



BSI Standards Publication

Information technology — Home electronic system (HES) application model

Part 3-8: GridWise transactive energy framework

National foreword

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TECHNICAL REPORT



**Information technology – Home electronic system (HES) application model –
Part 3-8: GridWise transactive energy framework**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

INFORMATION TECHNOLOGY – HOME ELECTRONIC SYSTEM (HES) APPLICATION MODEL –

Part 3-8: GridWise transactive energy framework

FOREWORD

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ISO/IEC TR 15067-3-8, which is a Technical Report, has been prepared by subcommittee 25: Interconnection of information technology equipment, of ISO/IEC joint technical committee 1: Information technology.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
JTC1-SC25/2944/DTR	JTC1-SC25/2965/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the ISO/IEC 15067 series, published under the general title *Information technology – Home electronic system (HES) application model*, can be found on the IEC and ISO websites.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

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. Customers' loads, generation, and storage will impact the management of an increasingly unpredictable power system. Because of this growth in flexible distributed energy resources deployment, attention is being devoted to addressing not only the economics of the electricity grid, but also the control system implications for 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 can also be used to optimize operations within a customer's facility.

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 necessitate new approaches to how electric power is managed and delivered, and the associated economic and business models. Conventional wisdom is that once variable generation resources reach 30 %, the current control systems for the grid will be simply inadequate [1]¹.

Transactive energy systems provide a way to maintain the reliability and security of the power system while increasing efficiency by coordinating the activity of the growing number of distributed energy resources. These multiple goals pose a multi-objective control and optimization challenge. This is one reason why 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 [2].

In the past, these systems could be considered simply end nodes on the physical power grid that act as simple "dumb" loads. But they are becoming increasingly more interactive with the grid, providing intelligent load, storage, and generation sources. They now need to be considered integral and active components of the grid as a whole. Building energy systems account for a majority of the electric power consumed in the United States. For example, the 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 [3]. Recent EIA data shows that this projection was correct and electricity use in buildings is currently just over 70 % each year [4]. From the grid perspective, buildings are examples of loads that will 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 loads, 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. This document describes the considerations and basic elements for all stakeholders. This provides an opportunity for discussing how various approaches can enable alignment of value streams and the creation of sustainable business models.

¹ Numbers in square brackets refer to the Bibliography.

Regulatory, policy, and business issues frame the discussion about the functional characteristics of TE systems. From these characteristics, this document 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.

This document further examines the practical dimensions of implementing TE systems by considering the cyber-physical system aspects. Here, too, this document avoids prescribing specific solutions, but rather identifies gaps and technology challenges that need to be addressed.

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 industry conferences such as DistribuTECH, showing considerable 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.

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.

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.

The United States Department of Energy has supported the GridWise®² Architecture Council (GWAC) in specifying 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. The GWAC developed this document to provide 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.

In creating the TE framework (this document), the authors presume an audience with a good understanding of interoperability, familiarity with ISO/IEC TR 15067-3-2 [5], 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. This document covers the topic of TE at an abstract, conceptual level without prescribing specific implementations. The audience for this document includes policy makers, regulators, vendors, utilities, researchers, practitioners, and end-use asset owners.

² GridWise is a registered trademark of Gridwise, Inc. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC or ISO.

In addition to this document, the GWAC produced a TE Decision Maker's Checklist [6] and a TE Roadmap (ISO/IEC 15067-3-7) [7]. 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 1). 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 [8]. Collectively, these explore TE interactions and provide examples where TE systems produce value.

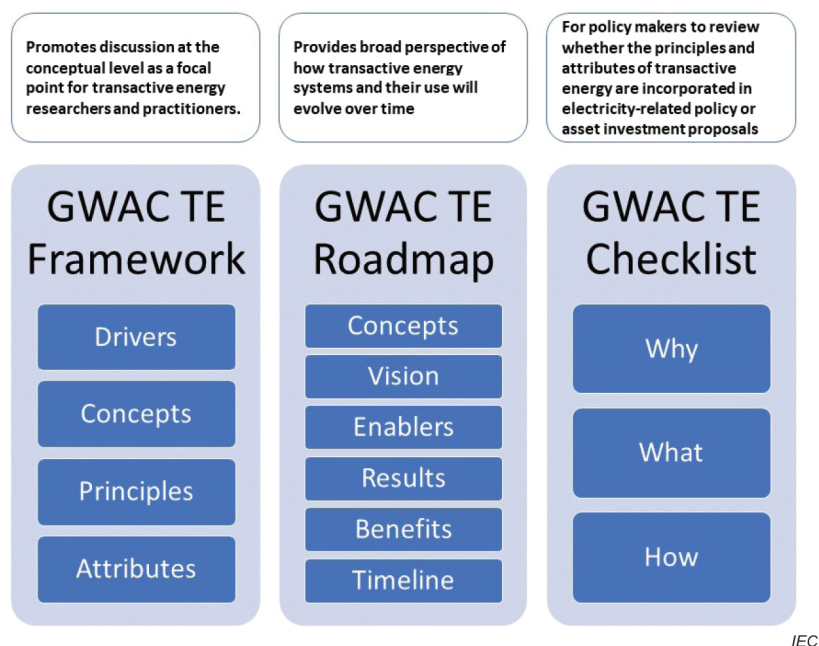


Figure 1 – Overview of GWAC transactive energy reference documents

INFORMATION TECHNOLOGY – HOME ELECTRONIC SYSTEM (HES) APPLICATION MODEL –

Part 3-8: GridWise transactive energy framework

1 Scope

This part of ISO/IEC 15067, which is a Technical Report, provides a conceptual framework for developing architectures and designing solutions related to transactive energy (TE). Transactive energy allows electricity generated locally by consumers using wind, solar, storage, etc., at homes or buildings to be sold into a competitive market. This document provides guidance for enhancing interoperability among distributed energy resources involved in energy management systems at homes and buildings. It addresses gaps identified as problematic for the industry 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.

This document builds upon ISO/IEC 15067-3 [9], with technology to accommodate a market for buying and selling electricity generated centrally or locally by consumers. The energy management agent (EMA) specified in ISO/IEC 15067-3 can represent the customer as a participant in TE. Transactive energy is important for achieving electric grid stability as power from renewable sources such as wind and solar fluctuates with time and weather.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

ancillary services

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

Note 1 to entry: 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.

3.2

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

Note 1 to entry: ISO/IEC/IEEE 42010:2011 describes architecture viewpoints, architecture frameworks and architecture description languages for codifying conventions and common practices of architecture description.

3.3

area control error

ACE

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

3.4

automatic generation control

AGC

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

Note 1 to entry: AGC can also accommodate automatic inadvertent payback and time error correction.

3.5

boundary deference

respect for ownership or system boundaries during interactions

3.6

congestion

characteristic of the transmission system produced by a constraint on the optimum economic operation of the power system, such that the marginal price of energy to serve the next increment of load, exclusive of losses, at different locations on the transmission system is unequal

3.7

customer

anyone taking (using) electric energy

3.8

cyber-physical system

smart system that includes engineered interacting networks of physical and computational components

3.9

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

3.10

distributed energy resource

DER

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

Note 1 to entry: 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.

3.11

distributed generation

DG

generation that is located close to the particular load that it is intended to serve

Note 1 to entry: General, but nonexclusive, characteristics of distributed generation include an operating strategy that supports the served load, and interconnection to a distribution or sub-transmission system.

3.12 **distribution system operator** **DSO**

entity responsible for planning and operational functions associated with a distribution system that is modernized for high levels of distributed energy resources (DERs) and handles the interface to the bulk system transmission system operator (TSO) at a locational marginal price (LMP) node or transmission-distribution substation

Note 1 to entry: A range of other DSO models are under consideration in the industry.

3.13 **framework**

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

3.14 **hedge**

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

3.15 **home energy management system** **HEMS**

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

3.16 **interoperability**

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

Note 1 to entry: In the context of the smart grid, systems are interoperable if they can exchange meaningful, actionable information. They share a common meaning of the exchanged information, and that the information can elicit agreed-upon types of responses.

3.17 **market**

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

3.18 **microgrid**

electrical system that includes multiple loads and DERs that can be operated in parallel with the broader utility grid or as an electrical island

3.19 **photovoltaic power** **PV**

technology that turns sunlight directly into electricity

3.20 **prosumer**

person or entity who both consumes and produces

Note 1 to entry: This term was coined by Alvin Toffler. From a smart grid perspective, "prosumer" would apply to DER situations in which the owner of electricity production or storage assets can also have a consumer relationship with a utility, aggregator, or other energy services provider [10].

3.21

regional transmission organization

RTO

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

Note 1 to entry: RTO can be a regulated independent entity. An RTO performs the same functions as an ISO but has added responsibilities for the transmission network.

3.22

reliability

measure of the ability of the system to continue operation while some lines or generators are out of service

Note 1 to entry: Reliability deals with the performance of the system under stress.

3.23

renewable energy resources

energy resources that are naturally replenished.

Note 1 to entry: Renewable energy resources include biomass, hydroelectric, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

3.24

resilience

ability to resist failure and rapidly recover from a breakdown

Note 1 to entry: See [10].

3.25

supervisory control and data acquisition

SCADA

highly distributed systems used to control geographically dispersed assets, often scattered over thousands of square kilometres, where centralized data acquisition and control are critical to system operation

3.26

smart grid

utility power distribution grid enabled with information technology and two-way digital communications networking

Note 1 to entry: A smart grid enables enhanced and automated monitoring and control of electricity distribution networks for added reliability, efficiency, and cost-effective operations.

3.27

transaction

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

3.28

transactive energy

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

3.29

transmission system operator

TSO

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

3.30 value

quantitative economic value and non-quantitative values such as comfort, savings, or other expressions of value that can come from a consumer

Note 1 to entry: Quantitative economic value can be stated in terms such as \$/kWh.

Note 2 to entry: 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.

3.31 value stream

sequence of activities required to design, produce, and provide a specific good or service, and along which information, materials, and worth flow

3.32 virtual power plant

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

4 Abbreviated terms

ACE	area control error
AEP	American Electric Power
AGC	automatic generation control
BTM	behind-the-meter
CAISO	California Independent System Operator
CPUC	California Public Utilities Commission
DER	distributed energy resource
DERA	DER aggregation
DG	distributed generation
DR	demand response
DSO	distribution system operator
EIA	U.S. Energy Information Administration
EV	electric vehicle
FERC	U.S. Federal Energy Regulatory Commission
GWAC	GridWise Architecture Council
HVAC	heating, ventilation, and air conditioning
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	independent system operator
LDA	local distribution area
MISO	Midwest USA independent System Operator
MUA	multiple-use application
NEM	net energy metering
P2P	peer-to-peer
PFR	primary frequency response
PJM	PJM Interconnection

PNWSGD	Pacific Northwest Smart Grid Demonstration Project
PUC	Public Utilities Commission
PV	photovoltaic
RTO	regional transmission organization
RTP	real-time pricing
SCADA	supervisory control and data acquisition
T&D	transmission and distribution
TCS	transactive control system
TE	transactive energy
TEF	TE Framework
TFS	transactive feedback signal
TIS	transactive incentive signal
TSO	transmission system operator
UDC	utility distribution company
ULS	ultra-large scale

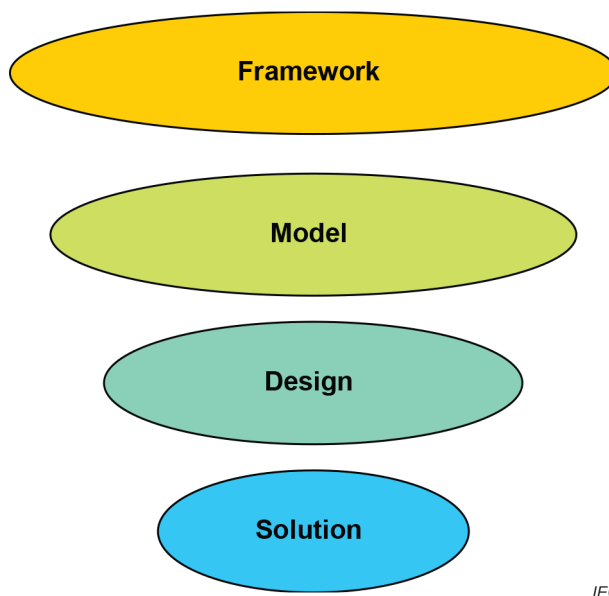
5 Context setting

5.1 Context for transactive issues

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" (TE), 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.

The concept of starting with a framework is based on ISO/IEC TR 15067-3-2 [5]. As illustrated in Figure 2, a framework describes 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.



IEC

Figure 2 – A framework provides high-level perspective

5.2 Report contents and organization

This document is organized in four main sections. Clause 5 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. Clause 6 refines the definition of TE and includes a set of associated attributes that can be used to discuss different approaches and implementations of TE systems. Clause 7 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 clauses 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. Annex A includes a template for documenting TE system case studies. Annex B and Annex C contain two example case studies.

5.3 The problem

A number of reports and studies have discussed the significant transformations occurring in the electric power system [2][11][12][13][14][15][16][17]. 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 [18][19][20][21][22][23]. In 2015, PV accounted for 58,6 TWh (0,2 quadrillion Btu (quads) in U.S. usage) per year, which compares with 301,86 TWh (1,03 quads) consumed by televisions nationally per year [3]. Yet PV is highly concentrated in some areas, and there the numbers have a larger net impact. The same effect is true for plug-in electric vehicles (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 [24]. 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 behaviour 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 EIA show PV increasing by an order of magnitude in the next 30 years [3]. Whether or not PV on its own has the ability to destabilize the grid, the trend suggests a significant increase in technology at the edge of the grid and a likelihood of increasing interactions occurring between devices as social networks and energy networks converge. This makes PV a strong catalyst for increasing 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 [25].

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 behaviour. 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 7.3.7).

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 [26]. 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) [27]. DSOs are discussed in more detail in 7.3.7.

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. (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.) 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 [17].

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:

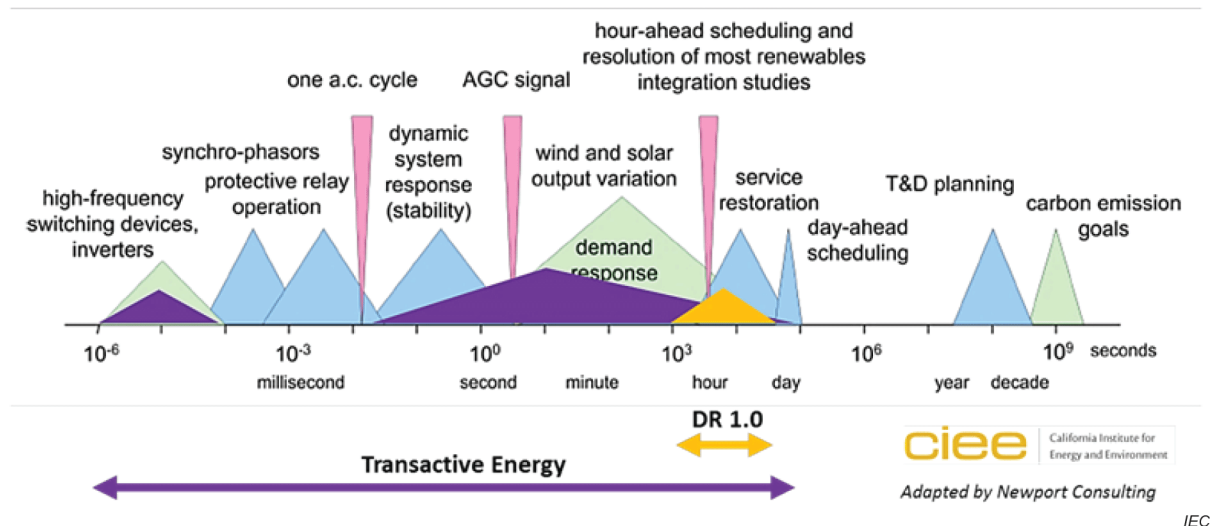
- wholesale prices/production costs minimization;
- need for stronger coordination at transmission-distribution interchange points;
- provision of ancillary services, ramping, and balancing (especially in light of renewables);
- managing transmission congestion costs;
- peak load management;
- resource 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 can 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 Clause 5 considers the challenges from these two perspectives, beginning with consideration of the time scales for which they apply, leading to subsequent subclauses that consider TE as a means to treat these two classes of objectives jointly for energy systems.

5.4 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 could be equally necessary to incentivize 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 [4][28].



SOURCE: [29]; used with permission.

Figure 3 – Electric power system timelines

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 centre, 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.

5.5 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 [30], which depicts interactions at the transmission, local, microgrid, and residential levels. These represent interactions that can use utility wires to deliver power and services, but that 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 Interconnection's (PJM's) five-minute markets in the PJM area, New York ISOs, and other organized markets;

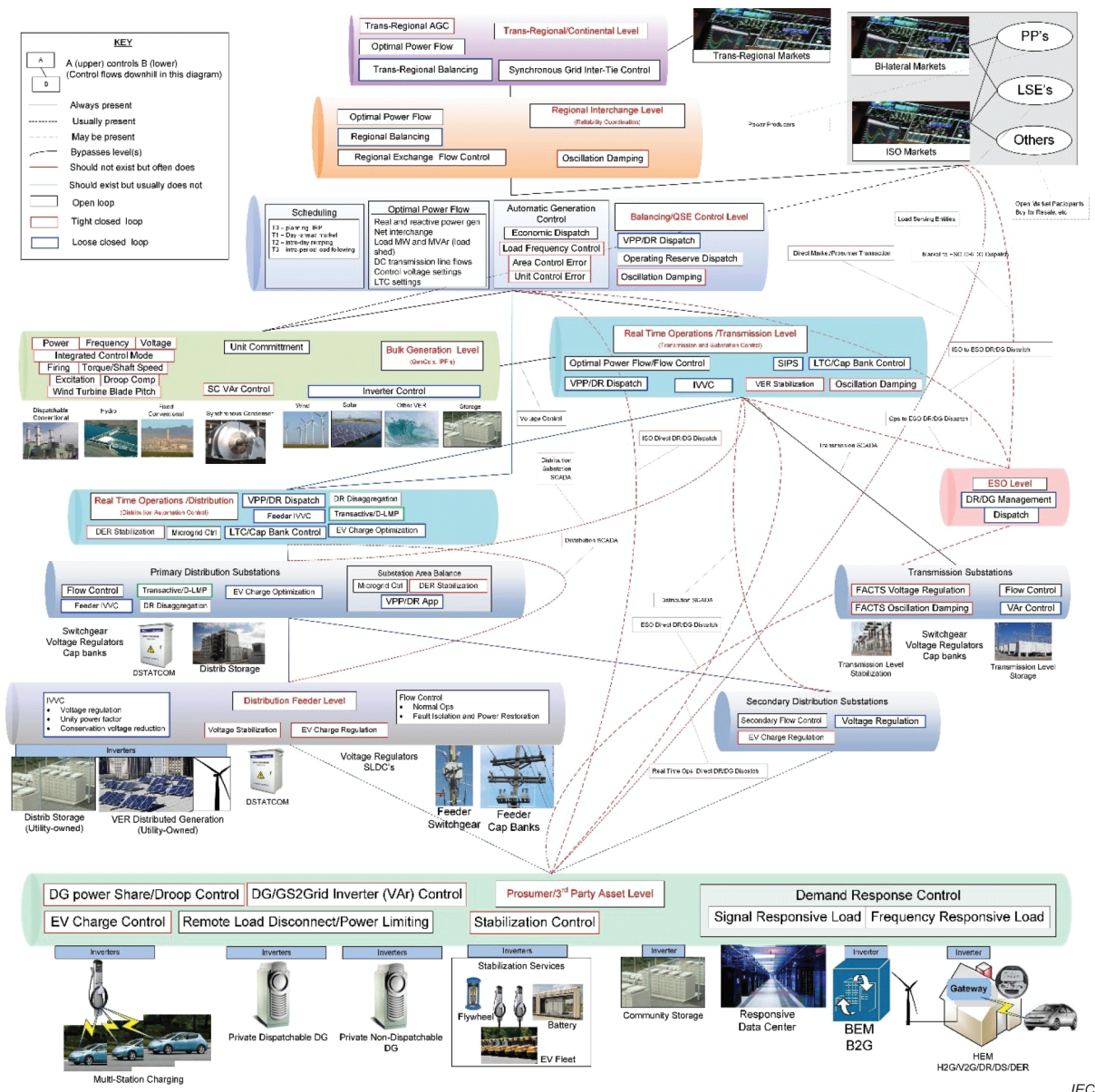
- changing retail customer relationships with the introduction of premises-level renewable resources and new loads such as EVs;
- formulation of policies going beyond renewable portfolio standards to promote development of very efficient high-performance buildings, including net-zero energy buildings;
- 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 behaviour of the grid such as the increasing capacity of behind-the-meter (BTM) sources of generation displacing conventional electricity generation that would otherwise occur, which has contributed to electricity sales declining in recent years [31][32];
- the need for new business and regulatory models [33]. 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 [34][35]. 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 [36]. There seems little doubt that regulatory models will need to evolve so edge devices can offer services. The topic of policy and market design is addressed more in 7.2.

5.6 Grid control systems context

"The mix of control methods either in use or contemplated today has resulted in a chaotic situation further compounded by the lack of true interoperability between and across many of these systems" [2], as shown 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 needs to evolve in line with changing requirements. Such evolution will lead to a more distributed 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. (The term "distributed" can be applied to systems architecture concepts as well as decision-making capabilities.)



IEC

SOURCE: [2]

Figure 4 – Growing complexity of electric power system control

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 need to 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.

6 Transactive energy

6.1 Transition from central power generation

When the electricity grid that America chose to build 120 years ago was originally conceived, it centred around large electricity generating plants 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 Clause 6 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.