Lawrence Berkeley National Laboratory

paper forthcoming in the
International Journal of Distributed Energy Resources, vol 4(4), Oct 2008

MICROGRIDS AND HETEROGENEOUS POWER QUALITY AND RELIABILITY

Chris Marnay
Technology Evaluation, Modeling, and Assessment
Ernest Orlando Lawrence Berkeley National Laboratory
MS90R4000, Berkeley, CA 94720-8136, USA
Phone (+1) 510-486-7028, Fax (+1) 510-486-7976
e-mail: C_Marnay@lbl.gov

Keywords: combined heat and power, dispersed storage and generation, microgrids, power quality, power system economics

ABSTRACT

This paper describes two stylized alternative visions of how the power system might evolve to meet future requirements for the high quality electricity service that modern digital economies demand, a supergrids paradigm and a dispersed paradigm. Some of the economics of the dispersed vision are explored, and perspectives are presented on both the choice of homogeneous universal power quality upstream in the electricity supply chain and on the extremely heterogeneous requirements of end-use loads. It is argued that meeting the demanding requirements of sensitive loads by local provision of high quality power may be more cost effective than increasing the quality of universal homogeneous supply upstream in the legacy grid. Finally, the potential role of microgrids in delivering heterogeneous power quality is demonstrated by reference to two ongoing microgrid tests in the U.S. and Japan.

1 INTRODUCTION

Consumption of electricity continues to grow in developed economies. For example, U.S. consumption of electricity is forecasted to increase roughly by half over the current quarter century[1]. Most analysts anticipate that *distributed energy resources (DER)* will provide a large share of the much expanded generation capacity required to meet this seemingly inexorably expanding electricity demand. For the purposes of this paper, DER consist of a diverse set of relatively small (≈<1-2 MW) assets such as micro combined heat and power (CHP) installations, photovoltaic arrays (PV) and other small renewable generation, fuel cells, local heat and electricity storage, demand response capability, etc. Further, given the urgency of tackling the climate change problem, many of these assets must be carbon-free renewables, end-use efficiency improvements, or highly efficient fossil-fired technologies.

The dominant theme of current thinking about the development of DER is in terms of the value they can provide to their owners and to the wider existing power system, and the technical challenge of integrating them into the current power system; however, the existence of DER, typically grouped in microgrids that exercise some autonomous control, may ultimately in turn change the nature of the familiar legacy grid itself, or *macrogrid*. In this paper, a *microgrid* is a local cluster of sources and sinks that operates semi-autonomously of the grid, being able to island and reconnect as circumstances dictate, and able to provide power quality and reliability (PQR) different from general macrogrid standards.

Rapid (if not accelerating) technological change surrounds us, and the nature of the power system will inevitably evolve over time. Emerging DER technologies cannot be divorced from this process; indeed, they may serve as one of its many engines. Trends emerging in the power system suggest that the centralized paradigm that has dominated power systems for the last century may eventually be replaced, or at least diluted, by an alternative one in which control is more dispersed, and in which universal quality of service is replaced by heterogeneous service locally tailored to end-use requirements.

2 BACKGROUND

In developed economies worldwide, the current power delivery paradigm has been in place worldwide for a long time, i.e. since the emergence of polyphase AC systems around the turn of the last century. In outline, this dominant paradigm consists of large-scale central station generation, long distance bulk transmission of energy over centrally operated high voltage meshed grids, and local distribution at ever lower voltages through simpler partially locally managed, uni-directional, radial lines. A key feature of this structure is that, in principle, universal service is delivered at a consistent level of PQR throughout large regions. For example, PQR targets are consistent virtually all across North America, and where standards cannot be met, it is usually the result of a local technical difficulty and not the outcome of a deliberate attempt to deviate from the universal norm. This predictability of service delivers an enormous economic benefit because all types of electrical equipment can be built to match the homogeneous universal standard. Indeed, this traditional paradigm has served developed economies well for a very long period during which the uses for and consumption of electricity have increased enormously, even at times spectacularly. As is often observed, modern life as we currently experience it seems impossible without such ubiquitous, universal, reliable, high-quality power. To be clear, higher PQR is unequivocally better than lower, i.e. it is an economic *good*; the current dilemma springs from the technical challenge and cost of improving PQR, not from any doubt about its desirability.

Changes in expectations for the power supply system on both the supply and demand sides are bringing us to a turning point in its evolution and quite possibly to the first paradigm shift in over a century. Improving traditional universal service to the point at which it can meet the requirements of sensitive or modern digital loads may be unnecessarily costly. The changes on the demand-side result from our seemingly unquenchable thirst for electricity in an emerging digital age that is significantly tightening our PQR requirements for some applications, while on the supply-side, intermittent resources' increased penetration, concerns about terrorism, restrictions on system expansion, and the uncertainties of volatile markets in energy-short times bring our ability to maintain current standards into doubt[2].

3 ALTERNATIVE VISIONS

The schematics in Figs. 1 and 2 below show two alternative visions of how the power system might be retooled to provide high PQR, a *supergrids* view, and a *dispersed* paradigm. These are only two stylized representations of many possible paths, and full justice cannot be given here to the technical intricacies of any specific forecast. The intent is only to contrast in a comprehensible way the central themes of multiple divergent alternatives. For more detail on a supergrids leaning view, see Gellings et al, Amin, or Amin and Wollenberg[3,4,5]. One vision for a dispersed grid is presented by the European Commission; while Lasseter or Marnay and Venkataramanan provide additional voices for the dispersed camp, but these are by no means the only contributors to this ongoing debate[6,7,8].

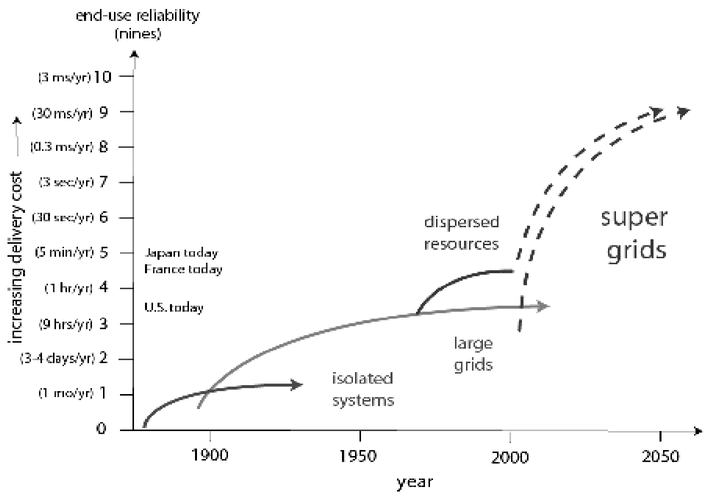

Figure 1: *Supergrids vision.*

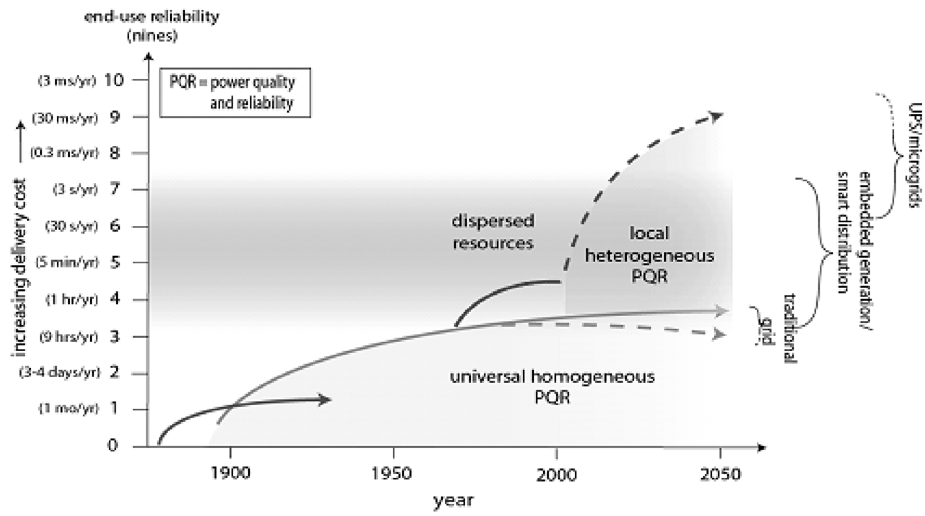

Figure 2: *Dispersed grid vision.*

The x-axes in both figures roughly cover the historic development of the existing power supply system, while the y-axes in both figures show availability in nines together with the equivalent annual expected outage duration. Typical U.S. electricity service today is in the 3-4 nines range or a few hours of expected annual outage, which is poor performance relative to most developed countries. Japan, for example, achieves significantly higher reliability, approaching 5 nines or only a few minutes of expected annual outage, and in certain favorable regions, even higher performance is achieved.[1]

---

[1] Note that the 14 August 2006 Tokyo blackout nonetheless demonstrates the fragility of electrical service, even in Japan.

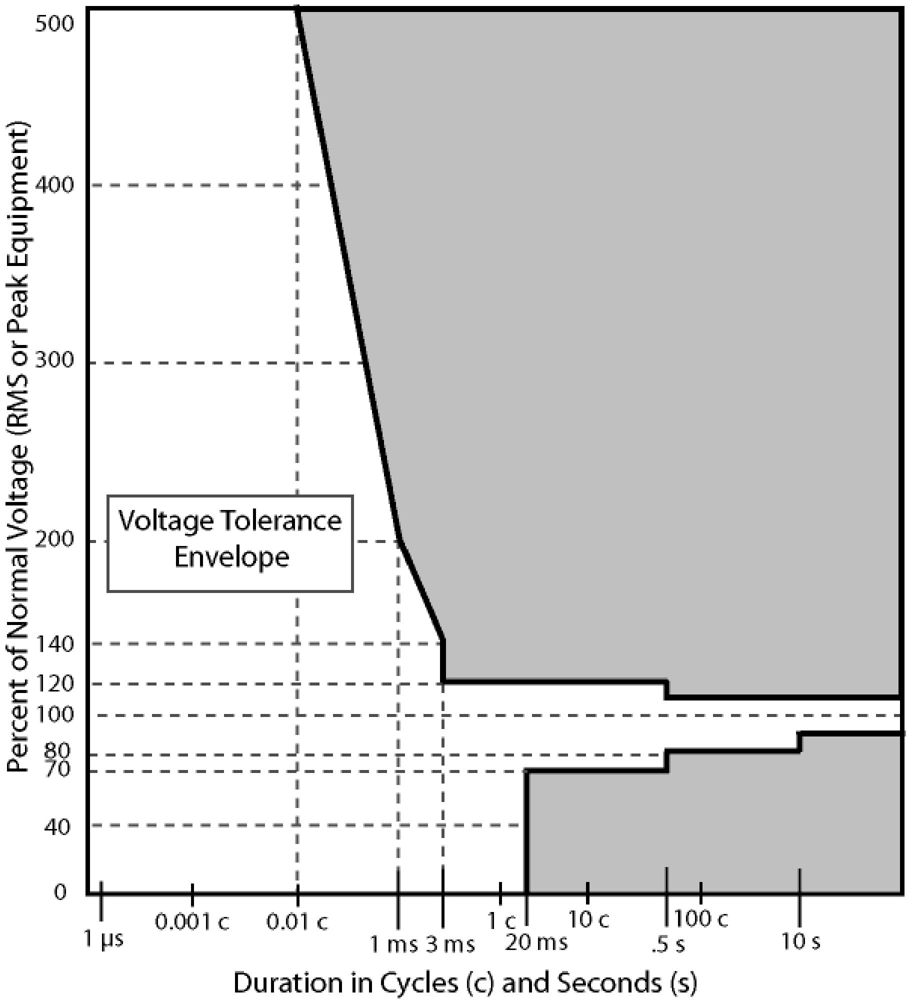

Figure 3: *CBEMA curve.*

Other dimensions of PQR are harder to portray, but in principle, similar arguments can also be made with respect to them. For example, consider the most costly PQ problem, voltage sags and swells. One widely used representation of these is their severity and duration relative to a *CBEMA curve*, an example of which, for 120 V 60 Hz single phase equipment, is shown in Fig. 3.[2] Electronic devices should function normally anywhere within the *Voltage Tolerance Envelope* to the left of or within the curve. For example, at the far left, total voltage collapse for a hundredth of a cycle should be survived, while on the far right, continuous steady-state voltage within ± 10% of rating must be good enough to ensure claimed performance. One basic measure of voltage performance might be the recorded number of violations (events falling in the shaded area of Fig. 3) experienced over a certain time period, e.g. total annual infractions. This value could appear on the y-axis of curves similar to Figs. 1 and 2, and could serve as the basis of cost estimates for both provision of and inadequacy of voltage. None of the above aims to suggest that representing PQR is trivial. Defining and collecting data on PQR for vast power systems poses a monumental challenge, which is of course why PQR is generally represented as a black-or-white indicator, e.g. CBEMA compliant or not, whereas in reality a broad range of PQR performance and consequences exists.

Returning to Fig. 1, the *large grids* curve shows that over the last century improved technology and interconnection over larger areas have steadily improved reliability. Nonetheless, in the U.S. case, following the northeast blackouts of the 1960s and 1970s, the need to provide local backup sources for

[2] While the Computer and Business Equipment Manufacturers Association (CBEMA) has since changed its name to the Information Technology Industry Council, the current (1996) version of this graphic is usually still referred to as the *CBEMA curve*.

critical loads was recognized and introduced into building codes and other regulations. A formal dispersed electricity supply system shown by the solid *dispersed resources* curve was thereby established, primarily in the form of the now ubiquitous diesel back-up generator.

3.1 Supergrids Vision

The steady rise of sensitive loads over more recent times has led to widespread additional use of backup generators, uninterruptible power supplies, and other equipment to ensure high quality energy supply to such loads. Protecting them from service that deviates from standards is at the heart of the divergence in visions. There are actually two types of sensitive loads, ones motivated by the business importance of high value added or "mission critical" loads, e.g. data centers, and ones required to guarantee vital services, most importantly those required for emergency response. The supergrids camp holds that deployment of diverse suites of new technologies can significantly improve the performance of all elements of the power supply chain built around the traditional paradigm, as shown in Fig. 1 by the lower dashed line. Despite the goal of across-the-board technical improvement, in practice, most of the innovation inevitably must come in the distribution system because most PQR problems originate there; for example, 80-90% of U.S. outages are caused by distribution failures. The distribution network forms the most vulnerable link because of its sheer size and dispersion, as well as its exposure to the myriad hazards of extreme weather, accidents, and mischief. Even in the supergrids view, inevitably there will be end-uses that require PQR beyond even the performance of the much enhanced delivery chain, but these can be kept to a reasonable minimum. Much attention is paid in this framework to the risk that DER pose to the overall supply chain, and consequently their role is necessarily limited. The extra locally provided PQR is shown in Fig. 1 by the upper dashed line. In other words, only the increased performance between the two dashed lines is provided by dispersed resources, representing a small share of all the delivered energy.

3.2 Dispersed Grid Vision

Fig. 2 shows an example schematic of a dispersed vision whose key feature is increased reliance upon rather than minimization of dispersed resources. In this view, traditional universal grid service is not improved significantly but rather holds steady at economically justified levels. *Sensitive loads*, i.e. ones of exceptional economic significance, public safety or military importance, or critical to maintaining infrastructure integrity, are then increasingly served locally in two ways: first, improvements in the distribution system (as in the supergrids vision) are deployed to improve on the existing system's weakest link; and second, widespread use of DER deployed close to sensitive end-uses protect them at the levels they demand. Finally, in this paradigm, as the lower dashed "traditional grid" line shows, some deterioration of universal PQR is possible, a phenomenon further discussed below.

3.3 Vision Comparison

A number of key differences between the two paradigms should be emphasized.

- While in the supergrids vision excellent performance is required throughout the supply chain because of the *weakest link* effect, in the dispersed vision, generation and high voltage transmission are not called upon to achieve significant improvements, although conversely they are not precluded. The level of bulk power PQR is determined somewhat independently of end-use requirements based on technical, economic, and security realities. This is perhaps the most important distinguishing feature of the dispersed vision, i.e., it does not depend on significant technical transmission breakthroughs and investments far upstream from the growing energy use and sensitive loads that are the root cause of the current dilemma.
- Improvements in the distribution system are envisaged in both visions. To some extent, they both depend not only on better distribution technology per se, but necessarily also on the existence of local generation embedded in the distribution system. In the supergrids view, embedded generation is perceived as a significant threat to improved PQR provision as well as a potential asset, whereas, the dispersed vision depends heavily on improved distribution rather than improved high voltage transmission and possibly including islanding by the local distribution network as well as by microgrids.

- In the dispersed paradigm, local to actual end-use loads (one might say in current terminology, on the "customer side of the meter"), a wide range of additional technologies is employed to ensure adequate service to loads requiring higher-than-universal-level PQR than is being delivered at the meter. The technologies in question include small generators powered be renewables or fossil thermal and possibly with CHP, storage devices, demand control, opportunistic local resources such as low quality non-traditional fuels, power conditioning equipment, etc. In some cases, this equipment may be clustered in electronics based microgrids.
- The supergrids paradigm follows in the tradition of attempting to provide identical service to all customers at all times. The dispersed paradigm represents a major break with that tradition in the sense that PQR of electricity arriving at customer meters might vary with local conditions, and the PQR at end-use devices varies even more so, based on their requirements. This aspect can be thought of, as is shown in Fig. 2, as delivered electricity, being of the familiar universal homogenous PQR (HoQ) upstream, but increasingly heterogeneous PQR (HeQ) down-stream depending on the sensitivity or value added of various end-uses. Further, the overlapping braces to the right of Fig. 2 are intended to show that levels of PQR delivered and how they are achieved are far from resolved, and no definitive dividing line between sources is yet apparent.
- The supergrids vision presents a technological treadmill committing the industry to the relentless improvement of the macrogrid supply chain. On the other hand, in the dispersed paradigm, the optimal level of upstream HoQ could potentially be even lower than current standards, as shown by the declining dashed traditional grid line in Fig. 2. In other words, since the demanding requirements of sensitive loads are satisfied downstream in the dispersed vision, then our expectations for the centralized grid upstream may well decline, rather than increase significantly, as in the supergrids view. This concept is explored further in section 4 below.

4 HOMOGENEOUS VS. HETEROGENEOUS PQR

The notion of HeQ is a somewhat new concept in power systems, and is central to the dispersed vision. Consequently, the nature of HeQ's role in the dispersed paradigm occupies the remainder of this paper.

While outages may be scheduled for periodic maintenance operations on the electrical system, unscheduled outages are generally much more disruptive and threatening to people and property. Outages' effects include unavailability of certain services and processes, such as refrigeration, manufacturing, etc., plus dependence on on-site backup generation, which is typically costly and environmentally damaging.

In contrast, deterioration in PQ has mixed and less dramatic effects, even if important and sometimes costly. It is caused by deviations in the features of the electrical power delivered to the load, such as voltage sags and swells discussed above, harmonics, phase imbalances, etc., which are triggered by periodic switching operations, by faults in the electrical systems due to weather, wildlife, human errors, or other causes. If PQ events do not lead to loss of an end-use device, they become important only when they trigger degradation in end-use service or reduce equipment performance and/or its durability. Thus, from an end-user perspective, both low power quality and poor reliability have consequences and costs, while the scale and drama of events might be quite different.

The essence of the supergrids paradigm is HoQ. In principle, near perfect electricity is delivered everywhere in the system at all times; nonetheless, HeQ creeps in because the expensive investments necessary to improve PQR are unlikely to be made universally and evenly across the system. Indeed, some heterogeneity is routinely tolerated, although it is rarely recognized as such. For example, remote feeders are restored more slowly than ones in densely populated areas; conversely, some key circuits receive exceptional attention, notably ones on which emergency or other vital services are interconnected. These limitations notwithstanding, the objective of the supergrids vision is an extension of the current paradigm in which HoQ is dramatically improved.

In the dispersed vision, as shown in Fig. 2, PQR diverges from the standard downstream of the substation. Safe and economic operation of the high voltage meshed grid relies as it always has on tight standards and centralized operation; however, downstream, PQR becomes increasingly heterogenous, with delivered electricity to the end-use potentially diverging considerably. Two obvious questions arise: First, given that HeQ is tailored locally to end-use loads and can deviate in either direction from the upstream HoQ, how should the standard for upstream HoQ be chosen? And second, why does HeQ make sense at the end-use level? The following two sections address these two questions.

4.1 Picking an HoQ Standard

As explained above, while the ideal is rarely achieved in practice, the prevailing current paradigm is to universally provide HoQ everywhere in the network. In the dispersed vision, this remains true only upstream in the grid.

Fig. 4 conceptually shows a possible approach to picking the optimum universal target PQR level for the economy to adopt. Again, PQR is represented by simple availability because other aspects of PQR are more difficult to quantify and visualize. The x-axis, corresponding to the y-axes of Figs. 1 and 2, shows increasing PQR on a pseudo-log scale, with approximately the lowest reliability we can currently imagine as acceptable to a modern economy to the left and perfection to the right. Again, the U.S. lies between three and four nines, while the world's most reliable systems approach the five nines range.

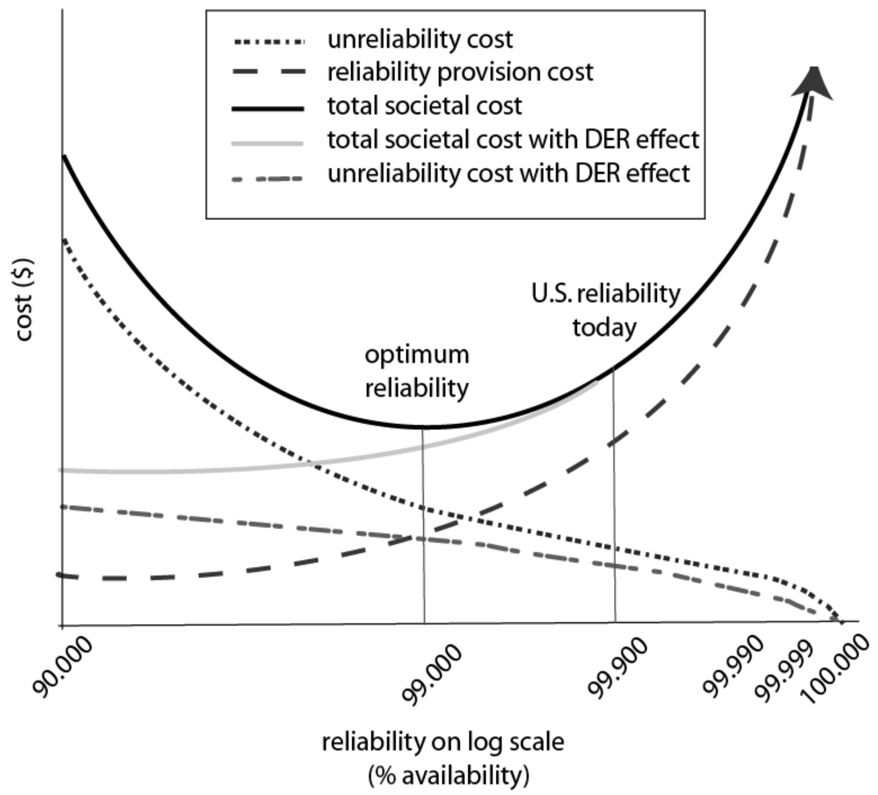

Figure 4: *Finding optimal HoQ*

The y-axis shows the societal cost of PQR. This cost has two components, the cost of providing reliability and the cost of the residual unreliability, with the sum of the two representing the total societal cost. The dotted *unreliability cost* curve shows what we all know well; namely, that poor PQR costs the economy dearly. These costs might be high to the left, where many developing countries find themselves, and would fall to zero on the right, if perfection could be achieved. The dashed *reliability provision cost* curve shows the cost of providing PQR. Better service incurs higher costs of two types, the equipment costs of a physically more robust system and the foregone electricity trade prevented by conservative grid operations imposed for reliability reasons. While likely substantial, the latter cost is poorly documented. The shape of the curves in Fig. 4 is purely conceptual since no comprehensive data are available to construct them. Nonetheless, it is quite clear that costs will be asymptotic as the grid nears unattainable perfection at the right of the x-axis.

The solid *total societal cost* curve simply represents the sum of the two other cost curves that show the cost consequences of having an imperfect system and the out-of-pocket cost of providing the prevailing level of PQR. The societal optimum is clearly at the point of minimum total social cost, which in Fig. 4 occurs to the left of the current U.S. performance of 3-4 nines, and even further to the left of where Japan would appear. Developed economies have generally chosen to push reliability to the right in Fig. 4, with relatively little consideration of the cost tradeoffs implicitly involved. It might also be observed that most developed countries have focused heavily on the unreliability cost curve with relatively little attention paid to the cost of providing PQR; however, this is not to say that reliability has been pursued at any cost because clearly choices are made; e.g., the use of overhead lines rather than under-grounding shows that limits to expenditures in pursuit of reliability indeed exist and trade-offs are implicitly made.

Ceteris paribus, widespread deployment of DER would tend to have the effect of lowering the unreliability cost because sensitive loads that require high PQR are still provided for locally, making systems more resilient to low HoQ. This effect is shown by a downward shift of the unreliability cost curve in Fig. 4 to the *unreliability cost with DER effect* level. Consequently, the societal optimal reliability could be pulled leftwards as shown by the grayed-out curve *total societal cost with DER effect* curve reaching its minimum to the left of its equivalent without DER, implying the heresy that the optimum level of macrogrid reliability may be below today's. Note however the important caveat that reliability provision cost is not independent of DER penetration, i.e. increased DER in the overall system could well simultaneously increase the cost of reliability provision, a fear of dispersed paradigm skeptics.

4.2 End-Use HeQ

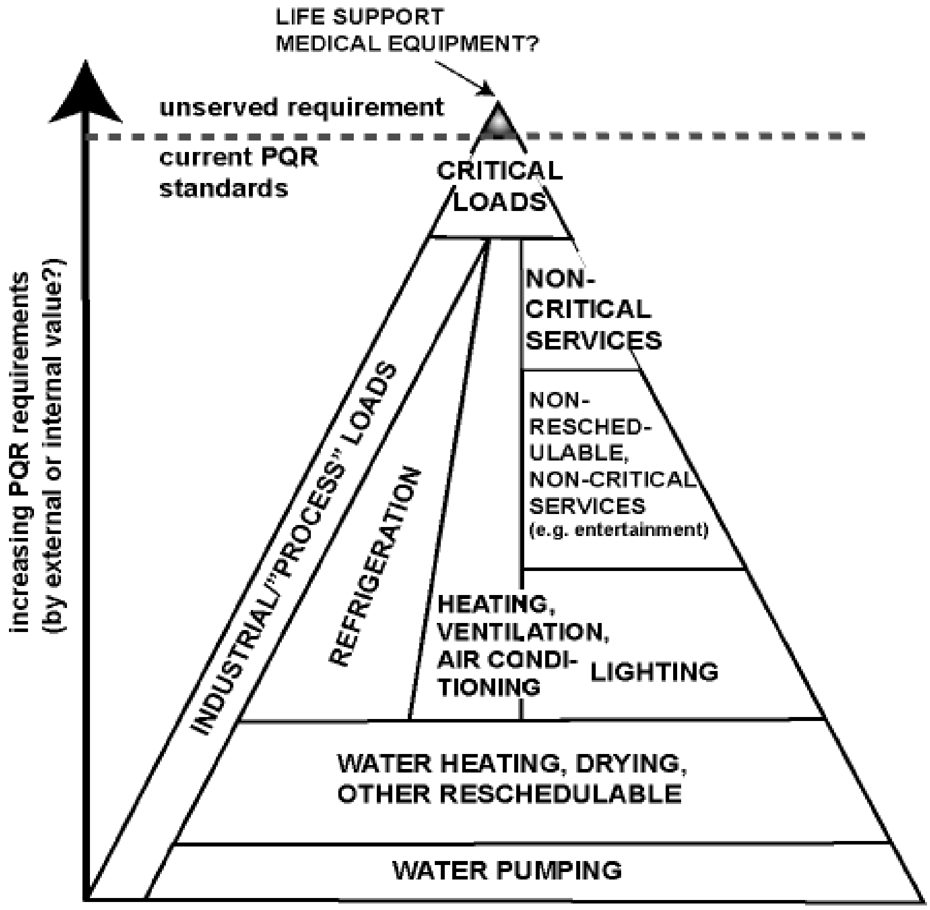

Figure 5: *An HeQ pyramid.*

In the power sector, understanding of the time and spatial differentiation in the value of electricity is familiar, and some notable efforts have also been made to estimate the contribution of various end-uses to system peak loads[9]. Consideration of how the value of electricity varies given the PQR requirements of the end-use served is much less common.

Various indices for measuring PQR are often used in quantifying levels of electrical service[10]. While technical analysis of electricity service PQR can be sophisticated, by contrast, analysis of PQR economics is at best rudimentary, which makes it difficult to relate its importance to the readily monetized energy side of power systems. In other words, notwithstanding its variation over time and space, it tends to be relatively easy to measure the economic value of electrical energy but dauntingly hard to measure the economic value of PQR. Nonetheless, it is intuitively appealing to think that delivering HeQ tailored to the requirements of end uses, as is the case in the dispersed paradigm, can generate higher economic benefits than delivering an HoQ that never quite matches the requirements, and at least one research program is exploring this issue.[11] Consider the pyramid shown in Fig. 5, which illustrates how various electricity uses might be classified according to their PQR requirements. Some common loads, such as pumping, are widely agreed to have low PQR requirements and appear at the bottom of the pyramid, and vice-versa. Other loads can be much harder to classify; e.g., refrigeration is reschedulable in many applications, but might be critical in others, such as medication storage. At the top of the pyramid, the exposed peak above current standards shows that not all requirements are currently met. The layout of end-uses shown is highly speculative and simply intended to show how HeQ might be considered. Indeed, there is no clear framework for classifying loads by their PQR requirement, and much less any commensurate data collection efforts. More important is the pyramid shape itself. It is clearly not a natural law that low PQR demanding loads vastly outnumber critical ones; however, if we behave in an economically rational manner, we would attempt to make them so. In other words, serving the low requirements loads at the bottom is cheap, and vice-versa for the sensitive loads at the top. We should be trying, therefore, to classify as much of the overall load in the base as possible. For example, for equipment considered a sensitive load, it is often only a small share of the energy that is essential, e.g. to run controls, while much of the energy consumed could be of relatively low quality. In such cases, two separate qualities of service might be delivered to the respective parts of the device.

Analysis of PQR requirements in a form like the pyramid could potentially lead to the clustering of like PQR loads on certain circuits and the provision of electricity of appropriate quality to that circuit, and the disaggregation of some loads into constituent parts of varying PQR requirements. At the same time, the effective provision of high PQR locally to sensitive loads could potentially lower the societal optimum for grid service, as mentioned above.

Systems could potentially supply multiple service qualities to different parts of the pyramid delivering significant economic benefits, much of which may be in the form of lower requirements for upstream HoQ. Further, the following points are emphasized.

- Little analysis or data collection has been done to establish the PQR requirements of loads.
- Matching the PQR delivered to the requirements of the end-use can potentially meet our goals at lower cost than universal PQR.
- A wise approach would disaggregate loads such that high PQR requirements are minimized because they are the costly ones to serve.
- Delivering HeQ poses some practical problems as well as benefits. All existing electrical equipment in the industrialized world is designed and manufactured with expectations of high HoQ. Deviations from this norm will likely incur consequences and costs that are currently unknown.
- Lastly but importantly, the concept of universal service is not only a technical one, but also a legal one. The legal basis under which different service quality is delivered to various sites is not yet clear, but it is reasonable to assume that tariffs would necessarily reflect the delivered power quality.

5 MICROGRIDS

In Fig. 2, HeQ is provided locally by embedded generation within the distribution system, by on-site generation and power conditioning equipment, and by microgrid technology. Providing appropriate HeQ to match the requirements of end-uses is a central feature of some microgrid concepts, notably the Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid, and the NTT Facilities microgrid being demonstrated in Sendai, Japan, shown in Fig. 6 [12,13,14,15]. In the case of the CERTS Microgrid, HeQ is provided by segregation of loads on separate circuits. Critical loads are placed near reliable sources in a grouping that can disconnect and operate islanded without need of fast electrical device controls. In the case of the Sendai microgrid, DC loads are served directly on a circuit dedicated to critical telecommunications equipment, and multiple qualities of AC services are provided to a medical school, a nearby high school, and a water treatment plant.

Figure 6: *Sendai microgrid installation. (source: NTT Facilities)*

6 CONCLUSIONS

Our current power system may be entering a period of significant fundamental change of a kind not seen for a century, and currently there are conflicting visions of what form the reshaped industry may take. Some of the uncertainty revolves around the requirements of modern economies for high quality electrical service and the most cost effective way of providing it. One viable possibility is through local control of PQR in microgrids. In addition to the technology needed to enable such a transition, effectively managing it will require new analytic tools and new regulatory regimes. Some of the economic and legal issues will require consideration of aspects of electricity service that have heretofore been for the most part beyond our economic capabilities. Development of new methods of analysis must be undertaken to confront the challenge.

7 ACKNOWLEDGEMENTS

The work described in this report was supported by the Office of Electricity Delivery and Energy Reliability, Renewable and Distribution System Integration Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. It builds on the contributions of my CERTS colleagues, including Joseph H. Eto, Robert Lasseter, Sakis Meliopoulos, John Stevens, and Giri Venkataramanan; on exchanges with colleagues with whom I have organized and attended many microgrid events, Hiroshi Asano, Johan Driesen, Nikos Hatziargyriou, Reza Iravani, Toshifumi Ise, Farid Katiraei, and Ben Kroposki; and on many other past and present collaborators. Many thanks go to all. Also, Kristina Hamachi LaCommare and Judy Lai assisted with graphics and editing, and their level heads have kept our microgrids work approximately on track in spite of ourselves. Finally, the comments of a thorough, constructive, and insightful anonymous reviewer significantly improved the manuscript. As usual, any remaining defects are entirely my own.

8 REFERENCES

[1] U.S. Energy Information Agency: *"Annual Energy Outlook 2008"*, DOE/EIA-0383 (2008).

[2] J. Apte, L. Lave, S. Talukdar, M.G. Morgan, and M. Ilic: *"Electrical blackouts: a system"*, Issues in Science and Technology, (2004).

[3] C. Gellings, M. Smotyj, and B. Howe: *"The future's smart delivery system: meeting the demands for high security, quality, reliability, and availability"*, IEEE Power & Energy Magazine, Vol.2, No.5, pp.40-48 (2004).

[4] M. Amin: *"Powering the 21st century: we can and must modernize the grid"*, IEEE Power & Energy Magazine, Vol.3, No.2, pp.94-96 (2005).

[5] M. Amin and B. Wollenberg: *"Toward a smart grid"*, IEEE Power & Energy Magazine, Vol.3, No.5, pp.34-41 (2005).

[6] European Commission: *"European SmartGrids technology platform: vision and strategy for europe's electricity networks of the future"*, EUR 22040, http://ec.europa.eu/research/energy/pdf/smartgrids_en.pdf (2006)

[7] R. Lasseter: *"Dynamic distribution using (DER): distributed energy resources"*, Proc. of IEEE the Power Engineering Society T&D Meeting, Dallas, TX, U.S.A. (May 2006).

[8] C. Marnay and G. Venkataramanan: *"Microgrids in the evolving electricity generation and delivery infrastructure"*, Proc. of the IEEE Power Engineering Society General Meeting, Montréal, Canada (June 2006).

[9] R.E. Brown, and J.G. Koomey: *"Electricity use in California: past trends and present usage patterns"*, Energy Policy, Vol. 31, No.9, (2003).

[10] R.C. Dugan, M.F. McGranaghan, and H.W. Beaty, *"Electric Power Systems Quality"*, Second Edition, New York, NY: McGraw-Hill (2003).

[11] Kurlinski Ryan E, Lester Lave, and Marija Ilic: *"Creating Reliability Choice: How Building Less Reliability into Electric Power Grids Could Improve the Welfare of All Customers"*, Proc. of the IEEE Power Engineering Society General Meeting, Pittsburgh, U.S.A (Jul 2008).

[12] For more background on microgrids, please see the presentations from the four Symposiums on Microgrids held at Berkeley, USA in June 2005, Mont-Tremblant near Montréal, Canada in June 2006, Nagoya, Japan in April 2007, and Kythnos Island, Greece, in June 2008. Available at http://der.lbl.gov

[13] R. H. Lasseter, A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromson, A.S. Meliopoulos, R. Yinger, and J. H. Eto : *"Integration of Distributed Energy Resources: The CERTS MicroGrid Concept"*, LBNL-50829, (2002). Available at http://der.lbl.gov

[14] N. D. Hatziargyriou, ed.: special issue on microgrids, International Journal of Distributed Energy Resources (2006/2007).

[15] Hirose, K., T. Takeda, and S. Muroyama: *"Study on field demonstration of multiple power quality levels system in Sendai"*, International Telecommunications Energy Conference, Providence, RI, USA, September (2006).