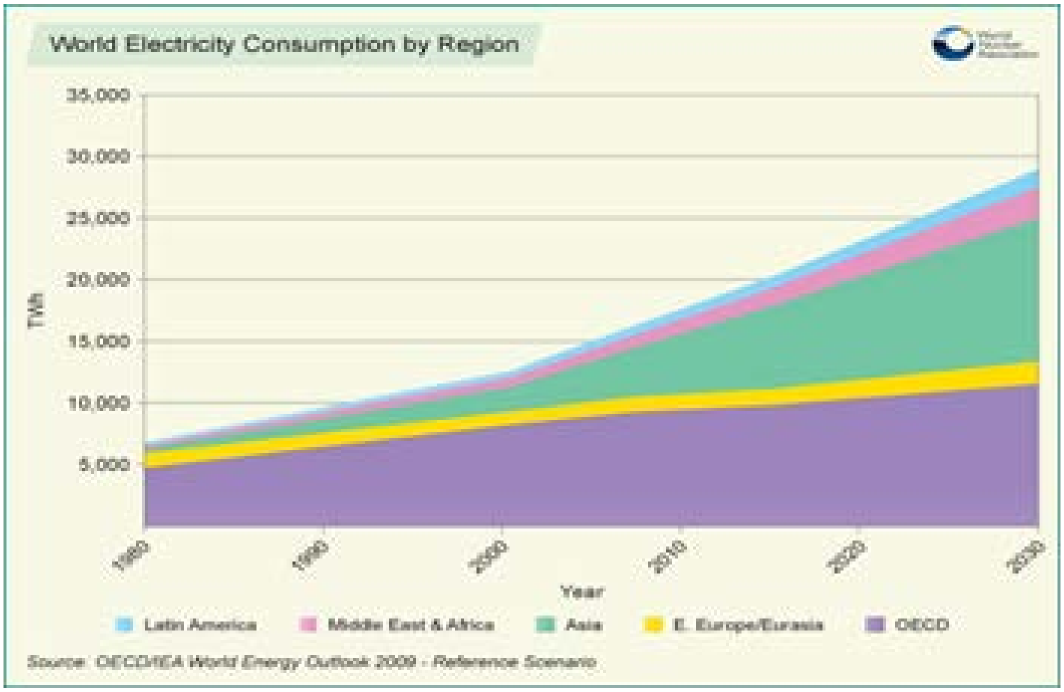
Estimated # of Interconnected 'Generation' Nodes

	1970		Today
Internet	50,000	→	7,500,000,000
Smart Grid	37,000	→	500,000
Enernet	37,000	→	1,700,500,000

Table 2 Quantity of interconnected generation nodes

If we take seriously the goal to transition the vast majority of our buildings, both new and old, to net zero energy use, we have to overcome more than just a mathematical mismatch. Buildings presently consume more than 65 percent of all electricity. Therefore, net zero buildings translate into 65 percent of all future electricity being generated by widely geographically distributed buildings. If the grid can only accept 15 percent of its power from distributed sources, we have a significant problem. And that's before adding electric vehicle charging and a host of newly powered killer apps destined to play on networked personal digital devices combined with powering the devices that make up the Internet of Things. So-called killer apps and the Internet of Things are the two fastest growing consumers of electricity. Combined information and computer technology devices will nearly equal the total load of lighting homes and businesses in terms of raw power consumption by the end of this decade.

Simply put, electrical energy has become the currency of future civilized society growth, outpacing consumption of all other energy forms by more than 2:1. Electricity demand almost doubled from 1990 to 2011, and is projected to grow 81 percent from 2011 to 2035. At the same time and unless something changes, approximately two billion people in the world will continue to have no access to electricity, making it an undoubtedly high priority issue for society to address.



Source: OECD/IEA World Energy Outlook 2009 - Reference Scenario

Figure 1 World electricity consumption continues to climb

Existing power grids simply cannot generate and distribute the amount of power needed to meet our world's growing demand without significant help. Furthermore, in the case of the unserved population, there are no grids at all. The original point-to-point phone system would be unable to handle today's data transmission requirements from the Internet. Fortunately, the Internet evolved in its place, partly out of inspiration, but mostly out of necessity. But today's challenge is: How do we power all these devices with clean sustainable sources of electricity? So far – not so well, and frankly its getting worse when examining the increasing real and future potential failure rates of the electrical system. Add to this dilemma the prospect of increasing terrorist threat through electromagnetic pulse (EMP) attacks or natural EMP disturbances from solar weather. The Council on State Governments reports that on average the United States loses $80 billion (USD) due to electricity blackouts each year.

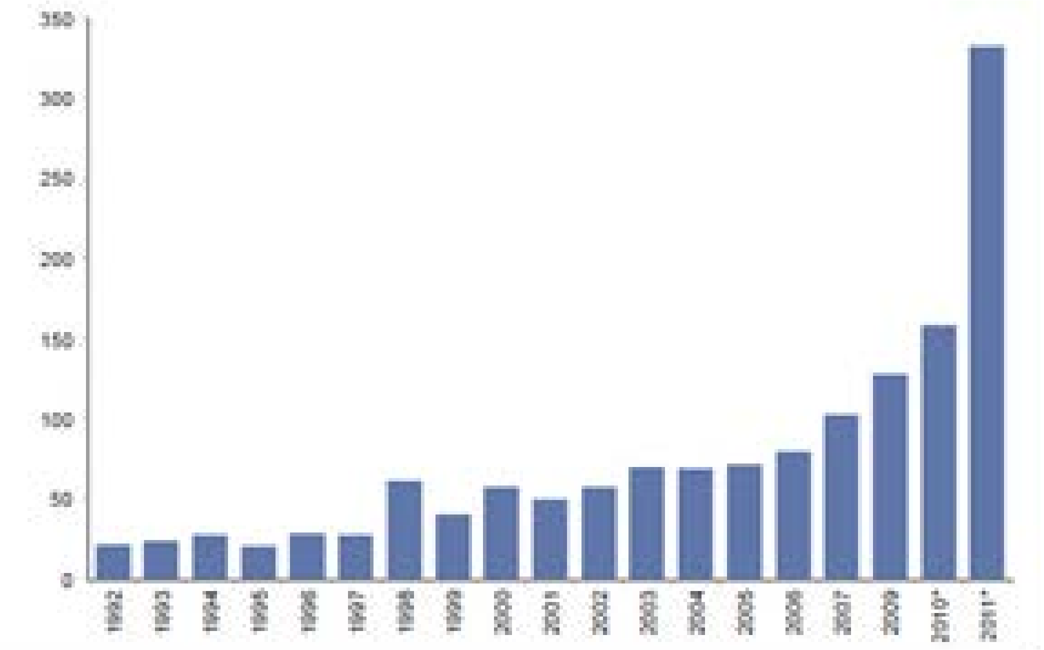
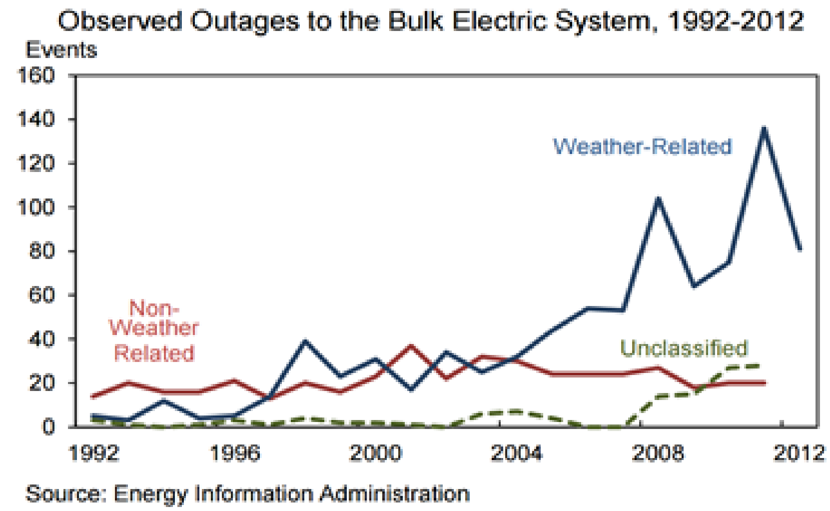


Figure 2 Major power disturbances in North America



Source: Energy Information Administration

Figure 3 Electric power outages in the U.S. have risen sharply over the past two decades

So a new question to ask ourselves is: Can we evolve an Internet of electricity – the Enernet - and do for power what the Internet did for data? That is, make it more available, more flexible, more efficient, and more resilient while becoming more ecologically and socially sustainable? The answer is “yes”, and especially if attention is paid to the lessons of the Internet. This evolution can likely be completed in a fraction of the time it took to create the Internet.

The good news is that, despite its growing issues, there already exists a really good bulk power system, including the grid and its centralized power plants, that play an important and continuing role going forward. The bad news is, distributed means for generating and storing power has been developing slowly. But this is changing, and this is where buildings become important. They are the key to providing such a capability, partly because they are massively distributed, one of the most important keys to overall system resiliency, and partly because they are the largest consumers of electricity. By making them more self-reliant, we remove the pressure on intrinsically vulnerable centralized grids that are increasingly prone to linear dynamic failures – better known as large area blackouts.

2. THE CASE FOR BUILDING MICROGRIDS

The balance of this white paper will focus on how existing building conversions and new building construction can meet the challenge of creating a massively distributed power generation capability. A subsequent paper will describe further how this 'repurposed' building stock will be 'ener-connected' and operate in the whole of the infrastructure of the Enernet.

The key for buildings to take on this new role of creating electricity is for them to operate as microgrids while transacting power with other similar buildings and with the local utility. That is, they must be independently capable of generating, storing, distributing, and using electricity in a safe, reliable, flexible, efficient, and effective way. Collectively, microgrids, even though connected to other microgrids directly and/or via the grid, must be able to survive short, or in special cases long, periods of being un-supplied or undersupplied with external power. Under certain circumstances, they will need to be temporarily disconnected (islanded) completely from the public grid to protect themselves from being caught in the occasional chain-reaction of linear dynamic failure in the bulk system that can propagate at the speed of light.

To do this, every microgrid requires the ability to store some level of power, from short interval ride-through buffering capability to long intervals of off-grid operation, at least for the critical loads therein. Each microgrid would ideally have the ability to receive and store power, receive and consume power, generate and consume power, and/or generate and transmit power to other microgrids, all while continuing to operate. Since microgrids are housed in buildings, they must be able to keep their own buildings operating.

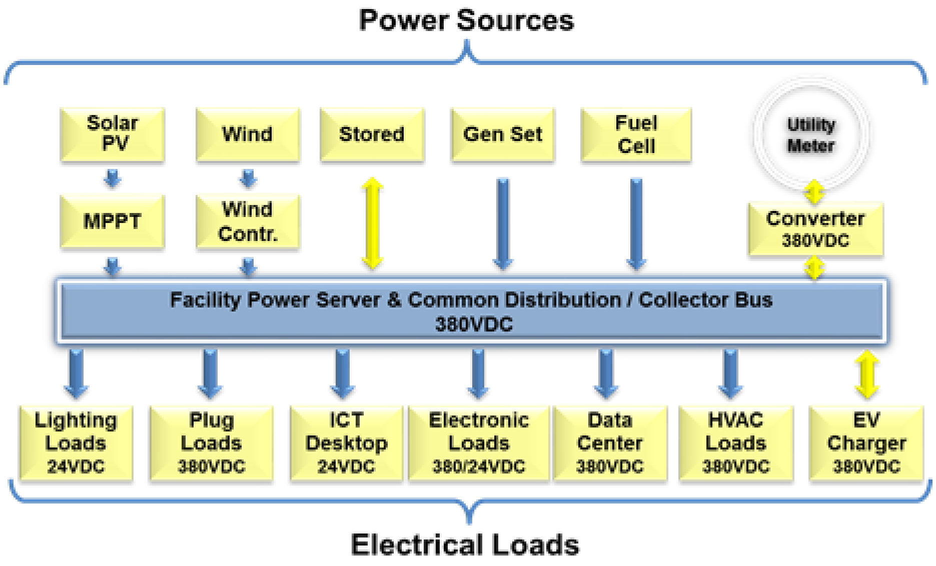


Figure 4 Typical building level microgrid architecture

3. BUILDING LEVEL MICROGRIDS IN A MACRO-GRID WORLD

Given this background, a key question is: What are the critical characteristics that building-level microgrids must possess in order for them to work efficiently and effectively? Those attributes are as follows:

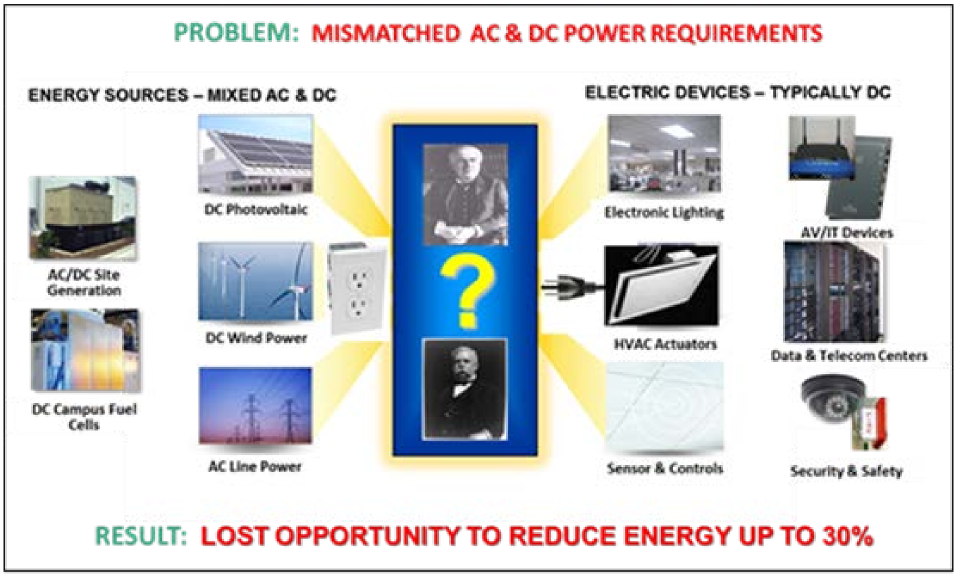
1. A building or campus level microgrid must make it easy and efficient to connect/couple/collect site-based means of generating clean energy for use in the building, while still providing alternative access to the external utility grid. (It might help to think of these building microgrids as the power producing equivalents of data producing personal computers and smartphones in the Internet). Typically they will natively produce DC power in relatively small amounts and at low (under 1500V) voltages. They will likely employ solar panels, fuel cells, wind turbines, and a myriad of newer devices to scavenge and uniquely harvest locally available clean, renewable power.
2. Building level microgrids must make it possible to store reasonable amounts of the power they collect for use on demand, at different times than when it was intermittently produced and collected. (Think of these devices as the power equivalent of computer memory or buffers).
3. These microgrids must make it easy to plug-in/power digital/electronic devices that range from small devices, such as thermal sensors and cameras, to large devices such as washing machines or building air handlers.
4. The microgrids should use a non-synchronous form of power (DC) whenever possible to reduce the need to manage the dynamic variations and need for system-wide synchronization of the power frequency in sources and loads. This is particularly important, as they are at the edge of the bulk grid where buildings dominate and most device loads exist. Synchronized frequency dependent AC power systems add complexity and cost while reducing reliability.

5. The power distributed to devices in buildings should match the intrinsic form of power of both local sources and loads to minimize power conversion loss where possible.
6. Building level microgrids should have the goal of managing power in a building as simple, reliable, resilient, efficient, convenient, and safe as possible while being highly flexible and feature rich. (Think of this as the plug and play, default, and feature setting equivalent to the Internet.) The next big question is: How do we get from A to B (which is mostly a case of getting from AC to DC), and what are the barriers that can slow this transformation?

The biggest single system challenge is transitioning from AC to DC power at the building level. While not a significant technical challenge, since it will actually simplify most operations, it does represent disruptive changes to the marketplace. The challenge of changing to a different form of power seems formidable. However, the problems of using the 100-year old AC system, to which we are accustomed, is likely to be even more problematic and therefore increasingly difficult, complicated, wasteful, time-consuming, inefficient, and expensive to pursue.

4. SEMI-CONDUCTORS AND MODERN SOLID-STATE POWER ELECTRONICS

The things used every day that need power in buildings have changed. For the most part they are electronic and use a different kind of power than what comes from the grid. Their internal chips need direct current, the kind of power that comes from batteries or other big chips, like solar panels. Some of the electronics are there to conserve energy, like dimmers, occupancy sensors, speed controls, etc. But our building electrical systems were not set up for direct current, so just about every device today has to convert the grid supplied AC to DC. In addition to adding cost, size, weight, safety, and reliability issues, these converters exact a toll by wasting energy.



(Source: EMerge Alliance)

Figure 5 Mismatched power requirements lead to lost energy

The change to DC is more practical today than ever before because of the rapid development of modern power electronics. Solid-state electronics can provide voltage conversion in DC circuits needed for typical applications in building operating at less that 1000 volts. They have made connecting devices using hundreds of volts, and ones using under just 10 volts in the same DC system, practical.

5. NON-SYNCHRONOUS OPERATION IS THE KEY

Practical voltage conversion of DC power to avoid transmission and distribution losses is not the only reason to consider DC use anew. There is the previously mentioned and growing problem of frequency synchronization and control with AC power systems. Simply put, if you do not synchronize and control frequency, generally set at 60 cycles per second (60 Hz), an AC system becomes unstable and can fail. The generation of AC electricity has traditionally been done through the use of large rotating alternating current synchronous generators that provide significant system frequency inertia to keep frequency constant. New solar and other non-synchronous DC generation is beginning to displace traditional synchronous generation. These DC power sources threaten system frequency inertia. Converting these DC generation sources to AC would introduce higher rates of frequency change. Since larger frequency deviations can be expected from DC power sources when converted to AC, most convention power system operators put a limit on the portion of generation that can be integrated from DC sources to about 15 percent of the total.

To attain frequency stability from DC power converted to AC adds cost, complexity, and reduced reliability and/or resiliency. This is particularly true with small systems, such as those contemplated to fulfill net zero energy building goals. The prospect of huge increases in the number of distributed site-based energy harvesting and generation systems that lack frequency inertia may result in unstable electric power grids or microgrids because frequency and phase synchronization are so critical in AC systems. The logical solution is to eliminate the synchronous requirement entirely by migrating to a non-synchronous, non-frequency dependent power format, namely DC.

This vision has been fully embraced by the EMerge Alliance, a non-profit, open standards organization. The Alliance is member funded and populated by representatives from industry, government and academia. It is focused on creating system application standards for both commercial and residential buildings and campuses. The standards consider both collection and distribution of site-based power and include consideration of transformative hybrid AC-DC, as well as pure DC microgrid architectures.

6. DC MICROGRID APPLICATIONS: WORKING FROM THE INSIDE-OUT

Any all-encompassing network of power would be absolutely massive since electric power is a global commodity. Because of this scope, it makes sense to try to achieve the overall system by allowing small increments of transformation over time. Since many parts of the legacy power system already exist and need to be reconciled in the transformative process, the implementation should be flexible and opportunistically undertaken. This can be done by not replacing aging devices but upgrading them with technology that embraces the newer hybrid AC/DC and pure DC schemes.

The diagram below illustrates the major application areas within a building. The EMerge Alliance has been working to address these application areas in modular fashion over time, up to and including the application of an over-bridging campus or building-wide microgrid layer to interconnect the sub-layer microgrids.

Figure 6 Modular microgrid layers by building application

This notion of modularity provides the following connectivity option for one or an interconnected group of in-building application layer microgrids as follows:

1. Connects directly the existing AC power distribution in the building to locally distribute safe, low voltage DC power.
2. Connects to both the existing AC system, as well as to on-site natively DC-based renewable generation resources, such as solar, wind, fuel cell, etc.
3. Connects to a DC power distribution layer microgrid that covers the entire building or campus, including storage with alternative connection to the AC grid as backup.

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4. Connects to a DC power distribution layer microgrid that is outside the building, perhaps operated by a local independent power service provider or by a utility that deployed universal transformers capable of delivering DC power to the building.

7. THE PATH FORWARD

The first of such microgrid deployments is just beginning, some being tested by private users and others by consortia such as the EMerge Alliance in cooperation with industry, government, and academia. These initial microgrid deployments are the first level validation of the vision the Alliance has embraced regarding the creation of an Enernet. It has also begun the important work of writing the standards that will guide the vision into reality. The EMerge Alliance has assembled a cadre of companies, plus private and public organizations, to affect the creation of a sustainable ecosystem of enterprises that can create the hardware and software for the network. As an open standards consortium, it has invited the entire industry to engage in transforming today's ailing and aging power systems into the next modern marvel of man's enterprise. It believes it has solidly started the journey down the path toward a twenty-first century Enernet wherein buildings play a new and prominent role

The path to net zero also means we must change how we produce and deploy energy. So here are a number of ways green design and construction professionals can help lead and get involved on an individual or organizational level:

1. **Continue your education in this topic**. Seek out information relating to microgrids and the use of DC power at various levels in power systems. Do not take it for granted that things must run on AC power just because they are fed with an AC wire or cord. Ask if the power is being converted, and partially wasted, to DC inside or through an external brick or charger. You do not need to be an expert on how all electrical devices work, but understanding a few basics will make you more effective in moving efficiency in the right direction.
2. **Contact vendors of products for microgrids** and other key elements of the Enernet and learn what they have to offer in products and services. Help them help you by letting them know your project's goals and general specification criteria. Ask for design help – after all, this is new to most people.
3. **Join or otherwise support standards organizations** to help write and promote the use of new standards that can move us forward in the development and deployment of the Enernet.
4. **Look for opportunities to deploy** available modules of building and campus microgrids in your design and construction work. Just remember that the industry is at the beginning, so not everything is at the same level or readiness. A modular, opportunistic approach is advised. Do what you can, when you can, but begin pushing things in the right direction.
5. **Give feedback** to those who are working to advance this architecture. Tell them what you need to accomplish your goals. As an industry professional, your advice is needed and is highly valued.

The underlying concept of building level hybrid AC/DC microgrids has come a long way since this concept was first embraced by the EMerge Alliance and others. At this juncture, no one can accurately predict how fast they will come into existence. But a few things seem certain: it will happen. Just like most innovations, it will unite the world like no other man-made mechanism ever has before. Just as the fundamental Internet has brought information, via computer and smartphones to the nearly a third of the world's population, so will building microgrids empowered with an Enernet allow a similar fraction to benefit from a new energy economy, largely based on electric power.

GLOSSARY

Terms:

Enernet, DC Microgrid, AC Macrogrid, Hybrid Microgrid, Distributed Generation, Renewable Energy, Clean Energy.

Enernet: A mesh network of massively distributed, non-synchronous, collection, conversion, storage, use, and exchange of energy that is largely self-configuring and managed by information based transactional frameworks.

DC Microgrid: A spatially localized grouping of electricity sources, storage and loads that predominately generates, interconnects and uses electrical power in its direct current (DC) form. They operate either connected to the traditional centralized grid (macrogrid) or function autonomously as physical and/or economic conditions dictate. Such microgrids are typically, but not always, connected to and operate in conjunction with other DC microgrids, AC/DC Hybrid microgrids and AC macrogrids.

AC/DC Hybrid Microgrids combine the use of the AC and DC forms of electricity in a localized grouping of electricity sources, storage and loads that generate, interconnect and uses electrical power in lower voltages.

AC Macrogrids: Utility operated, centralized generation, wide area transmission, and local distribution electricity grids that predominately use electrical power in alternating current (AC) form in high and medium voltages (above 1500 V) that otherwise require wave form, phase, and voltage synchronization for multiple power source interconnection. Such AC macrogrids can employ interconnected AC/DC hybrid and DC microgrids

Distributed Generation: Spatially dispersed smaller power sources that can be aggregated to provide power for larger systems or uses.

Renewable Energy: Any source or form of energy that is readily and naturally replenished.

Clean Energy: Any source or form of energy that does not pollute the environment.

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APPENDIX

The following is provided for additional reading.

ABOUT ELECTRIC ENERGY

Energy is the capacity for doing work. It exists in potential, kinetic, thermal, electrical, chemical, nuclear, or various other forms. Energy can be converted between forms and is thereafter designated according to its converted form. For example, photonic (i.e., solar) energy may be transferred to electrical energy (electricity) then to mechanical energy which in turn may do work to convert back to electrical energy and so on.

All forms of energy are closely associated with motion or kinetic energy. This runs the gamut of moving bit registers in semi-conductors to moving mountains of earth with bulldozers, and more. Late in the 19th century, the value of using the electric form of energy became widely recognized in its ability to do the "work" of lighting and powering motors. During those early days of electric power generation, distribution and use, there was a debate over what form of electric energy, alternating current (AC) or direct current (DC), was best.

Despite the early use of DC power, something heavily promoted by Thomas Edison to power his then recent invention of a practical incandescent light bulb, AC power has dominated the history of electricity use, and with good reason. Use of simple coil transformers and wire wound motors allowed both efficient transmission and use of centrally produced AC electricity. The AC coil transformer cost-effectively coverted voltage, which was key to preventing transmission loss (see a diagram of line loss based on the application of Ohms Law). The simple AC coil motor allowed for an effective conversion of the electrical energy to mechanical energy, which was an important application for industry.

Based on these two key attributes of AC electricity, George Westinghouse, with the help of Nichola Tesla and others, won the so-called "War of the Currents." Over the next hundred years, students of electrical engineering learned two fundamental axioms: AC is better than DC for electricity transmission and AC motors are great for doing mechanical work. As these maxims have essentially gone unchallenged from the turn of twentieth to the turn of the twenty-first century, the marvel of national and continental power grids based on AC power similarly evolved without challenge. Collectively, they have been one of mankind's finest engineering achievements.

But in 1947, in the labs of AT&T, something called the solid-state transistor was invented. Although not commercialized until the 1950s, the solid-state transistor enabled electrical power to be easily converted in form and voltage, albeit at limited (low) currents. Since then, DC has enjoyed a distinct functional advantage over fixed frequency AC: the ability to move electricity without the complexity of synchronizing or compensating for frequency. This has been key to the development of solid-state digital technology and modern electronic devices. One could easily argue that this evolution to performing work via the use of digital electronics belongs in the same engineering "hall of fame" as the use of electric power grids. The twenty-first century is increasingly using technologies based on solid-state electronics, the Internet of Things (IoT), distributed alternative energy generation (DG), power storage, and rechargeable electric vehicles, all of which use the native form of electricity, direct current.

The dilemma is that this has led to a constantly growing and basic incompatibility between our 100-year-old AC power grid supply systems and this increasing demand for native DC power. But so far, we've been able serve this disparate need by inserting power adaptors that can convert the electricity from one form to the other, sometimes more than once, between the source and the load. However, the increasing burden of this approach has included: less efficient use of power, lower power system and/or device reliability, increased system cost, and greater difficulty of electricity articulation/manipulation.

And our almost single reliance on centrally produced and distributed AC electricity has had other consequences. It is an approach that has scaling limits both up, and down. More power demand brings the need for bigger and more central power plants, more overland transmission lines, both of which are resisted by the public. Larger scale system dynamics lead to more frequent and greater cascading linear dynamic system failures (blackouts). Another impact of this scaling is that huge fixed plant assets of these central grids are costly.

Today, close to a quarter of the world's population live in underdeveloped regions without access to electricity. There are also a similar number struggling with inadequate systems and sources that almost daily leave some portion of the populace with a rationed amount to use. It is the belief of this author that these factors are and will continue to push the power meter strongly toward DC again, based on factors at least as compelling as those that drove us originally to use the AC form of electricity. To draw a direct corollary to the AC transformer and the AC motor technologies that drove the last 100 years of power architecture, note the development of solid state DC isolated gate bipolar transistor and electronically commutated DC motors. But it is even more compelling than that, since most clean distributed electric generation, storage and highly articulated use of electricity is done in DC format. Simply put, the current digital age is almost entirely based on DC power use.

But if that is true, how have we made it this far with our 100-year-old AC electric system? Thankfully, it has been on the back of the development of power electronics, only in this case, the kind that allows us to convert AC electricity to DC, but not without penalty. When most devices still ran on native AC power – fixed speed motors, incandescent lighting and resistive heating, and cooling apparatus – only a few devices needed the AC to be converted to DC – like radios, TVs, and stereos. But slowly and steadily the last few decades of electronic progress, now puts us well beyond the tipping point of DC power being the more predominant end use. It may not be easy to recognize, but much of what is thought to run on AC electricity, simply because that what we feed into the device, actually runs on DC. And this trend is accelerating not decelerating.

Some of the devices that run on DC "inside" include electronically ballasted fluorescent lighting, LED lighting, microwave ovens, induction cooking stoves and ovens, variable speed dishwashers, washing machines and dryers, variable speed HVAC, personal electronics including everything from the garage door openers, electric window shades, and blinds, security cameras, computing and communication devices, just to mention a few. So what started out as a few power converting bricks and "wall wart" chargers is now embedded in nearly everything. And no matter how neatly these devices are hidden, an increasing amount of AC power is wastefully converted one or more times between AC and DC before it is used. And it is important to understand that the lower the voltage and current these conversions are made, the greater the waste of energy. The conversion of a whole building's electricity from AC to DC at the utility pole could easily be accomplished above 98 percent efficiency while the same conversion done at each device and at much lower voltage struggles to achieve 80-85 percent efficiency. This does not include the waste materials and increased reliability issues that come with the present piecemeal approach.

Beyond this is the prospect of electric vehicle use. The electric power in these cars will be necessarily stored as DC electricity, and yet we now feed their chargers with low voltage AC power, again requiring wasteful conversion.

In addition to the electro-technical reasons for energy loss, there lies an even greater waste due to inadequate control and management of electricity as these losses are behavioral in nature. Present power systems are forced to deal with the relative difficulty and expense of trying to articulate AC power. In a digital world it seems almost ludicrous to be using a form of power that limits control and management of electricity use by making it difficult.

But the almost singular focus on electricity conservation leaves an even bigger dilemma. Notwithstanding the most optimistic forecasts for electricity conservation, population growth and the conversion from combustion engine to electric motor vehicles will almost double the demand for electricity in the next couple of decades. So any sustainable approach to electricity supply and use must include significant increases to electric generation.

While the present central production and distribution system based on AC power has served us reasonably well for the past century, it is increasingly judged incapable of meeting this rapidly growing demand. And even if the generation question could be successfully addressed, the problems associated with transmission and distribution would still thwart a successful outcome. Simply put, solely relying on the central electricity production and macro grid transmission and distribution approach is almost certainly ill-fated. And while efforts to make the current electrical grid "smarter," its intrinsic design lacks flexibility and resiliency. It is no wonder why, after more than 100 years of little change or significant technological advancement, its basic capability is increasingly being called into question as it shows its vulnerability under various "stress" conditions, many of which simply did not exist years ago. The increasing negative impact of natural disasters and the added prospect of accidental or purposeful man-made disasters have made this point time and time again.

Whether driven by the desire for energy independence, resiliency and/or environmental sustainability, the desire to move to a distributed clean-energy means of electricity production coupled with the goal of having "net-zero" energy buildings is fundamentally incompatible with the current unidirectional demand based grid system design. The need to combine millions of distributed electricity-generating sources (buildings with site based multiple means of generation) and power storage with the established central generation capability is an admittedly daunting challenge for the present AC system. Most fundamental to this difficulty is the highly sensitive synchronous nature of today's power distribution system. It is reminiscent of the days of synchronous computing – before the creation of today's non-synchronous Internet. Would the Internet have ever been possible if all the data creating microprocessors had to be tightly synchronized to a single clock rate? Yet by its very definition, that is what today's power grid is being asked to accomplish. It was not designed to do this and it is not likely to be easily modified to do so any time soon.

ABOUT DIRECT CURRENT (DC)

DC technology has several essential advantages over the currently used 50/60 Hz alternating voltage in power generation, collection, transmission and distribution systems:

1. **DC increases the flexibility in any grid, macro or micro**
   In today's AC distribution grids meshed structures are avoided due to the different phase angle of different connection points, high circulating currents can occur in grids when using AC technology. With DC connections frequency and phase angle are decoupled; therefore, DC connections can be easily installed in existing AC grids to increase the flexibility but not the other way around. Furthermore, in pure DC grids the connection of any/many grid points is in general possible. Therefore, a meshed structure can be easily achieved. An additional advantage for the load flow control in DC grids is that all converter stations are actively and freely controllable. So a higher proportion of distributed (renewable) energy production can be integrated maintaining a higher security of electricity supply.
2. **Better utilization of cables and wires**
   The stronger meshing potential of DC technology allows a higher utilization and redundancy in the cables and wires. In today's open ring buses, the power may have to flow through the opposite arm of the ring any time after the occurrence of a fault. Therefore, the utilization of cables is not very high. With increased meshing individual cables can be better utilized because different routes are possible for the power flow. As a result, the infrastructure of the distribution grid can be cheaper because a lower reserve path requirement is necessary.
3. **Increased efficiency**
   Power electronic converters for pure DC systems are highly efficient because they are soft switching and a higher operating frequency is possible compared to standard AC systems (50/60 Hz). Due to the increased frequency, particularly the losses in AC-DC conversion are reduced. In addition, the losses in the lines and converters can be significantly reduced by the elimination of reactive power in the grid.
4. **Reduced need of materials, lower costs, improved reliability**
   Due to the increased operating frequency, smaller passive components in the DC-DC converters are possible, which leads to a reduction in the usage of materials (especially copper and steel) and therefore to a cost reduction.
5. **Increased safety**
   AC and DC have slightly different effects on the human body, but both are dangerous above a certain voltage. The effect on a particular person is very difficult to predict as it depends upon a large number of factors - amount of current, duration of flow, pathway of current, voltage applied and impedance of the human body. Nevertheless, AC is generally rated as more dangerous because of following reasons:

- To produce the same effect, the amount of DC flow must be two to four times greater than that of the AC. The effect of current includes stimulation of nerves and muscles, and induction of cardiac atrial or ventricular fibrillation. Ventricular fibrillation is said to be the main cause of death by electric shock and the probability of a human suffering from ventricular fibrillation is much higher in the case of AC than DC.
- The total impedance of the human body is higher for DC and decreases when the frequency increases. Since the impedance for DC is higher, the severity of electric shock would be comparatively lesser than with AC at an equivalent voltage and current. And it is good to remember that AC voltages are generally stated as an RMS value, thus the peak voltage of AC is 1.3 times higher in actuality, i.e., 120VAC peaks at 156VAC and 220VAC peaks at 311VAC.
- It is comparatively easier to let go of a live wire with DC than AC. This is in contrary to the popular belief the AC would allow your muscles enough time to pull your limb away from the live wire because of the alternating cycles (AC frequency) as they pass through zero. DC current, on the other hand, has continuous flow due to the absence of frequency oscillations and therefore you can not pull your limb away from the live wire. This is simply a myth as the frequency is too rapid to allow any useful relaxation of the muscles, a condition called tetanus. As based on the information presented in IEC publication 60479, "Effects of current on human beings and livestock," the let-go of parts gripped is less difficult in the case of DC. This is based on actual experimental evidence, not hearsay.

While one could conclude that AC is more dangerous than DC, contact with all high-voltage electrical conductors should be avoided regardless of the type of electrical current. Thus extra-low voltage and controlled current DC is an increasingly preferred form of electricity when casual or incidental touch by humans is probable.

AN EPILOGUE CONCERNING CHANGE

Society is now at the dawn of a time of significant change in our electric power systems worldwide. The Enernet concept presented herein, simply tries to embrace a physical and operational scheme that contends with the rapidly emerging use of massively distributed, in scale, type and geography, renewable energy sourced electric grids. The Enernet will be a creature born of the renewable energy and microgrid industries, not the traditional centralized bulk power production and/or one-way power distribution industries. It will, indeed it must, allow change and evolve at the speed of the solar, wind, and other distributed energy and power electronics industries without unnecessarily marginalizing existing investments in bulk power generation and transmission if it is to remain economically viable and faithful to the potential for progress in our modern world. Its initial structure will be required to allow the effective use of massively distributed renewable energy microgrids. But its continuing evolution will bring new applications – like more productive and sustainable electro-active environments. It must also evolve to permit more sophisticated forms of transactional pricing and cost recovery. And finally, it must continue to change to accommodate yet future generations of power harvesting, transmission and use that will likely use technologies with different characteristics and requirements, e.g., wireless electro-magnetic wave form, photonic and digital energy transmission, a rapidly emerging Internet of [electric powered] Things, and more. New modes of access and new forms of service will spawn new applications, which in turn will drive further evolution of the Enernet itself.

The most pressing question for the future of the world's power systems is not how the technology will change, but how the process of change and evolution itself will be managed. The architecture of bulk power grids has historically been driven by a relatively small core of government and industry stakeholders. But the form of that group will need to change as the number of interested parties greatly increases, vis-a-vis the proliferation of building level microgrids and use of distributed power and powered electronics. With the dawn of this so-called Enernet will come a proliferation of stakeholders - stakeholders now with direct economic investments as well as an intellectual investment in the system and its more direct impact on them.

There are already debates over the reach of both public and private domain space enterprise and the form of the next generation of control of power generation and use, a struggle to find the next social structure that will guide power systems in the future. The form of that structure will be harder to find, given the large number of new, concerned and motivated stakeholders. They will simultaneously struggle to find the economic rationale for the new investment needed for infrastructure to support future growth. But if they stumble in this effort, it will not be because of a lack of technology, vision, or motivation. It will be because they collectively have not set a resolute new direction that allows everyone to move confidently and collectively into the future.

Coming Up Next in the Series: Evolution of the Enernet

This white paper series will next take up the subject of forming the actual Enernet of electricity. It will discuss the subject of microgrid interconnection and "Transactive Energy" and further, what role buildings, as major sources of power production, storage and use, will play.

But it will be more than a discussion of technology. The rapidly increasing capability of new and improved distributed and clean energy technologies has resulted in even more new demands being placed on electricity grids and the policy framework within which they operate. Changes in the type and location of production, metering, monitoring, control and use of electricity are advancing both the expectations and concerns of a rapidly expanding so-called prosumer class of private electrical energy stakeholders.

Challenges to the status quo in the policy making, stakeholder representation, and regulatory apparatus regarding public and private electrical systems will also be discussed as will the need to change traditional relationships between utilities, policymakers and consumers, most of whom will be building owners, in resolving the many new and emerging issues of the Enernet.

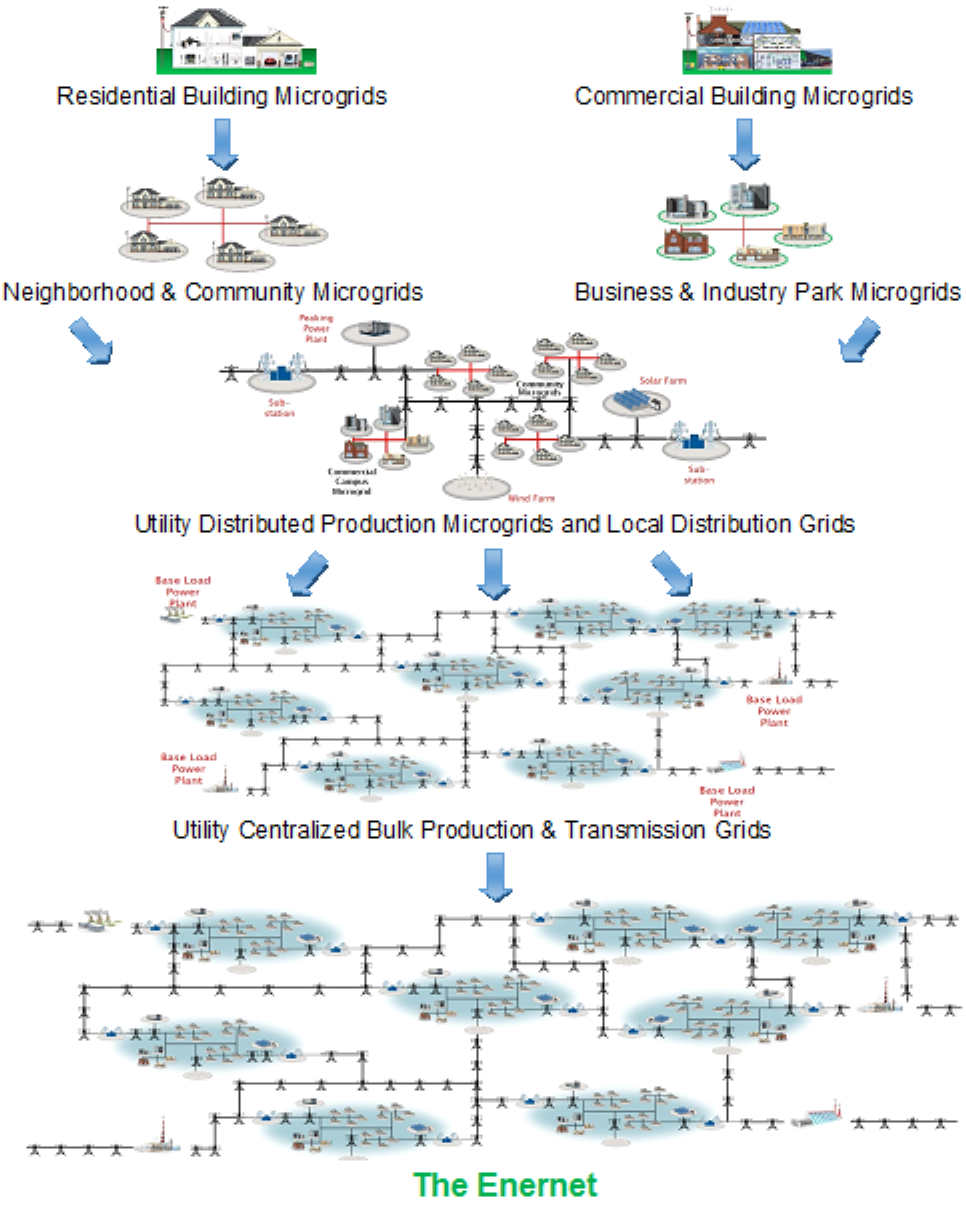

Figure 7. Evolution of the Electric Energy Network

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OTHER RESOURCE ORGANIZATIONS MENTIONED HEREIN

- **US Green Building Council**
  2101 L Street, NW
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  1-800-795-1747
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- **Electric Power Research Institute**
  3420 Hillview Ave
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- **EMerge Alliance**
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