Understanding Microgrids as the Essential Architecture of Smart Energy

Toby Considine
TC9 Incorporated
toby.considine@gmail.com

William Cox
Cox Software Architects
wtcox@coxsoftwarearchitects.com

Edward G. Cazalet, PhD
CEO, TeMix Inc.
ed@temix.com

Keywords: Microgrids, Micromarkets, Integration, Autonomous, Economic

Abstract

This paper describes microgrids in the smart grid architecture, autonomous systems interacting through the Energy Services Interface as defined by the OASIS Energy Interoperation [1] specification.

We define for the purposes of system architecture what a microgrid is. The several types of existing microgrids are defined, based on the motivations of those that operate them, the technologies they contain, and the operating characteristics they produce. This paper includes an analysis today's variety of microgrids and how they are leading us to future

We describe a model that represents component systems in a microgrid as systems able to negotiate optimal outcomes for energy allocation based only on the internal self-knowledge of each system, interacting through the means of software agents. These agents are each able to respond to changes of mission as conveyed by the timely application of abstract sets of priorities [policies].

We term the process whereby these outcomes are developed “micromarkets.” We further describe hoe how microgrids themselves can be organized into larger microgrids which are themselves operated by micromarkets.

We discuss the benefits of the micromarket model of integration. Micromarkets provide a simple model that can support each type of existing microgrids, both in technology, and in motivation. Autonomy in microgrids simplifies central control architectures.

We also discuss how the architecture of agents and micromarkets can be used to encapsulate the complexity of legacy systems, providing a path for existing systems into the future even as they reduce the effort required for the incorporation of new technologies.

1. INTRODUCTION

Our smart energy goals demand rapid innovation yet capital assets have long lives. This makes for growing diversity. Smart grid infrastructure must interact not only with technologies extant when that infrastructure is first deployed, but must continue to interoperate with new technologies over its long life. Interactions must specify a result, not a mechanism, an architecture style referred to as Service Orientation. Early deployments must not become a barrier to next generation deployments.

A microgrid is a small grid that can operate as a part of a larger grid or that can operate independently of the larger grid. A stand-alone microgrid never connects to a larger grid. In this paper, we consider autonomous microgrids, whether attached to a larger grid or not. Because autonomous microgrids operate themselves and hide their internal characteristics from external markets, microgrids are a natural fit with service orientation.

Microgrids can manage their own storage, conversion, and recycling of energy. They can choose to buy when energy is abundant and inexpensive. A microgrid able to do so is inherently adapted for DR events. So long as transactions clear in real time, virtual microgrids share almost all characteristics with actual microgrids.

The salient characteristic of distributed and renewable energy sources is volatility of supply. Current attention focuses on the supplier pain point, when excess supply is gone, when use is at its maximum, and to avoid calling expensive and often dirty sources into production. Long term interests urge us to focus at least as much attention on the surpluses, i.e., when the wind is blowing, the sun is shining, and there is more local power than can be consumed. Even the most successful wind farms do not reliably provide their product to end users. Site-based conventional generation is still subject to fuel availability and costs. Energy storage is only available until you use it.

Smart Grid Architecture addresses this diversity change by limiting direct interactions across each interface between domains. Management of generation, storage, and load is by service request; the resource providing the service may be a device, an aggregation of devices, or a virtual service. The energy services interface accepts requests for load response, for generation, for storage, and manages its internal operations.

2. BACKGROUND

The essential problems that smart grids are meant to solve are those of smaller operating margins accompanied by a more volatile supply. Operating margin is the excess electrical power over the amount used at any moment. Volatile supply is the result of using more sources such as wind and solar, whose output cannot be precisely predicted or controlled. Together, these changes lead to an over-supply or an undersupply at any given moment.

First generation efforts to compensate for low operating margins and intermittent supply were not satisfactory. Quick compensation for under-supply relied on fast-start technology that was inefficient, expensive, or both. Reserve near-line generation can cost as much, and require nearly as much fuel with its associated carbon costs as would putting the source on-line and re-introducing a higher operating margin. Many generation assets that only enter the market during shortage are not in the normal market because of greater expense or environmental costs.

Demand Response (DR) is the second generation effort to compensate for these issues. Although the term Demand Response technically includes increasing as well as reducing energy demand, in everyday use, it refers to direct curtailment of load through signals sent by the supplier or grid operator.

These signals were often less effective than hoped for. Many residential customers accepted the incentives but opted not to respond to the signals, either through disabling the controller or through ceasing participation during the critical high demand[1] months. Commercial and industrial sites have been known to comply with the control signal while ameliorating the effects on their business with other actions that increased overall electrical use.

Newer specifications based on the OASIS Energy Interoperation standard, including OpenADR 2.0, are defining service interactions. The intent is to pay for actual reduction in power consumption, or to meet a particular load curve, rather than for promises to turn a particular device on or off.

This change centers the focus of smart energy firmly on the end node. The end node becomes an entity that negotiates with suppliers, and controls its energy use to make those contracts.

2.1. What Motivates the End Node

The End Node[2] balances two factors, energy surety and economics. It wants to have the power and power quality it needs or wants available when it needs or wants it. The end node wants to acquire access to this power in a cost effective or economic manner. As the end node has little control over the total supply and the demand made by others, it must look inward to what it can manage itself.

To effect its market operations, the end node has a few broad approaches. (1) It can temporally shift its energy use, to use energy at a more economic time. (2) It can temporally shift its purchase of energy, finding a way to acquire energy now while using it later. (3) It can reduce its price risk by making committed purchases of load over time. This buys reduced price risk at the cost of possibly sub-optimal purchases. (4) It can generate its own power internally. Internal power generation is made more valuable by applying the use shifting and buffering as described above.

Energy efficiency is one tool an end node can use to improve energy surety, but it does not address directly the problems of smart energy. A maximally efficient end node may not be able to shift use. Buffering power, either in batteries or by pre-consumption always has some cost in consumption. On the other hand, a 30% reduction in process power requirement may be as effective as a 50% increase in buffering capacity. With enough efficiency, an end node may be able to achieve surety within the supply it generates internally.

Each End Node has a different definition of energy surety, and a different value that it achieves through surety. Each End Node may have a different competence in managing its processes and assets. As these cannot be known centrally, this creates what is known in economics as a knowledge problem [2] [3] as to the optimum allocation of power. As a market is the solution to a knowledge problem, market interactions are necessary and sufficient for interactions between a microgrid and its suppliers [4].

---

[1] Typically summer time cooling, but also the “cold winter mornings” in the Pacific Northwest United States

[2] In Energy Interoperation [1], Virtual End Node (VEN) as the relationship is recursive in navigating the composition or decomposition of microgrids we describe later in this paper.

2.2. What demotivates the End Node

The owners / operators /participants of the End Node(s) are concerned with the losses that participation in smart grids poses: loss of control, loss of privacy, and loss of autonomy.

The ***loss of control*** is straightforward. Before smart grids, you turn on what you want, when you want. Under a model based on central control, you can turn things on only if you are permitted to. How costly this is depends upon what are the effects of loss of control. It may be unnoticed. It may cause minor discomfort. It may reduce sales. It may destroy delicate manufacturing processes.

Microgrids limit external visibility and control to only those aspects that the microgrid chooses to expose. Typically, these are at the level of aggregate power use, and not at the level of individual systems. If those individual systems are themselves microgrids, then the containing microgrid itself gets the benefits of simpler operation, and the contained system the benefit of heightened security (see below).

Microgrids lessen the loss of control by localizing decision making.

The ***loss of privacy*** arises because smart meters are able to become surveillance devices that monitor the behavior of the customers [5]. Government commissions have expressed strong concern about this issue [6]. Published papers have demonstrated the use of simple power observations to infer detailed information about even the most intimate non-powered activities within a home. The traditional counter argument by suppliers is that they don’t care, and it would be too expensive to do anything with the data they collect. New techniques, such as those used for clickstream analysis, have reduced the cost and increased the accuracy.

The ***loss of autonomy*** is more subtle, and includes some aspects of the loss of control and of loss of privacy. Loss of autonomy includes not only the short term detriments, as above, but the longer term ability to change ones behavior to anticipate these demands, and the freedom to obviate them as one may determine best.

Microgrids are responsible for their own consumption, storage, conversion, and use of energy. Microgrids create autonomy while increasing control and potentially preserving and enhancing privacy. Microgrids are the means to eliminate the de-motivators for smart energy.

2.3. Increasing Concerns with Privacy

Privacy Concerns are a growing barrier to smart grid deployments... The techniques now known as Big Data are used to glean significant information through aggregating trivial observations. Published papers have demonstrated the use of simple power observations to infer detailed information about even the most intimate non-powered activities within a home. Similar techniques applied to commercial and industrial facilities can degrade physical security and safety, or reveal trade secrets. Secondary application of Big Data across information reveals personal information that is profitable to the party able to sell the information, advantaging to the party able to buy the information, and disquieting to the party observed. These techniques are becoming trivially cheap to apply broadly. Cheap data storage means that information once revealed is never lost, and its use cannot be controlled.

Microgrids, though, can manage their power use, storage, and generation to blur this information so it is never revealed. Microgrids provide a simple boundary at which to manage security and privacy.

2.4. On the Language of putting things together

Many of the concerns and contrasts drawn in this article involve the real costs of assembling things and making sure they work together. We have tried to draw consistent distinctions between similar notions by using the following language:

Integration is the cost of making things work together. When several systems are put together into one, the systems need to interact. Traditionally this is done by an engineer defining deterministic interactions between systems. It may also include some sort of system registration with a controller, etc.

Configuration is the periodic re-setting of parameters to as a system changes over time, or as the needs of those using the system change. There is some overlap with integration. Configuration may be a final step of integration. Minor changes, such as adding another instance, another air handler to an integrated facility, may be treated as configuration.

Operation is the ongoing regular changes in priorities or settings on a system. It may be as simple as changing the time of operation or the thermostat setting. Again, acts performed during operation may also occur during configuration.

2.5. Clouds

There are many proprietary and semi-proprietary definitions of clouds. We use cloud here in its broadest sense, i.e., as a non-deterministic expression that does specify particular technology or location.

We use the term **cloud** to represent a multimodal, multi-participant system wherein energy decisions are made, and energy transactions executed. The cloud may or may not be in the building, on the site, or located elsewhere. The cloud is not tied to a particular technology in use today. The cloud is not tied to a specific application contained in any of energy using or producing systems in the microgrid.

A particular microgrid or even a particular micromarket may be implemented through the use of one or more clouds. For brevity and clarity, in this paper, we write as if each microgrid makes decisions in its own single **cloud**.

3. CHARACTERISTICS OF MICROGRIDS.

Our vision of the smart grid architecture is recursive; each grid can be composed from a number of microgrids, and each smart microgrid replicates the architecture of the overall smart grid. A customer interface may front a home or commercial building, or an office park or military base. The office park and military base may contain their distribution network, their own generation, and their own customer nodes. There is no architectural limit on this recursion; recent commercial products provide room-level microgrids that support a single service, and manage generation, storage, and distribution internally.

In this section, we get more specific about the microgrids that are the end nodes we name above.

3.1. Defining Microgrids

A microgrid is more than islanded power grids and distributed generation.

A microgrid is a self-guided system with a specific mission that acts in such as to preserve its ability to perform that mission. To this end, it acquires and consumes electric power. A microgrid may store electrical power so that it will be able to perform its mission at a future time whether or not power is then available. It may acquire power in advance of need, so it has power to store. It may generate power, and acquire some knowledge of its ability to generate power to improve its planning.

During times of shortage, a microgrid may adjust its internal systems so as to get through the period of shortage. A microgrid may opt to perform some function sub-optimally during shortage so as to preserve energy for other functions more important to its purposes. For example, a microgrid may choose between availability and performance as dictated by its purposes.

Some microgrids may use less linear strategies. A microgrid may be able to recycle the effluent of its energy use to support other energy uses. A microgrid may be able to convert non-electrical power sources into electrical power. A microgrid may pre-consume electrical power into an intermediate form, even finished goods or activities, which may provide simpler storage.

3.2. The Fully Integrated Microgrid

Many of us make daily use of microgrids as defined above. The modern portable computer, tablet, or smart phone are each a microgrid. Each of these devices is sometimes connected to a power source, and sometime disconnected. These devices come with powerful algorithms to manage power use. Screens may dim when not in use. Disk drives may spin down if not accessed for more than a few minutes. These and many other strategies are used to preserve the ability of the system to provide service until it once again is attached to a power source.

These techniques are policy sensitive, that is, they can respond to high-level guidance. Often a simple slider bar will determine how aggressive a system is in managing its energy supply. Software is available to curtail specific functions that demand higher energy. For example, Wi-Fi uses electrical power at a high rate. Often, smart phones only run applications that require Wi-Fi in known locations. Some phones run software that will disable Wi-Fi except in locations where it has been used before. This is an example of policy-based management.

Fully integrated microgrids are available today because they are mass-produced. Because of economies of scale, their power use can be fully integrated into the software that operates them. This enables a competitive market for software that applies different type of policy (No Wi-Fi on the subway) to an existing system.

3.3. Self-Integrating Microgrids

The small fully integrated microgrids described above are useful for illustrating the effective use of microgrids today. They work because they do not have the challenges of larger microgrids: diversity of components, diversity of purpose and of technology, and few resources for integration.

With enough engineering time, and enough custom integration, we may be able to solve these issues for any single facility. There is neither enough engineering time, nor enough budget for custom integration for every facility. Ideally, systems within an end node would self-organize themselves into a microgrid, optimize the microgrids energy usage, and be able to respond to the market signals as a microgrid.

If my home is treated as a microgrid, it is a unique one. The mix of appliances and equipment in my house is different than in any other house in my neighborhood. One author (Considine) lives in a house that is nearly two centuries old; the structural shell that determines so much of energy use and storage is different than that of the 1970’s-era house across the street. The ways in which he uses energy, and the times, are different now, as an adult who travels frequently, than they were when he had children at home.

Even very similar equipment may have quite different energy use profiles. The motor in a top-loading clothes washer has an entirely different temporal pattern of use than that in a front loader. While these differences are trivial at the scale of the grid, within the scale of the microgrid, they may be significant.

Increasingly, these end nodes may have their own energy resources. They may have intermittent power generation from renewable sources. They may buffer energy in batteries, or as hydrogen, or by pre-consumption. A facility that stores energy as hydrogen may opt to use it as hydrogen, to fuel vehicles, or as a battery through a fuel cell, or even to increase effectiveness of generation though blending it with natural gas to use in a traditional generator [7].

The residential end-node has incredible diversity in purpose and in contained technology, even as it appears to be the simplest and most homogenous class of microgrid. There will never be enough time and resources to pay for custom integration of residential end nodes to support fully smart energy. We must look instead at ways for the components of residential end-nodes to assemble themselves into microgrids.

Each system in a home can leave the factory knowing fully only about itself, and how it uses energy. Within the confines of a home, the homeowner can assign, by policy, priorities to different systems in the home. The systems need to discover each other, and to negotiate with each other how to manage energy use within the over policy set at the microgrid [home] level.

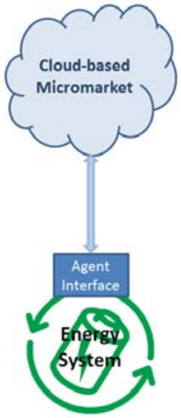
Similar challenges face commercial, whether small or large, institutional, industrial, and mixed sites.

3.4. Micromarkets and Microgrids

We use the term micromarket to name the inner decision-making process of a microgrid [8]. A market is any structure that allows buyers and sellers to exchange any type of goods, services, or information. Where the exchange is for money, it is termed a transaction. Previously, we have defined market segmentation based on market rules which include definition of the products traded and converging algorithms for clearing that market.

Hayek described markets as the way to solve the local knowledge problem, that while the data required for rational planning are distributed among individual actors, knowledge is unavoidably outside the knowledge of a central authority. Market-based systems for allocating control resources have repeatedly outperformed traditionally operated control systems in studies as early as 1994.[3]

As described above, the problem of integration and configuration is a knowledge problem. No system knows what the other systems in the microgrid will be. No system knows what the patterns of energy use the other systems exhibit. During operation, no system knows the priority placed, by policy, on each of the other systems in the microgrid.



1. A software agent hides a system's complexity while interacting with a market

Each system can, however, know itself. Software on each system can act as an agent able to express its needs and priorities within the micromarket of the end node.

It is easy to imagine a portable computer or a cell phone supporting an Energy Services (ESI) [1], and able to find and negotiate with the local micromarket. [4]

Integration is a problem of applying specific knowledge to a set of components as to their optimum interactions. Integration has typically been labor and knowledge intensive. In this model, the micromarket itself becomes the alternate solution to that knowledge problem, one that can adjust itself as new agents arrive or depart.

4. TODAY’S MICROGRIDS

Today, microgrids are springing up wherever the needs of the local site are not being met by centrally planned and operated electric power and distribution. Early leaders were those with special requirements for high power and availability. We refer to these as ***Industrial Microgrids***.

Others are forced to rely on a microgrid due to the expense of bringing power distribution to a remote location. We refer to these as ***Isolated Microgrids***.

Microgrids in undeveloped countries are unable to connect to larger grids, but their motives and operation are quite different than those of Isolated Microgrids. The scale is often smaller, even than home-based microgrids in the

---

[3] The seminal work is considered to be that of Huberman and Clearwater [29] [30].

[4] We showed in *“Energy, Micromarkets, and Microgrids”* [7] that there is advantage from having a logical micromarket attached to each microgrid.

developed world. We refer to these as ***Development Microgrids***.

Military Microgrids are an area of current attention and rapid development [9]. Driven in part by the recent doctrine of energy surety, these microgrids are characterized by diversity of mission, by changing technologies, by the need for Just-In-Tine (JIT) integration, and the need to re-allocate resources rapidly as mission and assets change.

There is a growing adoption of microgrids out of choice. These choices occur in areas well served by existing distribution grids. In many cases, they are in urban re-developments. The power requirements of these sites are often small; in part this because these sites have already made unusual commitments to site-based energy initiatives. We refer to these as ***Motivational Microgrids***.

4.1. Industrial Microgrids

Industrial microgrids harken back to the early days of electrical power, when industrial sites would produce their own power because no other power is available.[5]

Industrial sites with high power requirements have long relied on site-based generation. For some, such as Aluminum producers, electric power dwarfs all other supplies. If a site has power requirements similar to the capacity of commercial generating plants, in-sourcing this generation is a natural decision.

Some processes, notably in chemical processing and in regulated pharmaceutical environments, are subject to very large costs for power interruption. A small interruption in power may cause very large process costs, in lost product, in equipment degradation, in lost certification, and in high start-up costs afterward.

Other sites use large amount of energy, but in a form other than of electrical power. In particular, some plants rely on thermal energy. These may form wood-based products or be laundry facilities. Steam or hot water may drive a significant part of their activities. Once they have a boiler in place, using excess capacity to generate electrical power is a natural afterthought. This type of microgrid is usually referred to as cogeneration.

District Energy is cogeneration writ large. A District Energy may provide central distribution of steam or of chill water to a business district, hence the name. More often, District Energy is provided across a college campus or a multi-building industrial site. District energy is characterized by a multitude of choices and by substitution. For example, the same boiler can generate high pressure steam to spin a turbine or low pressure stream for district distribution. Chill water can be produced using electricity in compression chillers or using steam in adsorption chillers; many facilities switch day-to-day based upon weather and upon relative prices of electricity and steam. Hot waste-water from one facility may be the energy source for chilling the next. Modern Combined Heat and Power plants have similar capabilities.

Each of these types of Industrial Microgrids is driven by internal needs and economics. Industrial microgrids pre-date the concerns of Smart Grids. An Industrial Microgrid may learn to interact with smart grid concerns such as Demand Response (DR), but such concerns will never be the primary driver of their energy strategies.

The other side of the coin, the ability to sell surplus, is commonly limited or prohibited by regulatory action.

The service interfaces as specified by Energy Interoperation will enable Industrial Microgrids to interact with a smart distribution grid and with other microgrids. Industrial Microgrids will not allow any significant direct control of their internal systems by third parties.

As microgrids of all types gain renewable resources and site-based energy storage, the microgrid model will grows to resemble that of District Energy.

4.2. Isolated Microgrids

Isolated microgrids began as soon as wealthy early adopters put in the first light bulbs in the town. Today there are more often in isolated vacation homes, whether in the mountains or on islands, or even on yachts. Traditionally, these microgrids are fueled by fossil fuels transported by road or boat. A few relied on site-based sources, whether coal, or natural gas, or wood. Traditional local generators are the norm.

Many of these isolated sites are owned by economically well-off individuals. It is a rare site that can support sufficient density of power generation to support the level of amenity their owners expect. Today, intermittent generation sources from renewables are an amenity as well as a resource. This means that the normal requirements for economic justification can be reduced.

These owners often occupy these sites intermittently, that is, it is a vacation home or weekend retreat. Intermittent renewable sources sometimes are used solely for maintenance. Intermittent generation manages humidity in summer to prevent mold growth. In winter, intermittent generation can support keeping the pipes from freezing.

New approaches combine intermittent occupancy, intermittent generation, and storage to enable Isolation

---

[5] In the Industrial Revolution, water-driven manufacturing mills or plants were common.

Microgrids to operate with less and less combustion as an energy source.

Isolation Microgrids serve today as proving grounds for site-based storage and for temporal relocation of energy use.

4.3. Development Microgrids

Development Microgrids are small commercial operations in areas in which the existing infrastructure and economy are not based on long-standing assumptions of intermittent power. These microgrids actively compete with other energy sources on a day by day basis. These share many characteristics of Isolated Microgrids but are in areas with limited but competitive energy resources and infrastructure. [10] [11] [12] [13] [14] [15]

For example, a small solar generator may provide the primary electric power for a small village in sub-Saharan Africa. Cell phones provide not only the sole communications for commerce, but provide the essential banking services of the local economy as well. Villagers may vie to purchase the power to charge their phones from the limited power generated. If the price gets too high, a bicycle-based generator with a boy riding may provide a competing service.

In Bangladesh, Dean Kamen's slingshot micro-generation systems, a pocket generator the size of a washing machine is paired with a similar-sized water purification system to provide power and clean water in rural villages. [16] These pocket generators work on multiple fuels including cow dung. Because this LED lighting based on a DC infrastructure replaces burning wood for light, these pocket generators reduce deforestation. Cell phone charging is once again a critical service provided by these systems. Slingshots provide "civilization in a box" (light, water, telecommunications), and are the basis of ongoing micro-industrial transactions at the personal level within the village.

Development Microgrids work without the assumptions built into power markets in the industrial world a century ago, before the computing and telecommunications revolutions. As such, they are a proving ground for the new economics of distributed energy.

4.4. Military Microgrids

Military Microgrids are driven by the developing doctrine of energy surety and its little brother, power surety. Energy is a means to project force, whether through weapons, through intelligence, through command & control. In other words, protecting the energy position of a base is protecting the mission capability of a base.

Military Microgrids have some desiderata that push through the boundaries of traditional integration approaches:

- There should be no central network operating center (NOC) on a base that can be destroyed in order to destroy base-wide energy surety.
- Energy sources, each with unique characteristics arrive on and depart from bases. The base should be able to accept these sources with little or no reconfiguration. (Think everything from idling engines to PV on pup-tents)
- Energy uses change in priority with each change in mission. Advance? Hold? Defend? Withdraw? Redeploy?
- Even fixed base energy assets may be removed w/o planning (mortar shell hits the sub-station)
- Base energy uses include some exotics such as hydrogen cars, PEVs.

In pure Hayekian terms, there is a knowledge problem about energy sources, energy uses, and the best application of same. Each energy source on base has some capabilities that should be used to the fullest. Each energy use on base has a mission, whose import changes over time. Sometimes the import is situational, as the import of food protection grows to the refrigerator that "skipped" its last few cooling cycles.

The priority of each activity is set somewhere between a knowable baseline, situation awareness, and changing orders or "mission". Without too much stretch, claim that each system can know its priority by Policy, that is, through the techniques of policy-based management.

As the activities know their priorities, and the sources know their capabilities, bases need a clearing house that manages the optimum application of energy from minute to minute. If each source and use of energy is represented by an agent, then these agents can negotiate in a market. Systems that have more policy priority operate with larger budgets at certain times. But even the highest priority activity does not want to pay for energy it cannot use, at a time it does not want to use it. This provides the opportunity for the lower priority activities to make winning bids.

Such Microgrids in effect can be operated by micromarkets. Energy surety is an emergent behavior of the participants in the micromarket. Wherever two or more agents can establish communications, a market can exist. New agents are integrated by entering the market. Agents can build reputations through their participation in the market.

Just as in District Energy, there is the issue of optimizing between different results to get the same effects. Bases may store energy as hydrogen as well as in batteries. A given base may have both hydrogen-fueled and PEV vehicles, each requesting charges. These vehicles may get high priority, sometimes, depending on mission and occupant.

Hydrogen can be used to fill a Vehicle, or to generate electricity in a Hydrogen Fuel Cell, or to supercharge natural gas in a conventional generator.

Military microgrids create a premium for energy systems that can reconfigure themselves. Energy assets come and go. Energy using systems are in regular flux. Priorities for each system can change in a moment. Military needs are best met through solutions that do not require constant re-configuration at a single base and that can be re-used at all bases.

Military Microgrids will pioneer the ability to compose a microgrid from changing elements without continuous intervention. Military Microgrids will be proving grounds for autonomous self-organization and policy-based management.

4.5. Motivational Microgrids

Motivational Microgrids are sites that choose to operate as microgrids in the absence of the compelling needs itemized for the microgrid types above. Motivational Microgrids may be in the middle of a city, with easy access to traditional distribution. Motivational Microgrids are islanded because they want to be. Motivational Microgrids are driven by valuing one of the aspects of Microgrids far more than does the general public.

For example (based on personal conversations), consider the movement to renovate inner city industrial sites based on a “Green” ethos. The redevelopment minimizes energy use by using LEED approaches. Its tenants are motivated by local use and small environmental footprints. It adds some site-based renewable generation.

The particular site becomes frustrated with the local utility. It does not get the easy deals that it anticipated for its renewables. The distribution entity properly must defend its capabilities and its other customers from the effects of this site. Because of its already low energy use, it sees an easier path to self-sustainment in electrical power than would a traditional commercial / light industrial site.

There are a growing number of efforts that meet this description in older post-industrial settings across the US.

Another example from personal experience is the larger home whose owner places a high premium on privacy. He starts from a high energy profile, and opts for a natural gas fuel cell to opt out of the local smart grid efforts. Because a cooling tower would anger his neighbors, he decided to shed his heat load to support his Jacuzzi and pool. Today he is considering switching to absorption chillers[6] [ref] to take additional heat. Slowly, he is replicating the district energy model within his home [8].

Motivational Microgrids show us the future of consumer attitudes toward microgrids and energy. The occupants of Motivational Microgrids are willing to work out the internal models for applying site-based power management in non-traditional situations.

4.6. Hidden Microgrids

Many sites manage their own power surety today. The have generators on-site that they use to provide emergency power. Data Centers, Banks, Hospitals, and Emergency Responders are typical examples. The systems on these sites usually include power storage, even if only to support uninterrupted power during switchover from the distribution grid to their internal resources. These sites are often subject to regulatory limits on their site-based generation, particularly in urban environments.

These sites can be considered as microgrids. By adding an Energy Services Interface (ESI) based on Energy Interoperation, they could increase their energy surety through gaining improved situation awareness of the grid.

There are far more extant microgrids than we normally consider.

4.7. Summary of Today’s Microgrids

Microgrids are much more widely deployed today than generally acknowledged. We must look to them to understand how microgrids will be used in the future. We can generalize the interaction of supplier and microgrid using existing standards.

OASIS Energy Interoperation provides a common means for interacting with each class of microgrid. It makes no assumptions about the technologies or processes within a microgrid. It does not try to directly manipulate processes inside the Industrial or Military Microgrid. It does not limit the technologies or the diversity that can be deployed within the Microgrid. It was in fact designed to work “to, from, inside, and outside microgrids” [1]

Microgrids today support the ability of their inhabitants to manage their own processes and priorities based on superior local knowledge. Microgrids today are proving grounds for site-based storage and for temporal shift of energy use. Microgrids today are proving grounds for the new economics of distributed energy without requiring transformation of the larger distribution or markets.

Military Microgrids require autonomous self-organization and policy-based management. These techniques can be

---

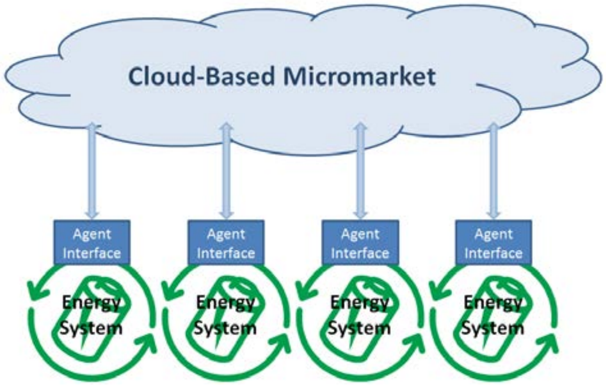
[6] Heat-operated refrigeration unit that uses an absorbent (lithium bromide) to absorb the primary fluid (water). The evaporative process absorbs heat, thereby cooling the refrigerant (water) which in turn cools the chilled water circulating through the heat exchanger.

applied within any microgrids where further segmentation is desired. Autonomous self-organization and policy-based management will scale up to aggregations of microgrids Aggregation of microgrids to provide resilience and reliability is already underway in Southeast Asian markets [17]. These techniques can apply to any microgrid.

Motivational Microgrids show us the future of consumer attitudes toward microgrids and energy, as early adopters pave the way. The occupants of Motivational Microgrids are willing to work out the internal models for applying site-based power management in non-traditional situations. Hidden microgrids, as described above, show that this approach is already taking off.

5. BUILDING OUT THE MICROGRID

What we have described above is a microgrid created when multiple devices are able to discover a micromarket and interact through an ESI using the Energy Interoperation specification to communicate. The owner / operator of the microgrid can assign different policies to each of the systems controlling how each interacts with the market.



2. Each agent competes in market to optimize its own system performance and mission.

Using Energy Interoperation, each agent can buy or sell power at specific times of delivery. Each agent can establish forward positions based on its own need to fulfill currently applied policy, able to make commitments to deliver or take delivery of power at future points in time. If the policy controlling one of the agents changes, then that agent informs the others by taking different positions within the market.

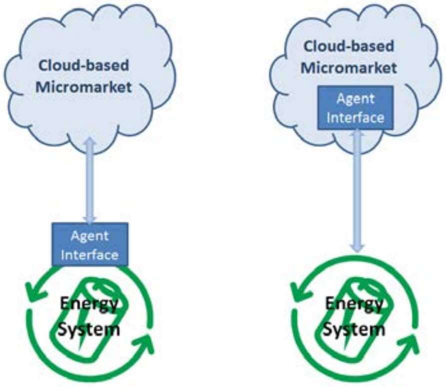
We do not however, define the form of this market here [8]. There could be a market maker, a single entity responsible for overall market performance. In such a model, all interactions would be transactions with a single market-making entity. Alternately, the agents could make a series of bilateral deals with each other. Successful micromarkets could work under either model.

5.1. Legacy, or you can’t get there from here

One of the challenges to any model of smart energy is the existing stock of energy using systems. On whatever day we start, those systems installed yesterday will not participate properly.

Many systems can be cost-effectively upgraded to support these agent behaviors. Smart phones and computers are routinely upgraded with new agents. Home networking gear is less routinely upgraded, but still can accept new software with little trouble. Home HVAC systems could be upgraded by adding an agent-capable networked replacement smart thermostat. Even home entertainment systems are now routinely networked. Video players, televisions, and DVRs each routinely receive updated software over the internet.

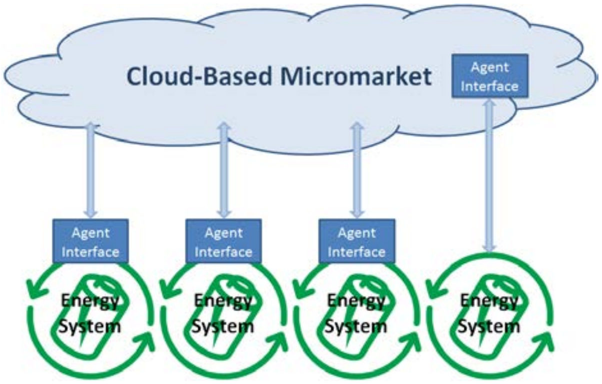
There are other devices that cannot so easily acquire an agent. These include most traditional appliances and lighting systems. They may be networked using more control-oriented protocols such as SEP (Smart Energy Profile). These systems can participate in markets using Mobile Agent [18] [19] re-location.



3. Agent functionality can be re-located to support legacy or low-capability systems

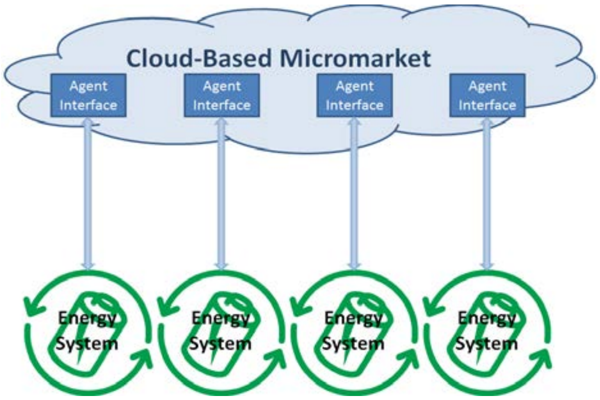
Service-Oriented Architecture has as a key principle the separation of how you do something from what service you request, and is an ideal technology to continue to use legacy systems with more scalable interoperation [20].

For control-oriented systems, the agent itself can be placed in the cloud that supports the micromarket. In this way, existing systems can be encapsulated within the micromarket, and the life of existing assets extended.



4. Essential operations of the cloud-based market do not change even if some systems are not agent-capable

In the illustration above, four agents are participating in the microgrid. One legacy system is unable to participate directly. Each is represented by an ESI. In this model, there may be advantages to a model based on a central market maker.



5 .A micromarket comprised entirely of low-capability systems can resemble legacy integration.

The model works as well if all existing systems are incapable of supporting agents. In this case, one role of each agent is to act as a traditional "driver", providing an abstract interface to the common operating platform of the end-node. The common operating platform may incorporate higher level models such as that in ASHRAE SPC 201 to understand the other effects on the platform. The platform is the micromarket.

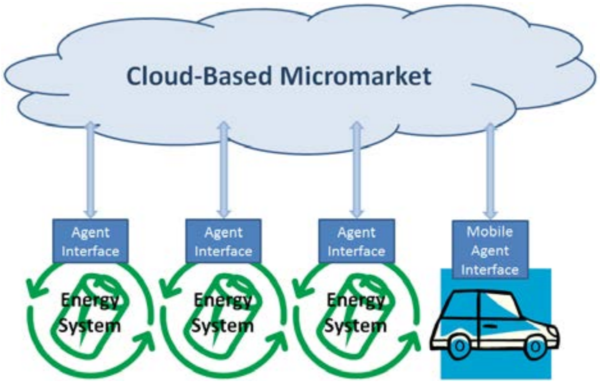
5.2. Incorporating Vehicles into the Microgrid

Traditional approaches to the smart grid treat vehicles as special cases, presenting challenges in billing and in integration. This is in part because vehicles are treated primarily as roaming batteries. Vehicles, however, present questions that are both simpler and more complex than these discussions.

Vehicles are run by demanding control systems that are ever-growing in complexity. The primary mission of a vehicle is quite different than that of most grid-attached systems. Within a single household, there may be large differences. A vehicle may be the sports car used on weekends, the delivery van used for short runs around town, the primary transportation for the household or even be driven solely by the teenager who is currently "grounded". In several states, self-driving vehicles have recently been authorized.

Vehicles also move, and must introduce themselves to a number of micromarkets. This puts a premium on security for vehicle interactions. My dishwasher may never see a new micromarket, and my vehicle may do so many times per week.

Under the microgrid model, these interactions are the same as any other in the microgrid. A vehicle must discover the local market, and negotiate its position. As any traveler, the vehicle may find that its currency is not accepted in the local market. A vehicle must assume that its market is untrustworthy, just as the local market may mistrust the vehicle.



6. While a mobile system such as a vehicle may require some additional services, it does not challenge the model.

Vehicle to microgrid interactions, though, are more complicated than mere power negotiations. Hydrogen vehicles may be negotiating for direct transfer of hydrogen stored in a fuel cell. Natural Gas vehicles may negotiate for a long slow charge.

These and other issues are discussed in the next section.

6. DIVERSITY OR ENERGY SOURCES AND TYPES

Up until this point, microgrids have been simplified to involve solely electric power. Any microgrid may have multiple ways to store and use energy, and multiple ways to acquire energy.

Traditional smart grid discussions assume that all power comes from the grid. On-site generation is valued for direct sale to the grid. Thermal storage is valued as a pre-purchase from the grid to replace purchases that would be made later in the day. This does not necessarily align with the perspectives of the end node. It also limits the ability of these microgrids to accept new technology in the future.

Assume a small commercial building with several energy collectors. It is normally connected to the grid, and buys its power from the grid. On-site PV cells generate a predictable flow of energy that is stored on-site in hydrogen cells. That energy in hydrogen may be used to improve the site's ability to respond to grid-based (DR) events or to grid failures for energy surety.

This commercial building also uses solar cooling to generate chill-water for a number of internal processes. Whenever the supply is greater than the internal use, that cooling is applied to thermal storage; this storage may be configured later use to support DR just as are systems that use the grid for pre-cooling. It provides exactly the same sort of asset for Demand Response as it would if purchased from the grid.

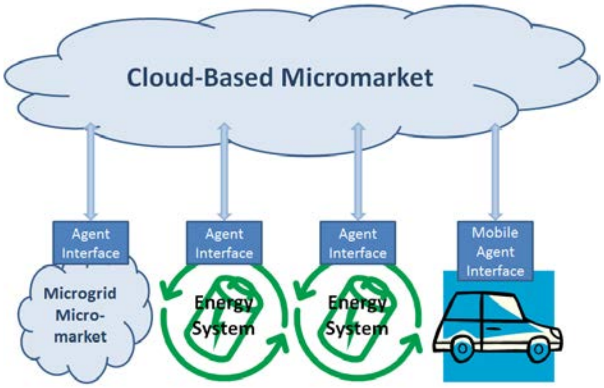
A commercial building may "host" a hydrogen vehicle that consumes the stored hydrogen. A visiting hydrogen vehicle may wish to fill up. In accord with building policy ("No outside sales unless half full"), and subject to a special market rule ("Sales to strangers are offered at a 25% premium to market") the visiting vehicle may request a purchase. The price offered, though, may be tied to the value of the hydrogen as a battery within the local power market.

The commercial building may have a fixed capacity for receiving natural gas. Some of that natural gas may be used on-site, to back-stop the power markets. It can also support slow filling of a natural gas vehicle. The availability of the natural gas to a vehicle may be limited by prior commitment deriving from the power market.

The micromarket model allows for the fungibility of energy sources. Diverse commodities can coexist in the same market. The complexity of this decisions making is hidden from the suppliers. The end node presents only an aggregate position to each of the markets it participates in.

7. BUILDING UPWARD FROM MICROGRIDS

Earlier in this paper, we suggested that a microgrid is the ideal participant in a micromarket. In that case, we used the example of a portable computer as a microgrid pre-adapted for participation in the home-based microgrid. A microgrid knows its energy needs and surpluses. A microgrid is aware of tis clearing positions in power. A microgrid is already operating under a policy basis, and is thereby ready to negotiate with other parties. All the microgrid needs is an external ESI that understands Energy Interoperation to be a full participant in the micromarket.



7. The type or complexity of the system represented by an agent does not change the micromarket interaction

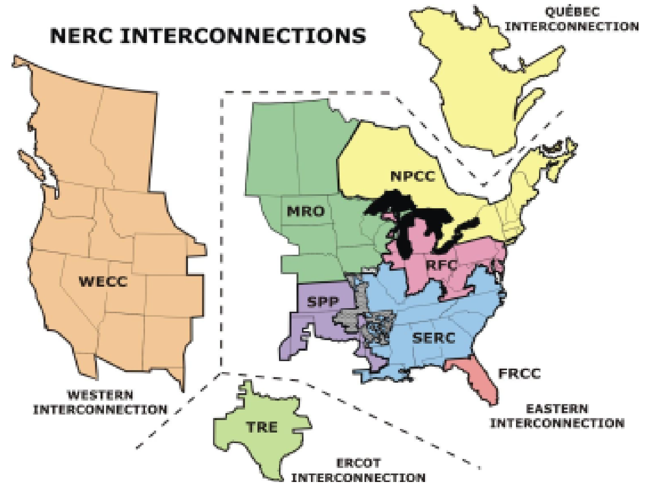
From there it is an easy step to building a microgrid entirely upon microgrids. The homes in a neighborhood could participate in the local microgrid. That microgrid's policy limits might include overall capacity of the neighborhood feeder. Microgrids that represent commercial buildings can participate in the office park microgrid. The office park may include local generation, say a wind farm above the common areas. The wind farm, then, is simply an independent participant in the office park micro market.

The composition and decomposition of microgrids is itself a microgrid. [21]

8. MULTIPLE MICROGRIDS AND MULTIPLE MARKETS

The model described above is consistent with that previously defined as Structured Energy [21]. We have not attempted to show all permutations and exceptions. The discussion above describes each system participating in a single market through an Energy Services Interface (ESI) as described in OASIS Energy Interoperation. That microgrid, in its turn, has a single ESI for communicating with the next level microgrid.

The US grid today has three connected grids, each with many markets and within an overall market that allows transactions among the micro grids with no single agent representing or operating each microgrid. Within those microgrids, functional markets for the same product may be distinct-; within ERCOT, the ISO only operates wholesale spot markets and not the retail and forward markets. Similar market rules can exist within the microgrids described herein.

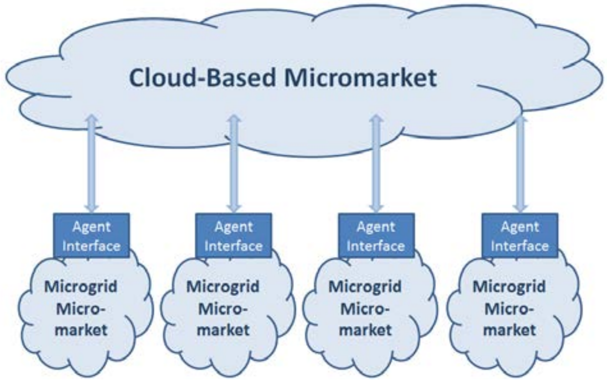


8. A high level look at the North American Grid of today shows many microgrids

Micromarkets for different types of products can coexist as well. Regulatory services markets can coexist with power markets. Microgrids that encompass district energy will have thermal markets as well.

There is an apparent one microgrid, one cloud architecture in the discussion above. Again, this was for brevity and for clarity. A microgrid can be supported by multiple clouds under this model. Multiple microgrids can have their markets in a single cloud.

We can compose up, decompose down. Microgrids simplify the smart energy conversation by defining a scope of concern. A home may contain several microgrids that cooperate in the homes master grid. That home may further participate in a community microgrid that is within a city microgrid. Each microgrid may always or sometimes be disconnected from other grids.



9. Each microgrid is itself an energy system that can interact in larger micro-grids (Recursion)

Each grid can be composed from a number of microgrids, and each smart microgrid replicates the architecture of the overall smart grid. An ESI fronts a node that may be a home or commercial building, or office park or military base. The node may contain its own distribution network, its own generation, and its own customer nodes. There is no architectural limit on this recursion; recent commercial products provide room-level microgrids that support a single service, and manage generation, storage, and distribution.

9. CONCLUSION

We have shown that microgrids are already much more prevalent today than is generally recognized. Agent based operation of microgrids simplifies the adoption of diverse technologies. Microgrids are locally responsive so they can more easily fulfill their own purposes than can integration based on far-off central offices. Microgrids inherently have more options for balancing intermittent energy generation and intermittent use than do larger grids, because the trade-offs are visible and local. Microgrids isolate and hide diversity to reduce barriers to innovations.

Microgrids are today the proving grounds for consumer acceptance and site-based management of smart energy. Microgrids today are pioneering consumer-based transactive energy.

We have described a model, of autonomous microgrids operated by agent interactions in a micromarket, that rationalizes the IT architecture of smart grids so that they can self-assemble, minimizing the integration costs that have limited acceptance of microgrids. By creating a common model across many types of microgrids, the model enables techniques and approaches developed in one class of microgrid to later be applied in another.

Smart energy will finally be an emergent behavior of diverse autonomous systems. The architecture described above provides a means for these systems to self-assemble themselves into aggregates [microgrids] that then can aggregate themselves into larger microgrids.

References

[1] OASIS, Energy Interoperation 1.0, 2012.

[2] F. A. Hayek, "The Use of Knowledge in Society," *The AMerican Economic Review,* vol. 35, no. 4, pp. 519-530, 1945.

[3] L. Kiesling, "The Knowledge Problem, Learning, and Regulation: How Regulation Affects Technological Change in the Electric Power Industry," *Studies in Emergent Order,* vol. 3, pp. 149-171, 2010.

[4] P. A. Centolella, "A Pricing Strategy for a Lean and Agile Electric Power Industry," October 2012. [Online]. Available: http://ElectricityPolicy.com.

[5] D. Carluccio, S. Brinkhaus, D. Löch and C. Wegener, "Smart Hacking for Privacy," in *Behind Enemy Lines*, Berlin, 2011.

[6] F. o. P. Forum, "SmartPrivacy for the Smart Grid: Embedding Privacy into the Design of Electricity Conservation," Information & Privacy Commissioner, Ontario, Canada, 2009.

[7] W. T. Cox, T. Considine and D. Holmberg, "Energy Ecologies—Models and Applications," in *Grid Interop*, Dallas, TX, 2012.

[8] W. Cox and T. Considine, "Energy, Micromarkets, and Microgrids," in *Grid-Interop 2011*, 2011.

[9] T. Podlesak, R. Lasseter, T. Glenwright, T. Abdallah, G. Wetzel and D. Houseman, "Military Microgrids," in *Great Lakes Symposium on Smart Grid and the New Energy Economy*, Chicago, IL, 2012.

[10] C. Kirubi, A. Jacobson, D. M. Kammen and A. Mills, "Community-Based Electric Micro-Grids Can Contribute to Rural Development: Evidence from Kenya," *World Development,* vol. 37, no. 7, pp. 1208-1221, July 2009.

[11] D.-R. Thiam, "Renewable decentralized in developing countries: Appraisal from microgrids project in Senegal," *Renewable Energy,* vol. 35, no. 8, p. 1615–1623, 2010.

[12] C. G. Kirubi, *Expanding access to off-grid rural electrification in Africa: An analysis of community-based micro-grids in Kenya,* Berkeley: ProQuest Dissertations And Theses, 2009.

[13] T. Bernard, "Impact Analysis of Rural Electrification Projects in Sub-Saharan Africa," *World Bank Research Observer,* vol. 27, no. 1, pp. 33-51, 2010.

[14] B. K. Blyden and W.-J. Lee, "Modified microgrid concept for rural electrification in Africa," in *Power Engineering Society General Meeting*, 2006.

[15] G. &. M. C. Venkataramanan, "A larger role for microgrids," *Power and Energy Magazine, IEEE,* vol. 3, no. 78-82, p. 6, 2008.

[16] E. Schonfeld, "Future Energy eNews," Integrity Research Institute, 8 March 2006. [Online]. Available: http://users.erols.com/iri/EnewsMar8,2006.htm. [Accessed September 2012].

[17] T. Mohn, "20/20 Visions for 2030: In the Wider World, Prosperity Requires Sustainable Energy for All," Electricity Policy, 27 February 2012. [Online]. Available: http://www.electricitypolicy.com/archives/4058-20-20-visions-for-2030-in-the-wider-world,-prosperity-requires-sustainable-energy-for-all-20-20-visions-for-2030-in-the-wider-world,-prosperity-requires-sustainable-energy-for-all. [Accessed September 2012].

[18] J. Cao and S. K. Das, Mobile Agents in Networking and Distributed Computing, Wiley, 2012.

[19] R. Gray, "Mobile agents: the next generation in distributed computing," in *Parallel Algorithms/Architecture Synthesis, Second Aizu International Symposium*, 1997.

[20] OASIS, *Reference Model for Service Oriented Architecture 1.0,* OASIS, 2006.

[21] W. Cox and T. Considine, "Structured Energy: A Topology of Microgrids (Presentation Only)," in *Grid-Interop*, 2010.

[22] B. Huberman and S. H. Clearwater, "Thermal markets for controlling building environments," *Energy Engineering,* vol. 91, no. 3, pp. 26-56, January 1994.

[23] B. Huberman and S. H. Clearwater, "A multi-agent system for controlling building environments," in *First International Conference on Multiagent Systems,* 1995.

Biography

Toby Considine

Toby Considine is a recognized thought leader in applying IT to energy, physical security, and emergency response. He is a frequent conference speaker and provides advice to companies and consortia on new business models and integration strategies.

Toby has been integrating building systems and business processes for longer than he cares to confess. He has supported and managed interfaces to and between buildings, cogeneration plants, substations, chilled water plants, and steam and electrical distribution. This work led to Toby’s focus on standards-based enterprise interaction with the engineered systems in buildings, and to his work in the Organization for the Advancement of Structured Information Standards (OASIS).

Toby is chair of the OASIS oBIX Technical Committee, a web services standard for interface between building systems and e-business, and of the OASIS WS-Calendar Technical Committee. He is editor of the OASIS Energy Interoperation and Energy Market Information Exchange (EMIX) Technical Committees and a former co-Chair of the OASIS Technical Advisory Board.

Toby has been leading national smart grid activities since delivering the plenary report on business and policy at the DOE GridWise Constitutional Convention in 2005. He is a member of the SGIP Smart Grid Architecture Committee, and is active in several of the NIST Smart Grid Domain Expert Workgroups.

William Cox

William Cox is a leader in commercial and open source software definition, specification, design, and development.

He is active in the NIST Smart Grid Interoperability Panel and related activities. He contributed to the NIST conceptual model, architectural guidelines, and the NIST Framework 1.0.

Bill is co-chair of the OASIS Energy Interoperation and Energy Market Information Exchange Technical Committees, past Chair of the OASIS Technical Advisory Board, a member of the Smart Grid Architecture Committee, and of the WS-Calendar Technical Committee.

Bill has developed enterprise product architectures for Bell Labs, Unix System Labs, Novell, and BEA, and has done related standards work in OASIS, ebXML, the Java Community Process, Object Management Group, and the IEEE, typically working the boundaries between technology and business requirements.

He earned a Ph.D. and M.S. in Computer Sciences from the University of Wisconsin-Madison.

Edward G. Cazalet

Dr. Cazalet is a leader in the design and implementation of markets for electricity, the development of smart grid standards, and the analysis of transmission, generation, storage and demand management investments. Dr. Cazalet has decades of electric power and related experience as an executive, board member, consultant, and entrepreneur.

He is a former Governor of the California Independent System Operator (http://www.caiso.com) and founder of TeMix Inc. (http://www.temix.com/), MegaWatt Storage Farms Inc. (http://www.megawattsf.com), The Cazalet Group (http://www.cazalet.com), Automated Power Exchange, Inc. (APX) (http://www.apx.com), and Decision Focus, Inc.

Dr. Cazalet has successfully promoted storage legislation and policy both in California and at the Federal level. He has advocated new electricity market designs to promote the integration of renewables and the use of price responsive demand as well as storage to support high penetration of variable renewables and efficient grid operation and investment by the grid participants including customers.

Dr. Cazalet is co-chair of the OASIS Energy Market Information Exchange (EMIX) Technical Committee and a member of the OASIS Technical Committees on Energy Interoperation and Scheduling.

Dr. Cazalet holds a PhD from Stanford University in economics, decision analysis and power system planning and engineering degrees from the University of Washington.