EXERGY™

ELECTRIC POWER
TECHNICAL WHITEPAPER

BUILDING A ROBUST VALUE MECHANISM
TO FACILITATE TRANSACTIVE ENERGY
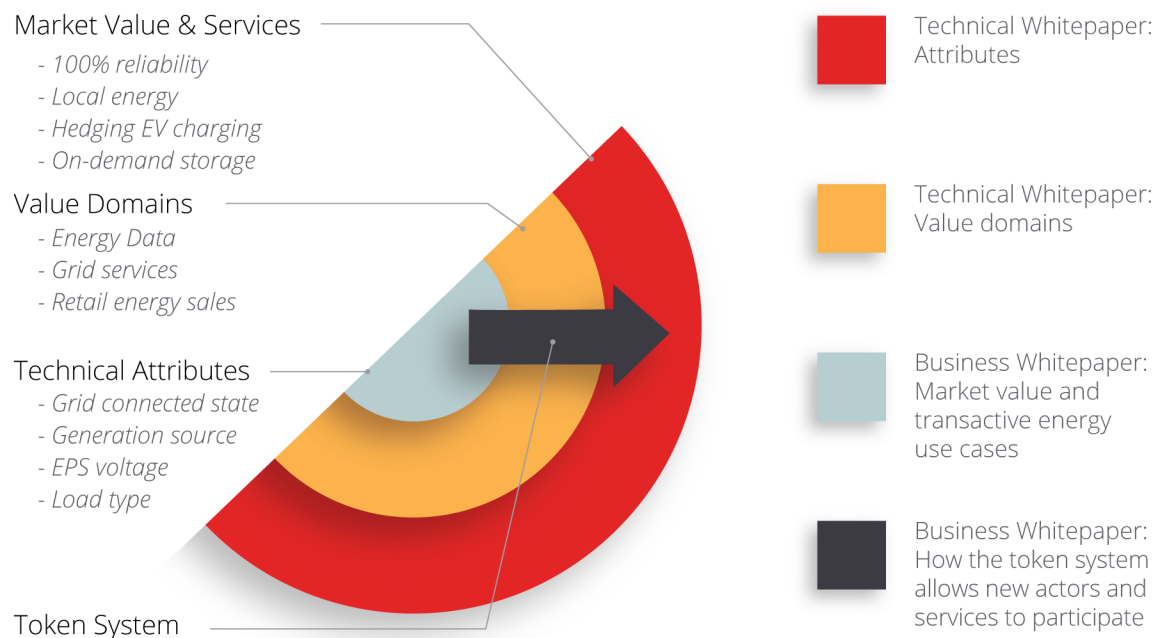
December 14, 2017

INTRODUCTION TO EXERGY™

From Brooklyn to Bangladesh, the new energy consumer wants comfort, security, a more engaged relationship and a promising future for energy production. A democratized energy marketplace is the only way to achieve this promise, and the Exergy project team, part of LO3 Energy, has developed a key piece of this paradigm shift. With Exergy, we are reimagining the customer's role in, and access to, increasingly open and competitive electricity markets.

In this Electric Power Technical Whitepaper, we define transactive energy and explain why it is linked to the physical concept of "exergy" or the portion of energy available for useful work in our economies. This paper defines and describes the value domains and technical attributes required for transactive energy in the multi-party electric power system emerging today. It introduces the idea that we should not consider kWh as the sole attribute of energy service, when equally crucial is where, how and when that kWh was generated for use. As grid edge energy solutions are adopted, the paper describes how a transactive energy marketplace optimizes for lowest cost, lowest carbon, more resilient networks supported by consumers, new energy service providers and system operators alike.

In the Exergy Business Whitepaper that accompanies this Electric Power Technical Whitepaper, we link the technical value domains to market value, starting from the services that consumers and third parties can provide, to one another and to the electric power system. We propose what the new Exergy token system will accomplish and how it can be utilized by energy system participants including third party developers, load serving entities such as retail electricity suppliers, and market operators.

Further publications are planned by the Exergy project team to go deeper into country and local level regulatory and policy drivers and barriers to delivering transactive energy and Exergy. Likewise, the deeper academic work that builds on the current work of economists to measure and account for exergy rather than energy will happen in parallel to the technical development of the Exergy token system.

Market Value & Services
- 100% reliability
- Local energy
- Hedging EV charging
- On-demand storage

Value Domains
- Energy Data
- Grid services
- Retail energy sales

Technical Attributes
- Grid connected state
- Generation source
- EPS voltage
- Load type

Token System

Technical Whitepaper:
Attributes

Technical Whitepaper:
Value domains

Business Whitepaper:
Market value and
transactive energy
use cases

Business Whitepaper:
How the token system
allows new actors and
services to participate

Abstract

The age of transactive energy (TE) in the sharing economy is upon us, and its widespread adoption depends on a secure and robust means for rewarding participation of the most low-carbon and cost-efficient assets and networks to deliver key energy services at the grid edge, where distributed energy resources (DERs) such as solar panels, electric vehicles, and new devices such as smart meters or appliances are rapidly being adopted. Digitization is coming to the energy industry as many key network, sensor, computing and communication technologies make it possible to drive decentralization of the electric grid and energy market. Distributed ledger methods have a vital role to play in securely exchanging grid edge data between devices and consumers, safely opening up the electric power market to broad participation and two-way power flow.

Contributors

Over the last two years, the LO3 Energy team has delivered the Brooklyn Microgrid and the world's first ever energy blockchain transaction in April, 2016. The team has developed a unique knowledge base of integrating blockchain with physical energy generation and management assets in a regulated environment. LO3 Energy has been recognized as being among early market leaders by Utility Week, Fast Company, E.On and Nominet Trust as well as been invited to speak on regulatory energy change in front of the US House of Representatives, European Commission, OECD, multiple regulatory bodies and industry conferences.

In addition to LO3 Energy founders Lawrence Orsini and Bill Collins, key Exergy team members that contributed to this technical whitepaper include:

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1.0 Transactive Energy Systems

Electric power system assets can be viewed as nodes within a network that, when properly connected and incentivized, deliver key value elements (or "network utility"), which include ultra-efficient energy production and consumption, autonomous grid-edge control, rapid restoration, and a wide array of societal benefits. This translates into high levels of specific value streams at the grid edge that ideally should be framed into a bilateral exchange of that value (we refer to this as transactive energy). These values streams currently cannot be tapped because of structural barriers to that simple exchange.

1.1 Consumers Matter in New Energy System

The major challenges in transitioning to this type of energy ecosystem is ensuring that energy access, resiliency, security, decarbonization, and democratization are achieved at the lowest cost and without negatively impacting the current grid reliability.

Exergy will utilize a blockchain-based token system to reduce barriers and facilitate the optimal coupling of local electric generation with parties that can evaluate, generate, store, trade, and utilize this generation most efficiently. This is squarely a customer-centric model—where customers (who may increasingly be operating within a microgrid) own and operate the DER assets. This supports a growing distributed energy ecosystem that best serves its own load demands in normal use, while coincidentally opening up direct and derivative service value streams to peripheral distribution system operators (DSO). This more traditional utility enterprise can both utilize the microgrid for its broader system balancing needs and provide energy transport services to link adjacent microgrids as it evolves its business model.

The services facilitated through "tokenization" of energy attributes will be packaged for exchange within a transactive energy market. Beside the basic physical commodity energy transfer (see Section 2.2.6 on the value chain of energy) there are broader societal values for attributes that major consumer sets and their government agencies consider high priority in the advancement of renewable energy. This includes energy availability (capacity) as an aspect of resiliency, energy flexibility (dispatchability) for accommodating increasingly diverse load balancing needs, and source generation provenance (sustainability).

Exergy is designed to enable a universal transactive energy system architecture that can be tailored to vendor specific solutions, addressing unique use cases within and across the electric power ecosystem.

1.2 Exergy Concept

In energy systems, exergy is the high-quality output available to be used. Academic studies based on the US economy show that the production-to-consumption energy conversion process is 86 percent inefficient , and there is a similar story the world over. Figure 1 below illustrates the trend in overall US energy efficiency as viewed through the energy flow from all fuel sources, conversions, and transmissions, through to end consumption. Studies show that there has been a stagnation in exergy levels in recent years.

By increasing exergy—improving the efficiency of energy systems—and decreasing heat waste, our economies become more productive. But today, economists focus more on measuring energy, not exergy, missing opportunities for creating a more robust economy[1].

Transactive energy is an opportunity to incentivize values other than simply kwh; the purpose of the Exergy project is to continue to link market actions and outcomes at the level of economic activity that is most effective for avoiding the combustion or delivery losses that drag down economic productivity.

[1] Laitner, Skip. Linking energy efficiency to economic productivity: recommendations for improving the robustness of the U.S. economy, WIREs Energy Environ 2015, 4:235–252. doi:10.1002/wene.135

1.3 Driving Trends for the Energy Market Evolution

The accelerating adoption of distributed renewable energy generation at the grid edge is the direct result of several self-reinforcing industry trends. These trends collectively are creating both benefits and drawbacks for the electric distribution system as it currently exists. Major benefits include reduced carbon emissions from the electric power supply chain, increased resiliency in microgrids, potential reduction in congestion at certain nodes, and possible deferral of infrastructure capital spend. Some drawbacks include difficulty in maintaining voltage and frequency within desired control limits as more grid-edge generation is absorbed back into the grid, as well as a disruption to the legacy utility business model, as efficiency improves and more energy is produced and consumed at a local, microgrid level.

A transactive energy platform offers a unique distributed market design that allows customers to engage grid-edge resources for a variety of critical services, to capitalize on the benefits while mitigating drawbacks. As electrical assets connected to the grid become more distributed, transactive energy enables dynamic pricing signals that assign relative value to a given unit of generated energy. This variance provides the economic signal that innovators respond to in order to manage consumer participation in the most economically efficient manner, lowering energy prices, reducing carbon emissions, increasing electric distribution system efficiency, and enabling a host of new potential services yet to be imagined.

Policy and regulation inhibit or accelerate these technology trends differently in each country or region. Subsidies for renewables have increased penetration of renewable capacity in regions where feed-in tariffs or investment tax credits have been employed, resulting in trend 1 below. But since 2000, the share of energy investments that funds competitive markets globally has decreased from one-third to just ten percent[2]. Without more innovation within and outside of regulated markets, the trends below threaten to attenuate low cost and low carbon energy transitions more than reinforce them. The regulatory environment can act as both as a driver and response to the technology trends, with profound financial implications, and this will be the topic of the forthcoming Exergy Business Whitepaper.

[2] https://www.economist.com/news/briefing/21717365-wind-and-solar-energy-are-disrupting-century-old-model-providing-electricity-what-will

The primary trends that are driving the need for (and viability of) transactive energy systems are:

Trend 1 Distributed energy resources (DER), including solar PV panel systems and the corresponding power conversion electronics and energy storage components, continue dropping in price, lowering affordability barriers and allowing more consumers to participate. The vast and increasing amount of independently owned and operated grid edge assets will be harnessed through transactive energy methods.

Trend 2 Consumer choice is failing consumers. In the markets where consumers have choice in their energy supply, they are being offered renewables at a premium, when in fact the design of the grid makes it difficult to decarbonize even as new renewable generation is added. Consumers increasingly expect to be able to scrutinize and verify their choices and act out their values through consumption. Transactive energy provides a way to better capture key attributes such as provenance or 'greenness' and pass those on as service offers.

Trend 3 Interconnection standards are becoming more widely adopted, enabling easier plug and play grid connection of DER, which lowers cost and timeline barriers for distribution system interconnection. Microgrid technology is also rapidly advancing the development and wider adoption of standardized systems that can interoperate at the grid edge.

Trend 4 Rapid advances within the Internet of Things (IoT) domain, coupled with increasing availability of low cost communication network bandwidth are permitting intelligent monitoring and control capabilities at the edge of the grid. This added precision applies to both generation and load management. This in turn results in improved capabilities for intelligent aggregation, automation, and monetizing an aggregate response through grid services.

Trend 5 Regulatory imperative: Already 195 countries have agreed to aggressive greenhouse gas emissions abatement measures through the Paris Agreement on climate change. In parallel, the focus in many countries is to move toward power sector deregulation, designed to encourage more competition (which advances innovation), by separating the functions of generation, transmission, distribution and retail supply into different business processes and corporate entities. The movement toward low carbon and more "new market entrants" in the energy sector is already in motion, but the rate of these changes taking place may still vary.

Trend 6 Computing and network processing power continues to advance at roughly the rate of Moore's Law with the advent of 10nm process semiconductors running at lower power levels and faster clock speeds, and the 5G wireless standard that will soon dramatically reduce latencies and raise bandwidth in the telecom network. Artificial intelligence and other computing advances open up further opportunities for transactive energy.

Trend 7 Aggressive maturation of the sharing economy, which by its nature drives economic value to the most direct and efficient solution, often utilizes peer-to-peer connection. Blockchain, as a transaction foundation, also enables these highly-decentralized models to thrive. This is a critical aspect of meeting the growing demand for consumer choice (Trend 2).

1.4 Effect on the Current Grid

Figure 1 illustrates how the energy value chain can be disrupted by large efficiency improvement potentials in the various conversion stages, as energy is released from its stored form in fuels (left side of diagram), then transformed and transmitted as electric power to its end use (on the right side, by sector). The majority of energy is dissipated as waste or rejected energy at the Electricity Generation conversion box and the end use sectors and transportation consumption functions. These paths represent the primary focus of enabling our transactive energy use cases described in this paper.
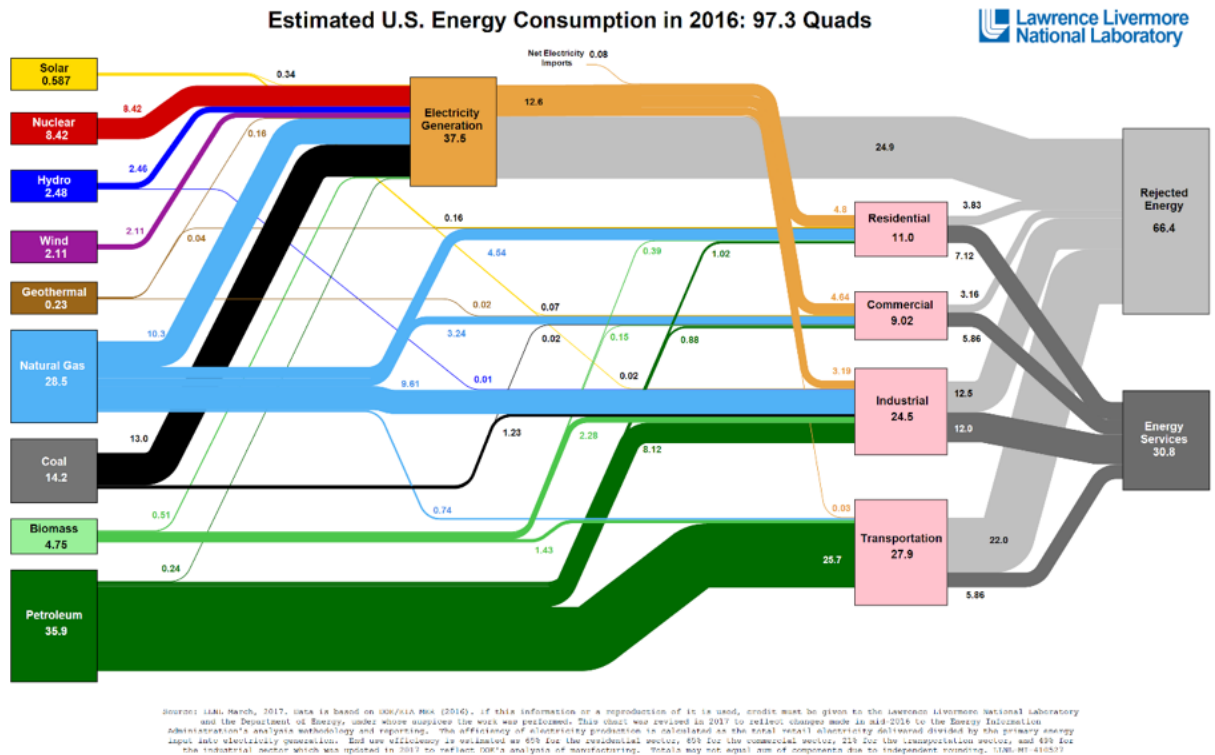

Figure 1 The Big Picture for Efficient Energy Services

Electricity generators face competitive market forces as legacy grid-center technologies such as coal fired and nuclear powered steam turbine generation become uneconomic, due to both higher overhead and operating costs (as compared with natural gas fired units) as well as the efficiency loss and vulnerability points from transmitting electric power over long distances through multiple transformers to the ultimate consumer. On top of that, the cost of utility-scale renewable energy with wind and solar plants is reaching parity with gas fired generation, and continuing to drop. That affects other system components as well, driving adoption barriers lower for smaller DER facilities at the grid edge.

Distribution system operators (legacy electric utilities) are facing much higher levels of system instability caused by the intermittency of this injected renewable energy. Adding to the instability is the decrease in system inertia resulting from the reduction of spinning generation, and the replacement of highly inertial traditional load with the more "instant on/off" digital power electronics. These largely regulated monopoly grid operators also find that their state regulators are under increasing pressure to reform their policies, and to authorize rate structures that accommodate higher market participation of customer-owned DER as part of the solution.

This effect is exemplified by Germany, where generous feed-in tariffs have resulted in successive years of strong renewable energy development[3]. Several other countries, as well as a few US states, are beginning to experience similar effects. The progressive model of the distribution system platform (DSP) proposed in these regions

[3] https://flowcharts.llnl.gov/content/assets/docs/2016_United-States_Energy.pdf

attempts to move the incumbent utility franchises away from their traditional middleman role of wholesale-buying and retail-selling of power, and into one of creating and maintaining a "distributed power trading network" with sufficient hosting capacity to allow for diverse and flexible grid edge participation. This is particularly in keeping with reducing the rejected energy component identified in Figure 1.

These seven market trends create the opportunity for a platform able to facilitate necessary exchanges of grid services between large numbers of interoperable (and largely low carbon) DERs made up of a variety of generating, storing, and load-balancing resources. Any such platform must also maintain or enhance grid reliability and availability, and incentivize active participation from members. Such a platform encourages the development of self-sufficient microgrid systems and is presently being pursued through intensive modeling and simulation studies within the US DOE National Labs as well and the US DOC NIST organizations.

Transactive energy modeling studies will soon give way to practical implementations that facilitate these decentralized balancing models. The transactive energy platform evolves distributed energy resource management (DERM) for the traditional electrical power grid supply chain; supplementing traditional direct control methods with increasingly indirect yet aligned market-driven transactions. The result is a modernized grid that uncovers potential services, value propositions, and an open path for collaboration and participation within the energy ecosystem.

1.5 A New Way Forward – Exergy

Individual transactions that are processed under the transactive energy paradigm may be viewed as compensated commodity products and grid service provision, or viewed more basically as an efficient balancing and clearing of rights and obligations for the underlying services. In our context of the energy markets, these typically fall under the following value domains, where purchases can be made in either spot (for immediate delivery) or futures markets. Transactive energy value domains include the following, in order of likely maturity for commercial development application:

Order	Transactive Energy Value Domain	Primary Time Domains[4]
1st	Energy Purchase (consumptive or persistent)	TD3, TD4
2nd	Grid Management Services (Capacity, Real Power, Reactive Power, Freq Regulation)	TD1, TD2
3rd	Energy Consumption and Demand Data	TD2 - TD4

Table 1 Transactive Energy Value Domains

Beyond existing wholesale markets, these value domains cannot easily be accessed by third party service providers, particularly at distribution network or local levels. The Exergy blockchain and token system overcomes this by creating a digital mechanism to access and synthesize the critical attributes from the transactive energy value domains, while establishing and maintaining a network participation authorization.

There are many use cases that LO3 Energy will undertake to create smart solutions that require capturing specific attributes of energy generation or load consumption of a transaction. These attributes can be dynamic and variable, and require a series of key data capture events and time stamp alignment for proper transaction clearing. For this we have developed a new token system.

The specifics of what the token system is and how it works are described in the accompanying Exergy Business Whitepaper, which elaborates on the design, creation, and interaction of these digital objects/entities and how they interact with the distributed ledger through self-executing smart contracts. But to proceed specifically with the technical application of the transactive energy paradigm, we refer to the Exergy token system to represent the full token system and mechanics that will enable the following capabilities:

- Provide a precise identification of the unique physical event that occurs with the creation, transmission, storage, or consumption of energy
- Incorporate a representation of the ownership right to the energy services associated with the event
- Ensure authenticity, validate formation, and facilitate privacy and security of transactions
- Allow for differentiation of generation type, location and other important characteristics

The Exergy token system will represent the means to facilitate value exchange transactions that grow in complexity from the First, Second, and ultimately through the Third transactive energy value domains identified in Table 1. Since the system works without a central repository or single administrator, the Exergy token system represents a means to achieve fully decentralized operation with peer-to-peer trading partners at the core of an expanding ecosystem that can gradually augment classic utility distribution system services as their business models evolve toward full DSP/DSO providers, or provide transactive capability in off grid situations where no alternatives exist.

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[5] Time Domains are further discussed in Section 2

2.0 Technical Attributes and Value of Transactive Energy

The concept introduced in the previous section envisions a dual-token system that captures the full potential of a transactive energy value exchange. The design of this system governs the exchange methods and processes for transactive energy at the grid edge. In this section we examine key time and value domain considerations, core data attributes needed within Exergy that are the basis of a transaction-enabling token system.

Subsequent sections explore specific use cases involving energy services within the broader framing of transactive energy that require incentivization made possible by the Exergy token system. Our goal in these two sections is to describe the specific energy services, and broader societal values, that can be realized by enabling broader participation in an accessible transactive energy platform. Our aim is to create a platform and development environment that invites project developers, utilities and software innovators such as LO3 Energy to collaborate and build solutions that continue to align and reinforce transactive energy value propositions.

As noted, the Exergy token system is used to facilitate transactions for a series of energy services that fall within multiple value domains—ranging from basic peer-to-peer local energy sales to connected microgrid reliability services. The value is created not only by generation and supply of energy, or demand for energy, but the time scale at which the energy supply and demand are made available. Depending on the specific service type, the formation and validation of data may be impacted by the time domain governing the practical application of blockchain technology for these services.

Exergy is designed to operate over the same physical parameters as the grid and at the speed needed for local settlement. The system incentivizes the permission to operate within the local instance (such as a microgrid) of an application, and organizes the devices to provide the right data and communications for transactions, and finally facilitates the settlement to the secure, immutable blockchain. The forthcoming Exergy Business Whitepaper will describe in detail how the tokens interact within the use cases.

After conveying the time scale concept, we will explore the specific attributes of energy transactions that will be digitized and embedded in Exergy for various use cases. The token approach should also enable the relatively easy assembly of multiple adjacent use cases to support evolution to a broader participative energy solution. That will be the focus of Section 3.

2.1 Grid Service Time Scales

The timing and latencies of the transactive message sequence play a critical role in determining which use cases can best be executed through a blockchain based solution. Figure 2 illustrates the approximate regions that are currently viable (using known communications network technology) for appropriate implementation based on the underlying grid services that are required in the specific use case.

The graphic below illustrates these grid service types, and breaks up the time domains into quadrants to better describe the relative applicability of public-blockchain based solutions within each. Notable observations include:

- The TD1 indicate grid frequency monitoring that occurs in thousandths of a second (millisecond). Currently this data is stored and used for later offline state analysis, or for device self-management, although the early use of this for real-time control in systems is beginning to appear. The application of public blockchain for this quadrant is highly unlikely due to the extreme latency and overhead issues.

- Moving to the TD2, where single or multiple seconds frame the duration, this begins to include the faster grid services that are utilized for control and balance of the electric distribution system. The application of blockchain within this time domain is challenging due to the latency and overhead issues, but this may be overcome through selective buffering and algorithmic data compression.

- Moving right to the TD3, where minutes or hours encompass the service duration, the application of Exergy to transact these services is ideal. This is squarely the domain of the energy services, although some of the longer duration grid services such as demand response or black start grid service restoration could be supported through a blockchain based solution.

- Moving to the TD4 time quadrant, these time domains encompass multiple days and reflect larger energy asset investment decisions. The solution could lend itself to transactive energy for forward market hedging and derivative products as well.
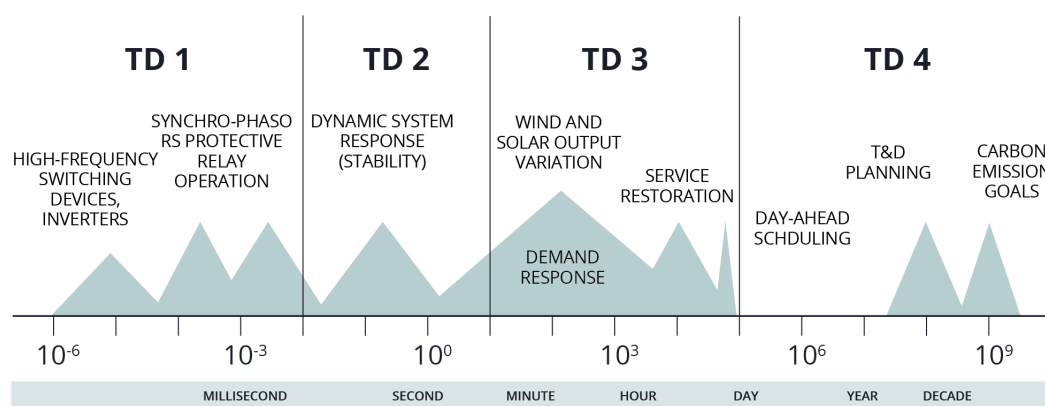

Figure 2 Timing Domain for Grid Services and Exergy Token Use Cases

For those applications where the time domain is appropriate, blockchain is well suited to energy transactions at the grid edge, which are too expensive for a central authority to settle at scale. It allows for simple services, such as where peers transact directly (where appropriate), to help mitigate utility overhead costs, and provides the ability to secure information shared between participants and verify or settle transactions autonomously.

The token system creates a market-based incentive for business processes to accelerate or automate, which generally drives toward the most efficient and scalable solution.

The Exergy blockchain is designed to operate over the same physical parameters as the grid and at the speed needed for local settlement.

2.2 Grid Service Value Elements and Attributes

Exergy incentivizes efficient supply/demand balancing medium for transactive energy exchanges between participating assets of the type shown in Figure 3. The Grid Modernization Laboratory Consortium (GMLC) initiative from the US DOE has grouped four broad categories of electric grid service types that can be derived from operation of these assets and that are needed to maintain efficient balance and operation of the evolving smart grid. Exergy provides the means for securing and digitizing all required value elements associated with DER for clearing the market for grid services in these category segments:

- Energy-related grid services (peak load management, energy cost, supply capacity)
- Regulation-related grid services (frequency regulation, spinning reserve, ramping)
- Distribution voltage management
- Artificial inertia grid services

These categories relate to broad areas of economic opportunity for a transactive energy system to expose qualified participating resources to market "offers" that can earn them compensation through subsequent value exchange. Historically, the data required by market participants has been very difficult to obtain (under the legacy non-participative utility energy business model), because information collected by utilities is typically limited to that needed by their proprietary and closed energy billing systems. Only recently has the Green Button Data[5] initiative in the US been developed as a voluntary national standard approach to giving utility consumers (or their authorized third party solution providers) access to their personal energy use data. But there is no global standard, and every country faces similar challenges with how to expose data for utilization by the industry without compromising privacy. Any more advanced information on other Area EPS system attributes (that could enable visibility to conditions establishing locational price signals) is collected through their proprietary operational systems and is not disclosed. The Exergy token system supports unlocking this data to promote responsive transactive energy service in these categories.

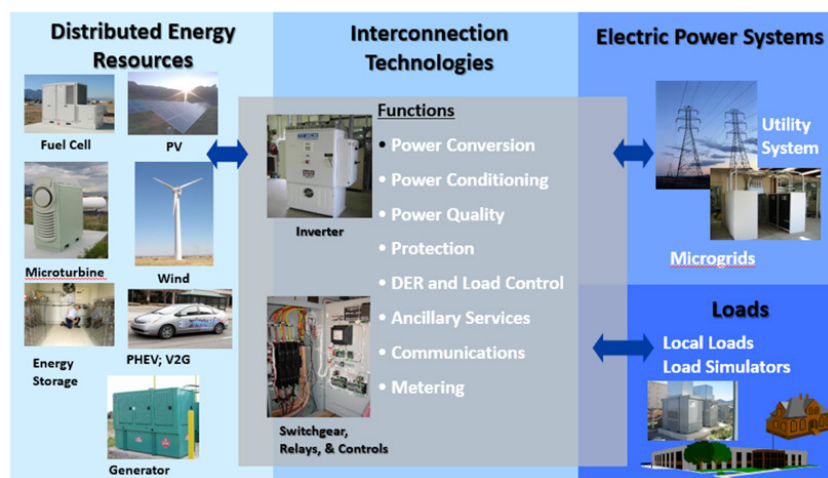## Distributed Energy Resources Interconnection

Figure 3 DER Asset types and Grid Integration

The attributes that are sampled and digitized within Exergy come from the types of distributed energy assets shown in Figure 3, as they exist and operate within a defined service territory. Note that while not listed directly under DER generation assets, the "Loads" class may be able to operate as a service agent when equipped with intelligent IoT based controllers. Collectively, these assets can be used to represent key capacities and state variables to establish effective pricing for transactive energy methods that trigger service delivery offers, and subsequently drive efficient transaction clearing.

[5] http://www.greenbuttondata.org/

2.2.1 Grid Connection State

Exergy will contain an indication (either direct or derived) of the state of distribution grid interconnection at the DER point of common coupling (PCC).

When allowed by the area electrical power system (EPS) to remain in ride through mode, operation in this range indicates a point of increased utility grid stress, and as such should increase the value of persistent DER services provided during this time. Note that for system voltage the permissible operating bands depend on the category of DER that is deployed. Figure 4a illustrates the bands for Category 1, which represents the most common (and therefore tightest) performance range in currently deployed DER. Increasing transactive value (designated by higher $$ value) is possible for assets that continue to support grid stability during periods of farther excursion from nominal system voltage. These services are elaborated in Section 3.2, Use Case 3: Microgrid.
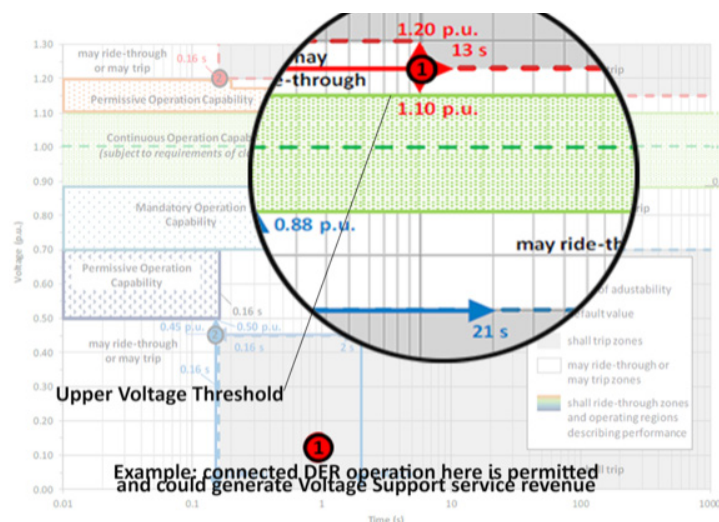

Figure 4a Voltage Ride Through

The ride through designation data field can be derived from either an instantaneous or an average EPS voltage measurement that indicates ranges above 1.1 or below 0.9 p.u. from sampling nominal system voltage, or in the future could be created directly from a DSO provided low-latency signal when monitoring at the PCC. System voltage as an Exergy input element is described further in Section 2.2.4.

Ride through requirements also apply to frequency ranges. Figure 4b illustrates the regions of operation for the mandatory and optional EPS abnormal frequency deviation ride through for the Category I, II, and III DER. More detail on these categories and how they relate to Exergy attributes can be found under Section 3.2 describing the Microgrid Services Use Case. System frequency as an Exergy token system input element is described further in Section 2.2.5.
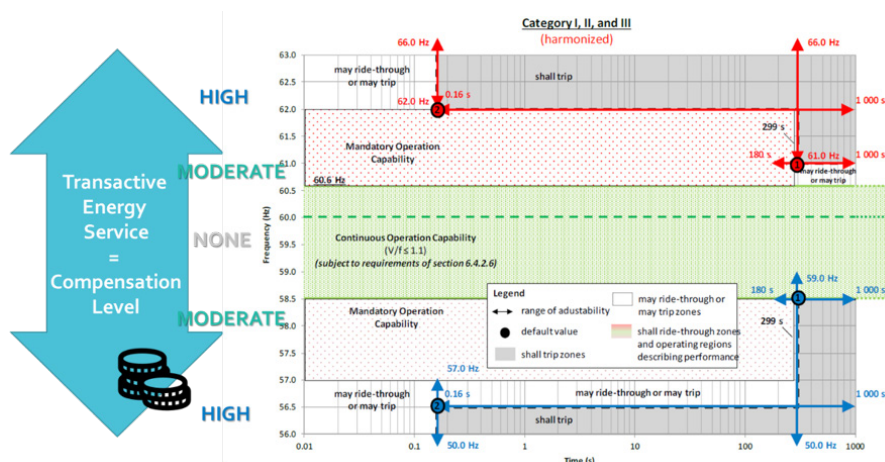

Figure 4b Frequency Ride Through

2.2.2 Generation Source Type

Exergy will capture and preserve a designation of the generation source type that creates the unit energy production designated in Section 2.2.6 while at zero carbon emission. If desired, Exergy shall allow for more discrete identification through optional sub classification of specific type characteristics of the ZCE generation.

	Primary Class Use EPA Classes- Carbon Intensity	Optional ZCE Subclass
Gen Source Type*	ZCE (zero carbon emission)	Wind, SolarPV, Hydro, Nuclear

Table 2 DER Environmental Attribute

This data comes from the nameplate configuration of the generation asset, and must be securely accessed and verified. The attribute can then also support transactive energy value capture for non-energy purposes such as renewable energy credits (RECs) or other recognized value streams.

Exergy will also capture and preserve a designation of the DER response classification of the generation assets associated with the unit energy production designated in Section 3.2. This is supported by the categorization scheme being introduced with the 2017 IEEE1547 DER interconnection standard. This permits the distinction of DER asset types specifically with regard to their capabilities for two very important transactive energy grid support service types: distribution system voltage and abnormal condition ride through. By capturing the appropriate designation, the Exergy token system can become an instrument for monetized grid service that properly values the contribution of the DER as a grid stabilization service resource. The following table summarizes this classification scheme.

	Category	Characteristics
Distribution System Voltage (V, Vr)	A	Typical DER capabilities
	B	Better response capabilities with supplemental control equipment, and required where there are high penetration of DER subject to high load variation.
Abnormal Condition Ride Through (V,F)	I	Typical generally available DER response capabilities
	II	Better response capabilities
	III	Advanced DER response capabilities ref CA Rule 21 smart inverters communications enabled functions

Table 3 DER Response Categories (per IEEE1547-2017 revised)

The IEEE 1547 standard also provides in its informational annex a categorization of representative (anticipated) specific generation types operating in specific end use profiles, through which these combinations are identified as requiring specific abnormal ride through category treatment. This may prove useful in the Exergy token system design for supporting transactive energy applications that require exposure to these characteristics.

| DER Type | DER Application Purpose | | | | | | |
	Retail Self Generation	Combined Heat and Power	Waste Fuel Recovery	Renewable Energy	Merchant Generation[1]	Critical Backup[2]	Peak Shaving
	A	B	C	D	E	F	G
1 Engine or turbine driven synchronous generator	Cat. I	Cat. I	Cat. I	Cat. I	Cat. I	Cat. I	Cat. I
2 Wind turbines (all types)	Cat. II	N/A	N/A	Cat. II	Cat. II	N/A	N/A
3 Inverters sourced by solar PV	Cat. II[3]	N/A	N/A	Cat. II[3]	Cat. II[3]	N/A	N/A
4 Inverters sourced by fuel cells	Cat. I	Cat. I	Cat. I	Cat. I	Cat. II	Cat. I	N/A
5 Synchronous hydrogenerators	Cat. I	N/A	N/A	Cat. I	Cat. I	Cat. I	N/A
6 Other inverter applications	Cat. II	Cat. II	Cat. II	Cat. II	Cat. II	Cat. II	N/A
7 Inverters sourced by energy storage	Cat. II	N/A	N/A	N/A	Cat. II	Cat. II	Cat. II
8 Other synchronous generators	Cat. I	Cat. I	Cat I	Cat I	Cat. I	Cat. I	N/A
9 Other Induction generators	Cat. II	Cat. II	Cat. II	Cat. II	Cat. II	Cat. II	Cat. II

Table 4 Application Specific DER Response Categories (per IEEE1547-2017 revised)

2.2.3 Load Coupling Classification

The nature of the served load can be an important distinction to represent the value of optionality for the energy consumption. The primary differentiation should be whether the generated energy is immediately consumed for useful work (exergy expended) or stored for future work (exergy preserved).

A refined treatment of this attribute could allow for enablement of specific use profiles that permit exposure to specific transactive energy value streams within interoperability control protocols.

	Primary Class	Optional Load Coupling Subclass
Load Coupling Classification	Consumed, Stored	Consumed: Exergy Conversion Ratio Stored: EV, Battery, Flywheel, Pumped hydro, Thermal

Table 4a DER Load Coupling Characteristics (per IEEE1547-2017 revised)

An important aspect of this attribute is the flexibility that it can give in conjunction with other attributes. Distinguishing the coupled load type and binding it to an islanded grid connect state could allow for very specific treatment of served loads within a transactive energy framework. This distinction might allow Exergy to be used for determining priority and assigning value within an islanded microgrid. For example, valuing the charging of an electric vehicle more highly as an energy use than powering a resistive heating element. (See description for electric vehicles in Section 3.2 Use Case 2)

2.2.4 EPS Voltage

The voltage levels of the system are important as a proxy measure of system stability, and can work as value element in Exergy in conjunction within the classifications of Sections 2.2.1 and 2.2.2. These voltages can be measured at the PCC for both the generation and the load within the DER and can be compiled into Exergy as the verification of DER operation that falls within the distribution voltage support designation identified in the EV Managed Services and Microgrid use cases in Section 3.2. Deviations in EPS voltage can be corrected through compensated insertion or absorption of active power (kVA) or reactive power (kVAr) by any of the properly valued DER assets that are staked with the XRG token and are delivering services under transactive energy value domain #2.

Measurement and encapsulation of this attribute within the token system also permits valuable system state data to be preserved for development of future transactive energy market pricing models and subsequent derivative contracts that may support the transactive energy value domain #3.

Voltage support services are typical of the services found in time domain TD2 and TD3 from the previous discussion in Section 2.1.

2.2.5 EPS Inertia

Variations in EPS inertia will show up in changes to the phase angle or system frequency that can be corrected by the insertion or absorption of kVA (real power) or kVAr (reactive power) in accordance with the category I, II, or III voltage and frequency ride through characteristics identified in Figure 4a and 4b. This requires relatively fast reaction capability with minimal latency from either the network monitoring and control data channels or the inertial physics of the electrical response.

Phase angle and frequency may be measured with fairly high precision by the phasor measurement unit (PMU). These devices are typically deployed within high voltage transmission lines, but are becoming more decentralized and are beginning to appear at EPS substation relays as IoT advances enable low cost sensor deployment closer to the grid edge.

Frequency support service is typical of the services found in time domain TD1 and TD2 from the previous discussion in Section 2.1.

2.2.6 Energy Production

The traditional unit of billable electric power over time (generally expressed in kWh) represents the core value element that literally "creates" the commodity to be traded within the transactive energy system. When this traditional energy unit is digitized in conjunction with other attributes the opportunity is opened up for more refined and efficient applications.

The rapid advancement in IoT technologies and high speed telecommunication networks is leading to the acceleration of smart meter platforms. Incorporating smart meter data into blockchain-enabled tokens allows this core value element to signify intelligent and rational transactions. The token system built around this attribute supports the efficient supply and demand balancing for this commodity by reflecting attributes such as the state of the electric grid, nature of the generation and load, and a measure of efficiency (or proximity) that reflects any losses or congestion in the system.

2.2.7 Location Proximity

The geospatial location of both the generation source and the coupled load, along with characteristics of the circuit path, play an important role in the determining of relative value for transactive energy. The existing wholesale market structures will create a locational marginal pricing (LMP) for the energy that varies over time based on aggregate supply and demand.

A distribution (D) component that is added to this will create a pricing difference function applied to the LMP that reflects the congestion level at the last segment of circuits that serve the end loads. More than any other indication, this component will serve as both a short term (request for services) and long term (build new capacity) market signal to drive the incremental participation of the DER technologies.

3.0 Energy Services and Transactive Energy Use Cases

3.1 Market Segmentation

The Exergy token system is a more efficient implementation mechanism for many use cases within currently functioning electric power ecosystems. Additionally, a very important differentiator of the token system is to more easily allow integration of multiple use cases into a broader network utility solution.

The use cases here represent the more common services that are currently used across the span of the legacy electric power system. In Figure 5, typical uses are individually characterized and presented along two dimensions: complexity or difficulty involved in using public blockchain-based transactive energy methods, and relevance to practical industry needs (in terms of performance effect). Overlaying this classification scheme is a grouping by industry application segment, which is indicated through color coding.
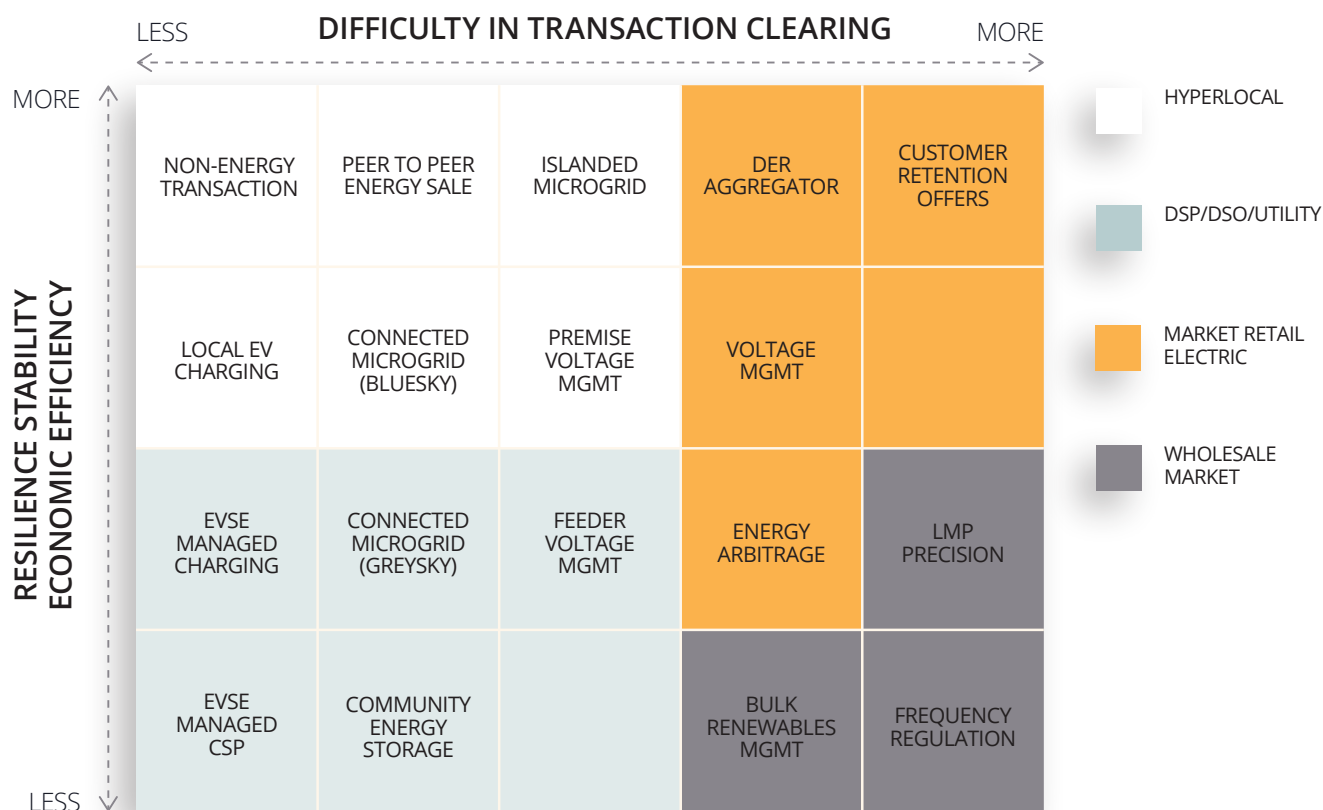

DIFFICULTY IN TRANSACTION CLEARING

LESS ← → MORE

RESILIENCE STABILITY ECONOMIC EFFICIENCY (MORE ↑ / LESS ↓)

NON-ENERGY TRANSACTION	PEER TO PEER ENERGY SALE	ISLANDED MICROGRID	DER AGGREGATOR	CUSTOMER RETENTION OFFERS
LOCAL EV CHARGING	CONNECTED MICROGRID (BLUESKY)	PREMISE VOLTAGE MGMT	VOLTAGE MGMT	
EVSE MANAGED CHARGING	CONNECTED MICROGRID (GREYSKY)	FEEDER VOLTAGE MGMT	ENERGY ARBITRAGE	LMP PRECISION
EVSE MANAGED CSP	COMMUNITY ENERGY STORAGE		BULK RENEWABLES MGMT	FREQUENCY REGULATION

Legend:
- HYPERLOCAL
- DSP/DSO/UTILITY
- MARKET RETAIL ELECTRIC
- WHOLESALE MARKET

Figure 5 Representative Energy System Use Cases

Short descriptions of these industry application segments are provided below in preparation for the specific discussion of use case implementation. Enabling these Use Cases through a token system allows solution evolution spanning several industry segments—leading to a more tightly integrated overall electric power system that increasingly operates through participative and market-driven mechanisms.

3.1.1 Hyper Local

This group of token-enabled use cases permits energy production and consumption services at the very edge of the electric grid. These services yield both environmental and efficiency benefits, and support local community resilience.

The group of four hyper local use cases identified here are; non-energy trading, peer to peer energy, EVSE peer sharing, and islanded campus microgrid.

3.1.2 DSP/DSO/Utility

This is the segment of the electric power market that is the slowest to adopt new competitive business models, as most of these entities operate under monopoly franchise regulation and are incentivized to keep reliability their primary goal. Increasing amounts of connected DER at the edge of the grid however now require these grid operators to obtain more precise grid state data monitoring, and the variability of this DER drives a growing need for distributed grid operations services. Traditional control systems used by these operators do not scale and are not economically viable, opening up the potential for increasingly transactive means of using the local energy assets for that purpose.

Common use cases identified as generally residing in this segment are; Voltage Management, Community Energy storage, EVSE managed charging, connected community microgrid.

3.1.3 Retail Electric Market

Unlike the distribution services provided by entities listed in section 3.2, the retail electric commodity supply chain is undergoing a more recent transformation to the competitive market. Not all countries and states have yet moved to this model, but where these retail energy providers are allowed to serve customers (through the legacy utility DSO wires), there is an opening for differentiating by energy provenance. The use cases discussed in Section 3.2 are typical for serving customer needs in this segment, although use of blockchain solutions generally drives higher complexity because of the multipartite relationships. One potential advantage for these participants may be easier customer acquisition and onboarding.

3.1.4 Wholesale Market

The competitive electric power wholesale market concept was created in the US during the 1990s under a period of deregulation of the generation markets. By pooling multiple bidding generator outputs into a competitive wholesale market, and coordinating that generation with aggregate load across specific regions through central balancing authorities, this competitive process incentivized investment and innovation to lower energy cost and encourage clean power production.

A First Example: The Brooklyn Microgrid

LO3 Energy has developed a blockchain-based energy platform that is already running the hyper-local Brooklyn Microgrid. Blockchain technology allows devices at grid edge to securely and directly transact for PV-generated energy sale among microgrid participants. The Exergy token system will more efficiently implement this use case, and will also allow for expansion to adjacent use cases as the Brooklyn Microgrid evolves into a broader and more integrated DER solution. A goal of the token approach is to enable a common extensible platform that can facilitate valuable network utility from diverse but synergistic use cases, opening paths for effective community participation. The section below illustrates this evolution concept as envisioned for the BMG. Each referenced use case is then examined in more detail within the next section.

Peer-to-Peer Energy Sales: The Base Case
Today, prosumers and user's energy interactions are tracked and recorded on the blockchain. Soon, users will be able to set preferences via a mobile app or web interface, enabling customer devices and local grid systems to transact this energy exchange in near real-time, through self-executing contracts that seamlessly blend local energy with grid supplied energy.

Tracking Non-Energy Value Exchanges: Recognizing More Value
Non-energy value can also be held by the blockchain for the purpose of transacting, for instance, Renewable Energy Credits (RECs). Neighbors may value solar-over gas-generated power, or even their relative's energy over a traditional utility central generator utilizing fossil or nuclear. The value of environmental attributes like these will be different in communities all over the world, but the Exergy token structure allows for these differences to remain localized and also to change at the pace of regulatory reform that will expose market incentives to shape transaction behavior.

Electric Vehicles: Igniting a Change in Vehicle Power

EVSE Peer-Sharing

Electric vehicles are poised to rapidly create capacity challenges, exacerbate peak, or cause outages if not managed effectively. Smart charging begins to tackle this. Utilized in conjunction with the Exergy system, the connected EV can be intelligently and flexibly charged through local peer sharing/coordination services enabled by the blockchain. This represents a relatively low-complexity adjacent use case that could be adopted into the BMG solution to increase network utility by attracting EV drivers to connect their "assets" to the microgrid.

Managed EV Charging

Beyond that simple use of allowing peer-to-peer asset sharing, clusters of EVs managed through Exergy can collectively deliver valuable load management services that may be monetized. Managed charging, i.e. battery power transfer rate modulation in response to pricing or control signals, offers a powerful and economic means for absorbing excess renewable or base load generation and time-shifting its consumption. Eventually with flexibility advances anticipated from autonomous vehicle adoption, the ability for EV participation in grid services will only increase and the token system will be pivotal to capturing and compensating the true value of these aggregated and responsive mobile energy storage assets.

Microgrid Services: Plug Out, Power On
As Exergy becomes a platform for digital representation of the essential DER attributes (ownership, performance and participation), it is possible to aggregate and manage these resources into a useful application for the microgrid operators, whether those microgrids are connected to (paralleled) or are separated from (islanded) the areas electric power system. (See Section 2.2 for DER services)

For the most part, the control systems supporting this process have evolved within the transmission and generation community to utilize industry standard monitoring and data systems that are built with robust reliability and security safeguards, along with specialized equipment to facilitate fast frequency response. Although transactive energy methods are being evaluated for clearing large wholesale energy exchange, moving this segment of the industry to token-based solutions that incorporate more local energy segments would be highly complex and offer less added value at this time.

There are currently several practical limitations and barriers to achieving the design and use of a token-based transactive energy platform:

- System control vs transactional exchange – The time domains required to utilize transactive energy for system control applications are typically too short to utilize blockchain effectively. (Exchange of energy in relatively large blocks can be accomplished because there is sufficient time to buffer and process.)
- Lack of standardized interoperability protocols
- Rigidity of jurisdictional regulation (siloed technology)

These topics will be covered in subsequent papers that elaborate on the token system architecture and business and regulatory aspects of implementing that system for use cases.

3.2 Use Case Profiles

The individual use cases described in the evolution of the Brooklyn Microgrid are explained in more detail within this section describing the specific attributes needed for each. We also highlight how a common token system facilitates adjacent use cases that ultimately link different segments of the broader energy ecosystem.

Use Case 1 - Local Energy Sale

The current method utilized for this service is a blockchain implementation using specific hardware (known as TAG meters). This method permits the designation of certain kWh units of locally produced energy to be "tagged" and offered for consumption by adjacent local participants using the same component. The transaction is "cleared" within this closed system between the meters through machine-to-machine management of distributed ledger entries.

Adding the token function to this system will incentivize the capture of unique attributes (such as the source of the energy) that may reflect and respond to important pricing influence for the local energy network operation. It allows third parties to participate in managing aggregation of energy consumers and exposes data to dynamic market pricing, creating the ability to better reflect the true costs and benefits of locally produced energy. The two key attributes needed for the effective implementation of the local energy transaction are identification of generation source (i.e., clean renewable generation) and the unit of energy created for consumption, as illustrated in Figure 6a.
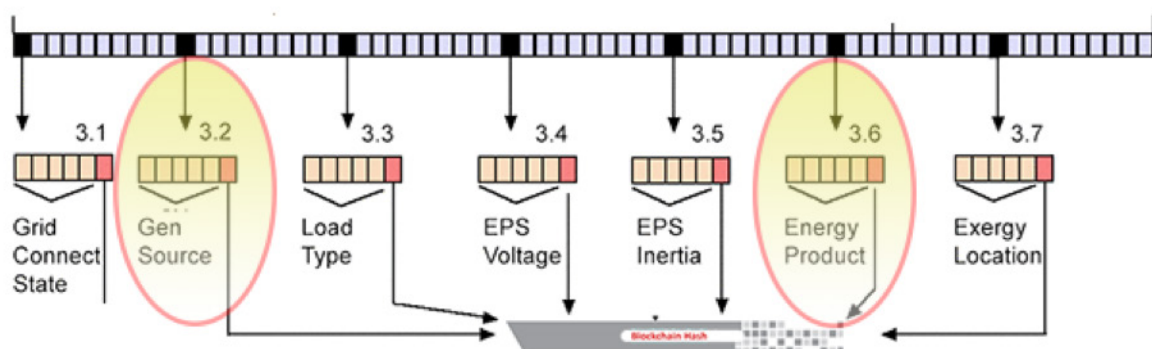

Figure 6a Digitalization of the Energy Attributes for Local Energy Services

Generation Source Type (ref Sect 2.2.2)

The token system captures and preserves a designation of the generation source type that creates the unit energy production designated in Section 3.2 while at zero carbon emission. If desired, the token could allow for more discrete identification through optional sub classification of specific type characteristics of the ZCE generation. This may allow later coupling of the solution into the wholesale generation markets segment illustrated in Figure 5.

	Primary Class Use EPA Classes – Carbon Intensity	Optional ZCE Subclass
Generation Source Type*	ZCE (zero carbon emission)	Wind, SolarPV, Hydro, Nuclear

Table 5 Source Generation Source Classification

The token system will also capture and preserve a designation of the DER response classification of the generation assets associated with the unit energy production designated in Section 2.2.6. This is supported by the categorization scheme being introduced with the 2017 IEEE1547 DER interconnection standard. This permits the distinction of DER asset types specifically with regard to their capabilities for two very important transactive energy grid support service types: distribution system voltage and abnormal condition ride through. By capturing the appropriate designation, the token system can become an instrument for monetized grid service that properly values the contribution of the DER as a grid stabilization service resource. These advanced grid services will be described further in the Microgrid Use Case #3 section below.

Energy Production (ref Sect 2.2.6)

The traditional unit of billable electric power over time (generally expressed in kWh) represents the core value element that literally "creates" the commodity to be traded within the transactive energy system. The token system can represent the embodiment of the efficient supply/demand balancing medium for this core energy commodity by allowing for later inclusion of the (approximate) losses that are encountered between the generation point of origin and the eventual consumption.

The granularity (or frequency) of the metering and encoding of energy is directly related to the time domain aspects described in Section 2.0. At a minimum, the energy commodity purchase can be cleared in blocks of 5, 15, or 60 minutes as the current wholesale market operates. If this sampling is performed fast enough however, certain advanced grid service transactions which rely on dynamically varying the power flow can also be enabled through the same token system.

Use Case 2 - EV/EVSE Services

The use case(s) for token-based electric vehicle services starts with the efficient location of, and access to, charging stations that can deliver the locally produced energy into the onboard energy storage system (aka EV battery) at optimized power transfer rates. This allows for a natural evolution from use case 1 of a community energy system operating on the token to grow its functionality and efficiencies into the transportation function within the hyper local domain. Note that this energy storage element could also be a stationary battery of equal size that is collocated with the renewable generation as well. These types of integrated solutions are rapidly gaining market penetration.

In a more advanced application of this use case, which both enhances and expands beyond the local energy microgrid, the token-enabled EV charging network supports a proactively aggregated and managed charging service that can take advantage of the inherent flexibility of the EV load profile. When many electric vehicles can be pooled, and their owners have a means of transacting on the flexibility of their load profile, an important value thread can be exposed in the form of grid services to the balancing authority. This offers a natural bridge of the token-based solution into adjacent use cases that reside in the DSO/DSP segment shown in Figure 5. The full evolution in this use case leads inevitably to bidirectional power flow for full V2G operation, and could therefore ultimately connect common transactive energy value streams with energy retail and wholesale segments. The engagement of many non-traditional participants into the token system value chain is also likely. Examples of this are vehicle OEMs and dealers as well as commercial fleet managers.

The traditional utilities found in the DSP/DSO segment are all actively seeking mechanisms to expand their rate-based support of an intelligent EV charging infrastructure; the token system offers a potential path for these utilities to incorporate a customer service that supports this use case and also base their stake in a value chain tied to that investment.

Continue...

In addition to energy metering, the two additional attributes needed for the effective implementation of EV recharging transactions are identification of Load Type (i.e. specifically energy storage) and the location where the battery charge consumption (and ultimately reverse flow energy discharge) takes place.
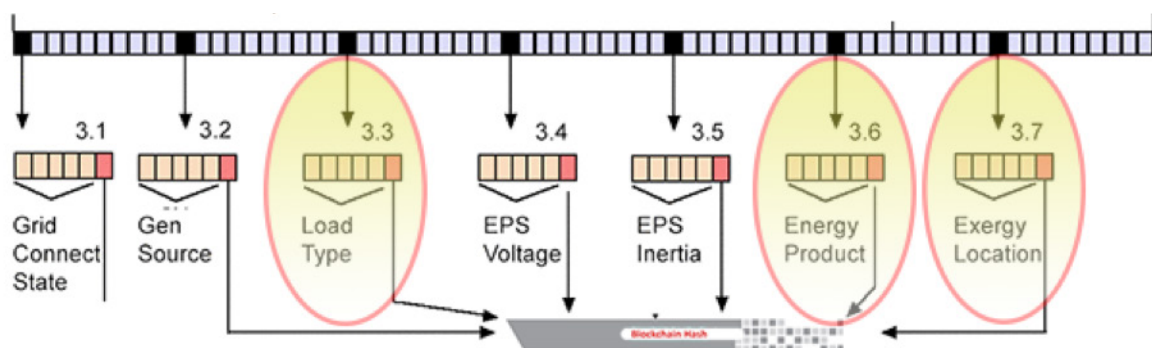

Figure 6b Digitalization of the Energy Attributes for Electric Vehicle Services

Load Coupling Classification (ref Sect 2.2.3)

The nature of the served load can be an important distinction for the token to represent the value of optionality for the energy consumption. The primary differentiation should be whether the generated energy is immediately consumed for useful work (exergy expended) or stored for future work (exergy preserved). The EV itself might self-identify as an electric transportation asset, which can allow unique participation options within a transactive energy framework.

A refined treatment of this attribute could allow for identification of other use profiles that permit exposure of the EV to specific transactive energy value streams and utilization of the token system within specific interoperability control protocols that are fast emerging, such as the IEEE 2030.5 smart energy profile or the open ADR transactive energy profile.

	Primary Class	Optional Load Coupling Subclass Type Detail
Load Coupling Classification	Consumed, Stored	Consumed: Exergy Conversion Ratio Stored: EV, Battery, Flywheel, Pumped hydro, Thermal

Table 4b Load Coupling Attributes

Distinguishing the coupled load type allows for very specific treatment of served loads within a transactive energy framework. This distinction can allow the token system to be used for prioritizing mission criticality of the connected EV within an islanded microgrid. For example, the charging of an electric vehicle can be valued more highly as a deferred energy use over the immediate powering a consumptive heating element. From a grid balancing perspective, the coordination of power flow to EV batteries may help address the conundrum of the "duck curve"[7] in areas where solar PV generation is driving narrow windows of supply over capacity. These are all services that can be tokenized and therefore monetized.

Location Proximity (ref Sect 2.2.7)

The geospatial location of the EV is important for the involvement of this storage asset within the transactive energy network. Existing wholesale market structures create a locational marginal pricing (LMP)[8] for the energy that varies over time based on aggregate supply and demand balance, while the distribution (D) component that is added to this will create a pricing difference function applied to the LMP that reflects the

congestion level at the last segment of circuits that serve the end loads. In other words, the time that energy is consumed and where it is generated or used becomes as valuable as kWh, and likely will increase in importance the more both supply from renewables and demand from loads like EVs increase. The LMP pricing model to manage intermittent, multi-party energy markets will also need to evolve.

More than any other indication, this component will serve as both a short term (request for services) and long term (build new capacity) market signal to drive the incremental participation of the electric vehicle. The blockchain-based token system will ensure that these signals are efficiently created, communicated, and consumed (responded to).

When the full pricing signal reflecting true locational marginal costs can be delivered to the smart charging system, automated decisions can be made to delay or accelerate recharging to optimize the energy transaction based on individual needs and functional price fluctuation. As the auto industry begins to deploy autonomous vehicle platforms, a discretionary location dynamic will become possible that could group low utilization EV assets to connect their batteries for grid services in more impactful locations.

There are three general categories of services that are of value to (or from) electric vehicles that could be exchanged in the transactive energy model. These are defined by the perspectives of two interest, or stakeholder classes, 1) the vehicle owner (or, in the future case of autonomous vehicle ridesharing operations, the fleet owner) and 2) the electric power delivery system operator. We've generalized these service categories and stakeholder perspectives as follows:

- Vehicle charging – of value to the EV owner to the extent that mandatory minimum drive range is delivered exactly as expected. There is generally no preference on energy source or power flow as long as the above condition is met. This basic energy transaction falls into the time domains that are easily handled through blockchain.

- Timed charging – this is the simplest of the smart charging paradigms. If grid capacity (or a certain renewable supply mix) is available, charge at the maximum power draw. This has value to both stakeholder classes in the sense that feedback from the grid can facilitate appropriate draw on grid capacity in order to supply sufficient electricity to properly recharge the vehicle. It also may involve some additional complexity in managing through blockchain(s).

- Demand charging – this is a sophistication of timed charging that considers the draw on the local grid from multiple vehicle charging demands, which would include the pace of charging required to meet consumer expectations for range availability in time for next vehicle use. Demand charging would include timing of charging use and the rate of charging—the amount of total charging demand in kW compared to the maximum possible charging demand. For example, an electric vehicle departing at 6 a.m. and needing two hours and 50 miles of travel might only need to draw 5kW starting at 3 p.m. in order to meet driving demand, while a vehicle expected to need 5 hours of travel and 200 miles, would need to draw 16 kW starting at 1 a.m.

- FUTURE bidirectional power flow. An advanced—not currently available—electric vehicle service in support of the grid will include discharging the vehicle battery in support of the societal needs related to electric grid services. When this is performed primarily as a resilient energy sourcing (i.e., powering a facility during grid outage), the blockchain-based token system can support the associated transactions. If this function serves to coordinate voltage or frequency regulation then the faster time domain requirement may pose a challenge to delivering these services on a public blockchain.

Use Case 3 - Microgrid

The use case(s) for a connected DER microgrid open important value streams through transactive energy services. This allows for a natural evolution from use case 1 (a community energy system that is simply creating and selling local energy or RECs) into leveraging the functional utility of the underlying DER assets to respond to large commercial building campus or broader distribution grid balancing needs. The DER microgrid can exist in one of two discrete states: grid connected (or paralleled), or grid-disconnected (islanded).

The simplest implementation of this use case through blockchain is, paradoxically, the more complicated "grid connected" mode of microgrid operation. This is because the overall inertia of the larger area electric power system (EPS) allows for longer response times (moving into quadrant 2 from the "Time Domain" graphic) where the token can then utilize buffering techniques for the faster services. The islanded microgrid (Local EPS) has far less inertia to rely on during self-balancing and thus requires much faster control feedback loops—better solved through more direct and dedicated control systems that are part of the microcontroller (and therefore not the "transactive energy" driven control).

Microgrids, minigrids, and other configurations that fall outside the traditional grid, such as off-grid community installations starting from point solar solutions, are not an insignificant portion of tomorrow's energy markets. New microgrid investment is expected to reach 23bn by 2021 by some estimates[9]. In emerging or developing markets where grid infrastructure is not sufficient to connect large scale renewables, microgrids are a viable short term alternative solution[10].

Two additional attributes needed for the token system to effectively engage microgrids into transactive grid service opportunities are grid connection state and the area EPS voltage and inertia states in order to properly characterize the area EPS state (level of instability) at the time of the DER service provision. This is fundamental to properly valuing and compensating the assets.
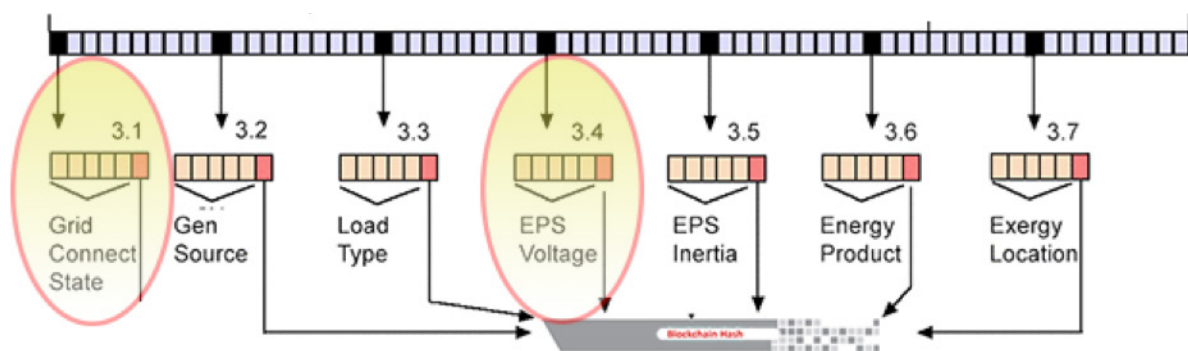

Figure 6c Digitalization of the Energy Attributes for Connected Microgrid Services

Grid Connection State (ref Sect 2.2.1)

Three mutually exclusive and discrete states are possible, and the state data will be captured from an IEEE1547-compliant inverter either locally from on-board data registers or remotely through its communication channel. These states are listed below in order from lowest to highest expected commercial value for the transactive energy participants. Note that although all of these states will support preferential peer-to-peer exchange based on those anticipated higher exergy values, only the second state will exclusively require that mode of operation. It is anticipated that the first state will generally bias toward preferential transaction from this mode, where the third state will likely bias toward preferential grid service transactions.

- Parallel operation (steady state connected)
- Islanded operation (steady state disconnected)
- Ride through (temporary state, permissible region connected)

EPS Voltage (ref Sect 2.2.4)

The voltage levels of the system are important as a proxy measure of system stability, and can serve as a value element in the token system in conjunction with the other measured attributes. These voltages can be measured at the PCC and both the generation and the load within the DER, and can be compiled into the token system as the verification of DER operation that falls within the category A or B distribution voltage support designation identified in section 2.2. deviations in EPS voltage can be corrected through financially compensated insertion or absorption of active power (kVA) or reactive power (kVAr) by the properly valued DER assets.

Measurement and encapsulation of this attribute within the token system also permits valuable system state data to be preserved for development of future transactive energy market pricing models and subsequent derivative contracts, and begins to open up the currently opaque grid data that is inhibiting the innovation and efficiency gains offered by transactive energy solutions.

EPS Inertia (ref Sect 2.2.5)

Variations in EPS inertia will show up in changes to the phase angle or system frequency that can be corrected by the insertion or absorption of kVA (real power) or kVAr (reactive power) in accordance with the category I, II, or III voltage and frequency ride through characteristics identified in section 3.1. This requires relatively fast reaction capability with minimal latency from either the network monitoring and control data channels or the inertial physics of the electrical response.

Phase angle and frequency may be measured with fairly high precision by the phasor measurement unit (PMU). These devices were typically deployed within high voltage transmission lines but are becoming more decentralized and are beginning to appear at EPS substation relays.

How a Token Driven Connected Microgrid Operates

Microgrids that are designed to be flexibly operated in parallel with the area EPS are becoming commercially feasible with advancement in the fields of smart inverters, IoT, advanced communication networks and protocols, high power solid state switching electronics, and related control system technologies. Design methodologies such as the DOE Sandia Labs' Energy Surety MicrogridTM (ESM) approach are developing blueprints for implementing these flexible distributed energy resources for delivering various combinations of local and area EPS grid services. The US DOE is also advancing significant work on grid modernization under their DSPx program (distribution system platforms – Next Gen) where DER incorporated into microgrid configuration can interoperate and participate seamlessly with the connected area EPS. Various depictions of configurations for the connected DER are shown in Figure 6c.

Potential Benefits

- Preferential NORMAL (blue sky) dispatch of highest value (most efficient, cleanest) generation
- Low disruption transition services between Islanded and connected states
- Enables a connected DER in RIDE THROUGH (grey sky) to be fairly compensated for delivering valuable grid services from the classes shown below.

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[11] Africa's Largest Wind Plant Could Relocate from Kenya to Tanzania http://allafrica.com/stories/201710160847.html?aa_source=nwsltr-kenya-en

Grid Service Class

- Distribution voltage management
- Artificial inertia grid services
- Regulation-related grid services (frequency regulation, spinning reserve, ramping)
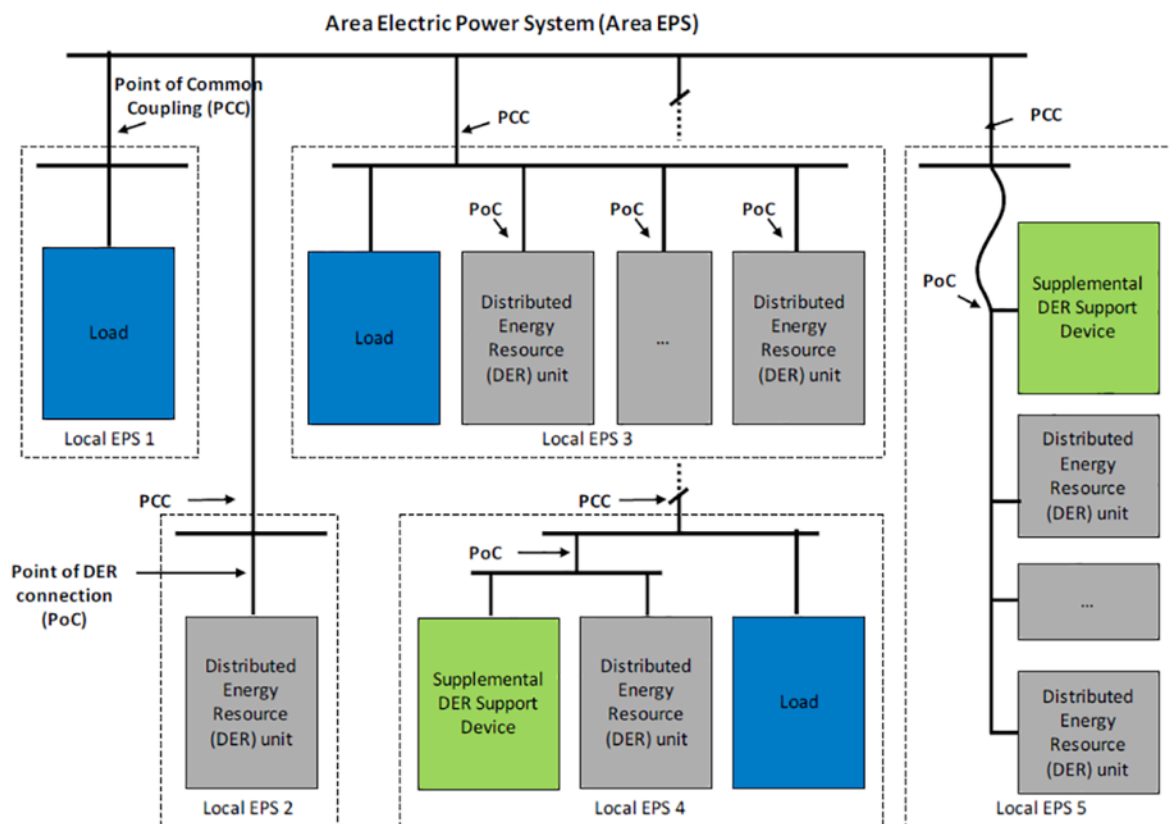

Figure 7 DER/Microgrid Interconnection (per IEEE1547-2017 revised)

A local EPS microgrid that is connected at its PCC and is operating in parallel with the area EPS can serve as a valuable resource if the local generation and/or intelligent load response DER can automatically respond to periods of area EPS instability where voltages or frequency are beyond normal operating bands (see Figures 4a and 4b). These unstable conditions are increasingly likely as penetration levels of variable generation rise along individual distribution grid feeder circuits. This application is specifically being enabled by the rapid advancement of IoT sensor and actuator technology coupled with low latency communication networks, where balancing can increasingly be automated at the grid edge through hosting capacity services that begin to extend and evolve some wholesale ISO/RTO control models down to the retail DSO level.

Having these services implemented through transactive energy methods using the token system will open the market for a far more decentralized grid. The major beneficiaries of this will be the resilient communities that invest in their hyper local energy ecosystem while also preserving options for flexibly supporting the electric distribution system operator (DSO) that needs to add circuit specific balancing tools within their franchise, and seeks to drive their business model toward demonstrating increasing hosting capacity for DER on their distribution system. This may also open up the opportunity for demonstration of innovative new utility business models where shared risk and return can help break down current regulatory barriers to more efficient solutions.

Exergy plays dual roles for the connected microgrid—one for blue sky operation, and a second for distressed

grid state that may result from large fluctuations in circuit branch DER output, which could result in extended periods of ride through connection—not quite tripping the microgrid, and enabling persistently connected DER assets (see Figure 5) to help stabilize and restore the area EPS. This use also supports seamless power circuit switching for the transition between these two states, using the token to enable the dynamic state transition as well as for the relevant grid service transactions required within each relatively steady state.

Normal Operation (Blue Sky)

Because operating in this mode is a typical steady state, the normal operating priority can encourage local generation to serve local load based on the most economic transaction point when all losses are considered along with other non-energy provenance attributes. The properties of location proximity and energy production will supply signals that reflect efficient energy purchase and distribution locally, and can be rudimentarily accomplished despite metering and franchise barriers as a means to inform and enable regulatory reforms that could make this a more mainstream solution. The connected DSO/DSP utility along with the retail energy provider will likely move to a standby tariff structure that could be implemented through the blockchain which will allow service billing based on the readiness of the area EPS to cover local generation deficits. Furthermore, a quality of service dimension could be enabled through the token system which permits competitive differentiation by participants in these provider segments. These topics will receive additional elaboration in the upcoming Business and Regulatory Whitepapers.

Ride Through Operation (Grey Sky)

Recall that Exergy attributes support the distinction of grid connection state, generation type, and load coupling. These features may be used within a microcontroller system to identify and quantify the relative value of the generation supply along with that of flexibility of the load to achieve a transactive "clearing" function and ensure that the distressed EPS can call on the connected microgrid for support. If the economic advantage of these services exceeds the opportunity cost of degraded microgrid self-service, transactive energy services can proceed. In addition, the demonstration can seek to show how the token system can enable graceful separation of the microgrid into or out of an islanded state as a form of certified transaction.

As identified within Sections 3.1 and 3.2 and graphically depicted in Figure 4a and 4b, the revised IEEE1547 DER interconnection standard designates regions of permissible operation of the DER assets relative to allowable voltage and frequency deviations within the hosting Area EPS. Operation of the DER within these permissible regions allows a preserved grid connection to potentially serve as the conduit for providing any of the identified grid service classes previously identified. Although this operating mode requires tighter coordination with the DSO/DSP segment, it remains within the technical feasibility of a token solution that can unlock the data needed for creating market signals that will solicit the response of the DER for required balancing and reliability services.

These flexible states of the area EPS-connected microgrid play an important role in moving this transactive energy application into the mainstream. It is envisioned that with the advent of technologies such as SiC high power switching and ubiquitous IoT, the connected microgrid can become an extremely valuable and responsive EPS asset.

While we do not delve here into each use case represented in Figure 7, these will be added in further revisions.

4.0 Conclusion

Global aspirations of societies today are to create energy resiliency, security, access, decarbonization and democratization at lowest cost. The trends toward renewable variable generation and increased electrification to provide for global energy needs also increases complexity within the centralized grid architecture and market arrangements, and the disruption coming to this industry is not in doubt.

As these global aspirations are born out at local level, a number of transition issues arise: who pays for the electricity grid as those who can invest in renewables become more self-reliant? How do we avoid outages as we plug in distributed loads such as EVs? How can we most rapidly provide energy access to millions in rural, urban or natural disaster areas without waiting for a centralized grid? How do we ensure renewables are not inadvertently increasing carbon emissions because intermittency requires fossil fuel backup under today's market designs?

A more efficient, resilient, and participative electric power ecosystem has never been more needed as our world transitions into a more dynamic and uncertain political, technological and environmental era dealing with transition to a low carbon and highly automated future. Nor has this type of ecosystem ever been more possible than now, with the rapid advances in affordable DER, edge and cloud computing power, high speed telecom network, IoT, AI, and blockchain. The work ahead lies in creating a decentralized, efficient way to manage new prosumers and billions of devices coming to electric power ecosystems.

The concept described here is the first step for transactive energy application development, highlighting the attributes, their value to the electric power system, and the ways that they can be combined in specific use cases to facilitate the optimal coupling of local electric generation to parties that can value, procure, store and utilize this generation most efficiently. The resulting transactions will clear within a participative market-driven environment operating as close to the grid edge as possible, with an increasing level of automation by using self-executing contracts on a distributed ledger. The attributes include information on the load type and proximity as well, and may support service agents drawing from intelligent IoT based controllers that can begin to expose and incorporate the full value streams of smart load management from facility EMS and EV charging. Collectively, these participating assets can be used to represent key capacities and state variables to establish effective pricing for transactive energy methods that trigger service delivery offers, and subsequently drive efficient transaction clearing.

The concepts described in this paper are intended to frame the potential application of an energy services token system to enable a more participative energy paradigm. How the token system allows consumers, industry players and new market entrants to access and "stack" the value domains outlined in this paper is described in detail in the Business Whitepaper.

We are just beginning to see the potential for consumers to optimize electricity systems and the economic utility of them. With Exergy, we create the path for participation to enable this new transactive energy marketplace.

Glossary

ACRONYM	TERM	MEANING/CONTEXT
DER	Distributed Energy Resource	Energy generation, storage, and even consumptive assets and systems that are located in close proximity to the grid edge.
DSO	Distribution System Operator	An entity responsible for developing, operating, and ensuring maintenance of power distribution systems.
A-EPS	Area Electric Power System	The traditional electricity distribution network that delivers (and bills for) electric power to a facility. Also known generally as "the utility".
L-EPS	Local Electric Power System	This is the increasingly common form of self-generation and load management that falls within a geographically coincident location. Also known generally as "the microgrid".
PCC	Point of Common Coupling	The specific electrical interconnection point that defines the boundary between the A-EPS and the L-EPS. This is where a "microgrid" is disconnected when necessary for complete local operation under utility service disruption (such as a storm)or as desired.
IoT	Internet of Things	Represents the growing capability of previously disconnected assets and systems to now have sampling and communication functionality that are useful for more efficient and balanced participation.