PNNL-34505

Transactive Energy Communication Interface Standards Landscape

July 2023

Steven E Widergren
Donald J Hammerstrom

Prepared for the U.S. Department of Energy
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Summary

This report reviews the state of communication interface standards that show promise for transactive energy (TE) approaches to the coordination of distributed energy resources (DERs). Transactive energy represents distributed, optimal-seeking coordination approaches for managing and incentivizing the participation and operation of large numbers of energy-related devices and systems. The concept assumes intelligent agents interact with other agents on behalf of their owners to balance the supply and demand of energy and coordinate other operation services in an electric system. They do this by exchanging value signals for services in near-term and future periods using market mechanisms. The technique is particularly applied to coordination of flexibility in operating DERs. The integration of large numbers of devices requires that they be able to connect and interoperate easily and reliably. Given the many technologies and solution providers integrating products, communications interfaces based on clear, unambiguous specifications with supporting tests require standardization and adoption by the community of system integrators. It reviews promising standards to highlight challenges and gaps. And it offers structured comparisons between standards and the features offered by their ecosystems of participants.

Acronyms and Abbreviations

CEN	European Committee for Standardization
CENELEC	European Electrotechnical Committee for Standardization
CTS	common transactive services
DOE	Department of Energy
DER	distributed energy resource
DR	demand response
DSO	distribution system operator
EFI	Energy Flexibility Interface Specification
ESI	energy service interface
ETSI	European Telecommunications Standards Institute
eMIX	Energy Market Information Exchange
FAN	Flexiblepower Alliance Network
ICT	information and communication technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEEE-SA	Institute of Electrical and Electronics Engineers-Standards Association
IMM	interoperability maturity model
NIST	National Institute of Standards and Technology
OASIS	Organization for the Advancement of Structured Information Standards
OpenADR Alliance	Open Automated Demand Response Alliance
PV	photovoltaic
PNNL	Pacific Northwest National Laboratory
SBLC	Smart Buildings, Loads, and Customer Systems
SEPA	Smart Electric Power Association
SGIP	Smart Grid Interoperability Panel
SEI	Software Engineering Institute
SOA-RM	service-oriented architecture reference model
TE	transactive energy
TeMIX	transactive energy market information exchange profile
TECM	Transactive Energy Concept Model
TES	transactive energy system
UFTP	Universal Smart Energy Flexibility Flex Trading Protocol
USEF	Universal Smart Energy Flexibility
VEN	virtual end node
VTN	virtual top node
XML	extensible markup language

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1.0 Introduction

This document describes the state of information and communication technology (ICT) standards and tools related to the integration and deployment of transactive energy systems (TES). It provides a view of the standards landscape that classifies the scope of relevant standards, organizations related to standards development, and communities of organizations (ecosystems) advancing interoperability and the adoption of the standards as realized in project deployments. In addition, this report highlights gaps and challenges facing the adoption of TES-related standards. It synthesizes information to propose areas of work on standardization and related methods or tools that will ease TES integration.

This work supports a strategic plan for simplifying the integration of TES components where the responsibility for managing the components may lie with different participants and technology solution providers, but they must be able to connect and interoperate in a predictable and reliable fashion. The material intends to inform Department of Energy (DOE) performers working on integrating distributed flexibility using TE techniques to focus standards development and interoperability efforts in the following areas.

- Information models, transactive contract models (agreements on terms and conditions)
- Technology platforms to apply standards (e.g., distributed ledger technology, OpenFMB, Internet of Things)
- Standards group coordination opportunities
- Community collaboration opportunities (consortia and users’ groups)

1.1 Strategic Context

Several factors contribute to conceiving a one and only set of TE standards. The implementations of TES remain immature, with no predominant standardized technology solutions. There is great diversity in the efforts to integrate and aggregate the flexibility of distributed energy resource (DER). Every jurisdiction has special aspects to the way they define grid services, and the definition of program terms and conditions for DER participation change with each demonstration or experiment. Given this situation, a single transactive mechanism is highly unlikely to be adopted. No matter what type of mechanism would be chosen, the program agreement’s terms and conditions need to be specialized according to the policy decisions of each adopting jurisdiction. In addition, multiple standardization initiatives will move forward in parallel as they cannot be independently stopped or controlled.

Given these many challenges, a successful approach to TE communications must recognize the immaturity of the industry and emphasize concepts, structures, and architectural concerns that will allow for different transactive mechanisms and contract terms and conditions to coexist, at least until mature business propositions and best practices for implementing transactive approaches become available. The proposed approach to progressing TE standards emphasizes socialization of concepts and structures and ways to organize the things that must be specified in order to design a transactive system. Such an approach can bring greater opportunities for commonality across various efforts.

Examples of areas for facilitating commonality include energy services definitions, nomenclature, system architectural aspects for defining points of interface used in in transactive approaches, and information model harmonization. Common ways of expressing programmatic (contractual) terms and conditions can be developed to support specialized TE business processes.

A concept model for TES was developed as part of this strategic plan under the auspices of the Smart Electric Power Alliance (SEPA) (SEPA, 2022b). The work promotes terminology for describing a TES. Harmonization of terms at a conceptual level such as this helps communicate ideas within the TE community while allowing different approaches to TE design and implementation.

The development of a plan for advancing TE standards needs to bring utilities, aggregators, consumer advocates, and regulators along in the discussion so that policy frameworks that are consistent with transactive approaches can be designed. Understanding the TES communications interface standards landscape, identifying shortcomings, and proposing actions to advance interoperability in the TE community will be important contributions to that discussion.

1.2 Introduction to Transactive Energy

TES concepts arose from the vision for a smart electric power system that uses inexpensive computational capabilities with pervasive communications to enhance efficiency, reliability, and resilience under a changing mix of DERs. A key aspect of the smart grid transformation is to involve self-aware, automated systems in customer facilities that act on behalf of their owners' preferences to coordinate equipment operation with electric system operations. The TES approach shifts dependence from more traditional centralized control schemes toward distributed decision-making approaches that support the optimization of the multiple objectives of all participants.

TE uses value-exchange mechanisms between participants to manage the operation of equipment in an electric system. TE could be practiced with any energy commodity, but this report focuses on TE in the electricity energy domain. A negotiated, dynamic price signal reveals the temporal and locational value of electricity, and the price signal thus incentivizes consumers and producers alike to respond using any energy flexibility they can and will offer. Energy flexibility that has been offered then acts as a type of feedback to balance energy production and consumption and inform discovery of an energy price signal. Practitioners of TE should defer to the definition of TE in the GridWise® Transactive Energy Framework:

> "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." (GridWise Architecture Council, 2019)

This report addresses the landscape of standards that facilitate TE implementations and particularly focuses on the integration of resource operational flexibility at the edges of the electric system. The TE domain is still attracting innovators, and new paths will likely emerge through the standards landscape. 8.0Appendix A lists some areas of disagreement in existing TE-related standards that might invite new pathways.

1.3 Scope of Standards Landscape

The number of standards associated with electric power communication interfaces is vast. Other efforts have identified many smart grid-related interface standards; however, far fewer relate to TES applications. This document focuses on existing ICT interface standards and development efforts used by, or recommended for, TE deployments. In addition, it includes methods and tools for characterizing TES communication standards and interoperability specifications. These tools help compare functional coverage, maturity (of application and interoperability), and the related ecosystems of organizations and services supporting standards development and their adoption through implementation profiles in specific projects.

Market-based approaches for distributed decision-making coordination can be applied to many control and coordination applications. In the case of TES, this report focuses on applications related to coordinating DER at the distribution level. Example TES scenarios are described in (SGIP, 2016). These scenarios include coordinating DER operation for peak heat days, wind energy balancing, high-penetration photovoltaics (PVs) with need for voltage control, and electric vehicle charging overload, among others. Whether the issue to address is local to the distribution system or at the bulk system level, the coordination involves the following types of actors (see Figure 1) interacting in a TES at the distribution level.

1. Primary transactive actors
    a. Customer with DER
        i. Site managers
        ii. Site owners
    b. DER Coordinator
        i. Distribution system operators (utilities)
        ii. Electricity retailers
        iii. DER aggregators
    c. Transactive market manager
        i. DERMS
        ii. Retail market operator
        iii. Exchange clearinghouse
2. Secondary actors: supplementary entities in the transactive process
    a. Meters and sensors
        i. Facility smart meters for status and settlement
        ii. Submeters
    b. Device controller (controls equipment)
3. Supporting actors:
    a. Technology solution providers: products and services
        i. Automation suppliers
        ii. Integrators
        iii. Meter and sensor suppliers
    b. Standards development organizations
    c. Testing and certification organizations

   d. Industry consortia and trade associations
      i. Government agencies

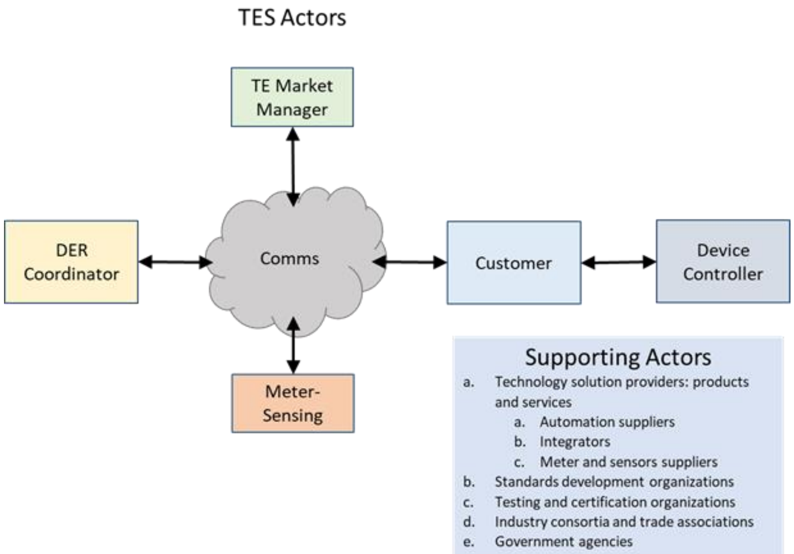

Figure 1. Actors involved in TES application scenarios of interest

The following criteria were used to screen standards and related material as applicable to the scope of this report:

- Relevant material relates to TES application scenarios and technology deployment. The standard applies to a TE approach used to configure and coordinate DER operation in a distribution system setting.
- Relevant material addresses the information exchange interface for TE coordination. The standard applies to the information exchange interface used between actors in a TES.
- Relevant material addresses the informational and organizational categories of interoperability (as opposed to the technical aspects of communications connectivity, networking, and protocol syntax). The report presumes a layered approach to technical categories of communication. Well-known communications standards, like WiFi, Ethernet, Bluetooth, and internet protocols, are only mentioned and not reviewed as TE standards.
- Relevant material includes de facto standards or other published specifications with reference implementations, including public or proprietary works that hold promise for widespread adoption is in scope.

1.4 Report Contributions

This report offers context and methodology for describing a TE standard landscape in the electricity domain. The methodology supports views that point out gaps and challenges, as well as comparisons among standards and interoperability-related initiatives. The report's context and methodology for evaluating the TE-related standards can help future efforts steer or facilitate the efforts of standards community participants toward a stronger and more comprehensive set of standards for TE deployments.

Several compilations of smart grid standards are reviewed, as the standards in the TE standards landscape are necessarily a subset of smart grid standards. Relatively few standards were found specific to TE. However, some standards initiatives are recognizing the need to support a separation of responsibilities in managing different parts of the electric power system, particularly when it involves the operation of electric distribution equipment and equipment managed within the premises. This recognition of collaborative grid operations and premises operation concerns leads to support for principles like distributed decision-making that are important to the future of TE systems.

Some standardization challenges may have derived from a too-abstract definition of TE, resulting in disagreements that persist in a loosely organized TE community that innovates faster than it can standardize. The report uses the context of SEPA's new TE concept model. The TECM's concepts and relations are a useful basis for assessing existing standards' relevance specific to TE and for identifying gaps in the TE standards landscape.

The report also assesses standards development, which is now underway, and less formal guidance from working groups and historical pilot studies. These ongoing efforts may facilitate interoperability at various levels of maturity while supporting the TE community, implementing profiles, defining conformance tests, and expanding applications beyond conventional grid domains. These are all important dimensions of the TE standards landscape.

Findings include challenges in formalization of patterns, templates, or other mechanisms to support business process modeling and supporting services, such as meter data exchange requirements, that will allow technology solution providers to roll out deployments more easily across electric utility jurisdictions. In addition, the consortia and communities that drive implementation profiles and provide services for testing, conformance, and registries for cybersecurity and qualified products are emerging from existing DER integration groups (such as SunSpec and the OpenADR (open automated demand response) Alliance), but a focused TES ecosystem is otherwise non-existent.

The report recognizes some gaps in the TE standards landscape and makes specific suggestions how to improve the TES communications standards situation. These suggestions are intended to inform the development of programmatic plans with actions for TE community engagement.

2.0 Smart Grid Standards Landscape Efforts

The TE standards landscape is a subset of a smart grid standards landscape. No compilations of standards were found to focus narrowly on TE, but several organizations gathered lists of standards that are more broadly foundational for smart grids. This section provides an overview of several such lists. A few standards with potential for TES applications emerge from this great body of work.

2.1 SEPA Catalog of Smart Grid Standards

The Energy Independence and Security Act of 2007 assigned the National Institute of Standards and Technology (NIST) to advance smart grid interoperability. NIST established the Smart Grid Interoperability Panel (SGIP) to assemble a catalog of standards in the smart grid domain. The responsibility to maintain the catalog later fell to the SEPA after the merger with SGIP in 2017. Eighty-one standards were identified, and these standards are available both as a simple list and via the SEPA Navigation Tool—an online tool that allows users to navigate the 81 annotated standards according to their relevance to the NIST framework of smart grid domains (SEPA, 2022a). A snapshot of the SEPA Navigation Tool user interface is provided below in Figure 2. This chart is used to find relevant ICT standards that exist within and between the domains shown.

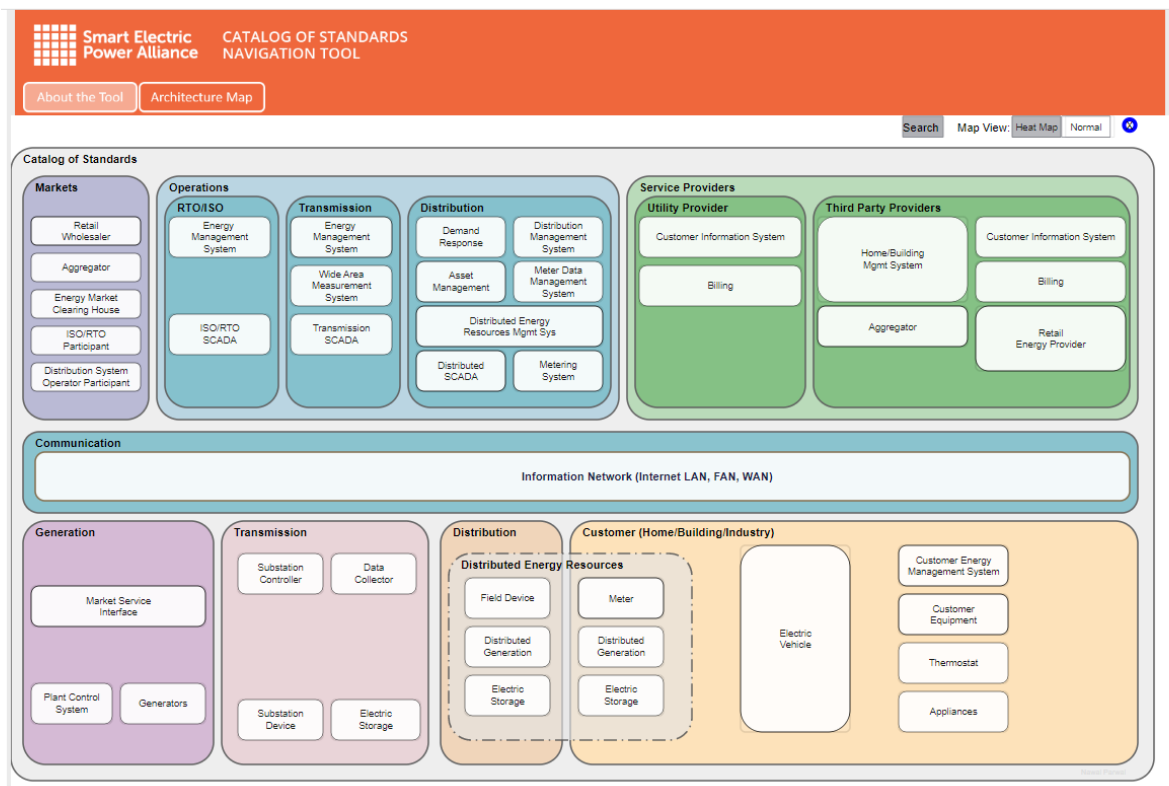

Figure 2. SEPA Catalog of Standards navigation tool

2.2 NIST Interoperability-Related Smart Grid Standards

The NIST *Framework and Roadmap for Smart Grid Interoperability Standards, Release 4* references NIST Technical Note 2042 to document a collection of 169 standards relevant for smart grid interoperability (NIST, 2021) (Song et al., 2019).

The technical note reviews candidate standards from these following three sources and was intended to address functional categorization (information, communication, physical, test, guidelines, cybersecurity components mapping) of relevant standards.

- Eighty-one standards in the SEPA Catalog of Standards; see Section 2.1 for details
- Seventy-two standards from the *NIST Special Publication 1108r3, a Framework and Roadmap for Smart Grid Interoperability Standards, Release* 3 (NIST, 2021)
- Nineteen standards in a position paper that was jointly authored by EURELECTRIC and European distribution system operators (EDSO) titled "Distribution System Operator Priorities for Smart Grid Standardization" (Lorenz, Granstrom P-O, & Chapalain, 2013, as cited in (NIST, 2021)). Most of these standards are from the perspective of electric utility applications and include distribution feeder automation, interconnection of DER with the electric system for distribution system management, and communications electromagnetic compatibility requirements.

A major finding of this work is the need for interoperability profiles that specify particular options and configurations in standards that can be applied to product implementations so that interoperability between different product implementations can be tested. Few of the standards were found to have adequate testing and certification available.

TE markets are mentioned in the NIST *Framework and Roadmap for Smart Grid Interoperability Standards, Release 4* but that source does not comment on TE-related standards (NIST, 2021).

2.3 IEEE 2030 Smart Grid Standards Mapping

The Institute of Electrical and Electronic Engineers (IEEE) P2030 Smart Grid Interoperability Reference Model addresses interoperability from three architectural perspectives: power system, communications, and information technology (IEEE SA, 2011). It provides end-to-end system engineering approaches to encourage interoperability between subsystems and entities using all three architectural perspectives. The reference model is the foundation for an extensible series of standards in specific application domains like vehicle electrification (numbered P2030.1) and energy storage (numbered P2030.2).

While the organization of systems relevant to electric power provides coverage for a large space of concerns, a TES focuses on interfacing and coordinating with the customer domain in this model. Under IEEE standards association umbrella, IEEE-SA (standards association) standardized the smart energy profile, which has its origins in the Zigbee Alliance, in P2030.5 (see Section 4.5). The objective of this standard is to provide an internet protocol-based approach to communicating with a variety of DERs. The 2030 reference model does not cover standards outside of IEEE, but it recognizes IEC 61970 and 61968 that define the Common Information Model as well as IEC 61850 concerning substation automation (Mater, et al., 2019).

2.4 IEC TR 63097:2017

In 2008, the International Electrotechnical Commission (IEC) brought a group of international experts together to develop a "framework for IEC standardization, which includes protocols and model standards to achieve interoperability of smart grid devices and systems…" called IEC TR 63097:2017 "Smart Grid Standardization Roadmap" (IEC, 2017). The initiative's goal has been to define a set of harmonized global standards to support grid deployments. It includes a suite of standards covering requirements, design, integration, testing, and validation.

Like the NIST (and SEPA) smart grid framework, the scope of applications covers the electric power system. While the work focuses on coordinating IEC standards work, it recognizes relevant standards from other organizations (e.g., IEEE-SA) and has its own catalog of standards to navigate. It includes the communications interactions for integrating DER and cites many standards that are equipment oriented (e.g., wind, storage, electric vehicles, PVs).

Little of this work was directly related to TE standardization, though aspects of IEC standards, such as information modeling in IEC 61970 (Common Information Model) can be relevant for TE. The roadmap references *IEC 61850-7-420, Communication networks and systems in substations – Part 7-420: Communications systems for distributed energy resources logical nodes* for data exchange, with DER equipment and systems that supervise, control, and operate this DER equipment. The IEC 61850 series of standards originated in substation automation, where utilities have ownership and control of the equipment; however, the ownership, control, and privacy situations are different at the grid edge.

In 2018, IEC adopted the OpenADR 2.0b specification from the OpenADR Alliance as the IEC 62746-10-1:2018 standard. This is a service-oriented standard that aligns better with the service-oriented paradigm seen in TES. The relevance of this standard for TES will be discussed later in the document. Please see the IEC webstore (https://webstore.iec.ch/) for access to all of their mentioned standards.

2.5 CEN-CENELEC-ETSI Smart Grid Standards Framework

The European electrical standards organizations European Committee for Standardization (CEN), European Electrotechnical Committee for Standardization (CENELEC), and European Telecommunications Standards Institute (ETSI) created the smart grid coordination group to organize and review the many standards relevant to European smart grid projects. The work is captured in "Final Report on Standards for Smart Grids" (CEN-CENELEC-ETSI, 2011). These organizations have formal ties to the International Organization for Standardization, IEC, and International Telecommunication Union (ITU-T) international standards bodies. They are frequently incorporated in European government rulings on technology deployment, and they can often lead to IEC standards. The European Union prefers to adopt IEC standards (if appropriate) because of their broader international recognition. Like the NIST, IEEE, and IEC smart grid standards work, the report covers the entire smart grid. The information predates the material in IEC TR 63097:2017.

Other reports from the smart grid coordination group provide information on information security and a framework for considering smart grid use cases and organizing standards across interoperability layers and application domains (CEN-CENELEC-ESTI Smart Grid Coordination Group, 2012) (CEN-CENELEC-ESTI Smart Grid Coordination Group, 2012). This framework borrows some concepts from the GridWise® Architecture Council's Interoperability Context-Setting Framework (The GridWise Architecture Council, 2008).

3.0 Assessment Methodology

The following constructs and processes support evaluation, navigation, and representation of the TE communication standards landscape.

3.1 Relevant Tools and Frameworks

An approach to categorization helps portray similarity and differences of relevant standards in the TE interface standards landscape. But which categorization is best for this purpose? Many entities participated in the definition and characterization of smart grid and smart grid-related standards. Many of the efforts parsed the challenge into various domains to cover the expansive sets of existing electricity subsystems; existing stakeholders; and new stakeholders and subsystems anticipated for the smart grid’s new integrations with communication, metering, information, and control systems. Some of the important and influential smart grid categorizations are annotated here:

- IEEE defines domains, entities, interfaces, and data flows for each of three interoperability architecture perspectives—power systems, communication technology, and information technology (IEEE SA, 2011). The domains are bulk generation, transmission, distribution, service providers, markets, control/operations, and customers. Interfaces are the logical connections between entities, which were broadly defined as objects, networks, or systems within the various domains.
- The *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0* more simply listed the domains of its smart grid conceptual model: customer, markets, service provider, operations, generation, transmission, and distribution. Each domain was further assigned roles or services (NIST, 2021).
- In the *NIST Review of Smart Grid Standards for Testing and Certification Landscape Analysis*, standards under review “were functionally categorized as relating to information model and model mapping, communication protocol and protocol mapping, physical performance specification, test methodology, guideline and best practice, and cybersecurity” (Song, et al., 2019). This context was established to support the NIST report’s focused treatment of smart grid testing and certification.
- The *GridWise Interoperability Context-Setting Framework* introduced an interoperability model, referred to as the “GWAC Stack,” consisting of three main interoperability layers and their sublayers (The GridWise Architecture Council, 2008). A diagram of the GWAC Stack is reproduced in Figure 3.

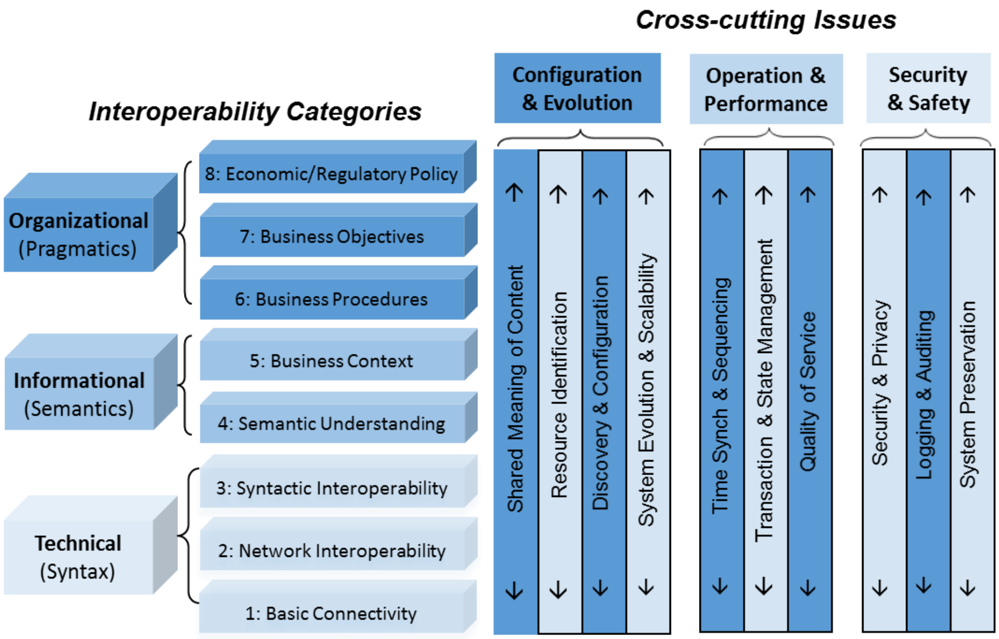

Figure 3. GWAC Stack – interoperability context-setting framework

- DOE's Grid Modernization Laboratory Consortium's Interoperability Maturity Model adapted the GWAC Interoperability Context-Setting Framework to create a model to explore the interoperability properties in smart grid communication interfaces for smart grid devices and systems integration (GridWise Architecture Council (GWAC), 2008) (Grid Modernization Laboratory Consortium, 2020). It borrows from a capability maturity model used for integration concepts promulgated by the Carnegie-Mellon Software Engineering Institute (The SGMM Team, 2010). Figure 4 shows the five levels of interoperability maturity and characteristics associated with maturity levels in various areas that provide evidence.

GRIDWISE Architecture Council Interoperability Maturity Model		Maturity Characteristics			
		Community / Governance	Documentation	Integration	Test / Certification
Maturity Level Statements	Level 5 Optimizing	Managed by a community quality improvement process	Adopts and open community standard	Integration metrics used for improvement of the standard	Test processes are regularly reviewed and improved
	Level 4 Quantitatively Managed	Processes ensure currency and operation	References community standard w/o customization	Integration metrics are defined and measurements collected. Reference implementations exist	Community test processes demonstrate interoperability. Members claim interoperable performance
	Level 3 Defined	Managed by community agreement	References community standard w/ some customization	Integration repeatable w/ predictable effort	Tests exist for community w/ certification. Members claim compliance to standard
	Level 2 Managed	Managed by project agreement	Documented in a project specification	Integration is repeatable w/ customization expected	Testing to plan w/ results captured
	Level 1 Initial	Management is ad hoc	Documentation is ad hoc	Integration is a unique experience	Testing is ad hoc

Figure 4. Interoperability Maturity Model maturity characteristics

- The *GridWise Transactive Energy Framework, Version 1.1* describes the principles, characteristics, and the attributes of a TES (GridWise Architecture Council, 2019). It provides context and terminology for TE deployment roadmaps and designs. The TE attributes in this document influenced the SEPA TE Concept Model work, shown in Figure 5 below.
- The SEPA *Transactive Energy Application Landscape Scenarios* whitepaper describes the TE application landscape, including types of actors and scenarios that explore interactions between actors with the objective of identifying areas for standard interfaces between interacting parties (SGIP, 2016). The document includes a model of a generic transactive agent that classifies interactions with other transactive agents, as well as local devices and systems (Figure 5). The transactive interactions on the right of the figure can be regarded as steps or phases of the interaction process.

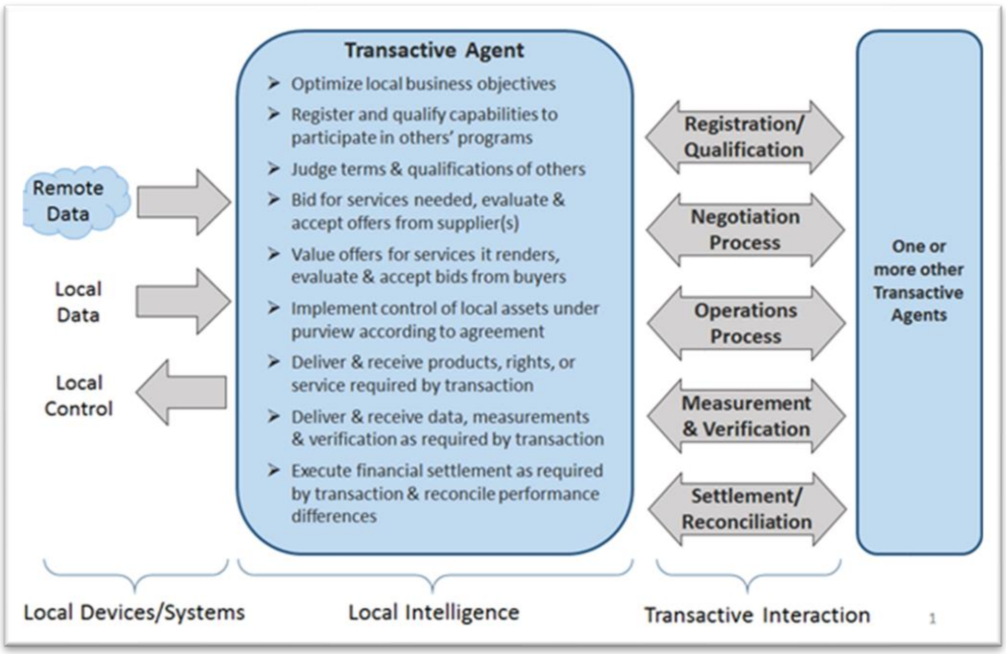

Figure 5: Model of transactive agent interactions

- The recently released SEPA TE Concept Model is somewhat different in that it offers concepts and relations that are specific to and common to TES (SEPA, 2022b). It pertains most closely to the informational category in the interoperability context-setting framework. Figure 6 shows the set of concepts and relations that were included in the concept model. The model has divided the concepts between a transaction layer that addresses the objects that participate in the creation and coordination of transactions and the electricity distribution layer, which includes the physical objects that inform and react to the transaction-level objects. The concept model could mature to include additional layers in the future.

A subtle property of the SEPA TE Concept Model is that instantiations of its concept objects may exist in multiple smart grid domains of the type listed in the prior bullets (e.g., wholesale, transmission, etc.). Relations (i.e., the arrows) may link TE concept objects between smart grid domains.

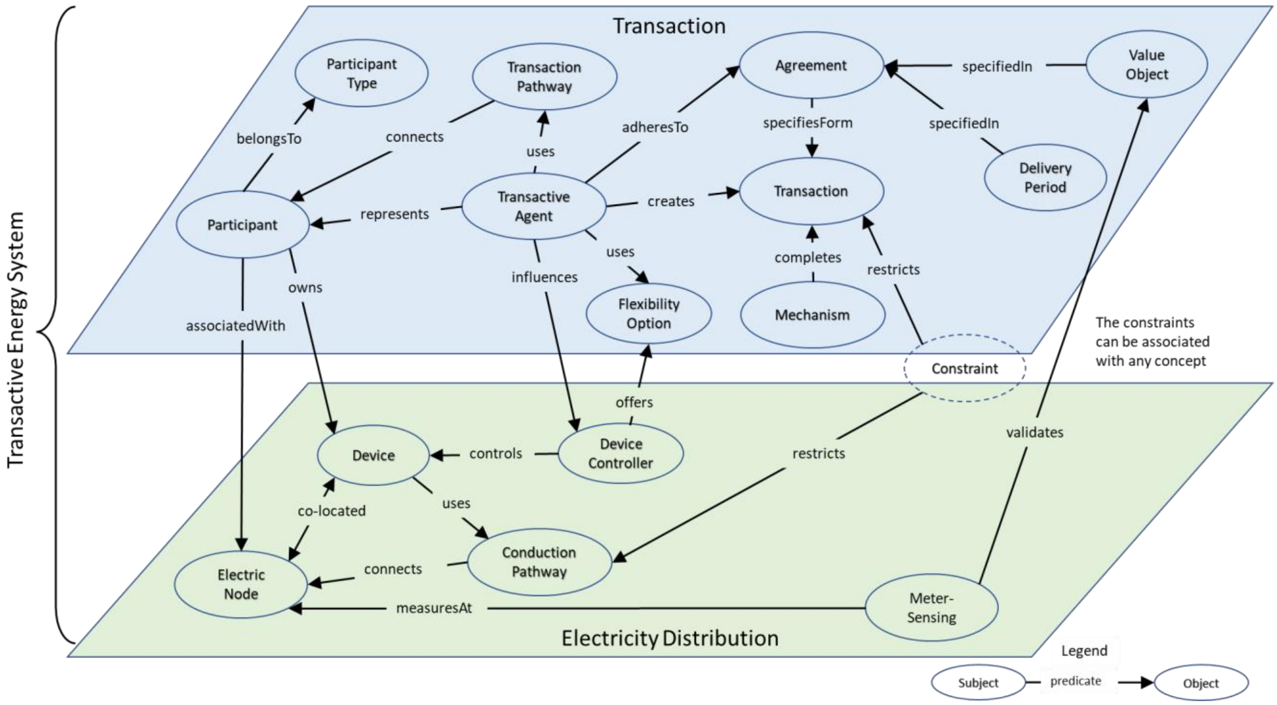

Figure 6. SEPA transactive energy concept model

The transaction layer of Figure 6 is a unique aspect of TES. The electricity distribution layer is shared with the smart grid and conventional demand response and therefore does not require much discussion in this report. The diagram is redrawn in Figure 7 to deemphasize the importance of concepts of the electricity distribution layer that do not share direct relations with any concept of the transactive layer.

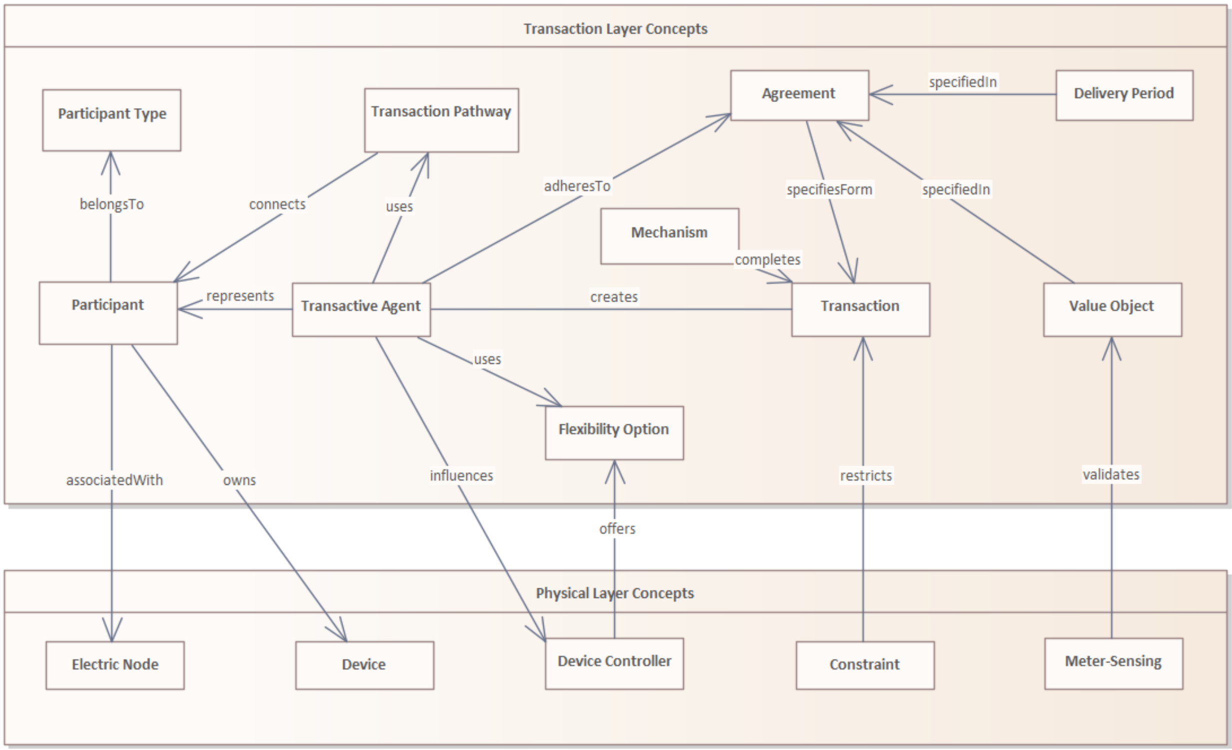

Figure 7. TECM in a form suitable for mapping of the transaction layer concepts and relations

All of the above categorizations are relevant to TES. Because TE is a subset of smart grids, this report need not address aspects of TES that are generic to smart grids. Instead, this report addresses unique aspects of TES integration. Ultimately, the following aspects guide the useful categorization and selection of domains for the TE standards landscape:

- A TES may exhibit a fractal nature, meaning that its objects are similarly instantiated in multiple smart grid application domains. The objects replicated among the smart grid domains should not be treated as wholly unique objects. This is a property of the abstractions in coordination and control approaches, such as TES. This report uses the concepts, objects, and relations of the TECM, which recognizes the fractal nature of TESs, for discussion of the evolving TE standards landscape.
- The primary emphasis of this report is on the interactions between transactive agents which coordinate DER operation with the electric system. Considering Figure 1, this involves the interfaces between DER coordinator, TE market manager, and customer actors. The boundaries of responsibility for the transactive agents align with the DER coordinator (including aggregators) and the customer facility. Of secondary importance are the interfaces between the customer and device controller actors.
- The entities of a TES (e.g., the entities in Figure 6) may benefit from standardized information modeling. The entities are not themselves interfaces, but they may create, consume, or be in messages at an interface. Information models should clearly identify the roles and responsibilities of each entity of the TECM.
- Finally, the interfaces shown in the transactive agent interaction model should be subjected to the interoperability categorization introduced by the GWAC Stack. The lowest technical

layer and its subcomponent layers are not likely to be unique to TE, and standards in these layers are not a focus of this report.

3.2 Approach to Assessing Standards

The previous section describes relevant tools and models that suggest dimensions for exploration when reviewing TES-related standards. The following dimensions were considered for reviewing and contrasting the state of related standards:

- Interoperability categories (GridWise Architecture Council, 2008)
  - Basic connectivity, network interoperability, syntactic interoperability, semantic understanding, business context, business procedures, business objectives, economic/regulatory policy
- Interoperability cross-cutting issues (GridWise Architecture Council, 2008)
  - Configuration and evolution, operations and performance, security and safety
- Interoperability maturity model maturity levels (Grid Modernization Laboratory Consortium, 2020)
  - Initial, managed, defined, quantitatively managed, optimizing
- Transactive interaction areas (SGIP, 2016)
  - Registration/qualification, negotiation process, operations process, measurement and verification, settlement/reconciliation
- TECM select concepts for interface standards (SEPA, 2022b)
  - Transactive agent, transaction, agreement, device controller, meter sensing
- Actor domains
  - TE market manager, DER coordinator, customer, device controller, meter sensing

From these dimensions, various two-dimensional diagrams were considered to provide visual insight into the standards and their coverage of functional and interoperability issues. While higher dimension graphs can be considered, the visual complexity becomes difficult to communicate. Feasible pairings of the dimensions include:

- Interoperability categories and actor domains;
- TECM and information maturity model (IMM) maturity levels;
- Interop cross-cutting issues and IMM maturity levels; and
- Interoperability categories and transactive interaction areas.

4.0 Specific Transactive-Energy-Supportive Standards

Relatively few standards are found to specifically address TE. This section annotates standards considered in TE-related project implementations.

4.1 OASIS Suite of Transactive Energy Specifications

There is a suite of OASIS TE specifications that is important to the TE standards landscape. The development of these standards is intertwined with a TES implementation, named the Transactive Energy Market Information Exchange (TeMIX) profile, which was later adopted as the name of a company that implements TES. The specifications are as follows:

- Energy Interoperation Version 1.0 (OASIS, 2014)
- Energy Market Information Exchange (eMIX) Version 1.0 specification, which includes a simplified TeMIX implementation profile (OASIS, 2012)
- Common transactive services (CTS) (OASIS, 2021).

These specifications reference one another and several important OASIS specifications that are not specifically applicable to TE.

This suite adopts a definition of transaction and perspective that, while useful for many existing and emerging TE implementations, may be too narrow for some TE innovators. The specifications were strongly influenced by proven wholesale energy market practices. A transaction within this suite is initiated by the offering of an electricity quantity and paired strike price at which the electricity might be purchased or sold in some future delivery period. A transaction exists only after a specific buyer is paired via a matching engine with a specific seller for the exchange of all or part of the parties' quantities being offered for sale or purchase. This exchange model works well for bulk offers from fueled electricity generators and for the binary control of demand-responsive assets during short, real-time electricity market intervals.

The OASIS suite aspired to be general enough to be applied to the exchange of alternative services (i.e., beyond the provision of energy itself) and even, in some cases, to the exchange of alternative energy commodities. This generality may prove important as future TE innovators explore novel grid services and the integrations of currently distinct energy markets (e.g., a combined electricity and heat market).

Despite potential limitations of the perspective under which the OASIS suite of TE specifications was developed, many of the elemental constructs within these specifications are potentially useful in TES designs.

4.1.1 Energy Interoperation

The standard specifications in this subsection reference OASIS Energy Interoperation Version 1.0 (OASIS, 2014). The standard is consistent with the OASIS service-oriented architecture reference model (SOA-RM), which is adopted by other OASIS standards and implemented in web services applications. This standard supports applications communicating with participants to distribute dynamic prices, demand response event signals, as well as TE interactions.

The standard references the OASIS eMIX and WS-Calendar standards and the SOA-RM and W3C extensible markup language (XML) schema definition language. In this regard, it is based on widely adopted software standards for defining data models and supports the service-oriented interaction paradigm.

Energy interoperation also references the early work of OpenADR and recognizes the virtual top node and virtual end node architecture applied in that work. The OpenADR Alliance coordinated with the effort and adopted elements of energy interoperation in their specification.

4.1.2 Energy Market Information Exchange

The OASIS eMIX Version 1.0 specification provides an XML model for the exchange of energy price, bid, and availability information and other characteristics of energy that is being traded (OASIS, 2012). eMIX includes enough detail to facilitate existing wholesale electricity market exchange practices, but its documentation includes a simplified profile for TeMIX that is arguably more suitable for the exchange of DER flexibility in electricity distribution systems, as was described in (Barrager and Cazalet, 2016).

4.1.3 Common Transactive Services

The OASIS CTS specification was intended to be a simplified protocol of OASIS Energy Interoperation 1.0 that coordinates exchange of any commodity in a market (OASIS, 2021) (OASIS, 2014). It also references and purports to simplify eMIX and the TeMIX implementation profile. Useful interaction patterns are defined by CTS for the offering, transaction, and delivery of a commodity like electricity. Additionally, the specification provides templates for participants' registration in a market and for communication of a party's market position and the market's product offerings and status.

While this specification anticipates and facilitates the communication of market information for a series of market time intervals, it appears to currently lack the ability to convey multiple price-quantity pair opportunities in the same market interval, as is needed to express rich supply or demand curves. CTS is therefore well suited to real-time binary electricity bids and offers, but it may inherently lack facility to express rich energy and price flexibility, including the communication of inflexible supply and demand energies.

CTS was meant to simplify the interactions of the TeMIX implementation profile, but the advantages of this simplification are arguable. TeMIX, Inc. subsequently evolved their implementation for the Retail Automated Transactive Energy System project, sponsored by the California Energy Commission (Cazalet et al., 2020).

CTS defines conformance self-test requirements for those who would claim that their own implementation is conformant to CTS. Since CTS is derived from existing OASIS specifications, conformance implementations of CTS must also conform to referenced portions of WS-Calendar and Streams (OASIS standards for representing schedules and conveying time series of information for transformation into the WS-Calendar model), as were referenced by the prior OASIS specifications and used to specify the scheduled energy exchange.

While CTS is an approved standard from a recognized standards development organization, its creation involved a small group of individuals and no other implementers, besides TeMIX, appear to be involved.

4.2 Energy Flexibility Interface

The Flexiblepower Alliance Network (FAN) developed the Energy Flexibility Interface Specification (EFI), Version 2.0, with staff from TNO, an independent scientific research organization in the Netherlands, (Werkman et al., 2019). The primary contribution of the EFI specification is its description of four types of device energy flexibility, including the XML/UML models that are needed to represent these devices' energy flexibilities in a TES. Its four categories of energy flexibility are inflexible, shiftable, storage, and adjustable. This categorization is based on the specification's predecessors, including PowerMatcher™ (Kok, 2013).

While the specification codifies a simple and potentially useful representation of devices' energy flexibilities, the energy flexibility is divorced from the value of the energy flexibility, the pairing of which was more strongly taught by its predecessors. The standard is useful for equipment manufacturers or those integrating equipment within a transactive facility (e.g., a home) to express their flexibility characteristics. This can be useful for a facility manager to translate into a transactive interaction with an outside party (such as a distribution system operator or an aggregator of flexibility from multiple facilities).

The PowerMatcher 2.0 TE trading platform is maintained in FAN. It is complementary to EFI, using the EFI expressed data to develop trading information. A facility manager adds the value of flexibility and conforms to the market agreement This makes the EFI standard relevant for a facility to support a transactive system interaction.

4.3 USEF Flexibility Trading Protocol Specification

The Universal Smart Energy Flexibility (USEF) Foundation developed a framework for integrating flexibility that involves aggregators interacting with end-users (prosumers) to offer flexibility services to distribution system operators (DSOs) or coordinated DSO/TSOs (USEF Foundation, 2021) (de Heer et al., 2021). A subset of this framework is the USEF Flex Trading Protocol (UFTP) which specifies bi-lateral trading market interactions between aggregators and DSOs (USEF, 2020). The protocol covers the following process steps: contract, plan, validate, operate, and settle. The validate phase is inserted to validate that the planned exchange can be distributed safely to honor physical transport constraints.

UFTP supports day-ahead, intraday, and real-time (15 minute in Europe) trading. Bidding takes place at congestion points, which means there is a market created at each congestion point. DSOs can procure flexible energy or options for flexible energy (like reserves). The settlement is done against an agreed upon baseline for the aggregator's customers. The approach makes UFTP appropriate at the aggregation to DSO level but leaves the aggregator to customer DER coordination unspecified.

The protocol specification uses a client-server approach to message exchange over internet protocol. Privacy and security are addressed by guidance. The protocol includes a privacy and security guideline of design principles for implementers.

UFTP messages are encoded in XML. The standard includes a messaging schema and information semantics with an ability to extend the messages to support forward and backward compatibility. While the protocol is targeted for aggregator-to-DSO interaction, it could have problems being repurposed to address the DER coordinator, TE market manager, and customer interactions, as shown in Figure 1. Scalability could be a major issue.

The work does not appear to be formalized using a recognized standards development organization's process; however, several implementations are reported in Europe. Work has also been done to harmonize the work with the OpenADR 2.0b specification in the form of market trading templates.

4.4 OpenADR

OpenADR was developed in California for integration of building energy flexibility in demand response programs. It was documented by the OpenADR Alliance, and a profile specification of standards was standardized by the IEC. OpenADR includes an optional price-reactive mechanism. It evolved to adopt the OASIS eMIX and Energy Interop standards to support a bilateral transactive mechanism.

A revised standard, OpenADR 3.0, has been drafted which claims to simplify the standard for price reactive system implementations.

In 2016, the OpenADR Alliance and USEF Foundation announced OpenADR DR program templates that use the USEF trading framework. This work does not appear to be formalized through a recognized standards development organization's process.

4.4.1 IEC 62746-10-1, OpenADR 2.0b

The IEC profile specification includes a data model and demand response services in a SOAP-based publish and subscribe paradigm between virtual top nodes (VTNs) and virtual end nodes (VENs). The functionality supports demand response, pricing, and DER communications. The specification is independent of the communications transport layer; however, internet protocol interactions are profiled for interoperability. In addition, cybersecurity mechanisms are specified.

Relevant for TE implementations, the specification makes no assumptions about specific loads, storage, or generation control strategies. There is no coverage of specific market mechanisms or business agreements between participants.

4.4.2 OpenADR 3.0

OpenADR 3.0 was recently designed as an alternative interface to OpenADR 2.0b. Due to its newness, experience with the standard in project implementations is unknown. The fundamental structure of the standard has changed. This makes OpenADR 3.0 incompatible with 2.0b. Instead of using SOAP-based message exchanges between VTNs and VENs, a VTN (server) is set up as a web service representational state transfer (REST) resource server that stores information and events. VENs (clients) read and write the information on the VTN using this REST-based interface. The maintenance of the state of information is fairly straightforward and laid out in the REST application programming interface.

The new specification is written in YAML (a machine-readable markup language) and this facilitates generating code for VTNs and VENs. This helps establish VTN and VEN communication, but it does not cover the business logic for setting up a DER coordination program or for a facility to managing its energy-related devices to appropriately interact with such a program. In this case, it is unclear if it supports a TE compliant interaction, though simple price distribution (prices to devices) appears to be addressed in a reference implementation.

OpenADR 3.0 has been developed in the OpenADR Alliance, which is not a formal standards development organization. A final version is anticipated to be posted in summer of 2023.

OpenADR 3.0 does not reference the OASIS, eMIX, and Energy Interop standards. There is no testing or certification program available, but a programmers' guide and these sorts of interoperability advancements are being discussed. Process steps for enrolling (qualify and configure) or settling and interaction do not appear to be explicitly supported though extensions can be made.

One way that OpenADR 3.0 was simplified was that the business logic for the VTNs and VENs is fully custom. For example, a program or tariff is coded and represented by the developer without standard constructs, such as what were represented in eMIX and Energy Interop standards. In this regard, the specification outlines the structure of interaction at a software development level with a project-defined (not standard) way of enrollment, price-for-service negotiation, operation, measurement and verification, or settlement. Even cybersecurity and auditing are project-based, though there is a security model described based on common industry approaches. Credentials and authentication are included as needed, not by nominative specification. This makes the value of testing, certification, and branding of OpenADR 3.0 compliance questionable.

A TE program or implementation profile could be considered that used the building blocks and REST-style of interaction specified in OpenADR 3.0. Whether such extensions could be specified by the OpenADR Alliance, the IEC, or another standards development organization, could be part of strategy to move a TE-related standard forward.

4.5 IEEE Std 2030.5 – IEEE Standard for Smart Energy Profile

This standard is designed for interactions between smart grid operations and customer equipment. It originated as a Zigbee™ smart energy standard and was revamped to be layered on internet protocol standards and adopts the REST architecture widely adopted in web services approaches used by many industries (IEEE SA, 2011) (IEEE SA, 2023a). The intent is to work with mainly end-use devices, such as smart thermostats, meters, electric vehicle charging systems, smart inverters, and appliances.

4.5.1 Support from other IEEE Std 2030 Components

The standard is organized into function sets concerning interactions with specific device types, such as smart inverters, electric vehicle chargers, or demand response load control. Because of this, it is not strictly device agnostic and favors device specific integration (like direct control of power inverters) (Mater, et al., 2019). Nevertheless, the standard contains device agnostic function sets as well—in particular, a pricing function set that could be applied to any device with business logic to understand how to react to dynamic prices.

The standard includes an information model which is based on IEC 61850 (substation automation communications). It also has a suite of support services, such as discovery services, that allow system components to reveal themselves and be found by other components. Subscription and notification and time synchronization functions are also provided. The standard includes a way to update software and the version of the interface. A cybersecurity model based on public key infrastructure for security certificates is specified.

The standard has gained traction in the PV smart inverter space in California (e.g., Rule 21 (CPUC, 2021)) and Hawaii. It is also being applied to integrate the flexibility in smart electric vehicle charging. It has a command-and-control interface; however, it also supports price reactive information exchange.

The industry ecosystem for the standard includes the SunSpec Alliance. This group has specified a smart inverter implementation profile, called the common smart inverter profile, with testing and certification for California applications. This has advanced interoperability and eased integration of smart inverters in California. It also provides a guide for developing other implementation profiles for the integration of other equipment (e.g., smart electric vehicle chargers).

4.5.2 Energy Grid of Things, Portland State University Project

The 2030.5 community in IEEE and SunSpec indicate interest in eventually supporting a TE interface. A DOE-sponsored Energy Grid of Things program funded several projects for supporting an energy service interface (ESI). The ESI concept is consistent with the service-oriented principles of a TE interface, but does not specify a market-based, distributed optimization approach. One such ESI project was led by Portland State University (Bass, 2022). This project created an implementation profile of the IEEE 2030.5 standard to support a device-agnostic interface for coordinating DERs with system operations. The ESI makes sure the information exchange between an aggregator and DER owners protects privacy, provides security, develops trust, and ensures interoperability.

The project based the ESI design on IEEE 2030.5 and developed an implementation profile (Bass and Slay, 2021). The profile, "…primarily uses *flow reservation request* and *flow reservation response* resources (content in a server) to estimate DER capacities and abilities to participate in grid-DER services. These estimates are conveyed through four parameters: energy, power, interval, and duration. Each DER uses the flow reservation request resource to request energy at a specified power from the GSP (grid service provider). The interval of the flow reservation request allows the GSP to determine the time period when the DER is available to participate. The duration is the amount of time the DER can be dispatched during the interval."

The project divides interactions between a grid operator and a grid service provider (an aggregator of DER flexibility), and between a grid service provider and service provisioning customers who operate the DER. 2030.5 is used by the aggregator and the customers. It is not used between the grid operator and the aggregator. The aggregator-customer interaction uses the 2030.5 flow reservation request/response resources to reserve the use of DER capabilities. The aggregator calls on these capabilities based on the service request of the grid operator. It is unclear how the aggregator chooses which customers to respond to a service request for a grid operator. Similarly, it is unclear the process and calculation mechanism used for customer compensation for responding to a request; however, the only service that an aggregator uses for interacting with a customer appears to be a reservation for energy. It is up to the aggregator to call upon that reservation to meet any number of grid operator requests.

The project systematically reviewed its design with the IMM criteria referenced in Section 3.1. The review indicated that a majority of criteria are addressed but pointed out that resource discovery and logging and auditing are not presently implemented. The project emphasized the security and trustworthiness of its approach.

The distributed decision-making and optimization seeking aspects of a TES do not appear supported in this design; however, one could imagine an exchange of value (e.g., price, quantity curve) being exchanged that could augment the base capabilities of this use of 2030.5. Selection of customer DER and their compensation for participating could then be clarified. The project documentation does not recommend changes to the 2030.5 standard; however, support for some basic TE information exchange to support value-based decision-making is lacking. Rather than strictly using a reservation request, 2030.5 support for scheduling energy with customers would provide more straightforward support for TES.

4.6 IEEE P2418.5 Standard for Blockchain in Energy

P2418.5 is an initiative to standardize the use of distributed ledger technology in energy system control and coordination. IEEE published a position paper *titled IEEE Blockchain Transactive Energy* (Rahimi, et al, 2021). The intent is for this work to guide a formal IEEE P2418.5 standard effort; however, the material is mainly informational with considerations for topics that would be covered in a standard. There is some discussion of electric system and control architectural structure. There is mention of a plan for standards development, but there is no substantial material for implementation to a standard. There is also mention (without reference) to blockchain standardization that is underway and may become applicable to a blockchain TE reference model that relies on a distributed ledger technology platform.

As of this writing, the IEEE-SA P2418.5 Working Group is in the process of completing a guide titled "IEEE P2418.5 Blockchain in Energy Standards." Its coverage is broader than TE and will address other areas of energy systems. The project summary reads, "This standard provides an open, common, and interoperable reference framework model for blockchain in the energy sector. It also covers three aspects: 1) Serve as a guideline for blockchain use cases in the electrical power, oil and gas, and renewable energy industries and their related services. 2) Create standards on reference architecture, interoperability, terminology, and system interfaces for blockchain applications in the energy sector by building an open protocol and technology agnostic layered framework. 3) Evaluate and provide guidelines on scalability, performance, security, and interoperability through evaluation of consensus algorithm, smart contracts, and type of blockchain implementation, etc. for the energy sector" (IEEE SA, 2023b).

A draft version of the guide indicates that it is also an informational document that defines terms and explains concepts relevant to distributed ledger technology, its cybersecurity properties, and challenges for energy system applications. However, there is no material for standardized technical interfaces for implementations.

5.0 Organizations that Support TES-Related Initiatives

The following organizations support initiatives that relate to TES. The nature of the organizations and their activities that may impact standardization are presented.

5.1 OpenADR Alliance

The OpenADR specification has its origins in demand response projects in California initiated by the Lawrence Berkeley National Laboratory. The OpenADR Alliance was formed in 2010 to bring interested stakeholders together to advance the OpenADR technical specification and provide support for development and testing of OpenADR implementations. As a consortium of interested parties, the alliance advances updates to the OpenADR standards, developments conformance, certification, and testing programs and advocates for an OpenADR ecosystem of products and services. OpenADR 2.0b (Open ADR Alliance, 2023) and the 3.0 standard in progress (OpenADR Alliance, June 2023) are outputs from this organization.

While there the organization retains strong ties to California-based participation with utilities and solution providers, it is an international organization with implementations in many regions of the world and expanding interest. For example, the OpenADR Alliance has collaborated with the USEF Foundation in Europe.

5.2 SunSpec Alliance

The SunSpec Alliance™ originally focused on advancing the installation and integration of solar PV power inverters, and as with the OpenADR Alliance, has had a strong presence in California. The organization widened its mission to accelerate the growth of DER beyond distributed generation to include storage systems and demand response. Its standardization work includes participation in implementation profiles and standards updates to Modbus™ communication control, IEEE 1547 (IEEE, 2023a), Orange Button™ information model exchange (SunSpec Alliance, 2022), and IEEE 2030.5. For 2030.5, the organization has had good success with the common smart inverter profile for California Rule 21 integration of photovoltaic PV systems using 2030.5, with a public key infrastructure certificate program to aid cyber-secure deployments on 2030.5, and a relatively new implementation profile for vehicle-to-grid interactions (CPUC, 2021).

The 2030.5 implementation profiles have helped drive interoperable deployments. The organization was an active participant in the GMLC 1.2.2 Interoperability Project, which was instigated by IEEE 2030.5 interoperability steering committee work that identified actions for IEEE-SA and SunSpec to undertake to further advance interoperability. SunSpec leadership has indicated interest in service-oriented, device agnostic approaches, such as TE, that respect equipment owner privacy, and operational responsibility.

5.3 SEPA

SEPA began as a distributed solar generation integration consortium. In 2017, the NIST-formed SGIP merged with SEPA as part of SEPA efforts to focus on electric utility carbon reduction including the integration of all types of DER. The SGIP-SEPA merger initiated new member activities to advance communication interoperability for integrating DERs into system operations. This includes the maintenance of a catalog of smart grid standards (including IEEE

2030.5 and OpenADR) as well as member working group activities. The follow working groups are related to TE standardization and interoperability.

5.3.1 Energy Services Interface Task Force

The Energy Services Interface (ESI) Task Force is a task force under the SEPA Architecture Working Group. It embraces the ESI concept articulated in the GMLC 1.2.2 effort (GMLC 2023). The ESI represents an interface to interact with any type of DER, or collection of DERs (such as a facility with a mix of DERs) and uses performance-related agreements to avoid command and control, thus hiding the details of the DER facility from the interface. The concept is fully consistent with supporting a transactive mechanism.

This group defined use cases for specific grid services and is attempting to offer a reference specification of existing standards that could support electric vehicle charging to grid use cases consistent with the ESI concept. The DOE-GMLC 2.5.2 effort is also socializing ESI specification material for reviewing standards, such as 2030.5 and OpenADR, to clarify challenges and gaps in supporting the ESI concept (Liu, et al., 2022).

5.3.2 SEPA Transactive Energy Working Group

The SEPA Transactive Energy Working Group developed a set of transactive use case scenarios and adopted a general model for TES (see Section 3.1). The working group includes a business and regulatory activity as well as a TE field guide task force to capture TE implementation best practices. The general TE model is being used by the SEPA Grid Architecture Working Group. Many people in this group are also in the ESI TF. All participants are interested in standards that advance the integration of DER into system operations.

5.4 IEEE

The electrical engineering professional society, IEEE, convenes groups interested in TE and advancing standardization.

5.4.1 IEEE-SA SC21

IEEE Standard Association (SA) SC21 Standards Coordinating Committee on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage is a formal standards development association supported by IEEE members. SC21 coordinates a series of standards under *IEEE 2030 Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System, and End-Use Applications and Loads*.[1] The Smart Energy Profile, initially created by Zigbee, has evolved into IEEE standard 2030.5 (Section 4.5). The 2030.5 standards working group is releasing an updated version of the standard.

5.4.2 IEEE Power and Energy Society SBLC

The IEEE Power and Energy Society's Smart Buildings, Loads, and Customer Systems Committee (SBLC) sponsors the IEEE-SA P825 *Guide for Interoperability of Transactive Energy Systems with Electric Power Infrastructure* (IEEE SA, 2023c). The IEEE SBLC Architecture Subcommittee focuses on the architectural integration of DER with system operations. The

[1] Formerly SCC21.

nature of interfacing and coordinating DER operation with system operations are key topics for the group.

5.5 Linux Foundation Energy

The Linux® Foundation promotes open-source software and platforms for a variety of applications. Linux® Foundation Energy is an initiative focused on open-source technology to support energy decarbonization. It is an umbrella organization for a host of technical projects and technology platforms. Energy Market Methods is one such platform. The Energy Market Methods effort's objective is for "Standard open-source methods to enable demand flexibility as a resource, supporting energy programs and distributed energy resource (DER) markets" (The Linux Foundation, 2020) (CalTRACK, 2019). It provides features on top of Linux that become embedded in smart devices for coordinating energy-related operation. Though the coordination mechanism is not clear yet, the effort could represent an opportunity for TE.

5.6 IEC Technical Committee 57

IEC Technical Committee 57 drives international standards in the power system industry. The standards have been primarily directed to the utility space. The European Union has a directive to use IEC standards over country-based standards if appropriate. Information modeling standards and equipment interface standards are referenced and adopted for DER integration in the United States and across the globe.

The OpenADR standard, IEC 62746-10-1, is linked with this technical committee.

5.7 Flexiblepower Alliance Network

FAN promotes flexibility integration in Europe. It has developed the EFI (see Section 4.2), which is helpful for standardizing a representation of energy flexibility for equipment. TE has been a topic of interest at their conference, FLEXCON, but a market-based exchange standard for DER coordination has not been part of their standardization efforts to date.

The group is not a formally recognized standards development organization. Collaboration is noted between FAN and the Universal Smart Energy Framework (USEF) Foundation as complementary efforts.

5.8 Universal Smart Energy Framework Foundation

The USEF Foundation supports market designs for energy flexibility exchange. The group defines a framework for integrating flexibility into the power system considering the entire value chain including wholesale and retail environments with various aggregator models that interact with electricity end-users, or prosumers (de Heer, et al., 2021).

The group is not a formally recognized standards development organization. Collaboration is noted between the USEF Foundation and FAN as complementary efforts, where USEF provides the trading protocol and FAN classifies and integrates devices, particularly in buildings, so that they can be coordinated to perform in a TES. USEF has also collaborated with the OpenADR Alliance.

6.0 Results and Discussion

Appendix A presents a broad-brush view of the TE-related standards mentioned in Section 4.0. This categorical assessment was used to identify gaps and challenges that exist in the identified standards. Section **Error! Reference source not found.** provides key recommendations to address deficiencies in standards and implementation profiles that can advance TES deployment. The following subsections highlight observations about the state of the standards landscape.

6.1 Gaps in the Transactive Energy Standards Landscape

Reviewing the TE-related interface standards, along with supporting material and organizations, reveals a number of gaps if systems with components from multiple technology providers are to easily integrate and interoperate.

- The TECM work in SEPA covers high-level concepts and relations for describing TES but lacks the formality of semantic modeling that is needed in testable interface standards.
  - Bringing the TECM work into selected standardization processes, such as IEEE 2030.5, OpenADR, or OASIS CTS, would clarify semantic meaning and data structures. It also offers an opportunity for harmonization among different standards.
  - The semantics would also be helpful for extending existing standards, such as OpenADR and IEEE 2030.5, to explicitly support TE implementations.
- There is incomplete coverage by interface specifications across the GWAC Stack interoperability levels and transactive lifecycle areas.
  - Business interoperability requires a minimum degree of end-to-end consistency that is not currently supported well by the TE standards landscape. Complete coverage will likely involve multiple standards and the use of implementation profiles that bring specificity of implementation for interoperability testing.
  - In the case of TES, business interoperability addresses the inherent business objective(s) that are being valued by the system. While signal recipients may not need to precisely know the business objective, some degree of end-to-end interoperability is needed if the global business objective is to be successfully valued by the system and achieved.
  - Business level interoperability may include the existence of measurements and supporting measurement systems that would inform system feedback or market qualities (e.g., time interval granularity); that could mean the difference between achieving a business objective or not at an interface.
  - Business interoperability requires support for representing the registration and qualification details for discovering and entering a TE program. Basic discovery and account creation mechanisms need to be extended to support deployments needs. Ease of mass deployment goes beyond technical standards to encompass implementation profiles that support product and program testing and certification.
- TE standards testing and certification processes are immature.
  - The immaturity of the DER coordination marketplace and lack of trust with the performance of transactive approaches has led to relatively small, specialized projects.

  - Standards participation and success requires a business community ecosystem with major TES deployments. Project investments can financially defray the cost of participation in creating standards and profiles for testing, certification, and product branding that benefit all stakeholders.
  - The SunSpec Alliance is an example of ecosystem progress in this area, with 2030.5 and Modbus implementation profiles and testing, but it has not been applied to an IEEE 2030.5-based implementation profile for TE.
- There is incomplete coverage and a lack of deployment experience across electric system applications of TES.
  - Many examples exist at the interfaces between energy suppliers, DER coordinators, and customers. This is natural because of the increasing penetrations of controllable and uncontrollable resources.
  - Systems typically defer to existing electricity markets in the wholesale and transmission domains. Not all grid locations possess dynamic electricity markets in these domains. Any lack of transparency, dynamics, or limitations of existing markets in these domains may limit the practices of TE in the other domains.

6.2 Policy Barriers in the TE Standards Landscape

The marketplace for designing and deploying standards-based TES faces business and regulatory policy challenges.

- Regulatory commissions struggle to find the balance between policies that provide rules and market-based incentives for DER coordination, while protecting a competitive environment for energy service companies and technology solutions providers of TES. Regulatory barriers include these issues:
  - Current practices limit entities and devices that may participate in markets, as opposed to adopting DER- and participant-agnostic approaches;
  - Historical assumptions and codification favor direct control and demand response approaches;
  - General lack of time-varying economic signals suitable for DER coordination in the electricity domain; and/or
  - Tariff-setting processes that hinder transparency of the time value of electricity.
- Jurisdictional fragmentation of electricity regulation with weak cooperation between regulatory bodies allows for the experimentation of many approaches but hinders harmonization needed to scale and evolve technology solutions. These business interoperability barriers then occur:
  - Minimum aggregation requirements and the inconsistent definition thereof;
  - Ill-defined and complicated value propositions for TES participants; and/or
  - Lack of standardization among existing value signal tariffs.
- Despite visionary business initiatives to stimulate growth in the coordination of flexible resources, the financial and environmental rewards appear insufficient to sustain a speedy transformation. These issues limit adoption of TE:

- Despite smart devices that can manage energy use, there is a general lack of autonomously responsive devices.
- Internet-of-Things interfaces are contributing to coordinating energy use, but standardization is in flux. Particularly, there is a lack of wide-spread adoption of standards among smart device energy management providers, even with efforts like EFI.
- Incentives remain uncertain concerning TE market mechanisms and for those entities who might manage TE markets.

- The immaturity of business models in the marketplace favors proprietary platform solutions. These issues then slow the development of interoperable solutions:
  - Smart device providers use proprietary interfaces to manage thermostats, lighting, electric vehicle charging, and other equipment and protect access by others to their devices.
  - DER coordination solution providers offer flexibility platforms to aggregate DER, but do not integrate with other platform providers.
  - Smart devices integrated in one flexibility platform may be locked in from moving to another platform provider.
- The immaturity of the marketplace for coordination of flexible resources has led to many standards and initiatives with related consortia and communities that help drive deployments based on an evolving set of implementation profiles (see Section 5.0). These groups are increasingly providing services for testing, conformance, and registries for cybersecurity and qualified products based on standards, but are not necessarily supporting TES principles. A focused TES ecosystem for progressing standardization does not exist.

7.0 Recommended Activities to Advance TES Standardization

In developing a plan to advance standardization for TES, the standards landscape effort identifies the following areas as deserving attention.

Clear, Broadly Held Definition of TE

The GridWise Architecture Council's definition of TE (Section 1.2) is currently too abstract to support a strong, community-focused effort to advance TE standards. The scope of standardization will remain murky until the TE community converges on a concrete, distinctive definition of TE. The GridWise Architecture Council, or a standards community group, can be assembled to establish conformance self-test criteria based on qualities that any TES must possess. Doing so can focus standards-related efforts. Even those innovators whose systems do not then qualify as TES would be eligible to use elements of the resulting TE standards-related material in their own designs.

Support Valid Market Mechanisms

Because multiple valid market mechanisms exist for the practice of TE in the electricity domain, the TE standards activities should support all such mechanisms. Those standards that are applicable across all market mechanisms are most useful. This suggestion may lead to models, templates, or other such structures that can support the representation of different market mechanisms so that they can be communicated unambiguously in implementations. In this regard, machine readable tariffs that describe the information and interactions needed to support a market mechanism deserve attention.

Specific technical standards related to the application of distributed ledger technology to TES is lacking (see Section 4.6). Making solid use of distributed ledger features, such as smart contracts, for supporting machine readable tariffs in TES deployments deserves consideration as a standardization activity. Adopted formats for representing terms and conditions consistent with the chosen market mechanism can provide a way for standards to support valid market mechanisms.

Promulgate and Strengthen the TECM

The SEPA TE Concept Model (see Section 3.1) provides context for harmonizing and evolving TE standards because it is specific to TES and it recognizes the instantiation of TE concept objects among multiple conventional smart grid domains, a property that is unique to some TES. However, as the SEPA TECM is being socialized and TES concepts mature, the concept model deserves critical review and update to help harmonize terminology in competing TE standards. Existing ambiguities and conceptual gaps need to be resolved if they are to provide useful context for incorporation into TE-related standards. Consideration should be given to codification using information modeling tools like those used in semantic technologies. Note that at the time of this writing, an effort is underway by the SEPA Architecture Working Group to incorporate TECM concepts and develop an ontology.

Related to this suggestion, information models used in the TE-related standards should also be reviewed in the context of TE systems. The objective would be to strengthen the TECM, but also to consider information model harmonization across the standards.

Detailed Evaluation of Targeted Standards and Profiles

OpenADR and IEEE 2030.5 are known to have ecosystems of implementers. Discussions with the OpenADR Alliance and the SunSpec Alliance indicate interest in transactive energy. A detailed evaluation of the appropriate aspects of these standards and their related implementation profiles will specify gaps in supporting TES. Such evaluations would best be done with participants in their respective communities. Besides providing insights, the activity would be educational and could engender buy-in for actions by the groups to better support TES. The GMLC IMM (Section 3.1) can be used to evaluate the support and interoperability maturity of the standards, implementation profiles, and ecosystems.

In addition, using the IMM would explore the associated standards and their ecosystems for the existence and availability of corresponding conformance tests and interoperability testing. Standards in the TE standards landscape should include precise self-certification and community branded test criteria depending on assessment of level of maturity.

Note, OASIS CTS and USEF also deserve closer scrutiny. In the case of CTS, a community of implementation stakeholders is not apparent. Having broader industry experience and commitment to the standard would make it more attractive for investing in a detailed assessment and improvement planning.

Open Interfaces for Proprietary DER Coordination Platform Integration

Unitary device controllers (e.g., smart thermostats) and energy management systems (a building or factory supervisory control system) often use proprietary protocols or specializations of standard protocols that only interoperate with the control and coordination system provided by a DER coordination platform provider. To encourage innovation and enable marketplace evolution, the requirements for interface standards that allow smart energy devices and systems to migrate between different transactive platforms deserves study and engagement with industry stakeholders and standards organizations.

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Appendix A – Broad Classification to Contrast Standards

The following subsections present broad views to compare TE-related standards that are discussed in Section 4.0. The two-dimensional landscape diagrams are ill equipped to present detailed gaps in the standards. However, these views provide insights into their similarities and differences in terms of application scope, interoperability maturity, and coverage of TE concepts and approaches.

Note, the IEEE P2418.5 blockchain energy standard is a guide and does not specify any interoperability categories rigorously. Therefore, it is not represented in most of these views.

A.1 Landscape of interoperability categories and actor domains

The following table diagrams the broad coverage of standards considering the GWAC Stack (Figure 3) interoperability categories and the actor domains in Figure 1.

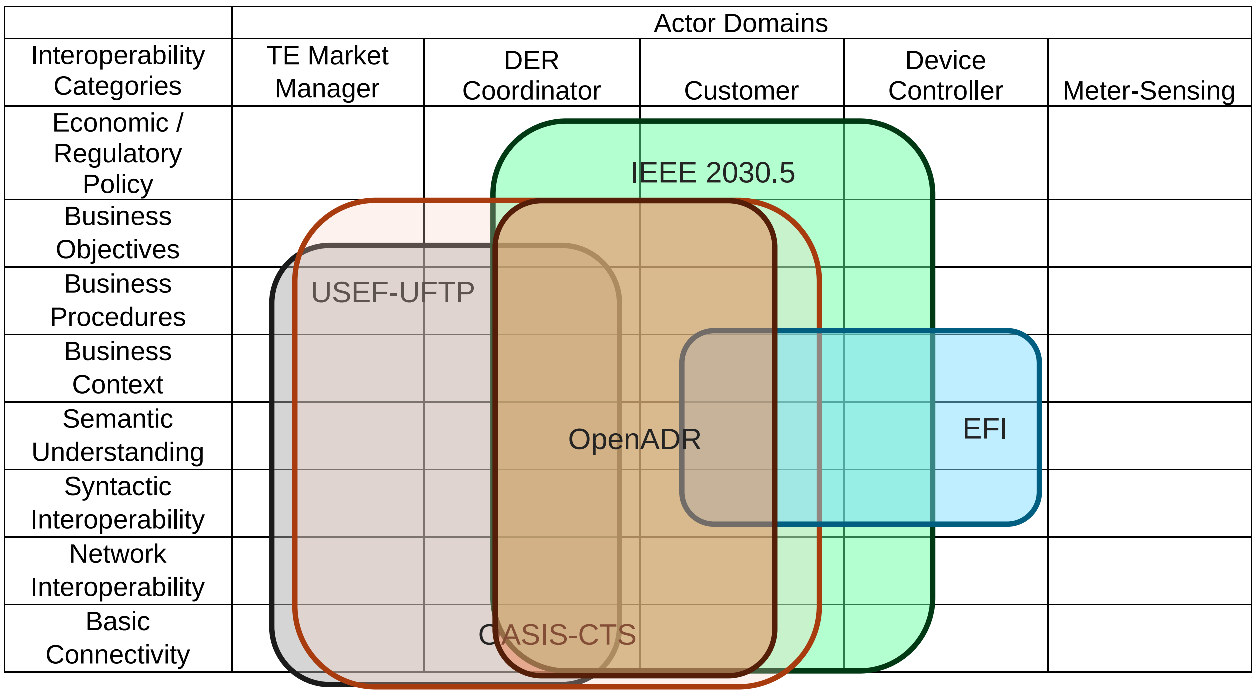

Table 1: Landscape of interoperability categories and actor domains

- OASIS CTS: This standard targets DER coordinators interacting with customers using TE market mechanisms. The boundary of scope does not include protocols for talking to device controllers and it assumes that metering is handled through other means (meter management system or other meter communications protocol standards). It also is layered on networking protocols, deferring to their specifications. It includes an information model with a TE business context and business processes; however, alignment with economic/regulatory policy is lacking from the standardization process. This includes the lack of an ecosystem of organizations working with policy makers to make sure interoperability is achieved.
- EFI: This standard focuses on the information modeling aspects for representing flexibility of various types of equipment in a standard way from device controllers. It is specified in XML, which supports a level of syntactic interoperability, but it does not cover networking protocols or specific business process interactions. In this regard, it can complement a transactive system.
- USEF UFTP: This protocol specification is targeted for TE market interactions between DER aggregators and DSOs. The work assumes aggregators (i.e., DER coordinators) have their own means to control DER. USEF uses the example of The PowerMatcher as a platform for interactions with customers. For this reason, the ability to use UFTP for DER coordination is unclear. While the protocol has been implemented in European projects, the involvement of policy makers appears to be done on a project basis and not in the standard itself.

- OpenADR: This standard originated with demand response applications. While it supports the distribution of dynamic prices and demand response events, there is no explicit support for an TES. There may be discussions to harmonize with OASIS CTS, but OpenADR 3.0 takes a separate path from CTS without explicit support for a TE market. OpenADR assumes interactions with device controllers and metering are handled outside their specifications. Policy makers appear to be involved on a project implementations, particularly in California.
- IEEE 2030.5: IEEE 2030.5 is shown to cover aspects of the economic/regulatory policy category because of the common smart inverter profile experience with California Rule 21, which includes regulatory alignment that has advanced integration with multiple technology solution providers in multiple service provider jurisdictions. Besides this, 2030.5 has coverage similar to OpenADR. However, it does include specific device control modeling and interactions. From a TE point of view, that distracts from the equipment agnostic nature of the market interface, which 2030.5 does not specifically model.

A.2 Landscape of TECM and IMM Maturity Levels

The following table diagrams the broad coverage of standards considering the interoperability maturity levels (Figure 4) and key concepts in the TECM (Figure 7).

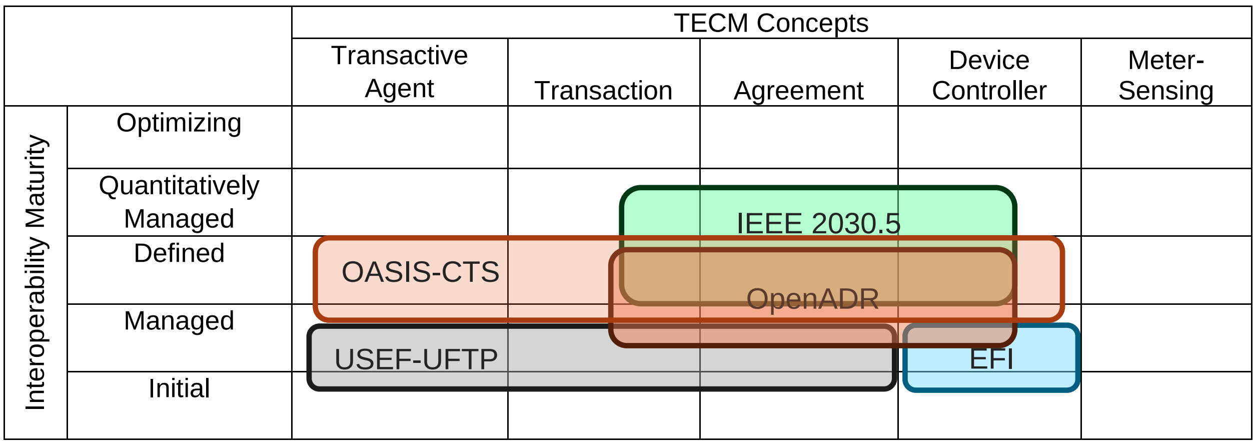

Table 2: Landscape of TECM and IMM maturity levels

- OASIS CTS: OASIS provides a recognized standards development process that was followed in creating CTS. It includes aspects supporting the main TECM concepts, except it defers interactions to metering information to other systems and standards. While energy interoperation and eMIX have been around for a while, CTS is relatively new, and no field implementations are known. This leads to the assessment of a defined standard level or maturity.
- EFI: This specification focuses on representing flexibility from device controllers. It is defined by FAN, which is not a recognized standards development organization. This results in the maturity assessment of managed.
- USEF UFTP: USEF has a rich specification of a transactive market for system operators to interact with DER aggregators. This supports concepts of transactive agents, transaction, and their agreements. The gap not represented in this figure is the lack of specification for interactions with customers who own and operate flexibility resources. USEF is also not a recognized standards development organization, leading to the managed level of maturity.
- OpenADR: This specification does not support transactive market interaction explicitly, though there was harmonization of aspects of OASIS eMIX and energy interoperation standards. The specification works with device controllers and has some notion of a transaction based on dynamic prices and events. While the OpenADR Alliance is not a recognized standards development organization, aspects of its specification are capture in an IEC standard. It also has been deployed in many demand-response projects, and the specification and user's implementation guide have gone through an update process with stakeholders. This leads to the defined level of maturity.
- IEEE 2030.5: The coverage of TE concepts in IEEE 2030.5 is similar to that of OpenADR. It does not specifically support TE mechanisms, but aspects of the specification and implementation profiles could be used for support price responsive. The cooperation with the SunSpec Alliance has produced implementation profiles with testing and certification

processes. The standard's ecosystem has fed multiple versions of the standard that are sensitive to upgrade paths, leading to interoperability maturity processes at the quantitatively managed level.

A.3 Landscape of Interop Cross-Cutting issues and IMM Maturity Levels

The following table diagrams the broad coverage of standards which consider interoperability maturity levels (Figure 4) and the interoperability cross-cutting issues of the GWAC Stack (Figure 3).

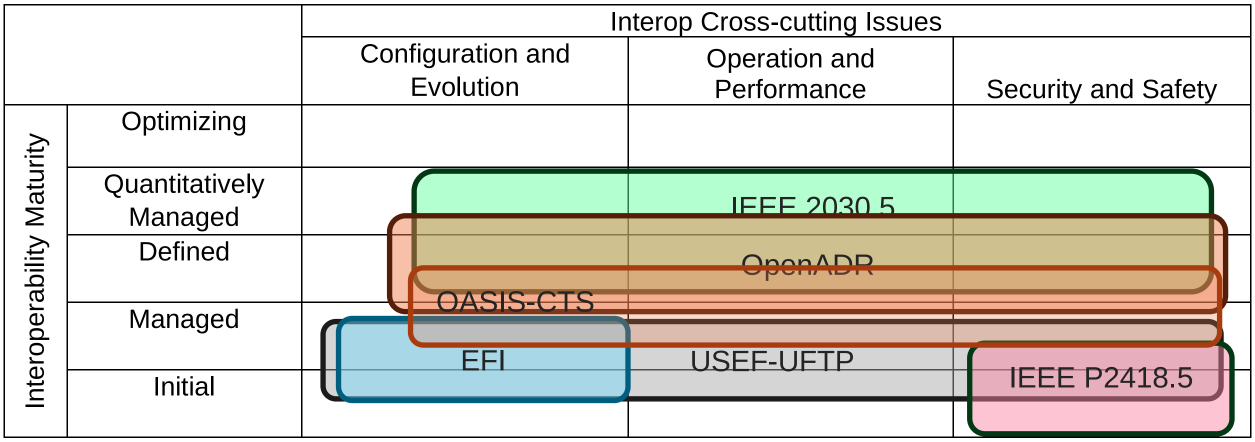

Table 3: Landscape of interoperability cross-cutting issues and IMM maturity level

- OASIS CTS: The CTS standard covers most of the IMM cross-cutting issues. It is based on other internet and web services standards. The ability to support upgrades and configure systems is specified, well-defined, and widely accepted by state management techniques. Its cybersecurity and encryption techniques are also specified. It is represented overlapping defined and managed levels of maturity because of the lack of field experience and upgrades to the standard.
- EFI: As an information model used for flexibility representation. EFI covers configuration and evolution aspects of interoperability; however, other crosscutting issues are not covered in this specification. As FAN is not a recognized standards development organization, its maturity level is represented as managed.
- USEF UFTP: As USEF is not a recognized standards development organization, its maturity level is represented as managed. However, for the UFTP specification, it broadly covers the interoperability cross-cutting issues.
- OpenADR: The OpenADR specification also broadly covers the interoperability cross-cutting issues and is at a defined maturity level with connection to the IEC.
- IEEE 2030.5: The same can be said for 2030.5 as OpenADR. The strong interaction between the IEEE-SA working group and the SunSpec Alliance, which includes implementation profiles, testing, and certification, enhance its maturity level. In addition, an encryption key authority has been setup for project implementations that further supports cybersecurity maturity aspects.
- IEEE P2418.5: The draft report from this group is a guide. The work focuses on digital ledger technology for secure distributed system interactions. This explains the focus on the initial and managed maturity level related to the security and safety cross-cutting interoperability issues.

A.4 Landscape of Interop Categories and Transactive Interaction Areas

The following table diagrams the broad coverage of standards which consider the interoperability categories of the GWAC Stack (Figure 3) and the transactive interaction areas in the transactive agent model (Figure 5). Most of the standards cover some discovery and registration process but focus mainly on the operations process while delegating measurement & verification, and settlement/reconciliation to project specific specifications.

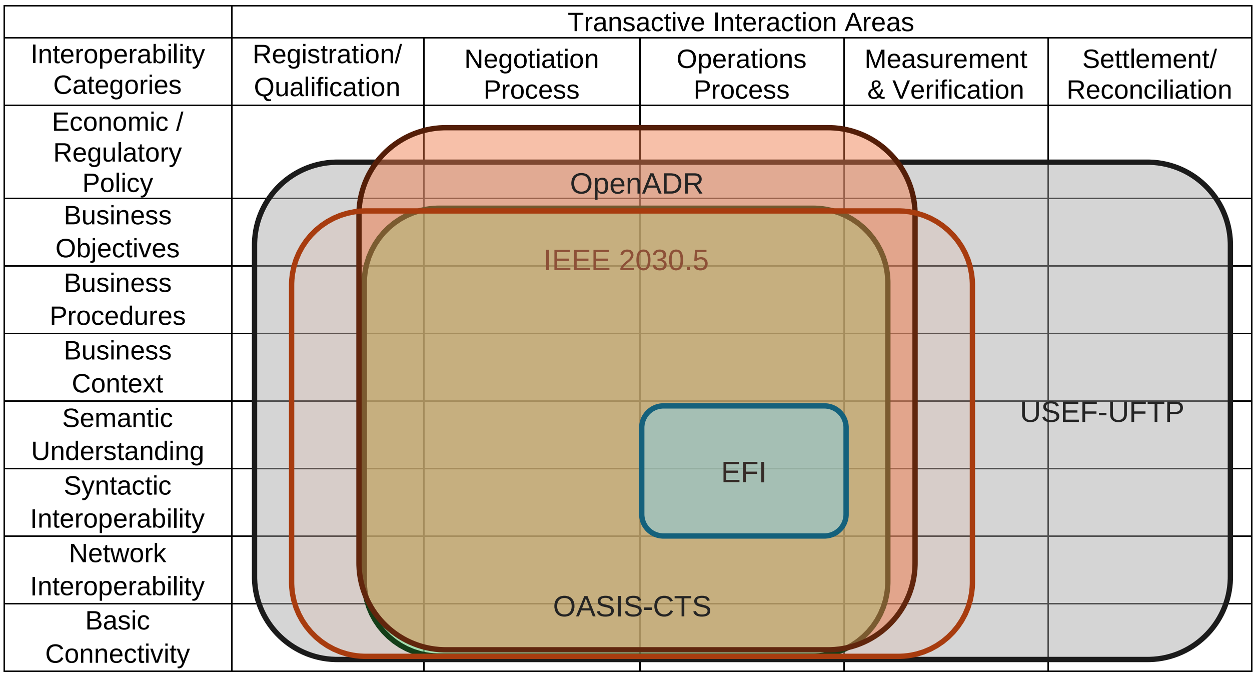

Table 4: Landscape of interoperability categories and transactive interaction areas

OASIS CTS: The CTS standard explains a lifecycle of interactions for a transactive system. It expects that a transactive program is set up by an energy service provider with a detailed customer registration and qualification process. However, the standard does specify the messages necessary to create a party identifier and discover and register in a CTS marketplace. The negotiation (pre-transaction) phase and operations phases are specified. There is an information model for representing measurement information that can be used for settlement, but access to sensing equipment and the actual settlement would be defined on a project implementation basis.

EFI: This standard only pertains to the flexibility representation at the syntactic and semantic interoperability categories. These are relevant during operations and for other software to create transactive interactions.

USEF UFTP: The UFTP specification describes a lifecycle that traverses the areas in the landscape above. Together with the framework, the material describes the approach to setting up a TE market between DSOs and DER aggregators.

OpenADR: The specification and user's guide describe methods to discover and register for a demand response service; however, details of customer qualifications and registration information are project specific and not profiled. The interactions between VTN and VEN for demand response negotiation and operation are described; however, verification, measurement, and settlement details are project specific.

IEEE 2030.5: 2030.5 is similar to OpenADR regarding the lifecycle of interactions. The experience and formalization of implementation profiles strengthens the specification of project-specific details. In addition, the involvement of policy makers in these profiles helps makes sure economic/regulatory policy aspects support interoperability.

Appendix B – Areas of Contention in TE Definition

For the purposes of this document, the definition of TE includes a two-way agreement on a negotiated price for service. Distributed decision-making and price discovery are key, as are grid architecture principles of layered decomposition. However, the people and organizations involved in DER flexibility integration debate several issues that may affect standardization and interoperability related to TES. Examples follow:

- Definition of transactive energy: The GridWise Architecture Council's definition of TE (above) is abstract and open to interpretation. Debate continues concerning which qualities a TES must possess to claim conformance—to claim that it is, in fact, a TES. One area of practitioner disagreement is whether a TES must include feedback of the available energy flexibility from participating consumers and producers. In short, does a price-reactive approach, which is silent on price causation and does not require any messaging feedback signal, qualify as a TES? This report distinguishes one-way, price-reactive standards capabilities from those which support a two-way negotiation interface to explicitly support price discovery mechanisms. Another area of contention is whether the "use of economic or market-based constructs" necessarily implies that a price signal must be used. Can, for example, energy flexibility be centrally calculated and enacted via direct demand response in a TES? This report distinguishes standards capabilities that lack a decentralized decision-making approach and requires direct control as being non-transactive.
- Grid domain: Debate continues whether TE applies throughout an electricity grid; whether TE is applicable only between the electricity distribution suppliers and their customers; or, even more narrowly, if TE is only applicable with specific sets of behind-the-meter assets. Furthermore, some innovators think of a TES as domain-independent, where the participants' roles and responsibilities are defined independently of in which domain the participant resides. In the extreme, TE nodes could be placed at every location where energy decisions might be made (e.g., electricity producers, substations, feeders, transformers, premises, distribution panels).
- Distributed versus centralized decision-making: To what degree must decision-making be decentralized in a TES? Decentralized decision-making is feasible in a TES if coordination principles of layered decomposition are followed (Taft, 2019). This means that a global objective can be achieved by allocating component (or subproblem) calculations among decentralized system locations. In principle, decentralized decision-making decreases system complexity and decreases latency of control actions. This report emphasizes standards that show promise to support distributed decision-making and therefore emphasizes a community of transactive agents, their clean lines of decision-making authority, and their ability to decompose the way the optimization problem is solved.
- Market objective: Economists offer precise definitions of economic efficiency that may be applied to the electricity commodity. TESs can be objectively compared using these metrics. However, market outcomes are increasingly being weighted to reward or penalize new social objectives like renewable energy, reduced CO_2 production, and social equity. Market outcomes change as these weights change. But the process that drives the application of these weights and changes made over time is messy and decisions are often inconsistent when viewed across the maze of regulatory jurisdictions. The jurisdictional authority to assert such values is part of the economic and regulatory policy interoperability characteristic that needs clear specification in defining the design of a TES.
- Market mechanism*:* There exist multiple valid market mechanisms by which TES resolve and finalize transactions. Examples include bilateral trading, matching engines, and double-

sided auctions. Even within each of these example mechanisms, participants' strategies differ with delivery interval duration and with the future horizon over which value and quantity must be predicted and planned. The market mechanism does not define participants' strategies but sets up the rules of a multi-player game. Each participant is responsible to develop their own strategy for interaction; however, investigation of market designs (establishing the rules) has shown the importance of features that avoid or can monitor foul play while still allowing the freedom of players to seek the best (fair) strategies for their individual objectives. The immaturity of TES experience points toward important lessons to be learned on market mechanisms.

- Services provided: TE innovators have been extending the practice of TE beyond the basic scheduling the supply of electricity toward new grid services, like voltage management. Even demand and ramping services, which could in principle be derived from the common energy supply service, place differing requirements on TES. These services may be interdependent, meaning that the provision of one service via TE will likely reduce the provision of the other services. Services cannot be effectively provided by a TES if participants along a TE value stream are unable or unwilling to measure or value the service or its effects.

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