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ARTICLE: Smart Grids, Energy Metering

Micro-Systems Driving Energy Metering in Smart Grids

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Abstract— Energy is a precious societal resource, and increasingly rated for its 'quality' or lack thereof as a contributor to greenhouse gases (GHGs). Modern electrical energy systems operate at the intersection of technological advances in microelectronics, communications, and control. From individual components and systems such as computer systems to their aggregates and *enclosures* such as data centers and buildings, microelectronic advances in radios, processors, storage and networking are enabling low-cost and effective embedded sensing and its use in operational controls. In the context of energy distribution systems, this trend has led to popular visions of 'smart electrical grids' that dynamically match generation, transmission, and storage for the most efficient and reliable usage of electromagnetic energy. This article examines the technology components and their use methods that make an electrical grid efficient and reliable by increasing the visibility available to grid operators and end consumers alike. We show how 'microgrids,' which are self-managed grids with local co-generation capabilities, can be used as testing grounds for the prototyping and testing of smart grid technologies. Using the prototype of a microgrid at the campus of the University of California at San Diego, we present energy data that points to promising methods for operation of various types of buildings that leverage the coordinated use of sensing, information processing, and building HVAC systems. Based on measurements and analyses, we show that for the emerging class of 'mixed-use' buildings – that is, buildings with a non-trivial component of energy use by IT equipment -- significant possibilities exist to reduce total energy use from 10% to 30% based on effective duty-cycling of the IT equipment, without affecting the availability of the building and compute resources.

Index Terms— Smart grid, energy efficiency, low-power methodology, microgrid.

I. INTRODUCTION

Energy is an increasingly important societal resource because it directly correlates with the economic welfare of a populace. Consequently, modern human history is one of effective, and lately efficient, transformation of energy into useful work. In the past, “work” referred to mechanical work in the form of movement of people or goods, or conversion of mechanical work into environmental comfort. Energy not converted into useful work was lost as heat – often necessitating cooling expenses – thus affecting the efficiency of the energy-work conversion process. The modern age – at least, since the last energy-related political crises of the 1970s – is characterized by its growth in capabilities and use of information processing that converts electrical energy into information storage, movement or display – again, with losses being dissipated as heat. With mechanical or information work, energy costs and other associated costs are increasing due to demand/supply imbalance and, more importantly, due to the adverse environmental impact of traditional energy sources. In recent years, the awareness of conserving natural resources, such as fossil fuels used for producing electricity, has increased at a rapid pace. Furthermore, numerous efforts to find alternative eco-friendly ways to produce electricity, such as solar power or wind energy, have also emerged. Despite various advances in both research and development into finding and cultivating new sources of clean energy, the demand for electricity continues to grow as infrastructures are electrified and information-enabled. Already the annual energy use by information processing equipment exceeds that of the aviation industry.[1]

The power distribution system, or the “grid”, is responsible for transporting energy from sources of energy production to the end consumers of electricity. The basic architecture of the grid has remained unchanged despite significant advances in computing technologies in the last fifty years. The electrical grid infrastructure is comprised of three elements: power generation, transmission, and distribution [1]. Electrical power generation consists of the power plants, either coal-fired or using alternate fuels such as natural gas to produce steam that is then used to drive turbines for producing electricity. The transmission element consists of a country-wide interconnected network of high-voltage electrical lines that transfers generated electricity toward energy consumption centers. This network of power transmission lines is collectively called the *power grid*. These transmission lines carry the electricity to electrical substations, where the voltage is stepped down using transformers. From here the electricity is fed through the *distribution grid* that connects to the end users, such as office buildings and residential homes.

Given the inherent complexity of the entire electrical grid, it is not without its own share of limitations. A key challenge with the electrical power grid today is lack of visibility: grid operators often do not have awareness of the electrical situation in real time [2]. This is important since the cost of energy storage is very high, and hence the current practice is to match energy consumption closely with energy generation. While electricity production costs can range from 3 cents to 24 cents per kW-H, storage costs in power conversion systems can range from hundreds of dollars per kW (battery storage and power conversion systems) to thousands of dollars per kW for grid-scale storage systems, due to the relatively short lifespan of these storage systems and the very high cost of maintaining infrastructure such as pumped water, compressed air, etc. for these systems. Furthermore, to reduce losses due to transmission inefficiences over longer distances, grid operators prefer electricity to be consumed close to where it is generated. Grid operators must then ensure that there is enough power supply to meet the power demand at any given time. When this fails, cascading power outages can potentially bring down the power grid, as was seen in the northeastern U.S. blackout of 2003. Limited

[1] http://greenlight.calit2.net/

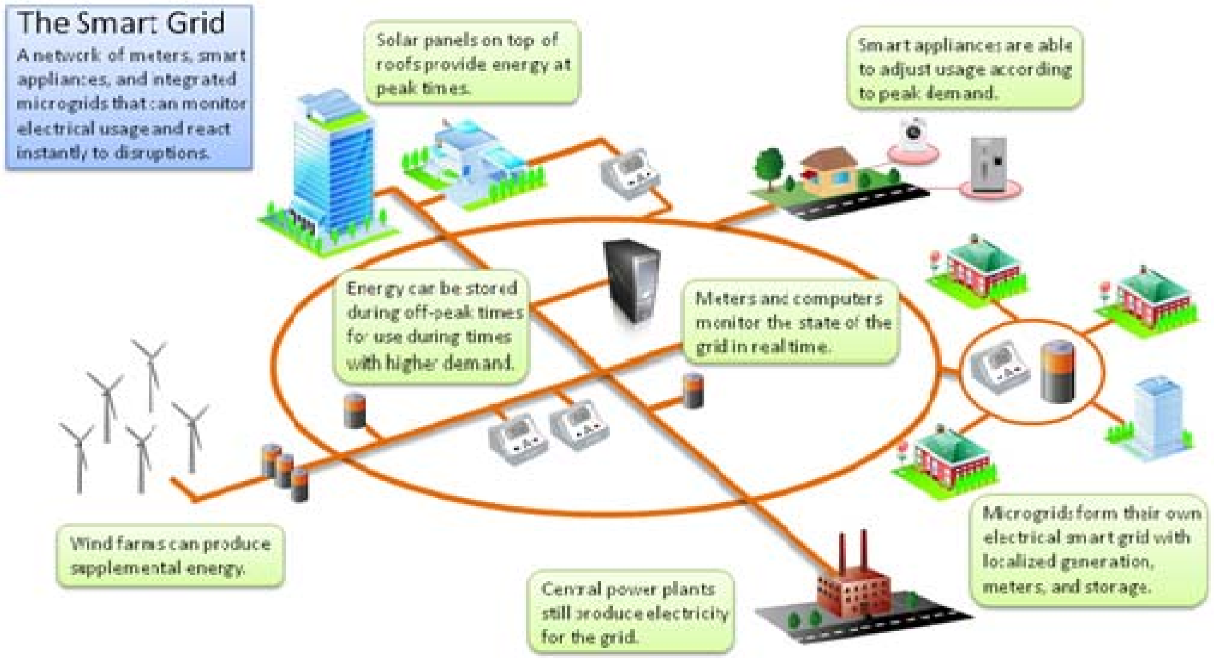

Figure 1: A typical smart grid with associated components.

awarness of the grid exacerbated the blackout, which affected 45 million people and caused an estimated estimated $6 billion in losses [3].

While the costs for grid failure are extreme, the consequences of lack of visibility and awareness remain significant even at a smaller granularity, such as at the level of buildings. Without an accurate accounting of where energy is being consumed, it is impossible to enact energy-efficient *policies* for a building or campus center. Conventional meters (such as the ones that are connected to most buildings) only measure kW-H for billing purposes, and only provide energy use information at the "whole building" level. Having real-time energy usage information and finer-grained energy use data can allow facilitiy managers to better set energy use policies, such as lowering energy usage during high peak times. In our research work, we focus on enterprise buildings: with buildings estimated to account for more than 70% of total electricity consumption in the U.S. [4], and contributing over 40% of total greenhouse gases, any improvement in energy efficiency in buildings will have a significant impact on nationwide energy consumption.

These issues have motivated investment in the modernization of the entire electrical delivery infrastructure. The current electrical grid infrastructure is centralized and relies on antiquated transmission and distribution grids that do not have sufficient visibility and functionality. A number of modernization efforts aim to add more intelligence to the grid, so as to make it more transparent to its operators and users. Currently, this is being accomplished through deployment of 'smart' energy meters, increased visualization of energy usage, provision of real-time pricing information, and tracking of changes in electrical demand. Economic studies have suggested that this visibility in turn can lead to better consumer participation, such as facilitating demand response to limit peak electricity usage [5]. Another goal is to design grids that facilitate the bidirectional flow of electricity, and promote the use of distributed generation; both of these have many benefits in terms of reducing costs and our carbon footprint.

Figure 1 shows some of the components that make up a prototypical smart grid today. Modern energy economics still lead to centralized power plants – coal, gas, hydro or nuclear – being the most cost-efficient for baseline electricity use. However, such plants are augmented by local generation using renewable sources such as wind power or solar panels on top of buildings. Microgrids are smaller self-contained grids that are able to generate electricity and monitor the flow of energy through their power lines. Storage elements and processing elements are able to detect disruptions in real time and reroute power accordingly. Also, appliances and energy consumers can react to power fluctuations and implement demand response mechanisms to reduce peak load. In the following section, we describe a concrete example of a microgrid and how it can provide not only a meaningful testbed but also a prototype for the smart electricity grid of the future.

II. A SMART MICROGRID

The key attribute of a microgrid is the *distributed* production of electricity. In doing so, it actually takes a step backwards – to the early days of electrical systems predating even Tesla – but with important architectural differences. Conventional electrical generation often occurs in large power plants located far from the actual end users due to structural elements (dams or gas/nuclear power plants). A microgrid instead relies on localized and distributed energy generation [9], supported by small power generation plants located near the energy consumers themselves. The distributed energy production can be achieved using a mixture of non-renewable sources such as gas turbines and renewable sources such as photovoltaic (PV) systems. Recent advances in materials science and engineering have made photovoltaic systems cost-effective and efficient – and the dominant sources of clean energy. PV systems use large arrays of solar cells to convert sunlight into electricity, and can be mounted on top of buildings, thus servicing the energy needs of the buildings to which they are connected. An inherent advantage of PV installations is that their energy production matches very well with the peak loads of buildings, which occur during the middle of the day when solar cell output is also at a maximum. Other small-scale generators include micro-turbines, which generally produce in the range of 30-100 kW [10]. In most cases, microgrids are still attached to the greater power grid, thus allowing electricity flowing from outside to augment locally generated energy. Likewise, surplus electricity produced by the microgrid can flow back into the main power grid. In some cases this ability to feed back energy into the grid has been crucial in 'demand response' scenarios to protect the larger grid during acute energy shortages [7].

Distributed energy generation has many other advantages over centralized electricity generation [10]. Overall energy efficiency can be improved due to reduced transmission losses when power is produced closer to end users. Many of the energy sources for microgrids are more environmentally friendly, e.g., photovoltaic systems which produce less carbon than centralized power plants burning coal or natural gas. Microgrids also have a lower impact on the distribution network, as production is more closely matched with demand.

Finally, microgrids also confer another important advantage – the ability to truly experiment with and monitor electrical usage at a controllable scale. Understanding energy usage requires detailed knowledge about the dominant patterns of energy consumed, its transmission through the grid, and how events (such as disrupted transmission) affect it. New technologies that affect smart grid design can be studied in isolation on a microgrid before being deployed on a larger scale. These include new energy storage methods, enhanced smart metering, improved control, and real-time observation of the microgrid.

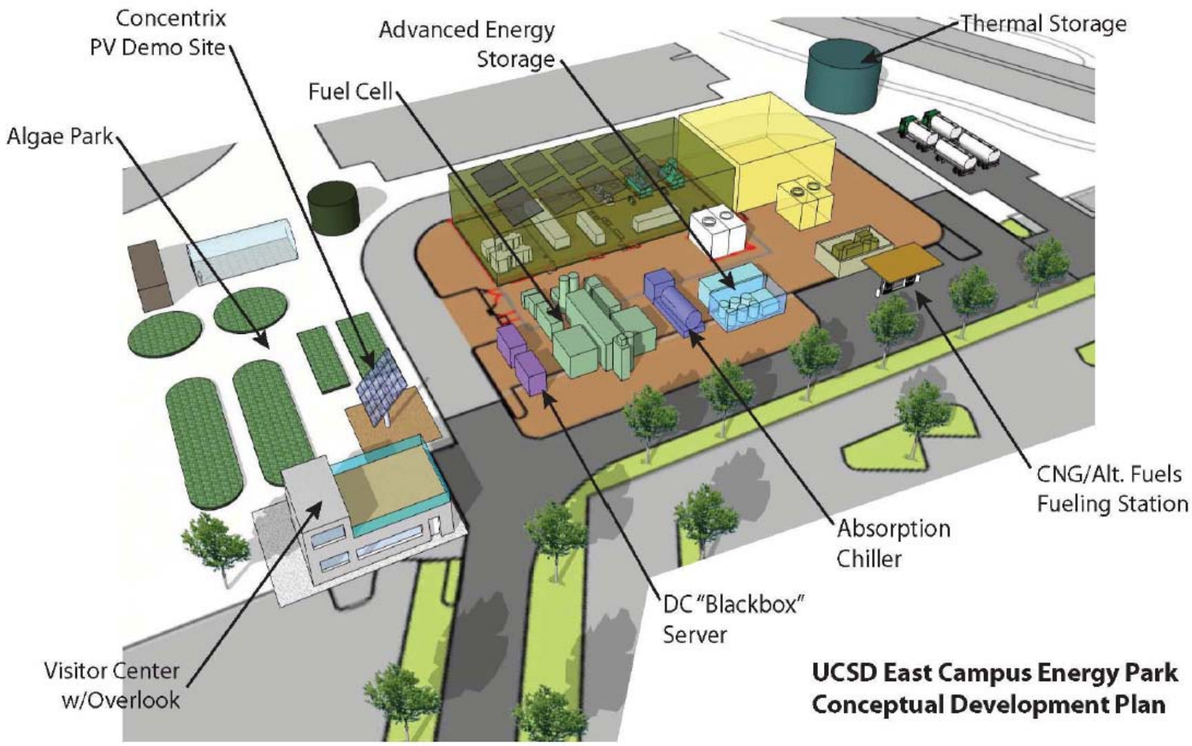

Figure 2: Localized co-generation and storage of energy for the UCSD microgrid. (Source: Byron Washom, UC San Diego.)

Many smart microgrids currently exist as research testbeds. One research effort is the Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid, a project of the University of Wisconsin [8], which researches how microgrids can associate with the greater distribution grid. A key goal is to look into ways that microgrids can provide greater reliability. For example, if there is a disruption in the overall power network, the microgrid can isolate itself and not suffer any power disruptions. When conditions return to normal, the microgrid can automatically resynchronize itself to the grid [8]. Many related technologies are being actively researched in support of this goal, such as real-time monitoring systems and improved integration of distributed energy resources.

The Pacific Northwest National Laboratory has created a smart microgrid called GridWise [25] which seeks to understand how smart grid technologies can affect how energy consumers interact with electricity markets. The focus of GridWise is on the design of information technologies that will help change the electricity grid to a distributed network with self-healing properties, thus increasing electrical efficiency and reliability.

Another example of a microgrid is the San Diego campus of the University of California [7]. The UC San Diego campus is situated in the coastal community of La Jolla and is spread over an area of 1200 acres. The total population of UCSD is approximately 45,000 people, of which 10,000 students live on campus. With over 450 buildings, the campus resembles a small town. Under a campus-wide sustainability initiative [22], UCSD has taken on an ambitious goal to reduce energy usage significantly and use cost-efficient renewable energy sources with the objective of becoming energy self-sustainable (or, off the electrical grid) within the next couple of years [23].

To support this goal, the campus has extensive energy generation, storage and management systems in place to deliver both electricity and thermal energy in the form of high-temperature and chilled water to the various buildings across campus. The centralized Energy Management System (EMS), by Johnson Controls, is connected to sixty of the largest buildings across campus, managing

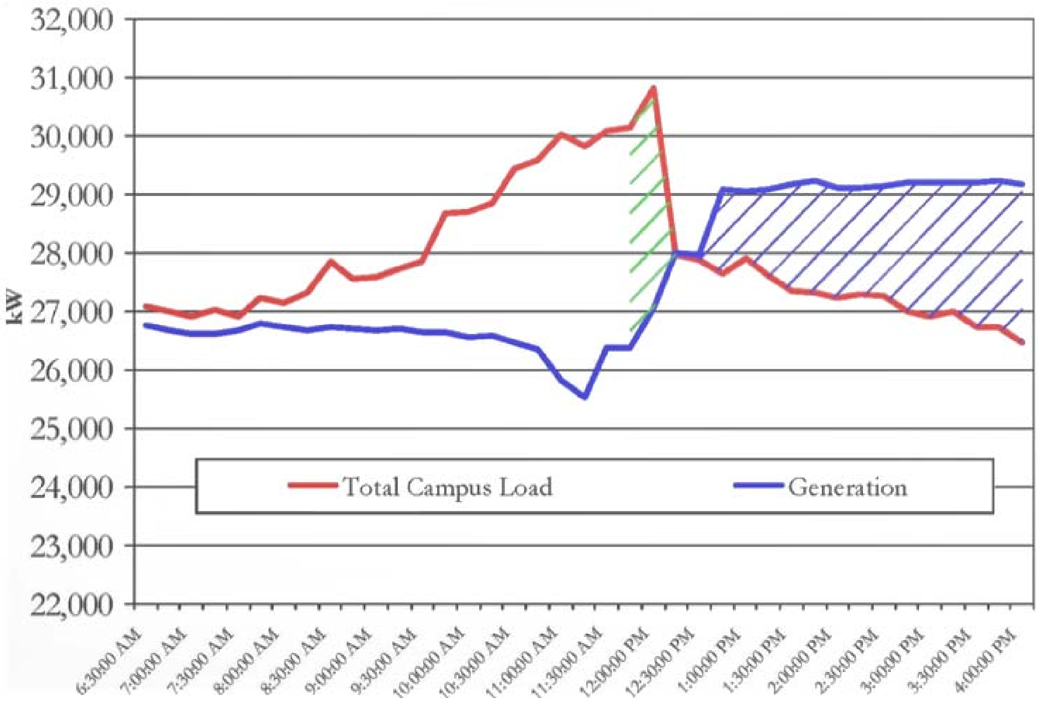

Figure 3: Graphic showing the UCSD microgrid increasing energy production and reducing energy consumption to feed back to the main grid during a power emergency in San Diego. (Source: Steve Relyea, UC San Diego.)

their HVAC systems. The high-temperature and chilled water loop is delivered from a Central Utilities Plant (CUP), which includes a 30 MW co-generation system comprising two 13.5 MW gas turbines, a 3 MW steam turbine and a 1.2 MW solar cell installation. The co-generation plant operates at a combined efficiency of 74% and enables UCSD to self-generate more than 80% of its electricity demand. The CUP has a capacity of 15,000 tons of chilling with a 40,000 ton-hr thermal energy storage (TES) tank. Three chillers are driven by steam turbines and five chillers are electrically driven. UCSD currently participates in the San Diego Gas and Electric (SDG&E) capacity bidding program and modulates demand response (DR) manually by shifting chilled water demand from electric chillers to the TES tank, ramping the steam turbine generator by using standby conventional boilers, and changing campus-wide thermostat and static pressure set points in non-critical areas throughout the campus.

With its own electricity generation, the UCSD campus is a prototypical microgrid. Figure 2 highlights some of the localized co-generation and storage of electricity on part of the campus. The UCSD microgrid is able to produce much of its required energy demands, and is also capable of feeding back electricity to the main grid during emergencies. Figure 3 shows a plot of the UCSD demand response mechanism in action during the widespread wildfires in San Diego County during summer 2007. Due to extensive fire damage, the local electric utility company asked UCSD to help prevent instability in the grid that could cause a large-scale outage. UCSD was able to respond by reducing campus electrical load by several megawatts, and by increasing energy production to actually feed energy back into the grid, all within the short time span of a couple of hours.

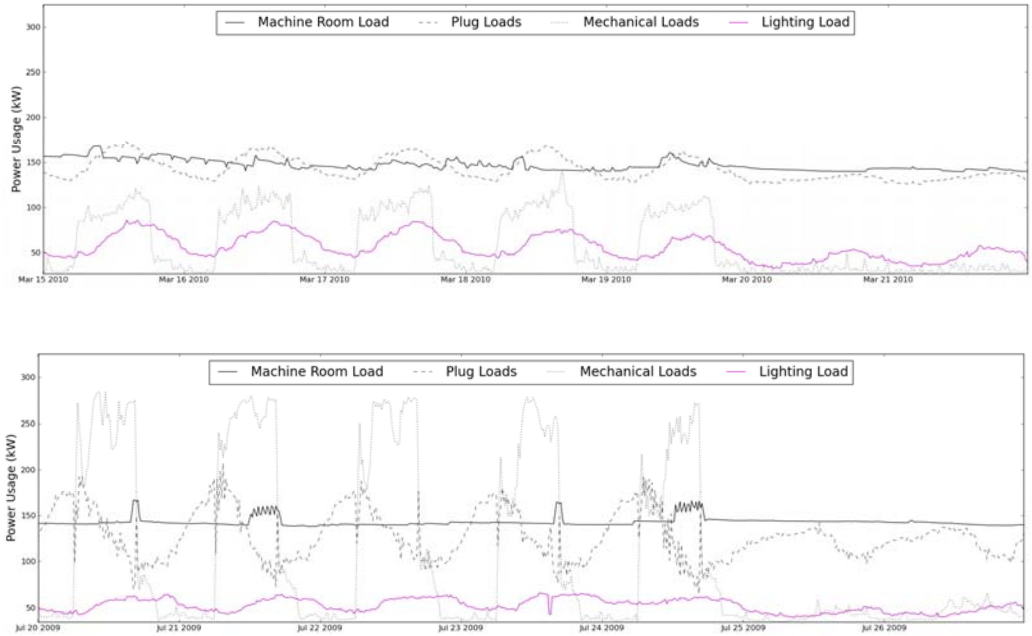

Figure 4: Breakdown of energy usage in the CSE building at UCSD.

Since the UCSD campus is a microgrid, it becomes an ideal candidate for application of smart grid technologies in order to better understand their impact on energy usage. Electricity meters have been deployed across the campus to better monitor where energy is being consumed. The sixty largest buildings have been metered with three-phase commercial grade, high-accuracy Schneider Electric PowerLogic meters that report real-time energy use data back to central campus servers. These meters can measure various electrical parameters such as power factor, voltage levels, real and reactive power, and minimum and maximum demand.

To provide an even more detailed usage breakdown, we have instrumented one of the newest buildings (completed in 2004) on the UCSD campus, the Computer Science and Engineering (CSE) building, with sub-metering to provide finer-grained energy use data. The CSE building is unique in several aspects that make it an ideal testing ground for conducting research in energy efficiency in a mixed-use building as part of the microgrid. The building has a closed-loop system that provides zonal and floor-by-floor control of air flow, temperature, and lighting conditions. It also provides dynamic control of window shading, is coupled to the central campus chilled water loop, and has local refrigeration capabilities. It nominally houses 600 occupants, which increase to 1000 people at its peak (during classes and labs). The CSE building has approximately 750 desktop PC machines, one machine room for computer servers, and six instructional computer labs with over 200 additional PCs for undergraduates. The combined non-server IT equipment (desktop PCs, networking equipment) accounts for over 25% of total building energy consumption, even during low occupancy periods such as nights and weekends. The machine room holds a large number of server nodes. Cooling for the machine room is provided by the campus chilled water loop in addition to additional HVAC units that run on electricity.

The energy measurement infrastructure within the CSE building not only measures total energy usage by the CSE building, but also provides a detailed breakdown into the four logical subsystems: *lighting loads*, *mechanical load* (includes all climate control equipment such as air handlers, pumps, etc.), *machine room loads* (includes servers, networking equipment, UPS), and finally, all of the *plug loads* (everything else plugged into the wall sockets; a large fraction of the plug load energy use can be attributed to desktop PCs). Figure 4 shows the detailed power consumption breakdown for each of these logical subsystems over a two-week period during March 2010.

By collecting and analyzing this energy use data, across different levels from entire buildings to energy breakdown within buildings and finally to energy use by end users, the UCSD microgrid presents an ideal opportunity as a extensive test bed to push forward the research and development of smart grid technologies.

III. METERING AND MONITORING

One of the key technologies that must be at the foundation of smart grids is the *smart energy meter*. While conventional meters are only able to measure aggregate energy consumption (kW-H), smart meters have several attractive features that allow them to do significantly more. First, they are able to log, in real time, energy consumption at fine granularities and store the values in digital form. Smart meters have a significant communication component that allows them to report their measurements over a wired or wireless data network. In some cases, smart meters can even communicate with surrounding infrastructure devices, for example in homes, to send real-time pricing signals to end energy consumers. Finally, smart meters often have a control component allowing the utility to remotely power them off in demand response scenarios. Smart meters can typically measure many additional electrical parameters, such as max and min power demand, current, voltage, and power factor, and can notify the utility about power outages. Smart meters are therefore invaluable, since real-time knowledge of the electricity grid situation is vital to the implementation of energy-efficient policies and understanding of electrical usage both across the microgrid and inside individual buildings. Advances in solid state technology, microprocessors, and communication infrastructure have made possible these improved smart meters. Classic energy meters were based on electromechanical properties, which rely on principles of induction to determine energy usage. A smart meter, by contrast, has microcontroller and digital signal processing for calculation of additional electrical parameters, as well as communication circuitry that allows it to transmit and receive information through the network..

Energy metering at the scale of buildings can be done in either a “top-down” or a “bottom-up” manner. Each approach has advantages and limitations when considering factors such as coverage, accuracy, and granularity of measurements. Most of the time a combination of both approaches is needed to allow detailed visibility into the energy consumers within a microgrid. In a “top-down” approach, commercial-scale energy meters can be deployed to measure the total energy usage in a building. To get a further breakdown, additional meters can be placed on individual subsystems, such as lighting or the mechanical subsystem. The advantage of metering in this way is that good coverage can be achieved, and all the energy use in the building can be accounted for, giving a critical overall view of the energy use in the building. However, the disadvantage of this approach is that due to the coarse granularity of measurements, individual plug loads cannot be identified. Several commercial vendors provide meters for top-down measurements, including Schneider Electric and GE.

Using the “bottom-up” approach, individual plug load meters are added to each outlet to measure the energy usage of the corresponding plug load devices, such as computers and monitors. Using this bottom-up approach to meter an entire building and get complete coverage may require potentially tens of thousands of meters for a medium-size building. Therefore, cost issues per meter become important, as does the design of the network infrastructure supporting the data collection from all of the meters. Several research prototypes [12] of networked energy meters have emerged recently that primarily focus on the wireless network design by leveraging existing platforms and techniques developed within sensor networks. The ACME project at UC Berkeley implements a wireless sensor network for monitoring AC energy usage across a building environment [12]. UCLA's ViridiScope [13] attempts to monitor energy consumption via indirect sensing of measurable signals of appliances. Several commercial meters also exist in this space, including those manufactured by WattsUp Devices [11] and Kill-A-Watt meters.

For meters to be ubiquitous, however, additional technological improvements must be made. Meters must be cheap in order to be deployable at a wide scale; this represents a clear challenge for chip and board designers to create more cost-efficient ICs for energy measurements. Wireless communication will also be the de facto method of communication for these meters to ease deployment within existing buildings, and thus improvements in reliability and power efficiency of RF chips will be needed. Another important aspect that must be addressed is standardization that would allow a common set of open protocols to be defined that can be used by different meter manufacturers and developers of the software infrastructure. Currently, meter manufacturers use a myriad of closed and proprietary protocols, such as BACNet and ION, to communicate energy use data to proprietary databases. Using open protocols could allow application developers to access energy data more easily, and to build different user interfaces and a richer set of applications. This would also enable smart meters to talk to smart devices – e.g., smart lighting fixtures – thus enabling easier demand response and improved energy efficiency.

IV. PRESENTATION AND VISUALIZATION

Visualization of the metering data is vital if grid operators and building managers are to make better decisions and policies with respect to energy usage. Visibility of this data requires communication technology that allows meters to send data to a centralized server, as well as software that can display this information in an effective manner. Only through visualization of the recorded data can human operators have full situational awareness of the energy grid. Visualization further enables managers to perform energy audits that uncover where the energy is actually going in their buildings.

Many projects and programs exist that provide visualization of energy data. One effort of note is the Visualizing Energy Resources Dynamically on Earth (VERDE) tool, a U.S. Department of Energy project that seeks to provide real-time awareness of the electrical grid [14]. Built on Google Earth, VERDE will combine geographic and weather data with real-time sensor readings to give a “health status” of the nation’s electric infrastructure. Besides tracking the real-time status of the national electric grid, VERDE also can model and simulate grid behavior and analyze contingency plans for emergencies.

Commercial companies are also active in this space. Lucid Design Group provides clients with a website (called the Building Dashboard) that displays aggregate energy usage. Many college campuses have their own visualization projects, e.g., UC Berkeley, UC Davis, and UC Santa Barbara all have their own efforts [15][16][17]. As part of the smart microgrid efforts, we at UCSD have also developed a visualization platform called the Energy Dashboard [7]. This website displays in real time collected energy information from all the meters across the campus. Energy Dashboard displays energy usage for entire buildings down to fine-grained energy usage of plug loads within a building. It is thus possible to see trends in energy usage across the entire spectrum of electrical end-uses. Figure 5 shows an energy usage map for the campus; this particular view allows managers to quickly grasp energy consumption in real time.

The value of these visualization efforts lies in the discoveries that can be made regarding how energy is used. For example, several interesting observations can be made when viewing the UCSD Energy Dashboard data and comparing energy usages of buildings. UCSD is a college campus and thus has a diverse collection of buildings, including lecture halls, residential units, and research laboratories. UCSD also is the home of the San Diego Super Computing Center (SDSC). With its large collection of computing equipment, SDSC uses more than three times the amount of energy than a typical research building. Even the CalIT2 unit, which is housed in a large six-story building with over six major research labs and many office units, consumes half of the energy of SDSC. These observations reinforce the fact that IT equipment is a major consumer of power, one that can now be quantified in part because of the availability of visualized data.

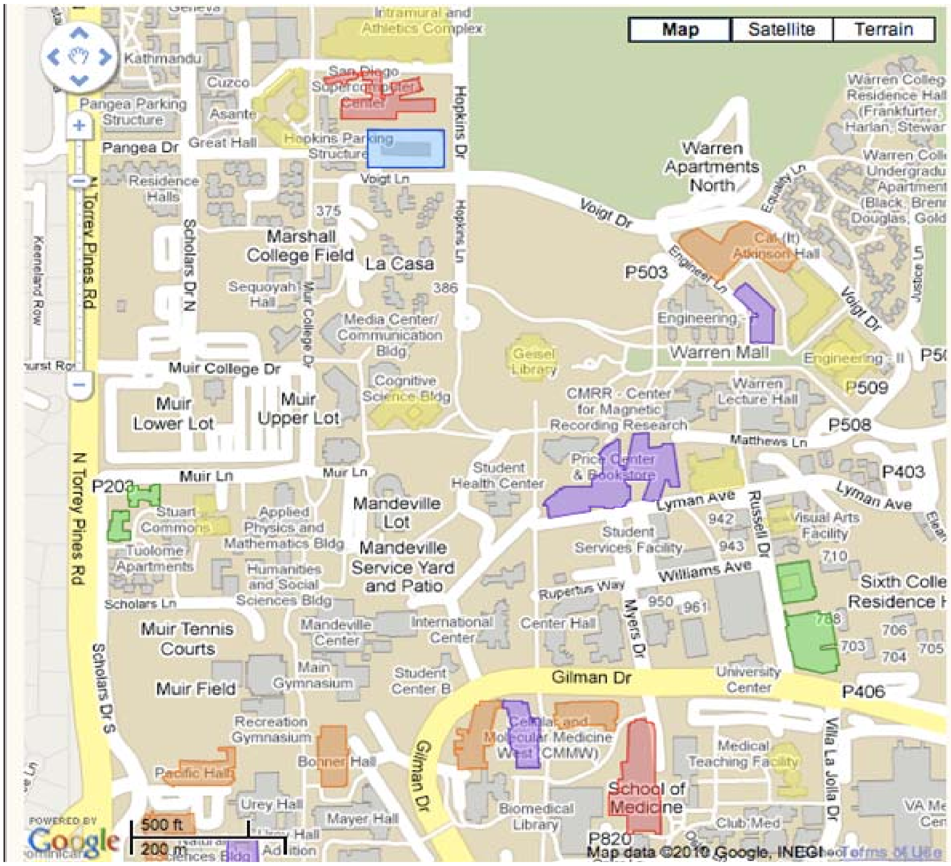

Figure 5: Real-time energy consumption map of the UCSD campus.

We can even view the detailed energy usage of an individual building [7][18]. Visualization of the UCSD CSE building displays many interesting trends common to multi-use buildings. For one, IT loads (desktop PCs and servers) dominate within CSE; in non-summer months IT is the largest consumer of electricity in the building. This informs policy-makers that in order to cut down on energy usage, targeting of IT would yield significant energy savings. Another interesting observation is that IT loads remain high even at night and during weekends, when occupancy is low. This suggests that computer users simply leave their machines on, even when not in use. When asked about this, several users indicated that they do not want to turn off their computers, or even put them into a low-power “sleep” mode, because they require network connectivity of their computers even when not actively using them. This has motivated such research projects as Somniloquy [19] and SleepServer [24] that find ways for users to switch their computers into low-power “sleep” mode while yet maintaining network presence. Through visualization of the energy data, we have observed that users who utilized these energy-saving architectures consumed 40% to 80% less energy than other users. Furthermore, by observing their own energy use patterns using the Energy Dashboard, users typically became more aware of their usage and tried to conserve even more. This preliminary data therefore points to the social engineering aspects and benefits of visualizing real-time energy usage by end users.

Presentation and visualization of energy usage data is therefore both a critical component and a key benefit of smart grid technology. Situational awareness and detailed energy audits are important if grid operators and facility managers are to make better decisions regarding energy usage. Processing the enormous amounts of raw data and displaying it in ways that make intuitive sense and provide useful information is a challenge, but one that is made more tractable by modern hardware and software.

V. ENERGY CONTROL OF THE AC/DC DISTRIBUTION ARCHITECTURE

The future of the smart grid is not just limited to better situational awareness and energy accounting. Entirely new approaches and technologies have the potential to transform our energy grids towards new directions. For example, our current distribution lines are high-voltage AC lines, which make sense for centralized power production. AC is more efficient and loses less energy than DC over long transmission and distribution networks. However, as the architecture of the grid includes more microgrids, which means more distributed generation of electricity, the benefits of DC distribution could become apparent. In such a distribution system, AC power from generation plants can be converted to high-voltage DC using AC-to-DC converters. It will be possible to apply more efficient power factor correction in high-voltage DC power distribution units than is feasible with traditional AC-AC step-down transformers. In addition, DC distribution networks convey many advantages such as less noise, and are thus more suitable for electronically controlled feedback networks. Since energy is stored in UPS units, these can be directly connected to the high-voltage DC lines, acting as both energy routers and buffers, and allowing fine-grained control over such mechanisms as adaptive power factor correction. A smart microgrid will also contain multiple power distribution units (PDUs), and thus over the network it becomes possible to perform load management, sharing of energy storage, and routing of energy resources. This allows a power distribution center to have increased reliability and better contingencies in case of electrical disruptions [21].

VI. SUMMARY AND CHALLENGES FOR FUTURE SMART GRID TECHNOLOGIES

Driven by a host of technology developments, economic incentives and environmental awareness, the smart grid is quickly becoming a reality. There are new technologies and innovations on the horizon that will revolutionize how electricity is produced, transmitted and delivered to end users. We have discussed a few of these futures, primarily as exemplars.

Many technological challenges still remain to be solved. At a high level, security and reliability, as well as deployment of smart metering, remain as difficult challenges for utility companies. There is currently no universal common standard in use by all utilities and players in this field, and indeed many varying standards and protocols, often proprietary, have been adopted by different companies. A smart grid will need to have common accepted standards in order for devices to properly communicate.

Having a common standard for the smart grid is essential, and is a key focus for smart grid development in the United States. Under the Energy Independence and Security Act of 2007, the National Institute of Standards and Technology (NIST) has been the responsibility to coordinate development of standards for smart grid devices and systems [26]. This is critical, as a smart grid will be composed of meters and actuators that must be able to communicate with each other. Whichever communication standard wins out, IC designers will need to fill the space with inexpensive chip solutions so that all device manufacturers can incorporate the communication standards into their products.

More accurate simulations need to be designed that can effectively model a smart network grid. Just as in chip design, having accurate and fast simulations is essential for deployment smart grid systems in real electrical networks. Next-generation grid simulators include GridLAB-D [27], which can simulate distribution systems at a very high level of detail. These simulators require an immense amount of computing power, and hence novel (FPGA-based or other) architectures might help accelerate these simulations.

Battery technology, too, will be an important factor for smart grid deployments. As power consumption and generation are more closely matched, the ability to store energy cheaply and reliability will become vital. Lithium-ion batteries are commonly used in small applications, but at a large scale their use remains expensive. Other battery technologies such as hydrogen fuel cells, which have the potential to store a vast amount of energy, might prove to be useful.

There is room for improvement at the chip level as well. Smart meters rely on analog and digital components, such as communication chips (wireless or wired) and processors. Systems-on-chip contain processor cores and other components on the same die, and as chip technology advances (whether through novel architectures or smaller feature sizes), the cost and size of smart meters is reduced. For example, if a single chip can contain most of the features that are required by a smart meter (processing core, communications core, power measurement core), then smart meters will become increasingly cheaper, which is vital for wide deployment of these systems. Various chip companies such as Texas Instruments, Analog Devices and Teridian already offer SOCs to measure energy usage; advances in chip fabrication will continue to bring more functionality into smaller form factors and at lower cost.

Integrating energy measurement systems onto system boards is also an option going forward. Appliance manufacturers can install energy measurement capabilities directly into their products (refrigerators, television sets, computers) and enable a smart home grid where home owners can track electrical usage in detail. Also, by allowing actuation for energy conservation (i.e., turning them off), appliances can better support demand response schemes that lower total electrical costs by limiting energy consumption during peak (expensive) times.

Security of the smart grid is another critical concern. This must be addressed at all levels of smart grid development, from the integrated circuits and system boards up to the high-level software infrastructure. It is well known that the national electrical infrastructure is vulnerable to attack, and hence security is of primary importance within the national focus on smart grid development. A future network of smart meters will generate an enormous amount of valuable data that must be protected for reasons of privacy and security [30]. It is important to build security into the network at the start, rather than retrofitting later at greater cost. Trusted computing modules and similar efforts can provide additional security at the system level, while new encryption schemes and security protocols can provide security at the communication level. Widespread deployment of smart meters mandates that such schemes be in place to protect these devices at all levels.

Perhaps the most important challenge (and benefit) that the smart grid offers is reliability. The topic of reliability stretches from individual devices and systems, up to the macro-level view of the entire infrastructure. The annual cost of outages is on the order of tens of billions of dollars [31], so ensuring reliability is a critical goal for any electrical grid modernization. Reliability will depend upon advances in a wide range of areas, including energy harvesting from renewable sources, storage devices for energy, smart metering devices, and IT infrastructure [28]. The IT infrastructure is in fact vital for the smart grid, as the smart grid is fundamentally a network for data and electricity, and the IT management must be capable of monitoring and controlling the grid in real time.

Finally, resilience of the grid is also a critical concern: the current electrical grid has potential vulnerabilities to attacks such as disruption of a subnetwork to cause a cascade-failure of the entire network [29]. Smart grid technologies such as real-time monitoring and energy routing can help minimize the danger from these failures, and thus increase reliability of energy delivery under extreme circumstances.

REFERENCES

[1] US Department of Energy, *A Primer on Electric Utilities, Deregulation, and Restructuring of US Electricity Markets,* 2002.

[2] US Department of Energy, *The Smart Grid: An Introduction,* 2009.

[3] New York Independent System Operator, *Interim Report on the August 14, 2003 Blackout,* 2003.

[4] US Department of Energy, *Buildings Energy Data Book,* 2009.

[5] US Department of Energy, *A National Assessment of Demand Response Potential,* 2009.

[6] United States Energy Independence and Security Act of 2007.

[7] Y. Agarwal, T. Weng and R. Gupta, “The Energy Dashboard: Improving the Visibility of Energy Consumption at a Campus-Wide Scale“ *Proc. First ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings (BuildSys ’09),* November 2009.

[8] R. Lasseter, “CERTS Microgrid”, *International Conference on System of Systems Engineering*, 2007.

[9] IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems.

[10] S. Abusharkh, R. Arnold, J. Kohler, R. Li, T. Markvart, J. Ross, K. Steemers, P. Wilson and R. Yao, “Can Microgrids Make a Major Contribution to UK Energy Supply?”, *Renewable and Sustainable Energy Reviews* 10 (2006), pp. 78-127.

[11] WattsUP, WattsUP Energy Meters, http://www.wattsupmeters.com.

[12] X. Jiang, S. Dawson-Haggerty, P. Dutta and D. Culler, “Design and Implementation of a High-Fidelity AC Metering Network, *Information Processing in Sensor Networks*, 2009.

[13] Y. Kim, T. Schmid, Z. M. Charbiwala and M. B. Srivastava, “ViridiScope: Design and Implementation of a Fine Grained Power Monitoring System for Homes”, *Proc*. *11th Intl. Conf. on Ubiquitous Computing*, 2009.

[14] US Department of Energy Oak Ridge National Laboratory, “Electric Grid Situational Awareness”, *NASPI Meeting*, 2007.

[15] UC Berkeley Campus Dashboard, http://www.demandless.org/building/.

[16] UC Davis Utilities Consumption Dashboard, http://facilities.ucdavis.edu/dashboard/.

[17] UCSB Energy Demand, http://energy.ucsb.edu/ASP-HTM.asp.

[18] UCSD Energy Dashboard, http://energy.ucsd.edu/.

[19] Y. Agarwal, S. Hodges, J. Scott, R. Chandra, P. Bahl and R. Gupta, “Somniloquy: Augmenting Network Interfaces to Reduce PC Energy Usage”, *Proc. USENIX Symposium on Networked Systems Design and Implementation*, April 2009.

[20] M. Ton, B. Fortenberry and W. Tschudi, *DC Power for Improved Data Center Efficiency*, Lawrence Berkeley National Laboratories, March 2008.

[21] S. Govindan, J. Choi, B. Urgaonkar, A. Sivasubramaniam and Andrew Baldini, “Statistical Profiling-Based Techniques for Effective Power Provisioning in Data Centers”, *Eurosys* 2009.

[22] UCSD Sustainability 2.0: A Living Laboratory, http://sustain.ucsd.edu.

[23] UCSD Green Campus Program, http://greencampus.ucsd.edu.

[24] Y. Agarwal, S. Savage and R. Gupta, “SleepServer: A Software-Only Approach for Reducing the Energy Consumption of PCs within Enterprise Environments”, *to appear in Proc. USENIX Annual Technical Conference*, June 2010.

[25] D. Hammerstrom et al., *Pacific Northwest GridWise Testbed Demonstration Projects*, PNNL-17079. 2007.

[26] National Institute of Standards and Technology, *NIST Framework and Roadmap for Smart Grid Interoperability Standards*, Release 1.0. NIST Special Publication 1108.

[27] D. Chassin, K. Schneider and C. Gerkensmeyer, “GridLAB-D: An Open-Source Power Systems Modeling and Simulation Environment” *Transmission and Distribution Conference and Exposition*, 2008.

[28] K. Moslehi and R. Kumar, “Smart Grid – A Reliability Perspective“, *IEEE PES Conference on Innovative Smart Grid Technologies*, January 2010.

[29] J. Markoff and D. Barboza. “Academic Paper in China Sets Off Alarms in U.S.” *The New York Times*, March 20, 2010.

[30] P. McDaniel and S. McLaughlin, “Security and Privacy Challenges in the Smart Grid“, *IEEE Security and Privacy* 7(3), May 2009.

[31] K. Hamachi-LaCommare and J. Eto, “Cost of Power Interruptions to Electricity Consumers in the United States“, LBNL-58164, February 2006.