Decentralized Energy Management Architecture for Service-Oriented Cyber-Physical Electric Grids

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***Abstract*—The centralized control architecture of today's electricity grid has performed particularly well as an engineered system, but it is reaching an unsustainable level of strain. Further, new electricity industry objectives – sustainability, energy security, and energy service support – necessitate a reevaluation of traditional hierarchies. A decentralized control architecture is needed to unify the desired new features of the grid with emerging objectives and growing demand. Such an architecture is described here in terms of functionality, properties, core elements, and a division into layers. The organizing concept is the prosumer, an economically motivated power system actor that can consume, produce, store, or transport electricity. Autonomous networked control can provide system reliability using solely agent- (prosumer-) based behaviors. Energy services provide a method to trade energy products among actors, creating a multi-scale abstraction that organizationally simplifies many processes. Backward compatibility and incremental deployment are key features of the architecture that can support its utilization as a guiding future grid design framework.**

***Index Terms*—Decentralized Management, Distributed Power System Control, Future Grid Architecture, Cyber-Physical Electric Grids.**

I. INTRODUCTION

THE operation and control paradigm used today by the electricity industry is largely centralized, based on traditional Supervisory Control and Data Acquisition (SCADA) architecture originally proposed in the 60's, following the advent of the digital computer [1,2]. By using this centralized control paradigm the industry has been successful in achieving its objectives of providing reliable electricity at reasonable cost.

Requirements of secure integration of less predictable and variable renewable energy, deployment of smart grid sensing and communication infrastructure, and emerging consumer objectives result in substantially amplified communication, data management, and computation requirements and in highly complex decision-making problems [3-5].

The future grid will consist of billions of devices and millions of spatially distributed decision makers. These new (smart) devices are equipped with advanced electronics and embedded systems. The emerging decision makers, i.e., microgrids, buildings, homes, etc., are being instrumented with sensing and communication systems to enable automation, while electricity users have ever-growing access to ubiquitous information about electricity use [6, 7].

Formidable benefits to the electricity system, the electricity industry at large, and consumers can be achieved if these actors and system devices can be coordinated in an intelligent manner. The centralized architecture suffers from fundamental scalability limitations when the number of control points and decision-makers increases drastically. Thus, there is a need for an evolved model for managing the electricity infrastructure and the industry at large, one that reduces complexity, enables decentralized decision-making, allows for more flexible control, and supports desirable value propositions.

This paper describes a decentralized paradigm that will enable the electricity grid to operate with architectural characteristics similar to the internet: highly accessible, scalable to billions of actors, layered, and flexible. The paper adopts a broad and holistic approach, touching a wide domain of emerging concerns. Its architectural scope is therefore the operation and control of the entire electricity infrastructure.

Rather than proposing or designing an architecture around a specific existing or developing technology, we start with the requirements both explicitly and implicitly stated in the academic literature and industrial community. We then discuss a framework that allows for many different technologies to contribute to grid operation and further propose some examples of what those might be. Thus, we seek to define an architecture that clearly reveals the challenges and needs for future grid design. Additionally, such a framework can be used to parse many of the preexisting smart grid architecture proposals for the purpose of comparison, a task that can be difficult otherwise due to inconsistent vocabularies and different sets of requirements and objectives.

Section II of this paper describes the fundamental objectives of the future grid, which the proposed architecture supports, as well as user needs and desired properties. Section III describes the core concepts and elements of the decentralized architecture, including distributed decision-making, cyber-physical prosumer abstraction, management of temporal scales, autonomous control, and prosumer services. Section IV describes the layered structure of the architecture and the tasks accomplished by each layer. Section V offers a discussion demonstrating how the proposed architectural elements map to the desired objectives and functionality of the future grid, as well as a comparison to some other proposed architectures. Section VI provides the conclusions to this work.

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II. Objectives of the Future Grid

A. *Five New Objectives of the Future Grid*

Unprecedented efforts are being made across the globe in the quest to modernize the electricity industry. Numerous projects on integrating renewable energy, advancing the smart grid, realizing consumer empowerment, and installing new devices such as battery systems and synchronized phasor measurements units (PMU) are reshaping the industry as we know it. These developments in the electricity industry are not isolated, but are rather a natural step in the evolution of the industry and a response to:

a) The need for the grid to achieve *more ambitious objectives* of economic optimization (e.g., increased asset utilization) and ultra-reliability demanded by a modern society, and

b) The need to achieve *new objectives* associated with sustainability, support for energy security, e.g. through increased transportation electrification, and support for energy services.

It is critically important to recognize that the electricity industry has *new objectives* – desired capabilities and performance that are substantially different from its traditional functionality. It is equally important to recognize that the electricity grid is an extremely large and expensive engineered system whose bulk infrastructure cannot change rapidly and is increasingly taxed with age. It has been recognized that the new objectives cannot be achieved by simple additions or by incrementally deploying technologies in the grid [8, 9]. In order to realize the new objectives, new functionality must be extracted from the grid without having to replace the majority of the investment. This can only be achieved if the core paradigm used to manage and control the infrastructure is reviewed. In other words, realizing the above objectives of the future grid is not only an *engineering problem*, but an *architectural problem*. This has been recently recognized by various efforts such as the EPRI Smart Grid Enterprise Architecture [10], IEEE Smart Grid Vision Project, and PSERC Future Grid Initiative [11].

The five objectives for the future grid: superior economy, ultra-reliability, sustainability, energy security, and service support, can be mapped to the seven objectives that have been identified for the smart grid [3]. This is illustrated in Table I, where the bullets illustrate importance in ascending order.

The five future grid objectives could also be mapped to economy and reliability alone (the traditional objectives) or even to economy alone. However, mapping functions to energy security, sustainability, and energy services is not straightforward. The following discussion on the consumer objectives supports this notion.

TABLE I
SMART GRID AND FUTURE GRID OBJECTIVES

Smart Grid Objectives	Eco	Rel	Sus	ESec	Ser
Self-Healing		●		•	
Consumer Empowering	•		•		●
Power Quality		●			
Tolerant of Attack		●		•	
Variety of Generation Options			●	•	
Maturing Electricity Markets	●				•
Optimize Assets	●				

B. *The Complex User Demand for Electricity*

It has been claimed that electricity consumers only care about the price of electricity. However, studies by the Smart Grid Consumer Collaborative (SGCC) reveal that the relation between the user of electricity and a provider is more complex [12]. Table II lists the major properties of electricity demand.

TABLE II
DESIRED CHARACTERISTICS OF ELECTRICITY

Property	User wants:
Quantity	Enough electricity to meet its needs.
Cost	To pay as little as possible
Reliability	Uninterrupted electricity supply
Quality	Close to nominal frequency, voltage, power factor, phase balance, etc., so that loads and appliances are not damaged
Efficiency	To use electricity in an efficient manner
Sustainability	To contribute to addressing environmental problems
Ubiquity	Availability of power at various locations
Differentiation	Options and choice
Simplicity	To be hands-off
Data Privacy	Maintain appropriate data access privileges

Current electricity system operations, the electricity delivery system, the regulatory framework, and electricity markets do not exploit all these features and often do not consider some of them. In particular, the organization of the electricity industry has traditionally assumed that the user will be completely satisfied if the first four characteristics listed in Table II are met. This assumption isolates the consumer from contributing to the new objectives of the future grid. Let us discuss the last five characteristics in more detail, assuming that the first four characteristics remain constant.

Efficiency: Given equal cost, quantity, reliability, and quality, the user prefers efficient use. Users are increasingly aware of energy waste and the notion that electricity needs to be produced somewhere at the expense of fuel. All things equal, the consumer tends to choose not to waste electricity. Correspondingly, all things equal, the user exhibits preference for energy-efficient appliances, light bulbs, etc., as demonstrated by the success of the Energy Star program in the United States [13].

Sustainability: Not all electricity is equal. Users prefer electricity that is produced by cleaner renewable sources [14]. Currently, the user has no method to differentiate energy delivered, except from locally produced renewable energy. Thus sustainability objectives are indirectly and partially achieved. Currently, most of the sustainability objectives are met through Renewable Portfolio Standard (RPS) mandates. Despite this fact, the user associates sustainability objectives with conservation and efficiency, for example, by linking deferred electricity from fossil fueled power plants to saved fuel and decreased emissions [15].

Ubiquity: Several growing trends are converging toward a need for ubiquitous power. Significant expansion of distribution systems will be needed to support many new EV charging stations and distributed generation sites. Military microgrids, specifically mobile microgrids, are indicators of a need to quickly establish stable networks and seamlessly interface to larger networks when available. Additionally, the use of battery technologies in many types of devices will only continue to grow in type and quantity, creating new challenges and opportunities for system control. These varied trends are all expressions of increasing need for universal power availability.

Differentiation: Users have varying requirements for electricity and would be willing to pay different amounts for different characteristics. The Texas retail market, for instance, considers provider choice and has offered a variety of services such as pay-as-you go electricity [16]. Direct differentiation of electricity itself is possible through temporally sensitive pricing [17, 18], reliability-tiered pricing [19], and introduction of green electricity products [20-22].

Simplicity: One of the major objectives of the future grid is increased consumer participation [23-25], which specifically means that the consumer (possibly helped by enabling technology) becomes a much more active and sophisticated decision maker. Demand response actions in particular could represent up to 45% of the expected smart grid benefits in the U.S. over the next decade [26]. However, several efforts towards consumer empowerment have in fact caused consumer backlash, forcing some energy providers to offer smart meter opt-out programs [6, 27]. With new technologies deployed and new pricing policies implemented, the number of options offered to residential customers in terms of choices increases drastically. This also increases the number of decision parameters and makes energy management too complex for customers to solve manually. While customers value usage or pricing information, they also want to be hands-off: the per capita time spent consuming information in the U.S. has risen nearly 60 percent from 1980 levels [28]. Home energy management systems can realize the benefits of enhanced control while recognizing this desire for simplicity [24, 25].

Data Privacy: It has become clear that completely accessible smart meter data is not only unacceptable to consumers but also a vulnerability [29]. Further, data privacy must not be addressed *ex post facto* solely by data encryption strategies; rather, it is an architectural element [30].

C. *Mapping Grid Objectives to User Needs*

The electricity grid must be modernized in order to serve emerging societal objectives. As long as the future electricity user requirements are met, the grid and the industry have achieved their objectives. Table III maps the grid objectives to the needs of the electricity user. It shows how the future grid objectives described in this manner would meet all the needs of the electricity user. This table demonstrates that electricity as a service is much more than reasonably reliable cheap electricity; rather, it is recognizing that society relies on the electricity industry not only to provide commodity electricity, but to support much more complex objectives associated with energy use and national strategy.

The energy user hence evolves as a complex agent who relates energy to its own objectives. For example, there is growing recognition of the fact that efficient use of electricity has implications for social capital and obligation [31].

TABLE III
USER NEEDS AND FUTURE GRID OBJECTIVES

User Need \ Objectives	Eco	Rel	Sus	ESec	Ser
Quantity		●			
Cost	●				
Reliability		●		●	
Quality		●			
Efficiency	●		●		●
Sustainability			●		
Ubiquity				●	●
Differentiation			●		●
Simplicity					●
Data Privacy	●				●

The emerging needs of many grid users can be addressed through creation and trading of new electricity services. By defining and bounding new ways for consumers and producers to use the grid, users transition from a stiff system disturbance to an intelligent agent, a crucial architectural aspect that has grown in recognition in the power systems literature [32].

D. *Limitations of the Centralized Architecture*

The centralized grid control architecture, based on SCADA systems initially designed in the 60’s, has grown and assimilated many new technologies without altering the underlying structure. However, this system will not continue to be scalable for the following reasons:

Expanding data requirements: The number of monitoring and control devices is increasing by several orders of magnitude over traditional data acquisition. In a centralized architecture, the control center faces a dilemma between incomplete information (e.g. coarse granularity) and an information tsunami [33], both of which prevent effective control action [33-36].

Communication bottlenecks: Centralized control will require moving massive amounts of data and hence expensive, mostly dedicated communications.

Intractable control and optimization problems: Traditional methods for real-time dispatch are based on instantaneous optimization without look-ahead capabilities and are deterministic; that is, they do not handle uncertainty and variability (as from renewable sources) [37]. Most current forms of stochastic optimization will be result in problem sets that are intractable in the required timeframe even with the most powerful supercomputers [38].

Risks of controlling large-scale renewable energy: It has been recognized that integration of large amounts of renewable energy poses operational challenges and can result in system events [39].

Growing complexity of system operations: Support for operator situational awareness is struggling to keep up [40]. The number and complexity of reliability and compliance procedures is growing rapidly as the industry integrates renewable energy and addresses concerns such as inter-area oscillations, the effects of demand response, and deployment of energy storage.

Growing complexity of market and regulatory framework: Current electricity markets exhibit fundamental market design limitations such as lack of direct interaction between consumers and producers, ad-hoc established market temporal scales, and conflict of interest between utility revenue and energy efficiency [41, 42]. New propositions are needed that allow the markets to mature with direct participation of all the actors.

Cyber-security: Centralized control remains a cyber and physical security target [43, 44]. It is based on the concept of bulk energy control centers, which require major infrastructure to be physically protected and usually redundant facilities, hardware and software infrastructure.

Data Privacy: A centralized framework results in the central organization controlling non-owned assets. This results in the need to send significant amounts of data from those non-owned control points. Data privacy concerns have been pointed out in smart grid pilots in the United States and have resulted in pushback from consumers [27, 45].

E. Baseline Questions

The proposed architecture must thoroughly address the limitations of the existing operation and control framework, enable the new grid objectives, and provide a platform for innovative propositions. The following fundamental questions center our discussion:

a) How should emerging devices such as wind and solar sources, storage, EVs, and flow controllers be managed to achieve desirable objectives of functionality, safety, and performance?

b) How must information be exchanged among the different actors to enable control and operation, and what sensing, communication, data management and computation are needed?

c) How can the simultaneous operation of a large number of such devices be coordinated through the existing grid to achieve system-wide objectives such as high utilization, reliability, and resilience?

d) How will these technologies impact and enable more mature markets that provide access to desirable services, energy innovation, and value propositions for all the current and emerging actors in the industry?

F. Desired Properties

In addition to providing functionality that satisfies the objectives of Table I, the future grid architecture must have some properties that support its viability. The below properties should be upheld to the extent possible by any element of the architecture to support a cohesive whole.

Robustness: The architecture must support the reliable operation of the grid under attack and loss of infrastructure modules including power, control, communications, and computation components.

Scalability: The architecture should not rely on algorithms or processes that lose effectiveness when scaled to millions of grid decision-makers.

Technology Independence: The architecture must provide for a clear, common interface for existing and developing technologies to assimilate with the grid without requiring extensive redesign. For example, a residential photovoltaic installation should satisfy an interface that guarantees certain adaptive behavior to forgo the need for detailed feeder protection studies.

Backward compatibility: To facilitate a smooth transition that may require an extended time table, the architecture must be compatible with existing processes and must support continuity and integration of legacy systems.

Incremental deployability: The architecture must support incremental deployment of the various systems and technologies as part of the transitional period and as part of an effective interface design behind technology independence.

III. Future Grid Architecture: Core Elements

In this section we present the core elements of the management architecture for the future grid. These elements support the objectives mentioned in Table I as well as the requirements of users listed in Table II.

A. Distributed Decision-Making

The deployment of massive sensing and communication infrastructure downstream from distribution systems to microgrids, feeders, and the customer facilitates a much more refined process of electricity use optimization. As a result, both the utility and the final electricity user will optimize objective functions associated with energy [24, 25, 46, 47]. These objective functions of the user and the provider may not necessarily be aligned.

In the centralized architectural framework, there is one system level objective function, which corresponds to minimizing the total operating cost of a given geographic region for a given period of time. The various actors (producers, consumers, and distribution utilities) yield control of their assets to the Independent System Operator (ISO), who conducts centralized optimization and control. Smart grid pilots have pointed out the realization that users of electricity will no longer have the same objective function as the utility. In the long term, users may benefit from installation of local generation, such as rooftop solar panels or energy storage, to hedge against real-time pricing or pursue sustainability or environmental goals. Because of the diversity of objectives that the power grid actors have and the common goal of maintaining a reliable system, a control platform should optimize individual behaviors in concert to achieve system level objectives. Distributed operation and control design implementations fall across a spectrum between cooperative (as in frequency droop control) and competitive (as in price-based unit commitment or so-called transactive control [48]).

Certainly, a combination of cooperative and competitive strategies will be necessary to obtain a reliable grid with equitable opportunities for users to maximize their profit.

Ultimately, the disparate classes of industrial, commercial, and residential consumers will evolve into similar economically motivated entities equipped with much more powerful information and control technologies. These actors will pursue their own long- and short-term energy objectives and will have all the incentives to invest, operate, and control more advanced technologies to meet their energy objectives [49]. The management architecture must provide the necessary elements to support such distributed decision making, and it must provide the mechanism so the various players can meet their objectives subject to system level constraints of reliability and sustainability.

Proposition 1: *Decision-making in the future grid will take place in a distributed manner, and it will be characterized by numerous actors pursuing their own energy objectives while adhering to protocols to address system level objectives and constraints.*

B. Spatial Scales and Cyber-Physical Prosumer Abstractions

Clients of the electricity grid can be modeled under a scale-free cyber-physical abstraction. Fundamentally, the users are evolving into *prosumers*: economically motivated entities capable of producing, consuming, storing, or transporting electricity. The prosumer is an electric power system with an owner or operator who establishes an energy-related objective function for the system. It is equipped with sensing, communication, and decision-making logic that assist it in pursuing those objectives. The prosumer abstraction, originally developed in [50, 51], is illustrated in Fig. 1, which shows a generic power system with connections to external supply, local production and storage, and some loads.

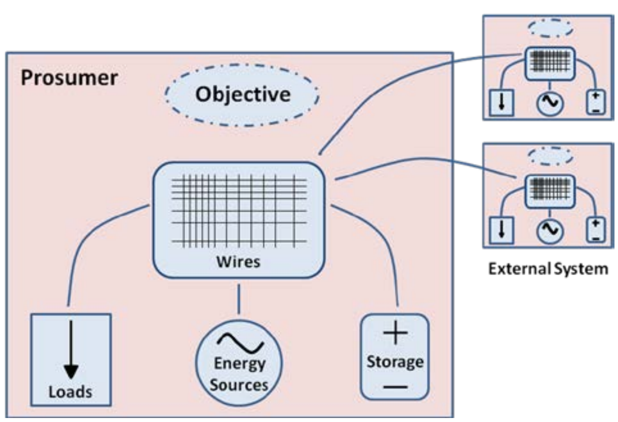

Fig. 1. Prosumer abstraction to generic elements.

The prosumer, denoted by $\wp$, has a fundamental task of obtaining enough power to balance its load. Let us denote by $i \in N^{\wp}$ the nodes inside prosumer $\wp$. The prosumers must enforce the equation:

$$\sum_{i\in\wp} P_i^G = \sum_{i\in\wp} P_i^D + \sum_{i,j\in\wp} (P_{ij} + P_{ji}) - \sum_{i\in\wp} P_i^{SD} + \sum_{i\in\wp} P_i^{SC} + \sum_{i\in\wp} P_{ij}^I \quad (1)$$

where the subscripts *G*, *D*, *SD*, *SC*, and *I* denote generation, demand, storage discharge, storage charge, and interchange, respectively. P_{ij} denotes the flow in line from nodes *i* to *j* as measured at node *i*. P_{ji} denotes the flow from nodes *j* to *i*. Thus $P_{ij} + P_{ji}$ corresponds to the active losses in the line.

Electric power systems exhibit similar physics at various scales (self-similarity). They are all electric circuits subject to Ohm's and Kirchhoff's laws. The balancing equation (1) is identical for all prosumers regardless of their scale. This allows us to generalize the prosumer abstractions to power systems of any scale and to express the interactions among various power systems as interactions among prosumers.

Proposition 2: *Every power system that has an identifiable owner or operator and an energy-related objective function can be represented as a prosumer. All the interactions between existing power systems of any scale can be modeled as interactions among prosumers.*

A corollary of this proposition is that a prosumer cannot belong to another prosumer. Nested structures, in which a prosumer is inside another prosumer, are not allowed.

Example 1: Utility and Commercial Building. A building is no longer a load in the distribution utility. Under the proposed architecture, the building is a prosumer who contracts for generation services from the utility prosumer. Both the utility and the building are seen as prosumers acting on the same logical level, although they have different size.

Example 2: Electric Vehicle. The electric vehicle can be modeled as a prosumer with various interaction modes. While disconnected from the grid, it may serve a specific objective determined by its owner, such as to optimize for energy-efficient driving. When connected at home, the EV prosumer may yield its objective function to the home, and instead send a constraint, such as the need to be fully charged by 5am the next day. Hence the EV becomes an asset of the home prosumer objective function. Similarly, when connected to the office parking lot, the EV prosumer may impose charging constraints. We note that the EV may also be providing other prosumer services such as deferrable load frequency regulation. This is illustrated in Fig. 2

Example 3: Transmission-Only Prosumer. A transmission company is a prosumer who may provide nothing but transmission services. In the pure transmission case, the condition that the interchange must be exactly equal to the system losses must be enforced, according to the following equation.

$$0 = \sum_{i,j\in\wp} (P_{ij} + P_{ji}) + \sum_{i\in\wp} P_{ij}^I \quad (2)$$

The transmission prosumer must therefore provide transportation services while ensuring system security and reliability by enforcing transmission constraints. Because of the natural monopoly of transmission and distribution infrastructure, the design of such services must be carefully regulated, as it is today, to mitigate the exercise of market power. Some existing work [52-54] has proposed schemes for transmission market bidding with an eye toward secure market design.

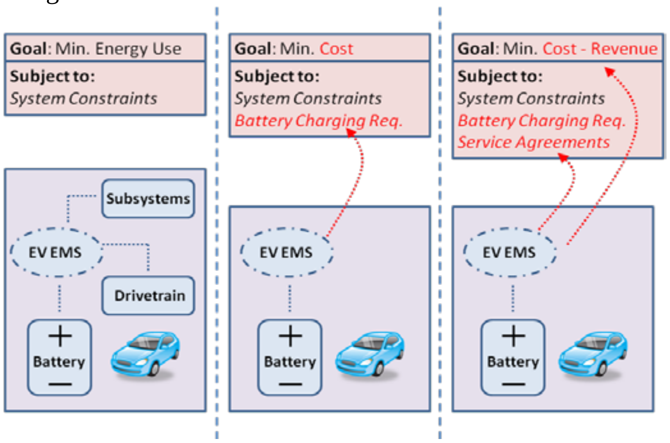

Fig 2. EV prosumer interactions. a) Standalone mode, b) Passive mode (provides charging constraint only), c) Multi-service mode (prosumer may provide energy and ancillary services).

C. *Coordinated Temporal Scales*

In the long term, the power balancing problem is solved by the actors engaging in long-term contracts. This is true for both large interconnections and for a homeowner who has a contract with the local utility. In the day-ahead time frame, a complex co-optimized market is used in order to determine generation, load, and reserve schedules of balancing entities within an ISO. Currently, microgrids and smaller prosumers do not contribute to power balancing; they simply draw their required power and pay for it at a rate consistent with their consumption level.

Emerging dynamic pricing, demand response, distributed storage, and frequency regulation programs by smaller prosumers are clear indicators of a trend towards procurement of services to balance power using distributed resources at a variety of temporal scales [55, 56]. At the quasi-transient level, the balancing problem becomes one of regulating frequency, which involves system dynamics. Equation (3) summarizes the traditional simplified Bergen-Hill model of electric machine system dynamics involving a generator at node *i*:

$$M\ddot{\delta}_i + D\dot{\delta}_i = P_i^{Mech} - P_i^D - \sum_{j\in N(i)} P_{ij}(\delta_i - \delta_j) \tag{3}$$

where M is the machine inertia, D is the damping, and δ is the bus *i* voltage angle. Assuming no storage, in the steady state the generated power minus the power demanded is equal to the power injected to the grid at node *i*. The full dynamics model of realistic power systems is much more complex than (3) involving models for governor and valve dynamics and exciters and stabilizers. However, fundamentally the conventional generation dynamics are driven by machine inertia and hence correspond to a second order model [57]. Time scales of interest are from 30 milliseconds to about 30 seconds in practice.

On the other hand, inverter-based sources do not natively demonstrate the dynamics of machine systems, but the common frequency droop model for power control does exhibit a strong similarity to (3). As shown in [58], this dynamic inverter model can be represented by

$$D\dot{\delta}_i = P_i^{ref} - P_i^D - \sum_{j\in N(i)} P_{ij}(\delta_i - \delta_j) \tag{4}$$

which is identical to (3) under $M = 0$ and a replacement of input mechanical power by a control reference. This is a first-order model having inherently greater controllability than the corresponding second order model. Therefore, distributed inverter-based sources have the potential to support grid operations by offering novel energy services difficult to implement with traditional machine sources [59]. As will be discussed later, emerging lines of research in autonomous networked control can be applied here to analyze these inverter networks and design appropriate controllers to maintain stability with realistic communication networks.

The longer-term plant dynamics, as well as renewable and DER variability, govern system behavior on the order of minutes. Daily human activities govern the system behavior in the hour to hour time frame. In the longer times scales seasonal and long-term contractual aspects govern the system.

Table IV lists the various time scales and the balancing methods. Fundamentally, there is a continuum of prosumer mechanisms that allow for power balancing. Smart grid technologies, storage, demand shifting, and renewable variability are forcing power systems to address all these time scales, shifting from a reactive, passive behavior [60-63] to dynamic operational and scheduling behavior.

TABLE IV
POWER BALANCING TIME SCALES

Time Scale	Driver	Mechanism
24-hr and longer	Seasonal planning Provider decisions	Contracts
30 min - 24 hr	Human activity Energy storage	Energy Scheduling
30 sec - 30min	Wind/solar variability	Reserve Services
30 ms-30 sec	Machine dynamics	Freq. Regulation
< 30 ms	Power electronics	Fast Freq. & Voltage Regulation

Prosumer operation will incorporate the following aspects:

Dynamic, rolling horizon framework: Forecasting, estimation, scheduling, and interaction with other prosumers will be scheduled in advance and adjusted as new information becomes available [64].

Coordination of multiple time scales: The prosumer must address the day-ahead time frame with at most hourly granularity. Faster time scales may include minute-to-minute or second-to-second, and they will affect and be affected by operations in larger time scales [65]. The control dynamics associated with various implementations of these rolling horizons is an area of needed research. For example, a 24-

hour day-ahead schedule, rolling 6-hour commitment, and a 30-minute dispatch schedule may be an effective strategy for a generating company, but not for a residence.

Stochastic framework: Methods to address uncertainty in load and generation forecasts can alleviate some risk [66]. This has architectural implications, as a massive number of intelligent actors may be able to reach a more useful coordinated understanding of an uncertain behavior than a single centralized manager.

Adaptive: Learning capabilities in intelligent prosumer controllers can improve responses of many static protocols [60].

Proposition 3: *Prosumers, from large utilities to homes and EVs, will operate based on a look-ahead dynamic energy optimization mode that is multi-scale in nature and stochastic and adaptive by design.*

D. Distributed Autonomous Control

Recent advances in distributed networked control and multi-agent theory allows for a formalism under which the various actors of the future grid, i.e., the prosumers, will interact as autonomous agents pursuing their own objectives while observing system level constraints, which can be enforced in a decentralized manner [67, 68]. Applications of the theory of autonomous control have been recently proposed in the areas of multi-agent economics [69], power networks of inverters [70-72], power system protection [73], and microgrid control [70, 74-76].

A basic prosumer control paradigm is illustrated in Fig. 4. The prosumer has a certain need of power, which corresponds to a desired amount of imbalance or interchange. Let us denote this desired power as $\hat{p}_k$. Results from [68] demonstrate that prosumers can, in a decentralized fashion, reach a state of agreement on power interchange that minimizes total error from the vector of $\hat{p}_k$ and respects power balance. Interchanges at this state are denoted by $\tilde{p}_k$. Finally, let us denote by p_k the actual physical power interchange. The physical interchange may or may not be equal to the desired power or to the agreed upon value. Prosumers interact in this way to arrive at a network state given by the vector of p_k at time $t + 1$.

The following constraints apply:

$$\sum_k p_k = 0, \quad \sum_k \tilde{p}_k = 0 \tag{4}$$

Note that the sum of desired prosumer interchanges is not necessarily equal to zero. Agreement on $\tilde{p}_k$ to ensure power balance can be obtained in many ways. A fair approach, used in [68], is to arrive at consensus in which all prosumers share equal error (possibly weighted) measured by $\hat{p}_k - \tilde{p}_k$. System constraints, such as limits on the flow between two prosumers, can be enforced in a decentralized manner [77].

Proposition 4: *In the fast time scales, prosumers will monitor and adjust power imbalance to match a previously reached agreement. The agreed upon power imbalance will be determined using a control law implementable in a decentralized manner as a function of* $\hat{p}_k$. *Enforcement of the behavior of the prosumer will be based on the difference between the agreed upon interchange and the realized interchange,* $p_k - \tilde{p}_k$.

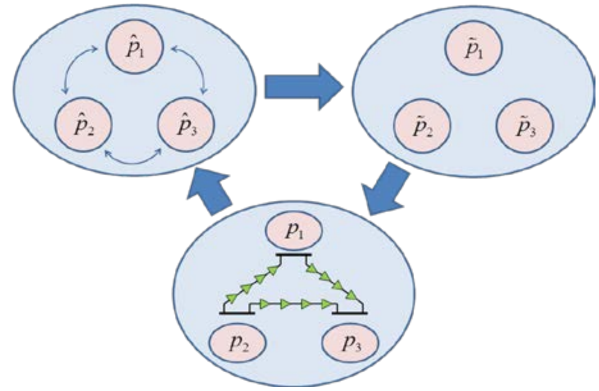

Fig. 4. Prosumer state variable progression.

Various market design mechanisms can be implemented to discourage prosumers to deviate from the agreement, providing a consistent mechanism to address malfeasance or the impact of internal device malfunctioning.

E. Prosumer Services Cyber-Infrastructure

The prosumer as a generic power system entity with various tasks of generation, consumption, and storage is simplified by the prosumer fulfilling its fundamental task of power balancing. We illustrate the relation between these tasks and imbalance with a few examples:

a) Power Plant: A power plant desires to produce and inject to the system as much power as possible. It hence engages in contracting, scheduling, maintaining, and dispatching activities in order to meet a contracted and scheduled power.

b) A Net Consumer: A consumer has a demand that needs to be met for a given horizon. The consumer engages in contracts for the procurement of electricity to meet the demand. It further engages in demand response or critical time pricing programs.

c) Microgrid: A microgrid produces, consumes, and stores. In order to achieve power balance, it schedules available local production (which may include renewable energy) and determines the needed power purchases from the external provider to meet its load, including possibly demand response. Functionality such as islanding further requires availability of enough local generation.

As we have mentioned, the prosumer balancing task requires balancing energy for a period of time and balancing power instantaneously. The examples a), b) and c) above can be seen as cases of a general objective of meeting a certain desired level of imbalance. The prosumer will utilize all its hardware, control, software systems, and decision logic in order to optimize an objective function associated with this imbalance. In a decentralized setting, the prosumer imbalance is determined based on the actions of all the prosumers.

To the external prosumers, the imbalances are abstracted from the specific generation, consumption, and storage capabilities. The concept of virtual power plants [78-82] already utilizes an abstraction of generation services, in which generation can be obtained from generation, demand response, discharging storage systems, or their combination.

The prosumer service architecture must:

a) Specify which services will be provided. The design must address how the prosumer translates the physical capabilities of its infrastructure (generation, consumption, storage, and transportation) and aggregates those capabilities into a service. For instance, consumption, generation, and storage can be abstracted into a balancing service. Transportation services may be abstracted as a transfer service that encapsulates grid security, including contingency considerations.

b) Determine how the prosumer, based on its infrastructure capabilities and objectives, decides which services to offer and the optimal strategy to procure its needed services (see Fig. 5). The resources have capabilities that differ, for instance, on how fast the resource can be made available, how likely is a certain resource to be available, how likely it is to actually work (dependability), and its cost to operate.

c) Determine how the services are implemented in software and published and consumed by prosumers. In order to exchange services, the prosumer requires a cyber-infrastructure that ensures that each prosumer can register, publish, discover, and consume services. The services are transactional and are exchanged in a marketplace. Because both the autonomous control protocols (which ensure reliability) and the dynamic energy scheduler (which ensures optimality) operate in a decentralized mode, the marketplace is much thinner and hence may be more efficient compared to existing electricity markets.

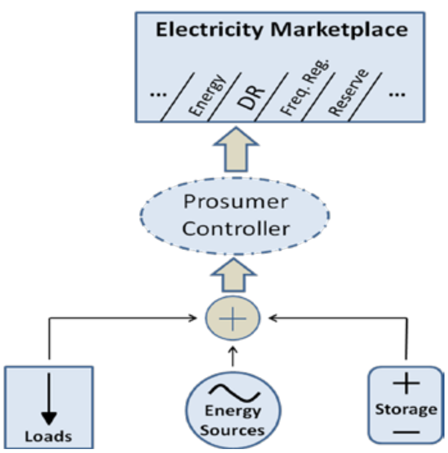

Fig. 5. A prosumer may compose several assets to form a service that is offered in the marketplace, which may have no visibility to the specific implementation of the service beyond a quality-of-service requirement.

Proposition 5: *A real-time web-services paradigm must be utilized in order to enable decentralized prosumer control and the procurement and consumption of prosumer services. Prosumer services must interpret the infrastructure capability into abstracted services associated with imbalance and transportation.*

The core architectural elements listed in this section enable and ensure that the desired functionality is achieved through the architecture.

IV. Future Grid: Layered Architecture

A. Layering Requirements

The prosumer abstraction enables many power grids, large and complex as well as small and simple systems, to be modeled as prosumers. It is desirable that in the future grid all these prosumers be able to interact with each other in a seamless manner. A flat architecture [50, 51] emerges in which prosumers are visible and can interact with potentially any other prosumer in the grid. Under this structure, the implementation complexity of use cases that today involve many hierarchical organizations (such as EV assisted frequency regulation) is drastically reduced.

The core architectural elements listed in the previous section and the future grid infrastructure must be arranged in a cohesive and modular paradigm to allow stakeholders to test, design, and implement decentralized power system control technologies. A layered framework supports those objectives.

The high-level view of the layers involved in the proposed architecture is illustrated in Fig. 6.

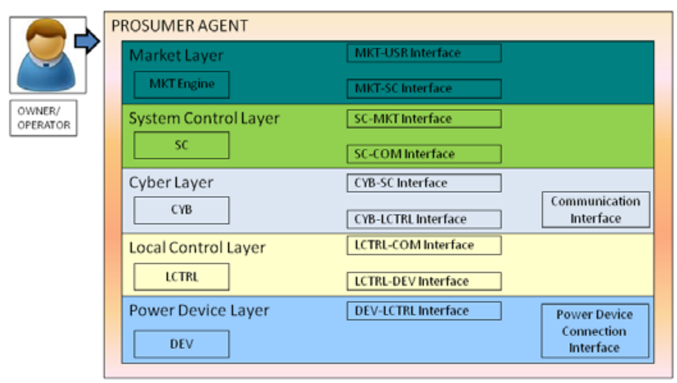

Fig. 6. Layered architecture of each prosumer.

Proposition 6: *A layered, cyber-physical architecture that combines the core elements with the infrastructure components of the future grid will enable scalability, and interoperability of decentralized control.*

Each layer is agnostic of the implementation of the other layers and communicates through well-defined interfaces.

We now describe in more detail the various layers of the architecture and their interactions.

B. The Device Layer

The device layer corresponds to the electric power devices themselves: generating machines, PV panels, turbines, transmission lines, transformers, batteries, and any other fundamentally electrical equipment. The device layer involves core high-voltage T&D technologies, but it also includes low-voltage wiring, light bulbs, and the electrical components of appliances such as motors.

C. The Local Control Layer

The local control layer corresponds to the hardware and software used for controlling stand-alone devices. Examples of these are a generator governor or an EV battery charger. This layer involves the device instrumentation, sensors, actuators, controllers, embedded algorithms for local control, and local protection devices.

D. The Cyber Layer

This layer consists of communications, information, and computation infrastructures. It is a platform that supports control logic and economic decision making at the system level. Because the architecture is decentralized, the following is expected:

a) The computation is associated with prosumers optimizing their own objective functions subject to coupling constraints. The computation layer must therefore support distributed, embedded computation.

b) The information layer will support distributed information management: e.g., distributed databases.

c) The communication architecture and network topology is consistent with a decentralized information paradigm.

E. The System Control Layer

The system control layer addresses the system security and reliability functions of the grid. It involves two aspects: control internal to the prosumer (monitoring, optimization, and internal network communication) and coordination of prosumer action with the wider system to ensure system security and reliability in a decentralized manner. The internal system control may include some of the functions currently available in EMS and DMS systems, such as state estimation or security assessment. The external function must address interactions with the external world. This includes prosumer initialization (self-identification, recognition, agreement, assignment, and formation protocols), as well as decentralized reliability protocols.

F. The Market and Service Layer

By the same token, the market layer consists of two aspects. The internal aspect addresses the economics of the internal prosumer, such as production, storage, demand shift and other costs. This aspect also addresses satisfaction functions that realize objectives of economics, sustainability, and support for energy security and energy services. The external function addresses interactions concerning service prices and hence the interpretation of price signals, service transactions, negotiation, collaboration, and strategic decision-making.

Overall, the proposed layered architecture supports a scalable generalization of power systems based on prosumers. The layers shown in Fig. 6 have specific implementations for prosumers of various sizes such as an electric utility, smaller prosumers such as a building, and the smallest prosumers such as an electric vehicle. Each internal layer can be implemented with unique algorithms and levels of detail. The layer interfaces and distributed protocols are unified and shared by all the prosumers.

V. Discussion

A. Meeting Desired Functionality

Table V describes how the future grid objectives are achieved, and Table VI describes how the desired architectural properties are achieved.

B. Industry Evolution

The various layers of the prosumer architecture abstract some of the functionality that is contained in the current electricity domains as proposed by the Gridwise Architecture Council Reference Model [4]. This reference model is being used by the industry in several ongoing smart grid projects. We note the following limitations of the current Reference Model in Fig. 7:

a) Large scale renewable energy resources would belong to the Bulk Generation domain. Mid-scale and small-scale DER belong to the Distribution and Customer domains, respectively. Thus “generation” would be distributed in three of the four infrastructure domains.

TABLE V
ACHIEVING DESIRED ARCHITECTURAL FUNCTIONALITY

Functionality	How it is achieved
Ultra-reliability	All prosumers contribute to reliability though balancing services. Autonomous control protocols consistent across all scales for robustness under communication loss. Limited data exchange supports cyber-security.
Economic Efficiency	Prosumers pursue individual economic objectives while adhering to unified reliability and control protocols. Incorporates all industry actors. Removes conflict of interest between profit and energy efficiency. Leverages existing sensing and communication infrastructure.
Sustainability	Enables prosumers to achieve their energy objectives including energy efficiency and conservation. Creates opportunities for novel green energy service propositions.
Support for Energy Security	Integrates EVs architecturally as mobile prosumer service providers, supporting transition away from gasoline-powered vehicles.
Support for Energy Services	Allows the proposition of many innovative services by any actor under a unified framework.

TABLE VI
ACHIEVING DESIRED ARCHITECTURAL PROPERTIES

Property	How it is achieved
Robustness	Reduced communication and data exchange requirements through decentralized control. Grid autonomously self-stabilizes upon fault or loss of channels.
Scalability	Prosumer abstraction and flatness allows integration in networks of any size or structure.
Technology Independence	Characteristics of power devices are abstracted, providing a framework for interoperability.
Backward-compatibility	Model compatible with current generation control, but generalized to power systems of any scale.
Incremental deployability	Incremental downward deployment by allowing utilities, microgrids, etc. to provide services. Incrementally enabling energy services allows a stepwise approach to the future grid.

b) Large storage such as pumped hydro would belong to the Bulk Generation domain. Utility-scale storage would be assigned to the Transmission or Distribution domains. Small-scale storage, such as home batteries or EVs, belongs to the Customer domain. Thus storage is distributed among the four infrastructure domains.

c) The consumer requires operation services such as installation, market services such as selling excess electricity, and other services such as energy efficiency programs. In addition, the consumer should also be able to provide services, for instance, a building offering EV charging in its parking lot. Services would then be distributed among five domains: Distribution, Markets, Operations, Services, and Consumers.

The prosumer architecture represents a higher abstraction where portions of the domains' intelligence have been embedded in the prosumer layers as shown in Fig. 7.

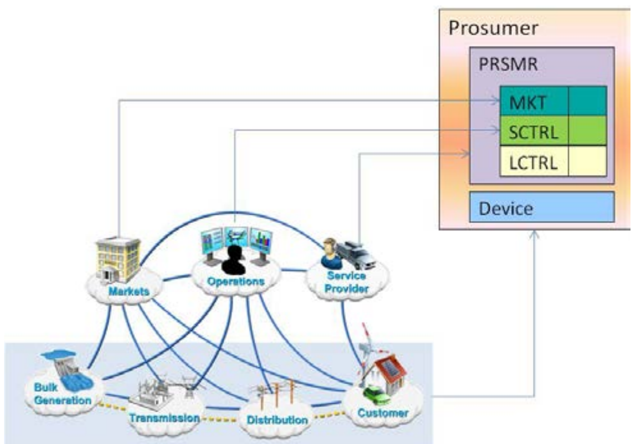

Fig. 7. Industry model evolving to prosumer model.

In order to address the limitations of the existing reference model, we propose an evolution to a prosumer that is strategically designed to achieve:

a) Abstraction of energy services in a single agent type.

b) Encapsulation of some of the service requirements in the prosumer, realizing a distributed intelligence.

C. *Brief Selection of Smart Grid Architectures*

Several smart grid control algorithms and frameworks, both centralized and decentralized, have been proposed to effectively deal with some of the challenging requirements of the future grid. Here we mention a few relevant propositions and describe their relation to the proposed architecture.

In [83], a method for efficiently using distributed renewable generation in distribution networks is described along with the algorithms needed and a compatible communication system design. In the prosumer-based architecture, this represents one application that many prosumers connected to a distribution network could agree to deploy. Each prosumer would use its local control capability to form a service that it could, through the communication network, offer other prosumers several hops away in order to satisfy the system control objective of power balance. Therefore, this method has clear components in each of the middle three layers of Fig. 6.

Power system reliability is shown to have many implications for communication system design in [84]. One of the salient design principles gleaned from this analysis is that functions requiring fast communications over short distances (e.g. within a neighborhood) must be separated from functions that operate over longer distances and have longer dynamics (e.g. forward market operations). This observation and the communications architecture presented would inform the implementation of the communication layer, the upper interfaces, and various blocks in the system control layer since functions with different characteristics are separated.

A collaboration between European standards groups CEN, CENELEC, and ETSI has designed a reference architecture [85] as an extension to the NIST smart grid framework with distributed energy resources. This model also simplified the NIST interoperability layers into business, function, information, communication, and component layers in the same direction as our proposed architecture layers. There remain several limitations in this proposal. For instance, recent panels have recognized that distributed storage and electric vehicle "domains" are needed. Additionally, distributed energy resources can be part of either the distribution domain or the consumer. A prosumer model more clearly addresses these limitations.

It should be recognized that these various frameworks solve challenging problems associated with the future grid without claiming to be a comprehensive power system architecture. It is possible that many of the decentralized control frameworks in the literature are in fact compatible within the same architecture as long as their objectives, communication requirements, control interactions, and economic implications are understood. The prosumer-based architecture provides a way to compare various control strategies using common categories and terminology to identify areas of conflict or overlap.

VI. Conclusion

The forces growing to influence the power grid and electricity industry will push the centralized control architecture to its breaking point. A new framework is needed to unify many of the new value propositions and features expected of the future grid. As the basic unit of the model proposed here, the prosumer encapsulates the functions of any electricity system actor in an abstracted sense.

From this reformulation of the grid, a service-oriented structure emerges to support the trade of energy products between prosumers. Because of the time-sensitive nature of these services and their correspondence to physical grid actions, this structure forms a time-aware cyber-physical system alongside the power grid. Rather than a liability, this new cyber-physical system enables not only trading of energy services but also the ability to conduct distributed agent-based protocols to ensure system reliability. Autonomous networked control has demonstrated non-intuitive and widely useful results with applications, until now, largely outside power and energy fields. A new control architecture has the opportunity to use these results to great benefit.

Explicitly assigning objective function responsibility to each prosumer results in some simplifications. One example is the conflict between energy provider profit goals and consumer energy efficiency goals. This decoupling is not a problem inherent to the prosumer architecture. More generally, many regulatory policies might be simplified through the standardization of energy services traded among prosumers.

Prosumer models are general enough to describe the current industry architecture either in a regulated or deregulated setting. Specifically, the difference amounts, to a large extent, to a redrawing of boundary lines between prosumers with respect to who owns and operates the transmission lines. Further, the prosumer models are backward-compatible in the sense that, for example, any of today's residential loads is a prosumer with stochastic behavior and a single service – purchase and consume energy in real time.

This architecture ties together several significant trends in ongoing academic and industrial research and provides indicators of specific needs. One crucial element is the identification of agent-based behaviors, requiring only local and limited communicated information, that can ensure system-level reliability and security for the power grid. Following from this is the need to design or identify a communication system to allow for potentially any pair of agents in the system to communicate a small amount of data with respect for time sensitivity. Finally, there is a quickly growing need to develop optimization algorithms that can solve problems of unit commitment and dispatch over multiple areas and in a stochastic setting. The development of these pieces will represent important strides in the evolution of power grid control architecture.

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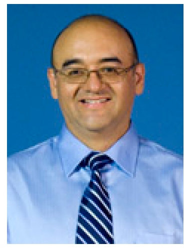
BIOGRAPHIES



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