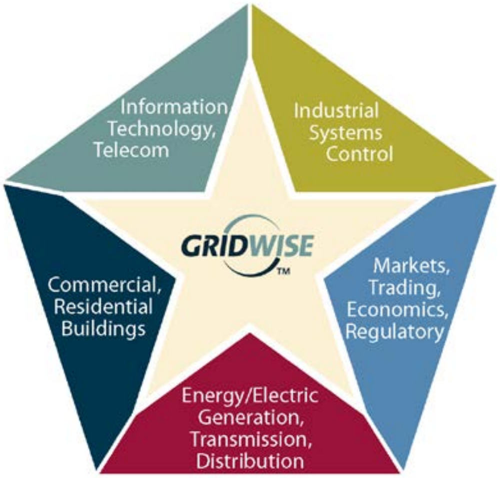


GridWise Transactive Energy Framework
Version 1.0

Prepared by

The GridWise Architecture Council

January 2015

About this Document

The GridWise Architecture Council was formed by the U.S. Department of Energy to promote and enable ***interoperability*** among the many entities that interact with the electric power system. This balanced team of industry representatives proposes principles for the development of interoperability concepts and standards. The Council provides industry guidance and tools that make it an available resource for smart grid implementations. In the spirit of advancing interoperability of an ecosystem of smart grid devices and systems, this document presents a Transactive Energy framework to provide the context for identifying and discussing development and application of this technology. You are expected to have a good understanding of interoperability, familiarity with the GWAC Interoperability Context-Setting Framework, and knowledge of energy markets and their business models. Those without this technical background should read the *Executive Summary* for a description of the purpose and contents of the document. Other documents, such as checklists, guides, and whitepapers, exist for targeted purposes and audiences. Please see the www.gridwiseac.org website for more products of the Council that may be of interest to you.

RIGHT TO DISTRIBUTE AND CREDIT NOTICE

This material was created by the GridWise® Architecture Council and is available for public use and distribution. Please include credit in the following manner: *The GridWise Transactive Energy Framework is a work of the GridWise Architecture Council.*

DISCLAIMER

This document represents a step toward establishing a context for discussing and evaluating transactive energy issues. It forms a basis for engaging entrepreneurs, system architects, and system integration experts in discussions that lead to improvements in this early material. It was prepared by the GridWise Architecture Council, interested collaborators of the Council, and employees of Battelle Memorial Institute (Battelle) as an account of sponsored research activities. Neither Client nor Battelle nor any person acting on behalf of either:

MAKES ANY WARRANTY OR REPRESENTATION, EXPRESS OR IMPLIED, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, process, or composition disclosed in this report may not infringe privately owned rights; or

Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, process, or composition disclosed in this report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the GridWise Architecture Council or Battelle. The views and opinions of authors expressed herein do not necessarily state or reflect those of Battelle.

Executive Summary

Over the past decade, the use of demand response and other flexible distributed resources for market efficiency and grid reliability has grown dramatically. Federal and state policy objectives point to an important role for customers' loads, generation, and storage in the management of an increasingly unpredictable power system. As we consider the need to substantially scale the use of flexible distributed energy resources, growing attention has been devoted to the need to address not only the economics, but also the control system implications to ensure grid reliability. This has led to a focus on an area of activity called "Transactive Energy." Transactive energy refers to the use of a combination of economic and control techniques to improve grid reliability and efficiency. These techniques may also be used to optimize operations within a customer's facility.

The U.S. Department of Energy has supported the GridWise® Architecture Council ("the Council") in developing a conceptual framework for developing architectures, and designing solutions related to transactive energy. The goal of this effort is to encourage and facilitate collaboration among the many stakeholders involved in the transformation of the power system and thereby advance the practical implementation of transactive energy.

Building on workshops sponsored by the Council in 2011 and 2012, the Council began to address the topic of transactive energy in a workshop portion of each face-to-face meeting. This culminated in the First International Conference and Workshop on Transactive Energy held in Portland, Oregon, on May 23 and 24, 2013. At the conference the Council announced plans to release the first version of a "Transactive Energy Framework" document in October 2013.

The valuable input from industry researchers and practitioners at these conferences and workshops reinforced to the Council that there was a need for the following:

- clear definitions
- explanations of technical and economic drivers motivating transactive energy
- addressing of transactive energy from multiple perspectives including
    - business and policy considerations
    - business models
    - value creation
- conceptual or reference architectures for transactive energy systems
- identification of the implementation challenges of such systems.

The Council developed this document to address these needs by providing definitions of terms, architectural principles and guidelines, and other descriptive elements that present a common ground for all interested parties to discuss and advance transactive energy.

The motivations for transactive energy come from the increasing diversity of resources and components in the electric power system and the inability of existing practices to accommodate these changes. Expanded deployment of variable generation on the bulk power side, distributed energy resources throughout the system, and new intelligent load devices and appliances on the consumption side—all of these necessitate new approaches to how electric power is managed and delivered, and in the economic and business models involved. Conventional wisdom is that once variable generation resources reach 30%, the current control systems for the grid will be simply inadequate [1].

Transactive energy systems provide a way to maintain the reliability and security of the power system while increasing efficiency by coordinating the activity of the growing number of distributed energy resources. These multiple goals pose a multi-objective control and optimization challenge. This is one reason why transactive energy embraces both the economics and engineering of the power system. The same considerations outlined for the electric grid apply to building energy systems and other local energy systems such as microgrids [2].

In the past, these systems could be considered simply end nodes on the physical power grid that act as simple "dumb" loads. But they are becoming increasingly more interactive with the grid, providing intelligent load, storage, and generation sources. They now need to be considered integral and active components of the grid as a whole. Building energy systems account for a majority of the electric power consumed in the United States. Recent U.S. Energy Information Administration (EIA) estimates project that buildings (residential and commercial) will account for around 70% of electricity consumption in the United States in 2014 [3]. From the grid perspective, buildings are examples of loads that may be integral, active components of the end-to-end electric power system. Within buildings, the same need exists to achieve similar economic and reliably optimized solutions to manage energy and potentially to realize new revenue streams through participation in markets related to electric power systems. The growing adoption of electric vehicles presents a new class of controllable and possibly even generating loads that can interact with the grid.

Asset owners, system operators, and other economic entities involved in the generation, transmission, and use of electric power all have a stake in a reliably efficient power system envisioned with the use of transactive energy. There is a clear need to align value streams for all of these parties by using incentives for participation in an actively managed system. In this document, we describe the dimensions and basic elements for all stakeholders. This provides an opportunity for discussing how various approaches may enable alignment of value streams and the creation of sustainable business models.

Regulatory, policy, and business issues frame the discussion about the functional characteristics of transactive energy systems. From these characteristics, this report also presents a conceptual or reference architecture illustrating the principal functional entities and relationships. The intent of this material is not to define a specific solution but to describe the transactive energy environment and to enable comparisons among various approaches.

We further examine the practical dimensions of implementing transactive energy systems by considering the cyber-physical system aspects. Here, too, we avoid prescribing specific solutions, but rather identify gaps and technology challenges that may need to be addressed.

The Council intends the Transactive Energy Framework to be a starting point for further development through engagement with the broad community of smart grid researchers and practitioners. We welcome feedback on the document and encourage others to adopt its framework concepts and terminology for their discussions within the growing transactive energy community.

About GridWise® and the Architecture Council

The GridWise vision rests on the premise that information technology will revolutionize planning and operation of the electric power grid just as it has transformed business, education, and entertainment. Information technology will form the “nervous system” that integrates new distributed technologies—demand response, distributed generation and storage—with traditional grid generation, transmission, and distribution assets. Responsibility for managing the grid will be shared by a “society” of devices and system entities.

The mission of the GridWise Architecture Council (“the Council”) is to enable all elements of the electric system to interact. We are an independent body that believes tomorrow’s electric infrastructure can be more efficient and secure by integrating information technology and e-commerce with distributed intelligent networks and devices. To achieve this vision of a transformed electric system, the Council is defining the principles for interaction among the information systems that will effectively and dynamically operate the grid. The Council, which is supported by the U.S. Department of Energy, includes 13 representatives from electric energy generation and delivery, industrial systems control, building automation, information technology and telecommunications, and economic and regulatory policy.

The GridWise Architecture Council is shaping the guiding principles of a highly intelligent and interactive electric system—one ripe with decision-making information exchange and market-based opportunities. This high-level perspective provides guidelines for interaction between participants and interoperability between technologies and automation systems. We seek to do the following:

- Develop and promote the policies and practices that will allow electric devices, enterprise systems, and their owners to interact and adapt as full participants in system operations.
- Shape the principles of connectivity for intelligent interactions and interoperability across all automation components of the electric system from end-use systems, such as buildings or heating, ventilation, and air-conditioning (HVAC) systems, to distribution, transmission, and bulk power generation.
- Address issues of open information exchange, universal grid access, distributed grid communications and control, and the use of modular and extensible technologies that are compatible with the existing infrastructure.

The Council is neither a design team nor a standards-making body. Our role is to bring the right parties together to identify actions, agreements, and standards that enable significant levels of interoperation among automation components. We act as a catalyst to outline a philosophy of inter-system operation that preserves the freedom to innovate, design, implement, and maintain each organization’s role and responsibility in the electrical system.

Contents

Figures

Tables

1. Introduction

As stated in the introduction to the GridWise Interoperability Context-Setting Framework, “The GridWise Architecture Council (GWAC) exists to enable automation among the many entities that interact with the electric power infrastructure” [4]. That introduction goes on to discuss the important role of interoperability as a key objective to enable “a larger, interconnected system capability that transcends the local perspective of each participating subsystem.”

Since the Interoperability Context-Setting Framework was published significant progress has been made in developing interoperability standards and implementing them while smart grid technology has been deployed. During this time the attention of the GWAC has turned to a related question of how to take advantage of the increased availability of two-way communications and intelligent, communicating devices and sensors within the electric power infrastructure and end-use sites of electric power. The topic of transactive energy as a means to effectively manage and control an increasingly complex electric power infrastructure has emerged as a focal topic in GWAC’s work to build on previous interoperability work.

The GWAC’s work in this area began with a workshop convened by the Council and hosted by Open Access Technology International, Inc. (OATI) at OATI’s Redwood City, California, facilities in May 2011. This workshop brought together a small group of people, ranging from researchers to independent system operator/regional transmission organization (ISO/RTO) staff, all of whom had been either working on projects referred to as “transactive” in some aspect, or had been taking part in the various discussions about transactive approaches for the power system. One of the outcomes of this workshop was an initial working definition of transactive energy:

> The term “transactive energy” is used here to refer to techniques for managing the generation, consumption or flow of electric power within an electric power system through the use of economic or market-based constructs while considering grid reliability constraints. The term “transactive” comes from considering that decisions are made based on a value. These decisions may be analogous to or literally economic transactions.

The Council continued to consider the topic in a second workshop with larger participation in March 2012 at IBM’s research facilities in Yorktown Heights, New York, and in May 2013 it organized the First International Conference and Workshop on transactive energy in Portland, Oregon. Leading up to the latter event, the Council also held a series of workshops as part of its regular face-to-face meetings. From those workshops and the conference it became apparent that transactive energy involves not only economic aspects, as covered in the definition above, but also the operational reliability and related control objectives and technology within the electric power infrastructure. The Council believes that both elements must be considered to move forward with the practical development and application of transactive energy.

At the First International Conference and Workshop, the plenary sessions provided a combination of information about the changing nature of the electric power infrastructure, related challenges and opportunities with buildings as the largest user of electric power, the broad elements of transactive energy as identified by the efforts of the Council, and some examples of current or planned projects applying transactive energy technology. The workshop sessions of the conference were used to gather input from the community on policy and regulatory considerations, business models and value creation, architectural views, and challenges for the cyber-physical systems in implementing transactive energy systems. The results of the workshops helped in the preparation of this document including a refined definition of the term “transactive energy” that is discussed in Chapter 3.

1.1 *Why Develop a Framework?*

The GWAC addressed this question in “The GridWise Interoperability Context-setting Framework”[4]. A subset of that material is included here. As illustrated in Figure 1 below, by framework, we mean something at a high, organizational or conceptual level that provides neutral ground upon which a community of stakeholders can discuss issues and concerns related to a large, complex system.

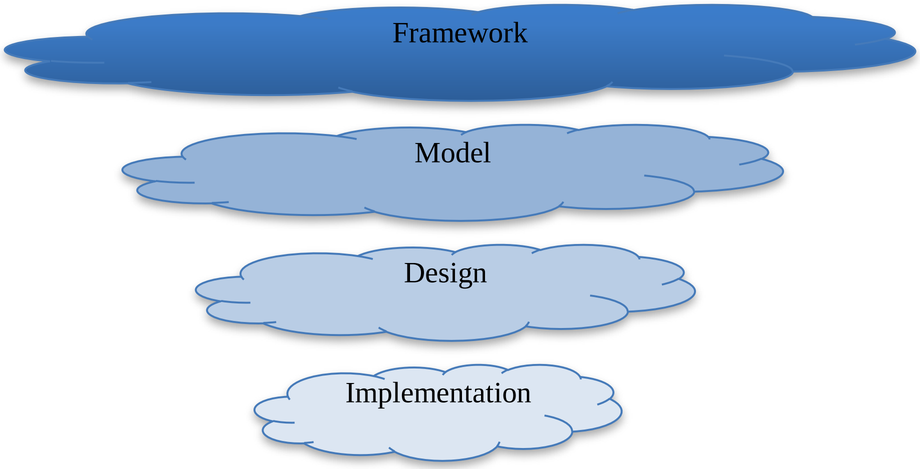


Figure 1: A framework provides high-level perspective.

The intent of the Transactive Energy Framework is to promote discussion at the conceptual level of common features or elements of specific models, designs, or implementations of transactive energy systems. At this conceptual level the framework is intended to be broad and overarching.

1.2 *The Importance of Multiple Viewpoints*

In promoting broader discussion multiple diverse stakeholders need to be considered. Consequently, transactive energy involves contributions from multiple disciplines spanning both economics and engineering. The implications of the potential new approaches for managing and controlling electric power systems call for a broad involvement of economists, regulators, policy makers, vendors, integrators, utilities, researchers, end-consumers such as building owner-operators, and other stakeholders. The diversity of thought provided by multiple viewpoints is important to achieving a framework that addresses the variety of perspectives and needs these stakeholders bring to the table.

A framework is a method and a set of supporting tools that can be used for developing an architecture. The Transactive Energy Framework is a tool that can be used for developing a broad range of different architectures for implementing transactive techniques. This document discusses approaches for designing a transactive system in terms of a set of building blocks, and for showing how the building blocks fit together.

1.3 *Audience for this Document*

In creating the Transactive Energy Framework, the authors presume an audience with a good understanding of interoperability, familiarity with the GWAC Interoperability Context-Setting Framework, and knowledge of energy markets and associated business models. People with this level of background should be reasonably able to understand the proposed ideas, critically review them, and participate in reworking or refining the framework so that it becomes a shared creation with tools that propagate and serve the diverse smart grid community. The document covers the topic of transactive energy at an abstract, conceptual level. This is because the Council does not want to prescribe specific implementations and because we hope to engage an audience that includes policy makers, regulators, vendors, utilities, researchers, practitioners, and end-use asset owners. Subsequent work products are expected to engage subsets of this broad audience at levels that best communicate with each targeted segment.

1.4 *Report Contents and Organization*

This document is organized in four main chapters. Chapter 2 summarizes the context and motivation for transactive energy approaches. The changing nature of the grid and the combination of regulatory, policy, economic and engineering challenges due to those changes are summarized. Chapter 3 refines the definition of transactive energy and includes a set of associated attributes that may be used to discuss different approaches and implementations of transactive energy systems. Chapter 4 puts transactive energy into a framework of regulatory and policy considerations, business models and value creation, conceptual system architectures, and the general cyber-physical considerations important in implementing transactive energy applications. The intent throughout all of these chapters is not to prescribe a specific transactive energy solution. Rather, the intent is to provide a common point of reference and encourage broad discussion of the concepts and approaches possible for designing and implementing transactive energy systems or applications.

2. Context Setting

The intent of a transactive energy framework is to provide the context for identifying and debating transactive issues to advance actions that simplify the integration and monetization of distributed energy resources within the complex power system. The framework recognizes that these objectives can only be achieved when agreement is reached across many layers of concern. These layers span the details of the processes and technology involved to link systems together, to the understanding of the information exchanged, and to the objectives of customers, businesses, organizations and economic and regulatory policy.

This document frames the topic by defining the meaning of the term “transactive energy,” presenting attributes of transactive energy systems, and enabling the discussion of methods for accommodating increasing numbers of distributed energy resources within power systems. The framework is then a useful tool for further development of the topic.

2.1 *The Problem*

A number of recent reports and studies (for example, [1, 2, 5-7]and [8]) have discussed the significant transformations occurring in the electric power system. These transformations include growth in the use of renewable energy resources in the bulk power system, proliferation of distributed energy resources of various capacities in both transmission and distribution systems, an increasing number of installations of local renewable resources at end-use points, and load growth through electrification of transportation and other end-uses. Some of these transformations, such as the deployment of distribution-level photovoltaic (PV) systems, represent relatively minor quantities of generation to date. The continued penetration of small-scale PV systems may have less impact on the grid than casual conversations might suggest, yet it still has the capability to be a force worthy of consideration. Today PV accounts for 0.2 quadrillion Btu (quads) per year, which compares with 1.03 quads consumed by televisions nationally per year [3]. Yet PV is highly concentrated in some areas and there the numbers have a larger net impact. The same effect is true for plug-in electric vehicles, which make a small impact overall but present significant challenges where they become concentrated in small areas.

The fact remains that we are deploying more and more technology on the grid, in businesses, and in homes. Devices are becoming smarter and increasing amounts of renewable sources of energy are being deployed, driven by state renewable goals and growing social desire for environmental stewardship. Daniel Burrus stresses the need to understand the difference between hard and soft trends so we might know which parts of the future we can be right about [9]. Hard trends give us the ability to see disruptions before they happen and the insight we need to create strategies based on a new level of certainty. Hard trends also provide a way to accurately predict changes in consumer behavior based on game-changing technology shifts. Soft Trends can be changed and therefore influenced, producing another way to influence the future. Whether or not PV and plug-in vehicles represent hard trends or soft trends, current projections by the Energy Information Administration (EIA) show PV increasing by an order or magnitude in the next 30 years [3]. Whether or not PV on its own has the ability to destabilize the grid, the trend suggests a significant increase in technology at the edge of the grid and a likelihood of increasing interactions occurring between devices as social networks and energy networks converge. This makes PV a strong catalyst for increasing transactive energy (TE) adoption and general understanding of the topic.

At the edge of the grid where consumption occurs, there is growing interest in high-performance and net-zero buildings as well as building-to-grid integration. These considerations of end-uses of electric power are among the issues that have significant ability to influence the extent to which devices, people, and organizations interact with each other to meet personal goals and to influence future grid operations, value creation and realization.

Of particular concern is growth in the use of intermittent resources in both the bulk power system and at end-use points served by distribution systems. Historically, the electric power system was operated as a load-following system. Loads were variable but predictable, generation was dispatchable, and there was no significant amount of bulk energy storage in the power system; so generation resources were operated through periodic dispatches that roughly aligned supply with demand and allowed automatic closed-loop controls to adjust generation to precisely match load. This approach yielded a reliable source of electric power and system frequency served as a key indicator of overall system stability. While this system and many other aspects of the power delivery chain were originally designed for reliability, in recent times there has been a significant move toward operation for economy and sustainability. This has led to the introduction of new energy sources whose characteristics are quite different from what was originally designed, as well as the introduction of non-passive load behavior. This move has also introduced opportunity as energy markets open up to smaller participants, including non-utility players. This trend can unlock new economic value through new kinds of energy services, but raises the issue of how such services can be technically coordinated with grid operators in a secure manner that does not compromise system manageability or reliability.

The increased use of intermittent resources, such as wind and solar power, has made it increasingly difficult to continue to use the load-following operational model. The variability of the generation resource has resulted in a new problem that involves the presence of somewhat predictable variability in both generation and loads. Over time it is predicted that the old model of generation following load will be superseded by a future model of load responding to supply [10]. During the transition between these two paradigms, the new problem is one of finding a means to manage that variability most efficiently, while maintaining system balance, stability, supply security, and reliability.

In addition to the use of intermittent resources, the increased use of distributed energy resources (DERs) has increased the complexity of the electric power system. While distribution systems were originally designed assuming power flow from bulk power generation to end-use load points at the edges of the distribution system, incorporation of DERs increasingly violates that assumption, with significant consequences for grid operations when penetration levels of DERs pass tipping points that are becoming well recognized. Introducing DERs at the edges and also at intermediate points now creates the possibility of power flows in multiple directions, as well as loop flows in distribution circuits. These changes were not anticipated in the present generation of grid controls, so they introduce new challenges for distribution system operators.

Electrification of transportation introduces new challenges, too. Electric vehicles hold great promise for helping achieve carbon footprint reductions by reducing our use of fossil fuels for transportation.[1] They also present the possibility of increased peak loads if electric vehicle owners all want to charge their vehicles in the evening when they get home from work. This impact is significantly more pronounced for Level 2 AC charging or for DC Fast Charging. A 2007 study by Pacific Northwest National Laboratory showed, however, that we have the capacity to accommodate a 70% penetration of electric vehicles if we manage their charging through the use of “smart” charging technology [8].

---

[1] This assumes the carbon content of the grid is less than the carbon content of petroleum, as it currently is.

Considering the situations summarized above, we are faced with a set of issues requiring simultaneous or joint solutions. This is because these problems are not isolated in only one element of the electric power system and because the coupling that exists via the electrical physics of the grid causes the various elements to interact in ways that can be detrimental if they are not properly addressed. New objectives arising from the emerging trends discussed above are as follows:

- wholesale prices/production costs minimization
- provision of ancillary services, ramping, and balancing (especially in light of renewables)
- managing transmission congestion costs
- peak load management
- resource ramp management
- minimization of new transmission capacity, relief from existing dynamically constrained capacity limits
- minimization of new distribution capacity
- management of distribution voltages in light of rapid fluctuations in rooftop solar PV system output
- accommodation of new loads and integration of responsive loads
- maintenance or improvement of the services power provides in homes and buildings.

Achieving these objectives may be thought of as a multi-objective optimization problem. There have typically been two approaches to achieving the operational objectives of the electric power system—the use of economic systems such as markets and the use of control systems technology. The remainder of this chapter considers the challenges from these two perspectives, beginning with consideration of the time scales for which they apply, leading to subsequent chapters that consider TE as a means to treat these two classes of objectives jointly for energy systems.

2.2 *Time Scales*

The fundamental problem in operating an electric power infrastructure is maintaining balance between supply and demand. The physics of the electrical power system will force balance to be maintained; otherwise imbalance outside of the tolerance of the system will cause the system to fail through a chain of events resulting in blackouts. The key objective of the operators of the system is to supply power to loads reliably (within specified limits), thereby avoiding blackouts. To achieve this objective actions take place on a range of time scales from years to milliseconds.

Figure 2 illustrates the relative time frames involved in the electric power system. On the right, the time frames are slow—days to years to decades. Even in those time frames, however, the initial steps for maintaining the balance of supply and demand take place with utilities estimating load changes and entering into long-term contracts to meet their basic estimated needs. In nearer time frames—hours to days—markets or other economic interactions take place to balance supply and demand now that the load for tomorrow or for the coming hour can be more accurately estimated. Recently, some of the regional system operators (ISOs or RTOs) have begun to operate markets on intervals as short as five minutes to manage supply and demand.

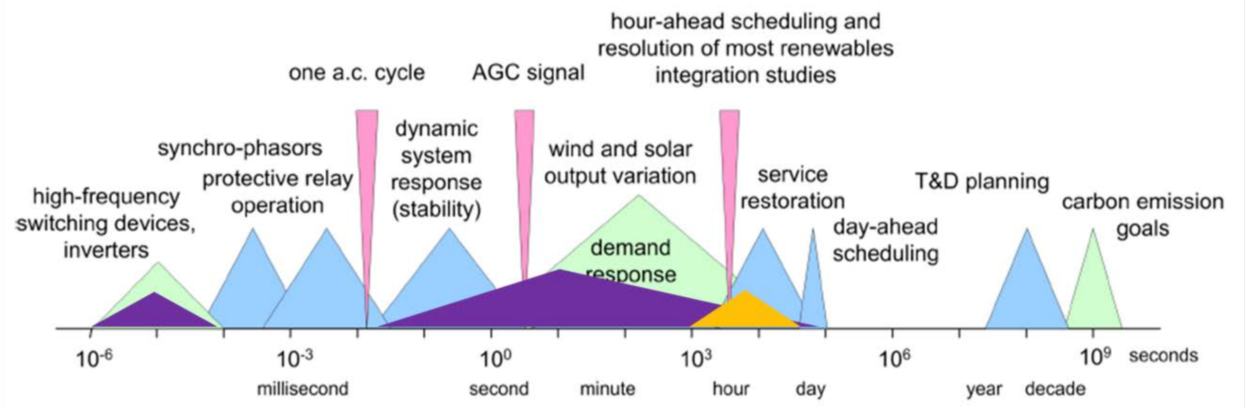


Figure 2: Electric Power System Timelines (used with permission) [11].

The left half of Figure 2 represents the faster time frames of operation ranging from microseconds to minutes. Action on these time frames is taken by an automatic control system such as automatic generator controls (AGC) responding to signals such as area control error (ACE) or local measurements that drive components such as voltage regulation or protective relays. Historically, controls have been hierarchical in nature, using supervisory control and data acquisition (SCADA) technology to link remote control points or sensors to a centralized control center, and having human operators in the loop for many kinds of grid control operations. As the emerging trends develop, operations will increasingly shift to the left in Figure 2, meaning that human-in-the-loop control is likely not sustainable going forward and that more automated control with human supervision will be needed. Also, the number of data paths, connection points, and control points is growing and becoming exceedingly complex.

2.3 *Economic/Market Context*

The increasing diversity of resources in the physical system has implications for the existing economic- and market-based elements of the power system. These impacts are illustrated in the Transactive Energy Infographic [12], which depicts interactions at the transmission, local, microgrid, and residential levels. These represent interactions that may or may not use utility wires to deliver power and services, but that may nonetheless affect grid performance. These changes are driving and will continue to drive impacts in several ways, such as the following:

- development of new market structures to deal with the variability of large-scale renewable resources; for example, energy imbalance markets
- the emergence of markets operating on shorter and shorter time scales such as Energy Imbalance Markets (EIMs) in the west and PJM’s five-minute markets in PJM, New York Independent System Operator, and other organized markets
- changing retail customer relationships with the introduction of premises-level renewable resources and new loads such as electric vehicles
- formulation of policies going beyond renewable portfolio standards to promote development of very efficient high-performance buildings, including net-zero energy buildings
- the emergence of the distribution system operator (DSO) construct to take on the responsibility for balancing supply and demand variations at the distribution level and linking the wholesale and retail market agents

- “hidden” changes in the behavior of the grid such as the increasing capacity of behind-the-meter sources of generation displacing conventional electricity generation that would otherwise occur, which has contributed to electricity sales declining in four of the past five years [13].
- the need for new business and regulatory models. The traditional utility model is predicated on load growth, but efficiency has severed the link between population/economic growth and energy growth. This change plus the shorter time scales for adding DERs when compared to traditional generation sources, and the increasing technical capabilities to facilitate cooperation and coordination between DERs, users, and devices creates a need to re-evaluate our cost of service regulation model.
- requiring action in the time frame of minutes (see Figure 2) at major system-to-system interfaces between transmission and distribution or distribution and retail customers. Thus, the changes impact both the economics of electric power systems and the control of both the power systems and the end-uses of electricity.

With respect to regulatory changes, investor-owned electric utilities point to a paradigm shift caused by the need for large new capital additions at a time of declining sales growth and reduced credit worthiness. They urge the development of new regulatory frameworks that provide for cost recovery outside of the traditional rate case [14]. Perhaps a regulatory tool to stimulate innovation is required such as a tiered recovery mechanism based on levels of customer participation and/or customer satisfaction [15]. There seems little doubt that regulatory models must evolve to address the ability for edge devices to offer services. The topic of policy and market design is addressed more in Section 4.1.

2.4 *Grid Control Systems Context*

“The mix of control methods either in use or contemplated today has resulted in a chaotic situation further compounded by the lack of true interoperability between and across many of these systems” [2], as shown below in Figure 3, which depicts inter-tier control, with control flowing downward. The diagram in Figure 3 is difficult to read because grid control is becoming increasingly complex. The curved red lines on the right side of the diagram illustrate the recent proliferation of new control relationships. These represent attempts by the utilities to deal with new functions and requirements within the bounds of existing control infrastructure. It is clear that the overall control architecture of the full electric power system is becoming chaotic. This is due to the mismatch between the old grid control requirements, for which existing control systems were well-designed, and the emerging requirements that violate many of the long-standing grid-operating assumptions. Less apparent however, is how markets, which have historically operated in a manner mostly decoupled from short-term grid operations, might integrate with grid control on short timescales appropriate for the new grid functions.

To provide for joint market and control functionality (i.e., TE capability) in an environment that supports new grid capabilities, it is clear that overall grid control architecture must evolve in line with changing requirements. Such evolution will lead to a more distributed[2] kind of control especially at the distribution level, with much faster operation, human supervision rather than human-in-the-loop operation, and control coordination that spans multiple levels of the power grid hierarchy, while respecting local optimization and decision making.

---

[2] Note that the term “distributed” can be applied to systems architecture concepts as well as decision-making capabilities.

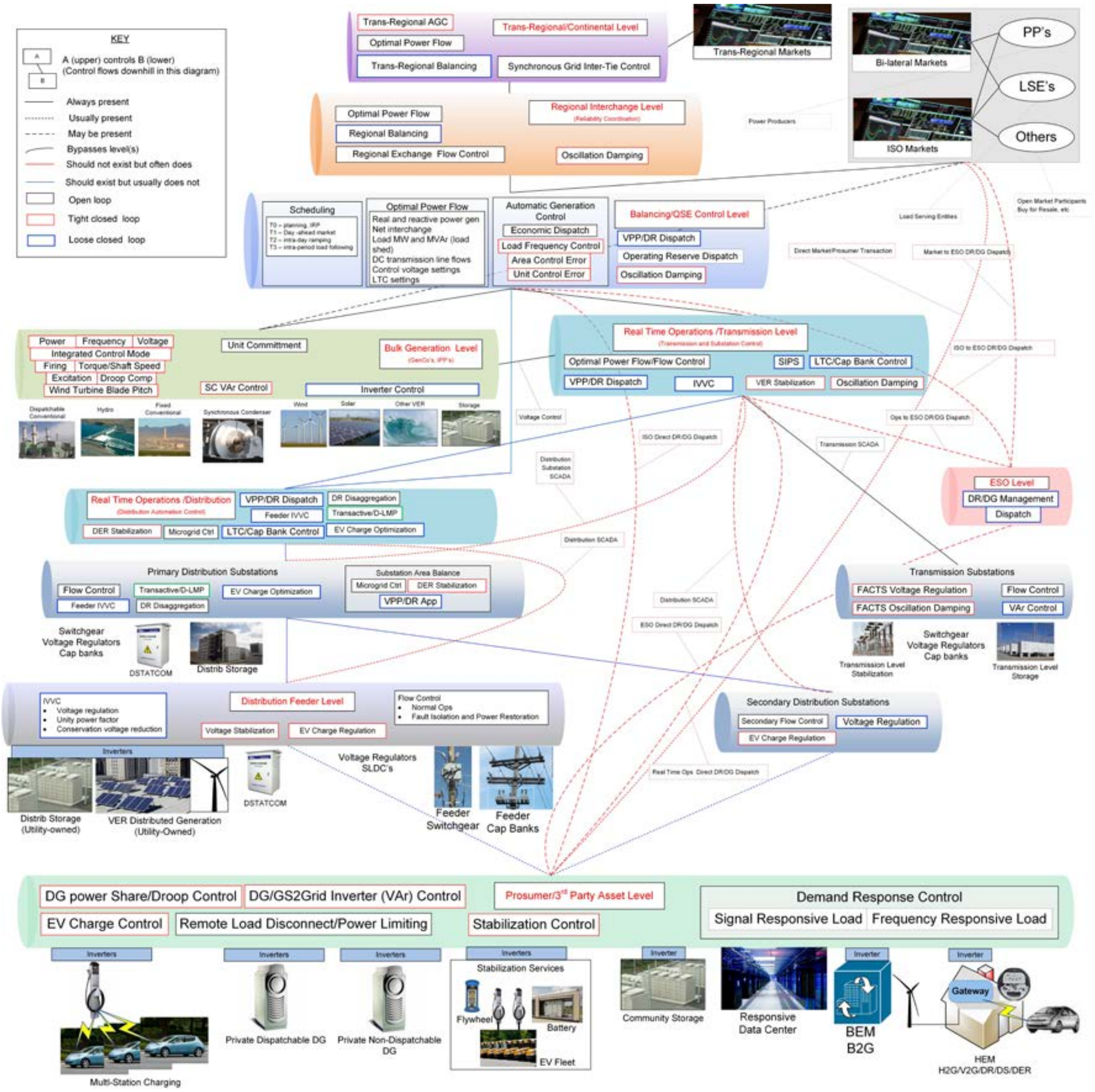


Figure 3: Growing complexity of electric power system controls [2]

Such a control framework will enable the TE functions by providing the following key characteristics:

- fusion of multiple control objectives while maintaining system stability
- disaggregation of control to account for local optimization, constraints, and decision making
- multi-tier control coordination and synchronization
- structural scalability for large numbers of participating endpoints
- simplified mechanisms for integration of markets, advanced grid controls, non-utility grid-connected energy assets (DER), third-party energy services organizations, and responsive loads
- low-cost control and communication gateways and sensing/control devices enabling extensive participation of end-use prosumers (producing consumers), devices, and systems.

Such control frameworks are not only possible, but feasible given recent trends in advanced grid control. Two key issues here are

1. How utilities make the transition from traditional controls to an advanced control framework, given investments in legacy control and communication systems.

2. The availability and ease of use of low-cost control and communication gateways and sensing/control devices enabling large participation of end-use prosumers, devices, and systems.

Fortunately, the emerging layered approaches, which draw upon several well-established principles from control engineering and network design, apply and set the stage for TE. It is important to understand the role of TE relative to other elements of system control and coordination. An overall coordination framework can coordinate TE and other forms of control. It would also facilitate properties such as

- local selfish optimization inside system coordination
- control federation, constraint fusion, and command disaggregation
- boundary deference, because multiple system, organization, and jurisdictional boundaries must be crossed
- means to ensure reliability and stability

These changing requirements for grid related control systems have several implications. One of the most challenging is to move from highly centralized control systems to more distributed controls systems. In making this shift, the desired end result will be a loosely coupled set of controls with just enough information exchange to allow for stability and global optimization through local action.

3. Transactive Energy

The purpose of this chapter is to provide definitions of TE, the basic terms associated with TE, and to describe the elements of TE systems or applications. Our purpose is to provide as broad a set of definitions as possible to be inclusive of different approaches and techniques. However, just because an approach fits within the scope of TE does not mean that it is necessarily viable. By defining terms we intend to provide a common language for describing and discussing TE systems, thereby enabling comparison of the features, functions, and elements of different approaches.

We begin this chapter by providing a definition to answer the question, “What is Transactive Energy?” This is followed by a list of attributes of TE techniques or systems. Finally, TE elements are considered. In this chapter we also examine TE in the context of the interoperability-layered categories defined in the “GridWise Interoperability Context-setting Framework”[4].

3.1 *Transactive Energy Definition*

> *A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter.*

This definition was developed based on extensive discussion of both the nature of the evolving electric power system, as summarized in the previous chapter, and the concepts that have been discussed at workshops on TE held by the Council starting in May 2011. The definition is purposely broad. One can argue that TE is not new because bulk power system operators use markets to help manage and maintain balance and reliability of the bulk power system. The broad definition allows us to recognize their existing use of such techniques and to also consider the how to enable new techniques that may be used in distribution systems, at the interface between transmission and distribution, and perhaps even more broadly.

The definition by itself does not provide a complete picture of the entire domain of TE. To provide a more complete view and to help facilitate discussion of various approaches to implementing TE we have defined additional attributes below.

3.2 *Transactive Energy Attributes*

The following attributes represent qualities or characteristics that describe significant dimensions of TE. These have been included to assist the reader in understanding the boundaries of TE systems and supplement the definition provided above. These attributes are intended to serve two purposes. First, they provide a broader view of TE by applying the definition in the context of possible implementations of TE. Second, in considering different implementations they provide a common way to describe the characteristics of specific TE systems. In this way they are intended to help promote discussion and comparison of different approaches.

architecture	All TE tools and methodologies are described as constituents or subsystems of a system architecture. A key distinction is whether the architecture is centralized, distributed, or a combination of the two. Note that the entire electrical infrastructure is an ultra-large-scale (ULS) system of systems as defined in the in the Software Engineering Institute's ULS Book, 2006 [16].
extent	A TE system will typically apply within some geographic, organizational, political, or other measure of extent. A geographic extent, for example, might be within a region and apply across multiple participating entities. An extent may be described organizationally, for example, if an implementation is intended for use within a single utility, building, or campus. Likewise, a transactive system may apply across political boundaries with different regulatory or policy constraints. Extent may also be considered relative to the topology of an electrical infrastructure including end-users. Thus, a transactive system may apply in transmission, distribution, or both; it may also be useful for managing energy within buildings or by end-users of electrical energy.
transacting parties	Fundamentally, TE involves transacting parties. In most cases these will be automated systems, possibly acting as surrogates for human parties. In some cases humans may be in the loop. A TE system must be explicitly describable by the entities that are parties to transactions. Because a TE system will provide services to various parties, its success in delivering these services will depend in part on the expectations and needs of each group and in part on the qualities of the delivered service. Understanding such criteria is a critical aspect of the monitoring and assessment of a ULS system [16].
transaction	A TE system must clearly define transactions within the context of that system. The following questions (and possibly others not anticipated here) must be able to be answered: Who are the transacting parties, what information is exchanged between them to create a transaction, and what is exchanged between them to execute a transaction? What are the rules governing transactions? What is the mechanism(s) for reaching agreement?
transacted commodities	Although the primary commodity transacted is energy, derivative products such as reliability-driven call options (e.g., Ancillary Services) may also be transacted among the transacting parties.
temporal variability	Transactive systems may interact across multiple timescales. For example, transactions within a single system may range from sub-second to five minutes or to some longer periodicity. It is also possible for transactions to be event-driven. In characterizing a given transactive system the timescale(s) of transactive interactions need to be specified and analyzed for compatibility. This will be a key to interoperability between different transactive systems.
interoperability	Transactions are enabled through the exchange of information between transacting parties. There are two elements to consider here: technical interoperability and cognitive (semantic) interoperability. The systems must be able to connect and exchange information (emphasizing format and syntax), and they have to understand the exchanges in the context that was

	intended in order to support workflows and constraints. For any given transaction the information exchanged during a transaction must be explicitly identified. Furthermore, one should be able to explain how interoperability has been addressed in support of the information exchanges.
value discovery mechanism	A value discovery mechanism is a means of establishing the economic or engineering value (such as profit or performance) that is associated with a transaction. Fundamentally, a value discovery mechanism is the process by which transacting parties come to an agreement on value. The inclusion of this attribute recognizes that the mechanism may be simple or complex. For at least some transactive systems, the value discovery mechanism is a key element of value-driven multi-objective optimization. Value realization may take place through a variety of approaches, including an organized market, procurement, a tariff, an over-the-counter bilateral contract, or a customer's or other entity's self-optimization analysis. Value discovery mechanisms should include considerations of economic incentive compatibility and acceptable behavior.
assignment of value	Assignment of value is fundamental to value discovery. For sub-elements of a TE system, a means may be needed for assigning value to objectives that cannot be addressed through a discovery mechanism or for values that do not have a common dimension that can be used for valuation. For example, end-users of electricity may have non-quantitative values such as comfort that require a mechanism to translate them into elasticity, thus enabling quantification in a transaction.
alignment of objectives	A key principle in the broad application TE systems is the continuous alignment of multiple objectives to achieve optimum results as the system operates. This alignment enhances the economic and engineering impacts of the dynamic balance(s) achieved by TE systems. Note that optimal relates to balancing the entire transactive system, and to achieving an optimum balance necessary to optimize objectives, variables, and constraints. It is important to understand that optimization does not simply add intelligence to existing business processes, it changes business practices.
assuring stability	The stability of grid control and economic mechanisms is required and must be assured. Consideration of system stability must be included in the formulation of TE techniques and should be demonstrable. Unfortunately, there are no public benchmarks for the stability of TE systems and during numerical optimization minor errors can build on each other, and sometimes spiral out of control. It is important to mitigate optimization instabilities because grid stability may be compromised by poor value optimization techniques. In addition to the need to assure stability from a control systems point of view, stability should also be assured with respect to existing grid stability limits.

3.3 *Transactive Energy Principles*

During the February 2014 GWAC workshop held at PJM in Philadelphia, the participants agreed on the need for a set of high-level principles that apply to TE systems. As discussed during the meeting, such principles are, in effect, statements of high-level requirements for such systems. A working group was formed to organize the material from the meeting and the following six principles were defined:

- Transactive energy systems implement some form of highly coordinated self-optimization.
- Transactive energy systems should maintain system reliability and control while enabling optimal integration of renewable and DERs.
- Transactive energy systems should provide for non-discriminatory participation by qualified participants.
- Transactive energy systems should be observable and auditable at interfaces.
- Transactive energy systems should be scalable, adaptable, and extensible across a number of devices, participants, and geographic extents.
- Transacting parties are accountable for standards of performance.

3.4 *Evolution of the Grid and its Impact on Transactive Energy*

As more and more DERs penetrate distribution systems, and more micro-grids and campus networks appear as well as entities such as virtual power plants, the potential for these and other entities, such as prosumers and smart buildings and smart equipment, to interact with each other will increase. A concern that is often expressed is that this will create a decentralized[3] control system that could affect grid reliability in a negative manner. These views are typically applied to today's system architecture and management techniques that are heavily centralized. The role of the utility will change in the long term and it needs to include consideration of TE techniques in order to support the evolution of a flexible energy coordination eco-system.

As the diagram in Figure 4 illustrates, the industry is in the early stages of transactive operations. As more and more intelligent devices are deployed, the opportunities for automation will increase, which will increase opportunities for TE. The time frame shown in the figure is aggressive and some in the industry suggest a longer time horizon will apply. Survey results from recent regional workshops conducted by DOE and the GridWise Alliance, however, concluded that there can be significant change in the electric power system by 2020 [17]. While not all elements of the electric power system will change at this pace, it appears likely that parts of the system will.

---

[3] Decentralized computing or control exists when multiple distinct (and usually but not always physically separated) elements operate independently. Distributed computing or control exists when the decentralized elements explicitly cooperate to solve a common problem. Mechanisms to ensure that decentralized elements stay focused on the common problem are known as coordination methods.

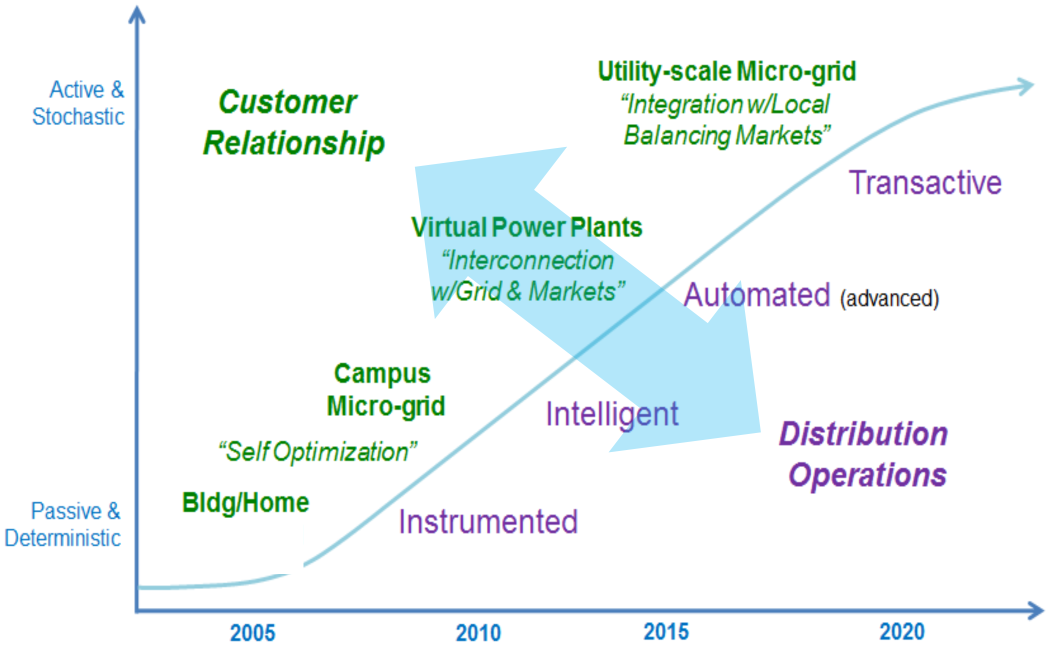


Figure 4: Stages of adoption of transactive operations for industry [18].

If a common approach can be established for TE implementations then a foundation may be created allowing various systems to cooperate to maintain reliability while also serving their own objectives to increase value. But this is either just a technical challenge nor just a business challenge but a policy challenge to consider at the state, regional, and federal levels. This is one reason why a framework such as that defined in this report is essential.

3.5 *Elements of Transactive Energy*

The elements of TE are the components of a transactive architecture that need to be addressed in the design of a system. They provide a starting point for discussion by presenting the basic structure for an approach to transactive architecture design with reference to a summarized GWAC Stack as defined in the GWAC's "Interoperability Context-Setting Framework" [4]. The GWAC Stack represents the dimensions of interoperability ranging from physical (or cyber-physical) at the lower levels, information interoperability in the mid-levels, and business models, market structures, regulation, and policy in the upper-levels. With these three broad groupings of the GWAC Stack in mind we can define elements of TE as depicted in the Figure 5.

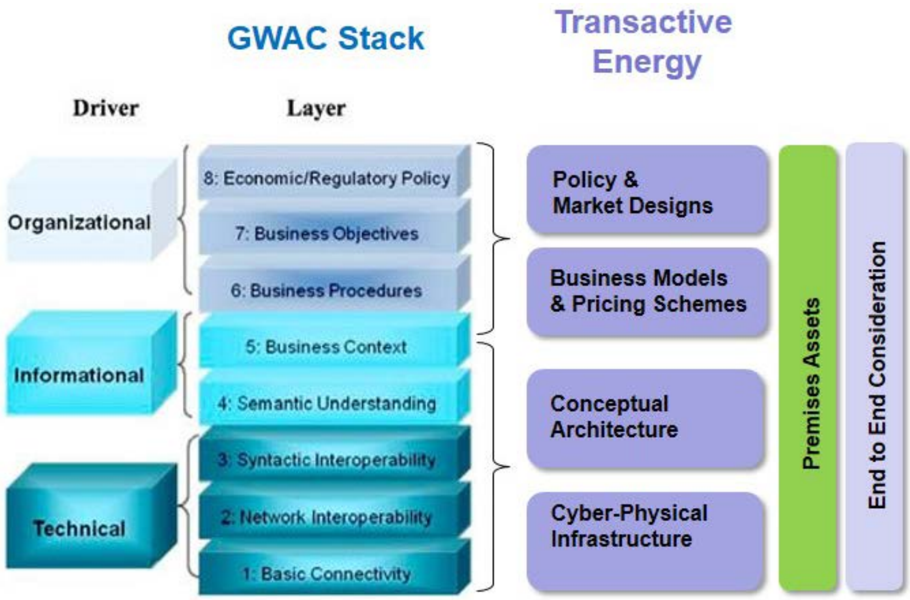


Figure 5: GWAC Stack with elements of transactive energy.

These three groupings from the GWAC Stack provide the elements that need to be addressed by any transactive design. A TE system within a smart building or corporate campus may face challenges different from a microgrid, a virtual power plant, or an energy trading or a demand reduction system. Nevertheless, all of them should address appropriate levels in the following areas during design.

- **Business/Markets/Policy/Regulation**. Ideally, policy makers would have a TE toolkit available to them that would include a catalog of policy guidance and mechanisms. The regulators could use this toolkit to compose TE policy specific to the needs of their regulated jurisdictions. Until the toolkit exists, transactive designs must address a set of broader and potentially more abstract questions (as identified in the attributes described in Section 3.2) including: Who or what are the transacting parties? What is the purpose and regulatory extent of transactions? How are transactions closed or settled? Is the economic "reward" directly associated with the transactions or separate? (For example, one can construct an "engineering-economic signal" that is used to drive system behavior based on monetizing all considerations; however, this signal is not used as a literal basis for the exchange of money).
- **Information Interoperability** (including system architecture). Information interoperability needs to address the semantics behind the valuation of transactions (meeting participant objectives), the operation of the TE mechanisms, and the control aspects of understanding the impacts of the transactive system on the electric grid. Thus, the semantics of information interoperability are directly linked to both the business and operational models. One challenge is how to include in the "business model" the engineering imperatives. What specific information is exchanged?
- **Cyber-Physical**. The Cyber-Physical Infrastructure element of TE deals with the technical layers of the GWAC Stack and the physical layers of the Control Abstraction Stack. The power grid includes two cyber-physical networks: the electrically connected network and the communications networks necessary to monitor and control it. Transactive energy designs need to address both of these infrastructure elements to the extent of understanding what physical connectivity is required to support the exchange of information in support of transactions and without detrimentally affecting the reliability of the electrical network.

4. Framework

This chapter dives deeper into the elements of TE described in the previous one. Building on the discussion of the GWAC Stack at the end of the previous section, as illustrated in Figure 5, the GWAC Stack may be mapped into four areas of concern for discussion of TE:

- Policy and Market Design
- Business Models and Value Realization
- Conceptual Architecture Guidelines
- Cyber-Physical Infrastructure.

One way to think about this mapping of the GWAC Stack to TE is to think of TE as a smart grid application taking advantage of the deployment of two-way communications capabilities and intelligent, communicating sensors and devices. With this view in mind one can apply the GWAC Stack and the set of principles described in the "Interoperability Context-setting Framework" to TE [4]. In doing so we are identifying the "interoperability" challenges to be considered for TE. As with the GWAC Stack itself, a number of cross-cutting and end-to-end issues need to be considered, including those related to the GWAC Stack and new ones specific to TE.

4.1 *Policy and Market Design*

An initial view of the policy and market design drivers is provided in Section 2.3 where the economic and market context is presented. This section begins with a more detailed discussion of policy considerations. These include traditional concerns such as system reliability joined by new concerns such as renewable portfolio standards and the variability of renewable energy resources as they become an increasing part of the power mix in response to those standards. The section then discusses policy and market design considerations stemming from TE.

From the Resnick Institute's Grid 2020 report [5], "The electric industry, driven by 30 years of energy policy, technology and commercial innovation, is experiencing significant growth in intermittent renewable resources, responsive demand, on-site generation and customer participation in markets. These growth trends point toward a significantly different electric system by 2020 in many parts of the United States. In essence, the electric industry is transitioning from the traditional vertical structure of deterministic centralized production and operations into a more horizontal structure that is increasingly variable and distributed in terms of productions and operations."

The report goes on to state that "to date, 37 states representing over 80% of the US population have enacted renewable portfolio standards or goals that require 10% to 33% of energy delivered to customers by 2020. These mostly variable resources present an operating challenge since the amount of power over the next month; hour or even the next minute is generally harder to predict than power available from hydro, gas, coal or nuclear plants. While many of these renewable plants were originally interconnected to transmission systems, more recently large amounts of rooftop solar have begun to create operating and economic issues for distribution systems."

Further, "Customers are becoming active participants in electricity markets and grid operations. The adoption of on-site generation and responsive demand capabilities is allowing customers to also provide excess energy and services in the market." This means that existing market and grid control systems, based on traditional centralized resources and one-way distributed power flows, require new policies, tariffs, operational paradigms, systems architectures, and market structures. Many policy issues must be addressed to ensure that this transition is successful. These policy development challenges arise for several reasons, including the following:

- **extreme reliability.** The power grid is extremely reliable and consumers expect it to stay that way. When a customer turns on a switch, the customer expects high-quality power to flow.
- **volatility of some renewable generation and customer demand.** How the variability of power from PV solar or wind generation and customer load/supply on the grid will affect the integrated electrical system is not well understood.
- **timescales of economic and grid control actions.** The grid is extremely reliable because it is controlled adaptively at timescales of seconds. By contrast, contracts between load-serving entities and power-generation companies last for many decades. In the coming decade, millions of independent agents, individuals, and devices will make economic and control decisions at vastly different timescales.
- **rapid changes in technology.** The cost effectiveness of solar power has improved significantly in a few years and may well continue to improve rapidly. The technology of energy storage systems is, likewise, improving. Similarly, the energy efficiency of common appliances/electrical loads continues to increase (particularly in the fields of lighting; heating, ventilation, and air-conditioning (HVAC); and water heating), combined with simpler techniques to remotely monitor and control these devices. The growing population of electric vehicles and their charging devices represent an entire new class of consuming (and potentially generating) assets. Bulk energy contracts span multiple decades and during that time advances in technologies may cause seismic shifts in the energy economy.
- **incentives for reducing dependence on fossil fuels.** Some governments and agencies provide substantial incentives for renewable energy generation and for improving energy efficiencies of homes, offices, and factories, and accelerating the adoption of electric vehicles. The influence of current incentives and expectations of future incentives makes long-term analyses of markets challenging.

The aforementioned items are a restatement of the objectives summarized in Section 2.1. As described in that section, the problem is to achieve multi-objective optimization. Transactive energy approaches are intended to do so through the combination of economic practices, such as markets, with distributed control systems so that all objectives may be addressed. The economic aspects of TE, however, relate to existing Federal and State policies and regulations. From an interoperability point of view there is a need, then, for alignment of regulation and policy in several dimensions. For example, TE systems may be implemented across multiple jurisdictions. This may happen horizontally if a TE implementation engages multiple utilities, especially if they are in multiple states. In addition, one may think of this as happening vertically for TE implementations that operate from "end-to-end" linking the bulk power and distribution systems.

For TE implementations engaging multiple regulatory jurisdictions there is a need for some consistency of approach in formulating related policy and regulations. At the same time, one can ask how any given implementation impacts existing policy and regulations. One concern, given the integration of engineering and economic mechanisms, is whether a given implementation violates any "firewall" requirements between markets and operations.

There is similarly a need to consider how a given TE implementation interacts with existing market structures. As already discussed in Section 2.2 and illustrated in Figure 2, power system operations occur on many time scales. The combination of engineering controls and economic structures is strongest in the time scales from seconds to minutes. The interfaces with existing market structures should be considered within this time band.

Going forward, there is a clear need for convergence of Federal and State policies, wholesale and retail markets, resource control systems, transmission and distribution control systems, and customer energy management systems to achieve the scale and scope envisioned in public policy. As such, policy action to transition from tariffs and incentives that are unsustainable in the long term to a TE framework that appropriately values energy services in supporting grid optimization must address each of the issues listed above. Such policy must focus on aligning stakeholder (Figure 6) interests to support the reliability of the power systems in an economically fair market design.

Figure 6: Transactive energy stakeholders.

By understanding each stakeholder's primary goal across the evolving energy landscape, fair energy policies and market mechanisms may be designed to motivate behaviors that support the overall health of the electric system *and* its participants. For example, consumers of energy (or by proxy distributed generation [DG] leasing companies that own and operate equipment at consumer premises) would like to maximize their return on investment in their energy technology. This means that despite incentives and favorable tariffs, additional mechanisms that monetize the participation of the consumers' energy equipment in reliability services may have strong appeal to the following:

- **Distribution utilities** that manage the delivery of power and are responsible for the reliability of the electric distribution network would like access to reliability services, such as voltage support and supplemental reactive power to help manage and balance a distribution system that now involves two-way power flows;
- **Independent system and regional transmission operators** that serve as reliability coordinators of the bulk electric system would like access to energy and ancillary services aggregated from customers that own DG across their control areas when supplies are tight or frequency is drifting out of tolerance on the system.

Hence, policies that align these interests would include pricing and valuation of consumer energy services. Such pricing and valuation should be optimized to contribute to distribution system reliability with mechanisms that aggregate from retail markets and participate in wholesale market support when required.

Using localized retail market mechanisms as opposed to standard cost recovery tariffs spread across utilities' customer bases represents a great challenge for cost of service regulation. Current service regulation is based on standard services provided in exclusive service franchises. It is very likely that regulatory innovations such as the following will be needed to enable at least some portions of the innovative transactive market strategies suggested above:

- retail rate redesign, to allow a larger portion of fixed network costs to be recovered through fixed charges, and also to establish more equitable rate incentives for DERs
- standardized regulatory treatment for investments in grid modernization, based upon sound principles of long-term customer benefit
- a regulatory policy that effectively separates allowed cost recovery for necessary infrastructure investments from earnings associated with new platform services. This policy provides more latitude for the use of customer intelligence in new service offerings, and establishes suitable affiliate rules that will enable utilities to partner with other companies in offering new products and services.
- policies that enable the creation of profitable local market coordination services to facilitate customer participation in providing energy service to bulk power system and distribution operations
- policies that confer upon utilities the right to own DERs and/or provide services related to these, and establish the conditions under which investments in these are subject to regulated cost recovery.

Ideally, policy makers would have a TE toolkit available to them that would include a catalog of policy guidance and mechanisms such that regulators could compose TE policies specific to the needs of their regulated jurisdictions. However, any policy would require flexibility to compensate for deficiencies in market design (such as undue market power or gaming) that are discovered in the course of market operations. In addition, regulators may take a conservative, phased approach to introducing TE mechanisms in their jurisdictions by using familiar tariff constructs and testing the effectiveness of certain pricing and market designs in limited pilots to ensure participants are properly incentivized and aligned through these mechanisms.

Transactive energy approaches for DER integration will differ from current approaches. It is important that policy makers recognize at least two of these differences:

- controllability of the large-scale influx of DERs is not currently addressed
- economic value is currently insufficiently expressed and captured.

As policy makers realize these fundamental differences between present and future systems, their focus should move to designing policies to maximize customer engagement and accommodate the scale of DERs that will enter the system in future. This should yield policies and market designs that support the following:

- **customer value.** Customers need to be exposed, if they so choose, to more than the limited value streams that exist today. There also needs to be mechanisms that are able to monetize the value streams in a transparent manner.
- **merger of economics and control.** Economic systems need to be designed that bridge the gap between operators and market makers and do not violate the control objectives. Regulators need to

ensure the full suites (toolkits) of mechanisms (organized markets, forward markets, tariff-based, and real-time prices) are available to express value streams to customers.

The objectives supporting the customer value and the economics of control principles that policy makers need to consider when designing markets and policies are as follows:

- Create a more level playing field for all stakeholders.
- Respect ownership, jurisdictional boundaries, and customer privacy,
- Expand opportunities for engagement between customers and the grid,
- Allow customers to control their relationships with the energy infrastructure,
- Increase customer choice to provide services to the system and the services they choose to purchase as both producers and consumers of energy.
- Spur technical and commercial innovation.
- Recognize and account for impacts on business models of current key entities such as the load-serving entities (LSEs).
- Optimize system reliability and capital infrastructure investment.

Meeting these objectives should achieve the goal of creating a fair and transparent energy market that allows economic value realization proportional to contributions to support grid reliability, support adoption of new DERs, and provide services that distribution and transmission operators may call upon to ensure a highly reliable power grid is available to power society.

4.2 *Business Models and Value Realization*

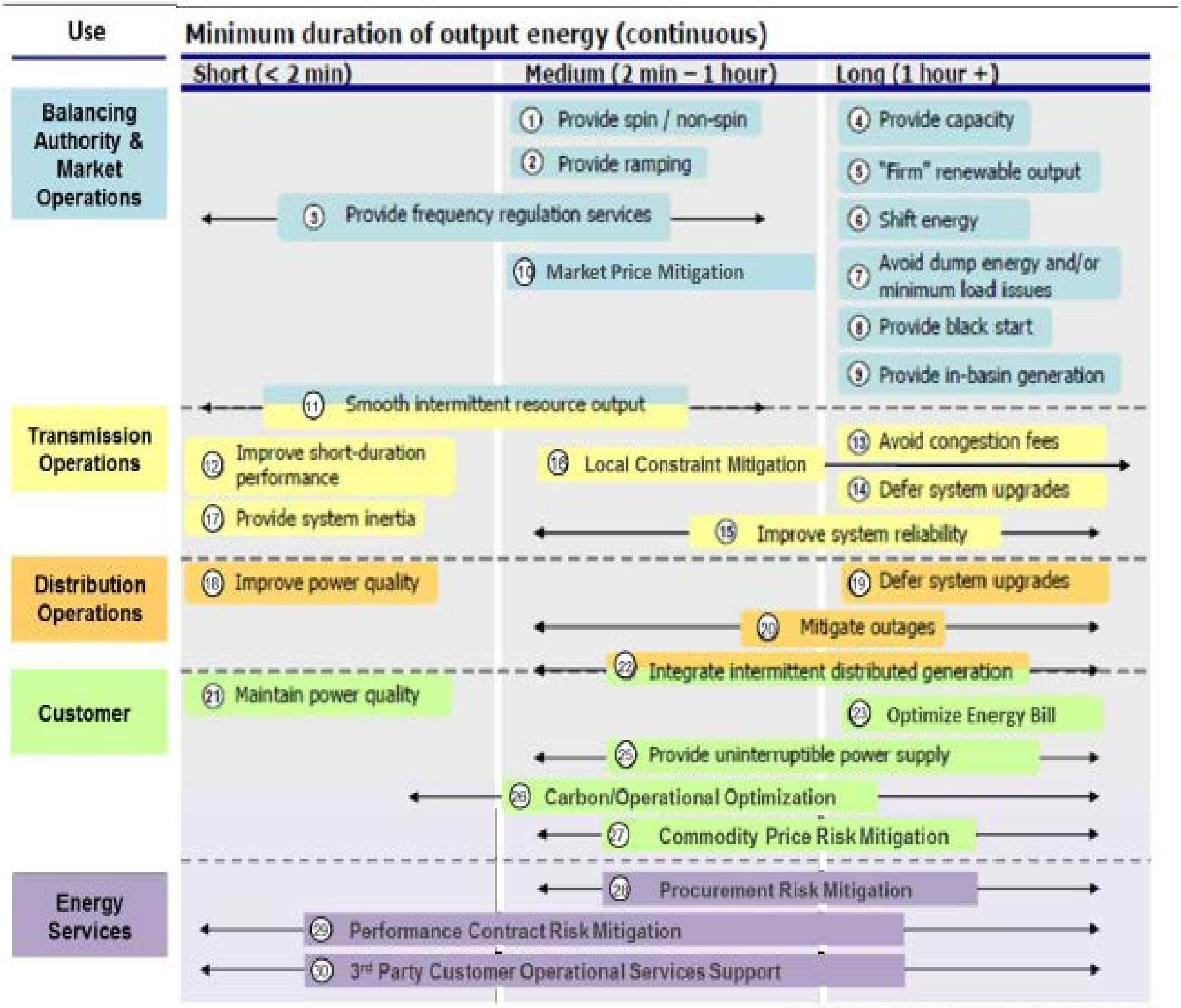
As described in Section 2.1 above, fundamental forces are driving a significant change in the electricity industry, and leading to the creation of a new energy paradigm. It is important to recognize that as the electric power system continues to evolve some business models may no longer be viable. However, opportunities now exist for businesses to avail themselves of opportunities by creating and sharing new value streams with customers, aided by new and innovative market designs and regulatory policies, as discussed in Section 4.1. In particular, the Transactive Energy Framework provides an opportunity for business models to evolve in a way that helps reconcile the need for increased customer choice and participation, while respecting the operational needs of the power system.

4.2.1 Customer Evolution and Value Streams

Growing penetration of DERs that are owned by customers or third-parties introduces change and opportunity for reformulation of business models. Utilities have the opportunity to engage the DERs as active elements of the overall electric power system and coordinate their flexibility to help alleviate problems introduced by variable resources and new variable loads. A key to achieving this coordination is clear understanding of both utility and DER owner value streams and respect for ownership boundaries. Building on these principles new business models may be defined.

4.2.1.1 Alignment of Value Streams

Fed by seemingly unlimited and increasingly accessible information, customer expectations (across the customer classes) of the reliability and quality of service, lower costs, and eco-friendly options are rising. In addition, customers have access to new revenue opportunities and value streams—aided by innovative market designs and regulatory policies—by providing services to the grid. Figure 7 shows 30 value streams that may conceivably be exposed to customers for providing services spanning across bulk power and distribution systems.



Source: SCE, Adapted by Newport Consulting

Figure 7: Value streams available to DERs.

Transactive energy approaches present an opportunity for utilities, in addition to third parties, to provide value-added services to customers and extend their business models beyond the regulated sphere. Viable transactive approaches, however, should introduce the opportunity to create and align value streams for all participating entities. In other words, the value realized by the distribution utility should not be at the expense of either the customer or the transmission system operator or the generator (the same applies for customer utility streams). The need for multi-objective (operational and economic) optimization requires this alignment. Existing business models may not support this value creation and alignment; they need to be examined from this point of view, adjusted when necessary, and in some cases new business models will emerge. This last point is especially true when considering the second-and third-degree opportunities that emerge from greater customer engagement for provision of various grid services.

4.2.1.2 Customer Choice

Customers are gaining the ability to have greater control over their energy supply and management options. To the extent that they exercise this capability, they evolve from passive consumers to active participants in managing the supply and delivery of electricity. This evolution, if adopted on a sufficiently large scale, could ultimately transform the entire electrical grid. Business models that use transactive approaches have the potential to extend greater control of customer assets to the customers themselves, while providing the necessary value streams to all participants.

Closely associated with the issue of customer choice is who controls any given asset. The most desirable outcome is that the asset owner controls the asset. The whole idea of transactive approaches is to provide an economic incentive for the owner to operate the asset in a beneficial manner that supports global optimization. The need to do this may be appreciated by considering the problem of coordinating the activity of millions of assets, spread across multiple utilities (and thus jurisdictions.)

4.2.1.3 Market Potential

The potential size of opportunity stemming from customer adoption of DERs and related services is difficult to quantify, but estimates from different sources suggests that it may total about $165 billion in incremental revenue through 2020. This rough estimate suggests that there is more than enough market opportunity to support lucrative new market ventures for utilities and other third-party service providers.

4.2.2 Adaptive Business Strategies

Given the technology-driven changes in electricity markets, and the need to tap into market potential, the challenge for utilities and third-party providers is to understand how the value chain in electricity markets is changing. This understanding should foster the development of business models that lead to proper alignment of values across the participating entities.

4.2.3 Business Value Creation and Capture

Delivering value to customers involves one of two approaches: *volume services* and *custom solution* oriented businesses. These two models are defined as follows:

- **volume**: a high transactional approach where significantly smaller dollar amounts and more frequent transactions with millions of customers are the objective
- **custom solution**: a complex-systems approach focused on growing a customer base of thousands with each generating a few high-dollar, high-margin transactions per year through customer intimacy.

With either approach, net operating margins will depend on the total value added, which in turn will depend upon three key factors: strategic platforms, control points, and sources of revenue, as described below. The business design concepts can be combined into successful business models as described in Section 4.2.3.4.

4.2.3.1 Platforms

Platforms are a set of information technology, physical infrastructure, and standardized business processes integrated to provide unique services. Two basic platform types apply to the volume services and custom solutions approaches, respectively:

- Volume businesses are increasingly using open marketplaces and portals (multi-sided interaction platforms) designed to enable multiple buyers and sellers to engage in a variety of transactions or simply find products and services.
- Custom solutions tend to rely on platforms that provide standardized business processes oriented to achieving specific desired enterprise or residential customer outcomes.

Depending on the business model (i.e., volume services vs. custom solutions) and value streams to be captured, a combination of different transactive mechanisms may be needed to properly align interests of all the participating entities.

4.2.3.2 Strategic Control Points

Every good business has at least one strategic control point (i.e., where influence can be exerted over the use of a value chain, or between networks of value chains to gain competitive advantage and improve profitability). Customer adoption of DERs has seen more utilities lose “control” over a substantial portion of their sales and profitability, not to mention the potential for additional reductions in sales due to energy efficiency measures. However, corresponding opportunities can add new value by providing network services and creating multi-sided platforms, using transactive mechanisms, that allow DER customers and others to realize the full value of their investments.

4.2.3.3 Revenue Models

Historically, the electricity industry has participated very narrowly by focusing on capturing value along the traditional electricity production-to-consumption value chain. Today, opportunities are available to capture additional value by “growing the pie” along other related dimensions. In fact, opportunities are already being monetized in the electricity industry in two of these dimensions. Including the conventional value chain, three degrees (dimensions) of value may be stated as follows:

1. Value from the primary energy channel; i.e., the traditional “core business” of the utility, including unregulated energy trading activities and support services such as energy efficiency and demand response programs.
2. Value from service/product sales through fees and revenue sharing from co-marketing, co-branding, or referrals that are related to the core business (e.g., appliance sales, energy equipment maintenance and financing).
3. Value from service/product sales that are not directly related to the core business, but are made possible by capitalizing on information/intelligence derived from the first two streams (e.g., non-energy related financial services, security, water-related services).

These three degrees of value can and are being combined to create more compelling business strategies for new and existing ventures. Transactive mechanisms will allow utilities to extend revenue streams beyond their core business via greater customer engagement for provision of grid services in return for monetary incentives; this will result in an alignment of the value streams of all interested parties. The values from the secondary and tertiary sources may be by-products of greater customer engagement fostering an eco-system of third-party providers of specialized services.

4.2.3.4 Business Models

The following discussion illustrates how the business design concepts above can be combined into successful business models that provide a variety of services using different transactive mechanisms.

Volume Services: Market Facilitator

One volume-based opportunity is to create an enabling platform for DER transactions among many market participants. It may be most natural for utilities to serve the role of market facilitators, although, other third-party providers may just as well be contracted to serve in such a role. Potential users of such a platform include not just retail commodity suppliers, but also demand response aggregators, third-party merchant DG and storage providers, and customers with excess distributed energy. In addition to recovering fixed infrastructure costs through access fees, incremental revenue might also be obtained from fees charged for managing transactions between participants—not unlike eBay and PayPal. This would include facilitating, clearing, and settling multi-party transactions related to bilateral and perhaps auction-based deals for DERs. It is likely that distribution utilities may also need to procure balancing services from these resources to manage distribution operations. Such services could include voltage and VAr optimization, phase balancing, and power routing, as well as coordination between distribution and transmission operations and bulk power markets. A transactive mechanism that fully aligns the interests of all participating entities—i.e., incentives for customer participation, as well as grid services at both bulk and distribution systems—would help maximize the value creation, and thus the revenue potential, of a business venture acting as market facilitator. Successful business ventures in this sphere would further serve to increase the penetration of DERs fostering an eco-system where providers of *custom solutions* proliferate as well.

Custom Solutions

Custom solutions involve a wide range of potential revenue sources. In addition to engineering solutions and energy portfolio management, direct revenues can be obtained from hedging services, brokerage services, operations and maintenance services, and supply management (including distributed resource aggregation). These services have been in existence since retail deregulation, but new indirect revenue opportunities are arising in the areas of lead generation and referrals, and third-degree opportunities may be possible from the sale of proprietary applications to non-competitive firms in other business sectors. Unique customer solution-based services have been provided by energy retrofit firms, onsite generation project developers, integrated energy service firms, energy brokers and information services firms, and commercial and industrial demand aggregators for more than two decades. The challenge has been that nearly all of these have faced at least three issues: 1) high customer acquisition costs, 2) difficulties in scaling operations profitably, and 3) inconsistent or limited revenue potential. Today, however, the convergence of expanded data management capabilities, sophisticated analytic models, cloud computing, and anywhere connectivity is allowing firms to develop new technology platforms that can form a new foundation for these businesses.

Business Benefits

Transactive mechanisms that properly align value streams across all interested parties will lead to greater proliferation of DERs. This in turn will lead to an increase in *volume services*, potentially leading to greater need for and provision of *custom solutions* as well. Utilities may be able to substitute volume services (and revenues) of one kind—provision of electrons—for a role as a market facilitator for better coordination and control of DERs, thereby extending the value streams.

4.3 *Conceptual Architecture Guidelines*

The purpose of this section is to provide guidance on the creation of a conceptual architecture for TE. This section does not provide such an architecture; that is, the work to be done by a core team of experienced system architects that and would represent the design of a specific example of a TE system. Rather, it suggests key elements and principles to be considered in the development of the Transactive Energy Conceptual Architecture (Figure 8), building upon principles and content that

- have been relied upon in previous related work, or
- have been useful in the development of TE concepts and frameworks to date, or
- represent the best thinking around methods and tools, as determined in the various GWAC workshops and working sessions on TE.

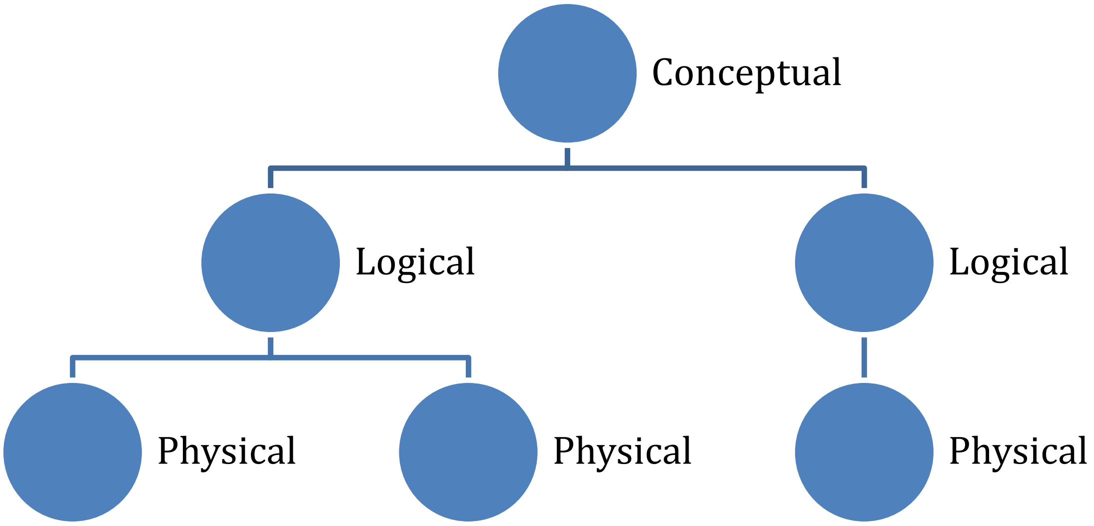


Figure 8: Transactive energy conceptual architecture

As depicted in Figure 8, conceptual architecture (also known as a reference architecture) is a top-level structural depiction of the abstract components, the relationships among these components, and the externally visible properties of these components. It does not specify how to implement any of the architectural elements; instead it provides the minimum number of constraints necessary to depict what needs to be done without specifying design decisions. A formal definition that has been of use in past GWAC and other architecture development work is as follows:

> A conceptual architecture is focused on the "what" aspect of the solution set. It is independent of any solution, and is benefits-driven. It provides a stable foundation for

architectural decisions that are made at the logical (how) and physical (with what) phases of the architecture process. A conceptual architecture supports one or more logical architectures and a logical architecture supports one or more physical architectures.

4.3.1 Guiding Architectural Principles

The GWAC recommends that a Transactive Energy Conceptual Architecture, like any architecture, be based on rigorous foundational principles wherever possible. To that end, the following principles are listed as starting points for the architectural foundation:

1. Strong consideration should be given to the inherent structure of the energy systems under consideration; the hierarchical structure of large-scale power delivery systems from the Balancing Authority to distribution grid endpoint on one hand, and the smaller scale less hierarchical structure of micro-grids on the other. Likewise, the existing control structure for involved energy systems should be considered when developing the structure of the TE architecture.
2. Self-similarity or an approximation may be evident in the relevant structures and should be considered as a means of obtaining scalability and organizational regularity (as a means of dealing with complexity), but recognize that differing goals may apply at different levels in the recursion.
3. Layering for optimization decomposition may be considered as a mathematical foundation for structure of the control and coordination portions of the architecture.
4. The architecture should be agnostic to the general physical layer (refer to the Control Abstraction Model): specific sensors and controls, energy types, etc., should not be specified nor eliminated by the architecture.
5. The ability of the TE system to operate should not be limited to any specific type of communications network or specific technology; e.g., it must not be limited to broadband Internet communications only.
6. The architecture should accommodate open international standards, and must not restrict implementations to proprietary interfaces, algorithms, communication protocols, or application message formats.
7. To the extent possible, the architecture should be adaptable to changes in underlying energy systems, in terms of structure, capabilities, business models, and innovation in value creation and realization.
8. The architecture should include plans for convergence of network types over time: physical networks (energy system infrastructures), information and communication networks, financial networks, and social networks.

4.3.2 Scope of the Conceptual Architecture for Transactive Energy

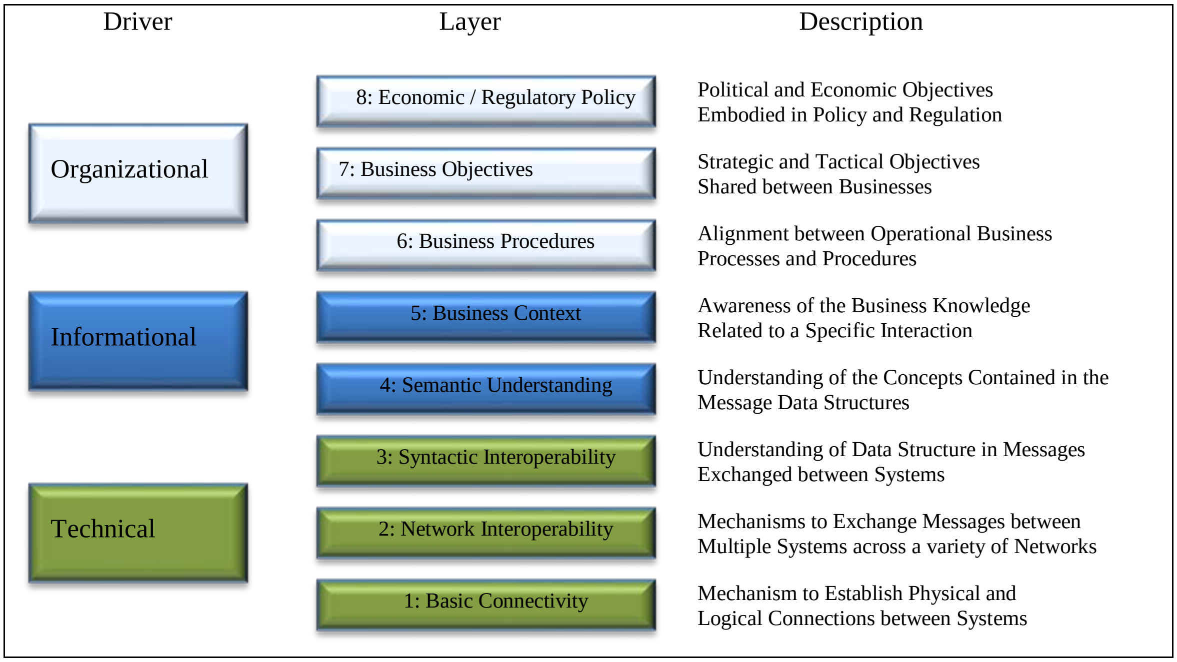
The scope of the conceptual architecture for TE must address the following elements:

- Reference Model: This is a depiction of the problem domain.
  - Domain diagram – graphical depiction of the problem space, showing key elements in relation to each other
  - Industry descriptions and emerging trends analyses
  - Key use case list – list of primary use cases as TE is understood today, with descriptions of each
  - Key systemic issues list – list of cross-cutting issues that apply without regard to a specific use case, but arise due to the fundamental nature of the problem

- Energy transaction mechanisms, regardless of the time relationship between the economic transaction and the energy make-move-use operation
  - Key abstract elements of TE architecture
  - Key properties of the elements
- Structure
  - Element relationships
  - Scalability
  - Resilience and anti-fragility
  - Manageability of ULS system effects
- Interfaces in a TE system to
  - traditional markets
  - distributed markets
  - traditional energy system controls
  - energy endpoints of any kind (make, move, use)
- Transactive Control
  - Transactive control abstract element and structure
  - Key properties of transactive control elements
  - Interface to traditional controls and energy markets
  - Integration with the existing power grid and other energy system control systems
- Coordination of transactive and traditional controls
  - Goal and structural alignment
  - Stability assurance
  - System and organization boundary deference
  - Multi-level constraint fusion
  - Control federation and disaggregation

4.3.3 Organizing Paradigms

The following are some of the key architecture models that have been used in the development of TE principles. The first two are the GridWise Architecture Council's Interoperability Framework (the GWAC Stack) in Figure 9 and the National Institute of Standards and Technology (NIST) Smart Grid Conceptual Model in Figure 10. One of the major benefits that TE management provides is an approach that can establish interoperability and integration across the entire energy value chain from bulk generation through end-use consumption and that can also convey objectives for one or more layers of the GWAC Stack. Within any layer, value can be determined for every objective or constraint, and by combining the values from all the layers, the needs of all layers can be represented at any interface point within or between domains in the Smart Grid Conceptual Model.



Driver	Layer	Description
Organizational	8: Economic / Regulatory Policy	Political and Economic Objectives Embodied in Policy and Regulation
	7: Business Objectives	Strategic and Tactical Objectives Shared between Businesses
	6: Business Procedures	Alignment between Operational Business Processes and Procedures
Informational	5: Business Context	Awareness of the Business Knowledge Related to a Specific Interaction
	4: Semantic Understanding	Understanding of the Concepts Contained in the Message Data Structures
Technical	3: Syntactic Interoperability	Understanding of Data Structure in Messages Exchanged between Systems
	2: Network Interoperability	Mechanisms to Exchange Messages between Multiple Systems across a variety of Networks
	1: Basic Connectivity	Mechanism to Establish Physical and Logical Connections between Systems

Figure 9: The GridWise Architecture Council's Interoperability Framework [4].

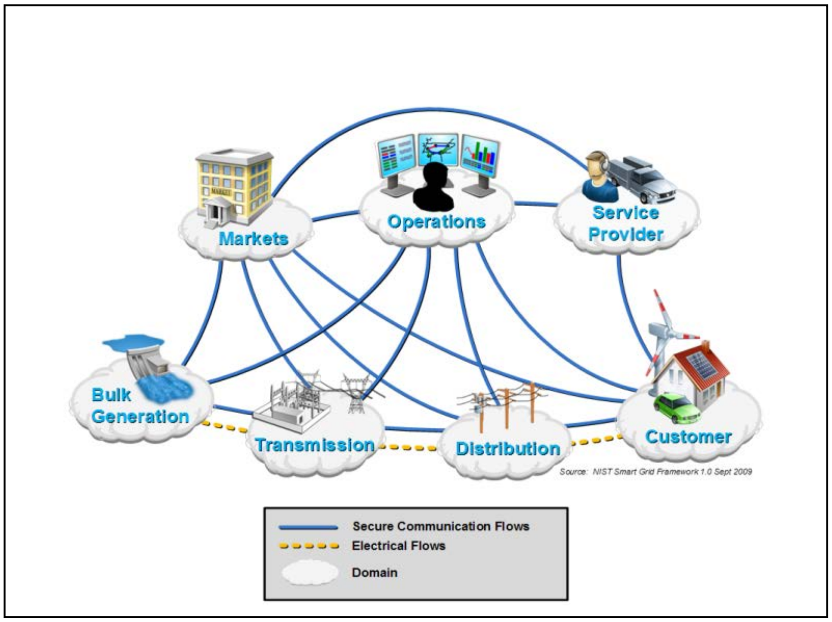


Figure 10: NIST Smart Grid Conceptual Model [19]

Transactive energy management is a relatively simple and flexible concept that can map onto any part of the electricity value chain, as discussed above. The Grid Vision 2050 Transactive Energy Abstraction Model in Figure 11 captures this thought: any transactive entity in the system can be decomposed using this model [10]. A good example is a storage entity that can at times be a user of energy or a maker (supplier) of energy. It can both respond to requests from other transactive entities in the system and it can issue requests to other entities.

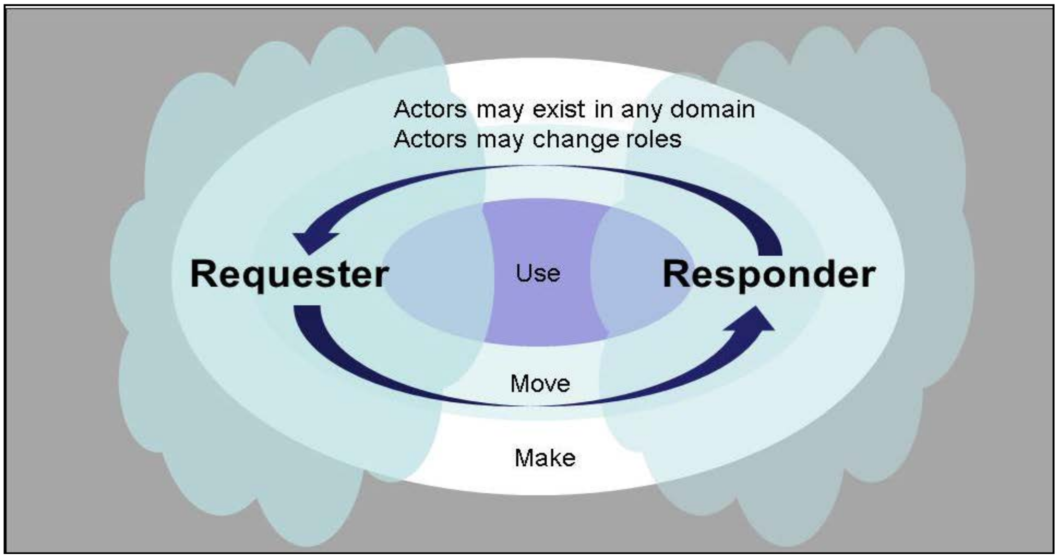


Figure 11: Grid Vision 2050 Transactive Energy Abstraction Model.[4]

Finally, because TE management is intended to address both business and operational issues in the system, it is helpful to understand how a traditional control abstraction model maps to the GWAC Stack, as shown in Figure 12. This helps put the concept of cyber-physical systems in context for TE management.

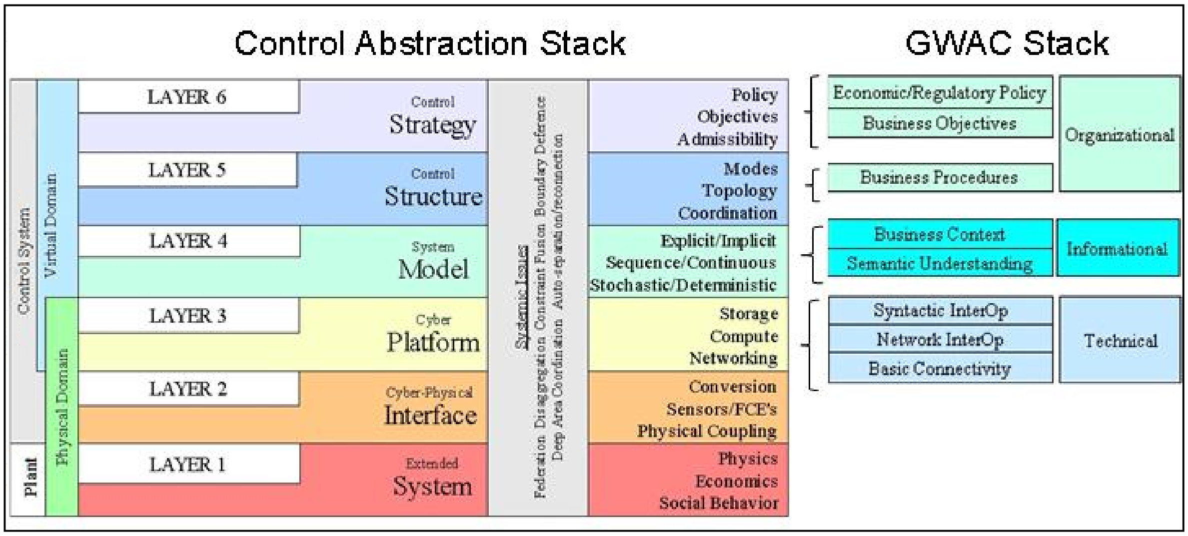


Figure 12: Integrated Control Abstraction Stack/GWAC Stack Model.

---

[4] Used with permission of EnerNex.

4.4 *Cyber-Physical Infrastructure*

The Cyber-Physical Infrastructure deals with the technical layers of the GWAC Stack, and the physical layers of the Control Abstraction Stack. The power grid architecture includes two cyber-physical networks—the electrically connected network and the communications networks necessary to monitor and control it. When the grid was first instantiated, there was no communications network of any kind, so the grid was designed to deliver power with highly optimized local control to protect equipment and support safe operation of the grid. As the grid has evolved, an increasingly pervasive communications network has emerged to support the ever-increasing demands on grid infrastructure and to ensure the continued safe and reliable operation of the grid as a system of systems.

The physical power grid is made up of a large number of interconnected networks; each of these networks grew independently to support local customers and then was connected to a larger, higher-voltage network to interconnect the local networks. Over time the local networks have acquired the name "distribution network" or "distribution grid" and the higher-voltage network has acquired the name "transmission network" or "transmission grid"; for the purposes of this section they will be referred to as distribution and transmission, respectively.

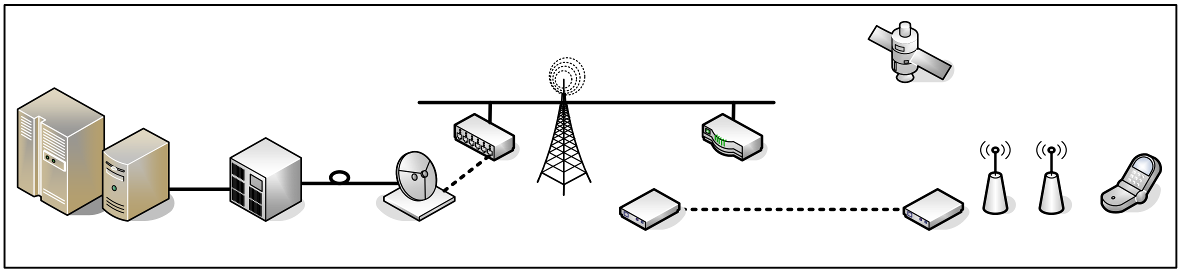


Figure 13: Grid communications technologies.

Because of the decentralized nature of the design and construction of the network, there are few common standards and the transmission SCADA systems is largely regionalized at best. Each operator working with its chosen vendors evolved its protocols as needed to support specific sections of the grid.

Transactive energy applications will operate in both the cyber domain, making use of the communications infrastructure, and the physical domain, delivering electricity products and ancillary services.

As we evolve the grid further to support the concepts and goals of TE, we must transform the cyber-physical elements of the grid. New sensors, actuators, and distributed and centralized control elements not necessary for the traditional operation of the grid must now be deployed. Existing, or legacy, systems must be pressed into service to support applications they were not originally designed to support. These devices and systems must support information gathering and automation in a manner that is much more flexible than has been needed for operating the traditional grid. Specifically, features such as asynchronous information exchange, staged data filtering and pruning, and layered and loosely decoupled system interactions are needed to enhance flexibility.

The integration of information technology and telecommunications with the traditional electric delivery infrastructure can introduce new vulnerabilities that must be addressed. Information security standards and methodologies have made tremendous progress in the past 10 to 15 years, but they require adaptation to meet the unique requirements of the electric power industry and the continuing evolution of hacking capabilities. Because security weaknesses can potentially be exploited to disrupt service over a wide portion of the grid, the costs of disruption can be high.

Security relates to both intentional attacks on the system as well as weaknesses and vulnerabilities that lead to unintentional failures, errors, and sub-optimal performance of system components and operations.

To make the grid work the way it needs to over time, new sensors, from relays and line sensors on the distribution system, to meters at the customer premises and updated sensors on the transmission grid are required. Initially TE systems will be overlaid on the existing system, using what is available to “make do.” But as things evolve, and sensors and other equipment are deployed, the system will become more robust and will be able to benefit from the newly introduced capabilities.

Today’s demand response programs (distributed generation, storage, and other possible energy elastic items connected to the grid) are a hodge-podge run by separate and disparate organizations, including ISOs, distribution utilities, aggregators, and retailers. While these work reasonably well, each operates independently of the others, and most require one or more operators in the loop to activate and monitor the demand response event.

One of the integrating roles of TE is to provide a translation and communications capability between demand response programs. This will allow an operator at the highest level in the system to send signals to the various operators and entities that run the grid, all the way to customer premises where the customer-programmed devices or the customer themselves can make a decision about whether to respond to the signal or not.

These multiple levels of control differ greatly from what exist today in that they require end-to-end communications, with interoperability between systems. Also, multiple parties influence the decision criteria at the various levels. Transactive energy solutions may be well suited to support these requirements, and should include the following design considerations:

- asynchronous information exchange
- disengaged data
- staged data filtering and pruning
- layered and loosely coupled system interactions
- customer device-based decision making (or the customer themselves directly)
- distributed control and control programming.

4.4.1 Hierarchy of Node Levels

There is a hierarchy of physical and logical levels in the current power grid across which TE systems and mechanisms would operate. The characteristics of the nodes within these different levels are relevant to TE. For purposes of discussion in this section messages originate at the top and flow down to lower nodes. It should be noted that this is just one example and that in the future one should expect messages to originate at any point in the system and flow from there as we move to more distributed systems.

4.4.1.1 Regional Nodes

At the highest level is a regional node, which is responsible for balancing a region. This regional node is responsible for millions of possible customers and a large number of energy sources, for instance, the Midwest ISO (MISO) is responsible for more than 130,000 MW of generation, 526 TWh of energy billed, and 48 million people served. This regional node is an example of the highest level of operational coordination that exists today and probably would be the highest level of node in an initial TE system.

Approximately a dozen of this type of node exist in North America. Each of these nodes already has a wholesale market with its own transaction architecture for energy, ancillary services, and hedging. Each regional node would be the origination point for wide-area TE messages, as well as more targeted messages that might focus on a single geographic area in the region (e.g., the MISO might focus a TE message on the Chicago area to reduce transmission congestion).

4.4.1.2 Control Area Nodes

The next level down would be a legacy control area containing a control center and its AGC system. These control areas tend to be much smaller than regional nodes, but all of New York City is in a single control area. The largest control areas cover more than 10 million people. When it comes to TE transactions a control area would receive TE transactions from a regional node, and translate that transaction into transactions to be sent onward to the generation units in its AGC and potentially to large customers who have either generation or demand response contracts, as well as on to distribution operators.

4.4.1.3 Distribution Nodes

Control areas can be made up of one or more legacy distribution systems, and each distribution system typically has a unique way of communicating with connected customers. It might be through an automated metering system, via text message, or via a radio station. The variety of methods means that each distribution node has to translate TE transactions that it participates in with other nodes into messages that are supported by its local systems.

Distribution nodes typically support less than 1 million customers, but a few can be as large as 10 million customers. There are more than 4,000 legacy distribution systems across the country, many of which have been aggregated into larger distribution networks, while retaining many of their unique characteristics.

At the conceptual level there are no differences between distribution nodes and control area nodes.

4.4.1.4 Market Participation Nodes

Market participation nodes serve a single market participant. In the case of MISO there are approximately 100 market participants. Many market participants are active in two or more regions.

4.4.1.5 Supply Nodes

Supply nodes cover any location that can provide additional generation from any source, whether it is a generator, a large manufacturing site that can switch to its own generation, or another site that can provide assured supply on a verifiable basis and at a known ramp rate. Supply nodes can be as large as 3,000 MW or as small as 1 W (though realistically supply nodes will probably be larger). By definition these nodes are registered with the regional node, or the control area node, and have a contract for services with that node.

4.4.1.6 Building Nodes

Building nodes represent any premises or loads that are connected to the overall system. This includes all customers of the distribution system. In some cases, the “building” is actually an equipment cabinet or even an electric vehicle and its charging equipment, potentially capable of supplying electricity to the distribution system. Ninety-nine percent of building nodes that are available are less than 5,000 square feet in size and on average draw less than 20 KW of power.

4.4.2 Transaction Train

At each level in the transaction chain shown in Figure 14 not only is a pure translation being done, but additional constraints or local parameters are added to the mix. For example, if a premises has a limitation of not raising the building temperature above 78 degrees and it is 77 degrees now, the premises may provide less in the way of response than if it either did not have the constraint or the current temperature were 72 degrees.

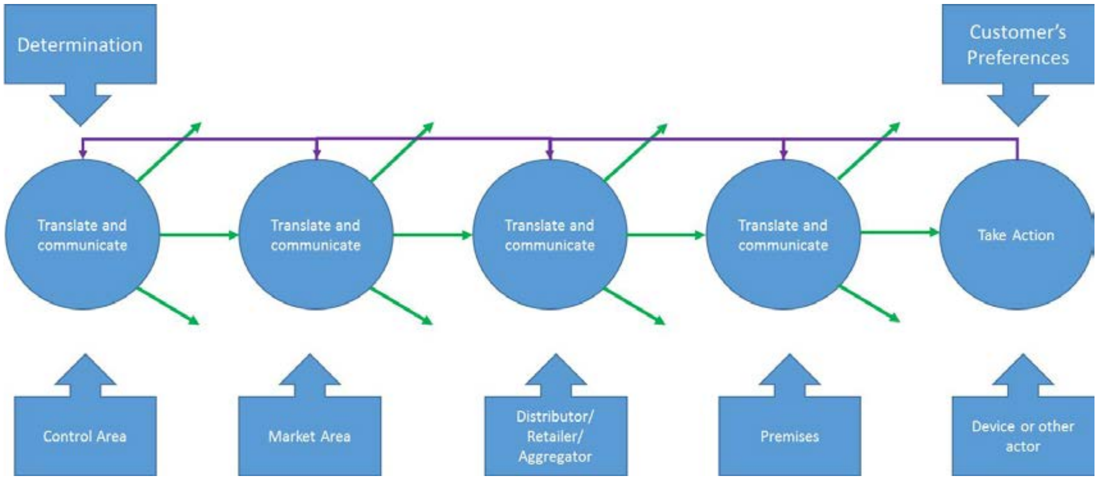


Figure 14: Transaction train model.

This example shown in Figure 14 is a logical view of one way to create a TE system. The message flow does not have to follow a hierarchy. It might be peer-to-peer, or it might jump from the regional node directly to the premises, which may respond very differently than it would have the day before. At the premises node level in residential premises appliances, lighting circuits, and consumer electronics will get smarter. These improvements in consumer products will be developed, not because of TE or the needs of the grid, but because the consumers will demand better control of their devices and controls that are easier to use [20]. As these references show, consumer electronics companies may find profitable business opportunities in supported smart grids including TE. Transactive energy features might be embedded in consumer products or in an energy management agent (as specified, for example, in the international standard for energy management [21]), so that transactions occur automatically according to parameters set by the customer.

Transactive energy can ride on these customer desires and provide yet another function for residential customers to use as they choose. Monitoring equipment at the breaker panel or at the meter for consumption and other power characteristics will eventually be available and be installed, either by the utility, by builders who want to be seen as leading edge, or by customers who want the neat new shiny toys. How it gets done does not matter, nor does the speed of the evolution, because as each node adds devices, these devices can, with the customer's consent, be added to the overall TE system.

Done early enough, and supporting the translation between enough existing protocols, TE can tie the different levels of the electrical system together into one interoperable whole. Providing customers with more choices and control, while reducing wasted energy and maximizing the value of new investments in the overall electrical system.

4.4.3 Node Characteristics and Responsibilities

Table 1 summarizes some of the characteristics of the various different types of nodes just discussed, along with the responsibilities of the nodes within a TE system, and the potential impact that disruption or failure of the node may have.

Table 1: Summary of node characteristics and responsibilities.

Level	Number (U.S.)	Transactive Energy Responsibilities
Regional	<20	1) Creating initial transactions
		2) Securing transactions in an approved fashion
		3) Transmitting transactions to an approved list of receivers
		4) Receipt, verification, acknowledgment of downstream messages
		5) Translation of downstream messages into information for the operators
		6) Logging and auditing transactions
Control Area	~200	1) Receipt, verification, acknowledgment of regional messages
		2) Translating regional messages into messages for lower level nodes
		3) Transmitting transactions to lower level nodes in a secure fashion
		4) Receipt, verification, acknowledgment of downstream messages
		5) Translation of downstream messages for transmission upstream
		6) Transmitting downstream messages upstream in a secure fashion
		7) Logging and auditing transactions
Distribution	~1500	1) Receipt, verification, acknowledgment of upstream messages
		2) Translating regional messages into messages for lower level nodes
		3) Transmitting transactions to lower level nodes in a secure fashion
		4) Receipt, verification, acknowledgment of downstream messages
		5) Translation of downstream messages for transmission upstream(a)
		6) Transmitting downstream messages upstream in a secure fashion*(a)
		7) Logging and auditing transactions

Table 1: (contd)

Level	Number (U.S.)	Transactive Energy Responsibilities
Market Participant	~500	1) Receipt, verification, acknowledgment of upstream messages
		2) Translating regional messages into messages for lower level nodes
		3) Transmitting transactions to lower level nodes in a secure fashion
		4) Receipt, verification and acknowledgment of downstream messages
		5) Translation of downstream messages for transmission upstream (a)
		6) Transmitting downstream messages upstream in a secure fashion(a)
		7) Logging and auditing transactions
Supply	~10,000	1) Receipt, verification, acknowledgment of upstream messages
		2) Translating transactions into local action
		3) Responding upward with actions taken or not taken

		4) Logging and auditing transactions
Building	~150,000,000	1) Receipt, verification, acknowledgment of upstream messages
		2) Translating transactions into local action
		3) Responding upward with actions taken or not taken

(a) If there are downstream nodes; most market participants will be end nodes.

5. Next Steps

The conceptual framework outlined in this report is intended to be a starting point for further work in developing architectures and designing solutions related to TE. We welcome feedback on this document and encourage smart grid researchers and practitioners, and other interested parties, to adopt these framework concepts and terminology for their discussions within the growing TE community.

Only by reviewing and debating the material and engaging with practitioners of energy markets will we understand whether this Transactive Energy Framework is realizing its objectives and how it can be refined to become an instrument of value.

Appendix A has a template for using the attributes of TE to describe specific TE systems. We invite others to use the template to document case studies of their TE systems. This will help test the definition and attributes defined in this framework and allow for discussion and comparison of different TE systems.

6. Governance

The Transactive Energy Context-Setting Framework is a living, evolving document that is intended to engage the community and provoke comments from those involved in TE and related issues related to the electric power system. A mechanism to correct, to update, and to clarify this framework and its derivative material is necessary.

A draft version of this document was publicly released in November 2013. Based on comments on that draft the document has been updated and Ver. 1.0 was published in January 2015.

7. Acknowledgments

The creation of this document has been a collaborative effort of the GridWise Architecture Council. Particular recognition is given to the members of the Transactive Energy Framework Team and supporting contributors.

Members of the GridWise Architecture Council when the draft of this document was created were Mark Knight (GWAC Chairman), Ron Ambrosio, H. Ward Camp, Paul De Martini, David Forfia, Jeff Gooding, Erich Gunther, Doug Houseman (Associate member), Alexander Levinson, Tracy Markie, James Mater, Thomas Sloan, Jeffrey Taft, and Kenneth Wacks.

The Pacific Northwest National Laboratory (PNNL) Team supporting the effort included Ron Melton (GWAC Administrator), Sherry Kowalski (GWAC Coordinator), Abhishek Somani, and Andrew Steckley.

Others who were involved in many of the Council meetings, workshops, and conferences resulting in the Framework include Ed Cazalet, Bill Cox, Ali Ipakchi, Terry Oliver, Farrokh Rahimi, and GWAC Emeritus Members Robert Burke and Dave Hardin.

PNNL’s support of the efforts of the GWAC in development of this document has come from the U.S. Department of Energy’s Office of Electricity Delivery and Energy Reliability and from the Office of Energy Efficiency and Renewable Energy. DOE staff involved have included Chris Irwin, Dan Ton, and Joe Hagerman.

The Council thanks those who took the time to read the draft version released in November 2013 and supply comments.

8. Glossary

ACE (area control error)

The instantaneous difference between a Balancing Authority's net actual and scheduled interchange, taking into account the effects of Frequency Bias and correction for meter error.

AGC (automatic generation control)

Equipment that automatically adjusts generation in a Balancing Authority Area from a central location to maintain the Balancing Authority's interchange schedule plus Frequency Bias. AGC may also accommodate automatic inadvertent payback and time error correction.

ancillary services

The services necessary to support the transmission of capacity and energy from resources to loads while maintaining reliable operation of the Transmission Service Provider's transmission system in accordance with good utility practice (from FERC Order 888-A [22].) Ancillary Services can include synchronized reserves, regulation and operating reserve, energy imbalance (using market-based pricing), and the cost-based services of scheduling, system control and dispatch, voltage control and black start.

architecture

"The fundamental organization of a system, embodied in its components, their relationships to each other and the environment, and the principles governing its design and evolution" [23].

congestion

A condition that occurs when insufficient transfer capacity is available to implement all of the preferred schedules for electricity transmission simultaneously.

cyber-physical

A system of collaborating computational elements controlling physical entities.

demand response

Changes in electric usage by end-use customers (including automatic responses) from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.

distributed energy resources (DERs)

A device that produces electricity and is connected to the electrical system, either "behind the meter" in the customer's premises, or on the utility's primary distribution system. A DER can use a variety of energy inputs including, but not limited to, liquid petroleum fuels, biofuels, natural gas, solar, wind, and geothermal. Electricity storage devices can also be classified as DERs. Some definitions also include demand response as a form of DER.

distributed generator or generation (DG)

A generator or generation that is located close to the particular load that it is intended to serve. General, but non-exclusive, characteristics of these generators include an operating strategy that supports the served load, and interconnection to a distribution or sub-transmission system.

framework

The description of a system at a high, organizational or conceptual level that provides neutral ground upon which a community of stakeholders can discuss issues and concerns related to a large, complex system.

Home Energy Management System (HEMS)

A system that regulates the energy within a household, controlling devices with the goal of achieving optimal energy usage and providing consumers with important information about their energy consumption.

HVAC

heating, ventilation, and air-conditioning

ISO (independent system operator)

An independent entity that coordinates regional transmission in a manner that is non-discriminatory against any transmission owners, operators, or users, and ensures a safe and reliable electric system.

interoperability

The capability of two or more networks, systems, devices, applications, or components to exchange and readily use information—securely, effectively, without intervention by the user or operator. In the context of the smart grid, systems are interoperable if they can exchange meaningful, actionable information. This means they must share a common meaning of the exchanged information, and that the information can elicit agreed-upon types of response.

LSE (load-serving entity)

Secures energy and transmission service (and related Interconnected Operations Services) to serve the electrical demand and energy requirements of its end-use customers.

market

An area of economic activity in which buyers and sellers come together and the forces of supply and demand affect prices.

microgrid

A microgrid is an electrical system that includes multiple loads and distributed energy resources that can be operated in parallel with the broader utility grid or as an electrical island.

PV

Photovoltaic, solar power technology that turns sunlight directly into electricity.

prosumer

A term coined by Alvin Toffler to describe a producing consumer. From a smart grid perspective, it would apply to distributed energy resource situations in which the owner of electricity production or storage assets may also have a consumer relationship with a utility, aggregator, or other energy services provider [24].

RTO (regional transmission operator)

A federally regulated independent entity that is responsible for managing all transmission facilities under its control, maintaining grid stability, and matching electricity demand to supply.

An RTO performs the same functions as an ISO, but has added responsibilities for the transmission network as mandated by the Federal Energy Regulatory Commission (FERC).

reliability

A measure of the ability of the system to continue operation while some lines or generators are out of service. Reliability deals with the performance of the system under stress.

renewable energy resources

Energy resources that are naturally replenishing. Renewable energy resources include biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

resilience

The ability to resist failure and rapidly recover from a breakdown [24].

SCADA (supervisory control and data acquisition)

SCADA systems are highly distributed systems used to control geographically dispersed assets, often scattered over thousands of square kilometers, where centralized data acquisition and control are critical to system operation [25].

smart grid

The term adopted by the industry for the utility power distribution grid enabled with information technology and two-way digital communications networking, allowing for enhanced and automated monitoring and control of electrical distribution networks for added reliability, efficiency, and cost-effective operations.

transaction

An exchange or transfer of exchangeable products, services, rights, or funds.

value

Value is defined broadly to include both quantitative economic value stated, for example, in terms such as $/kWh, and non-quantitative values such as comfort, savings, or other expressions of value that may come from a consumer. One of the challenges in implementing TE systems is to define mechanisms for “assignment of value” to translate between qualitative expressions of value or engineering parameters that need to be stated in terms of quantitative value.

value stream

Sequence of activities required to design, produce, and provide a specific good or service, and along which information, materials, and worth flows.

virtual power plant

A technical, operational, and economic construct that aggregates distributed supply and demand resources in a manner that enables an operator to treat the DERs as if they were a single power plant.

9. References

1. APS Panel on Public Affairs. 2010. *Integrating Renewable Electricity on the Grid*, Report, 40 pp. American Physical Society: Washington, D.C. Available online: http://www.aps.org/policy/reports/popa-reports/upload/integratingelec.pdf.
2. Taft, J. and P. De Martini. 2013. *Ultra-large scale control architecture*. in *Innovative Smart Grid Technologies (ISGT), 2013 IEEE PES*.
3. U.S. E.I.A. 2014. *Annual Energy Outlook 2014*, Report No. DOE/EIA-0383(2014), 269 pp. U.S. Energy Information Administration: Washington, D.C. Available at http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf.
4. GridWise Architecture Council. 2008. *GridWise Interoperability Context-setting Framework, v1.1*, 52 pp. GridWise Architecture Council: Richland, WA. http://www.gridwiseac.org/about/publications.aspx.
5. De Martini, P., K.M. Chandy, and N.A. Fromer. 2012. *Grid 2020: Towards a Policy of Renewable and Distributed Energy Resources*. Resnick Institute, California Institute of Technology: Pasadena, CA.
6. Kind, P. 2013. *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business*, Article, 26 pp. Edison Electric Institute: Washington, D.C. Available online: http://www.eei.org/ourissues/finance/Documents/disruptivechallenges.pdf.
7. De Martini, P. 2013. *DR 2.0: A Future of Customer Response*, Report (PDF), 58 pp. U.S. Department of Energy/Federal Energy Regulatory Commission: Washington, D.C. Available at http://www.demandresponsesmartgrid.org/Resources/Documents/FINAL_DR%202.0_13.07.08.pdf.
8. Kintner-Meyer, M., K. Schneider, and R. Pratt. 2007.*Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids: Part 1: Technical Analysis*. Online Journal of EUEC 1, (paper # 04).
9. Burrus, D. 2014.*Improve Planning By Separating Hard Trends From Soft Trends*. Huffington Post - The BLOG, (28 February): p. Available online: http://www.huffingtonpost.com/daniel-burrus/improve-planning-by-separ_b_4774287.html.
10. IEEE. 2013.*IEEE Smart Grid Research: Power*, in *IEEE Grid Vision 2050*. IEEE: Piscataway, NJ. ISBNs: 9780738183749, 9780738183732. p. 93.
11. von Meier, A. 2012. *To 33% and Beyond: Grid Integration Challenges for Renewable Generation*, in *UCLA Smart Grid Thought Leadership Forum*. Council on International Educational Exchange: Los Angeles, CA.
12. GWAC. 2014. *GridWise Architecture Council - Transactive Energy Flyer*, Flyer, 1 p. GridWise Architecture Council: Richland, WA.
13. U.S. Energy Information Administration. 2013. *U.S. electricity sales have decreased in four of the past five years*. Today in Energy [Daily Blog] [cited 19 January 2015]; Website:[Online Article]. Available from: http://www.eia.gov/todayinenergy/detail.cfm?id=14291.
14. McDermott, K. 2012. *Cost of Service Regulation in the Investor-Owned Electric Utility Industry: A history of adaptation*, PDF Report, 60 pp. Edison Electric Institute (EEI): Washington, D.C. Available at http://www.eei.org/issuesandpolicy/stateregulation/documents/cosr_history_final.pdf.
15. Knight, M. and N. Brownell. 2010. *How Does Smart Grid Impact the Natural Monopoly Paradigm of Electricity Supply? Part I* Online Article (PDF), 22 pp. GridWise AC: Richland, WA. Available at http://www.gridwiseac.org/pdfs/forum_papers10/knightp_gi10.pdf.
16. Feiler, P., et al. 2006. *Ultra-Large-Scale Systems: The Software Challenge of the Future*. B. Pollack, Editor. Software Engineering Institute of Carnegie Mellon University: Pittsburgh, PA. Available at http://resources.sei.cmu.edu/asset_files/Book/2006_014_001_30542.pdf.

17. GridWise Alliance. 2014. *The Future of the Grid: Evolving to Meet America's Needs,* Report, 40 pp. GridWise Alliance: Washington, D.C.
18. De Martini, P. 2013. *Transactive Energy*, in *1st International Conference and Workshop on Transactive Energy*. GridWise Architeture Council: Portland, OR. Available at http://www.gridwiseac.org/pdfs/gwac_tec_052313/tec_2013_proceedings_pnnl_sa_96361.pdf.
19. NIST. 2011. *Draft NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0*, NIST Special Publication for public comment. National Institute of Standards and Technology: Washington, D.C. Available at http://www.nist.gov/smartgrid/.
20. Wacks, K. 2011.*Smart Grid Impact on Consumer Electronics*. iHomes & Buildings, **8**(3).
21. ISO/IEC. 2012. *ISO/IEC 15067-3: Part 3: Model of a demand – response energy management system for HES*, in *Information Technology - Home Electronic System (HES) application model*, Standard ISO/IEC 15067-3. ISO/IEC: Geneva, Switzerland.
22. FERC. 1997. *Promoting Wholesale Competition Through Open Access Non-discriminatory Transmission Services by Public Utilities; Recovery of Stranded Costs by Public Utilities and Transmitting Utilities*, in *Order N. 888-A*. Federal Energy Regulatory Commisssion: Washington, D.C.
23. ANSI/IEEE. 2000. *IEEE Recommended Practice for Architectural Description for Software-Intensive Systems*, Standard 1471-2000. IEEE Standards Association: Washington, D.C. Available at http://standards.ieee.org/findstds/standard/1471-2000.html.
24. Hertzog, C. 2012. *Smart Grid Dictionary*. 4th ed. http://www.smartgridlibrary.com/publications/: GreenSpring Marketing, LLC.
25. NIST. 2007. *NIST Guide to Supervisory and Data Acquisition - SCADA and Industrial Control Systems Security*. NIST: Washington, D.C.
26. ISO/IEC. 2004. *Guidelines for product interoperability*, in *Information Technology - Home Electronic System*, Standard ISO/IEC 18012. International Standards Organization/International Electrotechnical Commission: Geneva, Switzerland.

Appendix A: Case Studies

The case studies provided in this appendix make use of the following standardized template. Use of this template by others in describing transactive energy (TE) case studies is encouraged.

Title of the Case Study

Case study characteristics and objectives

(Provide a description of the overall case study. Who sponsored it? What were the primary objectives? When was it implemented? What was the size and scope of deployment? What were relevant results and findings?)

Transactive Energy Attributes

a) **Architecture**

All TE tools and methodologies are described as constituents or subsystems of a system architecture. A key distinction is whether the architecture is centralized, distributed, or a combination of the two.

(Describe the basic architecture. Is it distributed vs. centralized? ...hierarchical?...)

b) **Extent**

An implementation of TE technology will typically apply within some geographic, organizational, political, or other measure of extent. A geographic extent, for example, might be within a region and apply across multiple participating entities. An extent may be described organizationally, for example, if an implementation is intended for use within a single utility, building, or campus. Likewise, a transactive technique may apply across political boundaries with different regulatory or policy constraints. Extent may also be considered relative to the topology of an electrical infrastructure including end-users. Thus, a transactive technique may apply in transmission, distribution, or both; it may also be useful for managing energy within buildings or by end-users of electrical energy.

(How do the transactive activities extend across geographic, organizational, political domains?)

c) Transacting parties

Fundamentally, TE involves transacting parties. In most cases these will be automated systems, possibly acting as surrogates for human parties. In some cases humans may be in the loop. A TE mechanism must be explicitly describable by the entities that are parties to transactions. Because a TE system will provide services to different parties, its success in delivering these services will depend in part on the expectations and needs of each group and in part on the qualities of the delivered service.

(Describe the parties taking part in the transactions. These may be intelligent systems and nodes, or human participants.)

d) **Transaction**

A transaction is simply a negotiated exchange of things. This also applies in TE where it is a communicative activity involving two or more parties that reciprocally affect or influence each other through a formal mechanism in order to reach an agreement. These agreements must not be one-time agreements but must be subject to continuous review, *and multiple agreements that may take place as frequently as sub-second timing. Rules need to be specified for every transactive system such that interdependent operations on the system are either all completed successfully or all canceled successfully.*

(Identify the economic signals involved and their sources. What is the definition of a "transaction" within the system? Describe the purpose and form of transactions. What values are exchanged between participants?...Automated, or human interactive? …)

e) Transacted commodities

What is transferred or exchanged between the transacting parties? This will typically be energy but could be derivative products.

(Describe the commodity or commodities exchanged in the transactions.)

f) Temporal variability:

Transactive elements interact across multiple time scales. For example, transactions within a single system may range from sub-second to five minutes or to some longer periodicity. It is also possible for transactions to be event-driven. In characterizing a given transactive approach the time scale(s) of transactive interactions need to be specified and analyzed for compatibility.

(Describe the time scales involved in the transactions. Are they event-driven transactions?)

g) Interoperability

Transactions are enabled through the exchange of information between transacting parties. There are two elements to consider here: technical interoperability and cognitive (semantic) interoperability. The systems have to be able to connect and exchange information (emphasizing format and syntax), and they have to understand the exchanges in the context that was intended in order to support workflows and constraints. For any given transaction, the information exchanged during a transaction must be explicitly identified. Furthermore, one should be able to explain how interoperability has been addressed in support of the information exchanges. specified and analyzed for compatibility.

(Describe the level of interoperability between transacting parties. Is there technical interoperability present? Is there cognitive or semantic interoperability present?)

h) **Value discovery mechanisms**

A value discovery mechanism is a means of establishing the economic or engineering value that is associated with a transaction. The value discovery mechanism is a key element of value-driven multi-objective optimization. Value realization may take place through a variety of approaches including an organized market, procurement, a tariff, an over-the-counter bilateral contract, or a customer's or other entity's self-optimization analysis. Value discovery mechanisms should include considerations of economic incentive compatibility and acceptable behavior.

(Describe how the operative economic or engineering values of completed transactions are determined. Is it pulled from an organized market? Or tariff? Or is it negotiated bilaterally?)

i) **Value assignment**

Assignment of value is fundamental to value discovery. For sub-elements of a TE mechanism, a means may be needed to assign value for the objectives that cannot be addressed through a discovery mechanism, values that are needed by the discovery *mechanism, or for values that do not have a common dimension that can be used for valuation.*

(Describe how the participating parties determine subjective value. This is the value that they assign to their particular objectives, and by which they would determine the acceptability of a proposed transaction.)

j) **Alignment of objectives**

A key principle in TE is the continuous alignment of multiple objectives to achieve optimum results as the system operates. This alignment enhances the economic and engineering impacts of the dynamic balance(s) achieved by TE. Note that optimal relates to the balance of the entire transactive system, and to achieve an optimum balance it is necessary to optimize objectives, variables, and constraints. It is important to understand that optimization does not simply add intelligence to existing business processes. It changes business practices.

(How are the objectives of each participant advanced by the transaction, as well as the objectives of other stakeholders not directly participating in the transaction? Do the transactions result in win-win-wins—such that not only the directly participating parties benefit from the transaction, but the objectives or other parties are also advanced or at least not eroded as a side effect of the transactions?)

k) Stability assurance

Transactive energy systems through their integration of both engineering and economic operational objectives are a form of control system. As such, the stability of a specific TE system much be considered. The stability of grid control and economic mechanisms is required and must be assured. Considerations of stability must be included in the formulation of TE techniques and should be demonstrable. Unfortunately, there are no public benchmarks for stability and during numerical optimization minor errors can build on each other, and sometimes spiral out of control. It is important to mitigate optimization instabilities because grid stability may be compromised by poor value optimization techniques.

(Has the system been designed for, or otherwise analyzed for, the potential impact of the transactions on the stability of both the physical grid and of associated markets? Have specific considerations or protections been included to assure that the transactions, under unique situations or through aggregated behavior, do not unintentionally introduce instabilities? Are there any recognized mechanisms for intentional instabilities to be introduced either for profit [e.g., "gaming" the market] or for malicious intent [e.g., terrorist attack.])

Participating agencies and organizations

(List the participating agencies and organizations.)

References

(List any relevant references such as project reports or published papers that were cited in the case study narrative.)

Pacific Northwest Smart Grid Demonstration (PNWSGD)

Project characteristics and objectives

The Pacific Northwest Smart Grid Demonstration Project (PNWSGD) is developing a transactive coordination and control system to continuously coordinate the responses of smart grid assets to meet a wide range of operational objectives and achieve benefits both locally and across the entire Pacific Northwest.

The project kicked off its five-year journey in February 2010. The project is one of 16 regional smart grid demonstrations funded by the American Reinvestment and Recovery Act (ARRA). The budget is $178 million total with $89 million from the U.S. Department of Energy and the remainder from project participants (meeting a minimum of 50% cost share). The participants include 11 utilities and 5 technology providers. The scope of the project includes about 60,000-metered customers across five states (Idaho, Montana, Oregon, Washington, Wyoming). The PNWSGD is the largest of the ARRA-funded smart grid demonstration projects in the nation.

The *primary objectives* of the project are as follows:

- Develop a communication and controls infrastructure using incentive signals to engage responsive assets including distributed generation, storage, and demand assets.
- Facilitate the integration of renewable resources.
- Validate new smart grid technologies and business models.
- Quantify smart grid costs and benefits.
- Advance standards for interoperability and cyber security.

Over 60 MW of total assets are engaged in the project. Assets are organized into asset systems and grouped into three categories of smart grid test cases: transactive control, conservation and efficiency, and reliability. The project has 33 transactive control test cases involving 8 different types of asset systems (conservation voltage reduction, building and commercial demand response, in-home displays, programmable thermostats, distributed generation, battery storage, residential demand response, and plug-in hybrid electric vehicle charging.)

The project is implementing transactive control at the interface between transmission and distribution (T&D) to test the ability of responsive asset systems to respond to changes in an incentive signal representing the operational needs of the bulk power system. Though the demonstration project is focused at this interface between T&D, the technique is a general technique intended for application throughout the system from generation through intermediate control or constraint points in T&D, to end-uses. The incentive signal represents a forecast cost of power delivered at any given point in the system. A corresponding feedback signal provides a forecast of net load to be served from any given point in the system.

Transactive Energy Attributes

a) **Architecture**

Transactive control is a distributed architecture matching the topology of the power system. In general, transactive control nodes, the name for the distributed control points, will have a mesh architecture in the bulk power system and a hierarchical architecture corresponding to the typical radial topology of distribution systems below that. For more complex distribution systems, including micro-grids, the architecture will correspondingly be a form of mesh network.

b) **Extent**

The transactive control technology is designed for implementation across any extent from use by a local utility, even just on a single feeder, to regional deployment across multiple utilities. The technology may be applied to end-to-end spanning generation, transmission, distribution, and end-use. It may be applied in both structured and unstructured markets and in markets with unbundled service providers.

Within the PNWSGD, 27 *transactive nodes* are implemented, 14 of which are *transmission zones* representing large regions of the Northwest transmission system, while the remaining 13 are *utility-site nodes.* Any two transmission zone nodes, connected by transmission lines, are obligated to exchange transactive signals that describe the predicted exchange of energy between the nodes.

c) Transacting parties

The transacting parties in this approach are the transactive control nodes. For the PNW-SGDP, the utility-site nodes create at least one transactive node, which includes information about the included circuits, and the responsive assets to be managed by the utility. Transactive signals at present are not sent to actual distributed assets in most cases, and hence, the utilities are free to devise control mechanisms for these assets. In principle however, transactive nodes may be disaggregated so that transactive signals are potentially exchanged between distributed assets directly, enabling more local information to be part of the *transactive control system.*

d) **Transaction**

PNWSGD's *transactive control system* (TCS) uses an engineering-economic value-based transactive signal, the *transactive incentive signal* (TIS) and a corresponding *transactive feedback signal* (TFS)—as the primary basis for the coordination of supply and demand in a distributed manner. The TIS is a price-like signal that represents the unit cost of power delivered to any given point in the system, taking into account factors including, for example, location, time, transmission congestion, and the transmission losses. The TFS represents the plan for consumption of power desired by nodes served from the node receiving the TFS. To clarify this last aspect: each transactive control node sends and received both TIS and TFS with all immediately neighboring nodes.

All TFSs are forecasts of future local power needs at the transactive nodes, expressed in kilowatts or megawatts. Together with bulk power-generation projections, renewable energy forecasts and other values, the TFS then allows for computation of an incentive signal at the neighboring transactive nodes, which is sent back to the nodes. This TIS is expressed in cents per kilowatt-hour and informs the transactive nodes about the cost of delivering power to that node.

This approach maintains fidelity to the actual value/cost of grid operations, while also providing transparency and a level playing field. By using such a signal, the information exchange is simplified, can be made able to integrate more resources at different operating levels of the system, and provides a higher level of robustness by allowing healthy parts of the system to adapt in response to system component constraints or failures. The PNWSGD is testing transactive control with more than 20 types of responsive smart grid assets applied to residential, commercial, industrial, and irrigation customers.

e) Transacted commodities

The commodity transacted in the PNWSGD is energy.

f) Temporal variability

Transactive signals (TISs and TFSs) are exchanged with immediate neighbors at least every five minutes. The signals themselves cover a 72-hour forecast period with variable granularity. For the first 12 intervals values are forecast for every 5-minute interval, for the next 20 intervals they are forecast every 15 minutes, for the next 18 intervals every hour, for the next 4 every 6 hours and for the last 2 every day. This is a total of 56 intervals. A formal model of this interval structure is defined. A formal transactive node object model is defined including temporal behavior.

g) Interoperability

Interoperability is supported at multiple levels. A reference implementation of the TCS has been created using the IBM Internet Scale Control System (iCS) tool compliant with the International Organization for Standardization/ International Electrotechnical Commission (ISO/IEC) 18012 interoperability standard [26]. This reference implementation addresses basic physical and logical connectivity.

Information interoperability is addressed through the formal definition of the structure of TIS and TFS using Extensible Markup Language schemas. A test harness and tools have been implemented for interoperability testing of transactive control nodes for proper formation and exchange of transactive signals.

h) **Value discovery mechanisms**

Value discovery is achieved through a negotiation process involving the exchange of TISs and TFSs between neighboring nodes. As a simple example involving two nodes—a supply node and a consumer node—the supply node sends a TIS with its forward forecast of the cost of power. The consumer node sends a TFS with its forward forecast of planned consumption. The supply node analyzes the TFS and responds with a new TIS representing changes in the cost of power delivered given the forecast of consumption. This change would be driven by changes in cost due, for example, to a constraint in ability to meet the forecast of consumption. The consuming node in turn responds to the change in TIS forecast by updating its consumption plan if the new forecast of cost is not acceptable. The algorithms for updating the TIS and TFS must be constructed to drive to convergence, otherwise oscillations may occur in this series of interactions.

As implemented in the PNWSGD, the technique is applied at the interface between T&D. Further, the TIS for the transmission system is based on a synthetic result. The utility nodes are implemented at the boundary of the utility and the transmission system. A limited set of nodes is associated with avoiding demand charges that have the "negotiation" interaction with interaction between the TIS and TFS within the transactive control node.

In summary, the TCS employs an implicit control mechanism, where the actual control of the grid is attained by continuous negotiations between neighboring transactive nodes. The transactive signals (TISs and TFSs) are continuously updated and exchanged between neighboring transactive nodes until a settlement is reached. The emergent TIS and TFS represent delivered cost of energy, and average rate of energy flow between the two transactive nodes, respectively. The mechanism allows for dispatch of grid assets to occur in a distributed manner while respecting the physical grid constraints and maintaining supply-demand balance.

i) **Value assignment**

Value assignment is the translation of engineering state into economic terms representing the cost of power. For example, if a distribution transformer is overloaded, algorithms regarding transformer service life can be used to calculate the cost of the overloaded state.

In the PNWSGD, value assignment is implemented for a variety of conditions modeled within the bulk power system and for the implementation of demand charge avoidance. Value assignment is implemented in a class of transactive control node functions referred to as "resource" functions.

j) **Alignment of objectives**

Transactive control aligns objectives through correspondence of the transactive control node topology with the electric power system topology. Owners of system elements (assets) are enabled to affect the cost of power (TIS) or consumption of power (TFS) through the transactive control nodes deployed at the points in the topology corresponding to their ownership of assets. The term "asset" is used broadly here to represent any generation, transmission, distribution, or consumption element. The focus of action is local—at each transactive control node the objective is to achieve local optimization through action based on a combination of global information in the TIS and TFS and local information from that location's assets.

In the PNWSGD, for example, the TIS associated with the transmission system represents the needs of the bulk power system, for example, supporting wind integration, to the local utility. The local utility then introduces its own needs, for example, avoiding demand charges, and the resulting TIS drives asset system responses.

k) Stability assurance

At this stage in the research, specific analysis aimed at the impact on overall grid or market stability has not been performed. The TCS is expected to be stable through the incorporation of the two signals—TIS and TFS. The use of the two together represents a form of closed-loop control. There is still, however, a requirement that the decision-making algorithms be designed to include functionality equivalent to damping to help assure system stability.

Participating agencies and organizations

Battelle Memorial Institute is leading the project and collaborating with 11 Pacific Northwest utilities and the Bonneville Power Administration (BPA) to create the TCS design, configuration, and testing, as well as the data analysis. On the technical side, the PNWSGD has included: Alstom Grid for operations software used to calculate TIS values for the bulk power system. IBM created a reference implementation of the TCS. 3TIER, Inc., a Seattle-based forecasting company, provided renewables and hydropower forecasting. Netezza Corp., which was subsequently acquired by IBM, provided highly parallel data storage. QualityLogic, Inc. is the organization in charge of interoperability testing, standardization, and conformance certification.

References:

AEP gridSMART® Smart Grid Demo

Project characteristics and objectives

The American Electric Power (AEP) gridSMART demonstration is developing a transactive coordination and control system to continuously coordinate the responses of smart grid assets to meet a wide range of operational objectives and achieve benefits, such as distribution feeder congestion management, peak load management, and provision of ancillary services. Several hundred residential customers in the northeast Columbus, Ohio, area have been recruited to examine how real-time pricing (RTP) mechanisms can be used to engage the heating, ventilation, and air-conditioning (HVAC) loads to earn incentives for the customers by changing their energy use-patterns. The demonstration uses automated home energy management systems to control HVAC thermostat settings depending on customer preferences and real-time energy prices. Preliminary commissioning of the residential systems occurred during spring and early summer of 2013 and the preliminary tests started in early June 2013.

Transactive Energy Attributes

a) Architecture

The system implements a distributed architecture with transactional participants spread across numerous residences beyond distribution feeders in Ohio operated by AEP.

b) Extent

The RTP system runs retail electricity markets on four distribution feeders operated by AEP in northeast Ohio. For the demonstration, four markets run simultaneously, engaging residential HVAC loads to provide demand response service based on RTP tariff (RTPs) derived from PJM’s real-time wholesale energy markets. There are over 250 participating households distributed over the four feeders.

c) Transacting parties

The end-use loads in participating households are HVAC systems controlled by HVAC Energy Management Systems (HEMSs), which are enabled to 1) change their energy consumption based on the cleared market price, 2) determine the price they are willing to pay for electricity, and 3) bid their desired demand. The residential customers are required to only enter 1) their desired temperature set-points and 2) comfort/economy settings. The participating households *transact* with the distribution utility by providing demand response based services. The incentives for providing these services are based on real-time market prices.

d) Transactions

Within each home is a programmable thermostat communicating with an HVAC unit. The thermostat runs an agent that monitors the market price of electricity and converts the residents’ desired temperature set-point and their preference setting for more comfort or more savings into an amount it is willing to bid for the next 5 minutes of electricity. It sends this price along with the amount of electricity needed to a residential energy management system. That system assembles all bids in the home (in this case the one from the HVAC thermostat) and communicates the information via a cellular connection to the dispatch system located in the operations center.

The dispatch system assembles the bids from all households on the feeder along with the market price for supplying electricity as determined by the RTP tariff (based on the locational marginal prices [LMP] at the local PJM load bus) for electricity in the feeder's service area. The dispatch system clears the market based on where supply and demand bid curves intersect. The clearing price is broadcast to all homes, where the smart thermostat adjusts the HVAC thermostat's temperature set-point. The clearing price is also sent to the service provider's operations system for billing. The billing system exchanges information with the smart meter at the home to obtain the energy used during the 5-minute interval so the bill can be calculated. The consumer display is part of the smart thermostat. It displays the estimated billing price for energy so the consumers can participate with other energy-saving actions, if they are monitoring the system.

e) Transacted commodities

The commodity transacted in the system is energy.

f) Temporal variability

The participating households' HVAC systems submit demand bids every 5 minutes through the HEMSs. The bid is in the form of a price-quantity pair, expressing a household's willingness to consume a given quantity if the market price is below its bid price. Real-time retail price (base price, the formula for which has been approved by the Public Utilities Commission [PUC] of Ohio) that results from market clearing is calculated as a function of PJM's wholesale energy price. If the distribution feeder becomes capacity constrained, i.e., experiences periods of feeder congestion, the cleared retail price can deviate from the base price. When the resources are engaged to respond to feeder capacity constraints or to provide ancillary services, any corresponding increase in price due to the imposed constraint is rebated back to the customer. If a household responds to an imposed constraint, it will also be provided an incentive payment calculated in proportion to its level of participation and the amount of energy shifted.

g) Interoperability

The HEMSs transact with the utility, i.e., AEP, by submitting price-quantity bids into the real-time double auction markets. The smart thermostats connected to HEMSs convert residents' comfort/economy settings and desired temperature set-points into price-quantity bids. The communication between HEMSs and the utility has a standardized form, allowing various vendors to provide products that enable customer participation.

h) **Value discovery mechanisms**

The demonstration's transactive control and coordination mechanism uses a *double auction* market as the means of coordinating the demand and supply in a distributed manner. Multiple households are on each feeder that in turn has its own double auction market, which clears every 5 minutes. In each market, the households (through their HEMSs and programmable thermostats) submit demand bids into the double auction market, and upon market clearing, receive a real-time price based upon which they adjust their energy consumption. A demand bid submitted by an HEMS consists of a price-quantity pair, expressing its willingness to consume. The real-time prices received by the HEMSs are a function of the PJM's wholesale energy prices (LMPs), and the real-time electricity tariff (adders to real-time prices) was approved by the PUC of Ohio.

With this market-based mechanism, "control" objectives are achieved by engaging household resources that respond to fluctuations in the real-time electricity market prices, as opposed to *direct load control*. Each participating household contains resources, such as HVAC units and electric water heaters, which bid their willingness to consume electricity in the form of price/quantity pairs. The market aggregates the information from all parties and determines the clearing point of price and quantity where the supply and demand curves intersect.

The double auction is a market mechanism that can be described as a two-way market, where both suppliers and end-use loads submit offers and bids, to sell and buy energy respectively, into a single energy market. The auction resolves the supply and demand bids into a common cleared market price and quantity, and delivers this information back to the participants. This approach is highly scalable and allows all parties to participate and achieve their objectives in a distributed manner.

i) **Value assignment**

Within each household, the HEMS uses the occupant's configuration of comfort/economy level and desired temperature set-point to determine the price that the occupant is willing to pay as a function of energy consumption, and this is bid into the double auction. Cleared price in the double auction determines whether a HVAC unit consumes energy or not. In case the cleared price is greater than the bid price, the HVAC unit turns (or stays) off. If the HVAC unit turns off due to high prices that result from feeder capacity constraints, the households are provided incentives for the provision of demand response service to the system.

j) **Alignment of objectives**

The RTP system provides incentives to shift the end-use resources, thus allowing these resources to participate in the balancing of supply and demand. The added flexibility in operations generates shared value streams for the utility and RTP customers. These include energy purchase benefits (reducing wholesale purchases in PJM's real-time market[5]), capacity cost benefits due to deferment of capital investments, and the potential for additional ancillary services. The transmission system and the system operator (PJM) benefit from provision of energy balance and ancillary services from demand-side resources that cost less than traditional generation resources.

k) Stability assurance

Automated response to real-time prices from HVAC systems ensures system stability as long as the markets clear and the signals are transmitted to HEMSs without delay. In a system with large amount of participating loads, occasional non-compliance of HVAC units to price signals (either due to loss of communication or manual intervention) may not cause system-wide disturbances.

Participating agencies and organizations

American Electric Power Ohio is leading the demonstration project. Pacific Northwest National Laboratory is designed the double auction market and real-time rate tariff and supported data analysis. Battelle Memorial Institute supported the project

---

[5] Most utilities purchase bulk of their energy in long-term bilateral trades, and only about 5% of energy is procured in real-time markets. Hence, reduction in consumer demand only affects a small fraction of utility's energy purchase cost. On the other hand, utilities would see a drop in revenues because of lower energy consumption.

implementation and the design of smart thermostats. The PUC of Ohio approved the real-time rate tariff used.

References

- **PNNL-SA-77870:** Widergren SE, K Subbarao, DP Chassin, JC Fuller, and RG Pratt. 2011. "Residential Real-time Price Response Simulation." In *Proceedings of the 2011 IEEE Power & Energy Society General Meeting, July 24-28, 2011, Detroit, Michigan*. IEEE, Piscataway, NJ. doi:10.1109/PES.2011.6038964
- **PNNL-SA-86100:** Widergren SE, MC Marinovici, T Berliner, and A Graves. 2012. "Real-time Pricing Demand Response in Operations." In *2012 IEEE Power & Energy Society General Meeting, July 22-26, 2012, San Diego, California*. IEEE, Piscataway, NJ. doi:10.1109/PESGM.2012.6345195