CONCEPT BRIEF

The Decentralized Autonomous Area Agent (D3A) Market Model

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A blockchain-based transactive energy implementation framework for the 21st century grid

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The D3A in Brief

- The legacy 20th-century model of centralized, topdown electricity grid dispatch needs to be rethought.
- Rather than "bolt-on" approaches for renewables and distributed energy resource grid integration, technological and other advances now make it possible to entirely rethink the way the grid operates, with energy and balancing built from the grid edge first.
- Operating under an evolving set of principles, a decentralized, recursive transactive energy market can achieve deep decarbonization, improve access to energy services for all customers, expand customer choice, and enhance grid resilience.
- Energy Web Foundation's dual-pronged approach of the Energy Web Blockchain and the Decentralized Autonomous Area Agent (D3A)—developed by EWF cofounder Grid Singularity—together offer a pathway for achieving this vision.
- The Energy Web Blockchain is an open-source network with unique governance, privacy, and scaling features tailored specifically for the energy sector.
- Blockchain's unique ability to manage immutable data, provide trustless consensus, and administer digital assets on a decentralized and cryptographically secure computing environment offers the potential to incorporate a dramatic increase in the number of controllable devices into electricity markets and enable customers to transact with each other directly.
- The D3A is a transactive market model that leverages smart contracts to perform control and financial settlement for energy resources of any size and type, nested and scaled up and down the electricity grid, from devices, to buildings, to neighborhoods and substations, to the bulk power grid.

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Today's electricity grid is immensely—and confoundingly—complex.

First, we extract fossilized biological remains and expend huge amounts of effort, capital, and energy to refine them into fuel. Then, we transport that fuel over vast distances and burn it, inefficiently, in massive, centralized facilities, to produce electricity. We then transport it again over those same vast distances across copper wires to billions of end points that act mostly independent of and oblivious to the greater system they occupy. And a fragmented web of rules and authorities at multiple levels regulate the entire process.

This works in practice, but it shouldn't work in theory.

The fact that electricity can be delivered at reasonable cost and reliability through this architecture is a testament to human ingenuity. But given today's regulatory objectives and commercially-available technologies, a new grid and market architecture is worth pursuing.

Emerging technologies like blockchain and artificial intelligence coupled with contemporary communication protocols and software are expanding the realm of possibilities. Combined, they offer an opportunity radically transform the grid, returning to locally based power production while supporting environmental goals, improving energy access, democratizing the electricity sector, and enhancing security.

Shifting Societal and Regulatory Objectives and Evolving Techno-economic Solutions Require a New Market Framework

The realities of today's electricity grid did not spontaneously appear—all of history is embedded in it. The grid is the sum product of myriad design decisions that were made sequentially over the course of decades. They were logical in the context of the available technologies and policy environments at the time, but are now worth revisiting.

In the years following the development of thermal generators and alternating current, policies emerged to promote reliable, affordable electricity supply for all customers. Since then, the degree to which society can achieve those objectives and how we might meet them has changed.

Moreover, societal and regulatory objectives have evolved since the grid's inception. To varying degrees, we now assign explicit value to resilience, customer choice, environmental outcomes (including carbon intensity), and customer equity (particularly access to benefits and services for low- and moderate-income (LMI) customers).

Meanwhile, mutually reinforcing technological advances—including the rise of cost-effective (and zero-marginal-cost) renewables, distributed energy resources (including flexible loads), and sophisticated software-enabled services—along with governmental policies, changing consumer behaviors, and external events such as extreme weather and cyberattacks are challenging fundamental assumptions about the way the grid operates (see Figure 1).

In contrast to the 20th century—when centrally managed electricity was delivered one way over vast distances from massive generation assets to customers, who in turn delivered money one way back to utilities—the 21st century grid is characterized by active consumer participation in markets (e.g., demand response), bidirectional power flows (e.g., net metering of behind-the-meter resources), and complex financial transactions between consumers, utilities, and third-party service providers. Nevertheless, the physical infrastructure, business models, and market mechanisms that support today's electricity system were designed in and for the 20th-century paradigm. Reconciling these legacy systems with new technological realities and evolving societal preferences is the great challenge for regulators, utilities, and grid operators all over the world.

An explosion of novel IT solutions—ranging from sensors, to smart devices, to energy storage—create value for customers and utilities alike. But they solve for single, specific problems rather than system-wide harmony. In fact, these solutions at times directly compete with—rather than complement—one another.

How can we run a grid that is rich in distributed and renewable resources while giving customers the access and choice that they want and ensuring reliability and affordability?

In order for the electricity system to deliver everything we now ask of it, the sector must fully embrace new technologies to support entirely new market models instead of applying them piecemeal over incumbent regimes. In other words, we must design the grid from the edge up, not attach piecemeal edge solutions to a centralized system. In the latter, the tail (grid edge) wags the dog. Rather, the grid edge should be the dog.

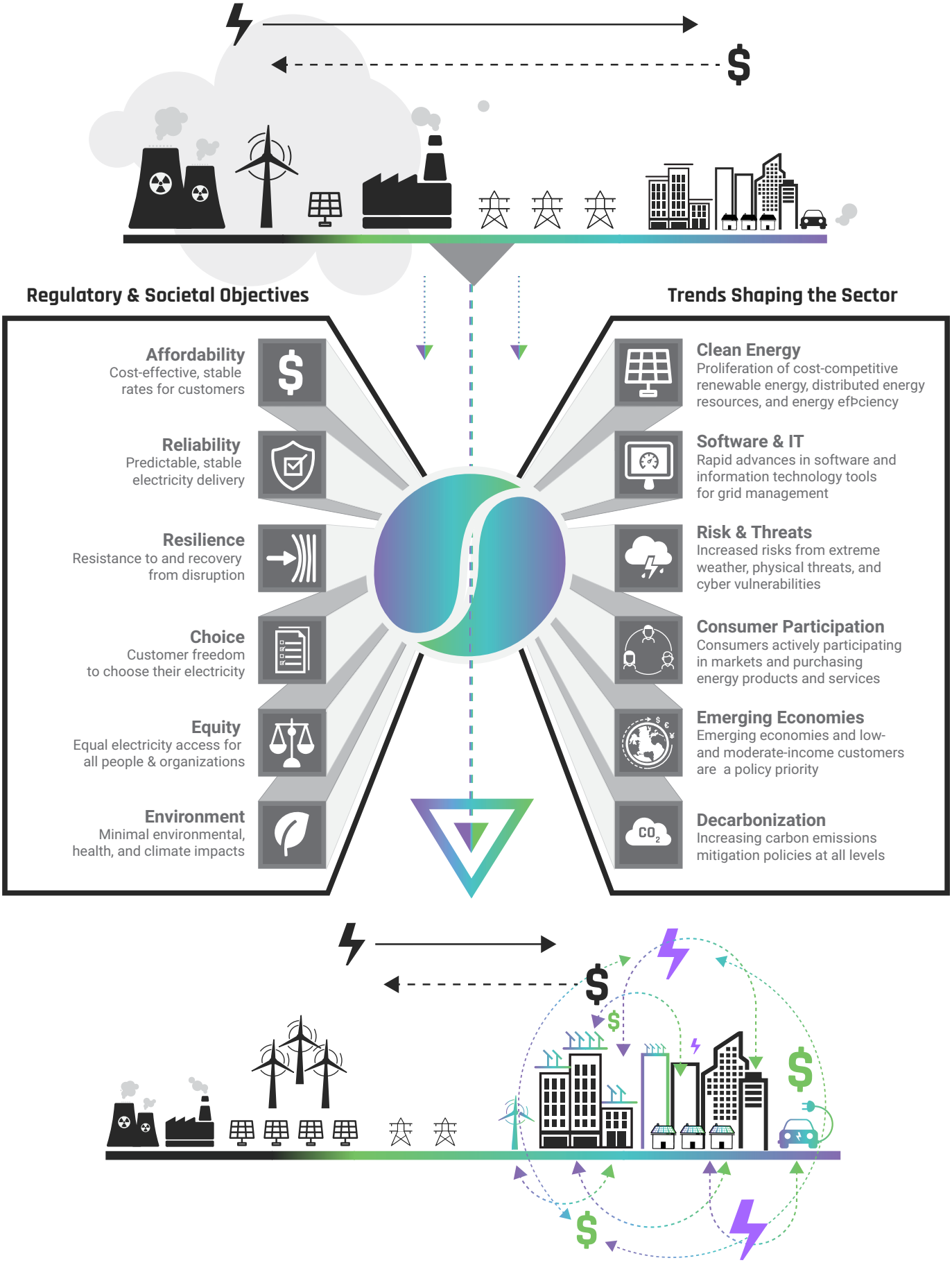
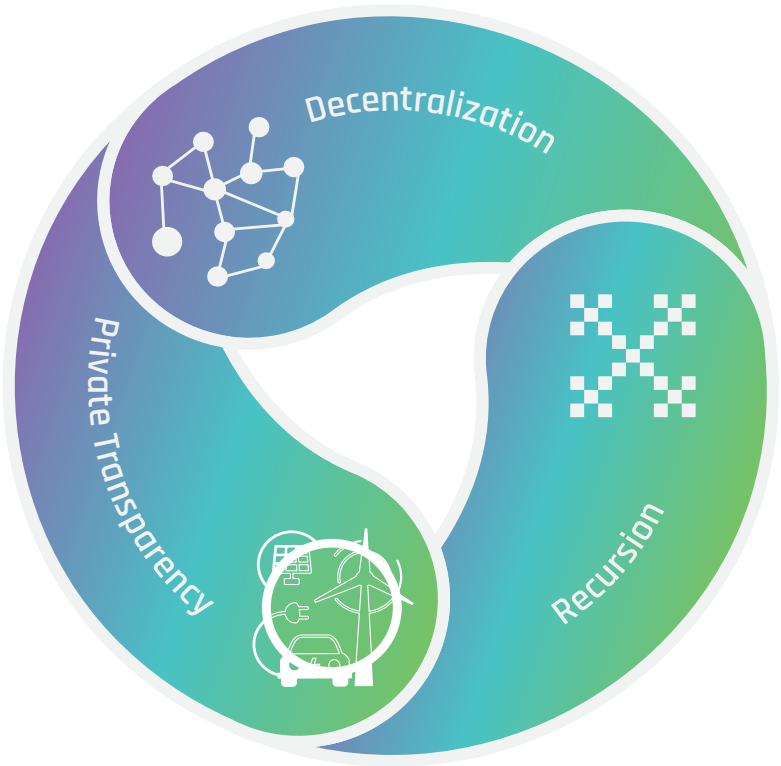


Figure 1: Objectives and Trends Influencing the Electricity Sector and Prompting a New Market Framework

Principles for a 21st Century Electric System

The confluence of technological advances, deeper understanding of both the natural world and contemporary threats to the electricity system, and evolving policy mandates present a unique opportunity to rethink the grid entirely. Drawing on decades of research and experience from academic, business, and governmental institutions, we believe three principles should inform design decisions for a new grid paradigm; one that is equally applicable in developed and greenfield settings (see Figure 2).



Decentralization	Recursion	Private Transparency
The grid should be fully decentralized — both in terms of physical infrastructure and operational management. This distinguishes between "distributed" and "decentralized" systems; the former implies a diverse asset base spread across geographic locations controlled by a single entity, while the latter includes both the distribution of resources as well as the transfer of authority and control from a central authority to a network of autonomous actors.	Grids should be recursive, where each component and each boundary area scale (e.g., device, building, neighborhood, distribution grid) is a self-contained ecosystem, replicated and nested within the next layer of the system, like matryoshka Russian dolls. All components and each scale of the system operate with identical information and control models and each have operational decision-making capabilities.	A privately transparent electricity market is one with as much "perfect information" as possible, defined by complete transparency of market conditions including the physical state of the grid, external conditions (e.g., weather), as well as anticipated and actual behaviors of market participants, all while protecting the identities and sensitive information of those participants in a crypto-graphically secure environment.

Figure 2: Principles for a 21st Century Grid

Principle 1: Decentralized

The grid should be fully decentralized—both in terms of physical infrastructure and operational management.

Distributed energy resources (DERs) inherently mitigate the greatest risk to grid stability: the grid itself. The overwhelming majority of blackouts are caused by failures in or damages to transmission and distribution infrastructure; locating right-sized supply resources near areas of demand reduces transportation, and hence risk of supply-chain disruption. Distributed renewable resources take this concept a step further. They have no fuel, and thus face no risk of fuel price volatility or delivery interruption. Emerging technologies like smart inverters, frequency relays, and active dispatch capabilities are transforming DERs from a "do no harm" resource to an active "support reliability" resource.

As demonstrated in recent hurricanes and floods, DERs are also more resilient to physical disruptive events than traditional infrastructure, and a system composed of many small assets is not at risk of cascading failures from any single point. Grids are virtually immune to traditional physical and cyber attacks when they are decentralized and thus built from the cellular level up—myriad independent pieces that are simultaneously self-sustaining and also communicating and transacting with one another to achieve higher-order functions and objectives.

Grid architecture should take a cue from some of the most successful decentralized systems in the natural world like ant colonies and aspen colonies, which function as single organisms but are made up of distinct individuals that behave independently in pursuit of a common objective. Or like the decentralized nervous system of a starfish. Individual cells organize into organs that together function as an entire organism with apparent higher-order functioning, yet do so without top-down centralized control. Further, a starfish arm cut off from the rest of the body can continue to function fully independent of the parent.

These examples help differentiate between "distributed" and "decentralized" systems; the former implies a diverse asset base spread across geographic locations controlled by a single entity, while the latter includes both the distribution of resources as well as the transfer of authority and control form a central authority to a network of autonomous actors.

Principle 2: Recursive

Grids should be recursive, where each component (e.g., a building, or a distribution grid) is a self-contained ecosystem, replicated and nested within the next layer of the system, like matryoshka Russian dolls.

Such recursive, nested systems—as in the D3A model described later—contrast with today's self-contained microgrids, minigrids, and picogrids. Such grids largely operate in isolation, either disconnected from the main grid or functioning more or less in mutual exclusion and each distinctly behind a point of common coupling to the rest of the grid. To truly unlock the potential of these systems, the macrogrid should be comprised entirely of smaller, interoperable grids motivated by the hierarchy of grid voltages ranging from the distributed system level to the transmission system level, using a shared communication and control paradigm that integrates with other components to coordinate operation, islanding, and integration.

All components operate with identical information and control models and each have operational decision-making capabilities; by establishing standards for information sharing and coupling/islanding, the grid becomes "agile," precluding cascading failures and optimizing operations at the bulk system level. Seamless islanding and re-integration of balancing areas not only provides physical resilience, but also protection from price volatility at different levels of the hierarchy. A recursive methodology for operational management is also desirable. Layered Decomposition, a mathematical approach to problem solving in which problems are broken into nested layers of sub-problems, is a maximally efficient method for composing large systems of arbitrary and changing size (like the electric grid).

Recursive design is innate in the universe. Moons orbit around planets, which in turn orbit around stars, forming stellar systems that cluster around supermassive objects to form galaxies, which in turn form clusters bound together by gravity. Though varying exponentially in scale, all objects operate under a common framework (the laws of physics in this case) and in simplistic terms, disruption (or destruction) of one component has limited impact on the broader system.

Principle 3: Private Transparency

A new grid should be characterized by private transparency: secure, canonical information sharing in support of market-based competition between all resources.

A privately transparent electricity market is one with as much "perfect information" as possible, defined by complete transparency of market conditions including the physical state of the grid, external conditions (e.g., weather), as well as anticipated and actual behaviors of market participants, all while protecting the identities and sensitive information of those participants in a cryptographically secure environment. With this quality of information at hand, investment and physical grid operation can tie directly with market-based signals.

This seemingly paradoxical principle evokes Schrodinger's cat and the wave-particle duality of light—it suggests something that simultaneously exists with two diametrically opposed qualities. But ubiquitous sharing of information in a way that fully protects privacy and guarantees security is critical to

[1] Taft, Comparative Architecture Analysis: Using Laminar Structure to Unify Multiple Grid Architectures, PNNL, November 2016

making the best investment and operational decisions for a grid. Private transparency—achieved when the state and availability of every resource is known but anonymized—can unlock latent demand for services and helps all stakeholders prioritize decisions based on relative value.

We believe these design principles will support the following desirable outcomes:

- Fostering a large number of buyers and sellers, allowing price competition to be used more extensively in price-setting;
- Minimizing barriers to entry or exit, enabling greater electricity market democratization, as individuals are able to capture value from active participation;
- Decommoditizing products such that customers are empowered with choice based on the attributes they value (provenance, for example);
- Minimizing transaction costs: buyers and sellers incur minimal costs when exchanging goods or services, searching for those goods or services, or enforcing contracts; and
- Minimizing externalities, ensuring both true costs and benefits—based on attributes like location, carbon intensity, and time—are reflected in the price of electricity.

The Solution: The Decentralized Autonomous Area Agent (D3A) Market Model

The Energy Web Foundation is developing an open-source solution that adheres to these principles and can unlock radical new opportunities to transform the electricity sector. The solution comprises two components:

1. **The Energy Web Blockchain:** a public, open-source, decentralized network capable of securely managing the electricity grid's transactions, customers, and devices with a first-of-its-kind governance model adapted specifically for the heavily regulated energy industry. The EW Blockchain is the digital DNA that encodes the system's information and transactions and underlies the intelligence by which it operates.

2. **D3A:** a transactive market model enabled by intelligent software agents that perform grid communication and control functions for physical assets. The D3A enables any energy-consuming or -producing device to interact with other devices in a trustless blockchain environment, optimizing operational decisions locally (based on user preferences and system conditions) within a defined physical boundary and aggregating to larger areas, all in real time with canonical data and communications up and down the value chain. The D3A is the digital market framework that guides system operation.

By combining these technologies, energy resources of any kind can collaboratively transact with each other in competitive futures, spot, and balancing markets, making operational decisions based on the true cost or value of each resource to the system. The software agent can be implemented at any level within a grid—from a water heater, to a building, to a neighborhood or substation, to a bulk power system—and support recursive markets based on bottom-up price clearing and balancing. The blockchain itself is a fully decentralized computing environment, and the areas controlled by the software operate independently but in concert with the broader system (see Figure 3).

The D3A—developed by EWF cofounder Grid Singularity—assumes electricity markets and products of today can be dramatically simplified: no more wholesale capacity markets, energy-only markets, primary reserves, secondary markets, and ancillary products. Instead, it assumes that all necessary grid services can be provided by recursive energy and balancing markets that operate from the bottom up. The former includes both a spot (real-time) and a futures (days to years ahead) market. The latter assumes automated responses from resources with ex-post settlement.

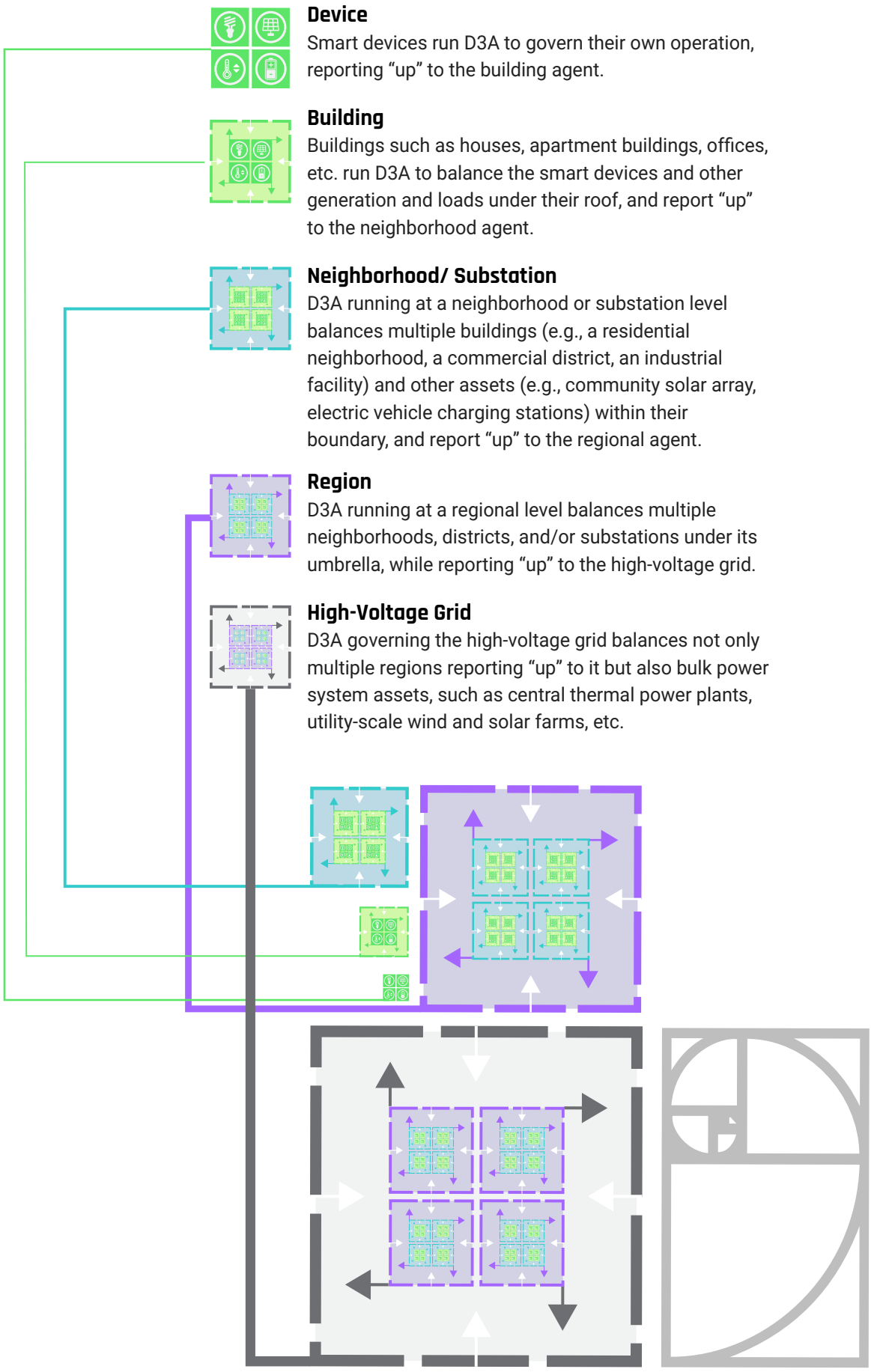
However, at the same time, the D3A does not prescribe how prices should be set. Instead, it gives system operators the flexibility to design a market signal and settlement mechanism based on local conditions. There is no "one size fits all" solution; options could range from a double-sided market in which each participant pays a unique price based on their preferences and supply and demand conditions (analogous to the stock market) to a time-bound (e.g., 5-minute) auction in which a clearing price is set for a specific region, or a number of alternatives.

The sum of these parts is a transactive energy (TE) market model running on blockchain, capable of scaling to any level within a grid. It turns the traditional model of top-down centralized dispatch of large-scale assets on its head, instead favoring grid-edge-up decentralized coordination, complemented by an evolved bulk power system.

The result is a grid that is:

- **Decentralized:** powered by distributed resources of all types;
- **Decarbonized:** capable of achieving high penetrations of renewable resources;
- **Democratized:** provides the greatest degree of freedom for consumers by increasing choice, improving access, and enabling participation; and
- **Resilient:** resistant to and rapidly able to recover from both physical and cyber disruption.

[2] Transactive energy systems are characterized by resources making operational decisions based on value and bi-directional communications between participants/resources enabling local problems to be solved locally. See GridWise Architecture Council for further reading.



Device
Smart devices run D3A to govern their own operation, reporting “up” to the building agent.

Building
Buildings such as houses, apartment buildings, offices, etc. run D3A to balance the smart devices and other generation and loads under their roof, and report “up” to the neighborhood agent.

Neighborhood/ Substation
D3A running at a neighborhood or substation level balances multiple buildings (e.g., a residential neighborhood, a commercial district, an industrial facility) and other assets (e.g., community solar array, electric vehicle charging stations) within their boundary, and report “up” to the regional agent.

Region
D3A running at a regional level balances multiple neighborhoods, districts, and/or substations under its umbrella, while reporting “up” to the high-voltage grid.

High-Voltage Grid
D3A governing the high-voltage grid balances not only multiple regions reporting “up” to it but also bulk power system assets, such as central thermal power plants, utility-scale wind and solar farms, etc.

Figure 3: The Fractal, Recursive D3A Implementation

D3A in the Transactive Energy Context

The concept of transactive energy is not new, and multiple projects have been implemented to date. Four projects in particular are noteworthy (see Figure 4).

	Olympic Peninsula Demonstration	Pacific Northwest Smart Grid	TeMix	PowerMatcher
Date & Location	2006–07, Washington & Oregon, USA	2010–15, 13 sites across northwestern USA	Ongoing pilot, California, USA	2004–2015, Multiple projects in The Netherlands & Denmark
Description & Objective	Consortium of local utilities and technology providers leveraged two-way communications and price signals to reduce congestion and integrate DER	Multiple field demonstrations run by utilities, co-ops, and non-profit to test incentive-signal based bidirectional communication and control system	Partnership between TeMix, local utility, and ISO to test Two-way subscription tariff and automated end device controls via TE market model operated on TeMix platform	Multiple projects leveraging open-source TE software. PowerMatching City: TE market with in-home coordination EcoGrid: real-time market for smart distribution network
Number of Assets	1 commercial and 112 residential customers w/ TE gateway and behind-the-meter assets; 3 distributed generators	Total of 1.9 million residential customers, 190,000 commercial, and 2,400 industrial customers across all field demonstrations	Up to 160 residential and 40 commercial customers with smart thermostats, storage, and building controls	PowerMatching City: 45 households with generation, storage, and flexible load; EcoGrid: Over 1,900 households and 18 commercial participants
Market Design	5-minute double auction with LMP the product of wholesale plus resolution of supply & demand bids	Distributed price determination at the device level; hyper-local LMP set for varying timescales up to 4 days ahead	5-minute LMP set by wholesale market with nested TeMix contracts both short term (sub-minute) and long-term (months to years)	PowerMatching City: sub-minute market with consumption and production optimized in near real-time; EcoGrid: 5-minute LMP
Key Outcomes	Reduced peak demand, managed congestion, and demonstrated impact of market signals on behavior	Demonstrated ability to increase demand response participation; established library of TE functions	Published series of papers providing comprehensive assessment of TE model; pilot work ongoing	PowerMatching City: optimized transactions with distribution coordination; EcoGrid: increased demand flexibility and reduced system peak

Figure 4: Transactive Energy Demonstration Highlights

Though many of these projects have been successful in enabling peer-to-peer transactions and integrating DERs, the challenge is scaling these frameworks to entire balancing areas, and eventually, nations. EWF's D3A concept offers a way to bridge that divide (see Figure 5).

Barrier	Addressable by D3A?	Addressable by EW Blockchain?	Description
Regulatory Restrictions			N/A
Market Design	✓		D3A supports flexible market design for energy & balancing
Data Integrity		✓	Cryptography makes tampering with data on chain impossible
Participant Privacy		✓	EW chain features secret (zero-knowledge) smart contracts
Cybersecurity		✓	Traditional attack vectors (e.g. DdoS, MITM) are ineffective
DER Interconnection	✓	✓	D3A provides granular visibility into DER state & availability in a secure environment
Scalability / Throughput		✓	Unique PoA, state channels, para-chain interoperability, and other methods unlock necessary speed
DER Dispatch	✓		Area agents automate response based on specified parameters
P2P Contracts / Settlement	✓	✓	Smart contracts securely perform legal and financial functions
Consumer Participation			N/A
DER Capital Costs			N/A

Figure 5: Barriers to Scaling Transactive Energy Markets

Pathways for Implementation

We believe EWF's solution can add value in any setting—from heavily regulated monopolies to platform/system operators to deregulated and/or competitive markets to greenfield territories in the developing world. We considered four pathways for how deployment of this solution might play out and provide recommendations for policymakers and market participants to maximize value from this new approach (see Figure 6).

Expanded Monopoly

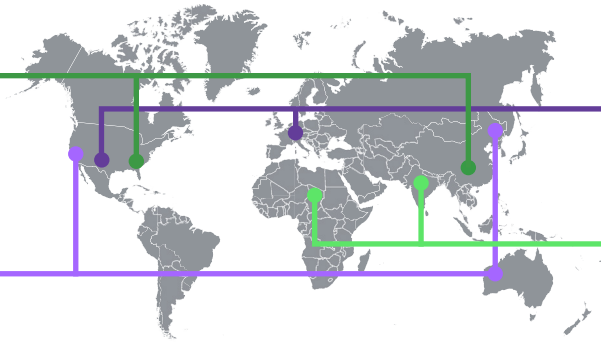
A regulated, vertically-integrated utility gets approval to leverage their balance sheet to directly own and/or invest in assets throughout their distribution network, including behind the meter. The utility deploys D3A to operate the grid while giving customers the ability to set their own preferences for participation.

- **Regulators:** pathway only available where regulators incent utilities to invest in DERs
- **Utilities:** rely on innovation / R&D departments to ID demonstration opportunities; recover costs through performance-based tariffs or service contracts
- **Customers:** only actively involved if utility deploys D3A via default "opt-out" program

Transformed Competitive Market

In fully deregulated territories, electricity market participants could begin implementing and deriving value from D3A at their discretion, from low voltage distribution networks to the bulk power level. Retailers provide D3A-as-a-service; sophisticated customers deploy D3A at their point of common coupling; DSOs leverage D3A below the bulk power level of the grid.

- **Regulators:** Establish standards for individual consumers, start-ups, and incumbents to participate in existing (wholesale) and new (transactive) markets
- **Utilities (retailers):** D3A becomes the universal "platform" for retailers to build their own business model
- **Customers:** sophisticated customers could use D3A to manage their own microgrids



Transformed Platform Operator

Incumbent system operators face increasing competition from a mix of market liberation, community-scale grid defection, and third-party service providers. Operators deploy D3A as a new grid architecture and create new markets for DER while utilities continue to serve key reliability / customer service functions.

- **Regulators:** DSOs may play a key role as investors on behalf of LMI communities
- **Utilities:** D3A may represent core of future business model under this pathway, with revenue stemming from transaction fees (D3A platform or T&D use) and/or service contracts
- **Customers:** D3A could support efforts to "defect" from incumbents (e.g., CCAs in California)

Emerging Economy

In rural greenfield settings, grids are assembled from the bottom up rather than the top-down. Individual homes or groups first invest in DERs (financed by off-grid energy companies) and build low-voltage lines to trade and share electricity with their neighbors. These self-organizing systems grow linearly, with D3A serving the role of retailer and system operator.

- **Regulators:** D3A could be regulated / adopted as de-facto standard for electrician strategy
- **Utilities:** Consider platform-operator or service provider model as an alternative to traditional capex investment
- **Customers:** Leverage D3A to support automatic minigrid interoperability with neighboring regions

Figure 6: D3A Implementation Pathways

The D3A Roadmap

The D3A vision is compelling, but a long road to reality lies ahead. EWF is engaging in two distinct workstreams for the D3A: 1) a cloud-based simulation environment for configuring and testing transactive markets in specific grid topologies; and 2) deploying the D3A market model on the EW Blockchain (see Figure 7).

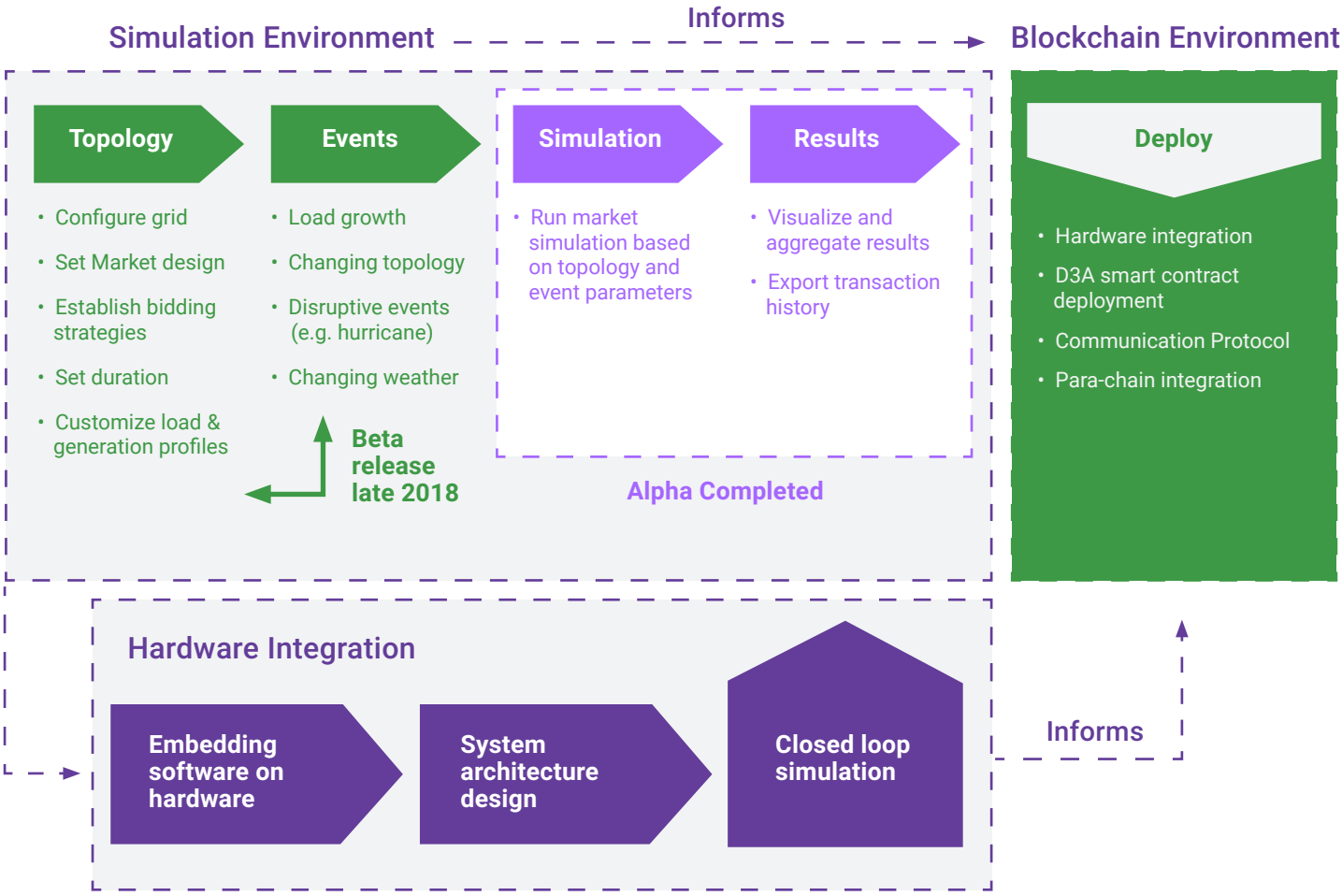


Figure 7: Energy Web Foundation D3A Workstreams

The alpha version of the simulation environment provides simple results from a simulated day of a 15-minute spot market for several pre-configured mini-grids. Over the course of 2018, EWF will add more features to the D3A that can be tested, including:

- Advanced grid configurations, with multiple tiers ranging from individual buildings to the bulk power system;
- Inter-area agent and other types of agents, which coordinate transactions between disparate components and grid tiers;
- Advanced bidding strategies for devices and area agents, which may change over time or in response to exogenous factors (e.g., weather, behavior of other participants);
- Grid events, including changing load profiles and grid configurations over time as well as disruptive events;
- Custom load and/or generation profiles, either uploaded by users or fed in from external data sources;
- Different market designs (e.g., one-sided vs. two-sided), exploring outcomes under varied price-setting mechanisms; and
- A balancing market.

Future Challenges

The purpose of the simulation environment is to help utilities, grid operators, regulators, and the public better understand the implications of a recursive, decentralized energy market and explore how different factors influence outcomes.

D3A, as currently designed, evaluates markets but does not perform detailed power flow analysis. There are questions about the physical stability and performance of a transactive system that must be answered in order to achieve the D3A vision. To that end, EWF is collaborating with EWF Affiliates and research institutions to test the D3A framework on physical devices in closed-loop environments and, eventually, select distribution grids.

Additionally, EWF is cultivating an ecosystem of partners actively working on TE demonstration projects and business models; our goal is to share information openly with other parties aligned in working towards making D3A a reality. By making D3A publicly available, we aim to enable a diverse population of utilities, hardware manufacturers, energy service companies, grid operators, and startups to experiment with transactive energy on their own and develop other applications or products on top of the D3A / EW Blockchain infrastructure.

Equally important to the D3A's success is the development of robust, compliant, secure smart contracts and a blockchain architecture capable of managing transactions between millions of market participants. Results from the simulation environment and feedback from regulators and market participants will inform the design of any open-source smart contracts, and the development process will be iterative over time. As of Q2 2018, the EW Blockchain is in the beta version of the test network. Though it's already capable of supporting limited D3A deployment, throughput will need to increase by several orders of magnitude to support widespread D3A implementation.

In addition, safeguards must be put in place to protect sensitive customer data (e.g., private keys) and transaction details. EWF's core technology roadmap is focused on scaling and privacy. Several methods for scaling are being developed—including increasing the number of transactions in each block to achieve tens of thousands of transactions per second on the main EW chain, as well as leveraging new technologies to seamlessly interoperate with other public and private blockchains, using payment channels, and conducting certain functions off-chain to reduce the number of computations sent to the blockchain.

Finally, at least three additional areas of focus remain:

- **Integrating the financial and the physical:** beyond pure market signals, the grid must maintain a tightly defined steady state (e.g., voltage, frequency);
- **The role of storage:** neither pure generation nor pure load, the growing role of storage will add a new dynamic to grid balancing; and
- **A need for forecasting:** grid operators will need predictive capability across multiple fronts (e.g., weather, demand, renewables generation)—we can't 'drive' the grid only by using peripheral vision and looking in the rear-view mirror; we also need foresight to achieve the grid's ongoing stable state.

In short, there is significant work to be done to deploy D3A in the real world and the current roadmap spans several years.

Later in 2018, EWF will publish a technical white paper describing the features and functionality of the EW Blockchain in detail, as well as a full report articulating the issues facing today's grid, detailed theory for design principles, and how D3A can add value in any setting. Following additional modeling and testing, EWF will also publish subsequent papers quantifying the results of the D3A market model on actual distribution grids.

Individuals or organizations conducting research, undertaking demonstration projects, and/or interested in physical implementation of D3A and transactive energy should contact:

D3A@gridsingularity.com