Economics for the Internet of Energy: A Techno-Economic Framework for Transactive Energy Prosumers

Report to the Strategic Energy Institute Program:
"Energy in an Information Age"

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Contents

Executive Summary

Traditional electricity consumers are becoming prosumers –energy subsystems such as homes, buildings, microgrids, etc. who not only consume, but who can produce and store energy. Prosumers are economically motivated, goal-oriented, and smart. In this project the team developed initial models for the interaction of energy prosumers in an electricity market context and developed concepts on a transactive framework that: a) supports decentralized system and scheduling of distributed energy resources (DER) while maintaining a reliable grid, b) enables prosumer bidding and hence societal global surplus maximization, and c) describes a cyber-infrastructure that enables real-time control and supports financial transactions.

Our first paper developed under this effort presents the fundamental rationale that drives the behavior of the energy prosumer, and that distinguishes it from a conventional consumer or producer. We illustrate this behavior using simple examples. The results show that prosumers maximise the total utility from its “internal” market, and make subsequent decisions based on their private equilibria. Prosumers can have incentives to join a market and exchange, especially when they can benefit from lower segments of quadratic cost curves or find their own generation too expensive. They further can have incentives to behave strategically, but only if they have some degree of certainty of their equilibrium condition. Strategic behaviour results in lower expected utility because of the uncertainty of being a consumer or a producer. It can be noted that strategic bidding is not a zero-sum game: the winning prosumer enjoys a smaller increase in utility because part of its strategy affects its consumer self.

Our second paper describes the architectural elements of prosumer-based electricity systems. The concept of prosumer is formally described as a motivated economic entity, which enables proposing a massively scalable architecture for various entities to exchange services. The mappings between new objectives, functionality, and architectural elements has been established. A decentralized services exchange platform is described that enables prosumers to exchange energy and energy-related services.

This research involved a student from the School of Economics, who has previous background in electric power. Through weekly discussion meetings the team developed multi-disciplinary concepts and the student continued her development towards becoming a power system economics expert. The PIs had conversations with Government Agencies on the potential benefits of expanding research in this direction. Recently, the emergency of block-chain and related technologies as a possible support for enabling distributed transactions is expected to further bring interest into this topic. We expect that in the near future various solicitations will be out, providing an opportunity to continue our research.

Distributed Services Architecture for Transactive Energy Prosumers

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***Abstract*—The centralized control architecture of today's electricity grid has performed well as an engineered system, but it is reaching an unsustainable level of strain. More demanding objectives such as resilience and sustainability require reevaluating the fundamental control design. A decentralized control architecture is needed to realize the desired new features of the grid. The organizing concept is the prosumer, an economically motivated power system actor that can consume, produce, store, or transport electricity. An energy services transactive platform is required for prosumers to trade energy services among actors. This document describes the elements of a distributed services platform for transactive prosumers.**

***Index Terms*—Prosumer, Decentralized Control, Energy Services, Transactive Platform.**

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].

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 services exchange.

This paper describes a services platform for decentralized transactive energy. This platform will allow the electricity grid to operate with architectural characteristics similar to the internet: highly accessible, scalable to billions of actors, layered, and flexible.

Objectives of the Future Grid

Five New Objectives of the Future Grid

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. It has been recognized that the new objectives cannot be achieved by simple additions or by incrementally deploying technologies in the grid. 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*. The five objectives for the future grid are:

a) Superior Economy,
b) Ultra-Reliability and Resilience
c) Sustainability
d) Energy Security, and
e) Services support

These objectives must be mapped to the customer or final user, in order to address societal needs.

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 [7]. Table I lists the major properties of electricity demand.

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 I 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.

TABLE I
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

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 Energy Star program in the US.

Sustainability: Not all electricity is equal. Users prefer electricity that is produced by cleaner renewable sources [8]. 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 [9].

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 [10]. Direct differentiation of electricity itself is possible through temporally sensitive pricing, reliability-tiered pricing, and introduction of green electricity products.

Simplicity: One of the major objectives of the future grid is increased consumer participation [11-13], 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. However, several efforts towards consumer empowerment have in fact caused consumer backlash, forcing some energy providers to offer smart meter opt-out programs [6]. 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. Home energy management systems can realize the benefits of enhanced control while recognizing this desire for simplicity.

Data Privacy: It has become clear that completely accessible smart meter data is not only unacceptable to consumers but also a vulnerability. Further, data privacy must not be addressed *ex post facto* solely by data encryption strategies; rather, it is an architectural element [14,15].

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 II 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.

TABLE II
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 energy user hence evolves as a complex agent who relates energy to its own objectives.

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 [16].

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, both of which prevent effective control action.

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) [17]. 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 [18].

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 [19].

Growing complexity of system operations: Support for operator situational awareness is struggling to keep up. 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. 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. 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].

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?

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.

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 requirements of users listed in Table I.

a) Distributed Decision Making: 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) Prosumer as a Subsystem Abstraction: 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.

c) Coordinated Temporal Scales: 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 Control: 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, $p_k - \tilde{p}_k$.

e) Prosumer Services Cyber-Infrastructure: 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.

Layered Control Architecture

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 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. 1.

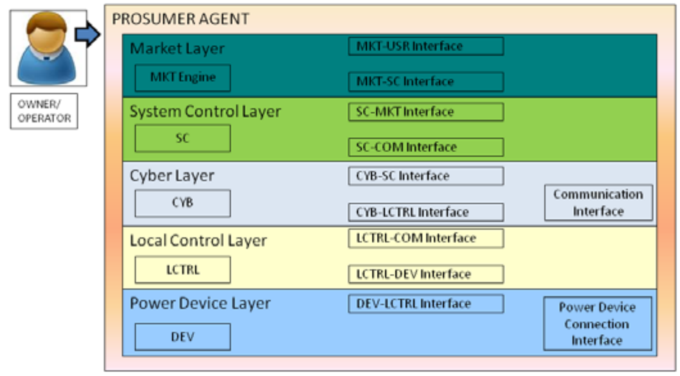


Fig. 1. Layered architecture of each prosumer.

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.

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.

Meeting Desired Functionality

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

TABLE III
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 IV

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.

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.

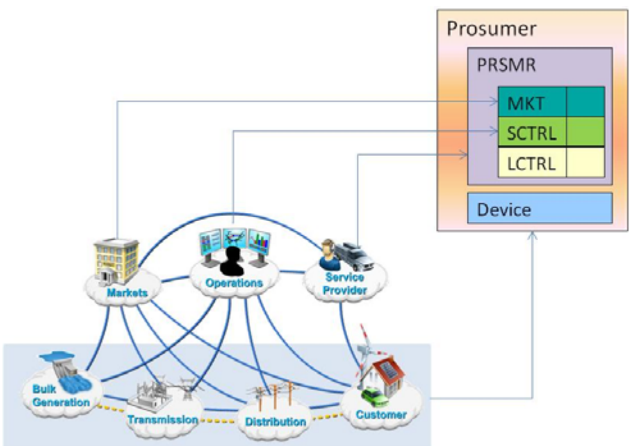


Fig. 7. Industry model evolving to prosumer model.

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.

DECENTRALIZED PLATFORM

From the proposed reformulation of the grid, a service-oriented structure emerges to support the trade of energy services 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.

The platform is illustrated in Fig.8. The platform sits on top of the communication protocols, and it contains a Communication Middleware. This middleware adds the necessary real-time properties and quality of services (QoS) to the regular, internet-based communications system. Over the middleware, is an Application Framework, which contains both the control and coordination protocols, as well as the other distributed applications.

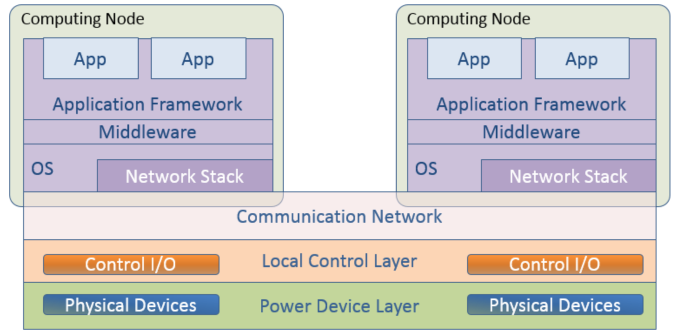
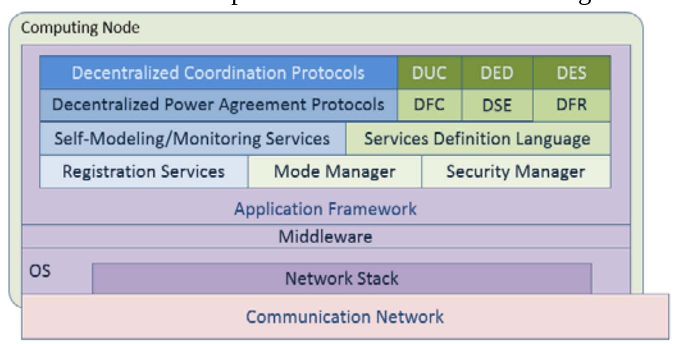


Fig. 8: Decentralized Coordination Platform

Each prosumer-node in the electricity system would implement a stack that utilizes this platform. This is illustrated in Fig. 9.



The computing node consists of the following modules:

a) Registration Services: Enables prosumers to be associated with a legal entity and to specify location and capabilities of the energy prosumers. The energy prosumer characterizes the various distributed resources and exposes a set of interfaces to the rest of the grid. The registration process must be approved by the registrar.

b) Mode Manager: The Mode Manager controls various modes of operations such as connected or islanded operations, and makes decision about positioning, timing, and collaboration.

c) The Security Manager: It addresses three levels of security: physical, electrical, and cyber. The cyber-security level addresses malicious as well as mal-functioning agents.

d) Self-Modeling: This module contains the model of the system, which includes modeling of the 5 layers. For instance it will have the parameters of the electric circuits contained within the prosumer, as well s models of the cyber-layer, descriptions of the various computational application, market software versions, etc.

e) Self-Monitoring: contains self-learning parametric state estimation systems to monitor all the physical assets as well as all the cyber-components in the system.

f) Services Definition Language: is a set of definitions that enables the prosumer to "talk" to other prosumers with the purpose of exchanging services (to exchange energy and energy related quantities, and to exchange money). The services definition language knows how to characterize the various distributer resources an expose them to the world as services offered by the prosumer.

g) Decentralized Power Agreement Protocols involve for real-timed dynamic control in the milliseconds to a few seconds: Decentralized Frequency Control (DFC), Decentralized State Estimation (DSE), and Decentralized Frequency Regulations (DFR). It also involves canonical decentralized functions such as initial power agreement.

h) Decentralized Coordination Protocols involve the protocols that realize coordination in the slower time scales from minutes to various days: Decentralized Unit Commitment (DUC), Decentralized Economic Dispatch (DED), and Decentralized Energy Scheduling (DES).

CONCLUSIONS

The architectural elements of prosumer-based electricity systems have been described. The concept of prosumer as a motivated economic entity enables proposing a massively scalable architecture for various entities to exchange services.

The mappings between new objectives, functionality, and architectural elements has been establish, which demonstrates the goodness of the proposed architecture.

A decentralized services exchange platform has been described that enables prosumers to exchange energy and energy-related services, and the major components of the decentralized platform has been described.

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BIOGRAPHIES

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A Fundamental Economic Model of Interacting Electricity Prosumers

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***Abstract*—Distributed energy resources (DERs) and automation systems enable traditional electricity consumers to also produce and to store energy. These energy prosumers can become much more active in energy management. They can provide benefits to the grid by exchanging energy and energy-related services. This paper presents the fundamental economics of energy prosumers. It shows that the energy prosumer can act simultaneously as producer and consumer, and design a strategy to maximize its revenue. Based on a linear bid/offer model, we show how prosumers operating in a market arrive at a stable equilibrium and present results for the case when prosumers bid strategically.**

***Index Terms*—Prosumer, Electricity Market, Distributed Energy Resources, Energy Bids, Optimal Bidding**

INTRODUCTION

MODERN MARKETS increasingly see sophisticated consumers. Evidence from sectors such as transportation and hospitality shows that consumers start offering their idle assets to the market thus becoming prosumers. New business models based on prosumer assets are putting substantial pressure on these industries, drastically changing historical business models [1]. Power markets are no exception. Just as Uber or Ridefinder drivers can share some of their private car rides, and Airbnb providers offer rooms or homes to guests, electricity consumers can choose to share some of their "own" electricity with others. Traditional energy consumers equipped with automation and distributed energy resources (DERs) have the necessary degrees of freedom to manage energy and to offer a variety of energy and energy related services that can benefit the grid and other prosumers [2]. DERs such as solar PV, energy storage, electric vehicles, and demand response, while more complex to manage, bring additional functionality to the grid, enabling cost reduction, supporting sustainability objectives through reduced emissions, and enabling higher levels of reliability and resilience ([3]).

DER physical energy and energy services exchanged at the point of common coupling can be abstracted. That is, to the grid, whether a house produces more power by a PV system, discharges a home battery, or decreases its consumption by the household loads, it is seen as the same service as power offered by the utility. The uniformity of power as a product allows every subsystem, such as microgrids, buildings, homes and even electric vehicles to become energy prosumers. These services have a significant impact on various aspects of the power system from the physical transfers of power to the exchange of information, to the design of markets and new industry business models.

This paper provides an overview and an illustration of the fundamental economics of interacting energy prosumers. We show how equilibrium is achieved within one prosumer and in an all-prosumer market, and how the prosumer characteristics affect the prosumer's strategic behavior and eventually market performance. The paper is organized as follows. Section II provides an overview of relevant literature. Sections III-V provide a model of equilibrium effects of interacting power prosumers. Section VI presents conclusions and future work.

LITERATURE REVIEW

Current research on prosumer behavior in power markets addresses three main aspects: market equilibrium, technical effects, and combined market-and-technology outcomes.

Market equilibrium models range from basic microgrid ([4], [5]) and grid feed-in models ([6], [7]) to models exploiting various types of equilibrium convergence ([8], [9]), incorporating transmission effects [10], individual preferences of prosumers [11], and collective strategies [12].

Technical models are plenty and investigate a wide variety of issues, such as reliability [13], optimality of power flows [14], fuel use [15], frequency [16], and storage levels [17].

A small number of models exist that show the combined technical and economic effects of prosumer participation in a market. These include profits from strategic behavior in markets with multiple small suppliers [18] or a Stackelberg leader [19].

Although there is a significant body of research addressing various aspects of modelling prosumer market equilibria and

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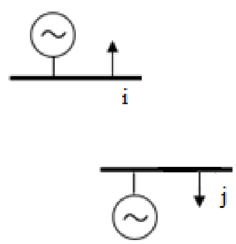
system effects, the underlying fundamental mechanism that motivates prosumer decisions has not been studied. We study two models for the prosumer: a) Autonomous prosumers. In this model, prosumers are electrically isolated. They have a desired consumption and a producing resource, and b) Connected Prosumers. In this model two or more prosumers interact with each other physically and through a market. We show how individual characteristics affect decisions and, through decisions, how prosumer-based power system operations and markets can function.

Equilibrium Effects in Individual Markets



In this model the prosumers are isolated electrically. They have no access to the grid or to a market. Each prosumer serves itself as in a Robinson Crusoe economy. This decision-maker makes decisions related to the single parameter: quantity.

Quantity decisions are driven by the balance of benefits and costs that originate from the utility function and capacity at hand. Let us suppose that the decision-maker has a valuation of active power: $-a_b x^2 + b_b x + c_b$ where a_b, b_b and c_b are coefficients representing how much value a given prosumer derives from 1 kWh, and the subscript b is used to denote “buyer” utility. The value function is concave in accordance with the law of decreasing marginal utility –a prosumer cannot equally enjoy an infinite amount of power. From a certain point the consumer will have a glut and would stop consuming. The decision-maker further has costs of producing power that depend on the technology, such as PV arrays, diesel, biomass, or wind turbines. Using the subscript s for “seller”, the cost function is $a_s x^2 + b_s x + c_s$ where a_s, b_s and c_s are cost curve coefficients. The cost curve is set to be convex in accordance with traditional fuel cost curves, as well as to allow for linear minimization. The total prosumer utility is therefore $u = -a_b x^2 + b_b x + c_b - a_s x^2 - b_s x - c_s$. The prosumer maximizes its utility when:

$$\frac{\partial u}{\partial x} = -2a_b x + b_b - 2a_s x - b_s = 0 \qquad (1)$$

The outcome of this process is an optimal quantity:

$$x = \frac{b_b - b_s}{2a_b + 2a_s} \qquad (2)$$

When a decision-maker is exposed to a market it becomes a prosumer with a different set of properties. A prosumer has to make decisions on a new component, price. In order to find the equilibrium price and quantity for this prosumer assume that it has

- consumer utility, $u_b = -a_b x^2 + b_b x + c_b - p x_b$ where and p is the price paid for electricity
- supplier utility, $u_s = p x_s - a_s x^2 - b_s x - c_s$

In fact, these representations are very similar to those presented above, except that they allow us to find the equilibrium price. The total utility is given by

$$u = u_b + u_s = -a_b x_b^2 + b_b x_b + c_b - p x_b + p x_s - a_s x_s^2 - b_s x_s - c_s \qquad (3)$$

Because the prosumer has no access to the grid, there is also a strict requirement on equilibrium quantity in order to satisfy the physical nature of the product. That is, there has to be balance of production and consumption, $x_b = x_s$. At the optimum:

$$\begin{aligned} \frac{\partial u_b}{\partial x} &= -2a_b x_b + b_b - p = 0 \\ \frac{\partial u_s}{\partial x} &= p - 2a_s x_s - b_s = 0 \end{aligned} \qquad (4)$$

$$\begin{aligned} p &= b_b - 2a_b x_b \\ p &= 2a_s x_s + b_s \end{aligned} \qquad (5)$$

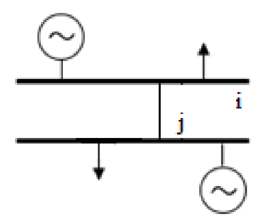
$$x = \frac{b_b - b_s}{2a_b + 2a_s} \qquad (6)$$

$$p = \frac{b_b a_s + b_s a_b}{a_b + a_s} \qquad (7)$$

Thus, the prosumer has precise understanding of its individual equilibrium in prices and quantities.

Equilibrium Effects in Perfectly Competitive Markets

Rationale



Suppose that now the prosumers are electrically connected to one another, and decide to enter a market, and that every transaction takes place at marginal utility price. The optimal volume the prosumer is willing to buy or sell is given by:

$$\begin{aligned} \frac{\partial u}{\partial x_{bi}} &= -2a_{bi} x_{bi} + b_{bi} - p = 0 \\ \frac{\partial u}{\partial x_{si}} &= p - 2a_{si} x_{si} - b_{si} = 0 \end{aligned} \qquad (8)$$

Therefore, for every prosumer the demand and supply curves are:

$$\begin{cases} x_{bi} = \dfrac{b_{bi} - p}{2a_{bi}} \\ x_{si} = \dfrac{p - b_{si}}{2a_{si}} \end{cases} \qquad (9)$$

The market supply and demand curves are sums of the individual supply and demand curves in the order of increasing and decreasing merit, respectively.

$$\begin{aligned} X_b &= \sum_{i=1}^{n} x_{bi}(p) \\ X_s &= \sum_{i=1}^{n} x_{si}(p) \end{aligned} \qquad (10)$$

The resulting volume and price are set at $X_b = X_s$. After the market price becomes available to prosumers, they compare it to their individual prices. Prosumers for which the market price is above their individual price become producers and prosumers for which market price is below their individual price become consumers. The amounts bought at market price are given by demand functions, the amounts sold at market price are given by supply functions and the amounts that change hands are determined as net production or consumption.

A prosumer does not necessarily enter the market. It can be totally self-sufficient and enjoy unmatched utility on its own. The decision to enter the market depends on individual characteristics, the most important of which are price elasticity of demand and cost characteristics of equipment.

Illustration

As an example, consider the case of a system with two prosumers. Their supply and demand characteristics are given in Table II, and the corresponding curves are illustrated in Figure 1.

TABLE II: PROSUMER COEFFICIENTS

	Prosumer 1	Prosumer 2
a_{bi}	1	4
b_{bi}	4	10
c_{bi}	0	0
a_{si}	1	4
b_{si}	0	2
c_{di}	0	0

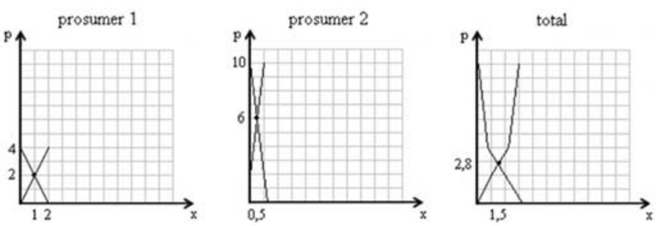


Fig. 1. Supply and demand curves of each prosumer and the market supply and demand curves

We now determine individual utilities corresponding to these prosumer valuations. The total utility of prosumer 1 is:

$u_1 = -a_{b1}x_1^2 + b_{b1}x_1 - a_{s1}x_1^2 - b_{s1}x_1 = 2$

The total utility of prosumer 2 is

$u_2 = -a_{b2}x_2^2 + b_{b2}x_2 - a_{s2}x_2^2 - b_{s2}x_2 = 2$

If the prosumers enter the market, their combined supply and demand functions are

$$X_b = \begin{pmatrix} \frac{10-p}{8}, & 4 > p \\ \frac{26-5p}{8}, & 4 < p \end{pmatrix}$$
$$X_s = \begin{pmatrix} \frac{p+14}{8}, & p > 4 \\ \frac{5p-2}{8}, & 4 > p > 2 \\ \frac{p}{2}, & 2 > p \end{pmatrix} \quad (11)$$

Using equations (5) and (6), the equilibrium price is $p = 2.8$ and the equilibrium volume is $X = 1.5$.

The equilibrium price is above the private equilibrium of prosumer 1 for which the price is 2 and below prosumer 2 for which the price is 6. Therefore prosumer 1 becomes a producer and prosumer 2 becomes a consumer.

$$\begin{cases} x_{b1} = 0.6 \\ x_{s1} = 1.4 \end{cases} \qquad \begin{cases} x_{b2} = 0.9 \\ x_{s2} = 0.1 \end{cases}$$

The price results in individual volumes of supply and demand of prosumer 1 and prosumer 2. At this price prosumer 1 is willing to consume only 0.6 kWh and is willing to sell 0.8 kWh to prosumer 2 for 2.8 $/kWh. The net demand of prosumer 1 is thus -0.8 kWh, prosumer 1 becomes a producer, and the net demand of prosumer 2 is 0.8 kWh, prosumer 2 becomes a consumer.

The total utility of prosumer 1 is

$u_1 = -a_{b1}x_{b1}^2 + b_{b1}x_{b1} + px_{s1} - a_{s1}x_{s1}^2 - b_{s1}x_{s1} = 2.32$

The total utility of prosumer 2 is

$u_2 = -a_{b2}x_{b2}^2 + b_{b2}x_{b2} - px_{s2} - a_{s2}x_{s2}^2 - b_{s2}x_{s2} = 3.28$

By transacting, both prosumers enjoy higher utility.

A simulation with more prosumers shows the same type of convergence. Below is the example of twenty prosumers with random values of a_{bi}, b_{bi}, a_{si}, b_{si}. The market price is 5.3 $/kWh and the total quantity exchanged in the market is 12.75 kWh. The net demand volumes are shown in figure 2.

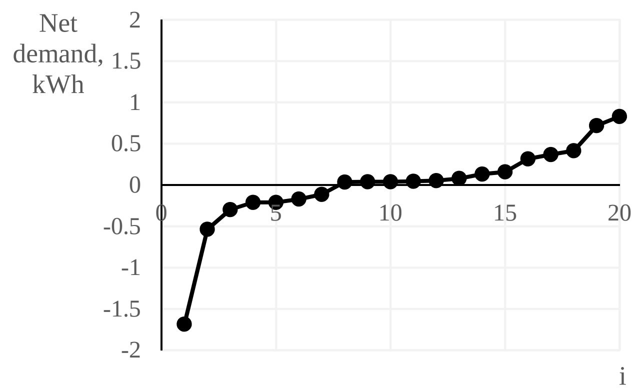


Fig. 2. Net demand volumes of each prosumer

As in the case of a two-prosumer market, the initial pool of prosumers splits into consumers and producers on the basis of individual prices and market price. The prosumers split about evenly, and the market clears at prices and volumes that best address the needs of prosumers.

EQUILIBRIUM EFFECTS WITH STRATEGIC BIDDING

A. Rationale

Now let us suppose that the prosumers can affect the market price by strategically adjusting demand and supply quantities. For each prosumer the utility function is given by

$$\begin{aligned} u = u_{bi} + u_{si} = -a_{bi}x_{bi}^2 + b_{bi}x_{bi} + c_{bi} \\ - p(x_{bi}, x_{si}, x_{bj}, x_{sj})x_{bi} \\ + p(x_{bi}, x_{si}, x_{bj}, x_{sj})x_{si} \\ - a_{si}x_{si}^2 - b_{si}x_{si} - c_{si} \end{aligned} \quad (12)$$

Thus, if a prosumer decides to unilaterally cause the price to increase, its decision is going to be affected by how much it gains as a producer and loses as a consumer.

More importantly, before the market clears the prosumer does not know if it is going to be a consumer or a producer. In the absence of expectations we have that $E(u) = \frac{1}{2}u_{bi} + \frac{1}{2}u_{si}$. It follows from the utility expression that the optimum depends on a_{bi}, b_{bi}, a_{si}, b_{si} and on the control variables x_{bi}, x_{si}, x_{bj}, x_{sj}. Let us examine how these control variables affect the utility. The behaviour of prosumer *j* affects the utility of prosumer *i* through $p(x_{bi}, x_{si}, x_{bj}, x_{sj})$ which has the same magnitude and opposite signs in equation (12). Because prosumer *i* does not know if it is going to be a consumer or a supplier, its expected utility is affected by price equally.

The individual behavior variables x_{bi}, x_{si} affect the utility of prosumer *i* through the effect of supply and demand quantities on the equilibrium price $\frac{\partial p}{\partial x_{bi}}$ and $\frac{\partial p}{\partial x_{si}}$. It has been shown above that the slopes of aggregate supply and demand curves are symmetric at the equilibrium. The effect of a change in x_{bi} is going to be equal in magnitude, but opposite in direction to a change in x_{si}, which gives

$$\frac{\partial p}{\partial x_{bi}} = -\frac{\partial p}{\partial x_{si}} \tag{13}$$

This in turn causes the prosumer to enjoy higher utility both from an increase in the quantity traded in the market and from a decrease in the quantity traded in the market.

These uncertain sensitivities of utility to control variables cause the strategic behavior to be unattractive for a prosumer who does not know if it is going to be a consumer or a producer in the market.

The ex post utilities from the previous section show that a prosumer may have incentives to bid strategically. The prosumer gains if it has a certain belief that once the market clears it would become a consumer or a producer.

B. Illustration

Imagine two prosumers that want to maximize u_{si}. The variables that characterize the utility of both prosumers are the same as in the previous section. The demand function also has the same form as in equation (11).

The detailed derivation for this case is provided in the Appendix. The ex post equilibrium is:

$$\begin{cases} x_{b1} = 0.28 \\ x_{s1} = 0.95 \end{cases} \qquad \begin{cases} x_{b2} = 0.82 \\ x_{s2} = 0.15 \end{cases}$$

Prosumer 1 becomes a producer and prosumer 2 becomes a consumer. The total utility of each prosumer is u_1 = 2.44, u_2 = 2.81. The utilities are still above individual levels, but the utility of the consumer has decreased substantially.

Now imagine that the same prosumers decide to approach their buying behavior strategically. The utility maximization yields the ex post equilibrium:

$$\begin{cases} x_{b1} = 0.45 \\ x_{s1} = 1.19 \end{cases} \qquad \begin{cases} x_{b2} = 0.79 \\ x_{s2} = 0.05 \end{cases}$$

Prosumer 1 becomes a producer and prosumer 2 becomes a consumer. The total utility of each prosumer is u_1 = 1.94, u_2 = 3.53. Prosumer 2 enjoys a higher utility, but now the utility of prosumer 1 is below that of its individual maximum.

As a result of strategic behavior, the expected utility based on $E(u) = \frac{1}{2}u_{bi} + \frac{1}{2}u_{si}$ is u_1 = 2.19, u_2 = 3.17, which is below the equilibrium for no strategic bidding.

The overall results of prosumer utility maximization are presented in Table III.

TABLE III: NUMERICAL RESULTS

	u_1	u_2
Autonomous prosumer	2	2
Connected (no strategic bidding)	2.32	3.28
Connected (average strategic)	2.19	3.17
Connected (strategic supply)	2.44	2.81
Connected (strategic demand)	1.94	3.53

It can be seen that for the given example both prosumers enjoy a higher utility from the market exchange. Further, uncertainty makes strategic bidding economically unattractive for them.

CONCLUSION

This paper presents the fundamental rationale that drives the behavior of the energy prosumer, and that distinguishes it from a conventional consumer or producer. We also illustrate this behavior using a simple example.

The results show that prosumers maximise the total utility from its "internal" market, and make subsequent decisions based on their private equilibria.

Prosumers can have incentives to join a market and exchange, especially when they can benefit from lower segments of quadratic cost curves or find their own generation too expensive. They further can have incentives to behave strategically, but only if they have some degree of certainty of their equilibrium condition. Strategic behaviour results in lower expected utility because of the uncertainty of being a consumer or a producer. It can be noted that strategic bidding is not a zero sum game: the winning prosumer enjoys a smaller increase in utility because part of its strategy affects its consumer self.

Since this paper attempted to illustrate the core concepts, it omits certain important extensions, both from the market perspective (such as dynamic convergence, grid access or capacity investment decisions) and the technical perspective (such as transmission constraints). These aspects are left for further research.

APPENDIX

In order to obtain maximum producer utility by the use of strategic bidding prosumer *i* solves two maximization problems, for lower and higher segments of the demand curve. Starting with the lower segment gives

$$\begin{aligned} u_{si} &= p x_{si} - a_{si}x_{si}^2 - b_{si}x_{si} - c_{si} \\ &= \left(\frac{26}{5} - \frac{8}{5}\left(x_{si} + x_{sj}\right)\right)x_{si} - a_{si}x_{si}^2 - b_{si}x_{si} - c_{si} \end{aligned} \tag{14}$$

The optimality for prosumer 1 is given by

$$\frac{\partial u_{s1}}{\partial x_{s1}} = 0; \quad x_{s1} = 1 - \frac{8}{26}x_{s2} \tag{15}$$

Accordingly, optimality for prosumer 2 is given by

$$\frac{\partial u_{s2}}{\partial x_{s2}} = 0; \quad x_{s2} = \frac{16}{56} - \frac{8}{56} x_{s1} \tag{16}$$

Substituting (16) into (15),

$$x_{s1} = 0.95 \text{ , } x_{s2} = 0.15, p = 3.44 \tag{17}$$

As predicted by oligopoly models, the total quantity traded in the market is lower and the total price is higher. Now substitute this price into own consumer quantities (9)

$$x_{b1} = \frac{b_{b1} - p}{2a_{b1}} = 0.28; \ \ x_{b2} = \frac{b_{b2} - p}{2a_{b2}} = 0.82 \tag{18}$$

Prosumer 1 becomes a producer and prosumer 2 becomes a consumer. The total utility of each prosumer is

$$\begin{aligned} u_1 &= 2.44 \\ u_2 &= 2.81 \end{aligned} \tag{19}$$

Utility maximisation for strategic consumer results in

$$u_{bi} = -a_{bi}x_{bi}^2 + b_{bi}x_{bi} + c_{bi} - \left(\frac{2}{5} + \frac{8}{5}\left(x_{bi} + x_{bj}\right)\right) x_{bi} \tag{20}$$

By similar optimality conditions,

$$\begin{aligned} \frac{\partial u_{b1}}{\partial x_{b1}} = 0; \quad x_{b1} = \frac{18}{26} - \frac{8}{26} x_{b2} \\ \frac{\partial u_{b2}}{\partial x_{b2}} = 0; \quad x_{b2} = \frac{6}{7} - \frac{1}{7} x_{b1} \end{aligned} \tag{21}$$

Substituting

$$x_{b1} = 0.45, \ \ x_{b2} = 0.79, \qquad p = 2.38 \tag{22}$$

As predicted by oligopoly models, the total quantity traded in the market is lower and the total price is lower. Now substitute this price into own producer quantities

$$x_{s1} = \frac{p - b_{s1}}{2a_{s1}} = 1.19; \ \ x_{s2} = \frac{p - b_{s2}}{2a_{s2}} = 0.05 \tag{23}$$

Prosumer 1 becomes a producer and prosumer 2 becomes a consumer. The total utility of each prosumer is

$$\begin{aligned} u_1 &= 1.94 \\ u_2 &= 3.53 \end{aligned} \tag{24}$$

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