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Electricity market design for the prosumer era

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Prosumers are agents that both consume and produce energy. With the growth in small and medium-sized agents using solar photovoltaic panels, smart meters, vehicle-to-grid electric automobiles, home batteries and other 'smart' devices, prosuming offers the potential for consumers and vehicle owners to re-evaluate their energy practices. As the number of prosumers increases, the electric utility sector of today is likely to undergo significant changes over the coming decades, offering possibilities for greening of the system, but also bringing many unknowns and risks that need to be identified and managed. To develop strategies for the future, policymakers and planners need knowledge of how prosumers could be integrated effectively and efficiently into competitive electricity markets. Here we identify and discuss three promising potential prosumer markets related to prosumer grid integration, peer-to-peer models and prosumer community groups. We also caution against optimism by laying out a series of caveats and complexities.

Advances in electricity generation and storage technologies coupled with declines in cost, the planned roll-out of smart metering and favourable regulation have all led to a rapid increase in the number of consumers in Europe and the USA producing or storing electricity at home — through solar panels[1], electric vehicles[2], batteries[3] or other means. In the UK, for instance, by the end of December 2015 more than 842,000 installations of solar panels provided an aggregate capacity of about 8,667 MW (ref. 4) and, if the country is to fulfil its expected potential, as many as 10 million homes in the UK may cover their roofs with solar panels in the next six years[5,6]. Overall, the global proliferation of solar photovoltaic (PV) panels has continued to accelerate, rising from a base of 3,700 MW in 2004 to more than 150,000 MW in 2014[7].

By 2020, the European Union expects about €45 billion to be invested in 200 million smart meters for electricity and another 45 million smart meters for natural gas[8]. These will facilitate the integration of small and independent energy producers to the grid. At the same time, globally, there are emerging markets and possibilities for home storage solutions (including the recent launch of the Tesla home battery[9]) that, together with smart-vehicle battery-charging strategies, have the potential to improve the sustainability and efficiency of the electricity system, and increase customer benefits[10]. The up-take of electric vehicles also continues to intensify, with the International Energy Agency[11] reporting at least 665,000 electric-drive light-duty vehicles, 46,000 electric buses and 235 million electric two-wheelers on the worldwide market in early 2015.

Smart home and home automation technologies with a variety of integrated energy management components[12–14] are also becoming more widespread. These technologies enable consumers to optimize their electricity use and match it with their needs and, when applicable, with their electricity generation and storage preferences, while saving money or energy in a simple way. The global home automation market in 2014 was valued at around US$5 billion and was estimated to reach US$21 billion by 2020[15].

In an attempt to promote a future decentralized grid, in the USA the state of New York is implementing its Reforming the Energy Vision (REV) strategy to accelerate the penetration of microgrids, building integrated solar PV systems and household energy storage technologies[16]. Californian utilities are aggressively reformulating market structures and tariffs to incentivize distributed energy resources, that is, energy resources that are usually small in capacity and situated on-site or close to the consumer[17].

This growth in technologies, combined with the changes in the electricity market, offers an unprecedented opportunity for positive, synergistic interactions via smart prosumer grids. Prosuming refers to when energy customers actively manage their own consumption and production of energy. It often describes consumers — households, businesses, communities, organizations and other agents — that rely on smart meters and solar PV panels to generate electricity and/or combine these with home energy management systems, energy storage, electric vehicles and electric vehicle-to-grid (V2G) systems. Smart prosumer grids alter a number of fundamental attributes of conventional grids and their consumers[18–22]. Such grids tend to enable homes and buildings to have sophisticated management capabilities, net metering or smart meters that differ from conventional grids. Smart systems tend to offer dynamic pricing and are built to accommodate distributed generation. Additionally, prosumer smart grids can incorporate various types of storage (batteries, appliances and cars), are friendlier to wind and solar sources of energy, and utilize large-scale digital networking and feedback. Indeed, in an attempt to capture some of these benefits, many countries have begun to embrace far-reaching reforms of the present system, and policies are already under way to cope with increasing amounts of power from intermittent sources and independent producers[23,24].

The emergence of the prosuming phenomenon presents two interesting paths for a low-carbon energy system. The first path sees millions of off-grid and self-sufficient agents manage their energy production and consumption autonomously. This path is valid mostly for agents that geographically, economically and technically can install sufficient renewable capacity and energy storage, in addition to smart-home or building-management technologies. This segment is, and will probably remain, relatively small. The second path sees prosumers connected to a grid. In this path, consumers transform from being merely paying passive agents to active providers of energy services to the grid. These prosumers can supplement, or may even compete with, traditional utilities and energy companies. Prosuming, through either path, can enable agents to save

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Table 1 | Comparing conventional consumers and smart prosumers in the electricity grid.

Dimension	Conventional grid consumers	Smart prosumers
Resilience and self-healing	Operators respond to prevent further damage, focus is on reaction and protection of assets following system faults	Consumers or their devices can automatically detect and respond to actual and emerging transmission and distribution problems; focus is on prevention
Information and consumer involvement	Consumers are uninformed and non-participative in the power system	Consumers are informed, involved and active
Quality of energy services	Produced in bulk, typically through centralized supply	More modular and tailored to specific end uses, which can vary in quality
Diversification	Relies on large centralized generating units with little opportunities for energy storage	Encourages large numbers of distributed generation deployed to complement decentralized storage options, such as electric vehicles, with more focus on access and interconnection to renewables and V2G systems
Competitive markets	Limited wholesale markets still working to find the best operating models, not well suited to handling congestion or integrating with each other	More efficient wholesale market operations in place with integrated reliability coordinators and minimal transmission congestion and constraints
Optimization and efficiency	Limited integration of partial operational data and time-based maintenance	Greatly expanded sensing and measurement of grid conditions; technologies deeply integrated with asset management processes and condition-based maintenance

money while also contributing to wider social benefits by diversifying energy supply and lowering greenhouse gas emissions from the electricity system and private transport.

Policymakers and utilities alike should be prepared for the likely reality in which many prosuming agents are operating with a significantly more decentralized electricity grid, and thus need to structure electricity markets in a way that utilizes prosumers to maximize the societal benefits while minimizing welfare losses.

In this Perspective, we focus on the second path of multiple services provided by numerous prosuming agents connected to the grid, and explore the promise of more prosumer-oriented electricity markets. We identify three possible models of prosumer-integrated markets: peer-to-peer prosuming models, prosumer-to-grid integration and prosumer community groups. We also, however, foresee a significant number of technical, market and behavioural barriers that require both a more holistic conceptualization of prosuming and tempered optimism about its future.

Defining prosumers and distinguishing prosumer grids

Grids with integrated prosumers present several advantages and opportunities compared with conventional grids, as summarized in Table 1. These advantages allow smart prosumer grids to improve system efficiency in a variety of ways. One is by enabling the use of smart controls and communication technologies to enhance the efficiency of home appliances. These so-called smart appliances include refrigerators and air conditioners that communicate directly with electric utilities, receiving real-time price signals and shifting load in response by adjusting their operation[25]. Another efficiency measure is to lend the storage capacity of electric vehicles and home batteries to balance renewable generation fluctuations[10]. Smart prosumer microgrids could be more cost-effective than increasing the quality of universal homogeneous supply upstream in the traditional energy system[26]. Additionally, prosumer markets may be good places to match the local demand and supply of d.c. and a.c. electricity more easily. Some even argue that prosumers are likely to become the most important value creators within the smart grid[27].

Fundamentally, markets for prosumption services are different from existing engagement platforms, such as demand-reduction or demand-response programmes. That is because, in prosumer markets, users on the demand side not only react to price signals, but also actively offer services that electric utilities, transmission systems operators, or other prosumers have to bid for.

Three potential prosumer markets

Decentralized systems with many integrated smart prosumers require markets that suit and mirror the nature of decentralized production and consumption[28]. Compared with existing electricity markets, a prosumer marketplace would be more complex because it is envisaged as a multi-agent system that includes not only different types of service, but also a wider variety of participant groups that fulfil diverse and changing roles, as well as a larger number of providers for each prosumption service[27]. Local markets are likely to be key for managing distributed renewable generation[29] and for coordinating decentralized decision models that satisfy large numbers of self-interested autonomous agents[30].

We identify here three possible innovative markets that prosuming could germinate: organically evolving peer-to-peer models; prosumer-to-interconnected or 'island' mode microgrids; and organized prosumer groups. Figure 1 visually depicts each of these market structures, illustrating how they would differ from each other.

Peer-to-peer models. Peer-to-peer markets (Fig. 1a) are organic and the least structured of the models we discuss. They involve decentralized, more autonomous and flexible peer-to-peer networks that emerge almost entirely from the bottom up. Inspired by the sharing economy concept that relies on numerous agents, some have suggested Airbnb and Uber models for the electricity grid, in which a peer-to-peer platform allows electricity producers and consumers to bid and directly sell and buy electricity and other services[31]. Under such a model, the distribution grid is paid a management fee plus a tariff for its distribution function, depending on the type and amount of service and the distance between provider and consumer.

Peer-to-peer markets may involve numerous long-term or *ad hoc* contractual relations between prosuming agents (for example, one agent generates electricity that is stored by another), or between individual service providers and consumers (for example, one agent sells electricity to another).

The Netherlands-based Vandebron, for instance, has launched a platform that enables individuals to buy green electricity directly from a local farmer. Similarly, the UK-based Piclo pilot programme is an online market for renewable energy for local commercial consumers. See Box 1 for details on both. Although currently both Vandebron and Piclo models are limited to generation and consumption, theoretically they could be extended to other prosumption services, including, for example, electricity storage or even energy services such as water heating.

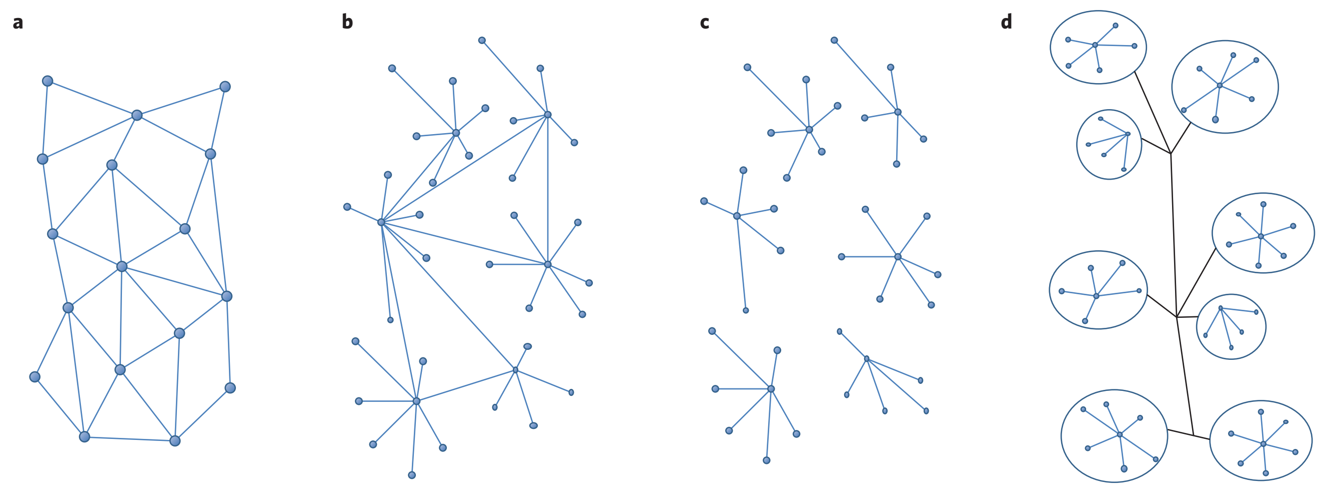

Figure 1 | Structural attributes of three prosumer markets. a, Peer-to-peer model, in which prosumers interconnect directly with each other, buying and selling energy services. **b**,**c**, More structured models involving prosumers connected to microgrids. These entail prosumer-to-interconnected microgrids, in which prosumers provide services to a microgrid that is connected to a larger grid (**b**), or prosumer-to-islanded microgrids, in which prosumers provide services to an independent, standalone microgrid (**c**). **d**, Organized prosumer group model, in which a group of prosumers pools resources or forms a virtual power plant. Dots represent prosuming agents; lines represent a transaction of prosuming service; circles represent an organized group of prosumers.

While the present electricity system is generally uniform and standardized in terms of safety and quality across most regions and states, at least in the developed world, who would be liable and accountable for providing safe, available and affordable energy services to all in peer-to-peer models is a huge question that poses a great challenge. Indeed, these organically evolving markets would need to follow sets of rules and guidelines that are more complex than those applied in existing sharing-economy models — rules that are set in respect and with reference to national or state energy priorities, and that align the interests of prosumers with those of the wider society. In addition, the associated transaction costs might be high in such models.

Prosumer-to-grid models. A second and more structured set of models involves brokerage systems for prosumers that are connected to a microgrid. The microgrid itself can operate in connection to a main grid (Fig. 1b) or operate autonomously in an 'island mode' (Fig. 1c). Conceptually, each mode presents different incentives to prosumers. If a microgrid is interconnected to a main grid, there is an incentive for prosumers to generate as much electricity as possible, because surplus generation could be sold to the main grid. In an island mode, however, prosuming services need to be optimized at the microgrid level and excess generation is an advantage only to the limit of storage and load shifting services availability. Similarly, it is likely that the option to sell prosuming services via local markets could alter energy management preferences and considerations of 'smart buildings', which today operate in standalone modes that optimize energy use and behaviour internally.

Integrated approaches for incorporating prosumers into the energy system include prosumer marketplaces, prosumption brokerage systems and predefined participation rules[30,32–34]. For example, the Neighbourhood Oriented Brokerage Electricity and Monitoring System (NOBEL) project was funded by the European Union with the aim to help network operators improve energy distribution efficiency[32]. The project suggested an energy brokerage system where individual energy prosumers can communicate their energy needs directly to both large-scale and small-scale energy producers as well as sport centres, industrial parks and shopping centres, thereby making energy use more efficient[32]. Others[35] have introduced a system based on market rules, which activates willing-to-participate users at the distribution part of the electricity system. Users can offer to adapt their electricity consumption or production in return for financial benefits or incentives. Guided by an optimization method, the system can reject or accept offers on the basis of market principles.

A more complex structure has also been proposed, which includes low and high marketplaces (corresponding to the low and medium-to-high voltage parts of the grid)[30]. In this structure, eight types of agent are identified and classified into three groups: agents that are indispensable for the trading process and are needed to impose the negotiated results onto the connected machinery; agents that take corrective measures when frequency deviation occurs; and auxiliary agents for organizational tasks. Prosumers in this model include

Box 1 | Examples of peer-to-peer energy services.

Vandebron, the Netherlands. Established in 2014, Vandebron ('from the source'; https://vandebron.nl), a Dutch start-up, provides an online peer-to-peer energy marketplace platform for renewable energy. Using Vandebron, local renewable electricity generators can sell their energy directly to households and businesses, with only a small flat subscription fee for both sides. This peer-to-peer platform allows producers to receive better rates for energy, while consumers know that they are paying for more local and renewable generation. As of February 2016, there were approximately 50 energy producers listed on the Vandebron website, supplying power to meet the demands of more than 30,000 households.

Piclo, UK. On October 2015, the UK start-up Open Utility launched Piclo — a pilot programme of its peer-to-peer trading service initiative (https://www.openutility.com/piclo/). This platform enables renewable generators to set the price for their electricity and sell it to local commercial energy consumers. Unlike Vandebron, which does not involve any utility or government agency in the process, Open Utility is partly funded by the national government's Department of Energy and Climate Change, and supported by the Carbon Trust and other industry experts. In early 2015, Open Utility had 25 producers signed up in Piclo, including wind farms and schools with excessive solar generation, and they aim to match those with businesses that prefer renewable energy. Backup power is offered by an electric utility to maintain reliability.

Box 2 | New York's REV strategy.

The New York state REV strategy includes various initiatives that promote decentralized renewable generation and management, and encourage consumers and the private sector to fill roles that are more active in the electricity system. Initiatives include the US$1 billion NY-Sun initiative, which significantly expanded solar power generation throughout New York and transformed its solar industry into a self-sustaining market. The REV community solar initiative (Solarize) facilitates the establishment of neighbourhood solar projects, which pool together community resources for the benefit of consumers and their community. The NY Prize community microgrids competition, launched in 2015, also sees community microgrid infrastructure as a foundation for REV's objectives. The US$40 million prize aims to engage communities in advancing plans for local power and resilience through partnerships with local municipalities and the private sector towards the implementation of community-based microgrids. Finally, the public service commission adopted a regulatory policy framework in 2015 that allows utilities to act as a market platform that enables third parties and customers to be active partners in the energy system. These REV initiatives, among others, are expected to lower energy costs for consumers, while offsetting the need to build a US$1 billion substation to serve various neighbourhoods and improve the resilience of the energy system as a whole.

every electric device that could serve as an energy sink or source and that is connected to a home gateway, which pools all prosumers in one house and tries to balance their energy offers and needs. Home gateways can act as a buyer or seller in the low-voltage marketplace, which is the local central contact point for all local home gateways and the place where, based on price, offers and requests are matched. In this marketplace, energy can be traded with multiple partners. Ambassadors are placed in-between two marketplaces — the high and low — and can buy and sell unsatisfied offers and requests in the local marketplace.

Organized prosumer groups. A third and final market typology sits between the two previously described ones in terms of structure and scale: community-based or community-organized prosumer groups (Fig. 1d). This typology would be more organized than peer-to-peer networks but less structured than prosumer-to-grid models. It is likely that these local prosumer markets will operate in a smart city environment. Such a setting may present opportunities for local organizations, neighbourhoods or communities to manage their energy needs efficiently and dynamically, taking into account local balancing resources (for example, smart buildings and homes), stakeholder needs and available prosumption services (for example, ref. 36).

Another proposal seeks to encourage end-users to become prosumers by enabling community-based facilitation and initiatives to stimulate local management of supply and demand[37]. Theoretically, communities or local authorities could pool their prosumption resources to generate a revenue stream for community benefit. Alternatively, new, probably small and medium-scale companies may emerge to act as aggregators or providers of distribution or energy services. These could operate like traditional entities, similar to energy service companies that pay upfront to implement energy efficiency upgrades and then receive a share of the monetized energy savings, but not necessarily confined to the commercial sector. An example is the Enco Group, which provides electricity to 2 million customers in the Netherlands and Belgium via a new software platform that allows it to use dispatchable resources (including customer-sited cogeneration plants, industrial demand-response and other distributed energy resources) as a single virtual power plant[38]. The New York REV strategy similarly presents various initiatives that promote such local organization (see Box 2).

An alternative model exploits groups of users in a community or organization that are large enough to be considered prosumer virtual power plants[36]. The concept of a prosumer community group has even been proposed as a way to manage prosumers[39–42]. The idea is for goal-oriented prosumer community clusters, with relatively similar energy behaviours located in the same geographical area, to allow efficient energy sharing among local members.

Caveats and complexities

A low-carbon, decentralized system, with numerous microgrids and a large share of intermittent renewable energy supplied by many producers, is in marked contrast to most existing traditional energy systems and electricity grids. Although such a system could produce tangible benefits, a transition to smart prosumer grids also raises a series of sobering challenges. These cut across technical, institutional, economic and social dimensions.

In terms of technology, smart prosumers require much more complicated control and management schemes, many of which are still being developed. The rapid diffusion of solar PV has already resulted in operability issues and grid disruption in some markets, as existing electricity systems were designed for unidirectional power flow from generators to consumers, creating problems in harmonic distortion, voltage spikes and power output fluctuations when households send electricity the other way[7]. Numerous studies from engineering and electric power systems design have suggested that the adoption of smart grids and integration of electric vehicles into V2G configurations remains dependent on future breakthroughs. Such breakthroughs can be related to aspects as diverse as the process of dispatching, methodologies for modelling and forecasting, the erection of charging infrastructure, communication and control protocols, and aggregation, to name a few[43–45].

Moreover, existing grids are not well designed to absorb excess power, making it difficult to store solar energy (or even wind energy) in times of saturated supply, leading in extreme situations to over-generation and negative electricity prices[46]. In California, for example, the Independent System Operator has warned that a 40% penetration of distributed renewable energy technologies in 2024 may cause it to face as many as 822 hours when supply exceeds demand on the network[47]. In that instance, diurnal and seasonal variation, in particular, pose many challenges for large-scale renewable integration[48]. Such technical barriers could complicate all four different prosumer configurations, although the ability to turn on and off prosuming virtual power plants could mitigate some of these concerns.

Economic and market barriers are just as potentially pernicious. If well integrated, the services provided by a large number of prosumers may improve the resilience and sustainability of the system as a whole, while reducing energy waste and, accordingly, costs (for example, ref. 30). Properly integrated agents do have the potential to ameliorate some of the diurnal and seasonal challenges related to grid management through a combination of dynamic tariffs for both distributed and dispatchable storage, and demand-response programmes.

If uncontrolled and unmanaged, however, a grid defection process may lead utilities into a financial 'death spiral', due to increasingly costly connections for new customers and limited sales opportunities[49–51]. Prosumers do, after all, challenge the core business models of incumbent electric utilities[7]. In addition, given that most electricity systems suffer from suboptimal tariffs that do not reflect time-of-use rates or even full costs[52], significant market reform could be a prerequisite to widespread prosumer adoption. It is often much cheaper and easier to see households interacting with incumbents using the existing market and physical infrastructure, especially when only some early adopting households need to offer response services to capture most of the system benefits[53].

Table 2 | Summary of three prosumer market models.

Prosumer market model	Role	Function	Profit optimization orientation	Relationship with conventional agents (for example, utilities)	Main challenges
Peer-to-peer	Facilitate the arrangement of transactions between two or more individual agents	Distribute prosuming services between agents	Individual agent	Prosumers compete with utilities over clients	(1) Cost of building and maintaining a highly distributed and diverse distribution network; (2) liability and accountability assurance for delivery of safe and high-quality energy services
Prosumer-to-grid	Aggregate or capture the value of prosuming energy services. Agents may sell prosumption services in two-tiered markets: local (microgrid) and regional (main grid)	Provide high-quality energy services by optimizing the integration of numerous individual prosumers into the system	(1) Individual agent, grid; (2) the local/main grid	Prosumers act mostly as partners that provide various services to the grid. At times, they can become a competitor for generation	Integrating and optimizing large amounts of data provided by numerous prosuming agents
Organized prosumer groups	Serve the interests of a group of prosumers (for example, community, organization)	Provide high-quality energy services by optimizing the integration of limited numbers of organized prosumer groups into the system	(1) Agent groups, grid; (2) the local/main grid	Prosumers act mostly as partners that provide various services to the grid. At times, they can become a competitor for generation	(1) Integrating and optimizing large amounts of data provided by prosuming groups; (2) complexity and high transaction costs of managing, arranging, optimizing and balancing agent relations within the group

In the social and behavioural realm, household solar PV systems continue to be impeded by information asymmetries, false expectations about performance, and resistance among both home builders and home owners across North America[54] and Europe[55]. A similar lack of consumer understanding, coupled with concerns over range anxiety (in which people express frustration or uncertainty about whether they can recharge their vehicles) and social norms in favour of conventional cars, stymies a more rapid diffusion of battery electric vehicles[2]. These studies suggest that rather than rushing to engage in prosumption, most people do not want to waste time thinking about energy or fuel, and view the costs of changing their behaviour as prohibitively high relative to the benefits. Such attitudes are further strengthened against prosuming when one considers that the sharing of data and prices could create perceived information insecurity and invasion of privacy[56].

A final important caveat is that energy transitions and substitutions, even to things with as much promise as the smart grid and prosumption, tend to be path-dependent and cumulative rather than revolutionary and fully substitutive[57]. Even if smart prosumer grids manage to reach most of the world's population over the next few decades — which is far from a certainty — conventional sources of energy (such as centralized grids, based on fossil fuels or solid biomass fuels for cooking) are likely to remain utilized, just as muscle power, animate power, wood power and steam power were discovered centuries ago yet remain in use today[58,59]. Prosumption and smart grids, in other words, may eventually supplement and enhance the global energy system, but will never fully substitute and replace it.

Discussion

In this Perspective, we have argued that prosumers could be integrated into the energy system via at least three engagement platforms and models. As Table 2 summarizes, each of these presents unique advantages and challenges for the distribution network and for energy management.

If structured well, these models could enable a differentiation between quality needs and the facilitation of sensitive loads by local provision of high-quality power. Moreover, trading in prosumption services could potentially open opportunities for localized energy service companies, and encourage the development of new businesses and arrangements between stakeholders that pool private and shared resources for the benefit of individuals, communities and the wider society.

If structured poorly, however, such trends could threaten grid reliability, erode sensitive protections on privacy and inflate expectations to the degree that the prosumer revolution satisfies nobody. Simplistic policy and wishful implementation may actually result in failure of these markets, with critical repercussions on sustainability, consumer empowerment and energy innovation efforts. A more informed and cautious perspective is needed.

In conclusion, designing electricity markets for the prosumer era could maximize residential and commercial energy efficiency efforts, democratize demand-response and prepare society for ubiquitous distributed clean energy technologies. However, this can be achieved only if proponents are able to recognize and support prosumer markets differentiated by services, role and function, and anticipate a series of compelling caveats and complexities. While the basic forms of prosumer markets have been subject to pilot schemes, large-scale advanced markets will require greater effort from researchers, vendors, policymakers and the overall industry if they are to be implemented further.

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Competing interests

The authors declare no competing financial interests.