Prosumer-Based Smart Grid Architecture Enables a Flat, Sustainable Electricity Industry

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Abstract — **Managing distributed energy sources, energy storage, and consumer's active behavior coupled with sustainability objectives, requires significant changes in the architecture and technologies used to control the electricity infrastructure. Electricity consumers are evolving into economically motivated "prosumers" that not only consume, but can also produce and store electricity. Prosumers can become smart energy ecosystems if they are equipped with technology and intelligence that allow them to achieving their own objectives.**

This paper demonstrates that any electric power system, from large interconnections to homes and appliances can be modeled as a prosumer. It shows that the emerging interactions and transactions related to electrical energy can be implemented using a prosumer-based architecture, which would replace the traditional, one-way, generation–transmission–distribution-consumer model. We propose a prosumer-based, service-oriented architecture, that is remarkably flexible and scalable, and which would ultimately enable a "flat" business paradigm across the industry. We describe the major components and services of this architecture, present an application to the problem of demand response, and discus several innovative features enabled by the proposed paradigm.

I. INTRODUCTION

A large number of initiatives are taking place around the World on smart grid technologies and projects [1,2]. The ultimate goal of these initiatives is to transform the electricity infrastructure to make it more flexible and secure, so it can support the needs of a more sustainable and efficient society driven by empowered consumers [3,4]. Many technologies from smart meters to distribution automation to renewable sources are being deployed at fast pace. However, there is growing concerns on policy and architecture, and a clear roadmap on how the various technologies and efforts fit together to achieve the objectives identified for the smart grid is not available. For instance, in the US, the penetration of smart meters will reach 25% by 2012 [5], but dynamic pricing programs have very low penetration. The FERC's National Assessment found that dynamic pricing currently has little to no influence in 40 states [6]. Therefore, the vast majority of consumers can do little regarding their energy utilization.

Work on the design and architecture of the future grid is as important as work on the technologies and products that would realize a smart grid vision. At the moment, it is difficult to establish a strong connection of how the current technologies being deployed realize each one of the seven smart grid goals identified by DOE [7].

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A significant part of the work on smart grid architecture has focused on information architecture and application interoperability. These are two important components, but they are not the architecture of the electricity industry. In the same manner as an intelligent building requires an information architecture and an architect of the building itself, the smart grid requires both elements. This paper deals with the *architecture of the entire electricity industry*. It does not address the technology aspects, which are the logical next step.

A key design concept in electricity systems is the direction of flows, which affects conductor sizing, protection schemes, etc. Traditionally, flow has been from bulk generation through transmission and distribution to the end consumer. Distributed renewable energy and storage can be attractive at commercial, residential and industrial level, in particular if the consumer is able to sell any excess of energy to the utility or to others. This requires allowing two-directional physical flow at the distribution level.

An interesting analogy of a network infrastructure which already provides two-way flow is the internet. The internet is one of the most notable developments in the history of mankind, allowing unprecedented exchange of information, creating millions of IT jobs and enabling innovation at massive scale [8,9]. The internet has enabled what Friedman [10] calls the "flat world", where information is widely available, individuals can learn about any topic, and businesses can dramatically increase their efficiency and reach. The internet has become a very powerful infrastructure because it is based on an open, distributed, flat architecture that enables the actors to interact with the rest of the World. For instance, a small company or individual can download, post, or create web pages and blogs in the same manner as a large company does; a person can chat with other person who is in the same building or across the planet. While there is still physical movement of electrons carrying the information through a myriad of routers and stations, the physical flow is transparent to the user who interacts at the same logical level with others.

Similar characteristics are now demanded from the electric grid: a small consumer with a solar panel should be able to: provide excess electricity to the utility, purchase power from different providers, and be hands-off letting its home energy management system schedule and optimize her energy utilization.

The central topic of this paper is the smart grid architecture that would enable a "flat" electricity industry. We describe how this architecture drastically simplifies controlling the grid while providing a platform that supports innovation across the industry and ensuring that the ultimate smart grid objectives can be achieved.

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II. Background

A. Smart Grid Architecture Efforts

The National Institute of Standards and Technology (NIST) has been entrusted with the task to coordinate the development of a framework for interoperability of smart grid devices and systems. NIST has proposed a conceptual reference model for the smart grid consisting of seven domains, as shown in Fig 1. A large portion of the ongoing development of smart grid technologies is based on this 7-domain model. NIST develops standards for smart grid and supports the interoperability stack and framework proposed by the GridWise Architecture Council (GWAC). The GWAC has the objective to identify architectures needed to facilitate the inter-operation of systems, devices, and institutions that encompass the nation's electric system [11]. As it will be described in the reminder of this paper, the proposed prosumer architecture is compatible with the GWAC interoperability stack and it can be seen as an evolution of the NIST reference model to a more flexible framework.

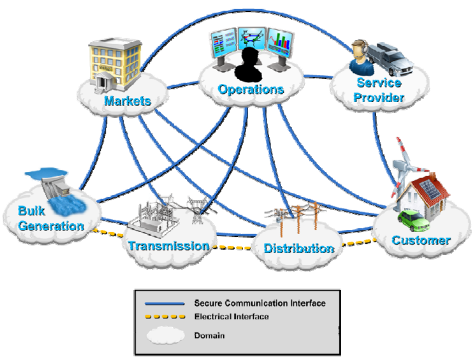


Fig. 1: NIST Conceptual Reference Model

B. Service Oriented Architectures

Over the last decade, Service Oriented Architecture (SOA) has gained popularity in the domain of enterprise computing due to the agility and adaptability it provides in order to meet the ever changing business level requirements. Web Services has emerged as the most popular technology for developing SOA based solutions because of wide acceptance of its standards. SOA is a design philosophy which aims at developing systems which are loosely coupled, flexible, reusable, and adaptable. The first generation of web services standards dealt with three aspects: Service Description (WSDL), Service Discovery (UDDI), and Messaging (SOAP). There is an ever-growing family of second generation web services standards that build on the first generation to provide additional capabilities such as transactions, reliable messaging, and security. Some examples of these standards are WS-Coordination, WS-Reliable Messaging and WS-Security [12].

There is a growing need for software architectures that can cope with the adaptability and reliability requirements of the future electricity grid. In this context a web services-based SOA would provide:

1) *Support for Development*: a) Improves the development process for new applications by using entity-based services, b) Opens the door to using model-driven software engineering, and c) Handles the interoperability issues among various vendors and different entities.

2) *Run- Time Support*: a) Allows easy upgrade and deployment of solutions through composition of web services, and b) Provides support for adaptability under changing management needs.

It is to be noted that the concepts of Web Services and SOA were developed in the domain of enterprise computing. Some of the requirements of a cyber-physical system (CPS) such as the smart grid are different from that of an enterprise computing system. Therefore, smart grid applications would require enhancements to the current web services infrastructure, such as support for *timeliness*. Modifications to web services standards to tune them to CPS demands are highly required and have been already proposed [13]. In addition, there is a need to improving the model driven software engineering techniques for web services so that they can be applied towards achieving the reliability and certification goals associated with a CPS-like smart grid.

III. The Prosumer

Traditionally, power system participants have been strictly producers or consumers of electricity. Today, distributed renewable energy sources, storage, and demand response, allow the consumer to produce and to store energy. This new emerging entity is called the "prosumer", an economically motivated entity that:

1. Consumes, produces, and stores power,
2. Operates or owns a power grid small or large, and hence transports electricity, and
3. Optimizes the economic decisions regarding its energy utilization.

Physically, the prosumer may consist of a combination of components: energy sources, loads, and storage; and an electric grid. The prosumer also contains controls to operate is system, and a market or other economic decision making system. The prosumer has a set of functions associated with interactions to the external world such as consuming or producing energy and participating in the market. It has also two internal functions: operate its power system, and economically optimize its energy use. Fig. 2 illustrates the concept of a prosumer.

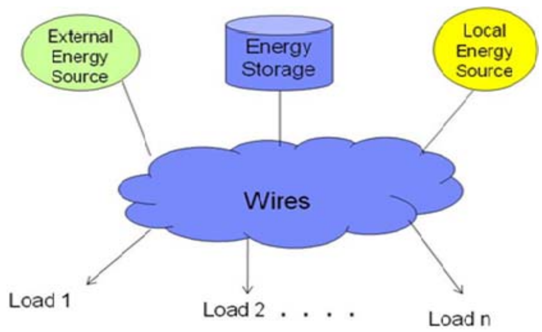


Fig. 2: A Generic Prosumer

It is important to note that Fig. 2 can represent a variety of electric systems, such as: Electric Interconnection, Independent System Operator (ISO), Utility, Microgrid, Industrial Facility, Commercial Building, and a House. Taking the model to the extreme, Fig. 2 can represent a laptop computer with a solar charger, where the loads are the processor, the disk, etc. All these electric systems can conform to a single concept of prosumer.

We also note that components such as the External Energy Source or any combination of the components shown in Fig. 2 can be seen as prosumers acting as loads, energy sources, transmission, or storage. The abstraction of electric power components as prosumers is illustrated in the Fig. 3, which shows the example of a larger prosumer that contains the wires and some of the loads.

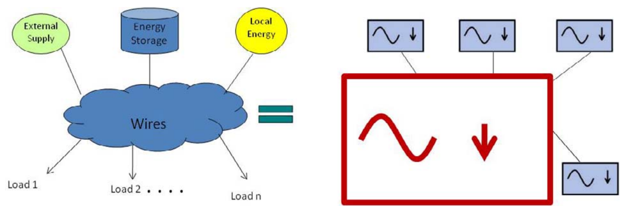
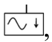


Fig. 3: Equivalence of power system components as prosumers and aggregation of components into a prosumer.

We use the symbol , to represent a prosumer. The concept of prosumer can be extended and used to model the entire existing electricity infrastructure. Fig. 4 illustrates this process. In a) the hierarchy of electric power systems from interconnection down to homes is shown. There may be other layers down to the "toaster" level if wanted. Fig. 4 b) shows how all the electric systems can be modeled as prosumers. Fig. 4 c) shows that instead of being organized in a hierarchical structure, all the prosumers would interact at the same level. These three figure are logically equivalent.

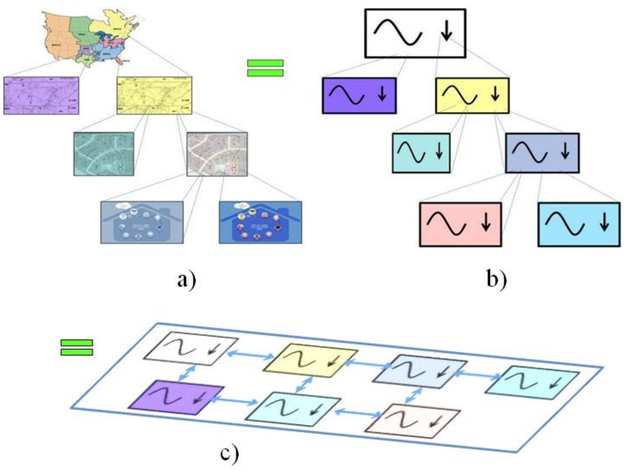


Fig. 4: Logical equivalence of electric power systems prosumers a) Existing hierarchical industry paradigm, b) All power systems modeled as prosumers, c) Prosumers seen as same level entities.

It is critically important to note that the prosumer abstraction shown in Fig. 4 allow us to claim that:

a) Any power system can be represented as a prosumer
b) Prosumers currently organized in a hierarchical structure interact only with other prosumers.
c) Prosumers can interact with all the other prosumers at the same level.
d) Because prosumers can contain all the components of electric power systems: production, storage, transportation, and consumption, all the interactions associated with electricity can be modeled through interactions between prosumers.

An architecture based on prosumer interaction can therefore be proposed. In this architecture all the prosumers are located at the same level interacting through common interfaces.

IV. Smart Grid Architecture

The prosumer-based layered architecture shown in Fig. 5 can be proposed in order to implement the prosumer interactions. Each one of the control layers above the device layer provides more intelligent mechanism for grid control. Each layer is agnostic about the implementation of the other layers and the interactions are defined based on service interfaces.

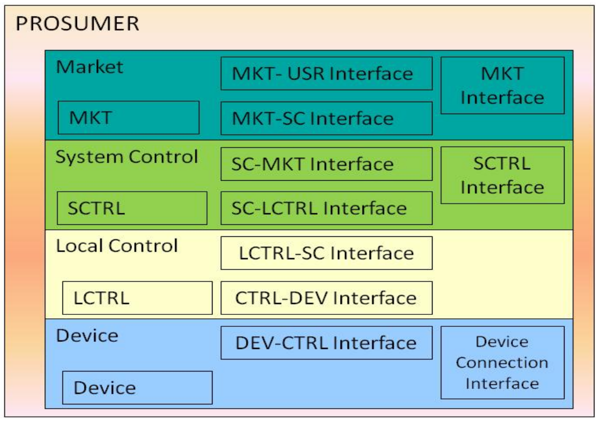


Fig. 5: Prosumer-Based Layered Architecture

A. Architecture Layers:

a) *Device Layer*: This layer represents the "bare metal" level of power system devices and is associated with physical connectivity of electric components. While "dumb" devices usually do not provide sophisticated interfaces to the local control layer, smart devices usually provide mechanisms for local control and beyond.

b) *Local Control Layer*: This layer represents the control mechanisms of devices such as: the governor or exciter of a generator, the LTC control of a transformer, the battery charger of an electric vehicle, etc. The local control is co-located with the device and it can include electromechanical, power electronics and software components depending on the type of controller. The local controller is capable of acting based on local information from the device, and it must provide interfaces for interactions with the system control layer.

c) *System Control Layer*: This layer represents the coordinated control required to meet the functional and performance system level objectives such as coordinated volt-var regulation, loss minimization, economic and secure operation, system restoration, etc. The system control layer continuously monitors the system devices and keeps track of the system state by using applications such as state estimators. The system layer takes all the information provided by local controls, and determines a set of control commands by using advanced grid security and optimization applications. The control actions are passed on to the local control layer for execution by the devices. EMS and DMS applications (plus the operator) are examples of systems control layer for ISO and electric utilities. Corresponding energy management applications are currently being developed for microgrids, buildings, homes, etc., forming corresponding prosumer system control layer.

d) *Market Layer*: This layer deals with the process of control decisions for the available resources incorporating economic objectives. Market layer's decisions are always updated by the system control layer according to the system constraints. The market layer utilizes all the system control information and uses advanced economic and financial applications such as LMP calculation, reserve co-optimization, risk management, load and price forecasting, etc., in order to generate control actions for the system control layer or price signals for the external world.

B. Prosumer Services and Interfaces

We propose a Web Services-based SOA infrastructure for smart grid by standardizing a set of entity-centric web services. This is illustrated in Fig. 6.

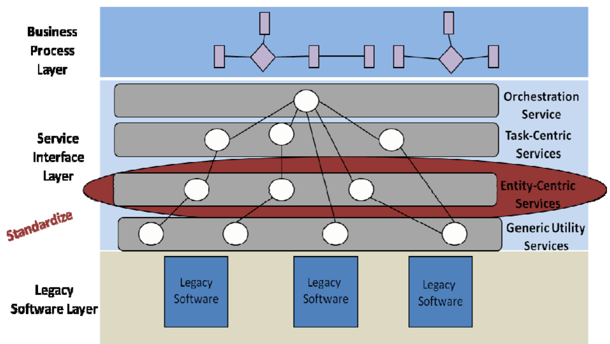


Fig. 6: Role of Entity-Centric Services in SOA

The prosumer is the main entity in our smart grid software infrastructure. From a software perspective, the prosumer is a (web) service, *PRSMR*, which is the composition of various services representing the control layers. The local control, system control and market control layers of the prosumer are services as well: *MKT*, *SCTRL*, and *LCTRL*, respectively. We propose a WSDL definition for each prosumer layer service and the prosumer service itself. The advantage of this approach is that these services conform to the same architecture for any type of prosumer from interconnection to home. The following illustrates the definitions of service interfaces for local control, system control and market services.

```
LOCAL CONTROL SERVICE (LCTRL) INTERFACE
<interface name= "LCTRLInterface">
  <operation name = "WhoAmI">
    <input message="getIDMessage"/>
    <output message="giveIDMessage/>
  </operation>
  <operation name = "DescribeCapability">
    <input message="requestCapabilityMessage"/>
    <output message="giveCapabilityMessage/>
  </operation>
  <operation name = "GiveRealTimeStatus">
    <input message="requestRealTimeStatusMsg"/>
    <output message="giveRealTimeStatusMsg/>
  </operation>
  <operation name = "ReceiveRealTimeControl">
    <input message="sendRealTimeControlMsg"/>
    <output message="AckRealTimeControlMsg/>
  </operation>
</interface>
```

```
SYSTEM CONTROL SERVICE (SCTRL) INTERFACE
<interface name= "SCTRLInterface">
   <operation name = "SetOperatingPoint">
     <input message="SetNewProsumerStateMsg"/>
     <output message="AckNewPrsoumerStateMsg"/>
   </operation>
     . . .
</interface>
```

```
MARKET SERVICE(MKT) INTERFACE
<interface name= "MKTInterface">
  <operation name = "NegotiateNewPrice">
     <input message="SetNewPriceMsg"/>
     <output message="AckNewPriceMsg"/>
  </operation>
  <operation name="DeterminePriceForDownstream">
    <input message="GoalForNewPriceMsg"/>
    <output message="DownstreamNewPriceMsg"/>
  </operation>
   . . .
</interface>
```

The details of power system quantities such as voltage, active and reactive power are contained in messages used in the definitions. For example, *giveRealTimeStatusMsg* of *LCTRL* service would include all the real time status values that are of interest to a service that controls that particular device. The prosumer service (*PRSMR*) consists of a set of numerous local control services (*LCTRL*), one system control service (*SCTRL*) and one market service (*MKT*). The prosumer service exposes the interface to the system and market services to the external world. Thus the *interface* of *PRSMR* consists of the interfaces of *SCTRL*, the interface of *MKT* and an operation to give out the identity of the prosumer.

Our proposed infrastructure moves the concepts of web services and SOA beyond the enterprise domain and applies them to the development of the cyber-physical energy system. The architecture for smart grid, built on the concept of a prosumer can leverage the cloud computing infrastructure in order to implement the architecture in a distributed manner. We argue that this prosumer-driven, web services-based distributed control architecture is suitable for supporting in a scalable manner, all emerging smart grid applications.

C. Detailed Example: Residential Demand Response

Let us consider the following prosumers involved in a demand response application: Utility, Neighborhood and Home, with corresponding prosumer services: *U_PRSMR, N_PRSMR,* and *H_PRSMR*. The following takes place in a demand response application scenario:

1) Based on wholesale electricity market rates and information about utility owned facilities, the market layer of the utility prosumer (embodied by *MKT* inside *U_PRSMR*) decides the time and amount of the required load reduction. These decisions are passed on to the system control layer utility prosumer (embodied by *SCTRL* inside *U_PRSMR*).
2) The system control layer runs state estimation and optimization applications to make decisions about the utilization of individual assets under utility control.
3) Now, there are two types of decisions:

a) Local operation of non-smart devices. For instance the system control layer of *U_PRSMR* passes on the commands such as desired output to storage owned by the utility to reduce ongoing charging.

b) Interactions with other prosumers. For instance the *U_PRSMR* passes a message requesting reduction of load to a neighborhood prosumer service *N_PRSMR*. This message may be in the form of a system level request to the *SCTRL* in *N_PRSMR* or as a price signal to the *MKT* in *N_PRSMR*

4) Assuming that the signal passed to *N-PRSMR* is a price signal, the *MKT* of *N_PRSMR* processes the price signal and sends instructions to its *SCTLR*
5) The *N_PRSMR SCTLR* looks at the state of the neighborhood electric system and makes decisions about the utilization of resources.
6) Again, there are two types of decisions:

a) Local operations of neighborhood non-smart devices, such as storage, capacitors (if needed), etc.

c) Interactions with other prosumers. For instance the *N_PRSMR* passes a message requesting reduction of load to a house prosumer service *H_PRSMR,* in the form of system level request to the *SCTRL* or as a price signal to *MKT* in *H_PRSMR*

7) The *H_PRSMR MKT* receives the pricing signal sent by the *N_PRSMR* and passes instructions to the *SCTRL* which request real-time state of all appliances and makes load reduction decisions that are passed on to the *LCTRL* of the house devices including PHEV, solar panels, etc.
8) The resulting state of the actions is passed from *H_PRSMR LCTRL* to its *SCTLR* and *MTK*, and then the aggregated information is passed to the corresponding layers of the *N_PRSMR* and *U_PSMR*, hence completing the demand response control interaction.

V. IMPLEMENTATION REQUIREMENTS

Having described the basic interactions under the proposed architecture, this section concentrates on the location of the computing resources and the software representing the intelligence encapsulated in each prosumer service. Clearly, the *LCTRL* for each individual device is co-located with the device itself. We propose the following locations for the *SCTRL* and *MKT* services of each *PRSMR* as seen in Table I. Prosumers can be set to match the current organization of the industry. As the electricity industry moves towards a more distributed architecture, prosumers will naturally combine, split, or grow and the location of the *SCTRL* and *MKT* services of various prosumers may migrate to the cloud.

Table 1: Location of *SCTRL* and *MKT*

Prosumer	Location
Home	Home Energy Management System
Neighborhood	Cloud Computing
Substation	Substation Control Room
Utility	Utility Control Centre
Control Area	ISO Control Centre

The power system control infrastructure will have a number of control applications running concurrently. Some applications such as protections will have higher temporal priority compared to others. Each one of these applications will require status updates or interactions among software agents at different rates. For example, applications like wide-area protection schemes and AGC require faster update rates while hourly demand response might require slower updates based on market conditions.

The implementation of the prosumer based control architecture requires a communication and middleware infrastructure that supports interactions among software agents at various different rates and can associate a preference to each of the applications.

VI. ADVANTAGES OF THE PROSUMER ARCHITECTURE

The propose architecture enables a transformational process for the industry in which the control and information architectures are decoupled from the existing institutions. These institutions would be free to evolve driven by technological and market forces. Fig. 7 illustrates the evolution from the GWAC 7-domain reference concept previously discussed towards a flat industry enabled by the proposed prosumer-based architecture. The markets domain evolves into the market layer of the prosumer; the operations domain evolves into the systems control layer of the prosumer; the service provider domain is transformed into the prosumer services; and, the other four domains: generation, transmission, distribution, and the customer evolve into the components of the prosumer. The fact that all the principal actors in the industry can be modeled as a generic entity, the prosumer, allows obtaining a flat electricity industry.

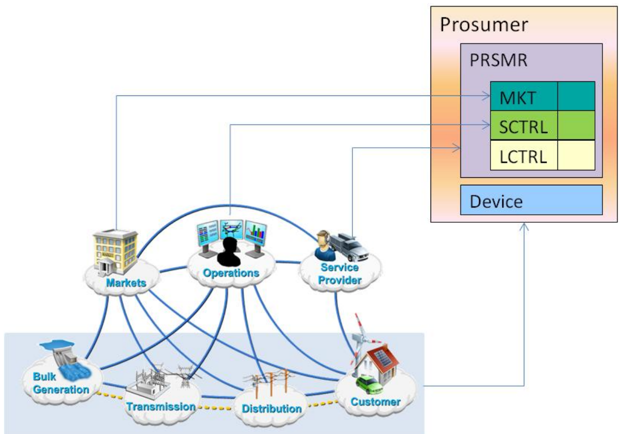


Fig. 7: Evolution of Domains to Flat Industry

The proposed architecture is capable of enabling several grid features that are currently not possible. We list five of them:

a) *Interactions with potentially all the prosumers in the interconnection*. Once the utilities, buildings, microgrids, houses, etc are recognized as potential providers of generation, storage, consumption, and (in some cases) transportation services, the architecture allows a prosumer to request generation or storage services from other prosumers not physically connected to it. If a user in Florida wants to purchase power from the Midwest, it can purchase generation services from a wind provider in Minnesota and the corresponding transmission services from providers. The model allows such transaction.

b) *Consumer choice of generation and storage*: as a consequence of a), consumers will be free to choose from a large set of generation providers. The utility physically connected to the house or building must simply provide transportation services, which will evolve into "shipping and handling" services.

c) *Support for Distributed Control*: The prosumer has a system control layer that can be used to control itself as a microgrid. Synchronization, volt/var regulation and regulation can be provided autonomously.

d) *Support for Autonomous Restoration*: Individual prosumers at the house, building level, etc can interact and coordinate restoration actions based on predefined protocols, to incrementally restore the grid.

e) *Ancillary Services Provision*: Prosumers can interact and coordinate the provision of ancillary services such as regulation and reserve in a distributed manner. The prosumer services will expose its regulation and reserve capabilities and negotiate the procurement with neighboring or distance prosumers. This will allow for instance frequency regulation contributions by electric vehicles and distributed storage.

f) *Remote Coordination*: The fact that prosumers can interact remotely allows synchronization of highly variable, distant renewable generation with schedulable loads such as electric vehicles and storage, hence minimizing the effect of variability.

VII. Conclusion

The traditional electricity consumer is now evolving into an entity with capabilities to generate locally and to store electricity. This represents a shift from the unidirectional assumptions and architecture on which the power system infrastructure was built. Because the electricity infrastructure is expensive and very large, it cannot be replaced. Thus the only mechanism to realize the economic, reliability, and sustainability goals of the future grid is to propose a new control architecture.

The advantages of realizing "flat" industries have been demonstrated in the communications and information industries and the vast majority of the developed world can be considered relatively flat for business purposes. If similar goals are desired for the energy industry, a similar "flat" paradigm must be proposed. This paper shows that all types of electric power systems can be modeled as a common entity known as the prosumer, which can provide services of generation, storage, transportation and consumption. Prosumers can interact with others at the same level, hence realizing the benefits of a flat industry.

A web services, service oriented-based architecture has been proposed for the future grid based on the prosumer concept. This architecture is compatible with the requirements for interoperability and scalability and can serve as platform for the development of a large number of innovative applications. The proposed architecture enables the transformational features of a flat industry, with substantial potential benefits to society.

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Biographies

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