Introduction: A different “Smart Grid” perspective
This paper looks at the “Smart Grid” roadmap from a very different perspective. Like many complex systems, electrical power distribution within the context of the “Smart Grid” is being envisaged and implemented by many different groups operating with diverse tenets and goals. One does not need to look very deeply into the literature of each group before the disparities begin to emerge. For example, the federal government is concerned with reliability, security, and acceptance. Power producers are most concerned with standards, effective generator dispatching protocols, and a stable market for power. The T&D (Transmission and Delivery) operators are concerned with line conditions, and state by state regulation variations. Finally at the distribution end, the local utility is most concerned with integrating Smart Meters, end user satisfaction, rapid response to outages, and variations to load. There are of course many other stakeholders, but this short list is simply meant to illustrate the diversity of perspectives. Within each group, engineers work diligently to solve their own problems that are most evident—sometimes in a way that inadvertently might increase problems faced by adjacent interests. Such is often the case as complex systems become increasingly complex without a clear holistic oversight to ensure that all issues are addressed and solved in the most advantageous domain. The evolving smart grid is only one of many such complex systems that manifest this characteristic – others include the federal economy, military battle space awareness, public education, sustainable communities – and many, many more to a lesser or greater extent. The common feature of all of these is that they have expanded beyond the ability of a single cognizant oversight with many diverse groups working toward a goal that is not generally
understood without sufficient communication between groups. This is not meant to be thought of as a bad thing – it is just a new kind of complexity that needs to be managed – and it should be clear that we need new tools to manage problems of this complexity. Not just new tools of collaboration but a new perspective in looking at the problem.

Traditionally the discipline known as Systems Engineering has been the area of endeavor that deals with the design, implementation, and validation of systems of interacting components. Over the past 50 years since its inception, systems engineering has evolved into a discipline that focuses on methods and processes with well-defined standards such as IEEE-1220, CMMI, and MIL_STD-499C detailing the specific approaches that must be followed. Unfortunately, with the increase in complexity, these approaches break down – especially when applied by groups working toward a stated common goal but without sufficient tools for collaboration. Systems Engineering as it is currently defined (e.g. Honour and Valerdi, 2006) embrace 1) Definition of Purpose, 2) Architecting, 3) Implementation, 4) Technical Management, 5) Scope control, 6) and Verification and Validation. While all of these components are essential, with increasing complexity, they are not in and of themselves sufficient.

The tools to deal with these increasingly complex systems interestingly enough come from the field of Complexity Theory. An excellent description of this relationship is provided by Waldrop (1992). In contrast to the methodical tools that make up the discipline of Systems Engineering, Complexity Theory embraces the principles of 1) Agents, 2) Reflexivity, 3) Emergent Properties, 4) ) Local Information, and 5) Adaptation:

- “Agents” – holds that a complex system is broken up into an aggregation of collaborative components, each operating in their own interest, and to a somewhat less extent in the interests in the system as a whole.
- “Reflexivity” – is the idea that these agents operating quasi-independently change the environment experienced by adjacent agents resulting in a plexus of complex interactions of action and response. It is in this domain of interacting agents that “Emergent Behavior” evolves.
- “Emergent behavior” – is a system response that was not anticipated by the designing engineer, but isn’t this is precisely what is necessary if a complex system is to be capable of responding to unanticipated situations?
- “Local Information” – It should also be evident that these agents are acting locally without complete knowledge of the total system performance – the complete antithesis of centralization.
- “Adaption” – leading from emergent behavior is the capability of a complex system to adjust to changes as components are added, subtracted, or degraded in a manner that ensure stability and optimized performance. A tall order, what? To an engineer who has grown up with the idea that predictability is the touchstone of a well-engineered system these ideas might seem a bit scary – well – they are!

The challenge, as Werbos (2009) so succinctly put it is “…the challenge here is simply to build a better (distributed) controller for the electric power grid. Many people say that the electric power grid is the most complex single piece of machinery ever built by humans”. In this talk we
accept this challenge and will put forward an alternative. Specifically, what are the possibilities and consequences of disaggregating a complex, centralized system into a plexus of collaborative agents. We refer to these agents as “Autonomic Microgrids”. The premise is what we believe is an example of the process by which “Complexity” is made “Simple”.

**Smart Grid Centralization**

As it is currently described by most advocates, it is hard to see the “Smart Grid” outside of the notion of “Centralization”. In the natural evolution of the national electric distribution system, the aspect of centralization is evident in the aggregation of smaller utilities into larger ones, the consolidation of the means of production under a central control, and the national balancing line efficiency using new synchrophasor technologies. In this way of looking at things, a few central suppliers/controllers provide electric power to a vast number of end users referred to as the “consumers”. The government’s view (DOE 2006) of “Smart Grid” emphasizes its features and benefits to society as illustrated on the right and described as “…intelligent, efficient, accommodating, motivating, opportunistic, quality-focused, resilient, and environment friendly.”. Centralization is expressed by the icon labeled “Operations Center”. A slightly different perspective is provided from an industrial perspective in a publication of the National Electrical Manufacturers Association (NEMA, 2011). Here, as is shown on the sketch on the left, they describe the “Smart Grid” as “The basic concept of Smart Grid is to add monitoring, analysis, control and communication capabilities to the national electric grid in order to improve reliability, maximize throughput, increase energy efficiency, provide consumer participation and allow diverse generation and storage options”. Here again centralization is expressed, in this case as the “Dynamic Systems Control” in the lower left of the diagram. There are of course many more representation of what is generally referred to as “Smart Grid”, but generally without exception all embody this notion of centrality.

The benefits of the “Smart Grid” is frequently described in terms of benefits to consumers – increased reliability, decreased cost, ability to personalize usage profiles, and the availability of usage data on an hourly or even in some cases on a minute to minute basis. For the most part the consumer role is a passive one, at least to the extent that it is expressed in the vision of DSM (Demand Side Management). In this concept, certain appliances can be “programmed” to use power during off-peak hours. However, as long as the end user pricing is “flat”, the
marginal value of these actions from the customer’s perspective is negligible – a problem that has been well studied as the “Tragedy of the Commons”, for example as explained by Hardin(1968). As we will present later in this talk, a key element of consumer acceptance will occur when end user pricing directly reflects current production and distribution costs – a circumstance that will also fuel significant innovation in end user technologies enabling adaptive load shifting.

While the flow is generally seen as one way, it is equally valid to pose a kind of symmetry – the “consumer” consumes electricity and supplies money, the public utility consumes money and supplies power. The major task in acceptance, then, is seen as helping consumers to understand and appreciate this largesse of benefits. But is this really the primary motivation? Unfortunately, that subject is somewhat beyond the scope of this presentation.

### Distributed Autonomic Approach

An alternative to centralization and we submit a better alternative, could be achieved by introducing the basic tenets of Complexity Theory as described in the introduction. For this we will assign what we refer to as the “Autonomic Microgrid” the role of “Agent” as described above. But first let’s look at the meaning of the world “Autonomic”. First of all, it does not have much to do with the word “autonomous”, although to some extent an autonomic component is autonomous. Also, it does not have much to do with the word “automated”. The notion of an autonomic systems was first put forward by IBM’s Thomas J. Watson Research Center in 2001 in what the referred to as the “Autonomic Vision and Manifesto”. This vision was succinctly described 2 years later by Kephart and Chess (2003). The situation that they were addressing was that computer systems were becoming so complex as to be extremely difficult to manage and predict. In many respects, the situation was very similar to the increasing complexity of the national electric grid. It was realized that a much different paradigm was needed, and autonomic systems was the new paradigm that emerged. The vision was described as “Systems manage themselves according to an administrator’s goals. New components integrate as effortlessly as a new cell establishes itself in the human body. These ideas are not science fiction, but elements of the grand challenge to create self-managing computing systems”.

An autonomic system has four necessary and defining characteristics as follow:

- **Self-Configuring** - able to self-integrate into a system of systems and adapt to changes in topology or usage.
- **Self-Healing** - capable of analyzing, anticipating, and correcting faults. (Adaptive)
- **Self-Optimizing** – Self-aware and able to autonomously optimize performance. (Introspective)
- **Self-Protecting** – Anticipate failure, request pre-emptive maintenance and repel cyber attacks.

Truly, as the vision is described, this does seem a little like science fiction, but as stated – it is not. In the remainder of this section we will describe how these same principles can be used to
organize the national electric grid – not as a centralized control paradigm – but as an aggregation of collaborating agents. This is truly “Complexity Made Simple”.

So, let’s look at each of these in a context as to how it might affect a different way of approaching “Smart Grid” Systems Engineering. The first of these, “Self Configuring” is of particular interest. Note that the definition refers to changes in both topology and usage. Topology refers to the way the grid infrastructure is organized and would include such things as an alternative energy producer coming on line, a new substation, or the installation of new interconnects to name just a few. The other aspect of “Self Configuring” addresses the problems of usage. There is a random variable in the equation – the human. Increased use of electric vehicles would be one example of such a change. It is conceivable to deal with this with an army of field engineers constantly adjusting and readjusting things to balance out the change, but humans make mistakes, and with increased complexity comes an increased likelihood of catastrophic failures such as occurred in some of the recent regional blackouts. Currently utilities are very concerned about this human variable and a system that can self-configure for this variability is required.

The second aspect of an autonomic system is “Self-Healing”. This is actually a close relative of “Self Configuring” in that it is an autonomic approach to dealing with the loss of a system component either from degradation, intentional removal of a system element for maintenance, component failure, or in today’s world, unfortunately, terrorism and cyber-attack. One way to deal with such things, especially the later, is to have a set of rules at a central control facility – “If this then that”. However, as is well known in the industry, it is very difficult to go beyond single point failures, and with the number of interconnections growing almost exponentially, dealing with single point failures in this manner is not sufficient. Particularly with respect to terrorism, a single point failure would be evidence of poor planning on the part of the terrorist. It is difficult to prepare for all of these, but a system that is capable of “Self Configuration” can. Such a thing is possible, and there are well understood methodologies for designing and implementing such systems.

It also turns out that “Self-Optimizing” is closely akin to the first two. What does “Self Configuring” or “Self-Healing” mean if not putting the overall system into a state where it is performing optimally following a change in configuration or a fault induced outage. However, “Self-Optimizing” goes beyond this. As a system becomes more complex, the effect that any modernization event or the introduction of new technology becomes much harder to predict. So, “Self-Optimization” becomes very important during the design, development, and long term maintenance phases as well. In this case, as design changes are considered, we implement an integrated optimization capability using the same “computational intelligence” capabilities that are used in the actual system operation in a simulated environment. This allows the design engineer to “instantly” see the outcome of intended design changes. But “Self-Optimizing” still goes beyond this. An operational, autonomic system can constantly be examining its own performance introspectively, that is looking into itself. In so doing, it can recommend...
topological or other changes that can improve its own performance beyond what it can achieve by adjusting the effectors that control performance on a second to second basis. Of course, such topological changes require human intervention, or in any case, if we want to avoid a “Terminator Scenario” it is best if machines cannot improve themselves without a human check on the consequences.

Finally, in today's world, the aspect of “Self-Protecting” is of critical importance. Again this aspect follows the last in that self-optimizing includes the off-line analysis of responses to incipient failure mode. This includes, of course, the development of response scenarios to terror attacks. That facet of “Self-Protecting” is applied at the individual Microgrid level. However, the distributed, collaborative system itself is intrinsically less vulnerable because of the absence of a centralized control center that must be protected at all costs. Recent events have shown that even what were once considered the most secure systems on earth are not as secure as we had thought. “Self-Protecting” also includes anticipation of failure so that transformers can be swapped out before they fail catastrophically, line outages can be evaluated so that alternative routings are available within seconds without further topological analysis. These scenarios are constantly being evaluated off-line both to evaluate potential improvements in system performance as well as to mitigate the risk of system component failures. Preparedness trumps responsivity in this case. All of these anticipatory capabilities are part of the self-awareness aspect of autonomic systems, what we call the “Introspective” aspect of an autonomic system architecture.

The Standards Issue
An interesting consequence of centralization is the requirement for validated standards. In a centralized design, standards both in terms of operational capabilities as well as standards that regulate interconnects are absolutely necessarily – especially as a system expands and becomes more complex. This engenders an overarching industrial oversight on what those standards might be. Generally standards take years to mature, and once in place are extremely difficult to change. At this point we want to state un-categorically that we have a total commitment to standards and completely understand their necessity.

With deepest regrets, I must say that standards are a “two-edged sword”. While strongly supporting the reliability of “standard” components as they are added to the existing topology, standards also can have a number of negative effects that should also be clearly articulated, understood, and mitigated if possible. One of these is that “standards” once in place have a stultifying effect on the introduction of innovative technology. Components that might otherwise add significant value are excluded, because they simply cannot be validated against existing standards. Standards also suppress innovation by making experimentation more difficult. It is nearly impossible to conduct a “pilot study” as a subcomponent of a critical, national asset without an incredible burden of prior proof that such an experiment will not in any way degrade the performance of the system. These problems are particularly disadvantageous to small businesses that can ill-afford the costs of such prior proofs of compatibility. This leaves innovation in the hands of only the largest firms, but there is concern
that such entities are not the most fertile environment for the development of what might be thought of in some seconds as “disruptive technologies”. We already see some of these effects where developing nations are surpassing the United States in taking advantage of the most modern and effective technologies, while we are burdened with evolving a legacy approach that in some case has greatly outlived its technological efficacy.

So how can these issues be resolved in the context of a distributed aggregation of autonomic microgrids? Well for one thing, the very nature of the distributed architecture supports the idea of localization and experimental pilots. Such experiments can easily be effectively islanded, and they are integrated into the broader collaboration, their effect on the overall system is very limited by the feature of localized connectivity. There is another concept thought that is probably equally important, and something that can equally benefit both centralized and distributed control. This is the notion of extensibility which can be built into the standards themselves with sufficient foresight. An example of this can be taken from the AEC (Architecture, Engineering, and Construction) community. The emerging BIM (Building Information Standard) known as IFC (Industry Foundation Classes) is a very clear example of an extensible standard. The IFC is derived from the internationally recognized solid modeling language known as STEP (Standards for Interchange of Product) and defined by ISO 10303-21 of the International Standards Organization. A complex construction project manifests to a large extent some of the degree of complexity found in the Smart Grid vision. Similarly, in the building industry, it is understood that technology evolves; methods of designing and constructing buildings evolve. There is another parallel between building a community and building a “Smart Grid”, and that is that there is a wide range of stakeholder interests that must be satisfied. Consequently, the IFC standard that is used as the common language for all groups involved in building/community design, construction, and maintenance, is designed to be extensible with specific requirements on how such changes are to be integrated as a whole. Such extensible standards, however, find a better fit with distributed system implementations where the needs of many different stakeholder groups must be satisfied.

We can think of the autonomic components, the microgrids, as being a kind of robotic system, although not of the sort that we usually think of as an anthropomorphic automaton. It has eyes (sensor), arms and legs (effectors), and a brain (computational intelligence). It is also expected to interact with humans in a most congenial manner. The components of the autonomic subcomponent of the “Smart Grid” then are as follows:

- **Sensors** – Introspection requires many sensors to provide a real time view of the state and performance of the microgrid.
- **Effectors** – Performance optimization is accomplished by adjusting the state of the system in response to observed state.
- **Computational Intelligence** – Brings it all together – observe, learn, optimize. Failure scenarios constantly modeled off-line.
- **Cognitive Interface** – Humans still involved, but less as controllers and more as guides or to provide the kinds of adjustments that only humans are capable of providing.
Together these make up a unit or agent that can locally produce power, utilize power, or exchange power with adjacent microgrids using a marginal value of energy concept. To one of the autonomic units the larger “Smart Grid” is experienced as just another autonomic component with which to negotiate under certain rules or standards to exchange energy for value. To the utility operator, the aggregation of capabilities that we call the microgrid is seen as a single component with a kind of “net metering” interface. As more and more of the larger scale network is aggregated into autonomic microgrid subcomponents, the national grid itself becomes simpler and easier to manage.

**Advantages of an Autonomic Approach to Smart Grid Integration**

Microgrids are localized components of a larger system where electrical loads and supplies are aggregated and intelligently controlled. Many microgrids join together to form the larger grid in a collaborative network. In this regard, microgrids are seen of the elements of this collaborative network, each being comprised of some combination of loads, generation, and storage. They can be a small as a college campus or as large as a sustainable community.

To summarize the advantages of autonomic Microgrid agents as distal components of the Smart grid:

1. Easily accommodates the integration of advancing energy related technologies.
2. Distributed control less vulnerable to cyber attack
3. Maintains optimal performance as components are added or deleted.
4. Adjusts to changing patterns of human behavior.
5. Scales with population changes and need.

and last but by no means least,

6. A necessary step in the broader vision of integrating and optimizing all critical resources (power, water, heat, fuel, etc.)

**Broader Context: Sustainability**

Before a conclusion, we would like to expand on that final point in the previous section. In extolling the virtues of the “Smart Grid”, an important element is almost invariably left out. The “Smart Grid” is all about maximizing the efficiency of energy production, distribution, and consumption. However, we submit that this perspective is entirely too narrow. The June 10 issue of IEEE Spectrum (image on the right) was almost entirely dedicated to the conflict between water usage and energy. Water is used for cooling either in circulation coolers or evaporators, a function that removes it from further use. One example sited was the competition for cooling water required by the Four Corners coal based...
generation facility and all of the other hotly contested uses for water in the Colorado River system. To look at energy alone without looking at the impact on other resources is to blind ourselves to major parts of the picture. In a real sense this demonstrates that even complex system of systems, such as the national energy network is also a component of, a higher order system of systems. Since nearly all systems except for the most fundamental manifest this hierarchical nature, we have chosen to think of system of systems in their more modern form as “Complex Systems” which embraces this hierarchal concept.

But things get even more interesting, because there are many more resources that need to be part of balancing the equation. Our current interests expand on the ideas presented here to look at the broader issues of sustainability. In the sustainability landscape, all resources are considered together and the consequences of the use and distribution of one are considered in the context with all of the others. The diagram on the left illustrates the pantheon of resources for a development project we have been collaborating with in Abu Dabi, UAE. The project was to design a plexus of collaborating autonomic agents as a living/working environment on a small island supporting roughly 25,000 worker/residents. To the maximum extent possible, this community is to be carbon neutral and to be as independent as possible with respect to all of the resources shown in the diagram. No automobiles are permitted on the island, with all transportation being provided by a “people mover” using a design from the Netherlands. Solid waste is to be converted to energy, water was to be recycled, purified, and when appropriate used for agriculture. Wind and solar systems were integrated into the design. For our part, we are adapting our computational intelligence engine to learn the best time to activate the various subsystems. For example, a fluid heat exchanger was considered to capture the concentrated heat from the day from the CSP (Concentrated Solar Power) system to shift it into the night. Waste from the residencies and working environments were stages so that energy could be produced at night. These were not models that were predetermined, but the computational intelligence learned from both modeling and experience how to integrate these activities most effectively. It was also expected, that patterns of use would be extracted using data mining tools, and these would then help the control logic – the brain – to stage activities as well as to adapt to changing patterns of use. This is a very high level view of this project, but the purpose of discussing it here was to illustrate how much things are truly intertwined in our complex world, and no matter how well we design and implement the “Smart Grid”, if we do it in isolation from these other considerations, then we will only have done part of the job – and indeed – only a very small part.
Conclusion
Like so many things, it not likely that there is a single correct answer. We are not saying that centralization is wrong – because it is not. We are also not seeing that the distribution systems should be wholly autonomic and distributed. But we will advance a test to know when we are close to the right balance. In our experience with engineering complex systems, there is a “sweet point” where humans do what humans do best and machines do what machines do best. In the centralization paradigm, all complex decisions are reserved to humans, only the most trivial responses being left to the machines such as the functioning of re-closers. At the other extreme, everything is left to autonomic agents – a kind of robot – and humans are almost entirely irrelevant. This can’t be the answer. So, let us leave you with this simple thought – the right balance is achieved in a complex systems when the degree of centralization compared to the degree of disaggregated autonomicity is such that humans are doing what humans do best, and machines are doing what machines can do most efficiently.

References