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DC Microgrids: Benefits and Barriers

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I. OVERVIEW

Our electric power system was designed to move central station alternating current (AC) power, via high-voltage transmission lines and lower voltage distribution lines, to households and businesses that used the power in incandescent lights, AC motors, and other AC equipment. Today's consumer equipment and tomorrow's distributed renewable generation requires us to rethink this model. Electronic devices (such as computers, florescent lights, variable speed drives, and many other household and business appliances and equipment) need direct current (DC) input. However, all of these DC devices require conversion of the building's AC power into DC for use, and that conversion typically uses inefficient rectifiers. Moreover, distributed renewable generation (such as rooftop solar) produces DC power but must be converted to AC to tie into the building's electric system, only later to be re-converted to DC for many end uses. These AC-DC conversions (or DC-AC-DC in the case of rooftop solar) result in substantial energy losses.

One possible solution is a DC microgrid, which is a DC grid within a building (or serving several buildings) that minimizes or eliminates entirely these conversion losses. In the DC microgrid system, AC power converts to DC when entering the DC grid using a high-efficiency rectifier, which then distributes the power directly to DC equipment served by the DC grid. On average, this system reduces AC to DC conversion losses from an average loss of about 32% down to 10%.² In addition, roof top photovoltaic (PV) and other distributed DC generation can be fed directly to DC equipment, via the DC microgrid, without the double conversion loss (DC to AC to DC), which would be required if the DC generation output was fed into an AC system.

This paper describes the operation of DC microgrids, potential national benefits, barriers to deployment, and policy measures that could accelerate this deployment.

II. DC MICROGRID TECHNOLOGY

The Energy Independence and Security Act of 2007, Title XIII, identifies the elements that characterize the "Smart Grid" policy goals. In summary, these are³:

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² See Section III below for discussion of 68% average efficiency (32% loss) of the current AC to DC conversion.

³ Energy Independence and Security Act of 2007 § 1301 et seq., 42 U.S.C. § 17381 et seq.

- reliability; security; storage; distributed generation
- energy efficiency; sustainability; renewable inputs
- IT/communications leverage/full cyber-security
- load awareness; demand side management; plug-in vehicles
- lowering unnecessary barriers to achieving the above

Each of these goals can be advanced through the use of DC microgrids, and often at lower cost with greater effectiveness than measures applied to the greater AC grid.

The national power grid system in the U.S. and around the world was not designed to handle the energy demands of the modern economy. To meet the contemporary needs of the grid's customers today, we should consider the tools available through DC microgrids, which can optimize the use of electronic devices, electrical storage, and distributed generation.

The national Smart Grid discussion should thus focus on ensuring that the grid optimally balances what we refer to as the "Power Equation" (power generated, less line and conversion losses, equals power used). The interest in DC microgrids over the past 10 years has been growing. The U.S. Department of Energy (DOE), the California Energy Commission (CEC), the Electric Power Research Institute (EPRI), several utilities and many entrepreneurs and investors have sought through Smart Grid initiatives to upgrade the interface between the utility grid. The vast majority of these efforts have been designed to operate in the AC currency of the national grid. The present discussion focuses on DC microgrids as a way to improve the efficiency, reliability and security of the implementation of the Smart Grid

⁴ There followed seven "Points of Varying Agreement", and a survey of who was doing what with microgrids at that time; survey available at http://www.electricdistribution.ctc.com/pdfs/Microgrid_Vision_Workshop_Presentation.pdf (last visited March 15, 2010).

⁵ MISSING

⁶ While for simplicity's sake, we refer in the paper to DC microgrids, these systems can be further defined as follows: *Nanogrids* – defined as an electrical power system as described in the two universal points of agreement that serves a defined space in one building; *Microgrid* – defined as an electrical power system as described in the two universal points of agreement that serves one building; and *Minigrid* – defined as an electrical power system as described in the two universal points of agreement that serves more than one building.

A. What is a DC microgrid?

Defining "microgrid" is important for our discussion, but not necessarily simple. The DOE and the CEC jointly commissioned a report from Navigant Consulting in 2005 that wrestled with this very definition. The final report identified two "Points of Universal Agreement" of what constitutes a microgrid, which remain valid today:

A microgrid consists of interconnected distributed energy resources capable of providing sufficient and continuous energy to a significant portion of internal load demand.

A microgrid possesses independent controls, and intentional islanding takes place with minimal service interruption (seamless transition from grid-parallel to islanded operation).⁴

These two definitions work easily in both the AC and DC domain, so we will borrow them both.⁵

DC microgrids can be deployed in a portion of a building, building-wide or covering several buildings. We will refer to these systems (whatever their scale) as "DC microgrids" in the balance of this paper.⁶

This defined physical area that the DC microgrid serves is an important element when considering the deployment— more so than power level — because an important design consideration of DC networks at these voltages has to do with scale. DC power is highly susceptible to impedance (or resistance) losses, which are those imposed by the transmission medium itself, usually wire. The nature of DC is such that resistance can quickly sap power, but the efficiencies of DC systems—as we shall see—are dramatic and must be considered in deciding the scale of a DC system.

All of these grids have the common need to adopt standards to guarantee interoperability. These standards are essential to the efficient development of the grid and the successful achievement of the key goals of the Smart Grid at a lower cost than possible in the AC domain, as discussed above.

B. What can DC microgrids do?

How would the grid look if its architecture optimized solar PV inputs, and maximized the efficiency of all of our electronic devices? What benefits would be gained by further accelerating these two fast growing elements of the Power Equation?⁷ Let us start with DC-powered electronic devices—which represent 50% of the electric load in many buildings today. In the 50 years following the advent of semiconductors in consumer products, electronic devices have become ubiquitous. Computing and Internet connectivity is showing up in many appliances, incandescent lights are giving way to electronic ones (either fluorescent or LED) and portable electronic devices continue to proliferate. Another element of the growing DC load is the Variable Speed Drives (VFD) for electric motors.

These electronic devices have been deployed in the millions to improve the efficiency of the nearly ubiquitous AC induction motor. By installing VFDs in front of their AC motors, building owners and operators are able to control the speed of the motor, which delivers an outsized benefit: for every one-eighth the motor slows in speed, one-third of the energy is saved. Therefore, when a pump, fan or blower motor can opportunistically be throttled back, a great deal of electricity is saved for the customer. The grid benefits too, by not suffering the demand spikes that are caused when regular AC motors are turned off and on because they cannot modulate their speed.

A VFD is not just an AC device that has AC going into it from the grid, and AC leaving it to the motor; instead the electricity must pass through a DC state, meaning that the AC motor connected to a VFD can become a DC consuming device, just like your cell phone, laptop, LCD or plasma TV and overhead lights.

Let us imagine these loads distributed throughout a building as they are now and imagine how we should power them, again borrowing the Smart Grid's guiding principles for our better-optimized Power Equation. Because we are looking for reliability and redundancy, we will want to create a DC environment to deliver power to these loads as the telecommunications has done historically in switching stations, and more recently to support servers in data center applications.⁸

But better redundancy is only the beginning benefit a DC network brings because a DC Network does not need the ubiquitous AC to DC converting power supply (like

⁷ See, e.g., Report of International Energy Agency at (per capital consumption and energy use by appliance), available at http://www.iea.org/papers/2005/AIXGapplianceenergyeff_TG.pdf (last visited April 15, 2010); 2007 Energy Information Administration Estimate, available at <http://www.eia.doe.gov/emeu/rec/contents.html> (last visited April 15, 2010).

⁸ Nippon Telephone & Telegraph (NTT) of Japan conducted a great deal of research in the 1990s about how to support the large amounts of new data running over its networks. NTT discovered that when it comes to reliability, AC does not come close to the reliability realized in DC power systems. Over nine years later, with more than two times the DC systems observed versus the AC systems, the DC systems delivered better uptimes by an 8:1 ratio. Given the trend of increasing data (which, thanks to Voice Over Internet Protocol, VOIP, most phone calls are digital rather than analog) NTT has deployed hundreds of new DC systems to support their data centers. A group convened by the U.S. utilities trade organization, Electric Power Research Institute (EPRI), has implemented such a demonstration in California and is working with interested parties to do more.

the brick that plugs into your laptop) for every electronic device. Assumed to be a necessity, power supplies currently on the market impose losses on the power going to the device, typically 15% to 40%.⁹ This range of losses in a DC microgrid can be readily lowered to 10% to 15% by using a higher efficiency conversion for multiple loads. This topology will persistently win out due to the superior economics of bulk conversion versus converter at every point-of-use.

Another benefit of the decision to incorporate DC microgrids is the superior compatibility of the DC power with electricity storage. During every major grid blackout (or brown-out, as periods of insufficient power production are called) experts note that further development of grid-scale power storage would vastly improve the stability of the grid. This concept, while technically possible, appears implausible because it evokes an image of some giant C-Cell Battery in the desert that would sustain the grid in case of emergency. This would simply be too expensive to make much sense. On the other hand, using distributed batteries connected to a DC network maximizes the battery's power by avoiding the conversion of its output, but also equals the sum of its parts precisely, such that 1000 small battery banks each having 10 hours of capacity to run a laptop needing 100 watts equals 1 megawatt hour just as if it came from a giant battery owned by the utility. But this analogy is too generous to the latter: power from the distant battery would suffer other losses the local battery would not. These include inversion losses (going from the DC in the battery to the AC of the grid), transmission and distribution losses (estimated to be 7 to 11% by the U.S. Department of Energy) and finally rectification losses when it gets to your electronic load. Collectively, these losses could add up to as much as 41% of the energy ultimately delivered to a DC device.¹⁰

These conversion losses and line losses can largely be avoided by use of distributed batteries in a DC microgrid. Thus, although the DC network improves the economics of batteries (which are themselves DC devices) by marrying them closely to the DC devices they back-up in a highly distributed fashion, storage can be added to our developing DC microgrid in preference to large centralized battery storage schemes.

Fortunately, adding DC storage to a DC microgrid is a comparatively simple piece of engineering compared to the complications of integrating DC storage in the AC domain where additional hardware is required. The oldest continuously operating electrical systems in the world, stretching back to the origins of Bell Telephone, use DC storage. Those early exchanges formed the model of reliability, if not universal connectivity — it took over 30 years to resolve barriers between exchanges so that callers could reach customers of other exchanges.

Moreover, we have in this set of DC building loads the opportunity to integrate — at higher efficiency — other renewable energy generators that are intrinsically DC sources such as solar PV, small wind turbines, or fuel cells. Unlike an AC system, these various DC elements can work in concert without regard to matching phases. In a DC system, only the voltage needs to be considered, whereas AC systems require each element to have identical wave shapes—or be synchronized—to operate. This coordination is achieved through a complex device called an inverter, which provides the perennial weak link in distributed generation systems.

⁹ Lawrence Berkeley National Laboratory (LBNL) estimates that the average loss in the installed base of internal and external power supplies (2008) is 32%.

¹⁰ This assumes a 5% inverter loss, 9% transmission and distribution loss (DOE range is 7 to 11%) and a rectifier loss at the device on an average of 32%, resulting in an overall loss of 41%. Note that with more efficient rectifiers supplying the electronic device, this loss can be reduced.

The DC microgrid thus can accommodate DC inputs because they enjoy a common currency. Therefore, given a suitably robust generator and ample storage, we now have quite an efficient local grid network that uses solar PV and integrates electrical storage at higher efficiencies than are possible in a conventional AC system. Existing plug-in devices pose a transitional challenge for DC microgrids because until these products are replaced by ones using a standard voltage, not all can be plugged in without a DC to DC converter.

The DC microgrid can also simplify and raise the efficiency of how plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) connect to the grid. Rather than automatically requiring the grid to negotiate opportunistic givers or takers of electric power, which could have large adverse impacts on the grid's stability, a DC microgrid can act like a high-efficiency buffer, optimizing generation and storage and increasing grid reliability. Moreover, because DC power has no phase to match, the connection to the vehicle is simplified, providing a more efficient path to its DC battery. As a system, the DC microgrid also creates more possibilities for the vehicle's stored or generated power by enabling either high efficiency on site use, or the more marginal economics of sending the power to the grid. This option is valuable and will help create more efficient markets for all DG connected in this manner throughout the system.

By locally managing sources and loads, a DC microgrid can optimize its net surplus of power (output to the grid) or deficit (input from the grid). This greater local management of both supply and demand creates a buffer to the grid and relieves some of its burden. Conventional means of Demand Side Management (DSM) do not accomplish these ends as efficiently. This becomes possible because of better exploitation of DC's natural characteristics, which remains the lifeblood of all electronic devices and the de facto fuel of the digital economy.

C. Perspective on the AC vs. DC battle

Looking back a century at the struggle for dominance in the business of electricity, a great battle was fought over which paradigm would hold sway, AC or DC. A great deal of business history was written about these attacks and counter-attacks, as well as a few torrid battlefield accounts, which all boil down to, for our purposes, four important points: (1) wholesale power production in large plants was cheaper than many distributed small ones; (2) AC could travel long distances with low losses, unlike DC; (3) incandescent lamps were the majority of the load and they operated on AC or DC; and (4) semi-conductors had not yet been invented.

These facts led to Westinghouse's triumph over Edison in many ways; however, they are also the reason why we need to resurrect some of Edison's arguments to better serve the load today. As the Smart Grid guiding principles remind us, our Power Equation has to protect the environment more, and has a growing need for Distributed Generating DC inputs like solar PV and DC Storage. Meanwhile, electronic devices are the fastest growing segment of the load, showing decades of momentum.

Examples of the convergence of the DC microgrids and the Smart Grid include the work of over 50 companies that have come together in a non-profit organization called the EMerge Alliance to promote low-voltage DC power standards for device manufacturers and systems integrators. This group expects the momentum of LEDs as a light source for common lighting applications to continue and eventually dominate the lighting market. LEDs typically plug into a 110-volt or 208-volt AC power supply that converts that power to 24-volt DC which is what the light source consumes to make visible light. Not coincidentally, 24-volt DC is the first DC power standard promulgated by the EMerge Alliance.¹¹

The companies that participate in the EMerge Alliance have developed products compatible with this DC power standard that enable a new kind of suspended ceiling that distributes low-voltage 24-volt DC power through the metal grid support structure in which ceiling tiles sit. This innovation in DC power distribution through the ceiling provides a new highly efficient channel for DC power generators to serve DC loads like electronically ballasted or LED lighting. If all of the new ceilings that are installed in the U.S. every year were specified to distribute DC in this new way, with solar inputs, these systems would accommodate over a Gigawatt of solar PV in the first two years.¹² Similarly, roof-top solar could be incorporated in its native DC form at 99% efficiency to a portion of offset air handling loads, potentially providing over 50 TWh of annual avoided peak load in the U.S. per annum.¹³ This is power that, as in the lighting example, brings both the user and the grid consumer base benefits which the AC paradigm does not, avoiding transmission and distribution losses as well as conversion losses at the building site.

III. ANALYSIS OF POTENTIAL NATIONAL BENEFITS FROM WIDESPREAD DC MICROGRID DEPLOYMENT

Identifying efficiency benefits that will come from widespread DC microgrid deployment involves gross estimates of the nation's highly diverse load set. On the aggressive end, we note the estimate from Virginia Polytechnic Institute's Center for Power Electronic Systems (CPES) which estimates that 80% of all electricity used in 2010 will pass through power electronic systems.¹⁴ Because this estimate relies on a measure of the status quo which is mainly AC, we can confidently assume that these conventional systems could all be improved in terms of efficiency by instituting higher-efficiency conversions of AC to DC networks, instead of converting the AC power at each point-of-use. More conservatively, however, we can identify specific benefits DC microgrids can bring to loads like lighting and adjustable speed drives for induction motors, and multiply that number by the best estimates of the total load used for those segments. The latter underestimates the full efficiency benefits of DC microgrids in action; the former suggests efficiency savings that, by using DC microgrids, they would approach over time.

What are our expectations for this new paradigm? Instead of the vertical, top-down, hierarchically driven grid we have today, we are presenting a horizontal, highly distributed architecture that is open to innovation. We should expect similar pay-offs

¹¹ See (public) Executive Summary of 1.0 version of the standard, available at <http://www.emergealliance.org> (last visited March 22, 2010).

¹² This assumes 600 million square feet of ceilings installed providing 1 watt per square foot of power, equaling 600 MW of solar PV.

¹³ See, e.g., Commercial, Industrial and Manufacturing Ventilation savings in the following tables.

¹⁴ Power electronics in this sense refer to systems that use semiconductor components usually found mounted on printed circuit boards. These ubiquitous devices control electrons through transistors, resistors, capacitors, diodes and the like to amplify, convert or otherwise transform the power input to them.

to the users of the system to resemble those achieved by information seekers via the Internet.

A. Energy savings (MWH)

The Lawrence Berkeley National Laboratory (LBNL) has estimated that the total amount of energy flowing into external power supplies for electronic devices in the U.S. is about 290 TWh/year.¹⁵ The U.S. Environmental Protection Agency (EPA) and the DOE's Energy Star program estimates that one-third to one-half of the power sent to these devices is lost as heat. This ultimately means that around 100-150 TWh/year are currently being lost in these conversions.¹⁶

Most of the comprehensive national electric power data available is about the output from the grid, not how that power is used. Borrowing largely from the U.S. Energy Information Administration's (EIA) categories and data, we can begin to build a ground-up, load-by-load assessment of the energy savings possible through the use of DC microgrids. Where savings are derived from improved power supply efficiency only, 70% or 75% efficiency is used as an average range for AC power supplies, which is generous given the LBNL estimates,¹⁷ and 90% is used for the bulk high-efficiency rectifier that would be used in a DC microgrid. These rectifiers are currently available in the market. The table below shows these sectors, the relevant loads, and the potential savings:

Residential power consumption by addressable load, 2006¹⁸

Device	MWh used	Potential DC microgrid savings	MWh saved
Refrigerators	160,158,600	40% ¹⁹	64,063,440
Indoor/Outdoor Lighting	103,113,000	15%	15,466,950
Furnace Fan	39,193,200	25%	9,798,300
Microwave	19,801,800	15%	2,970,270
Color TV	33,960,600	15%	5,094,090
VCR / DVD	11,593,800	15%	1,739,070
Cable Boxes	2,975,400	15%	446,310
Satellite Dish	1,846,800	15%	277,020
Desktops	17,647,200	15%	2,647,080
Laptops	1,333,800	15%	200,070
Printers	4,617,000	15%	692,550
Pool Filter Pump	10,054,800	25%	2,513,700
Ceiling Fan	9,849,600	30%	2,954,880
Water Pump	5,643,000	25%	1,410,750
Stereo Systems	5,130,000	15%	769,500
Evaporative Cooling	3,283,200	25%	820,800
Portable Stereos	718,200	15%	107,730
Cordless telephones/answer	4,514,400	15%	677,160
Rechargeable tools	2,154,600	15%	323,190
Residual ²⁰	82,285,200	10%	8,228,520
Total	519,874,200		121,201,380

¹⁵ Lawrence Berkeley National Laboratory Symposium, *What the Real World Tells Us About Saving Energy In Electronics*, available at http://eetd.lbl.gov/ea/nordman/docs/e3s_nordman.pdf (last visited March 22, 2010).

¹⁶ U.S. Environmental Protection Agency, Information About External Power Supplies, available at http://www.energystar.gov/index.cfm?c=archives.power_supplies (last visited March 22, 2010).

¹⁷ Lawrence Berkeley National Laboratory (LBNL) estimated average efficiency of 68%.

¹⁸ This 2001 data has interpolated for 2006 using the growth of households from U.S. Census data as proxy.

¹⁹ While 40% appears to be a large number, only US-manufactured DC refrigerators were discovered to actually deliver an 80% improvement, but not without some compromises such as more insulation leading to smaller cubic storage, necessary periodic defrosting, etc. This efficiency benefit discount is meant to accommodate these variations in the serviceability between AC and DC refrigerators.

²⁰ This residual load is uncategorized, but significant; therefore, this modest expectation of efficiency improvement of 10% should be *de minimus*.

Potential percentage savings for the residential sector’s addressable load: 25.32%; corresponding reduction in the total U.S. load: 2.98%. Addressable load refers to load that can be connected to a DC microgrid.

²¹ Energy Information Administration, Office of Energy Markets and End Use, Form EIA-871A, C, and E of the 2003 Commercial Buildings Energy Consumption Survey.

Commercial building power consumption by load 2006²¹

Device	MWh used	Potential DC microgrid savings	MWh saved
Ventilation	128,000,000	33%	42,240,000
Lighting	393,000,000	15%	58,950,000
Office Equipment	20,000,000	15%	3,000,000
Computers	46,000,000	15%	6,900,000
Residual	61,000,000	20%	12,200,000
Total	648,000,000		123,290,000

Potential percentage savings for the commercial building sector’s addressable load: 19.03%; corresponding reduction in the total U.S. load: 3.03%.

Manufacturing sector power consumption by addressable load 2006

Device	MWh used	Potential DC microgrid savings	MWh saved
Ventilation	64,274,133	20%	12,854,827
Lighting	64,274,133	20%	12,854,827
Office Equipment	64,274,133	20%	12,854,827
Computers	64,274,133	20%	12,854,827
Robotics	64,274,133	20%	12,854,827
Residual	64,274,133	20%	12,854,827
Total	385,644,800		77,128,960

Potential percentage savings for the manufacturing sector’s addressable load: 20.00%; corresponding reduction in the total U.S. load: 1.09%.

Data center power consumption 2005²²

Device	MWh used	Potential DC microgrid savings	MWh saved
Total Load	53,654,594	28% ²³	15,023,286
Total	53,654,594		15,023,286

Potential percentage savings for the data center sector’s addressable load is 28.00%, which corresponds to the reduction in the total U.S. load of 0.37%.

Two dimensions of this large potential savings number are notable: first, that data center power consumption doubled from 2000 to 2005 and is expected to double again by 2010, which highlights the urgency of achieving efficiency gains in this sector; and second, one-half of data center building-wide efficiency gain is due to the avoided cooling load from fewer watts escaping as heat inside the building envelope.

²² Marianne Kolbasuk McGee, Data Center Electricity Bills Double, INFORMATIONWEEK, Feb. 19, 2007, available at <http://www.information-week.com/news/infrastructure/management/showArticle.jhtml?articleID=197006830> (last visited March 22, 2010).

²³ DC Power for Improved Data Center Efficiency Report, Lawrence Berkeley National Laboratory (Mar. 2008), available at http://hightech.lbl.gov/documents/DATA_CENTERS/DCDemoFinalReport.pdf (last visited April 15, 2010).

This avoided cooling is easily measured in the extremely high-density power environment of a data center, but is nevertheless present in all DC microgrid installations at a smaller scale. This is mentioned in the “Additional Benefits” Section 3, following.

Summary table in terawatts²⁴

Sector	Potential TWh saved	Potential efficiency gain in sector(s)	Potential reduction in U.S. national load
Residential	121	25.32%	2.98%
Commercial	123	19.03%	3.03%
Manufacturing	77	20%	1.90%
Data Centers	15	28%	0.37%
Total	337	21.50%	8.28%

²⁴ *Id.*; please note that columns do not add up due to rounding; also, the summary table is the sum of the table results preceding it.

1. Generation capacity savings (MW)²⁵

These large potential benefits from efficiency would have an immediate positive impact on capacity, and capacity planning benefitting all grid stakeholders. Using contemporaneous data from 2006 for our load analysis, we can see how a lower load would deliver large benefits. The avoided 337 TWh of power generation, for example, could have allowed grid operators to shut down or avoid construction of about 75 GW of generating capacity.²⁶

²⁵ http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

2. Transmission and distribution

The key strength of the AC is its un-matched efficiency as an inexpensive long-haul operator. Lowering end-use loads and facilitated on-site generation reduces loads on the transmission and distribution systems. We should therefore use the AC currency of the grid to the maximum benefit, as we have done with DC. Because DC microgrids reduce end-use loads and facilitate on-site generations, they can significantly reduce loads on the transmission and distribution system.

Other high-voltage DC transmission schemes are outside the scope of this analysis. It is interesting to note, however, that short high-voltage DC power lines do regularly operate between large service territories of the grid so that these large synchronized pools of AC power can stay connected to each other without the burden of precisely matching the phase of their neighbor. This buffer is important when a large section of the grid is brought down for any reason. With DC connections to its neighboring grid territories, coming back on-line is easier when the reviving generator does not have to synchronize with a connected systems' precise phase.

²⁶ This calculation assumes peak load decreases in the same percentage as total load. Thus $8.28\% \times (2008 \text{ U.S. noncoincident peak load} + 15\% \text{ reserve margin}) = 75.2 \text{ MW}$. See, e.g., http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html (last visited Apr. 14, 2010).

3. Additional benefits for on-site power generation from DC Sources (e.g. solar PV, small wind turbines, fuel cells and variable DC generators)

Because DC microgrids are more efficient, they produce less heat inside the building envelope. As we saw in the data center application, this electrical efficiency benefit can double due to the avoided cooling load. This benefit is present in all DC microgrids, but has not been modeled outside the data center application in this analysis.

It should also be noted that multiple DC power inputs to the microgrid can be more simply integrated. No phase matching is required as in AC systems, and the efficiency observed extends to batteries, small wind turbines, fuel cells and variable speed DC generators. The latter has great potential in that they could respond in near real time to increased load demand, providing more battery-like surge capacity.

Combining multiple inputs raises the likelihood that several different fuels could be used at the building site, which increases the intrinsic security of the system.

IV. BARRIERS TO DC MICROGRID DEPLOYMENT AND RECOMMENDED PUBLIC POLICY INITIATIVES

Current federal environmental law and utility regulatory practices in many states do not recognize the full societal value of energy efficiency and renewable energy investments in general, or of DC microgrids in particular. The systemic flaws in our current regulatory framework are well-recognized; they include the failure of the current regulatory framework to internalize the social costs of greenhouse gas emissions. A price on carbon and other GHGs will increase the cost of fossil fuel generation and thus make both energy efficiency and zero-carbon renewable generation more cost-effective.

Further, many state utility commissions have not decoupled utility profits from volume of sales, leaving in place substantial disincentives for utilities to promote energy efficiency and distributed generation if they decrease utility demand. These issues are familiar ones and ones that we discuss only in summary fashion in this paper. Instead this paper focuses on the specific issues related to DC microgrid deployment. These specific issues include (1) information and education programs for construction industry and building code officials; (2) codes and standards; (3) federal tax law; (4) federal financial assistance programs; (5) utility rate design and regulation; and (6) renewable electricity standards.

A. Information and education program for construction industry and code officials

We recognize the importance of good communications about the benefits of DC microgrids. Historically, consumers have not appreciated their electrical service in its complexity, but that is changing rapidly with increasingly higher energy prices and innovations in time-of-use (TOU) pricing. Likewise, the awareness of environmental issues, such as carbon emissions and global warming, have piqued the interest of power industry professionals and prompted legislation to address these issues. Collectively, these forces have created an atmosphere of uncertainty around the future of our electrical system.

These facts highlight the need for an organized effort to disseminate information about the benefits DC microgrids offer. Some of this work has already begun by the EMerge Alliance through outreach to utilities, universities, the electrical trades and other interested parties. A “road-show” may be necessary to reach authorities having jurisdiction (AHJs), so that federal, state and local government can play an important role in supporting this effort. State and local governments, as primary regulators for

buildings, will find that conversion to a DC microgrid system provides a cost-effective method to further energy efficiency goals. Because local building inspectors have the responsibility to interpret the National Electric Code, advocates of DC microgrids should conduct informative presentations to the trade organizations and conferences that cater to these inspectors.

B. Codes and standards

The National Electric Code® (NEC)²⁷ is a living body of work that grows every few years through the efforts of thousands of electrical and electronics engineers and administrators. Fortunately, most of the work of putting together a DC microgrid falls under the existing code. Occasionally, however, the NEC remains silent on DC power installations below 600-volts DC, so that DC power is accommodated under rules that govern either AC or DC power systems of the same voltage. This is true, for example, for the insulation and shielding requirements for wires carrying electricity under 600 volts.

While often not prohibited, a lack of references to DC can give both electricians and AHJs reason for concern; therefore, newly articulated descriptions of DC systems should be considered, even when no new rules are established in their narrative. Well-established sections of the code in place for decades have defined the 48-volt DC domain that was once ubiquitous as the voltage in plain old telephone service (POTS). Twenty-four volt DC has had no such history, but systems operating below 30-volts DC, which strictly limit current to under 100 volts-amps are designated “Class 2,” denoting them as intrinsically safe from shock or fire hazard, which is an obvious advantage. The 24-volt DC standard promoted by the EMerge Alliance is in this category. That effort, coordinated with NEC committees’ input and guidance, will spread the word, but a timely roll-out would benefit greatly from some coordinated efforts from interested areas of the government and standards bodies such as National Institute of Science and Technology (NIST), the American National Standards Institute (ANSI), the National Electrical Manufacturers Association (NEMA), the U.S. Department of Energy, and its system of National Laboratories and Technical Centers.

C. Federal tax law

Federal tax law provides a range of tax credits and other tax incentives for energy efficiency, renewable energy and other low- or zero-carbon technologies.²⁸ However, these tax incentives do not provide any significant financial benefit for DC microgrid technology even though, as we note above, these microgrids can provide extensive savings in energy use and result in significant reductions in GHG emissions. Two specific changes in Federal tax law could help close this gap: a “negawatt credit” for DC microgrid systems, and a clarification of the production tax credit.

1. DC microgrid negawatt credit

Under this proposal, the owner of a DC microgrid would be allowed the equivalent of a production tax credit (currently about 2¢ per kWh) for each kWh of avoided

²⁷ NFPA 70, National Electric Code (2008)[®] is a United States standard for safe installation of electrical wiring and equipment, and part of the National Fire Codes series published by the National Fire Protection Association (NFPA).

²⁸ 26 U.S.C. §§ 45, 48(a)-(c) (2009).

conversion losses attributable to the operation of a DC microgrid. These avoided losses would encompass (1) savings from a centralized AC-to-DC conversion at the point where AC grid power enters the DC microgrid, and (2) avoidance of AC to DC to AC conversion for on-site renewable generation.

2. Production tax credit

Section 45 of the Internal Revenue Code of 1986 provides for a production tax credit of electricity produced by renewable generation facilities. The credit currently is set at 2¢ per kWh, and is adjusted for inflation. Tax credit qualification remains subject to numerous technical limitations, including a requirement in section 45(a)(2)(D) that requires that the output of the facility be sold to an unrelated person. This limitation disqualifies self-generation; that is, renewable generation that is consumed by the owner of the facility (or an affiliate of the owner).²⁹ One of the attractions of DC microgrids is their ability to use the DC output of on-site renewable generation without the double conversion loss (from DC output to AC to DC for equipment use) that occurs when on-site renewables must be integrated into an AC grid. We would recommend that section 45(a)(2)(D) be amended to make the sale-to-unrelated-party requirement inapplicable to on-site renewable output delivered into a DC microgrid and consumed on-site.

²⁹ “Self-generation” means renewable generation that is consumed by the owner of the facility (or an affiliate of the owner).

D. Federal financial assistance programs

DOE administers a series of federal financial assistance programs for advanced energy technologies. These include basic research and development under the ARPA-E program, various programs administered by DOE’s National Laboratories, cost-sharing grants administered by DOE’s program offices (in particular, the Office of Energy Efficiency and Renewable Energy and the Office of Fossil energy), and a massive loan guarantee program under title XVII of the Energy Policy Act of 2005. DC microgrid projects are eligible for assistance under most of these programs. However, because of the projects’ low visibility and the fact that they cut across jurisdiction of various DOE program offices, they have never been a major funding priority. The following changes in DOE’s financial assistance programs would advance the DC microgrid technology.

1. Designate responsible DOE program office

As noted above, responsibility for DOE’s DC microgrid programs, to the extent they exist, are scattered among a number of program offices, with none responsible for coordinating DOE’s support for the development and deployment of these systems. Designating a single program office (such as EERE) as responsible for coordinating DOE’s efforts in this area could significantly advance the pace and effectiveness of DOE’s efforts in this realm.

2. Strengthen DOE funding for demonstration projects

While commercial deployment of DC microgrid systems is proceeding in individual buildings, demonstrating multi-building and community-scale systems could benefit

from more effective DOE financial support, in the form of cost-share demonstration grants. DOE has ample authority under its organic RD&D statutes;³⁰ however, an appropriation specifically for this purpose (but not for any specific project or projects) would significantly advance demonstration of the technology and economics of these larger scale projects.

E. Utility rate design and regulation

1. Ratemaking issues

(a) DC Microgrids Under Conventional Utility Regulation

The traditional electric utility regulatory model is cost-of-service regulation of a vertically integrated power supplier who has a local retail monopoly. This model is still the norm in about half of the U.S.³¹ A DC microgrid system that (i) is end-user-owned, (ii) is behind-the-meter, and (iii) supplies no output back to the grid does not prevent regulatory issues under this model. The DC microgrid is simply another means of the customer's internal distribution of power purchased from the utility supplier. However, if any of the three conditions are not met, then, absent regulatory accommodation to this new technology, regulatory barriers (which incumbent utilities may exploit) can retard deployment of these systems. These potential barriers include:

Third-party systems—One attractive model for large-scale DC microgrids is a system which is owned by a third party (rather than the end-user), and which purchases AC power from the utility, converts it to DC, and resells it to individual users. This configuration raises two important questions under conventional utility regulation. First, is the utility sale to the system operator a wholesale sale regulated by FERC under the Federal Power Act, rather than a retail sale regulated by a state utility commission under state law? Second, is the sale to the end-user a retail sale that contravenes the utility's retail monopoly? No clear answer exists to either question because the answer relies on inconsistent FERC precedent relating to "submetering,"³² and vagaries of state law on exclusive retail service areas.³³ Because answering these questions on a case-by-case basis expends both time and money, a federal statutory solution would be the most efficient resolution. One approach would be to exempt utility sales to third-party DC microgrid systems from wholesale regulation under the Federal Power Act, conditioned on the state's regulating the utility sale to the third-party microgrid operator, permitting the operator to resell to end-users, and ensuring that the utility's rates to the microgrid are not unduly discriminatory.

Sales back to grid.—Another key benefit of a DC microgrid is the ability to collect distributed renewable generations (or other on-site DC generation), to efficiently convert it to AC and to sell it back to the grid. The sale to the grid is a wholesale sale and ordinarily falls subject to wholesale rate

³⁰ See Federal Nonnuclear Energy Research and Development Act, 42 U.S.C. § 5919 (2008); Energy Reorganization Act §§ 101-107, 42 U.S.C. §§ 5811-5817 (2008).

³¹ See, e.g., U.S. Energy Information Administration, "Status of Electricity Restructuring By State" (Jan. 2010), available at http://www.eia.doe.gov/cnea/electricity/page/restructuring/restructure_elect.html (last visited Mar. 8, 2010).

³² *El Paso Elec. Co.*, 114 FERC ¶ 61,175 (2006) (FERC has no jurisdiction over a customer that traditionally purchased its power under a state-regulated retail tariff, and has provided primarily a submetering function, because the customer is not reselling that power and thus no sale for resale exists); see also *Alabama Power Co.*, 95 FERC ¶ 61,002 (2001) (disclaiming jurisdiction); Cf. *City of Oakland*, 31 FERC ¶ 61,139 (1985), *rev'd on appeal*, *Oakland Bd. Of Port Comm'rs v. FERC*, 754 F.2d 1378 (185).

³³ See, e.g., state law retail restructuring programs for utilities in Florida, California, and Massachusetts.

³⁴ PURPA § 210(e); 16 U.S.C. § 824a-3(e)(1) (2009) (requiring the FERC to “prescribe rules under which geothermal small power production facilities of not more than 80 megawatts capacity, qualifying cogeneration facilities, and qualifying small power production facilities are exempted in whole or part from the Federal Power Act, the Public Utility Holding Company Act, and state laws and regulations” with respect to rates or financial or organization regulation of electric utilities if the Commission determines that such an exemption would be necessary to encourage cogeneration and small power production); see also *Sun Edison LLC*, 129 FERC ¶ 61,146 at P. 20 (2009) (finding that because the end-use customer makes no net sale to the local load-serving utility within which it has a net metering agreement, the sale of electric energy to the end-use customer in such circumstances does not constitute a sale for resale and thus not subject to FERC’s jurisdiction).

³⁵ 18 CFR § 292.601(c) (2009).

³⁶ 16 U.S.C. § 824a-3(e)(2) (2009) (establishing that no qualifying small power production facility exceeding 30 megawatts may be exempted under the rules prescribed pursuant to PURPA § 210(e)(1), unless that facility produces electric energy solely by the use of biomass as a primary energy source).

³⁷ FERC Order No. 688 (Oct. 2006), 18 C.F.R. § 292.309(a) (2009) (implementing PURPA § 210(m), 16 U.S.C. § 824a-3(m) (2009)).

regulation under the Federal Power Act (FPA), unless exempt under the Public Utility Regulatory Policies Act (PURPA).³⁴ PURPA generally exempts small renewable power generation and certain cogeneration (“qualifying facilities”) from regulation under the FPA. However, large renewable systems (above 20 MW)³⁵ and other on-site generation, (such as fuel cells and micro-turbines) are not exempt and sales of their output to the grid likely fall subject to FPA regulation.³⁶

PURPA also requires utilities to purchase the output of qualifying facilities. However, significant limitations exist both on the utility’s federal law obligation to purchase from these facilities and on a state’s ability to require purchase at rates above avoided cost. In major competitive wholesale markets (such as PJM, NY ISO, ISO New England), FERC rules have relieved utilities of their purchase obligations.³⁷ In addition, the federal purchase obligation, where it exists, is limited to “avoided cost”³⁸ – which is the cost the utility would have incurred if it had generated the power itself or purchased it elsewhere, as determined by the state utility regulatory commission. In most states, avoided cost is well below retail rates and may be insufficient to support many types of renewable generation.

Another issue relates to a state’s authority to require utilities to pay higher-than- avoided-cost rates. FERC precedent from 1995 purports to preempt certain state rules requiring utilities to pay qualifying facilities rates in excess of avoided cost.³⁹ To the extent these rules raise a problem for DC microgrids, they can be dealt with, at least in part, by changes in federal law that (1) permit these systems to sell output at avoided cost rates without regard to size, and (2) give states clear authority to require above avoided-cost rates.

(b) DC Microgrids in Restructured Electric Power Markets

In much of the U.S., electric power regulation has been restructured to allow retail competitions. DC microgrids face fewer issues in the markets than in cost-of-service areas. While their sale of AC power by a utility or other seller may be subject to FERC regulation, the resale of DC power to end-users will not raise questions under exclusive services area laws (which no longer apply). However, sales back to the grid in restructured markets raise similar issues to those discussed in retail cost-of-service markets.

2. Feed-in tariffs

A feed-in tariff is a standing offer by a utility to purchase the output of a renewable generator at a fixed or formula rate. A feed-in tariff applicable to DC microgrid renewable generation sold into the grid could significantly improve the economics of these systems.

PURPA’s avoided cost purchase obligation, discussed above, represents one form of a feed-in tariff—albeit a complicated one because in many circumstances it requires a case-by-case determination of the utility’s avoided cost. A more useful feed-in tariff

arrangement would entail a standardized rate set on the basis of the incentive necessary to deploy the resource rather than on the basis of the purchasing utility's avoided cost. However, this type of tariff is not permissible under federal law if it sets a rate above avoided cost, and a significant question has been raised as to whether it is permissible under state law, as we note in the discussion above.⁴⁰ Clarifying that PURPA does not preempt higher than "avoided cost" feed-in tariffs should provide grounds for states to move forward with innovative feed-in tariff proposals, which could benefit DC microgrids and other renewable systems.

In addition, feed-in tariffs should be designed to permit DC microgrid renewable generation to receive feed-in tariff credit for its entire renewable output, whether or not consumed within the DC microgrid. In return, the DC microgrid would pay the utility's retail rate for its entire internal load. This type of arrangement allows the DC microgrid to take advantage of the feed-in tariff for its full renewable output without incurring conversion losses that would be necessary if it physically delivered its full output to the grid and physically supplied its full internal load from the grid.

3. Utility ownership of DC microgrids

An alternative to third-party ownership of large scale DC microgrids is utility ownership of the microgrid. This model could be an effective means of deploying systems that sell DC power from a multi-building network to multiple end-users, particularly in states that have exclusive retail service territory laws. If the incumbent utility is the retail seller, then no retail service exclusivity issue arises; however, the DC microgrid service must still be authorized either under the general terms of the state's utility laws or by action of the state regulator. A more important issue is whether the utility will provide a useful and cost-effective DC microgrid service to end-users and whether the public is better served by having competitive offerings from a number of prospective microgrid operators.

F. Renewable Electricity Standard

Current proposals for a Renewable Electricity Standard (RES) require retail electric utilities to generate or purchase a minimum percentage of renewable energy resources each year. Generators of clean renewable energy resources are issued tradable renewable energy credits (RECs). Utilities may purchase RECs for use for compliance purposes, or they may produce renewable energy from their own facilities. Electricity savings from energy efficiency may also be used for compliance purposes.

The RES as currently formulated would provide full credit for renewables delivered into a DC microgrid system; however, the treatment of the efficiency gains from these systems is unclear. An RES provision specifically tailored to DC microgrids that provides explicit credit for efficiency gains (from lower conversion losses) for DC microgrids would resolve any confusion related to the applicability of the general provisions for computing electricity savings. Such a provision would direct DOE to determine electricity savings by rule, based on the difference between conversion losses for the average AC system minus demonstrated lower conversion losses for the DC microgrid.

³⁸ 16 U.S.C. § 824a-3(b) (2009) (explaining that no rule prescribed in PURPA Section 210(a) shall provide for a rate which exceeds the "incremental cost" to the electric utility of alternative electric energy). In the context of electric energy purchased from a qualifying cogenerator or qualifying small power producer, PURPA § 210(d) defines incremental cost as the "cost to the electric utility of the electric energy which, but for the purchase from such cogenerator or small power producer, such utility would generate or purchase from another source." 16 U.S.C. § 824a-3(d).

³⁹ *Cf. Conn. Light & Power*, 70 FERC ¶ 61,012 (1995) finding that the Federal Power Act preempted the Connecticut Department of Public Utility's ability to order a utility to enter into a contract at a state-set price because otherwise it would be impossible for the utility to simultaneously comply with the state mandate and the FERC mandate); *Midwest Power Systems*, 78 FERC ¶ 61,097 (1997) (finding that the Federal Power Act did not preempt a state law requiring utilities to purchase from state-designated facilities, but the FPA did preempt any order by the Iowa Utilities Board which set rates for wholesale transactions); see also Scott Hempling et al., "Renewable Energy Prices in State-Level Feed-In Tariffs," National Renewable Energy Laboratory (Jan. 2010), available at <http://www.nrel.gov/docs/fy10osti/47408.pdf> (last visited Mar. 9, 2010).

⁴⁰ See discussion, *supra* at note 38.

V. CONCLUSION

The DC microgrid concept represents a decentralization of the idea of the grid, and one that advances the goals of the current Smart Grid overhaul. The DC microgrid begins to change the paradigm from a centralized generation and distribution system of power delivery to a system that is more flexible and more accommodating of the load that has come to be: one that is more electronic, more ubiquitous, and more essential to our economy and our culture.

DC microgrids can create power systems that are more efficient and more compatible with the fastest growing segment of the load today: electronic devices. In turn, by catering to the needs of digital devices, we naturally expand the networks in which they operate (both power and control) to benefit from – or indeed require – redundant operation that is primarily available today through the other ubiquitous DC device, the battery.

But widespread deployment of DC microgrids will not happen automatically – the impediments to deployment identified above need to be dealt with. Our recommendations can be a first step in doing that.