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Lessons Learned from Microgrid Demonstrations Worldwide

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January 2012

This work was supported by the China Sustainable Energy Program of the Energy Foundation through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Executive Summary - English

While largely fossil-fuel based grids have supplied an increasing amount of electricity for our world with a commendable power quality and reliability (PQR) for more than a century, various concerns are now bringing the familiar universal centralized paradigm into question. One consequence is rapid research, development, and deployment of *microgrids*. Cost, reliability, energy efficiency, harvestable local clean energy, and climate change mitigation are the most commonly observed microgrid drivers, and various stakeholder groups including customers, technology providers, utilities, and governments are key stakeholders in the successful development of microgrid technology and policy. Essentially, microgrids can provide an avenue for increasing the amount of distributed generation and delivery of electricity, where control is more dispersed and quality of service is locally tailored to end-use requirements. Definitions for microgrids vary widely, but the two basic requirements most commonly cited internationally are: 1) a microgrid must contain both sources and sinks under local control, and 2) a microgrid must be able to function both grid connected and as an island.

In the interest of informing policymakers with illustrations from collective international experience, this work provides a brief overview of microgrid definitions, common characteristics, technology, barriers, and policy prescriptions, as well as thumbnail descriptions of successful microgrid projects worldwide. The survey leads to policy recommendations for starting a microgrid demonstration program and overall development of microgrid and distributed energy. Additionally, specific recommendations have been made for China specifically. The key findings can be summarized as follows:

Recommendations for Microgrid Demonstration Projects:

- *Recommendation 1: Ensure project's economic viability*
  Various tools have been developed internationally to assess a project's economic viability from the perspective of the microgrid customer who is usually seeking to cut energy costs and/or change PQR, while increasing control over electricity delivery on their site. The Santa Rita green prison project is a notable example, in which the deployment of microgrid technology has lowered peak demand and given the prison the ability to island in the event of an electricity service disruption.
- *Recommendation 2: Include customer microgrids*
  Many of the successful microgrid demonstration projects have used customer sites downstream of one meter, where there are fewer regulatory barriers. Maxwell Air Force Base, Illinois Institute of Technology, and Santa Rita green prison projects are all great examples of successful microgrid projects downstream of one meter.
- *Recommendation 3: Match technology with end-use requirements*
  Demonstrations built around energy supply resources not suitable for the site's energy loads are misguided. Matching power quality and reliability (PQR) of the energy supply to the requirements of end use loads is a defining feature of a successful microgrid, such as the Santa Rita green prison. On the one hand, sensitive loads (military bases, hospitals, data centers, etc.) require very high PQR while on the other hand, some customers' sites may not even need PQR as high as the legacy centralized grid, or *macrogrid*, provides.

- *Recommendation 4: Integrate energy functions: CHP and CCHP*
  Demands for electricity, heating, cooling, and other fuel use, should all be taken into account when designing an optimal microgrid. Even though there is often a policy preference for renewables, some of the best economic and carbon abatement opportunities lie with combined heat and power technologies (CHP) as well as combined cooling, heat, and power, technologies (CCHP), deployed successfully by the Sendai and University of California San Diego (UCSD) projects, respectively.
- *Recommendation 5: Consider all stakeholder interests*
  Since microgrids introduce a very new paradigm for electricity service delivery, proper design of microgrid projects or policies requires consideration of the interests of all stakeholders affected, including: microgrid customers, grid customers, independent power producers (IPP), transmission and/or distribution network operator (DNO), utilities, technology providers, and governments.
- *Recommendation 6: Promote results-oriented RD&D programs*
  Successful microgrid research, development, and demonstration (RD&D) programs should have defined outcomes as well as cost sharing between government and private sector partners. The Renewable and Distributed Systems Integration (RSDI) program under way at U.S. Department of Energy is a targeted research effort with the goal that each of the nine microgrid projects funded should demonstrate a 15% reduction in the local distribution network's peak load.
- *Recommendation 7: Allow for post-demonstration analysis*
  A key component of any demonstration should be analysis following completion of the project. Amassing enough data during a demonstration, and providing budget and opportunity for ex-post analysis can produce valuable results for the project itself, future projects, and overall policy.

Specific Recommendations for China's Microgrid Development:

In terms of the climate for microgrid development, Chinese policymakers will want to consider policies that could remove major regulatory barriers such as: 1) whether independent power producers (like microgrids) are allowed, 2) whether distributed energy resources are allowed to interconnect and island with the macrogrid, and 3) whether there are adequate incentives for microgrids to sell power into the macrogrid.

China's current feed-in tariff policies encourages the development of renewable energy resources but only for large scale power stations. Programs like the building integrated PV (BIPV) program and Golden Sun should continue to be promoted for smaller, distributed installations, but only after proper interconnection standards (compatible with IEEE and IEC standards) have been established. Programs should provide incentives for small installations which may otherwise remain islanded. Additional considerations can be given for other types of on-site generation (including wind, biomass, CHP, fuel cell, etc.) and what mixture of tariff and net-metering should properly support those technologies and any power or ancillary services they might provide to the larger grid.

Consideration of both the seven recommendations provided and the barriers outlined in this report will help China's policymakers develop a microgrid demonstration program with appropriate policy support. Indeed, taking stock of the international experiences to date will help China to build a very successful future for microgrids.

Executive Summary – Chinese – 执行摘要

尽管基于化石燃料的电网已经为我们提供了一个多世纪令人称道的电力质量和可靠性，然而，现在越来越多的关注与质疑集中在中央集中式模式的局限性上。因而，这也促使对于微网的快速研究、发展和部署。同时，对于成本、可靠性、能源效率、当地清洁能源与减少气候变化等因素的考量也都成为从事微网研究与实施的驱动力。此外，包括顾客、技术提供者、公用事业与政府部门在内的不同的利益相关集团也成为微网科技和政策成功发展的关键影响因素。事实上，微网提供了一条扩大分布式能源和电力输送的路径，从而使电力控制更分散、服务质量更加符合当地用户端的需求。尽管关于微网的定义各有不同，但是，通常有两个基本点被国际广泛认同：1）微网应包括本地控制下的电源和负荷；2）微网应能够联网和孤岛运行。

为了从已有的国际经验中总结经验教训从而为决策者提供帮助，本项工作简要地介绍了微网定义、特点、技术、壁垒，和政策规定，以及世界各地成功的微网范例。该工作为微网示范项目计划和分布式能源的整体发展提供了政策建议。此外，也专门提出了针对中国的具体建议。所有罗列如下：

微网示范项目建议：

1. 确保项目的经济可行

国际上，不同的工具被研发用于从微网客户端评估项目的经济可行性，从而减少成本、改变电力质量和可靠性并提高当地的电力输送控制。圣塔瑞特绿色监狱是一个典型范例，该项目科技致力于降低高峰需求，以及电力服务受影响时监狱电力自我供给的孤岛运行能力。

2. 引入顾客端

许多成功的微网示范项目均使用顾客端计量，从而避免规制和壁垒。麦克斯维尔空军基地、伊利诺斯科技大学、圣塔瑞特绿色监狱等项目都是这样的成功范例。

3. 与终端用户要求匹配科技

不考虑当地能源负荷，只注重能源供给源的示范项目很难成功，为最终用户端匹配相应的电力供给质量和可靠性是一个成功微网内在固有的特征，如圣塔瑞特绿色监狱项目。因为有些用户属于敏感负荷需要非常高的电力质量和可靠性，例如军事基地、医院、数据中心等；而另一些用户所需的电力质量和可靠性可能低于传统电网提供的标准。

4. 整合能源功能：热电联产和热电冷联产

设计一个最优化的微网应该考虑电、热、冷及其它燃料的综合使用。 尽管当前的政策偏好可再生能源，然而热电联产和热电冷联产仍然是最好的既经济又可减少碳的形式，在这一方面，成功的项目包括仙台大学和加利福尼亚圣迭戈大学等项目。

5. 考虑所有利益相关者的利益

微网引入了一个全新的电力服务输送范式，因而，微网项目的恰当设计或政策应考虑所有受影响的利益相关者的利益，包括：微网顾客、主网顾客、独立电力生产商、网络传输和配送运行商、公用事业、科技提供者和政府等各个方面。

6. 促进结果导向的研发和示范项目规划

成功的微网研发和示范项目规划应该定义项目产出结果以及政府与私有合作者之间的成本共享。美国能源部的新能源与分布式系统整合规划是以结果为导向的研究计划，其九个被资助项目致力于减少当地配送网高峰负荷的 15%。

7. 示范后分析考量

任何示范项目其一个关键部分在于项目完成后的分析：评估项目实施过程中累积的各项数据、项目预算和事后分析都能为项目本身及未来发展和总体政策提供有价值的信息。

专门针对中国微网发展的具体建议：

在微网发展方面，中国的决策者需要考虑设计和制定能够减少规制壁垒的一些政策，如：1）是否允许独立电力生产商（如微网）；2）是否允许分布式能源与中央集中式主网连接或孤岛运行；3）是否有足够的措施激励微网销售电力到主网。

中国目前的上网价格政策鼓励发展可再生能源资源，但仅适用于大型发电站。像建筑集成光伏和金太阳等计划，应在适宜的并网标准（兼容 IEEE 与 IEC 标准）建立后继续促进较小的分布式安装。计划应为可能会保持孤岛状态的小型装置提供激励。此外，为现场发电（包括风能，生物质能，热电联产，燃料电池等）应多做考虑，并且运用上网定价和净计量等其它方法，应致力于支持用于微网建设的那些技术、发电或可以提供给大电网的辅助服务等。

本报告中所罗列的上述七项建议也将有助于中国的决策者制定相应的政策与微网示范计划。事实上，迄今为止的国际经验将有助于中国在未来建立一个非常成功的微网。

Introduction

Purpose of this work

Numerous organizations and research programs have accumulated valuable lessons from their experience with microgrid pilot projects and other aspects of microgrid economic and technical development, as well as with the adoption of standards and other mechanisms to foster expanded microgrid use. Review of international experience can benefit organizations and countries just establishing microgrid research and development programs. In the interest of informing policymakers with illustrations from the collective international experience, this work provides a brief overview of microgrid definitions, common characteristics, technology, barriers, and policy prescriptions, as well as thumbnail descriptions of successful microgrid projects worldwide. The survey leads to seven policy recommendations for starting a microgrid demonstration program. While this work was started with the China context in mind (as China is preparing new policies involving microgrids), the recommendations are applicable to other regions just as well.

Microgrid drivers

While largely fossil-fuel based grids have supplied an increasing amount of electricity for our world with a commendable reliability and power quality (PQR) for a century, various concerns are now bringing the centralized grid paradigm into question. Microgrids are controlled semiautonomous clusters of energy resources and loads that can function connected to the grid or as islands. Motivations for promoting distributed generation and microgrids are apparent across at least four distinct stakeholder groups, with many common threads amongst them, as seen in Figure 1.

Energy customers are increasingly interested in improving their energy efficiency and reducing their energy costs, while the electricity supply industry is consistently worried about increasing or simply maintaining PQR while meeting new clean energy mandates and other requirements. Governments, both at the local and national levels, are driving clean energy adoption, in the interests of climate change mitigation, energy security, and other environmental goals. Additionally, technology providers from many diverse sectors, such as information technology and telecommunications, are playing a disruptive role in microgrid development by seeking out potential opportunities to innovate.

As seen in Figure 1, the interests of the customer, technology provider, utility, and government stakeholders in a new grid paradigm are profound and have common thread motivations of cost, reliability, efficiency, clean energy, and climate change mitigation. Many countries and regions around the world are looking to distributed energy systems and *smart grid* initiatives to address these challenges. Governments have enacted and implemented a series of policies to increase the share of clean energy and distributed generation. However, the interconnection of distributed generation to the conventional network brings technical challenges such as circuit protection, maintaining PQR, and stability issues. One of the disruptive forces promoting microgrids is the role of unregulated technology

providers. Companies keen to provide both hardware and services to current utility customers are developing and deploying technologies that can increase customer autonomy.

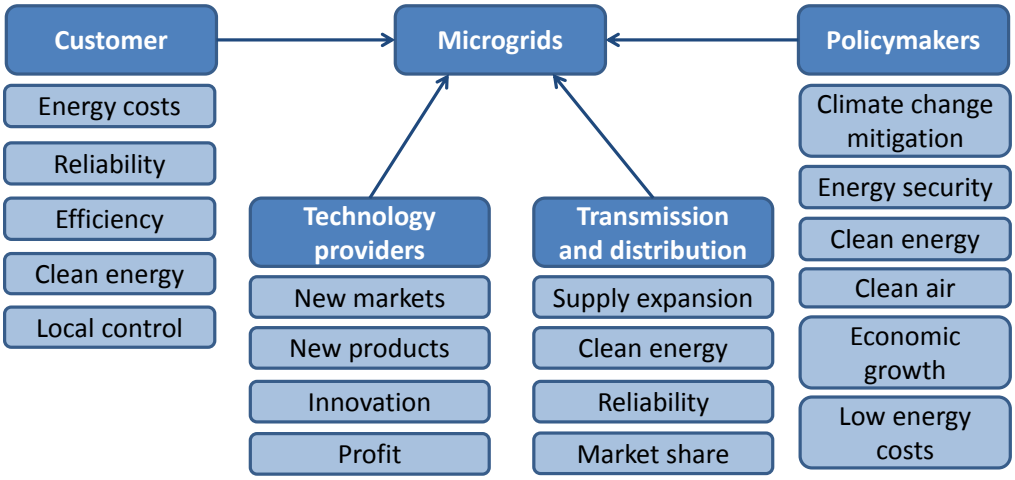

Figure 1: Drivers for microgrids across four stakeholder groups

Several technologies are enabling the transformation of electricity production, delivery, and use, but a key enabler of microgrids is power electronics devices. These are making control of small-scale systems feasible, economic, reliable, and safe.

Macrogrid limits

At the same time as strong drivers and innovative technology are enabling more dispersed control of electricity delivery, the conventional centralized power delivery system (macrogrid) paradigm is showing its limitations. Expanding supply to meet expected growing demand is unavoidable, especially in emerging economies for which the huge upfront investment costs can represent a major burden. Additionally, it is increasingly a priority (or mandate) for utilities to increase clean energy supply while fostering competitive wholesale electricity markets and maintaining or improving the PQR enjoyed today. These contradictions have led some to question the traditional paradigm. One challenge to the macrogrid is that clean energy generation, in the case of wind and solar, is often variable and relatively unpredictable compared to traditional fossil fuel based generation. Another issue is that much of it is expected to come from relatively small installations, e.g. residential rooftop photovoltaic (PV) systems, and some may even be mobile, e.g. plug-in electric vehicles (PEV). Controlling numerous, possibly millions, of new small supply sources has led analysts to consider alternatives, such as microgrids, that could manage these smaller scale and problematic assets locally. In other words, if small sources can be aggregated by microgrids, the legacy macrogrid could continue to be managed centrally and organize similar numbers and sizes of participants as are successfully handled today.

While some modern technologies can achieve excellent efficiencies as measured by historic standards, the overall systemic efficiency of generation delivers barely a third of the initial fossil energy to ultimate devices. This is mostly due to heat to electricity conversion losses in power generation with additional,

smaller losses of 5-10% occurring during transmission and distribution. One partial solution to this problem is smaller-scale generation closer to loads, which increases the potential for combined heat and power (CHP) improving overall efficiency significantly. While the power generation efficiency of CHP may not be as high as at a large-scale power plant, the ability to use waste heat directly results in a systemic efficiency. In many warm climates, using the waste heat to cool buildings can be attractive because doing so further reduces expensive on-peak electricity use and downsizes needed generating capacity.

Customer desire and government objectives to reduce energy costs and increase energy efficiency may be the most powerful drivers of microgrids. With the declining costs of clean energy and energy storage and attractive propositions of on-site efficiency and CHP, a growing amount of customers have an economic interest in producing their own power and purchasing less from the macrogrid. Moreover, many customer sites have reliability in mind, whether from the perspective of cost, energy security, or infrastructure interdependency. In fact, sites with exceptionally high PQR requirements are the likely early microgrid adopters.

Infrastructure interdependency has become a growing concern for governments, utilities, and customers alike, since our current power delivery system is highly vulnerable to both natural and malicious threats. The consequences of blackouts are serious in large measure because so many other critical infrastructures, such as communications, transportation, water treatment, etc., depend upon it. To some extent, independent and local power generation for key customer functions can reduce the severity of this problem.

Reliability is costly even though customers do not see it as a line in their electricity bills. Maintaining high levels of reliability incurs two significant types of costs. First, equipment investments to improve PQR, such as underground versus overhead lines, impose direct costs on utility operations. Second, the paramount concern with maintaining high PQR leads to conservative grid operations, for example, potentially economic exchanges of energy are foregone because approved transmission capacities are limited by reliability concerns. It may be that sustaining high PQR across the board no longer makes economic sense. If we are now able to provide PQR locally and more closely matched to the requirements of the customers, then the standards of the centralized grid can be rethought. In other words, the levels of PQR currently thought necessary in the macrogrid might be relaxed. While hard to quantify, the most benefit from microgrids may derive from this lowering of macrogrid costs.

Some have suggested that electricity delivery should move from its current highly hierarchical centralized paradigm to one that is more dispersed. One way to imagine an alternative is moving the control from the center to the periphery. Systems that have their sensitive capabilities out on the edge tend to be more robust, e.g. the internet's intelligence is in the laptops and data centers that it interconnects, rather than in the routers and other devices that move the packets around. Microgrids are one manifestation of a more dispersed grid control paradigm with peripheral intelligence. Some

analysts consider this one of three legs of the smart grid. The first is better operation of the tradition meshed high voltage grid, e.g. through operator visualization technology; the second is improved supply-demand interaction, e.g. through advanced metering infrastructure; and the third is decentralized control.

Definitions of a microgrid

The term *microgrid* loosely refers to any localized cluster of facilities whose electrical sources (generation), sinks (loads), and possibly storage (both electrical and thermal) function semi-autonomously from the traditional centralized grid, or macrogrid. Researchers have created a wide variety of more formal microgrid definitions depending on the context of technology and function, and the following two are frequently cited:

> *Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded (CIGRÉ C6.22 Working Group).*

> *A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode (U.S. Department of Energy Microgrid Exchange Group, 2010).*

As noted above, microgrids are one of three elements of emerging "smart grid" technology. The other two more widely recognized elements are: 1) improved operation of the traditional macrogrid, e.g. by deployment of phasor measurements, and 2) enhanced interaction between the grid and consumers, e.g. by deployment of advanced metering infrastructure. By contrast to these two well recognized technological changes, microgrids are new entities that have the potential to provide two-way benefits to their participants and the macrogrid. The emergence of microgrid technology represents one aspect of the push towards a more distributed power system.

Some developers using related technologies simply call their project a microgrid based on the use of renewable energy or distribution energy resources. For example, remote islanded networks using renewable energy are often called microgrids but lack connection to the main grid and are therefore not a true microgrid by the two prominent definitions. Although they are not strictly microgrids according the definitions given in this study, remote islanded networks often use very similar technology to microgrids and can still produce valuable and relevant lessons for microgrid development. Additionally, executing demonstration is often easier in remote systems where there is no macrogrid to be potentially affected.

The above CIGRÉ and U.S. DOE definitions have two basic requirements: 1) a microgrid must contain both sources and sinks under local control, and 2) a microgrid must be able to function both grid connected and as an island. Yet, various types of microgrids might not only operate with quite different technologies and objectives but also might fall under quite different regulatory regimes. On the one hand, microgrids can be wholly within one traditional utility *customer* site; most existing demonstrations are of this type. Alternatively, a microgrid might involve several sites connected by a fragment of the legacy distribution network. The difference between these two types is critical from the regulatory and policy perspectives. The former is downstream of a single (or very few) meter(s) or point(s) of common coupling, which implies a regulatory environment quite distinct from the latter case, which implies that part of a legacy regulated distribution utility is included in the microgrid.

The key word identifying a microgrid, and particularly differentiating it from traditional distributed generation, is *controlled*. While the macrogrid has traditionally been tightly centrally controlled, local small-scale generation was cast in a slave role, e.g. shutting down immediately in the event of a blackout. A microgrid must have semiautonomous capability. Note that the CIGRÉ and U.S. DOE definitions say nothing about the technologies involved, their scale, the motive, the fuels, or the quality of power delivered to loads. The microgrid's ability to present itself to the macrogrid as a controlled entity has two important implications: 1) it can provide complex services, e.g. buffering variable renewable generation or providing ancillary services to the macrogrid, and 2) it can coordinate with other entities in the network, such as other microgrids or other sites with generation, storage and/or controlled loads. In addition to the self-apparent benefits of potentially providing clean and affordable energy under local control and supplying valuable grid services, microgrids provide an opportunity to locally control PQR and tailor it to meet individual load requirements, in contrast to the familiar universal homogeneous PQR service from the macrogrid. For example, this might mean a local DC system involving PV and storage is the best solution even though PQR is poor, or in another case, it may mean highly reliable and clean power is required, such as for a site whose loads demand it, e.g. a telecom facility. In other words, the PQR of delivered power should match both that offered by the economically available resource and that of the loads it serves. Matching the PQR in this way maximizes the economic benefit.

Implications of microgrid development

Effective incentives to stimulate deployment of microgrids are not readily apparent. Identifying, quantifying, and capturing the benefits of microgrids, and likewise establishing efficient markets for their services will require new initiatives and poses some significant policy challenges. The policy and regulatory environment will have a profound effect on the adoption of microgrids, their composition, and their likelihood of success and sustained operation.

First and foremost, the economics of microgrids is driven by the incentives established by tariffs, fuel costs, and the market environment more generally. Creating effective mechanisms by which microgrids can exchange energy and services with the macrogrid, and hopefully capture a significant share of the

benefits they bestow, are a key policy priority. This problem is more complex that it seems for three reasons:

1) because microgrid economics are highly sensitive to details in tariffs and related agreements;

2) because the services that microgrids might provide to the macrogrid are either new, e.g. local voltage support, or have traditionally come from sources with very different characteristics, e.g. provision of grid ancillary services has come from large generating stations, the way services are defined reflects large station capabilities; and

3) because many of the benefits are localized and quantifying them is not only a technical challenge but can raise significant equity issues.

With respect to the third point, for example, a microgrid may merit compensation for providing local distribution network support in a certain location but the reason a problem exists in this one location may be the result of the somewhat arbitrary topology of the network. In other words, microgrids may be rewarded simply by virtue of quirks of the legacy network. As a second example, consider the benefits to the macrogrid by being buffered from variable renewable generation; this is a clear benefit, but not one that is readily estimated and compensated.

The rules, tariffs, and contracts on which payments are made, in both directions, will likely be the most potent driver of microgrid development, and the accuracy with which benefits such as these can be compensated and the transactions costs required will be major drivers of microgrid investment attractiveness. Consequently, a thorough policy analysis of their technical basis will be needed. To the extent that microgrids can provide benefits to the high voltage grid, e.g. by providing demand response and ancillary services, the markets for these too must be amenable to microgrid participation.

Microgrids can serve as aggregators of potential ancillary service providers, e.g. by jointly controlling PEV or stationary batteries and buildings equipment to offer service to the grid as a combined entity. In this case, the contractual relationship between the vehicle owners and the microgrid also requires regulatory scrutiny. Note that some of the relationships involved will be quite new, and the PEV case is a good example. Forming contracts between vehicle owners and owners of the buildings to which they interconnect represents a type of arrangement with which we have no experience. The economic, safety, and liability terms under which a PEV owner relinquishes control of his vehicle to the building owner are issues that must be resolved, and a clear policy environment on the topic can accelerate the process considerably.

Second, the technical rules by which microgrids interconnect and operate pose key policy questions. The costs of microgrid deployment can be significantly influenced by the details of technical rules and especially by any delays in application processing, so their establishment has to be based on an open standards setting process, and their enforcement has to be evenhanded. In the U.S. considerable effort

has ultimately led to passage of standards that are accepted by most states (IEEE 1547). One of the areas of particular sensitivity concerns the effect of connecting generation on the local distribution network and its customers. The costs of conducting analyses of these effects alone can be significant, and investments to mitigate any impacts can be substantial. The ground rules under which these studies are done and how any consequent remediation measures are paid for requires particular clarity. Also note that the effects of any one interconnect are not isolated from others. The sequence in which access to the network is granted to exporters carries consequences, so the process needs to not only be fast but also transparent and fair to interconnection applicants.

Third, as noted above, microgrids may or may not be subject to public utility codes, depending on the circumstances. In other words, in some cases microgrids might be considered public utilities, with severe regulatory and cost consequences. The rules under which microgrids become utilities and the rules under which they must operate in each case need to be carefully examined. As with many aspects of microgrids, small such considerations can have major implications for economics and feasibility.

Fourth, also as noted above, microgrids provide an opportunity to control PQR locally. The technical and regulatory environment will profoundly affect the way the technology is rolled out, in this regard. For example, can high pressure natural gas networks be legally installed in buildings under existing codes, and what safety and other measures are required?

Fifth, ultimately, much of the benefit from microgrid technology may be that it enables the macrogrid to evolve differently. If PQR is ensured in a more localized fashion, can the legacy macrogrid be freed to pursue some of the other policy imperatives of our times, e.g. to accept variable renewables as the dominant source of energy. How policies enable or hamper such a diverse path will be one of the greater long-term research questions and how the benefits are shared among the stakeholders must ultimately be resolved.

China's microgrid development

China has a number of policies in place likely to push microgrid deployment. First, it has a goal of achieving 15% non-fossil energy as a proportion of total primary energy consumption by 2020. Second, in 2011, China's National Energy Agency (NEA) drafted the *Management Methods for Distributed Energy*, an attempt to promote the microgrid concept and to facilitate the expansion of renewable energy and other distributed energy resources. Lastly, in the 12th Five-Year Plan (2011-2015), NEA is directed to use microgrids as the basis for 100 *New Energy City* pilots, and 30 microgrid pilot projects have also been proposed.

Some experts contend that China's current electricity system lacks the flexibility to integrate renewable energy on a large scale with acceptable cost and reliability. For instance, wind energy development in China has faced a number of barriers regarding interconnection and curtailment, given the geographic mismatch between the wind resource and demand centers as well as the relatively small amount of

dispatchable generation in China's grid. Additionally, China's growth in peak demand (China has had a relatively flat load curve in the past due to high demand from industry) will increase the need for daytime demand response and possibly solar PV generation. Microgrids, if properly deployed, can aid China in meeting its renewable energy goals in a cost effective manner while continuing to supply enough energy for its growing end-use demand.

Seven recommendations for a microgrid demonstration program

In this section, seven recommendations for successful microgrid demonstration programs are laid out, with relevant background and context from existing developments around the world.

- Recommendation 1: Ensure project's economic viability
- Recommendation 2: Include *customer* microgrids
- Recommendation 3: Match technology with end-use requirements
- Recommendation 4: Integrate energy functions: CHP and CCHP
- Recommendation 5: Consider all stakeholder interests
- Recommendation 6: Promote results-oriented RD&D programs
- Recommendation 7: Allow for post-demonstration analysis

The summation of these recommendations should suggest elements which have made prior microgrid projects and programs successful. The section following these recommendations is a more in-depth exploration of the specific barriers that microgrid development faces, especially interconnection and tariff policy.

Recommendation 1: Ensure project's economic viability

Given that a microgrid, by definition, will be connected to the macrogrid and will often provide demand response or ancillary services to the macrogrid, the project's economic viability must be considered from all of the following perspectives: the microgrid participants, the distribution utility, other customers locally, the transmission operator, and generator. Although demonstrations of new technologies shouldn't be expected to be fully economically viable, or even necessarily close, projects that are unduly expensive are perceived as failures and impede rather than trigger deployment. Consequently, while full financial viability certainly isn't required, the economics of projects should nonetheless be seriously evaluated during project selection.

First and foremost, the project's technical feasibility and economic viability should be addressed from the eyes of the microgrid participants. Researchers at Lawrence Berkeley National Laboratory have developed a tool from the customer's perspective. The Distributed Energy Resources Customer Adoption Model (DER-CAM) predicts and optimizes the capacity and minimizes the cost of operating distributed generation and CHP for individual customer sites or microgrids. Based on specific site load (space heat, hot water, gas, cooling, and electricity) and price information (electricity tariffs, fuel costs, operation and maintenance costs, etc.), the model makes economic decisions on the mix of technologies

the user should adopt and how that technology should be operated. A schematic for DER-CAM can be seen in Figure 2. The model has been used internationally for about 10 years.

Other evaluation tools are readily available. The National Renewable Energy Laboratory developed the HOMER computer model which evaluates the economic and technical feasibility of design options for both off-grid and grid-connected power systems for remote, stand-alone, and distributed generation applications. RETScreen, developed by Natural Resources Canada, is another similar tool, assessing economic feasibility of potential renewable energy, energy efficiency, and cogeneration projects at a particular site.

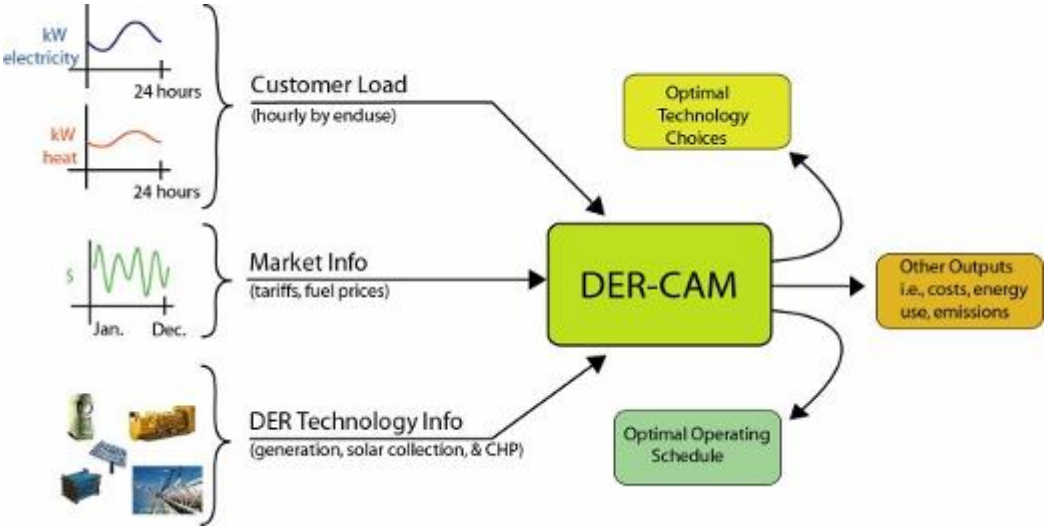

Figure 2: DER-CAM functionality

The following parameters will have a large effect on any project's economic valuation and therefore should be assessed:

Parameter	Description
Combined heat and power (CHP) integration	Whether CHP is used in microgrid.
Distributed energy resources (DER) mixture	The combination of DER used in microgrid. For example, are microturbines or renewable energy sources used?
Load mixture	Mixture of load types in microgrid. Are dispatchable or critical loads included?
Market characteristics	Whether energy or ancillary services can be sold to the distribution network operator, whether electricity is purchased at a fixed or varying rate, and whether other tariffs are applied, for example to reduce peak loading.
Isolation	Whether the microgrid is connected to the macrogrid during normal operation, or instead operates exclusively independently.
Capability of islanding	Whether the microgrid is capable of disconnecting from the grid in the event of a fault or other contingency.

The optimal least-cost solution to the supply of a site's energy demand is a combination of equipment purchase and dispatch of a chosen generation system. Optimality requires minimizing a complicated cost function dependent on often complex tariffs, fuel prices, and equipment characteristics. Uncertainty can enter in several ways, e.g. generation availability, real-time electricity prices, etc. Optimality can also be sought along other dimensions, e.g. carb footprint minimization.

One of the main parameters of interest for microgrid participants is a reduction in their electricity bills. Additionally, revenue from power or services sales may be important. For the distribution network operator (DNO), the main parameters of interest include reduced peak load, i.e. deferred capacity upgrades, local ancillary services such as voltage support, etc. On the cost side, accommodating interconnecting generation might require network upgrades, or conversely loss of load might result in stranded assets whose cost must necessarily be recovered over lower energy sales. In general, the DNO's assets closest to the interconnection point are likely to be most affected, and the policy case for passing costs or benefits along to the microgrid are strongest. For the wider grid, spinning and non-spinning reserves, voltage and frequency regulation, and black start capability might all be attractive. Yet, the macrogrid must be amenable to microgrid participation. Valuation of the functions that the microgrid provides to the macrogrid is needed in order to help promote and facilitate microgrid development.

As an example of a microgrid project for which economics was a primary consideration, consider the Santa Rita microgrid project (for more information, see page 31 in the appendix), which was intended to achieve a 15% reduction in the peak load of the local distribution feeder. Based on the 2 MW - 4MWh battery that the jail installed within the project, about a 5% reduction in peak load is possible. However, the jail has previously installed a number of other measures of distributed generation and energy efficiency upgrades that in total allowed an approximately 16% reduction in peak load. These investments include a rated 1.2 MW rooftop solar PV array, a 1 MW molten carbonate fuel cell, a chiller plant upgrade (912 kW peak saving), T-8 lighting retrofit (225 kW peak saving), induction lighting retrofit (217 kW peak saving), and freezer evaporator retrofit (71 kW peak saving). Most of these were innovative technologies and not economic on their own merits, but as described below, matching funding was required from Alameda County, the Jail's owner, thereby ensuring the project was at least reasonably close to being economic.

Recommendation 2: Include *customer* microgrids

Many of the successful microgrid demonstration projects have used customer sites downstream of one meter (or point of common connection [PCC]), such as a military base, campus, or jail. There may be multiple buildings and loads on that customer site, but there is one point of connection to the larger macrogrid and one billed customer. Maxwell Air Force Base (see page 33), Illinois Institute of Technology (see page 32), and Santa Rita Green Jail (see page 31) projects are all great examples of successful microgrid projects downstream of one meter. The primary motivation for including single customer demonstrations in any microgrid program is that downstream of the meter, regulatory barriers are much less daunting. Projects that involve legacy regulated public utility assets naturally face much tougher regulatory challenges.

If a microgrid project tries to incorporate elements (generation or load) beyond the meter, in most jurisdictions it will then be treated as a utility, which brings a number of regulatory burdens that the microgrid (given its size and capabilities) may not be able to bear. Once the customer is playing in the realm of the distribution network (in between the microgrid's meter and the local substation, as seen in Figure 3), an area that the utility controls and is responsible for guaranteeing the PQR and safety of, then many new technical and legal issues are brought into question.

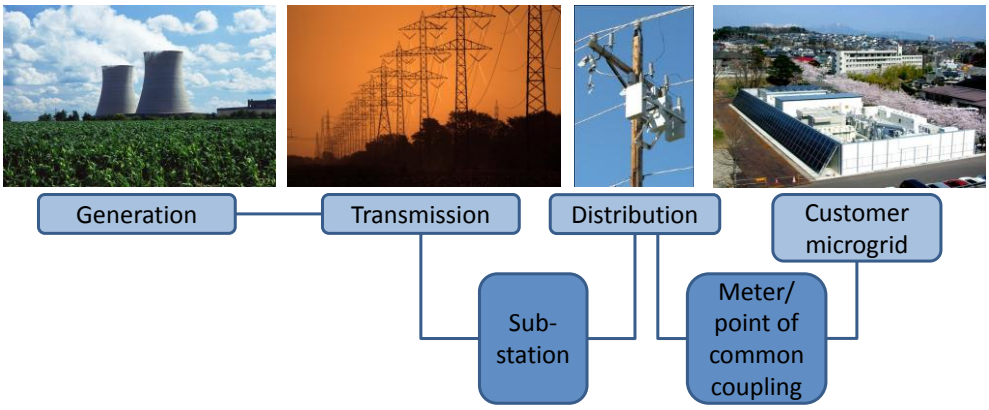

Figure 3: Power grid, from generation to customer microgrid

Recommendation 3: Match technology to end-use requirements

A key feature of microgrids is that the technologies applied are appropriate to requirements of its loads. Demonstrations built around resources not suitable for the loads are misguided. To determine what mixture of supply technologies a site needs requires knowing the end-use demand requirements and then matching those with a supply mixture of the appropriate PQR. Additional considerations beyond demand requirements, especially in the case of military installations, include the security of fuel and energy supply and the remoteness of the grid. Military bases are becoming increasingly common customer sites for microgrids for a number of reasons. Fuel supply is a classic military vulnerability, but additionally, bases are often built in remote locations and thus experience poor PQR from their electricity service provider.

Matching PQR delivered to the requirements of end use loads can also potentially save money; that is, the cost of matching PQR of supply to specific end user needs is less than the cost of universal PQR, or 100% reliability for all end users. This is part of a vision for a dispersed grid. Recently, a rise in sensitive loads (military bases, hospitals, data centers, etc.) has led to rise in the use of uninterruptible power supplies and backup generators in the case of macrogrid failure. Over 90% of macrogrid faults in the U.S. happen because of faults on the distribution network (due to its exposure to extreme weather and accidents), while faults on the generation and transmission side are rare. Sensitive loads can best be addressed in two ways: first, improvements in distribution system and second, use of supply closer to sensitive end-uses to protect them at the levels they demand. Microgrids provide a solution that meets both of these requirements, so long as the PQR of supply is matched with end-user requirements.

The use of multiple technologies, both on the supply and demand sides, is certainly more interesting from a technical standpoint, but should only be justified when the end-user requirements truly warrant it. As solar PV costs continue to fall, many microgrid customer sites will opt to install rooftop solar panels since payback periods are decreasing. Additionally, local or federal law may provide incentives for solar PV installations. The installation of solar however, will require backup generation or storage to serve sensitive loads. In the case of the Santa Rita Jail (see page 31), a 1.2 MW solar PV system was paired with a molten carbonate fuel cell with CHP capability, a 2 MW Li-ion battery, and two 1.2 MW emergency diesel generators. The jail needs power with as complete a guarantee of supply as possible so as to ensure the safety of its facility and staff, thus the need to back up solar PV with traditional generation from diesel generators and fuel cells, in addition to normal macrogrid service.

The Hachinohe Project (see page 29) was one of the initial projects funded by New Energy and Industrial Technology Development Organization (NEDO). With highly reliable grid power available as back-up, this project focused on a maximum renewable fuel mix. The system includes two 50 kW and three 10 kW PVs, small wind turbines, a 100 kW lead acid battery bank and three 170 kW gas engines fed by sewage and waste gas by-product. At the sewage plant, a 1.0 t/h wood-waste steam boiler is installed to supply heat to safeguard the bacteria and exhaust heat from the gas engines is reused by the gas fermentation process. The electricity is transmitted to schools, the local city hall and an office building by a private distribution line 5.4 km, 6 kV feeder.

Some microgrids only use a single supply technology for instances where the demand for PQR is low or a high load factor is not needed. For instance, consider a hypothetical sewage treatment plant which has a biogas digester and generator that produces the facility's power. Typically, biogas generators are not 100% reliable and the ultimate quality of power depends on the quality of waste gas. In this case, it may be possible to achieve adequate PQR using the waste gas. Note that a connection to the local distribution grid (with 99.9% reliability) is enough to secure the assurance needed, but other facilities require even higher reliability.

Recommendation 4: Integrate energy functions: CHP and CCHP

Many microgrid projects focus on delivering power while other forms of energy needs, such as heat, are neglected. Demands for electricity, heating, cooling, and other fuel use, e.g. cooking, should all be taken into account when designing an optimal microgrid. Even though there is often a strong policy preference for renewables, some of the best economic and carbon abatement opportunities lie with combined heat and power technologies (CHP) as well as combined cooling, heat, and power, technologies (CCHP). CHP equipment is designed to produce power from fossil or biofuels into electricity and use the waste heat from the conversion process either directly or to produce more power through turbines. Facilities with high heating loads will typically prove to be the most appropriate for CHP installation from a purely economic standpoint, but hotter regions with high cooling loads (such as San Diego) can also be good sites for CCHP. Analysis has shown that, surprisingly, medium-size commercial buildings (with peak electric loads ranging from 100 kW to 5 MW) are often good sites for distributed generation with CHP. Yet, optimal systems for such buildings can nonetheless be complex, involving solar thermal assistance to CHP waste heat use, or thermal storage.

The University of California San Diego (UCSD) microgrid (see page 34) is an excellent example of a CCHP system that consists of two 13.5 MW gas turbines, one 3 MW steam turbine, a 1.2 MW solar PV installation, a 3.8 million gallon cold water storage tower, a 2.8 MW methane powered fuel cell, and PEVs, together supplying 85% of the campus's electricity needs, 95% of its heating needs, and 95% of its cooling needs. The turbines produce 75% fewer emissions of criteria pollutants than a conventional gas power plant. By the use of an existing campus steam distribution system, UCSD uses waste steam from the turbines to drive chilled water for facilities' cooling, heating, and hot water needs.

The Sendai Project (see page 30) was also funded by NEDO also includes CHP. The system has two 350 kW gas gensets, a 250 kW MCFC, a 50 kW PV array, and a 50 kW battery bank. The microgrid directly serves some DC loads and additionally supplies four different qualities of AC service to a university, a high school, and a sewage plant. The integrated system consists of a two-way mode power module, DC-AC inverter, and a battery bank. The project provides power and heating simultaneously to improve energy efficiency and is still in operation in large part due to its economic viability.

Recommendation 5: Consider all stakeholders' interests

Microgrids can be a disruptive technology in some cases because they introduce functionality that did not exist before and that current institutions are not accustomed to; therefore, many of the barriers for implementing successful microgrid projects are institutional. As such, proper design of any single microgrid as well as a framework microgrid policy requires consideration of the interests of all stakeholders involved, including:

- Microgrid customers: residential, commercial, or industrial loads within the microgrid
- Grid customers: loads outside the microgrid but potentially affected by its existence
- Independent power producers (IPP): owner of distributed generation in the microgrid
- Distribution network operator (DNO): the entity responsible for correct operation of the grid
- Utilities or bulk energy suppliers: the entities outside microgrid who supply power to the grid
- Technology providers: equipment manufacturers, microgrid solution providers, and research organizations
- Society: everyone who might be affected by microgrid externalities
- Local government: policy-maker and often responsible for providing financial or legal support (such as in regulation or codes)

In an ideal setting, a properly functioning microgrid would provide energy for the needs of its customers while also providing energy or services to the larger macrogrid which the utility would find valuable. The local government and utility regulator would set codes whereby a microgrid could interconnect to the macrogrid and get paid for any energy or ancillary services it sold to the macrogrid. The barriers to achieving this *ideal setting* will be elaborated on in the section on microgrid barriers below.

Recommendation 6: Promote results-oriented RD&D programs

Successful microgrid research, development, and demonstration (RD&D) programs should have defined outcomes or targets as well as cost sharing between government and private sector partners.

Microgrid development has reached the stage where the potential benefits are known but have not been fully demonstrated or quantified. The potential for cost and efficiency savings is very large, but more individual cases of reaching that potential need to be seen. Therefore, it is important for RD&D programs to have defined objectives that will push the industry in the right direction.

Yet, while it is reasonable that a demonstration project have clear quantifiable objectives that will contribute to the body of knowledge about microgrids, project design has to be in line with Recommendation 1. In other words, having clear quantifiable RD&D goals is desirable, but the economics of the project should not be unduly compromised as a result. The demonstration should still be one that makes sense given local costs and benefits.

The Renewable and Distributed Systems Integration (RSDI) program started by DOE in 2008 is a targeted research effort (with nine projects in total receiving federal funds) with the goal that each microgrid should demonstrate that it can reduce the local distribution network's peak load by 15%. If these successes can be shown, it will show industry players (utilities, in particular) that microgrids are feasible not only on paper, but also in pilot projects, and that there are potential economic benefits involved for all players if microgrids are promoted in a pragmatic fashion.

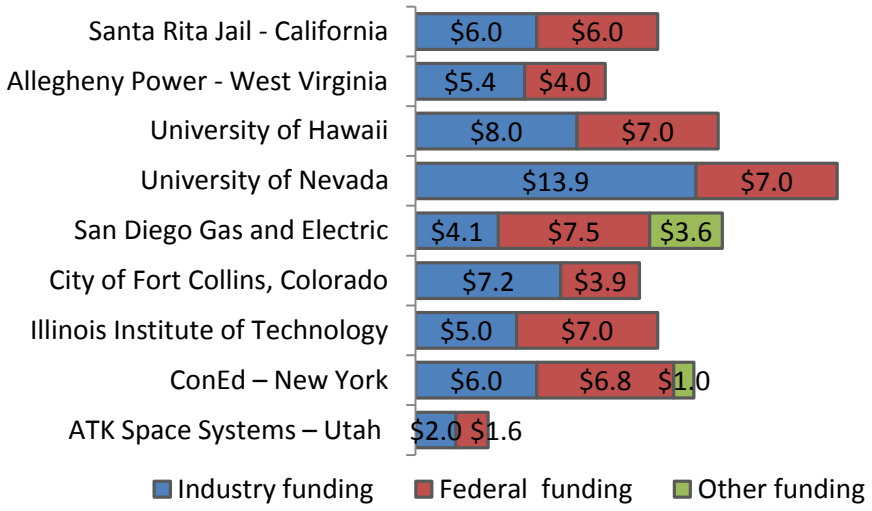

Figure 4: Cost sharing of Department of Energy's Renewable and Distributed Systems Integration (RDSI) projects

Cost-sharing between industry and federal government players is critical to ensure that industry parties (such as utilities as technology companies) have vested interests in the successful implementation of the microgrid project. The RDSI projects run by DOE are a good example of this. All projects have an industry cost shares in the range of 50% with a high of 67% (University of Nevada) and a low of 42% (Illinois Institute of Technology). So far, in developed areas like Europe and Japan, they have taken great efforts of special programs, e.g. *More Microgrids*, and organizations, e.g. NEDO, to engage in microgrids research. And more and more private sectors have or are being involved in demonstration constructions in order to seek future industrial development and competitive market opportunities.

Recommendation 7: Allow for post-demonstration analysis

A key component of any demonstration should be analysis following completion of the project. Particularly, it is important that important "what if" questions are answered. Inevitably, many decisions and choices made during planning and execution of a demonstration have a significant effect on the outcome. Amassing enough data during a demonstration, and providing budget and opportunity for ex-post analysis can produce valuable results. How the project's economics may have changed with different equipment sizes or different tariff structures would be particularly valuable points for policy makers.

The quality of analysis on microgrid demonstration projects to date has varied widely. The use of a third-party contractor to perform post-demonstration analysis may be advisable in situations where the main microgrid developer might provide a biased or incomplete opinion. Many microgrid project developers may be inclined to paint their project in an entirely positive light (due to funding concerns, for instance), without due assessment of the project's design flaws, shortcomings, or difficulties. They may also be unfit to perform an assessment from all angles, including technical, regulatory, and economic perspectives. If the project developer was a technology provider, then the post-demonstration analysis may only have information related to the technical aspects of the project, without due evaluation of policy and economic issues. If the developer cannot provide an unbiased and complete assessment of the project, then a third party contractor should be brought in to perform the assessment. Appropriate funds should be set aside ahead of time in either case.

Overview of microgrid barriers

From an interconnection standpoint, it is important to describe the technical, regulatory, and economic barriers that microgrids commonly face, and identify possible solutions. A policy environment supportive to microgrids that minimizes such barriers will require that the following questions have a "yes" answer.

- **Do policies or codes allow independent power producers, such as microgrids?** In Europe and Japan, through a series of electricity market liberalization measures, e.g. unbundling the generation and transmission, wholesale and retail sale markets reform, permission for entry to electricity generation has supported the development of distributed energy and microgrids.
- **Does local distribution grid utility/operator allow distributed energy resources to interconnect to the macrogrid (in both grid parallel and islanding modes)?** In developed countries, they have enacted diversified regulations on interconnection to encourage the penetration of renewables and distributed generations. Although these regulations exist, vested interest groups (including utilities) will still resist the wide deployment of renewables and distributed generation.
- **Is there an incentive for a microgrid to sell power into the macrogrid (net metering, guarantee of tariff, if not a feed-in tariff)?** The opportunities for microgrids can go beyond a level playing field. Tariffs with low transaction costs that allow microgrids to export at attractive prices are a powerful incentive for deployment, especially if these incentives are guaranteed for some fixed term.

California is a good example of a jurisdiction where the answers to these questions are all yes. Rule 21, first enacted into law in December 2000, adopted a standard practice for connecting distributed energy resources (DER) to the grid, specifying standard interconnection, operating, and metering requirements for DER generators. Additionally, California has a net metering policy, as do most U.S. states. Net metering stipulates that when the amount of electricity a customer is generating exceeds that customer's use, that electricity will be sold back to the grid, offsetting electricity used at different times during that billing cycle. In some states, at the end of a one-year billing cycle, a customer can choose to receive compensation for any net electricity generation for the year. In California, the price is set as the 12-month average spot market price for the hours of 7AM to 5PM. Net metering is normally limited to systems that produce renewable energy, with specific energy source limitations and system capacity limits varying from state to state. In California, the system capacity limit is 1 MW normally, and up to 5 MW for systems owned by local governments or universities.

California is also home to a specific feed-in tariff policy for distributed renewable energy generation systems up to 3 MW. The system owner is allowed to enter into a 10-, 15-, or 20-year contract with its local investor-owned utility (IOU) and be paid based on the time-differentiated market price referent table, set by the California Public Utilities Commission. This is in contrast to feed-in tariffs in Germany or Spain, whereby there is an additional premium tariff on top of the market price with a "sunset" feature such that the premium will decline over time as the cost of clean energy equipment falls. Feed-in tariffs are very commonly used in many EU member states, and Japan's new feed-in tariff policy (to be funded by a public interest surcharge) was passed in August 2011 and will be implemented beginning in July 2012.

Lastly, California has a decoupling policy which is helpful in protecting the utility's interests in the face of declining sales due to energy efficiency or potentially expanded generation by microgrids. Decoupling allows a utility's profits to be disassociated from its sales of electricity, by adjusting the electricity price such that predetermined rates of return or revenue targets are met over time. The decoupling policy effectively makes the utility indifferent to its electricity sales, since its cost recovery and return on investment are guaranteed. Such schemes improve the policy environment for customer energy efficiency or distributed generation by homeowners, businesses, or microgrids.

As for the technical procedures for connecting distributed energy resources to the grid, special codes are need to ensure safety and reliability of the grid. The Institute of Electrical and Electronics Engineers (IEEE) has developed a specific standard, IEEE1547: Interconnecting Distributed Resources with Electric Power Systems, which has very important implications for distributed energy resources and microgrids. While IEEE 1547 for distributed resources at large was first established as a standard in 2003, a specific standard for microgrids was not set until June 2011. It is called IEEE 1547.4: Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems. Now, there are standards for systems operating in both grid parallel and islanding modes.

The EU has also developed extensive codes on interconnection of distributed energy resources, although some minor revisions and adjustments are still needed to accommodate the full deployment of microgrids, such as with codes for intentional islanding. Japan revised its interconnection standards

under 1995's Electric Utility Industry Law amendment, which permitted owners with distributed energy resources to sell excess power to the utilities and required the utilities to provide standby electricity for them. Japan also established technical standards for proper interconnection equipment to ensure safety and PQR in the local distribution feeder, such as relays, switches for protection, and communication systems. But, it is unclear in these rules what the cost share for this equipment should be between the customer microgrid and the utility responsible for the local distribution feeder.

In the U.S., while interconnection standards outline the technical procedure for distributed energy resources operating in parallel with the grid (usually referencing IEEE 1547), these standards do not establish the level or quality of power that the grid can expect from that resource. These power quality requirements are usually found in tariff documents of the area IOU or regulatory agency. The fundamental requirement is that when a distributed energy resource is operating in grid parallel mode, the power quality of that grid's local operating area should not be diminished.

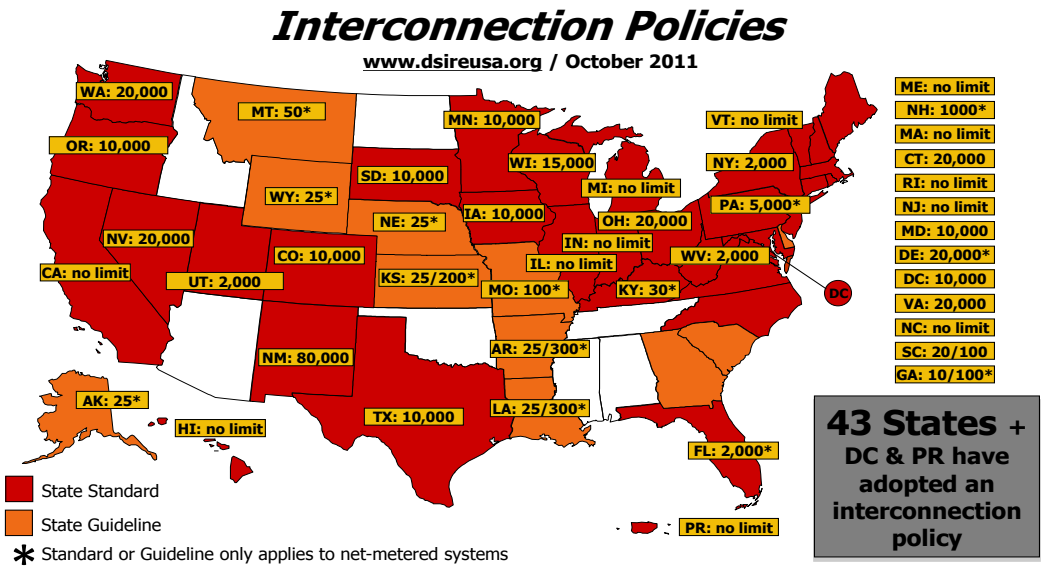

Figure 5: U.S. interconnection policies by state; Note: Numbers indicate system capacity limit in kW. Some state limits vary by customer type (e.g., residential/non-residential). "No limit" means that there is no stated maximum size for individual systems. Generally, state interconnection standards apply only to investor-owned utilities.

Interconnection standards describe the process by which a customer can connect an electricity generation unit (or distributed energy resource) to the grid, including the technical and contractual terms that system owners and utilities must abide by. Since most generation units are small in size, they are usually connecting to the distribution network, in which case it is the region's public utilities commission which establishes the standard and procedure.

In the U.S., 43 states (plus DC and Puerto Rico) have adopted interconnection policies as shown in Figure 5. Some states have set an upper limit of 10-80 MW for electricity generation units connecting to the grid, while other states have no upper limit. Some states have much more modest limits of 10-100 kW, which often only apply to net-metered systems.

Still, many of these interconnection policies only apply to systems that operate in grid-parallel or net-metering cases. Microgrids have the added functionality that they can run in an islanded mode. Since microgrids are still relatively uncommon, states do not yet have specific policies or standards for the interconnection of microgrids.

Recommendations for China

China is now well into a decade of critical growth for its renewable energy and microgrid sectors, with headline targets of 15% non-fossil energy by 2020, 100 *New Energy City* pilots, and 30 microgrid pilots. As China develops demonstration microgrid projects as well as new regulations to promote widespread microgrid development, policymakers should bear in mind the seven recommendations laid forth in this document and apply them to China's situation.

First and foremost, each demonstration project should have a proven economic viability. Additionally, a diversity of project sites can be chosen initially, to provide for different test beds for microgrid technology and policy. For instance, university campuses, groups of municipal buildings, or military bases are ideal locations downstream of one meter that will each have a diverse set of energy demands in terms of heating, cooling, electricity, PQR, and storage. China may also wish to consider larger district or city projects with multiple meters (such as the Xinjiang Turpan microgrid project), remaining aware of the regulatory difficulties that may arise when siting projects within the distribution realm of the grid. The types of supply technologies used should match the end-user requirements, and CHP technologies should be well considered at sites where there is high cooling or heating demand.

An abundant RD&D fund should be set up for research on distributed generation (including renewables) and microgrids, and both universities and research institutes should be encouraged to research these fields and apply for funding. To encourage positive results from funded projects, cost-sharing between the RD&D fund and the funding applicant should be required. Additionally, performance requirements should be set for funded demonstration projects, such demonstration of interconnection and islanding abilities, reduction of peak demand of the local distribution feeder, or on-site storage capabilities.

Chinese policymakers will also want to consider the barriers presented in the previous section, namely 1) if independent power producers (like microgrids) are allowed, 2) if distributed energy resources are allowed to interconnect and island with the macrogrid, and 3) if there is an incentive for microgrids to sell power into the macrogrid. While China's laws do allow for independent power producers, their policy environments for interconnection and incentives will need to be adjusted for the needs of microgrid development.

China has a number of feed-in tariff policies that encourage the development of renewable energy resources, such as small hydro, wind, biomass, and solar PV. The feed-tariffs for application of these technologies, in comparison to the wholesale price for coal-fired power, are shown in Figure 6. There is usually a gap between the feed-in tariffs for renewable energy and the tariffs paid to coal-fired power generators, and this gap is in part subsidized by a public interest surcharge of CNY 0.008/kWh.

China's Ministry of Housing and Urban-Rural Development (MOHURD) and Ministry of Finance (MOF) have also implemented some policies for smaller scale solar PV projects, such as the building integrated PV (BIPV) program and Golden Sun program. The BIPV program is for projects ≥50 kW and provides a CNY 20/W subsidy. The Golden Sun program is for projects ≥300 kW and provides 50% of the total cost for on-grid systems. These new subsidies allow for renewable energy adoption in buildings and city centers, yet many have complained that their projects have not been allowed to connect to the grid. Interconnection standards, compatible with IEEE and IEC standards, should be researched and implemented as soon as possible. Programs like the Golden Sun should continue to be promoted but only after proper interconnection standards have been set for smaller, distributed installations. Additional considerations can be given for other types of on-site generation (including wind, biomass, CHP, fuel cell, etc.) and what mixture of tariff and net-metering should properly support those technologies and any power or ancillary services they might provide to the larger grid.

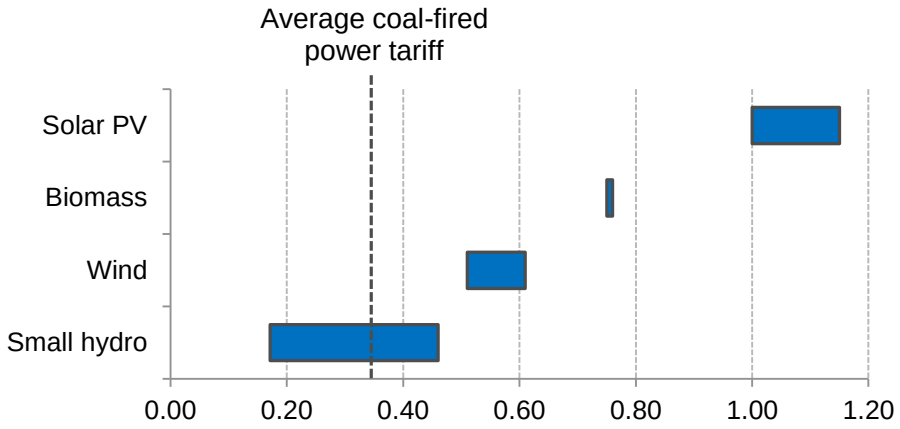

Figure 6: China's feed-in tariffs for renewable energy as compared with coal-fired power (CNY/kWh)

In summary, consideration of both the seven recommendations provided and the barriers outlined in this report will help China's policymakers develop a microgrid demonstration program with appropriate policy support. Indeed, taking stock of the international experiences to date will help China to build a very successful future for microgrids.

Acknowledgements

We would like to express our deep appreciation to the Energy Foundation's China Sustainable Energy Program for providing funding for this project. We would especially like to thank Lu Hong at the Energy Foundation for her support of this project. We also thank Wang Sicheng at the Energy Research Institute under the National Development and Reform Commission; Lv Fang, Yu Jinhui, Xu Honghua, Wang Yibo, and Zhang Jia from the Institute of Electrical Engineering within the Chinese Academy of Sciences; Wang Weisheng from the China Electric Power Research Institute under the State Grid Corporation; Professor Wang Chengshan from Tianjin University, and Lu Hong and Wang Man from the Energy Foundation for their comments and review.

This work was supported by the China Sustainable Energy Program of the Energy Foundation through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Appendix: Selected microgrid case studies

Hachinohe Project (an all-renewable microgrid)

The Hachinohe Project in Aomori Prefecture was part of the *Regional Power Grid with Renewable Energy Resource Project* funded by the New Energy and Industrial Technology Development Organization (NEDO). It operated from October 2005 to March 2008. The project was a collaboration between Hachinohe city, Mitsubishi Research Institute, and Mitsubishi Electric. NEDO's main goal for this project was to develop an optimum operation and control system, evaluate PQR, cost effectiveness, and GHG emission reductions. Meanwhile, the local governments wanted to construct a new industrial innovation zone centered on environmental and energy technologies.

The central feature of the system is that only renewable energy sources are used to supply electricity and heat. The supply sources include two 50 kW and three 10 kW solar PV systems, small wind turbines, a 100 kW lead-acid battery bank, and three 170 kW gas engines fed by sewage and waste gas by-product. At the sewage plant, a 1.0 t/h wood-waste steam boiler was installed to supply heat to protect the bacteria, and exhaust heat from the gas engines was reused in the gas fermentation process. The TOBU sewage plant treatment system was controlled by an information exchange network. The electricity produced was transmitted to schools, the local city hall, and an office building by a private distribution line 5.4-km, 6 kV feeder, and the whole system connected to grid at a point of common coupling. The energy management system was developed to meet demands for both electricity and heat, while minimizing operation costs and CO2 emissions. Islanding operation was performed for one week in 2007, the purpose of which was to evaluate the ability of the system to maintain and control power qualities. The project is no longer in operation due to funding shortage.

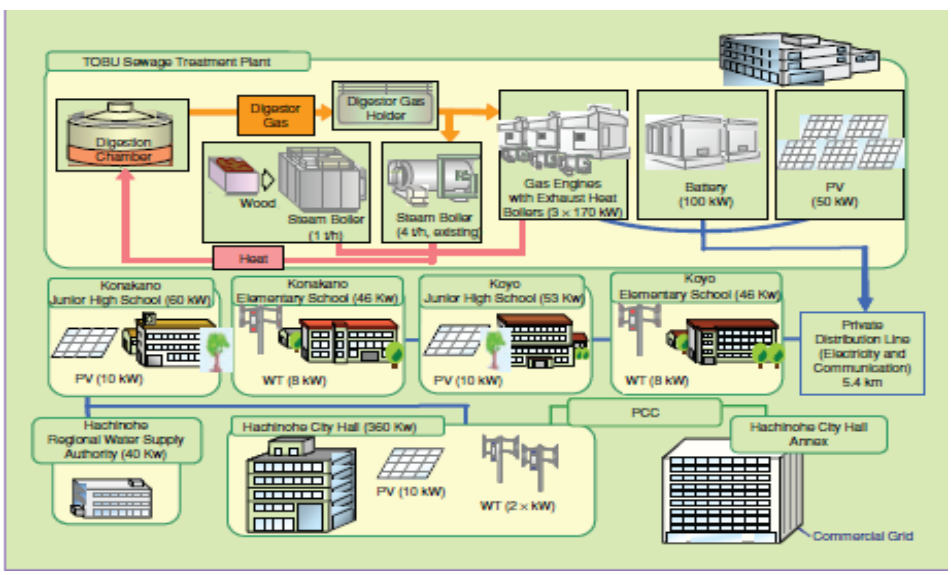

Figure 7: The System of Hachinohe Project (source: Y. Fujioka, et.al., 2006)

Sendai Project (multiple PQR service)

The Sendai Project was a multiple PQR supply network system sponsored by NEDO with collaboration from Nippon Telegraph and Telephone Corporation (NTT) from 2004 to 2008. It was completed in October 2006, and the project is still currently operating. The goals are to prove the feasibility that multiple POR levels reaching various microgrid loads, and to evaluate the economic viability of such a system.

This project includes its own solar PV array and gas-powered generators, providing reliable electricity within the microgrid's service areas and connected to the local distribution feeder at a single PCC. The system includes two 350 kW gas gensets, a 250 kW multi-chemical fast charger (MCFC) battery, 50 kW battery bank, two-way mode power module, and DC-AC inverter. The microgrid directly serves some DC loads and additionally supplies four different qualities of AC service to a university, a high school, and a sewage treatment plant.

This project's reliability was tested by the recent Japan earthquake and tsunami in March 2011. It functioned as an island for the two-day blackout that followed the disaster, and after reconnecting to the grid continued to function until natural gas supply was disrupted two weeks later.

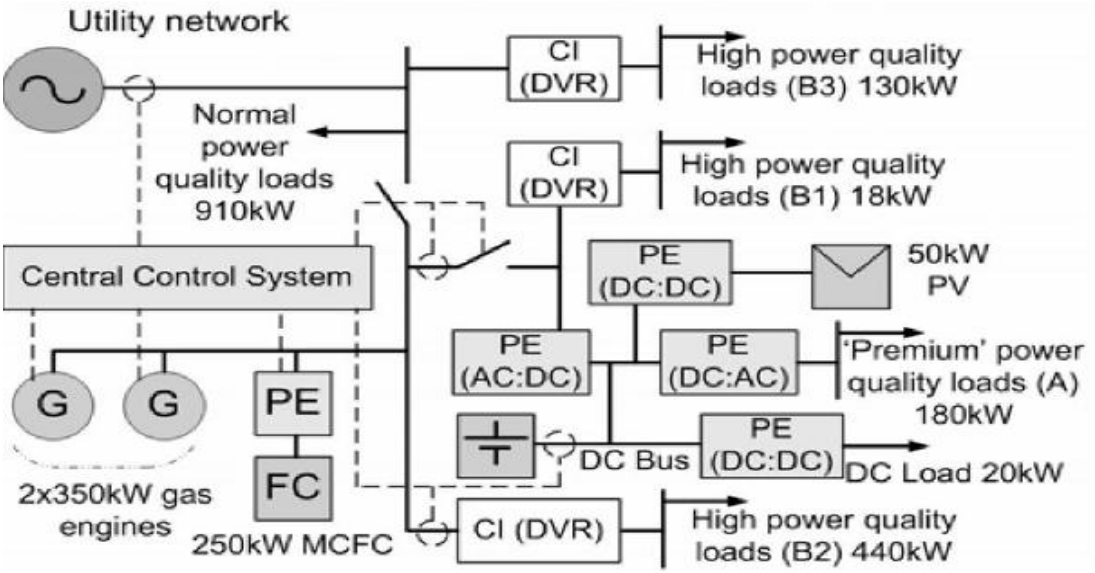

Figure 8: The System of Sendai Project (source: Mike Barnes, et.al., 2007)

Santa Rita Jail Project (a green prison)

The Santa Rita Jail houses 4,500 inmates and is located in Dublin, California, about 75 km east of San Francisco. Due to a series of installed distributed energy resources and efficiency measures at the jail, it is also called the "Green Jail". This project's objective is to demonstrate the first commercial implementation of the Consortium of Electric Reliability Technology Solutions (CERTS) microgrid technology combined with large-scale energy storage and renewable energy sources. This microgrid is sponsored by federal, state, and industrial funds together with four partners: Chevron Energy Solutions, Alameda County, Satcon Power Systems, and Pacific Gas & Electric Company.

This system consists of a 1.2 MW rated rooftop PV system installed in 2002, a 1 MW molten carbonate fuel cell with CHP, two 1.2 MW emergency diesel generators, 2 kW wind turbines, and retrofits to lighting and HVAC systems to reduce peak loads. With the upcoming installation of a 2 MW Li-ion battery for demand offset and time-of-use pricing, with CERTS microgrid control logic including fast static disconnect switch for islanding and plug and play control, the system will become a true microgrid. Thus, the system will be capable of islanding with seamless disconnection from the grid in the case of a power service disruption, and seamless reconnection.

Figure 9: Overhead view of the Santa Rita Jail project

Illinois Institute of Technology Project (a perfect power prototype)

There have been a number of drivers for the Illinois Institute of Technology (IIT) to construct the perfect power prototype. First, the occurrence at least three power outages per year resulted in a series of teaching and research disruptions with an estimated cost of $500,000 annually. The campus was also facing growing demand for energy and the need to add infrastructure to accommodate its growth, update costly old infrastructure, improve energy efficiency and reduce consumption. IIT, in collaboration with the Galvin Electricity Initiative (GEI) and other key partners, is leading an effort to develop and validate innovative smart grid technologies, and demonstrate smart grid applications, community outreach, and renewed policies for better serving the consumers. This microgrid is sponsored by $7 million of federal funds (DOE) and $5 million of industrial funds together for five years. Its main purpose and objectives are to create a self-healing, learning, and self-aware smart grid that identifies and isolates faults, reroutes power to accommodate load changes and generation, and dispatches generation and reduces demand based on price signals, weather forecasts, and grid disruptions. It plans to demonstrate a 20% permanent peak load reduction and with the potential to reduce peak load by up to 50% on demand, and achieve a 4,000 t/a reduction in carbon emissions.

The IIT prototype will be the first of a kind integrated microgrid system that provides for full islanding of the entire campus load based on PJM[1]/ComEd market signals. Specific innovative technology applications include: high reliability distribution system, intelligent perfect power system controller, advanced ZibBee wireless technology, advanced distribution recovery systems, buried cable fault detection and mitigation**.**

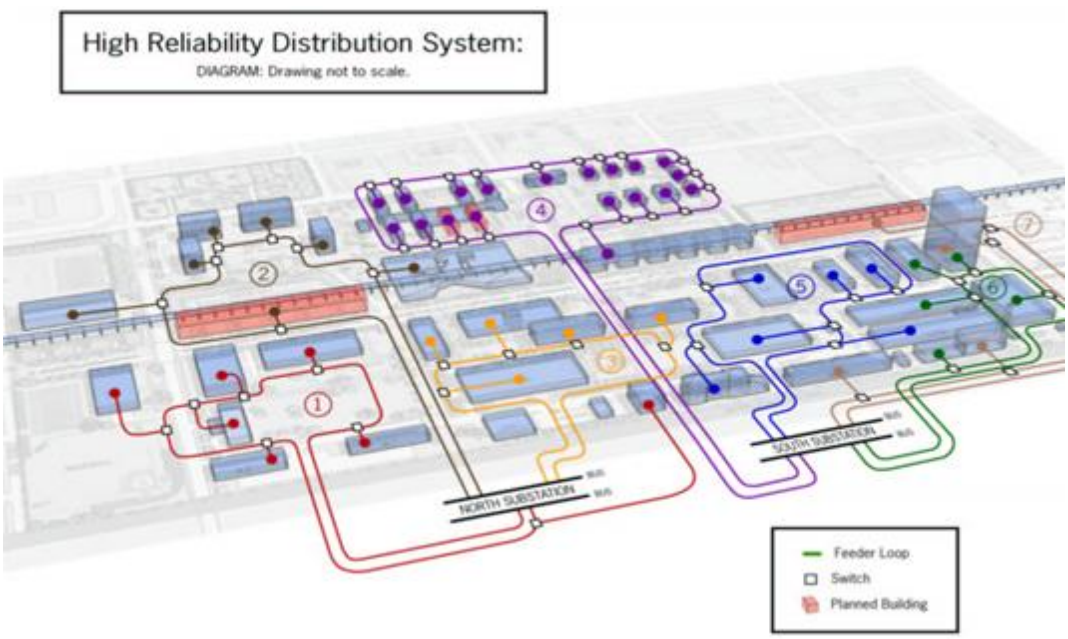

Figure 10: Diagram of IIT perfect power prototype

[1] PJM is the regional transmission organization (RTO) that Illinois is a part of.

Maxwell Air Force Base (a military microgrid)

The Maxwell AFB Microgrid is a research and development project to validate the basic functionality of autonomous engine controls based on the CERTS droop control concept. It does this by modifying the controls of existing diesel gensets and operating those with new generation that are located some distance away from the existing gensets but on the same distribution feeder. The goal is to determine if these generators can share the loads and maintain stability in an islanded mode.

The specifics of the project include two 600 kW diesel backup gensets that are located in one building and installing a new, CERTS-based 100 kW genset in a different building some distance from the first. The existing feeder connecting these two buildings will be sectionalized from the other loads by installing switchgear in the appropriate locations. This switchgear will isolate these two buildings from other loads on the feeder and create an experimental microgrid with two building loads and three generators.

Successfully demonstrating the stability of the controls will allow expansion of this microgrid to include more loads and additional generators, that will maintain a stable microgrid, even in the absence of a central command and control architecture common to most microgrids today.

The ability to modify existing generators while adding new gensets with the CERTS droop functionality is an important milestone in the future deployment of microgrids, because a vast majority of existing buildings with mission critical functions already have legacy backup gensets that still have ample operational left life in them. Also, integration of new gensets with CERTS controls and renewable generation sources with inverters that have similar functionality can be readily integrated into such microgrids.

UC San Diego Project (a large campus microgrid)

The UC San Diego (UCSD) microgrid project supplies electricity, heating, and cooling for 450 ha campus with a daily population of 45,000. The main two motivations for constructing the project are:

- Economic evaluation: After deregulation in California, the campus was able to purchase gas at an attractive rate to generate power by itself, for example, the built CHP plant had a five-year capital cost payback period based on avoided gas purchase costs.
- There is an existing campus steam distribution system for UCSD to have the ability to use steam to drive chilled water for cooling as well as hot water and heating.

The UCSD microgrid consists of two 13.5 MW gas turbines, one 3 MW steam turbine, and a 1.2 MW solar-cell installation that together supply 85% of campus electricity needs, 95% of its heating, and 95% of its cooling. The turbines produce 75% fewer emissions of criteria pollutants than a conventional gas power plant. For HVAC, it uses a 40,000 ton/hour, 3.8 million-gallon capacity thermal energy storage bank, plus three chillers driven by steam turbines and five chillers driven by electricity. A 2.8 MW molten carbonate fuel cell is running on waste methane, which is sponsored by California's self-generation incentive program funds and takes advantage of a 30% federal investment tax credit. The campus is connected to SDG&E by a single 69 kV substation. The UCSD uses a "straight SCADA system" for the building systems and energy supply to ensure their communication with each other. UCSD is installing a new, high-end master controller-Paladin, which will control all generation, storage, and loads with hourly computing to optimize operating conditions. It can receive as many as 260,000 data inputs/second. To support Paladin, UCSD will use VPower software to process market-price signals, weather forecasts, and the availability of resources. About 200 power meters on the main lines and at buildings' main circuit breakers, track use minute-by-minute. The UCSD campus has been installed with power meters throughout the main electrical lines and at the buildings' main circuit breakers. Lastly, DOE just gave USCD a grant to model the effects on the local distribution system from the ramping up and down of the solar PV system's output.

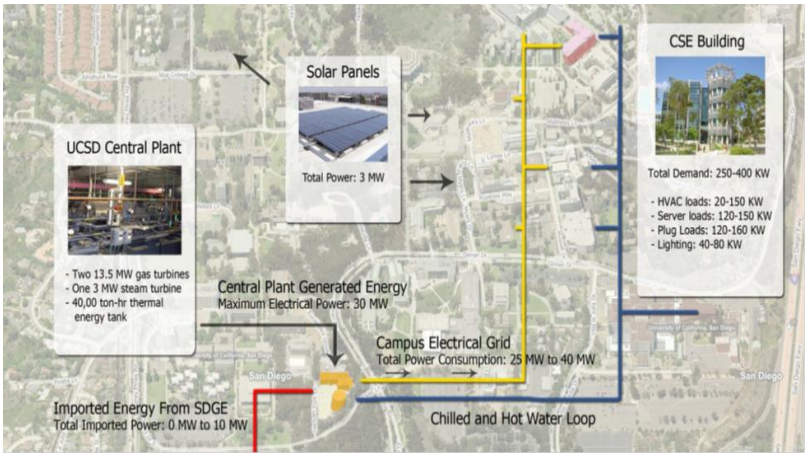

Figure 11: Energy Flow Through UCSD Microgrid (source: Yuvraj Agarwal, et. al., 2011)

Kythnos Island Project (a remote renewable microgrid)

Kythnos Island is located in the Aegean Sea, close to Athens. The Kythnos Island Project was funded by the European FP5 Microgrids program, the objective of which was to test centralized and decentralized control strategies for islanding.

It is a small village scale autonomous microgrid, composed of a 3-phase low-voltage network, solar PV generation, battery storage, and a backup generator. The grid is composed of overhead power lines and a communication cable running in parallel to serve monitoring and control requirements. There are 10 kW of PV at two locations, a nominal 53 kWh battery bank, and a 5 kW diesel genset. A second PV array of about 2 kW connected to an SMA inverter on the roof of the control system buildings provides power for monitoring and communication, backed up by a nearby 32 kWh battery bank. Three SMA inverters connected in a parallel master-slave configuration supply power to the 12 summer-only residences, whose minimal loads are primarily lighting and water pumping. When more power is demanded by customers than the PV systems can directly provide, one or more of the 3.6 kW battery inverters is activated. The battery inverters can operate in isochronous or droop mode. Operating in frequency droop mode permits passing of information to switching load controllers, which limit loads if the battery state of charge is low and also constrain the power output of the PV inverters if the battery bank is full.

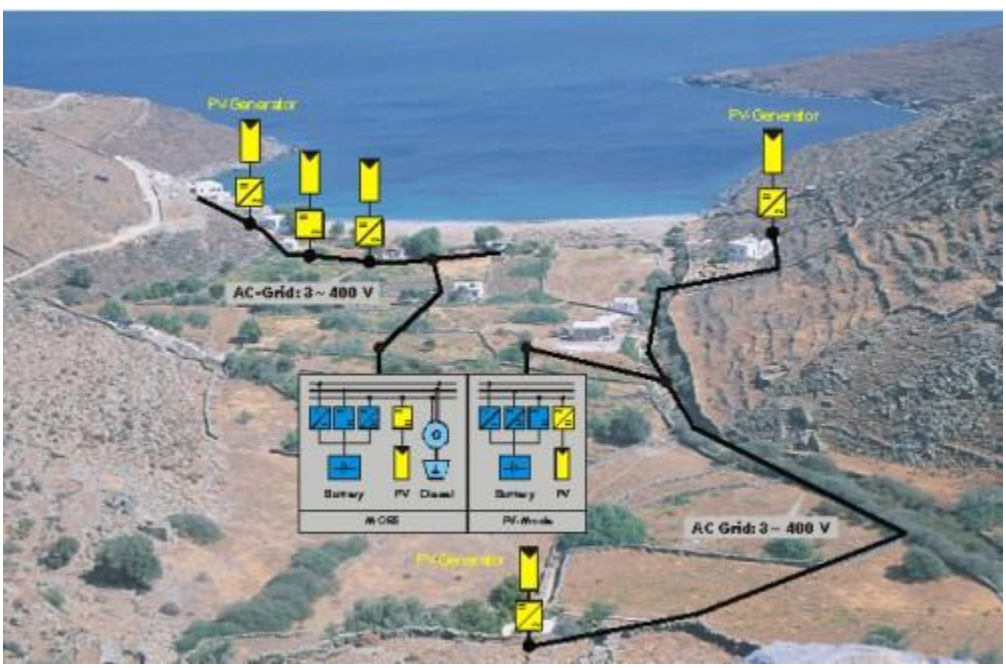

Figure 12: An Overview of Kythnos Island Project (source: http://www.microgrids.eu/index.php?page=kythnos)

MVV Project (a utility microgrid)

The MVV Project is located at Mannheim-Wallstadt in Germany, which is a 1,200 inhabitant ecological estate. It was funded by the "More Microgrids project" of the European FP6 and private investors.

The proposed system comprises residential and commercial units and load, a 4.7 kW fuel cell, 3.8 kW solar PV system, a 1.2 kW flywheel storage unit, and two CHP units rated at 9 kW and 5.5 kW (electrical). The total on-site load varies between 80 kW to 230 kW. The building's 60 kW ventilation and 48 kW boiler loads are controlled. At present, five PV systems, a total of 30 kW, and 1 CHP system have also been installed by private investors. The grid structure is suitable for further microgrid operations. The first goal of the experiment has been to involve customers in load management. Based on PV output availability information in their neighborhood, customers shifted their loads to times when they could use solar electricity directly.

Figure 13: Energy demand and supply display at MVV microgrid project

Aperture Center Project (a green field commercial building microgrid)

The Aperture Center in Mesa del Sol, Albuquerque, New Mexico will be the test site for a commercial microgrid. The project is a collaborative effort between U.S. and Japan. It is being carried out by NEDO, the New Energy and Industrial Technology Development Organization, a quasi-government agency from Japan, along with the State of New Mexico, Mesa del Sol, Public Service Company of New Mexico, Sandia and Los Alamos national labs, and Los Alamos County.

This demonstration is bringing Japanese technology to demonstrate how to integrate multiple generation sources including renewable energy resources along with multiple storage sources, and how they can be optimized to interact with the building load. A number of Japanese companies are participating in the project, including Toshiba, Sharp, Fuji Electric, Tokyo Gas, and Mitsubishi. Each of the Japanese companies has specific research they want to do in this project. The Japanese have funneled about $30 million statewide into many smart grid projects in New Mexico, including this project at the Aperture Center. The local utility company is only involved in order to ensure that it interconnects and operates safely within the distribution grid.

The system comprises a 50 kW solar PV system mounted on a shade structure over a parking lot and utility yard, currently under construction, that will contain an 80 kW fuel cell, a 240 kW natural gas-powered generator, a lead-acid storage battery power system, and hot and cold thermal storage. All parts will be interconnected through a control room and building management system in the Aperture Center. The project is on schedule to be up and running in mid to late spring of 2012.

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