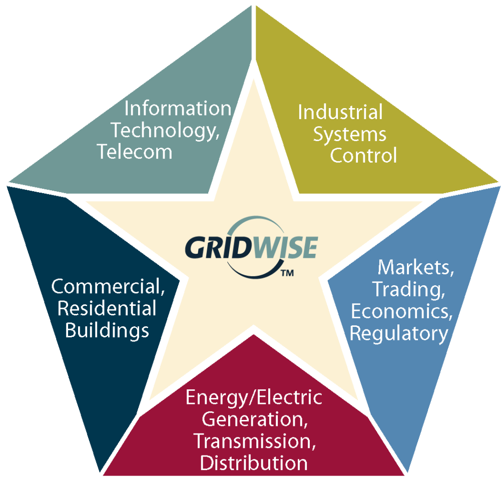

GridWise Transactive Energy Framework Version 1.1

Prepared by

The GridWise Architecture Council

July 2019

<u>About this Document</u>

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.

GRIDWISE Architecture Council

Executive Summary

Over the past two decades, the use of demand response and other flexible distributed resources for electricity 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 of the electricity grid, but also the control system implications, to address grid reliability. This has led to a focus on an area of activity called "Transactive Energy." Transactive energy (TE) 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 TE. 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 TE.

Building on workshops sponsored by the Council in 2011 and 2012, the Council began to address the topic of TE 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 (draft) version of a "Transactive Energy Framework" document in October 2013. The draft framework was updated based on feedback provided to the Council, and an updated Version 1.0 was published in January 2015. In January 2018, the Council started work to update the framework again based on discussions held during prior Council meetings. In the time between Version 1.0 and Version 1.1 (this document), much transpired, including three more Council TE conferences and the addition of TE to many conferences, showing broad interest in the topic, as well as new pilot implementations of TE systems.

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 TE
- addressing of TE from multiple perspectives, including
  - business and policy considerations
  - business models
  - value creation
- conceptual or reference architectures for TE 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 TE.

The motivations for employing TE systems 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 (APS 2010).

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 TE embraces both the economics and the engineering of the power system. The same considerations outlined for the electricity grid apply to building energy systems and other local energy systems such as microgrids (Taft and De Martini 2013).

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. For example, U.S. Energy Information Administration (EIA) estimated that buildings (residential and commercial) would account for around 70% of electricity consumption in the United States in 2014 (EIA 2014a). Recent EIA data shows that this project was correct and electricity use in buildings is currently just over 70% each year (EIA 2019b). 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 TE. 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 considerations 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 TE 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 TE environment and to enable comparisons among various approaches.

We further examine the practical dimensions of implementing TE 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 TE framework to be a focal 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 TE 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 and 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 electricity 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 electricity 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 electricity system from end-use systems, such as buildings or heating, ventilation, and air-conditioning 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.

Acronyms and Abbreviations

ACE	area control error
AGC	automatic generation control
BTM	behind-the-meter
CPUC	California Public Utilities Commission
DER	distributed energy resources
DERA	DER aggregation
DG	distributed generation
DR	demand response
DSO	distribution system operator
EV	electric vehicle
FERC	Federal Energy Regulatory Commission
GWAC	GridWise Architecture Council
IEEE	Institute of Electrical and Electronics Engineers
ISO	independent system operator
MISO	Midwest ISO
MUA	multiple-use application
NEM	net energy metering
P2P	peer-to-peer
PFR	primary frequency response
PV	photovoltaic
RTO	regional transmission organization
SCADA	supervisory control and data acquisition
TE	transactive energy
TEF	TE Framework
TSO	transmission system operator
T&D	transmission and distribution
UDC	utility distribution company
ULS	ultra-large scale

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1.0 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" (GWAC 2008). 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, the attention of the GWAC 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 (TE) as a means to effectively coordinate 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.

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 both the first conference and the subsequent four conferences, it became apparent that TE involves not only economic aspects, 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 TE.

There have also been several new TE pilots proposed and implemented, and panels on TE can be found at most conferences, including technology-focused conferences such as Institute of Electrical and Electronics Engineers (IEEE) Innovative Smart Grid Technologies and broadly focused industry conferences such as DistribuTECH, showing the broad interest in this topic. TE is also a frequent topic in technical journals, magazines, and blogs. These varied platforms for discussing TE indicate a broad acceptance of the possibilities offered and interest in ways to apply TE by service providers, utilities, and regulators.

1.1 Why Develop a Framework?

The GWAC addressed this question in the *GridWise Interoperability Context-Setting Framework* (GWAC 2008). 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.

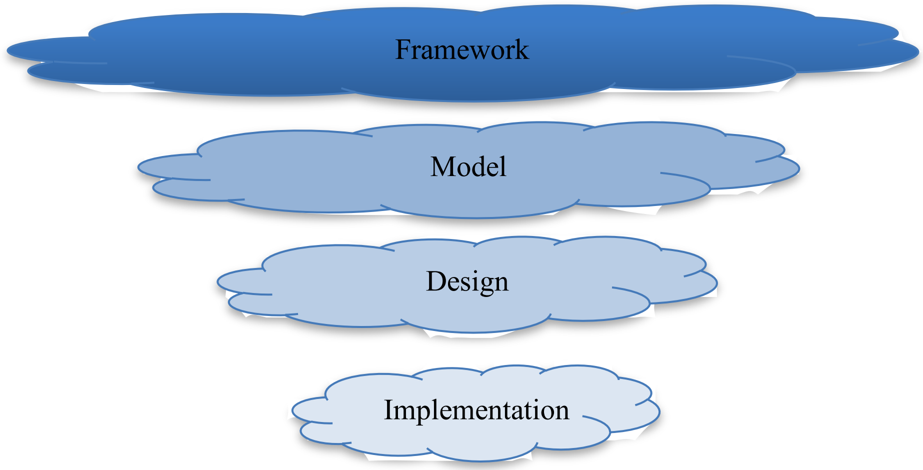


Figure 1. A framework provides high-level perspective.

The intent of the TE framework is to promote discussion at the conceptual level of common features or elements of specific models, designs, or implementations of TE 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, TE 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 TE 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 TE framework, the authors presume an audience with a good understanding of interoperability, familiarity with the *GridWise 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 that serve the diverse smart grid community. The document covers the topic of TE 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.

In addition to the TE framework (this document), the GWAC produced a TE Decision Maker's Checklist (GWAC 2016) and a TE Roadmap (GWAC 2018). Each document is designed for a different audience and each provides a different perspective on what transactive systems are, how they will evolve, and necessary policy considerations (see Figure 2). In addition, the Smart Grid Interoperability Panel (now Smart Electric Power Alliance) produced a TE Landscape Scenarios white paper presenting six high-level, operational scenarios. Collectively these explore TE interactions and provide examples where TE systems produce value.

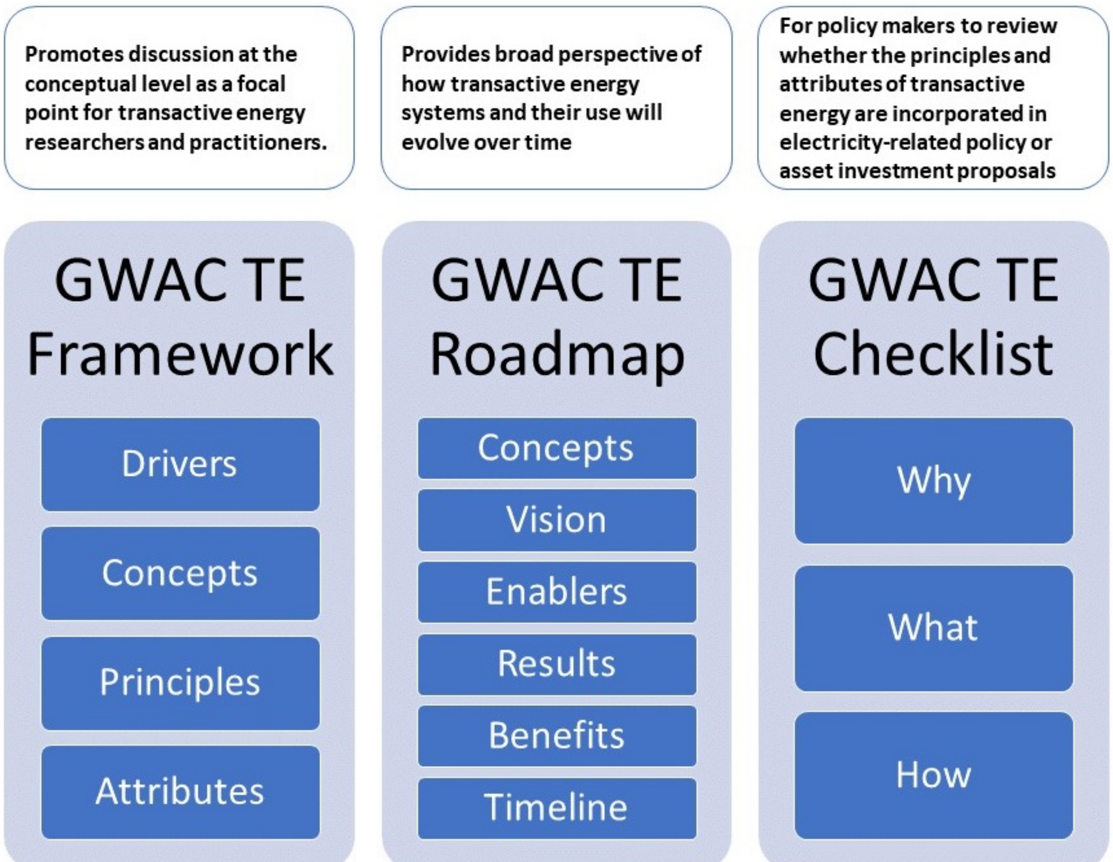


Figure 2. Overview of GWAC transactive energy reference documents

1.4 Report Contents and Organization

This document is organized in four main chapters. Chapter 2.0 summarizes the context and motivation for TE approaches. The changing nature of the grid and the combination of regulatory, policy, economic, and engineering challenges due to those changes are summarized. Chapter 3.0 refines the definition of TE and includes a set of associated attributes that may be used to discuss different approaches and implementations of TE systems. Chapter 4.0 puts TE 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 TE applications. The intent throughout all of these chapters is not to prescribe a specific TE 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 TE systems or applications. Appendix A includes a template for documenting TE system case studies and two example case studies.

1.5 Version History

The TE 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 pertaining to the electric power system.

- A draft version of this document was publicly released in November 2013.
- Based on review comments, the document was updated and published as Ver1.0 in January 2015.
- An updated version (v1.1) was published in July 2019 based on developments since the publication of Ver1.0.

2.0 Context Setting

The intent of a TE 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 from the details of the processes and technology involved to link systems together, to the understanding of the information exchanged, 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 TE 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 reports and studies (for example, APS 2010, Rahimi and Ipakchi 2012, Taft and De Martini 2013, De Martini et al. 2012, Kind 2013, De Martini 2013, Rahimi et al. 2016, and Kintner-Meyer et al. 2007) 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 the transmission and distribution (T&D) 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, initially represented relatively minor quantities of generation but have continued to deploy at increased rates and have the potential for significant disruption over time (De Martini and Kristov 2015, NARUC 2018, DOE 2017a,b,c, CAISO 2013). In 2015, PV accounted for 0.2 quadrillion Btu (quads) per year, which compares with 1.03 quads consumed by televisions nationally per year (EIA 2014a). 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 (EVs), 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 predict accurately (Burrus 2014). 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, projections by the U.S. Energy Information Administration show PV increasing by an order of magnitude in the next 30 years (EIA 2014a). 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 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. This also requires greater interoperability as the number of interacting devices and interfaces increase GMLC 2018.

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; hence, 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. (This topic is addressed further in Section 4.2.5).

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 generation resources 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 (Simard 2013). 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. 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 (DSOs) (Rahimi and Mokhtari 2014). DSOs are discussed in more detail in Section 4.2.5.

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 (240 V) alternating current charging or for direct charge Fast Charging. A 2007 study by Pacific Northwest National Laboratory showed, however, that we have the capacity to accommodate a 70% penetration of EVs if we manage their charging through the use of “smart” charging technology (Kintner-Meyer et al. 2007).

[1] This assumes the carbon content of the electric power for an EV is less than the carbon content of petroleum that would have been used, as is currently the case (DOE Undated).

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 addressed through coordinated approaches. New objectives arising from the emerging trends discussed above are as follows:

- wholesale prices/production costs minimization
- need for stronger coordination at transmission-distribution interchange points
- 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 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 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 has historically been 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 milliseconds to years. In the future, it may be equally necessary to incent loads to use intermittent supply.

Figure 3 illustrates the relative time frames involved in the electric power system. On the right-hand end, 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 the next day 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. (EIA 2014b, MMI 2016)

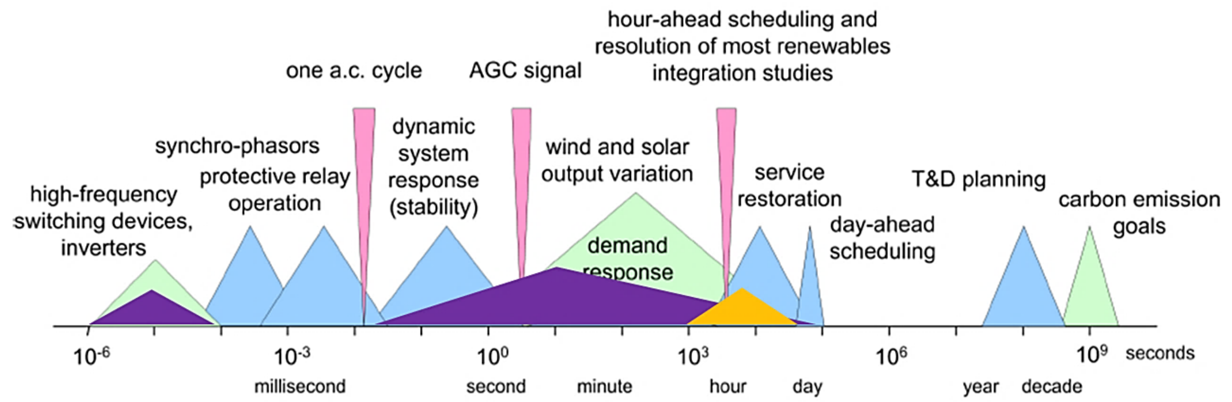


Figure 3. Electric power system timelines (von Meier 2012; used with permission).

The left half of Figure 3 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 generation control (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 3, 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, data paths, connection points, and control points are increasing in number 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 TE Infographic (GWAC 2014), 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, developments 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 in the west and PJM's five-minute markets in the PJM area, New York ISOs, and other organized markets
- changing retail customer relationships with the introduction of premises-level renewable resources and new loads such as EVs
- 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 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 recent years (Watson 2017, EIA 2018)
- the need for new business and regulatory models (New York State 2019). 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 than traditional generation sources, and the increasing technical capabilities to facilitate cooperation and coordination between DERs, users, and devices creates a need to reevaluate our cost-of-service regulation model.
- requiring action in the time frame of minutes (see Figure 3) at major system-to-system interfaces between T&D or between distribution and retail customers. Thus, the changes affect both the economics of electric power systems and the control of both the power systems and the end uses of electricity.

Regarding 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 creditworthiness. They urge the development of new regulatory frameworks that provide for cost recovery outside of the traditional rate case (McDermott 2012, New York State 2015). 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 Knight and Brownell 2010. There seems little doubt that regulatory models must evolve to address the ability of 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" (Taft and De Martini 2013), as shown below in Figure 4, which depicts inter-tier control, with control flowing downward. The diagram in Figure 4 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 more complex and could become 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 time scales 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.

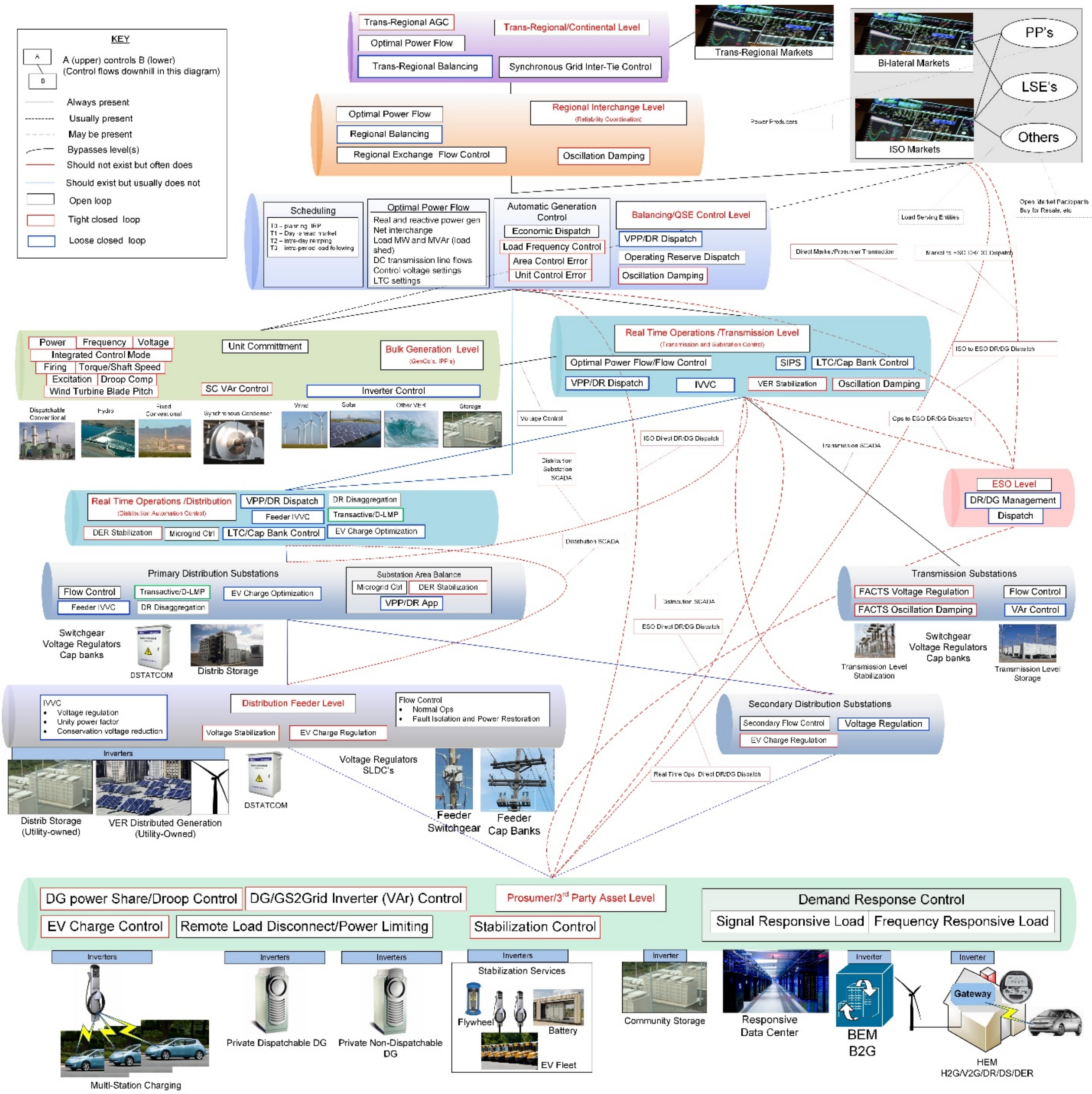


Figure 4. Growing complexity of electric power system control (Taft and De Martini 2013).

Such a control framework will enable 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 (DERs), 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 they 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 control 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.

3.0 Transactive Energy

When the electricity grid that America chose to build 120 years ago was originally conceived, it centered around large electricity generating plants (power plants, or, generation) that sent electricity in a single direction through high-voltage transmission lines. When the electricity reached communities, the voltage was "stepped down" and then distributed to buildings and eventually to appliances that use electricity (loads) like a toaster or furnace. Grid operators perfected this model, found ways to make sure everyone had electricity that was of a high quality and that did not create damage, shortages, or faults.

Over the last decade, new kinds of generation have emerged that are no longer located in one large, central power plant and that do not produce power in the same way that a single power plant can. They are now cheaper than ever and starting to proliferate on the grid. New kinds of loads have emerged, too. Devices have gained the ability to communicate with the grid and with each other. The purpose of this section is to provide definitions of TE, the basic terms associated with TE, and to describe the elements of TE systems or applications. The aim 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. Terms have been defined with the intent to provide a common language for describing and discussing TE systems, thereby enabling comparison of the features, functions, and elements of different approaches.

This chapter begins with an answer to the question, "What is transactive energy?" This is followed by a list of attributes of TE techniques or systems. Finally, TE elements are considered. This chapter also examines TE in the context of the interoperability-layered categories defined in the *GridWise Interoperability Context-Setting Framework* (GWAC 2008).

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 how to enable new techniques that may be used in distribution systems, at the interface between T&D, 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, additional attributes are defined 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 to 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 (Feiler et al. 2006).

extent A TE system will typically be used 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 humans. In some cases, humans may be in the loop. A TE system must be explicitly describable in terms of 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 (Feiler et al. 2006).

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 time scales. For example, transactions within a single system may range from subseconds to five minutes or to some longer period. It is also possible for transactions to be event-driven. In characterizing a given transactive system, the time scale(s) of transactive interactions must 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 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 intended context to support workflows and constraints. For any given transaction, the information exchanged during the 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 nonquantitative 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 of TE systems is the continuous alignment of multiple objectives to achieve optimum results as the system operates. This alignment enhances the economic and engineering effects 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:

- TE systems implement some form of highly coordinated self-optimization.
- TE systems should maintain system reliability and control while enabling optimal integration of renewables and DERs.
- TE systems should provide for nondiscriminatory participation by qualified participants.
- TE systems should be observable and auditable at interfaces.
- TE 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 Effects on Transactive Energy

As more and more DERs penetrate distribution systems, and more microgrids and campus networks appear, as well as entities such as virtual power plants, the potential for these and other entities, such as prosumers, 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 negatively affect grid reliability. These views are typically applied to today's system architecture and management techniques, which 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 ecosystem.

As the diagram in Figure 5 illustrates, the industry is in an early stage (Stage 1) of the evolution toward transactive operations. As more and more intelligent devices are deployed, the opportunities for automation will increase, which will increase opportunities for using TE systems. Survey results from regional workshops conducted by the U.S. Department of Energy and the GridWise Alliance concluded that there could be significant change in the electric power system by 2020 (GridWise Alliance 2014). 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.

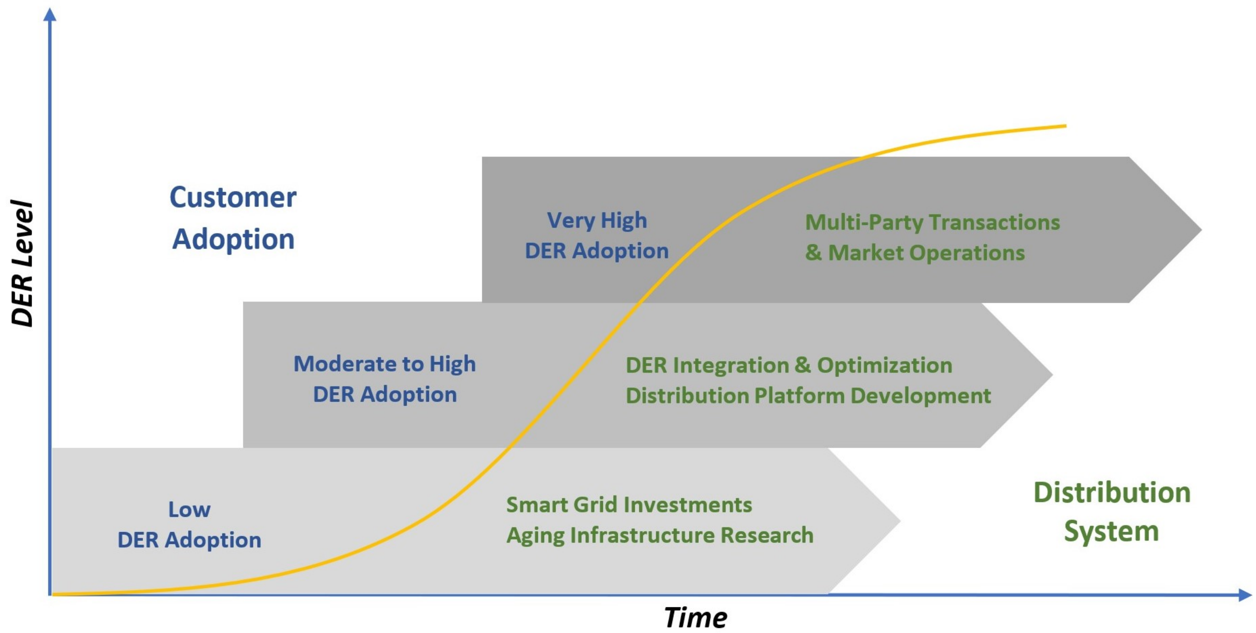


Figure 5. Stages of adoption of DER (adapted from De Martini and Kristov 2015)

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 neither 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. Further perspectives for consideration from a policy maker's perspective are described by GWAC (2016) to help decision makers evaluate options such as capital asset investments and new information technology opportunities to determine whether they conform to the principles and attributes of TE.

3.5 Strata of Transactive Energy

The strata 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 interoperability framework, the "GWAC Stack," as defined in the GWAC's *Interoperability Context-Setting Framework* (GWAC 2008). The GWAC Stack represents the dimensions of interoperability, ranging from cyber-physical at the lower levels, information interoperability at the mid-levels, and business models, market structures, regulation, and policy at the upper levels. With these three broad groupings of the GWAC Stack in mind, the strata of TE can be defined as depicted in Figure 6.

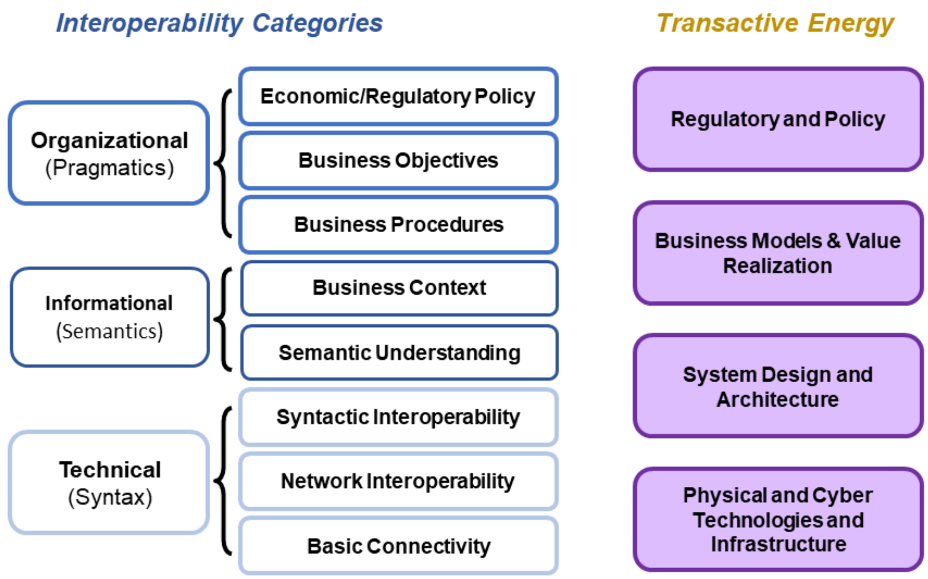


Figure 6. GWAC Stack with strata of transactive energy

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

Interoperability perspective

- **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 are 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

Transactive perspective

- **Regulatory and Policy**. This describes the actions needed by regulators and other policy makers to enable TE systems. The objective is to establish an environment that enables transacting parties to understand rules of engagement and compensation in addition to performance requirements. The actions also focus on achieving as consistent an approach as possible across jurisdictions to promote interoperability. The actions described may be carried out by different policy-making bodies, depending on the individual jurisdictions and types of utilities. Decisions at this level support development and implementation actions described in the Business Models and Value Realization stratum.
- **Business Models and Value Realization**. This stratum focuses on the various stakeholders, their roles in TE and how their business models need to evolve for them to provide and realize

exchange of money).

- **Information Interoperability** (including system architecture). Information interoperability must address the semantics behind the valuation of transactions (meeting participant objectives), the operation of the TE mechanisms, and the control aspects of understanding the effects of the transactive system on the electricity 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.[4] The power grid includes two cyber-physical networks: the electrically connected network and the communications networks necessary to monitor and control it. TE designs must 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.

value in each of the three stages (Figure 5). While the regulatory and policy stratum describes the actions policy makers need to take to establish the needed TE environment, this stratum focuses on the actions to assess and implement needed business model changes by various stakeholder types, recognizing that business model changes include value propositions on both supply and demand sides.

- **System Design and Architecture**. This focuses on the system design and architecture specifically dealing with information interoperability to support TE operation and control aspects to understand and manage the impacts on the electricity grid. This depends on the business model to define required information exchange between TE parties in content and timing.

- **Physical and Cyber Technologies and Infrastructure**. This addresses the technical layers of the GWAC Stack and the physical layers of the Control Abstraction Stack. It includes the activities aimed at the electrically connected network and the communications networks that are necessary to monitor and control the electric grid. This depends on the information exchange requirements considered in system design and architecture to ensure that information can be exchanged in support of transactions without detrimentally affecting the reliability of the electrical network.

[4] The Control Abstraction Stack is discussed in Section 4.3.

4.0 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 6, the GWAC Stack may be mapped into four areas of concern for discussion of TE:

- Regulatory and Policy
- Business Models and Value Realization
- System Design and Architecture
- Physical and Cyber Technologies and 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 *GridWise Interoperability Context-Setting Framework* to TE (GWAC 2008). Doing so identifies the "interoperability" challenges to be considered for TE. As with the GWAC Stack itself, a number of crosscutting 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 and resilience; they also include new concerns arising from the increasing adoption of DERs and the variability of renewable energy resources, which will provide a larger portion of the power mix as costs decrease and customer demand increases. Other policy considerations include cost and risk allocation issues associated with increased customer participation in electricity generation and markets, and growing customer control over their own demand. There are also policy and market design considerations stemming from TE.

The electricity industry is beginning a significant evolution in the fundamental operation and planning of the electricity grid. "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." (De Martini et al 2012)

Customers will play an integral role in this evolution. Indeed, "[c]ustomers 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." (De Martini et al. 2012) This means that market and grid control systems, currently based on centralized resources and one-way distributed power flows, will require new policies, tariffs, operational paradigms, systems architectures, and/or 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 expectations**. The electricity 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 and continue flowing.

- **Volatility of some renewable generation and customer demand**. The variability of power from PV or wind generation and customer load/supply on the grid will affect the integrated electrical system and will continue to be addressed.
- **Valuation of renewable behind-the-meter resources**. Properly valuing customer-owned DERs will depend upon, among other things, the location, visibility, dispatchability, and reliability of such DERs and require effective, timely communication between the DERs and the grid.
- **Jurisdictional boundaries**. Jurisdictional boundaries may blur as DERs become more capable and are aggregated to provide a broad range of grid services and support. Regulators may call for greater flexibility in responses to quickly changing conditions.
- **Time scales of economic and grid control actions**. The grid is extremely reliable because it is adaptively controlled at time scales of seconds. In the coming decades, millions of independent agents, individuals, and devices will make economic and control decisions at vastly different time scales.
- **Rapid changes in technology**. Solar power has rapidly become more cost effective. When coupled with advanced energy storage systems, PV may soon be, if it is not already, comparable in cost to traditional generating resources. Similarly, the energy efficiency of common appliances and electrical loads continues to increase, (particularly in the fields of lighting; heating, ventilation, and air conditioning; and water heating). There are also simpler techniques to remotely monitor and control these devices. The growing population of EVs and their charging devices represent an entirely new class of consuming (and potentially storing/generating) assets.
- **Effects of decreasing costs of renewables**. Careful analysis will be needed of the effects of lower costs on existing investments and business models, which were designed for traditional generating, transmission, and distribution infrastructure, along with careful consideration of how any related changes in costs and risks will be allocated.
- **Incentives for reducing dependence on fossil fuels**. Some governments and agencies provide substantial incentives for renewable energy generation, improving energy efficiencies of homes, offices, and factories, and accelerating the adoption of EVs. The unknown influence of, and possible changes to, existing and future incentives make long-term analyses of markets challenging.
- **Increased customer options**. More customers have more options for producing their own power, better managing their devices and consumption, and to using or storing their own electricity. As the number of such customers and the options they can choose from increase and are aggregated, the demands on the traditional electric system will be affected, as well as its performance. This likely will result in either less or more sporadic demand for certain electric system assets. At the same time demands on some portions of the electric power system will increase, but not at entirely predictable times or locations. Such changes in demand will change the way utilities and system operators need to plan and operate electricity systems, and implementing those changes will take time. Changing operational conditions may result in some assets being used more or less than originally planned. This will require the system operators to adjust how they plan for and manage their systems as DER penetration expands, to lessen economic risks and cost-shifting associated with deployment and use of new assets. Important policy and market issues will involve how such risks and costs will be allocated.
- **"Nonparticipating" customers**. A notable number of customers, whether by default or by conscious choice, will not participate in expanding DER utilization or TE developments or markets. Policy and market design will need to consider how such customers will be treated. Consideration should include, for example, the extent to which such customers will be permitted (at no additional cost to

them) to benefit from transactive markets they do not participate in, and/or "protected" from any costs traceable to accommodating increased DER penetration and/or TE markets.

The items listed above include restatements of some of the objectives summarized in Section 2.1. As described in that section, the problem is optimizing multiple objectives. TE approaches are intended to achieve this by combining 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, regulation and policy must be aligned in several dimensions. Note that TE implementations may operate from "end to end," affecting both the bulk power and distribution systems.

For TE implementations that engage multiple regulatory jurisdictions, consistency of approach may be needed in formulating related policy and regulations. Policy makers might consider a roadmap leading to model state rules and regulations, which jurisdictions may consider adopting to achieve any desired consistency. It may be necessary to ask how a given TE implementation could affect and/or be affected by existing policy and regulations. One concern, given the integration of engineering and economic mechanisms, is whether a given implementation would violate any "firewall" requirements between markets and operations.

The way a given TE implementation interacts with existing market structures must also be considered. As already discussed in Section 2.2 and illustrated in Figure 3, 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. Interfaces with any existing market structures should be considered within this time band.

Going forward, there is a clear need for more interplay of federal and state policies, wholesale and retail markets, resource control systems, T&D control systems, and customer energy management systems to achieve the envisioned scale and scope. Policy action to transition to accommodate a TE framework that appropriately values energy services in supporting grid optimization may need to address many or all of the issues listed above. Such policy should focus on aligning stakeholder (Figure 7) interests to support the reliability of the power systems in a socially and economically fair design.

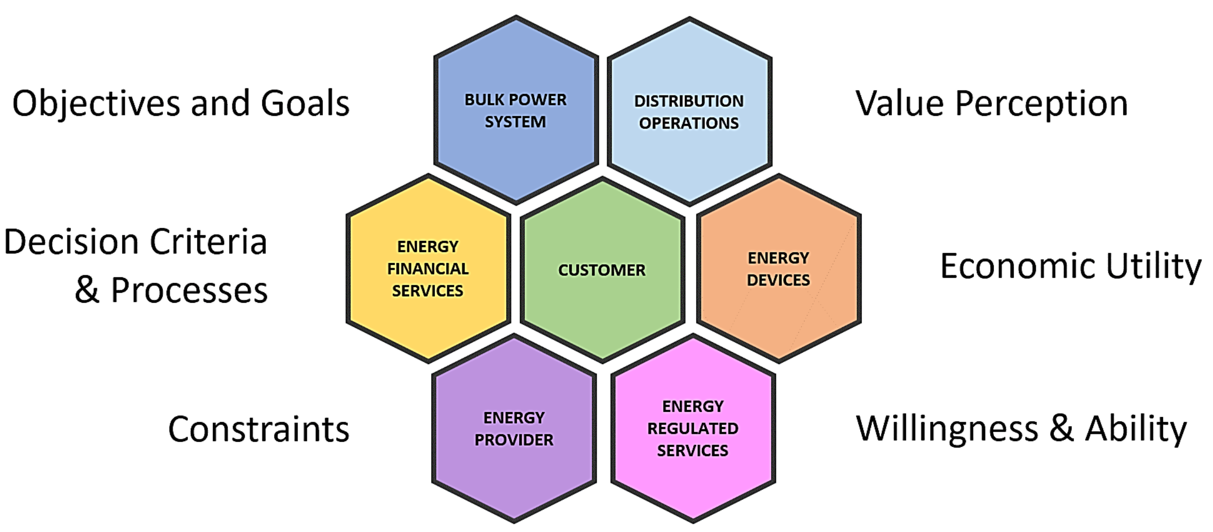


Figure 7. Transactive energy stakeholders

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 electricity 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 electricity 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.
- **ISOs and RTOs** that serve as reliability coordinators of the bulk electric system would like access to energy and ancillary services aggregated from customers who own DERs in 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 appropriate pricing and valuation of energy services. Such pricing and valuation should appropriately balance contributions to distribution system reliability with mechanisms that aggregate from retail markets and participation in wholesale market support.

It is very likely that regulatory revisions such as the following will need additional consideration to better enable at least some portions of the transactive market strategies described above:

- retail rate options, which may better align rates with real-time system demand (e.g., peak) so that prices better reflect demand, to allow customers to respond to more precise price signals and, with enabling technology, shift consumption to lower-cost time periods, and also to establish fair rate and compensation methodologies for DERs that avoid cost-shifting among customer classes
- standardized regulatory treatment for investments in grid modernization, based upon sound principles of long-term customer benefit
- regulatory policies that properly allow cost recovery for necessary infrastructure investments and also govern earnings associated with new platform services. These policies may provide more latitude for the use of customer intelligence in new service offerings, and allow for appropriate partnering by those offering new products and services.
- policies that enable creation of profitable local market coordination services that will make it easier for customers to provide energy service to bulk power system and distribution operations
- policies that allow utilities to own DERs and/or provide services related to DERs, and establish the conditions under which investments in DERs are subject to regulated cost recovery
- consideration of the appropriate roles for regulated monopolies.

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

Current TE approaches for DER integration are likely to require some revisions for at least two reasons:

- Controllability of a large-scale influx of DERs may not currently be adequately addressed.
- Economic value of, and costs associated with, large-scale influx of DERs may currently be insufficiently estimated or documented.

As policy makers face the fundamental differences between present and future systems, they will likely see a need to design policies that maximize customer engagement and accommodate the many DERs that will enter the system, with an eye toward policies and market designs that support the following:

- **Customer value**. Customers may want a broader range of potential value streams and additional mechanisms to monetize them transparently.
- **Merger of economics and control**. Economic systems will need to address any gap between operators and market makers without violating the control objectives. Regulators may want to evaluate to what extent the full range of mechanisms (organized markets, forward markets, tariff-based, and real-time prices) are needed to express the desired value streams to customers while avoiding cost-shifting among customers.
- **Understanding and proper allocation of risk**. More reliance on customers as market participants may affect operational risk (as well as customers not participating in TE), especially when weather, economic conditions, or noneconomic personal preferences affect performance that customers or their aggregators depend upon. Policy makers must also consider how such risks should be borne and how bearing the risk and providing backup should be compensated. Related questions include whether policy makers will find a contractual remedy for nonperformance adequate or additional protections will be needed (such as securing contracts with liquid collateral to cover defaults).
- **Proper planning activities**. With the growth of DERs and implementation of TE markets, traditional utility distribution, demand forecasting, and resource planning processes will need to evolve and be better coordinated to reap the services and benefits that TE provides locally. As customers begin to provide services to the distribution system, the DSO may no longer need to obtain services only from traditional sources, such as power plants or the transmission system; these changes must be accounted for.

Objectives that support customer value and the economics-of-control principles that policy makers desire when designing markets and/or policies likely include the following:

- creating a more level playing field for all stakeholders while avoiding cost-shifting
- respecting ownership, jurisdictional boundaries, and customer privacy
- expanding opportunities for engagement between customers and the grid
- allowing customers more control of their relationships with the energy infrastructure
- understanding and proper allocation of all costs and risks
- increasing customer choice to provide services to the system and purchase services from it as both producers and consumers of energy
- spurring technical and commercial innovation
- recognizing and accounting for effects on the economics and business models of current key entities such as nonparticipating customers and the load-serving entities
- optimizing system reliability vs. capital infrastructure investment.

Meeting these objectives should help create a fair, transparent energy market where economic value is realized in proportion to contributions to support grid reliability and adoption of new DERs, and provide services that T&D operators can use to maintain a highly reliable power grid.

4.2 Business Models and Value Realization

Significant changes in the electricity industry are creating a new energy paradigm. It is important to recognize that as the electric power system evolves, some existing business models may no longer be viable. At the same time, opportunities are emerging for businesses to create new value streams for customers and for the power system as a whole, aided by new and innovative market designs and regulatory policies, as discussed in Section 4.1. In this context, the TE framework offers a vision for business models to evolve in a way that helps reconcile the need for more customer choice and participation while respecting the operational needs of the power system.

The realization of TE as a central operating principle of the future electricity system depends on the widespread adoption of diverse DERs and their participation in decentralized energy systems and markets. Widespread adoption of DERs depends in turn on their ability to provide needed energy services and support major public-policy goals more effectively and reliably than continuing to rely almost exclusively on the traditional, centralized, "one-way-flow" electricity system. Those of us working to advance the TE vision confidently expect that a decentralized TE future is both feasible and desirable. Indeed, since publication of Version 1.0 of this document (TEF 1.0, 2015), the potential for DER adoption and business models based on their operational, commercial, and public-policy value is stronger than ever and is still highly consistent with the value potentials identified at that time. To date, however, few of those values have been realized at significant scale, although numerous projects and proceedings have been conducted and more are underway to advance DER value realization.

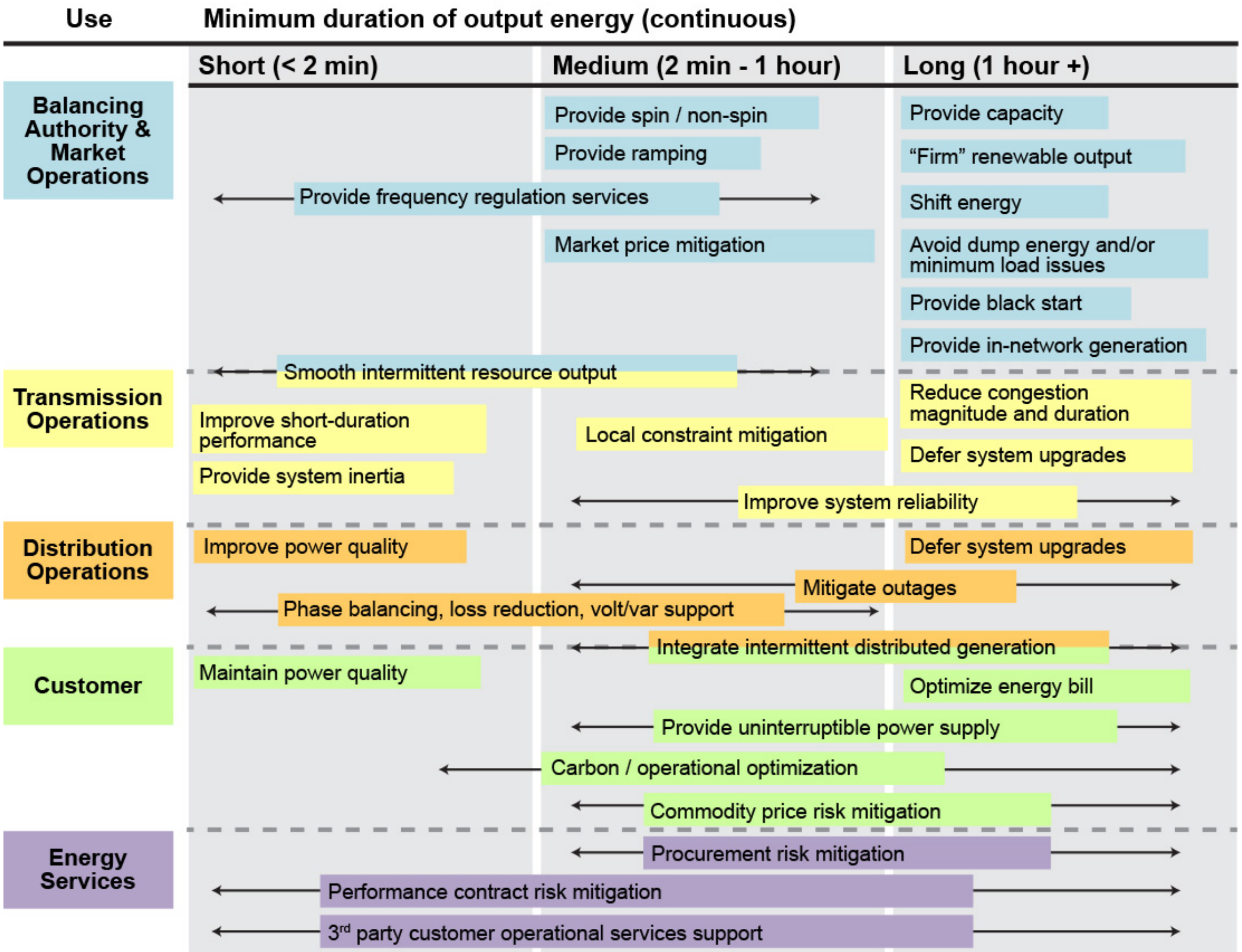
This section reviews the current landscape of potential DER value streams within the broader TE conceptual structure and describes the current status of DER value realization, the advancement efforts underway, the main challenges, and potential solutions.

To begin, Section 4.2.1 gives an overview of the services DERs can provide to energy end users and to the electric power system. These are mostly the same services identified in TEF 1.0, but with further technical discussion to suggest how system operating requirements traditionally supplied by services from conventional generators can be met by diverse DER types in a less centralized electric power system.

Section 4.2.2 focuses on services that are well recognized today, distinguishing between those DERs are already providing and being compensated for versus those for which some open issues need to be resolved. This section also raises the topic of service "stacking" or multiple-use applications (MUAs). Section 4.2.3 describes potentially significant DER values that are not yet recognized, much less quantified and defined as services that can be compensated. Section 4.2.4 discusses transactive markets and peer-to-peer (P2P) transactions. Section 4.2.5 discusses potential alternative DSO models. Section 4.2.6 summarizes the section with a discussion of how to reframe the "value of the grid" for a high-DER transactive electric power system.

4.2.1 Overview of DER Services and Technical Capabilities

We start the discussion of DER services and technical capabilities with Figure 8, a slightly modified version of Figure 7 from TEF 1.0, which is a useful technical listing of the range of valuable services DERs can provide to energy end users and to the grid.



Source: SCE: Adapted by GWAC

Figure 8. Services available from DERs

TEF 1.0 did not provide much description of these services, however, so this section provides (1) a short explanation of the less obvious services, and (2) some discussion of how DER capabilities can meet the same underlying system needs as services traditionally provided by conventional generators.

To that end, we distinguish services the DERs can provide in support of grid operations into three categories as listed below.

1. **Bulk Power System Services**
   - Spinning Reserve: Capacity that can be deployed within minutes (normally less than 10 minutes) following a system contingency (loss of a major generation or transmission resource). This service, traditionally provided by conventional generation sources, can as easily be provided by classes of DERs such as storage, demand response (DR), and EVs.
   - Non-Spin/Supplemental Reserve: Capacity that can be deployed within minutes (normally less than 10 minutes) following a system contingency. This service, traditionally provided by off-line fast-start conventional generation sources, can as easily be provided by classes of DERs such as storage, DR, or EVs.
   - Frequency Regulation: Fast ramping capacity that can respond to the 2–10 second AGC commands issued from the system operations control center. This service, traditionally provided

by AGC-enabled on-line conventional generation sources, can as easily be provided by different classes of DERs (storage, electric water heaters, EVs, etc.) with comparable or better performance than conventional AGC-enabled generation.

– Primary Frequency Response (PFR): Fast response autonomous acting capacity that can increase or decrease generation (or consumption) in response to system frequency variations. This service, traditionally provided by conventional turbine-generator governors or primary generation control loops, can be provided by some DER resources, notably storage/inverter sets and over- or underfrequency load adjustments in response to local frequency variations (including deadband and hysteresis relay settings). The term "synthetic damping" is sometimes used to refer to this grid service, particularly when it is provided by DERs. Emergence of PFR as a tradable grid service is relatively new. In both Federal Energy Regulatory Commission (FERC) Order 888 (issued April 1996) (FERC 1997) and FERC Order 2000 (issued December 1999) (FERC 1999) a single tradable product was defined as Regulation and Frequency Response. With the proliferation of bulk and distributed renewable resources, this product has been split into two separate products, namely Frequency Regulation (defined above) and PFR defined here.

– Synthetic Inertia: This is a relatively new grid service. Traditionally, system inertia has, for the most part, been provided by the rotating mass of conventional turbine-generators. With proliferation of low-inertia generation in bulk power, distribution, and customer-side production such as solar, the need for synthetic inertia is gaining attention. Some DERs can provide this service via local controls that enable them to respond to the rate of change of frequency.

2. **Distribution Grid Services**

– Volt/var support. Although this service is relevant to both bulk power and distribution operations, it is much more amenable to TE mechanisms in distribution. Traditionally in bulk power markets, this service has been provided by conventional generators and synchronous condensers through long-term contracts between suppliers and grid operators. To support distribution operations, DERs such as battery storage/inverter sets can provide volt/var support in a highly flexible and agile manner.

– Phase Balancing. This service is specific to distribution. Bulk power in steady-state operation is treated as a balanced three-phase system. This premise does not necessarily hold for low-voltage distribution feeders. For example, at a given time there could be solar PV generation on Phase A on some houses in a neighborhood, while EVs are charging on Phase B at other houses in that neighborhood. Flexible DERs can provide the means for phase balancing, enabling the distribution grid operator to deploy the DERs (in return for compensation).

3. **Both Bulk Power and Distribution Grid Services**

– Balancing Energy. This service has traditionally been a bulk power service, referred to as energy imbalance service in FERC Orders 888 and 2000 (FERC 1997, 1999). With the emergence of the DSO construct and the need for closer transmission system operator (TSO)-DSO collaboration and coordination at the transmission/distribution interface in managing system imbalances, balancing energy is gradually emerging as a service in support of distribution operations.

– Flexible Ramping. This is a relatively new service in both bulk power and distribution operations. Most bulk power markets do not obtain flexible ramping separately from energy and other grid services. This is particularly true where the balancing area does not face extremely high ramps in its net supply and demand, and where sources providing bulk power energy and ancillary services have adequate ramping capability. However, some ISOs/RTOs such as California ISO and Midwest ISO (MISO) recognize this as a separate product. Flexible ramping is also widespread in Europe. In fact, in recognition for the need for this service, the term "DFR" (distributed flexibility resource) is often used instead of "DER."

Because of its agility and operational flexibility, storage can provide many of the grid services listed above, and so can play an important part in the future high-DER TE grid (Rahimi and Ipakchi 2016).

Based on wholesale and retail market rules and protocols, the grid services mentioned above can be offered voluntarily by transactive agents to power system operators, either directly or through aggregators, including participation in utility or bulk power market DER programs, P2P trading of obligations, or other market activities (Rahimi and Mokhtari 2018). In this context, the “transaction” between the grid operator and the prosumer includes the agreement to procure a service before it is needed, while the signal that triggers the real-time response from the resource can be automated or autonomous at the resource (like PFR) or from a centralized source (like AGC). Thus, markets and controls are complementary functional modes that are all within the scope of TE, rather than TE only being responses to prices.

From both the system operator and the prosumer (DER provider) perspectives, forecasting the level of grid services needed by the system operator and the ability of the DER operator to provide those services are more complicated with more diverse DERs. For example, to run the five-minute wholesale market, an ISO/RTO needs a forecast of net load at each T&D interface about 10 minutes in advance. More generally, in order to perform real-time balancing, a TSO needs the same type of forecast. And while much work is underway to improve such forecasts, they are not yet adequate. And the problem gets worse with more diverse DERs. With only PV, good estimates of power output can be made with good information on installed capacity by location and weather forecasts, but estimating is more difficult with many more controllable devices that are responding to time-of-use rates, managing customer demand charges, or engaged in behind-the-meter (BTM) activities. Better short-term operational forecasting along with proper information and communication could change a view of DERs as a problem for system operation into seeing it as a solution to improve operational flexibility.

4.2.2 DER Services and Values Recognized Today

Figure 8 lists the DER services recognized today; not all of them are currently provided by DERs at a significant scale. This section first reviews what is working today and then identifies unresolved issues or challenges to expanding provision of services by DERs.

4.2.2.1 What Is Working Today

Three main DER business cases are widely applied today:

1. Customer-side, or BTM, rooftop PV generation, enhanced financially by net energy metering (NEM) tariffs. This most basic form of DER adoption by the end-use customer is essentially passive in the sense that the customer has no active interaction with the grid: the PV installation produces power that offsets some of the on-site load and, when PV production is greater than on-site demand, injects the excess into the grid, all without any active participation by the customer. Use of NEM tariffs has stimulated adoption of rooftop PV, but as it increases, the characteristic production profile of PV creates operational concerns because it does not align well with most end-use load profiles. This leads to congestion on distribution circuits with limited hosting capacity and contributes to the infamous “duck curve” (CAISO 2013) at the level of the balancing authority. Another concern about NEM is that it allows the customer to avoid T&D charges, which some argue causes unfair shifting of T&D costs to non-adopters while the NEM customer gets essentially free use of the grid as “storage” for the excess production. Hawaii was the first state to experience such rapid growth of PV under NEM that it had to suspend new PV interconnections until its tariff structure was revised to move away

from NEM and create stronger incentives for end users to install PV + storage to mitigate adverse grid effects.[5]

2. BTM storage aggregated over multiple sites to form a DR resource that participates in the wholesale market while providing retail rate management for the end-use customer. DR is a familiar, established vehicle for end-use customers, individually or in aggregations, to participate in wholesale power markets and economic dispatch. But until the advent of BTM DERs—especially storage—DR required the end user to reduce their consumption when called upon. Storage and BTM generators are now game changers for DR because storage discharge or generator output can maintain supply to the end-use load while simultaneously reducing the net load on the grid. In cases where the resource will function only to reduce load and will not inject power into the system, placing the DERs behind the end-use meter also represents a simpler, faster, and cheaper way for DER providers to interconnect to the system than connecting directly to the distribution utility's wires. Some wholesale markets have created DR regimes that measure the DR contribution to the market using a secondary meter at the DERs rather than measuring at the end-use meter where the DERs connect to the grid. This has enabled BTM DER, including managed EV charging, to use the DR paradigm to provide energy, capacity, regulating, and contingency reserves to wholesale power markets.
3. Utility-side or "front-of-meter" DER, mainly DG and storage, participating in the wholesale market. Front-of-meter DERs can participate in wholesale markets subject to some form of wholesale access interconnection tariff and procedure. This has been a viable option for DG, subject to a minimum size threshold, to provide energy, capacity, and reserves. In some areas, storage can participate in a similar manner, but as yet there are no industry-wide conventions for some important details such as how to optimize a storage resource in the economic dispatch and how to count the capacity value of storage. For the U.S. ISO and RTO markets, FERC Order 841 (FERC 2018), issued in 2018, directed these market operators to implement a participation model for storage that would allow it to participate in a manner that accurately reflects its operating characteristics (e.g., the optimization algorithms can track and respect the resource's state of charge) and to set prices as both supplier and purchaser. Order 841 also required that the minimum size threshold for participation be no higher than 100 kW. (In all these markets, the minimum size for a generator has been considerably higher, although a 100 kW size for a DR resource has been commonly acceptable.) As of this writing, the ISOs and RTOs have made filings to comply with Order 841, but FERC has not yet ruled on those filings.

In addition, there is growing interest in obtaining grid services from flexible DERs, also referred to as "distributed flexibility resources" (DFR). An ongoing topic in Europe and the UK concerns the role of DSOs in providing grid services from DFR for TSO operational needs, but consensus has yet to be reached on whether the TSO, the DSO, or both in some coordinated process should be controlling/dispatching flexible DERs (CEDEC et al 2018).

4.2.2.2 Open Issue: DER Provision of Grid Services

Transmission infrastructure substitution or deferral: Although there is much interest in the industry around "alternative transmission solutions" instead of building conventional transmission facilities, there is no clear regulatory path for DER-based solutions to function and be compensated as a transmission asset. In the U.S., the central problem is the absence of any framework or precedent for DERs to operate under the operational control of a TSO in a manner comparable to transmission facilities (which is not the

[5] For a review of potential alternatives to the original NEM formulation see *Sustaining Solar Beyond Net Metering* (Gridworks 2018).

same as the resource participating in a wholesale ISO market).[6] At a minimum, this would require a new coordination framework between the distribution utility (UDC)[7] and the TSO to make sure that the resource is able to provide the needed transmission services without being constrained by, or causing problems on, the distribution system (Wellinghoff et al. 2018).

One aspect that needs innovative thinking is how DER owners can share in the financial benefits of avoiding transmission upgrades when their activity changes the shape and magnitude of load so as to reduce the factors that would usually drive transmission expansion, but where there are no specifically identified "needed" transmission upgrades with estimated costs to be avoided. In 2018, the California ISO's comprehensive transmission plan identified $2.6 billion in cost reductions by eliminating or downsizing previously approved transmission upgrades. DER adoption was a major factor in reducing need for these upgrades, but the savings could not be attributed to specific DER installations, so the DER investors will not benefit from the cost reduction beyond their share in the overall cost reduction for all grid users.

<u>Distribution infrastructure substitution or deferral</u>: This is a more promising route for DER, and much work has been done to quantify locational benefits of DERs that include avoiding or reducing the need to upgrade distribution facilities. Still needed, however, are (1) distribution planning process reform to increase stakeholder participation and open greater opportunities for third parties to propose DER-based alternatives to meet needs, (2) rules for UDC procurement and compensation for DERs in these cases, as well as (3) revisions to utility incentive structures that currently emphasize return on investment in distribution assets.

<u>Wholesale market participation by individual DERs</u>: In the U.S., utility-side or "front-of-meter" DERs intended for wholesale market participation (in ISO/RTO areas) interconnect to the distribution system under FERC-jurisdictional wholesale distribution access tariffs. In this case, the associated interconnection procedures determine the need for any distribution system upgrades to accommodate the resource and assign the costs of such upgrades to the resource developer. These procedures can be lengthy and costly. In contrast, BTM DERs that do not produce net injections into the grid can connect under much simpler state or local (municipal) rules and can participate in the wholesale energy and capacity markets as DR resources. An as-yet unresolved question is whether BTM DERs can inject energy into the grid (i.e., produce energy in excess of load at the same point of interconnection during the same time interval) and be compensated as a wholesale resource while interconnecting under the simpler BTM interconnection procedures.

<u>Wholesale market participation by DER aggregations (DERA)</u>: As in the previous item, the simplicity of the DR participation model is very attractive compared to the injecting model. The subject of DER aggregation for wholesale market participation was the subject of a FERC technical conference in April 2018; there was a clear tension between the desire to remove as many barriers as possible to DERA

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[6] This was a major discussion topic in the 2018-19 CAISO initiative, "Storage as a Transmission Asset"; see Cusick et al. (2019) and the CAISO initiative page (CAISO 2018).

[7] The industry uses a few different terms to denote the distribution utility: UDC (utility distribution company), DO (distribution owner/operator), DNO (distribution network operator), EDC (electric distribution company) and DSO (distribution system operator). For purposes of this report, we use "UDC" to refer generically to the existing or traditional distribution utility, and "DSO" to refer to the possible variants of a future distribution utility that has been enhanced or "modernized" for high-DER penetration. In this usage, "DSO" does not imply any specific DSO model and carries no implication as to whether the existing UDC may evolve into this model, or there is need to create a separate "independent" DSO or "IDSO" that is independent of the owner of the distribution system assets. The focus of this section of the TE Framework is more on functions than on entities.

participation versus numerous operational concerns on the part of UDCs and technical issues around measurement and compensation.[8]

A related unresolved issue is the geographic scope of a DERA. In the U.S. context, except for California ISO, the other ISOs and RTOs at the FERC technical conference argued that a DERA should be limited to a single pricing node (i.e., T&D substation) for reasons of congestion management. Although not mentioned at the technical conference, the TSO and the UDC are likely to have conflicting preferences when it comes to the geographic extent of a DERA; i.e., if the DERA is offering services to the UDC, the UDC's needs are likely to be at the level of an individual circuit or distribution-level transformer, whereas the TSO's needs are likely to be at the system or nodal level.

The element common to all scenarios of DER/DERA wholesale market participation—except for the non-injecting DR scenario—is the need for a T&D coordination framework between the TSO and the UDCs. Several structured projects are now in progress in the UK, the European Union, and Australia to specify and assess alternative TSO-DSO coordination models. The UK started such a project, the Open Networks Project, in 2017 at the direction of Ofgem, the national regulatory authority. After a series of stakeholder consultations, the UK project arrived at detailed specifications for five alternative "future worlds" or TSO-DSO coordination models, all aimed at optimizing the use of flexible DERs to support reliable operation of the power system as a whole (ENA 2018). The project has now moved into the simulation and assessment phase and is expected to yield valuable insights useful to all regions dealing with TSO-DSO coordination to enable a high-DER power system. In 2018, Australia initiated its Open Networks Project modeled on the UK project (AEMO 2019).

One further element is needed, but as yet has not been well developed: a DSO market for distribution grid services. There is no question that many types of DERs can provide services and value at the distribution level in the power system, especially by shaping the loads on individual distribution feeders, which ultimately add up to the load the bulk power system has to serve. But the traditional one-way-flow industry structure cannot realize this value until there is clear specification of grid services definitions, their performance requirements, and mechanisms for procuring, dispatching, and compensating them.

4.2.2.3 Open Issue: Stacking of Services

An appealing, but thus far unrealized, concept for optimizing the value of DERs is that of "stacking of services" or "multiple-use applications." The concept is that the same DERs or DERA can provide and be compensated for multiple valuable services and stack the revenue streams. Thus, a BTM storage device might provide peak load reduction to the end user on whose premises the device is located, as well as congestion relief on its distribution circuit, as well as imbalance energy to the wholesale market. The concept first gained wide interest following its exposition in a 2015 Rocky Mountain Institute report (Fitzgerald et al. 2015). Since that time, many advocates and storage developers have sought to apply the concept in practice, but thus far the only variant that seems to have been successful is Example 2 in Section 4.2.2.1 above. Apparently, certain implementation issues around control priority, measurement, and accurate compensation have been difficult to solve.

[8] Note that the DER aggregation model approved by FERC in 2016 for the California ISO (called DER Provider or DERP) is available to DER developers, but thus far nobody has come forward to propose a DERA to use this model. It is not yet clear what FERC will include in any rulemaking on this topic, but for the moment, participation by injecting DERA in the wholesale market is on hold, though DERA using the DR model seems to be growing.

In 2017, the California Public Utilities Commission (CPUC) and California ISO collaborated to create a framework and set of principles to advance MUA for storage. The framework identifies 22 services a storage device could provide in five different service domains: the customer, distribution system, transmission system, wholesale market, and resource adequacy (capacity). The framework categorized each service as either a reliability service or a market service and proposed that a reliability service would always have priority over a market service. It also described three modes of MUA, where the services provided by the storage device are time differentiated, capacity differentiated, or simultaneous.

These elements were formally adopted by the CPUC in January 2018, but the decision left a small set of implementation issues unresolved and directed CPUC staff to conduct stakeholder workshops to resolve them (CPUC 2018).[9] The most challenging of these issues were: appropriate metering, measurement, and accounting for MUAs, and incrementality, which addresses the concern that the storage device might be compensated multiple times for the same performance. The August 2018 final report of the working group made some progress on the deferred issues but failed to reach a consensus on incrementality (Combs et al. 2018).

4.2.3 DER Values Not Yet Recognized and Quantified

This section discusses potentially significant commercial values and societal or public-policy benefits that DERs can provide but that are not yet well recognized, much less well defined as services with associated means for procurement and compensation. These fall into three main categories: (a) customized services to meet energy needs and preferences of end users, which go beyond individual customers (individual utility meters) and include communities and local governments, and emphasize the value of participating in a high-DER transactive network; (b) the ability to shape large new demands for electricity resulting from electrification of fossil-fuel using sectors of the society; and (c) the resilience value of local island-capable power systems.

It is worth noting that these value sources do not depend on wholesale market participation and revenues. This is an important consideration because, as has been observed with serious alarm by operators of conventional fossil and nuclear generators, higher penetration of renewable generation on the grid is eroding wholesale market prices and revenue streams, suggesting that DER business strategies that depend to a large extent on wholesale market revenues may not be sustainable.

4.2.3.1 End-Use and Community-Level Service Customization

The principle at work here is that energy end users do not care about kilowatt-hours per se, they care about the services and functions that require electricity. The advancement of small-scale technologies that are becoming ever more powerful and lower in cost is creating a BTM "market" for energy services that could be a potent competitor to the grid-based commodity energy market. That is, nearly all end-user types will be able to customize energy services and their desired level of reliability, resilience, and power quality with BTM equipment that meets a major share of their energy needs and relies on grid-supplied energy for residual needs and other transactions.

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[9] CPUC Decision D. 18-01-003, *Decision on Multiple-Use Applications* (CPUC 2018). Section 4.2 of the decision discusses the unresolved issues to be deferred to a working group; Appendix B of the decision provides the entire CPUC-CAISO "Joint Framework."

In this scenario, we need to expand the definition of “customer” beyond the individual utility meter to include diverse communities of customers, such as apartment complexes, subdivisions, neighborhoods, commercial/industrial parks, essential municipal services, activity districts, etc.

Clearly, growth of BTM DERs in this manner will further disrupt conventional utility rate structures for recovering costs of T&D assets, so new rate-making approaches will be needed. TE principles suggest that new approaches should derive from an updated concept of the “value of the grid,” i.e., the basic rationale for why energy end users should stay connected rather than permanently defect as defection becomes technically and economically more attractive. Imposing fixed connection charges or similar devices to shore up fixed cost recovery would make grid defection even more attractive; TE principles suggest that new cost recovery mechanisms should reflect the value end users receive from the electricity system as well as the effects they have on the system, i.e., cost-benefit and cost-causation considerations. The TE framework suggests that this updated value of the grid will be based on the transaction capabilities that derive from participating in a populous, well-functioning network.

With respect to charges for the use of the grid, a possible paradigm could be one where distribution services are unbundled and consumers/prosumers can pick the services they need, under a subscription tariff or in a pay-as-you-go regime.

4.2.3.2 Shaping of New Electrification Demand

Achieving decarbonization targets will require electrification of fossil-dependent activities, of which the main ones are transportation, buildings, industry, and agriculture (e.g., water pumping). Thus, while most standard long-term forecasts of electricity demand suggest very little or no growth due to the usual factors (e.g., demographics), once we account for accelerated large-scale electrification there will likely be substantial growth in electricity demand. The key questions are (a) what will be the shape of that demand (i.e., daily net load profiles, at various levels from the end-use meter, to the distribution circuit, up to the bulk power system), and (b) how can the shape of electrification demand be managed to minimize adverse operational effects and infrastructure upgrade requirements? For example, a distribution circuit with a high density of PV will be able to accommodate much more PV if combined with storage than if implemented as “naked” PV, because the latter will sooner confront the circuit’s hosting capacity.

The potential value of DERs in shaping such demand—and thereby facilitating decarbonization—is enormous. But as yet there are no effective methods to quantify this value, nor regulatory and market structures, such as distribution tariffs and distribution-level services, to compensate DERs for providing such value.

4.2.3.3 Resilience and Microgrids

Resilience has become a central theme in today’s electricity system discussions, and there are many different perspectives on what exactly it means and what strategies should be pursued to achieve it.

As a case in point, in 2017 the U.S. Department of Energy issued a Notice of Proposed Rulemaking on resilience emphasizing fuel security for large central power plants. FERC rejected that Notice of Proposed Rulemaking and opened a new proceeding to investigate grid resilience in ISOs and RTOs. The U.S. Department of Defense is interested in enhancing resilience of military bases. In short, a national discussion on resilience is underway in the U.S., even though the term may not yet be well defined.

We begin our discussion here by comparing resilience to reliability in the context of power system operations because the distinction between the two is often blurred. We then point out how DERs and TE concepts are applicable to each.

According to the National Infrastructure Advisory Council (2009) the critical infrastructure resilience is defined as *"the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to* ***anticipate****,* ***absorb****,* ***adapt to****, and/or* ***rapidly recover*** *from a potentially disruptive event."* Microgrids are good examples of power system/prosumer constructs to augment power system resilience. However, there are no standard metrics today to quantify resilience and monetize the resilience value associated with a microgrid or other resilience project. Qualitative measures can be used for comparison of different options.

In contrast, reliability is defined as the ability of the power system to deliver electricity in the quantity and with the quality needed to satisfy demand. For distribution operations reliability is generally measured by interruption indices such as

- System Average Interruption Duration Index (SAIDI)
- System Average Interruption Frequency Index (SAIFI)
- Customer Average Interruption Duration Index (CAIDI)

The main reliability products that are currently monetized in wholesale energy markets are ancillary services. As discussed above, DERs can provide these reliability services in a transactive setting.

To extend the TE framework to enable transactions based on valuation of resilience, standards for quantification of resilience must be developed. Once such metrics are developed and accepted, they can be used to construct bids and offers in terms of dollars per unit of resilience measure.

We close this section by offering possible resilience enhancement measures and a set of potentially useful metrics for further research.

Resilience enhancement measures*:* The following three categories of measures can help enhance resilience of a power system. For each category, we distinguish conventional measures from new measures that could leverage DERs, microgrids, and new technologies.

- Grid Hardening: This involves investment in grid infrastructure.
  - Conventional measures: generation, transmission, and distribution upgrade investments
  - Additional new measures: microgrids; leveraging DR/DERs (non-wires alternatives)
- Vigilance and Early Detection
  - Conventional measures: fault location and isolation; Remedial Action Schemes
  - Additional new measures: a number of emerging standards for both grid and grid-edge system operations, including ride-through standards (e.g., IEEE 1547-2018 [IEEE 2018]), microgrid interconnection standards, etc.
- Speedy Restoration
  - Conventional measures: manual system restoration
  - Additional new measures: automatic self-healing capabilities

Possible types of metrics to quantify resilience: The following metrics are suggested in the context of “with vs. without” analysis, i.e., measured as the difference between conditions with and without TE in place, for a resilience enhancement project:

- metrics based on early detection and self-healing capabilities (resilience measure compared to status quo)
  - reduction of the geographical scope of the effect of probable extreme events
  - reduction of the effective impact intensity of the extreme events
  - reduction of the duration of effects of the extreme events
  - reduction of the effects of probable extreme events on loss of human life
  - reduction of the effects of probable extreme events on economic losses
- metrics based on system hardening
  - number of malicious cyberattacks averted
  - number of natural disasters averted.

4.2.4 Transactive Markets and Peer-to-Peer Transactions

TE markets do not necessarily involve only P2P transactions, though some advocates of TE seem to view TE and P2P as the same thing. This TE framework takes a broader approach—also an evolutionary approach—by considering a staged approach to implementing markets on distribution.

A distribution-level market for DERs to voluntarily provide bid-based services to the distribution system is a transactive market. Such a market may be a place to start with distribution-level markets, because it is the simplest and may offer the greatest source of revenues for DERs in the near term, while P2P transactive exchanges are in an exploratory or infancy stage. DER services to shape electrification demand, as suggested in Section 4.2.3.2, can be of increasing value to the power system as the electrification of fossil-based activities (transportation, buildings, etc.) accelerates and creates new electricity demands while also introducing more diverse variable resources into the distribution system. Thus, efforts to create distribution-level services for DERs and markets for those services can provide a foundation for more cutting-edge distribution-level transactional markets in the future.

4.2.5 Distribution System Operator Models

The operational, planning, market, and regulatory issues raised by proliferation of diverse DERs and their active provision of services to multiple levels of the system lead us to consider the evolution of the UDC into a DSO with new and expanded functional capabilities. As yet there is no single, preferred DSO model, and it is quite likely that different DSO models will be adopted in different regions depending on such factors as their growth rates of DERs, their public-policy goals, and their starting place in terms of existing UDC regulatory framework, infrastructure (e.g., advanced metering infrastructure [AMI], situational awareness), and functional capabilities.

One central issue is whether a UDC-facilitated, distribution-level market would lead to conflict of interest between the open-access operational role needed from a market operator (DSO) and commercial interests of the UDC as a load-serving entity or a DER provider. Another issue is whether distribution system planning needs to exclude the owner of the distribution assets due to the latter’s profit structure as a rate of return on assets. These issues have led to independent-DSO models, or DSO models with a firewall separating the commercial activities of a UDC-DSO from the system operations, market operations, and planning functions.

The choice of any particular DSO model also has implications for the T&D coordination framework needed to accommodate large quantities of both wholesale-participating DERs and DERs participating in distribution-level markets. The coordination framework must specify roles and responsibilities of the TSO and DSO so as to ensure reliability and efficiency of the power system as a whole as the volume of DERs and grid-scale renewable generation grows.

In considering possible DSO models, it is helpful to think in terms of a spectrum of possibilities between two "bookends." One bookend is the Total DSO, which is characterized by the DSO's aggregation of all loads and DERs within a local distribution area (LDA) defined by a single T&D interface substation, so that the TSO sees only a single resource at that interface. In this model, the TSO does not need visibility or control of individual loads or resources within the LDA, nor does it need information on distribution system conditions within the LDA, because the DSO is responsible for representing the aggregate behavior as well as wholesale market bids and offers to the TSO as though the LDA were a single resource. In this model, the DSO operates a market within the LDA whereby individual loads and DERs may offer services to both the distribution system and the wholesale market, and then incorporates the results of clearing this market into its bids and offers to the TSO. In order to ensure nondiscriminatory treatment of all loads and DERs participating in the LDA-level market, the DSO would be subject to an open-access regulatory framework analogous to FERC's open-access framework for TSOs and wholesale markets (FERC 1997). In the Total DSO model, the TSO's and DSO's roles are clearly defined on their respective sides of the T&D interface. Thus, the Total DSO model illustrates the grid architecture principle of layered decomposition (Taft 2016) in its pure, conceptual form.

The other bookend is the Total TSO, in which the TSO has visibility and issues dispatches to all dispatchable loads and DERs within each LDA. To ensure that all dispatches are feasible and do not cause operational problems on distribution, the TSO models the distribution circuits in its optimization algorithms and has sufficient visibility to current distribution system conditions. The DSO's role in this model is reduced to maintenance and operation of the physical assets that compose the distribution system, subject to the scheduling and real-time operational control of the TSO. This model illustrates a fully centralized market optimization and control paradigm for the high-DER power system. The Total TSO model contrasts with the Total DSO model in that, rather than seeing a single resource at the T&D interface, the TSO would see potentially thousands of resources below each T&D interface in its optimization.

What is a DSO?

The distribution system operator is an emerging role in the overall grid, similar in many ways to a transmission system operator (TSO/ISO) like PJM or ERCOT, except that the DSO is responsible for the operation of the distribution grid.

A DSO may or may not be a distribution asset owner (utility) and may operate on one or more utility's assets. A wide range of roles have been suggested for the DSO, from forecasting to restoration and market making to control of the power flow.

For the purposes of this framework, a DSO could be any entity that operates the distribution grid and has insight into its power flows and operating conditions. The DSO would be expected to manage the stability of the grid and set an initial market in each interval (e.g., an hour) for each market area (e.g., a circuit or a circuit phase).

The DSO would monitor transactions between parties, and potentially adjust or cancel transactions that endanger the stability of the grid. The DSO may also monitor performance of each party in a transaction.

The DSO would also keep track of who could contract with who, based on the connectivity of the grid and qualification of the participants. As the grid acquires more automation, that list may change day by day, depending on the switch positions, new devices, and system dynamics.

Between the two bookends, there is a spectrum of possible "hybrid" DSO models that could be closer to one bookend or the other. Toward the Total TSO end of the spectrum could be a TSO that sees and dispatches all dispatchable loads and DERs but does not model distribution circuits. The TSO would model the distribution-level resources—potentially thousands below each T&D interface—as though they were located at the T&D interface and would coordinate with the DSO to ensure feasible dispatches and prevent adverse effects on the distribution system. Toward the Total DSO end of the spectrum could be a DSO that shares the aggregation function with several other aggregators, each of which submits its own aggregated bids and offers to the TSO at a given T&D interface. In general, the hybrid models have more complex TSO-DSO coordination requirements than the bookends.[10]

In addition to the operational considerations of alternative DSO models, further work is needed to develop their business models:

- How does a DSO recover the costs of providing services?
- What services and values do users of the DSO system and markets receive, and what rate structures are appropriate for these services?
- What services and values do users of the system provide to the system, and what compensation structures are appropriate for those?
- If the DSO is structured as a regulated monopoly, considering the "natural monopoly" character of the distribution wires system, what is the optimal boundary of the monopoly to ensure an open, competitive arena for innovation in services and technologies?
- Should the DSO functions be performed by an independent DSO that is structurally separate from the owner/operator of the physical distribution assets, particularly to remove the preference for building rate-based assets in infrastructure planning?
- What are effective and fair rate structures for recovering the costs of the distribution infrastructure?

4.2.6 Summary: Redefining the Value of the Grid

The North American Electric Reliability Corporation (NERC) functional model defines distribution provider thus: "The Distribution Provider delivers electrical energy from the Transmission system to the end-use customer." Clearly, that definition did not contemplate a high-DER power system where end users of energy could also be producers and diverse generation and storage resources are connected to the distribution grid and provide grid services. Under the traditional definition, the value of the grid was its function of moving electric energy in one direction, from the bulk power system to the end user. In a high-DER system, the value of the grid must be redefined to reflect the benefits that end users and DERs can receive by being connected to the DSO grid and participating in its markets.

As scalable local technologies increase in power and performance while declining in cost, many end users will consider permanently defecting from the grid. So, it will be incumbent on the DSO to offer enough value that most end users will decide to stay connected (except perhaps in emergency conditions) and participate in the grid's services and markets. But this goes to the heart of what this section has been about, i.e., to advance business models and market frameworks that will enable all participants—

[10] During 2016-17, the California ISO and the three California investor-owned utilities conducted a working group to develop initial approaches to T&D coordination to manage DERs participating in the wholesale market. This work is reported in *Coordination of Transmission and Distribution Operations in a High Distributed Energy Resource Electric Grid* (CAISO et al. 2017).

prosumers, DER providers, DSOs, and traditional end users—to realize the maximum benefits from the high-DER power system.

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 work would be done by a core team of experienced system architects and would represent the design of a specific example of a TE system. Rather, it suggests key elements and principles to be considered in development of the TE Conceptual Architecture (Figure 9), 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.

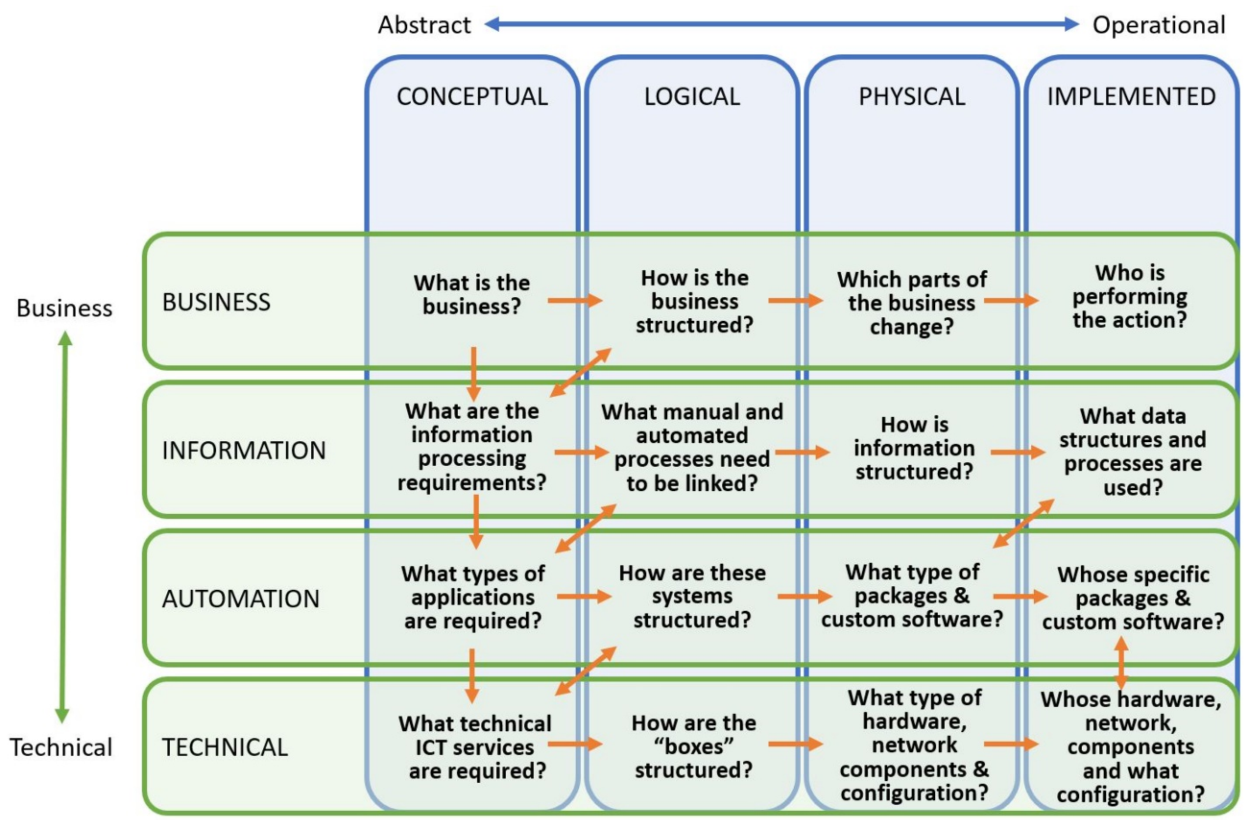

Figure 9. Architecture layers and iteration levels (Adapted from NIST Special Publication 1108r3 [NIST 2014]). ICT is information and communications technology.

As depicted in Figure 9, 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 Council recommends that a TE 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 the distribution grid endpoint on one hand, and the smaller scale, less hierarchical structure of microgrids 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 TE system architects should recognize that differing goals may apply at different levels in the recursion.
3. Layering for optimization decomposition may be considered. Such approaches provide a mathematical foundation for structure of the control and coordination portions of the architecture. Detailed discussion of such structures may be found in Taft (2016).
4. The architecture should be agnostic to the general physical layer (refer to the Control Abstraction Model, Figure 13): 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 creating and realizing value.
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, including
  - domain diagram – graphical depiction of the problem space, showing key elements in relation to each other
  - industry descriptions and emerging trends analysis
  - key use case list – list of primary use cases as TE is understood today, with descriptions of each
  - key systemic issues list – list of crosscutting 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 antifragility
  - manageability of ULS system effects
- Interfaces in a TE system to
  - traditional markets
  - distributed markets
  - traditional energy system controls
  - flexible energy resource endpoints of any kind (make, move, use)
- Transactive Control
  - transactive control abstract elements 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
  - multilevel 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 developing TE principles. The first two are the GWAC's Interoperability Framework (the GWAC Stack) in Figure 10 and the National Institute of Standards and Technology (NIST) Smart Grid Conceptual Model in Figure 11. 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.

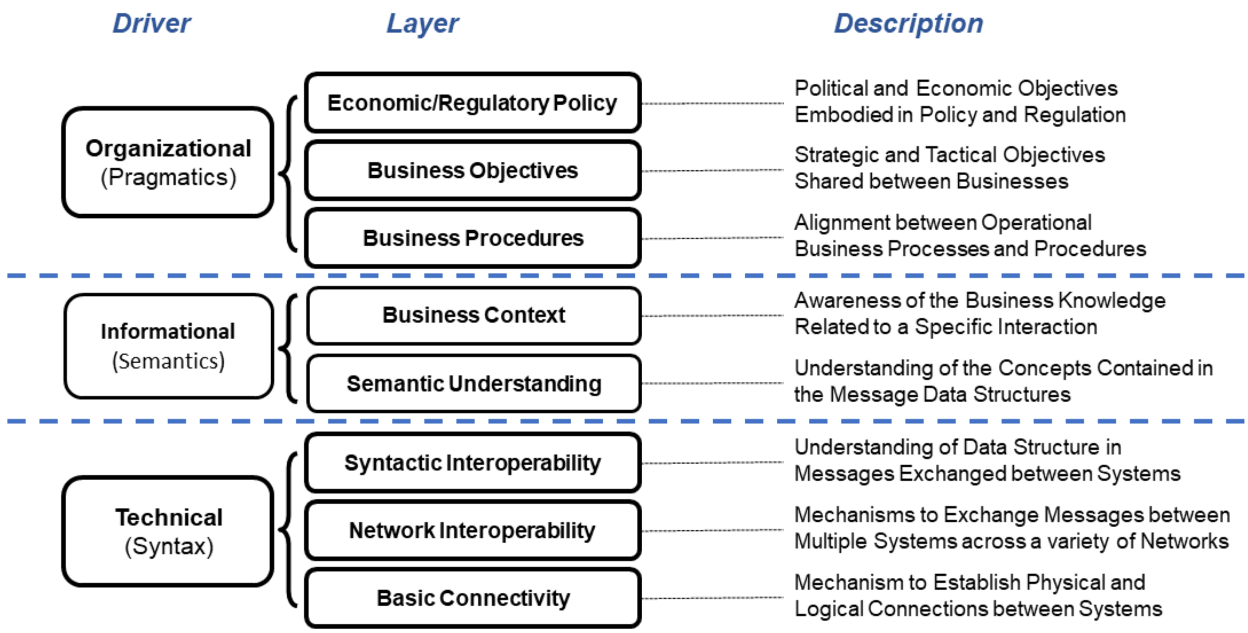

Figure 10. The GridWise Architecture Council's interoperability framework (GWAC 2008)

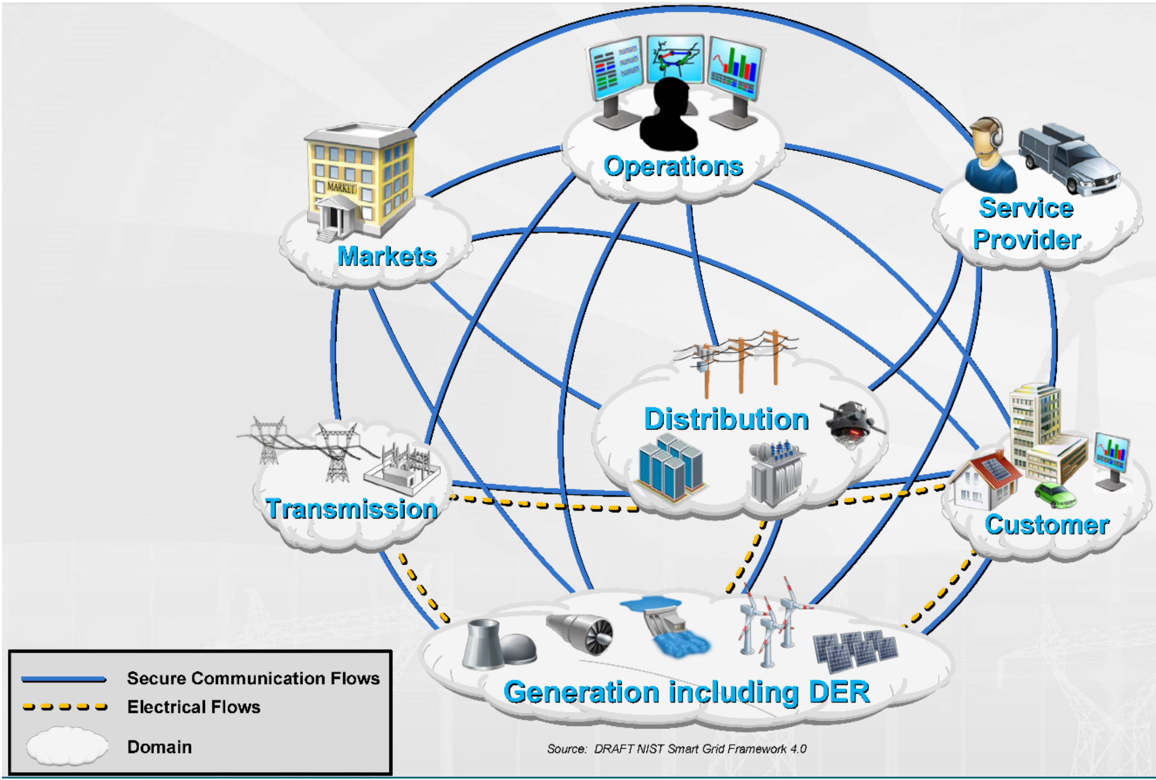

Figure 11. NIST Smart Grid Conceptual Model

TE 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 TE Abstraction Model captures this thought: any transactive entity in the system can be decomposed using this model (Simard 2013). A good example is a storage entity that can at times be either a user of energy or a maker (supplier) of energy. It can both respond to requests from other transactive entities in the system and issue requests to other entities.

Figure 12 emphasizes that actors may not only change domains but may also change roles within a domain. In a TE managed system, adopters are cautioned not to limit the role or domain, because these may change over time and use. As an example, an EV battery may be considered a load when it is charging and may be considered a generator when it is supplying energy to the grid.

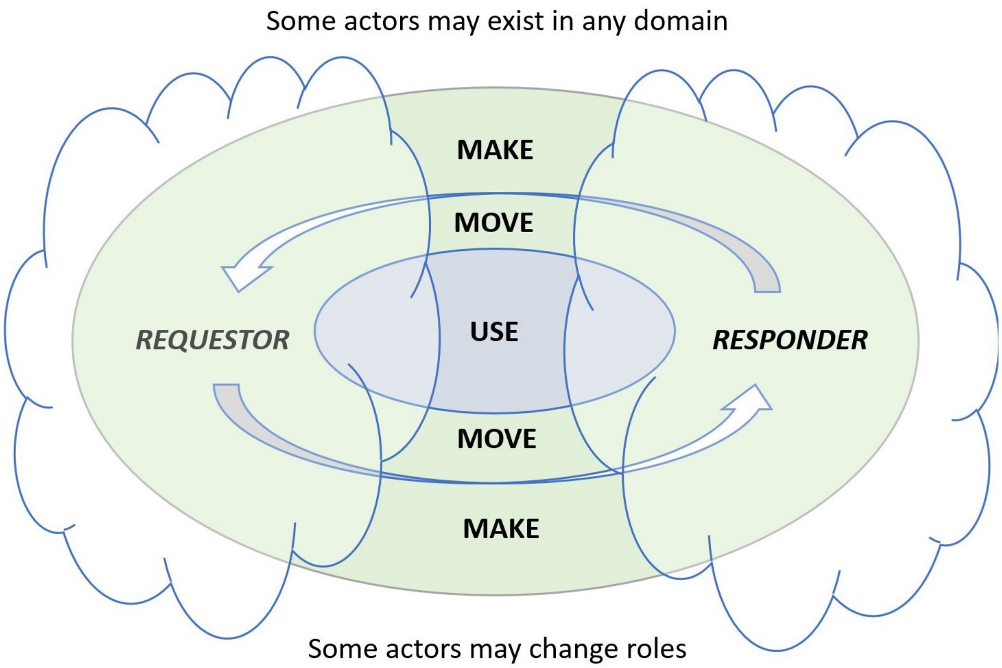

Figure 12. Grid Vision 2050 transactive energy abstraction model[11]

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 13. This helps put the concept of cyber-physical systems in context for TE management.

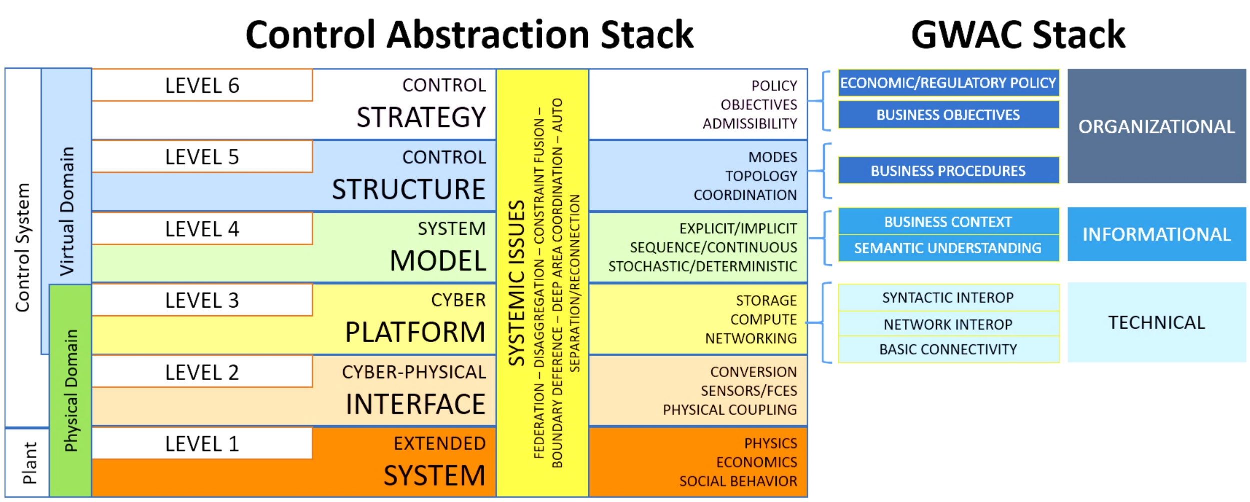

Figure 13. Integrated control abstraction stack/GWAC Stack model

[11] Used with permission of EnerNex and Ron Bernstein Consulting Group.

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 electric power grid architecture includes two cyber-physical networks: the electric power network and the communications network(s) necessary to monitor and control it. In the early days of electric power grid operations, there were few or no communications networks for monitoring and control of any kind, so the generation, transmission, and distribution equipment was designed to deliver power with locally optimized control to protect that equipment and support safe operation of the grid. As the grid has evolved, multiple communications networks have emerged to support the ever-increasing demands on the power delivery infrastructure and to ensure the continued safe and reliable operation of the grid as a system of systems.

Today, we consider the electric power grid to be a cyber-physical system (CPS). NIST (2017, p. 5) defines a CPS as follows:

> "Cyber-physical systems integrate computation, communication, sensing, and actuation with physical systems to fulfill time-sensitive functions with varying degrees of interaction with the environment, including human interaction."

NIST also describes CPSs as smart systems that consist of highly interconnected networks of physical and computational components (Roth et al. 2017). Pragmatically, since the cyber aspect is increasingly a critical component for operation, the health of the network supporting those components is also important. Just as the cyber assets are used to monitor the health of the physical grid, the health of the network supporting the cyber assets needs to be monitored.

4.4.1 Understanding the Electricity Grid

The physical electricity 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 names "distribution network," "distribution system," or "distribution grid," and the higher-voltage network has acquired the names "transmission network," "transmission system," "transmission grid," or "bulk electric grid"; for the purposes of this section, they will be referred to as distribution and transmission, respectively.

Transmission is traditionally built as a balanced three-phase system; that means that the same amount of power flows across the system on each of the three phases. The equipment built into the transmission system operates on all three phases at the same time. Very large customers, such as steel mills, are connected directly to the transmission network, taking high-voltage, three-phase power. Transmission is traditionally built as a highly networked (interconnected) system with multiple paths (or sources) for each load center, with the goal of preventing problem in one place from causing a widespread power outage. This configuration also facilitates the exchange of power between regions, the "wheeling" of power from one region through a second to a third, and larger power pools, all geared toward maximizing the instantaneous balance between generation and load with sufficient operating reserves.

Distribution is different from transmission. Spokes in a bicycle wheel (without the rim) serve as a good analogy for the distribution system. The power arrives at the hub from transmission and is delivered to customers via any of several circuits. Distribution customers are served by three-phase, two-phase, and single-phase circuits, with many different delivery arrangements (two-, three-, and four-wire services; wye and delta configurations). In the 1960s, industrial customers dominated electricity use, and three-phase customers used more power than all other customers combined (EIA 2019b). Often smaller (load) customers are served with a single phase, the other two phases of the circuit going off in other directions to provide for other customers. Today these single-phase, typically residential or small commercial, customers are the largest users of electricity (EIA 2019b). This creates new challenges in a TE world.

When a customer is attached to a single phase, they can only use (or deliver) power or energy from/to that single phase. Single-phase customers cannot interact directly (electrically) with the other two phases (up to a certain point on distribution), yet they may be interacting with other TE system participants on those phases because participants on one side of a street may be on a different phase and potentially see very different signals for pricing than the participants on the other side. Consideration of phases puts must be accounted for in designing and implementing TE systems so as to avoid unrealizable transaction commitments. Therefore, controls related to these limitations must be included in TE systems and may be embedded in the incentive signal, since systems rarely have perfectly balanced loads, currents, voltages, and impedances in all three phases, and highly unbalanced systems can cause severe problems.

TE applications will operate in both the cyber domain, by making use of the communications infrastructure, and the physical domain, by delivering electricity products and ancillary services. The cyber domain may overlay the physical domain geospatially or it may not map to it at all. But whether it overlays or not, it is important to have a secure, robust communications system.

As we evolve the electric power grid further to support the concepts of TE, we must transform the cyber-physical elements. New sensors, actuators, and distributed and centralized control elements must now be deployed that were not necessary for the traditional operation of the grid.

Initially, TE systems will be overlaid on any existing system, using what is available to "make do." Eventually, as more devices are deployed, the electric power and communications systems will become more robust and will be able to benefit from the newly introduced capabilities. Multiple channels of communication between TE system participants, from simple text message broadcasts to TE signals sent over the internet in a secure fashion, will provide greater flexibility, resilience, and latency. In the future, pricing signals could, for example, be sent in hourly intervals once or twice a day as a schedule; but, to evolve into a true transactive market, shorter intervals will have to be possible.

Existing, or legacy, devices and systems will be expected to support applications they were not originally designed to support, such as DER integration and TE. For a TE system, 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 through a central command and control paradigm. Specifically, features such as asynchronous information exchange, staged data filtering, and pruning will be part of the future communications system:

- Asynchronous information exchange, or "sessionless" communications, permits the interested parties to interact without a time- and bandwidth-consuming session.
- Staged data filtering could allow areas with little or no traffic that is TE related to filter out nonparticipant data, or data that has not changed.
- Pruning would allow trimming out areas that are stable or again had no currently active participants in a dynamic and continually refactored manner.

Both the latter techniques would lower bandwidth requirements and reduce latency for TE applications. The communications must be layered with loosely coupled system interactions to enhance flexibility.

The integration of information technology and telecommunications with the traditional electricity 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 network-compromising capabilities. Because security weaknesses can potentially be exploited to disrupt service over a wide portion of the grid, the financial and safety costs of disruption can be high. Any cyber system installed must be designed to support fail safe and fail useful mechanisms that address safety and reliability concerns.

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

Today's DR programs (DG, storage, heating, ventilation, and air-conditioning control, hot water heaters, and other possible energy-elastic items connected to the grid) are a hodgepodge run by separate and disparate organizations, including ISOs, distribution utilities, aggregators, retailers, and individuals. While this *ad hoc* collection works reasonably well, each organization operates independently of the others, and most require one or more human operators in the loop to activate and monitor a DR event. They also typically provide DR as shedding of load, rather than being oriented around grid needs, including potentially adding load when such system needs arise. This is the status quo because there is a lack of coherent measurement and verification mechanisms. Where there is pervasive advanced metering with short intervals and frequent data push to upstream applications, there is opportunity for quicker calculation of the actual benefit and performance of a DR program. A way to accelerate the transition to a more comprehensively measured and controlled system would be to push for more cohesive markets, akin to the wholesale markets for electricity, to evolve at the distribution level. Experiments regarding who, how, and what, will need to be done. The United Kingdom, New York State, and others are starting to experiment with DSOs and the market hub for TE may need to be considered as a role of the DSO.

Electric vehicle charging may join DR programs, adding to the capability of the system to both draw and provide energy as needed for broader system operation or economic goals. They also could be used to provide ancillary services such as frequency control or voltage support. Securely communicating to these vehicles may add complexity to the communications infrastructure.

One of the possible integrating roles of TE systems is to provide a translation and communication capability between DR 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 customers themselves can make a decision about whether to respond to the signal or not.

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

- asynchronous information exchange
- disengaged-resource data[12]
- staged data filtering and pruning

[12] Disengaged-resource data is information about generation, storage, and responsive demand that is not currently engaged in the TE market, but that could become engaged. Knowledge of disengaged resources provides planning and forecasting information that may make a significant difference in pricing.

- layered and loosely coupled system interactions
- customer device-based decision making (or the customers themselves directly)
- distributed control and control programming.

4.4.2 Hierarchy of Node Levels

There is a hierarchy of physical and logical levels in the electric power grid across which TE systems and mechanisms would operate. The characteristics of the nodes within these different levels are relevant to TE systems. For purposes of discussion in this section, messages originate at the top and flow down to lower nodes; that is, in a one-way, hierarchical flow. In general, one will expect messages flowing in reverse as well. It should be noted that this is just one example, and that as we move to more distributed systems, one should expect messages to originate at any point in the system and flow in any direction without hierarchical or directional constraints.

4.4.2.1 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, 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 node in an initial TE system. Approximately a dozen regional nodes exist in North America. Each of these 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, defined geographic area within the region (e.g., MISO might focus a TE message on the Chicago area to reduce transmission congestion; see Section 4.4.2.2, Control Area Nodes).

4.4.2.2 Control Area Nodes

The second level down in our presumed hierarchy would be a control area node containing a control center and its AGC system. These control areas are considered to be defined by the collection of generation tied to the AGC and tend to be much smaller than regional nodes; however, “smaller” is relative: all of New York City (pop. 8.6 M+) is in a single control area. The largest control areas cover more than 10 million people. To engage in TE transactions, a control area node would receive TE transactions from a regional node and translate them into transactions to be sent onward to the generation units in its AGC and potentially to large customers who have either generation or DR contracts, as well as on to distribution operators. The control area nodes will generally also communicate to the regional nodes in the process of establishing and executing transactions.

4.4.2.3 Distribution Nodes

Control areas are made up of one or more distribution systems, where each distribution system typically has a unique way of communicating with connected customers. It might be through an automated metering system, a text message, a radio station signal, or some combination thereof. 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 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 other than their position in the hierarchy.

4.4.2.4 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.

4.4.2.5 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, supply nodes are registered as a supplier with the regional node or the control area node and have a contract for services with that node.

4.4.2.6 End-Use Nodes

End-use 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 end use is an equipment cabinet or even an EV and its charging equipment that is potentially capable of supplying electricity to the distribution system. Around 99 percent of end-use nodes that are available are buildings of less than 5,000 square feet in size (if an actual building), and on average, draw less than 20 kW of power.

4.4.3 Node Characteristics and Responsibilities

Table 1 enumerates examples of the responsibilities of the nodes within a TE system

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, and 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, and acknowledgment of regional messages
		(2) Translating regional messages into messages for lower level nodes
		(3) Transmitting transactions to lower level nodes securely
		(4) Receipt, verification, and acknowledgment of downstream messages
		(5) Translation of downstream messages for transmission upstream

Level	Number (U.S.)	Transactive Energy Responsibilities
		(6) Transmitting downstream messages upstream securely
		(7) Logging and auditing transactions
Distribution	~1500	(1) Receipt, verification, and acknowledgment of upstream messages
		(2) Translating regional messages into messages for lower level nodes
		(3) Transmitting transactions to lower level nodes securely
		(4) Receipt, verification, and acknowledgment of downstream messages
		(5) Translation of downstream messages for transmission upstream[a]
		(6) Transmitting downstream messages upstream securely*[a]
		(7) Logging and auditing transactions
Market Participant	~500	(1) Receipt, verification, and acknowledgment of upstream messages
		(2) Translating regional messages into messages for lower level nodes
		(3) Transmitting transactions to lower level nodes securely
		(4) Receipt, verification, and acknowledgment of downstream messages
		(5) Translation of downstream messages for transmission upstream[a]
		(6) Transmitting downstream messages upstream securely[a]
		(7) Logging and auditing transactions
Supply	~10,000	(1) Receipt, verification, and acknowledgment of upstream messages
		(2) Translating transactions into local action
		(3) Responding upward with actions taken or not taken
		(4) Logging and auditing transactions
End Use	~150,000,000	(1) Receipt, verification, and 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.		

4.4.4 Transaction Train

At each level in the transaction chain shown in Figure 14, not only is a translation of the pricing and other information being done, but additional constraints or local parameters are added. For example, if a premises has a limitation of not raising the building temperature above 78°F and it is 77°F 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°F.

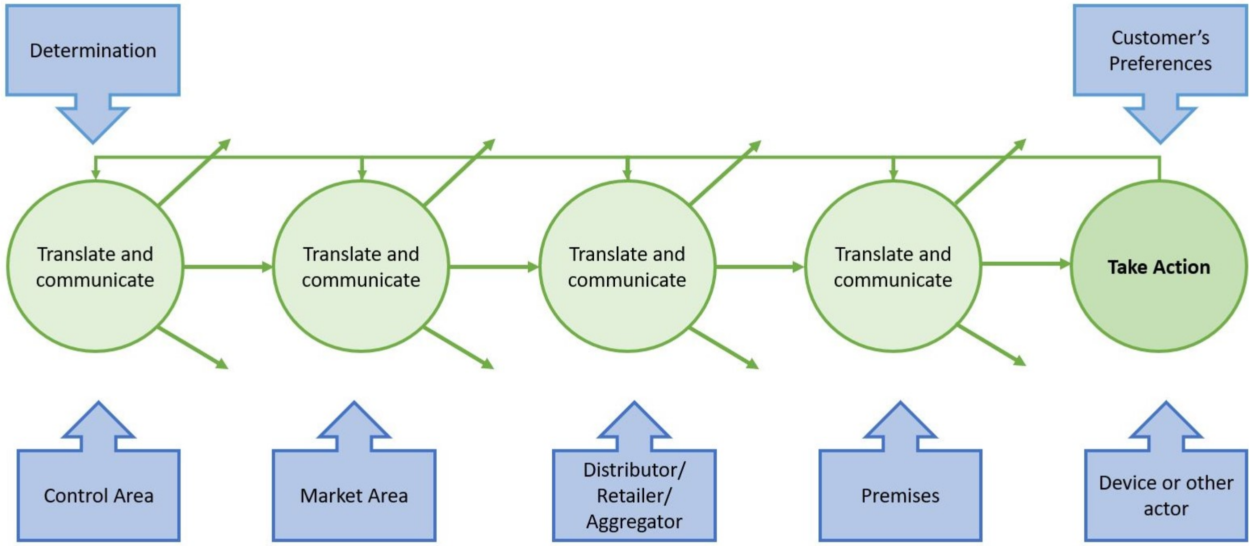

Figure 14. Transaction train model

The example shown in Figure 14 is a logical view of one way to create a TE system. Though the diagram has a hierarchical structure one should note that there are TE systems designs where the message flow does not follow a hierarchy. The flow, for example, might be P2P. At the building node level in residential premises, smarter appliances, lighting circuits, and consumer electronics will be introduced. 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 (FERC 1997). Consumer electronics companies may find profitable business opportunities in supporting smart grids including TE. TE features might be embedded in consumer products or in an energy management agent (as specified, for example, in the international standard for energy management [ISO/IEC 2012]), so that transactions automatically occur according to parameters set by the customer.

Voice response systems (e.g., "Siri," "Alexa," "Google Assistant," and others) combined with IoT (internet of things) devices offer a way for most customers to participate. Voice response means that customers can just say what they want to a voice response unit (e.g., "make it cooler") and the voice response unit can do the heavy lifting in working with the TE system. This may open TE up to many people who would otherwise be wary of the system or are renting and do not have access to a building energy management system. Like Wi-Fi, voice response systems may eventually become ubiquitous in homes. Despite this technology, making the system available to low income customers who may not have it is a concern that will need to be addressed.

TE can ride on these customer desires and provide yet another function for residential customers to use as they choose. Monitoring equipment, connected at the breaker panel or at the meter, for consumption and other electricity characteristics will eventually be available, and will be installed by the utility, by builders, or by customers themselves. Whether TE is added through installation of monitoring equipment or some other means does not matter, nor does the speed of the evolution, because as each node adds devices, these devices can, with the appropriate registration and consent, be added to the overall TE system.

If TE is deployed early enough, and if translation between enough existing protocols is supported, TE can tie the different levels of the electrical system together into one interoperable whole, providing customers with more choices and control while reducing energy wastage and maximizing the value of new investments in the overall electrical system.

5.0 Acknowledgments

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6.0 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 [FERC 1997]). 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
"Fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution" (ISO/IEC/IEEE 42010 2011).

boundary deference
Respect for ownership or system boundaries during interactions.

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

customer
anyone taking (using) electric energy

cyber-physical (system)
A system of collaborating computational elements controlling physical entities.

demand response (DR)
Changes in electricity use 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 resource (DER)
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 DR 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 nonexclusive, characteristics of these generators include an operating strategy that supports the served load, and interconnection to a distribution or subtransmission system.

distribution service operator (DSO)
: The DSO is an emerging role in the distribution grid with the task of facilitating transactive exchanges among grid-edge actors and between grid-edge and bulk power markets, while maintaining distribution grid reliability. A DSO may administer a bid-based retail market. A DSO may or may not be a distribution utility.

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.

hedge
: Protection against financial loss due to price fluctuation by prearranged purchase or sale for future delivery at an agreed-upon price.

home energy management system (HEMS)
: A system that regulates the energy within a household, controlling devices with the goal of achieving optimal energy use 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 not 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, and 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 responses.

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

microgrid
: An electrical system that includes multiple loads and DERs 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, "prosumer" would apply to DER 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 (Hertzog 2012).

RTO (regional transmission organization)
: 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 replenished. Renewable energy resources include biomass, hydroelectric, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

resilience

The ability to resist failure and rapidly recover from a breakdown (Hertzog 2012).

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 (Stouffer et al. 2015).

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 electricity 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 nonquantitative 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

The 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.

7.0 References

AEMO – Australian Energy Market Operator. 2019. Open Energy Networks – Joint Consultation with Energy Networks Australia. Available at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Open-Energy-Networks-joint-consultation-with-Energy-Networks-Australia.

APS – American Physical Society, Panel on Public Affairs. 2010. *Integrating Renewable Electricity on the Grid*. American Physical Society, Washington, D.C. Available at: http://www.aps.org/policy/reports/popa-reports/upload/integratingelec.pdf.

Burrus D. 2014. "Improve Planning By Separating Hard Trends From Soft Trends." *Huffington Post*, February 12, 2014; updated December 6, 2017. Available at http://www.huffingtonpost.com/daniel-burrus/improve-planning-by-separ_b_4774287.html.

CAISO – California Independent System Operator. 2013. *Fast Facts*. "What the duck curve tells us about managing a green grid." Folsom, California. Available at https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf.

CAISO – California Independent System Operator. 2018. *Storage as a transmission asset*. Folsom, California. Available at http://www.caiso.com/informed/Pages/StakeholderProcesses/StorageAsATransmissionAsset.aspx.

CAISO (California Independent System Operator), PG&E (Pacific Gas and Electric Company), SCE (Southern California Edison), SDG&E (San Diego Gas & Electric), and MTS (More Than Smart). 2017. *Coordination of Transmission and Distribution Operations in a High Distributed Energy Resource Electric Grid*. Available at https://gridworks.org/wp-content/uploads/2018/11/MoreThanSmartReport-CoordinatingTransmission_DistributionGridOperations.pdf.

CEDEC (European Federation of Local Energy Companies), EDSO for Smart Grids, eurelectric (Union of the Electricity Industry), and GEODE. 2018. *Flexibility in the Energy Transition: A Toolbox for Electricity DSOs*. February 2018. Available at https://www.edsoforsmartgrids.eu/wp-content/uploads/Flexibility-in-the-energy-transition-A-tool-for-electricity-DSOs-2018-HD.pdf.

Combs JS and R Meiers-De Pastino. 2018. *Compliance Report of Southern California Edison Company (U 338-E), Pacific Gas & Electric Company (U 39 E), and San Diego Gas & Electric Company (U 902-E) on Behalf of the Multiple Use Application Working Group*. R.15-03-011, Public Utilities Commission of the State of California, San Francisco, California. August 9, 2018. Available at http://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M233/K836/233836260.PDF.

CPUC – California Public Utilities Commission. 2018. *Decision on Multiple-Use Application Issues*. Decision 18-01-003 2018a. San Francisco, California. Available at http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M206/K462/206462341.PDF.

Cusick K, J Wellinghoff, and L Kristov. 2019. *Storage as a Transmission Asset: 2018 Progress and Report Card*. Center for Renewables Integration, February 2019. Available at https://www.center4ri.org/publications.

De Martini P. 2013a. *DR 2.0: A Future of Customer Response*. U.S. Department of Energy/Federal Energy Regulatory Commission, Washington, D.C. Available at https://s3.amazonaws.com/fonteva-customer-media/00Do0000000Yi66EAC/DR%202.0%20A%20Future%20of%20Customer%20Response.pdf.

De Martini P. 2013b. "Transactive Energy." In *First International Transactive Energy Conference and Workshop*, p. 54, May 23–24, 2013, Portland, Oregon. GridWise Architecture Council. Available at http://www.gridwiseac.org/pdfs/gwac_tec_052313/tec_2013_proceedings_pnnl_sa_96361.pdf.

De Martini P and L Kristov. 2015. *Distribution Systems in a High Distributed Energy Resources Future*. LBNL-1003797, Lawrence Berkeley National Laboratory, Berkeley, California. Available at http://eta-publications.lbl.gov/sites/default/files/lbnl-1003797.pdf.

De Martini P, KM Chandy, and NA Fromer. 2012. *Grid 2020: Towards a Policy of Renewable and Distributed Energy Resources*. No. 41879, Resnick Institute, California Institute of Technology, Pasadena, California. Available at http://resolver.caltech.edu/CaltechAUTHORS:20131010-162127988.

DOE – U.S. Department of Energy. (Undated). *Electric Vehicles*. "Reducing Pollution with Electric Vehicles." Office of Energy Efficiency & Renewable Energy. Available at https://www.energy.gov/eere/electricvehicles/reducing-pollution-electric-vehicles. (Undated web page).

DOE – U.S. Department of Energy. 2017a. *Modern Distribution Grid – Decision Guide, Volume III*. U.S. Department of Energy, Office of Electricity Delivery & Energy Reliability. Available at https://gridarchitecture.pnnl.gov/media/Modern-Distribution-Grid-Volume-III.pdf.

DOE – U.S. Department of Energy. 2017b. *Modern Distribution Grid – Volume I: Customer and State Policy Driven Functionality*. U.S. Department of Energy, Office of Electricity Delivery & Energy Reliability. Available at https://gridarchitecture.pnnl.gov/media/Modern-Distribution-Grid_Volume-I_v1_1.pdf.

DOE – U.S. Department of Energy. 2017c. *Modern Distribution Grid – Volume II: Advanced Technology Maturity Assessment*. Available at https://gridarchitecture.pnnl.gov/media/Modern-Distribution-Grid_Volume-II_v1_1.pdf.

EIA – U.S. Energy Information Administration. 2014a. *Annual Energy Outlook 2014 with projections to 2040*. U.S. Energy Information Administration, Washington, D.C. Available at https://www.eia.gov/outlooks/aeo/pdf/0383(2014).pdf.

EIA – U.S. Energy Information Administration. 2014b. "California's subhourly wholesale electricity market opens to systems outside its footprint." *Today in Energy*, September 30, 2014. Available at https://www.eia.gov/todayinenergy/detail.php?id=18191.

EIA – U.S. Energy Information Administration. 2018. *Electric Power Annual*. Table 1.1., "Total Electric Power Industry Summary Statistics, 2017 and 2016: Net Generation and Consumption of Fuels for January through December." U.S. Energy Information Administration, Washington, D.C. Available at https://www.eia.gov/electricity/annual/html/epa_01_01.html.

EIA – U.S. Energy Information Administration. 2019a. *Annual Energy Outlook 2019 with Projections to 2050*. U.S. Energy Information Administration, Washington, D.C. Available at https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

EIA – U.S. Energy Information Administration. 2019b."Electricity end use" in *Annual Energy Review*. Washington, D.C. Available at https://www.eia.gov/totalenergy/data/annual/.

ENA – Energy Networks Association. 2018. *Open Networks Future Worlds: Developing change options to facilitate energy decarbonisation, digitisation and decentralisation*. Energy Networks Association, United Kingdom. Available at http://www.energynetworks.org/assets/files/14969_ENA_FutureWorlds_AW05_INT[2].pdf.

EPA – U.S. Environmental Protection Agency. 2018. *Electricity Customers*. Washington, D.C. Available at https://www.epa.gov/energy/electricity-customers (last updated March 13, 2018).

Feiler P, K Sullivan, KC Wallnau, RP Gabriel, JB Goodenough, RC Linger, TA Longstaff, R Kazman, MH Klein, LM Northrup, and D Schmidt. 2006. *Ultra-Large-Scale Systems: The Software Challenge of the Future*. Software Engineering Institute of Carnegie Mellon University, Pittsburgh, Pennsylvania. Available at http://resources.sei.cmu.edu/asset_files/Book/2006_014_001_30542.pdf.

FERC – Federal Energy Regulatory Commission. 1996. "Open Access Same-Time Information System (formerly Real-Time Information Networks) and Standards of Conduct." Order No. 889. 75 FERC 61,078; 18 CFR 37. Washington, D.C. Available at https://www.ferc.gov/legal/maj-ord-reg/land-docs/order889.asp.

FERC – Federal Energy Regulatory Commission. 1997. "Promoting Wholesale Competition Through Open Access Non-discriminatory Transmission Services by Public Utilities; Recovery of Stranded Costs by Public Utilities and Transmitting Utilities." Order No. 888-A. 61 FR 21540-21736. May 10, 1996. Washington, D.C. Available at https://www.govinfo.gov/content/pkg/FR-1996-05-10/pdf/96-10694.pdf.

FERC – Federal Energy Regulatory Commission. 1999. "Regional Transmission Organizations." Order No. 2000. 89 FERC 61285; 18 CFR 35. Washington, D.C. Available at https://www.ferc.gov/legal/maj-ord-reg/land-docs/RM99-2A.pdf.

FERC – Federal Energy Regulatory Commission. 2018. "Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators." Order No. 841. 162 FERC 61,127. 18 CFR 35. Washington, D.C. Available at https://www.ferc.gov/whats-new/comm-meet/2018/021518/E-1.pdf.

Fitzgerald G, J Mandel, J Morris, and H Touati. 2015. *The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid*. Rocky Mountain Institute, Boulder, Colorado. Available at https://rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf.

GMLC – Grid Modernization Laboratory Consortium. 2018. *Interoperability Strategic Vision*. PNNL-27320, Richland, Washington. Available at https://gridmod.labworks.org/sites/default/files/resources/InteropStrategicVisionPaper2018-03-29.pdf.

GridWise Alliance. 2014. *The Future of the Grid: Evolving to Meet America's Needs*. Washington, D.C. December 2014. Available at https://www.smartgrid.gov/files/Northeast-Region-Workshop-Summary-Final.pdf.

GridWorks. 2018. *Sustaining Solar Beyond Net Metering: How Customer Owned Solar Compensation Can Evolve in Support of Decarbonizing California*. GridWorks, Portland, Oregon. Available at https://gridworks.org/wp-content/uploads/2018/01/Gridworks_SustainingSolar_Online.pdf.

GWAC – GridWise Architecture Council. 2008. *GridWise Interoperability Context-Setting Framework, v1.1*. GridWise Architecture Council, Richland, Washington, March 2008. Available at https://www.gridwiseac.org/pdfs/interopframework_v1_1.pdf.

GWAC – GridWise Architecture Council. 2014. Transactive Energy Infographic. GridWise Architecture Council, Richland, Washington. Available at https://www.gridwiseac.org/pdfs/te_infographics_061014_pnnl_sa_103395.pdf.

GWAC – GridWise Architecture Council. 2016. *Decision-Maker's Transactive Energy Checklist*. PNNL-25658. Richland, Washington. Available at http://www.gridwiseac.org/pdfs/workshop_051215/te_checklist_v0.20_20141009.docx.

GWAC – GridWise Architecture Council. 2018. *Transactive Energy Systems Research, Development and Deployment Roadmap*. PNNL-26778. Richland, Washington. Available at https://www.gridwiseac.org/pdfs/pnnl_26778_te_roadmap_dec_2018.pdf.

Hertzog C. 2012. *Smart Grid Dictionary*. GreenSpring Marketing, LLC, New Albany, Indiana. p. 408. ISBN 978-0984094479.

IEEE – Institute of Electrical and Electronics Engineers. 2018. *1547-2018 - IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*. April 6, 2018. DOI: 10.1109/IEEESTD.2018.8332112. Available at https://ieeexplore.ieee.org/document/8332112.

ISO/IEC – International Standards Organization/International Electrotechnical Commission. 2004. *Information technology -- Home Electronic System -- Guidelines for product interoperability -- Part 1: Introduction*. ISO/IEC 18012-1:2004, Geneva, Switzerland. Available at https://www.iso.org/standard/30797.html.

ISO/IEC – International Standards Organization/International Electrotechnical Commission. 2012a. *Information technology -- Home Electronic System -- Guidelines for product interoperability -- Part 2: Taxonomy and application interoperability model*. ISO/IEC 18012-2:2012, Geneva, Switzerland. Available at https://www.iso.org/standard/46317.html.

ISO/IEC – International Standards Organization/International Electrotechnical Commission. 2012b. *Information technology -- Home Electronic System (HES) application model -- Part 3: Model of a demand-response energy management system for HES*. ISO/IEC 15067-3, Geneva, Switzerland. Available at https://www.iso.org/standard/55596.html.

ISO/IEC/IEEE – International Standards Organization/International Electrotechnical Commission/ Institute of Electrical and Electronics Engineers. 2011. *ISO/IEC/IEEE Systems and software engineering -- Architecture description*. Standard ISO/IEC/IEEE 42010:2011. Available at https://standards.ieee.org/standard/42010-2011.html.

Kind P. 2013. *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business*. Edison Electric Institute, Washington, D.C. Available at https://assets.documentcloud.org/documents/1020804/disruptivechallenges.pdf.

Kintner-Meyer MCW, KP Schneider, and RG Pratt. 2007. "Technical Analysis and Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids: Part 1: Technical Analysis." *Journal of EUEC* 1, paper #04. Energy, Utility, Environment Conference 2007. Available at http://www.euec.com/published-abstracts/.

Knight M and N Brownell. 2010. *How Does Smart Grid Impact the Natural Monopoly Paradigm of Electricity Supply? Part I*. GridWise Architecture Council, Richland, Washington. Available at http://www.gridwiseac.org/pdfs/forum_papers10/knightp_gi10.pdf.

McDermott K. 2012. *Cost of Service Regulation in the Investor-Owned Electric Utility Industry: A history of adaptation*. Edison Electric Institute, Washington, D.C. June 2012. Available at http://www.eei.org/issuesandpolicy/stateregulation/documents/cosr_history_final.pdf. Alternate URL: https://www.ourenergypolicy.org/wp-content/uploads/2012/09/COSR_history_final.pdf.

MMI – Modern Markets Intelligence, Inc. 2016. "ISO-NE moves ahead with plan for 5-minute settlement." *PowerMarkets Today*, June 6, 2016. Available at https://www.powermarketstoday.com/public/ISONE-moves-ahead-with-plan-for-5minute-settlement.cfm.

New York State. 2015. *Order Adopting Regulatory Policy Framework and Implementation Plan*. DPS – Reforming the Energy Vision. February 26, 2015. New York State Public Service Commission, Albany, New York. Available at http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7b0B599D87-445B-4197-9815-24C27623A6A0%7d.

New York State. 2019. *Reforming the Energy Vision*. Albany, New York. Available at https://rev.ny.gov/.

NIAC – National Infrastructure Advisory Council. 2009. *Critical Infrastructure Resilience Final Report and Recommendations*. U.S. Department of Homeland Security, National Infrastructure Advisory Council, Washington, D.C. Available at https://www.dhs.gov/sites/default/files/publications/niac-critical-infrastructure-resilience-final-report-09-08-09-508.pdf.

NIST – National Institute of Standards and Technology, Cyber-Physical Systems Public Working Group. 2017. *Framework for Cyber-Physical Systems: Volume 1, Overview*. NIST Special Publication 1500 201, National Institute of Standards and Technology, Gaithersburg, Maryland. DOI: 10.6028/NIST.SP.1500-201. Available at https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1500-201.pdf.

NIST – National Institute of Standards and Technology. 2011. *Draft NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0*. National Institute of Standards and Technology, Washington, D.C. February 2012. Available at https://www.nist.gov/sites/default/files/documents/smartgrid/NIST_Framework_Release_2-0_corr.pdf.

NIST – National Institute of Standards and Technology. 2014. *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0*. Washington, D.C. September 2014. Available at https://www.nist.gov/sites/default/files/documents/smartgrid/NIST-SP-1108r3.pdf.

Rahimi F and A Ipakchi. 2012. "Transactive Energy Techniques: Closing the Gap between Wholesale and Retail Markets" *Electricity Journal* 25(8):29–35. Available at https://www.sciencedirect.com/science/article/pii/S104061901200228X.

Rahimi F and A Ipakchi. 2016. "Using a Transactive Energy Framework: Providing Grid Services from Smart Buildings." *IEEE Electrification Magazine* 4(4):23–29. Available at https://ieeexplore.ieee.org/document/7725892.

Rahimi F and S Mokhtari. 2014. "From ISO to DSO: Imagining a new construct – an independent system operator for the distribution network." *Public Utilities Fortnightly*, June 2014, pp. 42–50. Available at https://www.fortnightly.com/fortnightly/2014/06/iso-dso.

Rahimi FA and S Mokhtari. 2018. "Distribution Management System for the Grid of the Future: A Transactive System Compensating for the Rise in Distributed Energy Resources." *IEEE Electrification Magazine* 6(2):84–94. Available at https://ieeexplore.ieee.org/document/8369437.

Rahimi F, A Ipakchi, and F Fletcher. 2016. "The Changing Electrical Landscape: End-to-End Power System Operation Under the Transactive Energy Paradigm." *IEEE Power and Energy Magazine* 14(3):52–62. Available at https://ieeexplore.ieee.org/document/7452745.

Roth T, E Song, M Burns, H Neema, W Emfinger, and J Sztipanovits. 2017. "Cyber-Physical System Development Environment for Energy Applications." In *ASME 2017 Power and Energy Conference, PowerEnergy2017*, p. 738. June 26–30, 2017, Charlotte, North Carolina. American Society of Mechanical Engineers. ISBN 978-0-7918-5761-8. Available at https://ws680.nist.gov/publication/get_pdf.cfm?pub_id=922852.

Simard G. 2013. "IEEE Smart Grid Research: Power." In *IEEE Grid Vision 2050*, p. 93. IEEE – Institute of Electrical and Electronics Engineers, Piscataway, New Jersey. DOI: 10.1109/IEEESTD.2013.6577603. Available at https://ieeexplore.ieee.org/document/6577603.

Stouffer K, V Pillitteri, S Lightman, M Abrams, and A Hahn. 2015. *Guide to Industrial Control Systems (ICS) Security*. NIST SP 800-82, Revision 2. Available at https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-82r2.pdf.

Taft J and P De Martini. 2013. "Ultra-large scale control architecture." Innovative Smart Grid Technologies (ISGT), 2013 IEEE PES, p. 6. February 24–27, 2013, Washington, D.C. IEEE – Institute of Electrical and Electronics Engineers. Available at https://ieeexplore.ieee.org/document/6497906.

Thomas S. 2018. *Evolution of the Distribution System & the Potential for Distribution-level Markets: A Primer for State Utility Regulators*. NARUC – National Association of Regulatory Utility Commissioners, Washington, D.C. Available at https://www.naruc.org/default/assets/File/201801%20Evolution%20of%20the%20Distribution%20System.pdf.

von Meier A. 2012. "To 33% and Beyond: Grid Integration Challenges for Renewable Generation." In *UCLA Smart Grid Thought Leadership Forum*. March 28, 2012, Los Angeles, California. Council on International Educational Exchange. Available at https://uc-ciee.org/electric-grid/4/641/102/nested.

Wacks K. 2011. "Smart Grid Impact on Consumer Electronics." *iHomes & Buildings* 8(3):12. Available at file:///C:/Users/d3x241/Downloads/CABA_Magazine_Autumn_2011.pdf; Alternate URL http://kenwacks.com/Papers/iHB1011K.pdf.

Watson R. 2017. "EIA: U.S. residential electricity sales continues six-year decline." Electric Light and Power e-newsletter. Clarion Events, Tulsa, Oklahoma. Available at https://www.elp.com/articles/2017/07/eia-u-s-residential-electricity-sales-continues-six-year-decline.html.

Wellinghoff J, K Cusick, L Kristov, and E Enriquez. 2018. *Alternative Transmission Solutions: A Roadmap to the CAISO Transmission Planning Process*. Center for Renewables Integration. Available at https://www.center4ri.org/publications.

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.

A.1 Case Study Template

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 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 may take place as frequently as subsecond timing. Rules must 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 subsecond 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

(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 multiple-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 a transaction pulled from an organized market? Or from a 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.)

A.2 Pacific Northwest Smart Grid Demonstration

Project characteristics and objectives

The Pacific Northwest Smart Grid Demonstration Project (PNWSGD) developed 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. 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 five 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 American Reinvestment and Recovery Act-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 (DG), 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 eight different types of asset systems (conservation voltage reduction, building and commercial demand response (DR), in-home displays, programmable thermostats, DG, battery storage, residential DR, 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 microgrids, 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 PNWSGDP, 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 interval 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 four every 6 hours and for the last two, 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 (ISO/IEC 2004). 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 TIS.

(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 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

ISO/IEC – International Standards Organization/International Electrotechnical Commission. 2004. *Information technology -- Home Electronic System -- Guidelines for product interoperability – Part 1: Introduction*. ISO/IEC 18012-1:2004, Geneva, Switzerland. Available at https://www.iso.org/standard/30797.html.

ISO/IEC – International Standards Organization/International Electrotechnical Commission. 2012. *Information technology -- Home Electronic System -- Guidelines for product interoperability – Part 2: Taxonomy and application interoperability model*. ISO/IEC 18012-2:2012, Geneva, Switzerland. Available at https://www.iso.org/standard/46317.html.

A.3 American Electric Power gridSMART® Smart Grid Demo

Project characteristics and objectives

The American Electric Power (AEP) gridSMART demonstration developed 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 DR 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 home 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 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 (locational marginal prices s), 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 DR 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[13]), 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 number 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

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

[13] 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.

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.