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Effect of residential solar and storage on centralized electricity supply systems

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Residential solar photovoltaic systems combined with affordable battery storage are becoming increasingly likely to drive a consumer-led, low-emission evolution of modern electricity supply systems. In the past decade, a multi-billion-dollar boom in solar photovoltaic development across the globe has disrupted the way in which centralized electricity systems operate. At the same time, solar photovoltaic power has begun to make a material contribution to reduction targets for greenhouse gas emissions. Viable electricity storage solutions are now on the cusp of a rapidly declining price trajectory. When coupled with solar photovoltaic systems, battery storage could become one of the most disruptive influences to impact the electricity sector in decades, yet governments and the broader power sector are poorly prepared. In this Perspective, we examine emerging trends and proffer a systems framework to analyse the disruptive influence of residential solar photovoltaic and storage systems on existing centralized electricity supply systems.

A key focus of global climate change mitigation activities has been attempts to decarbonize centralized electricity systems. Although there have been some successes, a majority of mitigation scenarios indicate that the electricity sector must decarbonize more quickly, and more completely, over the next 50 years to avoid the worst impacts of climate change[1].

With the electricity sector contributing nearly 40% of global energy-related greenhouse gas emissions, this represents a significant challenge[2]. Modern centralized electricity systems, where electricity from large generators is transported to end-users along extensive transmission and distribution networks, are built on billions of dollars of investment, comprising infrastructure with very long asset-lives, supported by complex regulation. For existing electricity markets around the world, effective solutions to transition to a low-carbon economy in an economically efficient and socially equitable manner remain elusive.

Clean-energy advocates are quick to point to the steep increase in renewables as a panacea for future low-emission growth of the electricity system. Despite impressive double-digit annual growth over the past decade, renewable energy is growing from a low base and must be considered within the broader context of the electricity supply system where fossil fuels over the past 10 years have accounted for more than 75% of new electricity generation[2].

With electricity expected to increase its share as part of the total energy mix, a smoother, more efficient low-emission deployment pathway for the sector must be developed[1,2]. In this respect, one of the great emerging challenges for policy-makers and utility owners relates to the recent boom in residential solar photovoltaic (PV) power and the emergence of viable and potentially cost-effective electricity storage.

The rise and rise of solar photovoltaic power

Following PV module price drops of more than 80% in the past 5 years, global PV deployment has increased from a base of 3.7 gigawatts (GW) in 2004 to more than 150 GW in early 2014, contributing nearly 1% of total global electricity demand[2–5]. In markets in Italy and Germany, PV is meeting 7.5% and 6.5% of demand respectively[4]. Recent analysis[5] by the International Energy Agency (IEA) indicates that PV could generate up to 16% of the world's energy by 2050.

PVs, with average lifecycle greenhouse gas emissions of 49.9 grams of CO_2 equivalent per kilowatt hour ($gCO_2e\ kWh^{-1}$), compared with a global average for the electricity sector of approximately 532 $gCO_2e\ kWh^{-1}$, is now making material contributions to emissions reductions in some countries[6,7]. At the end of 2013, installed PV systems were avoiding approximately 140 million tonnes of CO_2 per year (ref. 5).

For the residential sector, where a substantial proportion of global PV capacity has been deployed so far, this is highly relevant. On average, 30% of total electricity demand is consumed by the residential sector in OECD countries[8]. Although some homes are not suitable for PV for reasons of size or shading, and generation can vary depending on location and siting, it is nonetheless clear that residential PV represents an important emissions mitigation target for policy-makers.

Despite recent growth, there is no indication that PV saturation is close, as rates of deployment continue to exceed expectations with at least 36.9 GW of PV capacity installed in 2013 (ref. 3). At the same time, PV system prices continue to fall, with US price reductions in 2013 exceeding 12% (ref. 9). These reductions are occurring at the same time as the costs to build new conventional generators increase substantially.

There is also the possibility that PV technology will continue to get cheaper. The average price of PVs has dropped by 20% with every doubling of installed capacity over the past two decades[10,11]. With analysts in the United States predicting the downward trend for PV pricing to continue, albeit at a slower rate, it is likely that the US Department of Energy will reach its target to drive down the cost of solar electricity to US$0.06 kWh to make solar "fully cost-competitive with traditional energy sources before the end of the decade"[12].

On the surface, these developments are positive. As an electricity generation technology, PVs have no moving parts, makes no noise, do not generate waste during operation, are sealed so can be used in almost any environment, are modular, and can be scaled up or down to meet load requirements. From a broader socio-economic

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perspective, PVs can improve energy security, increase energy sector resilience, drive reductions in greenhouse gas emissions, improve access to energy, create new industries and jobs, and provide power to remote communities[13]. PV use also encourages consumers to become actively engaged in managing their energy and provides them with greater control over their electricity bills.

Despite these benefits, the rapid rate of PV deployment has caused disruption to centralized electricity supply systems, resulting in operability issues[14]. Existing electricity systems were designed for unidirectional power flow from generators to consumers; increasing volumes of intermittent generation fed back into the grid from rooftop PV are now having an impact on power quality[15]. Managing many of the technical issues, such as harmonic distortion, voltage spikes and power output fluctuations, can be costly, but these issues are not insurmountable. More difficult to address are the emerging economic impacts. Residential households with PV participate in the electricity market as both generators and consumers, reducing total system demand, while effectively challenging the business models of entrenched utility providers.

A recent study reported that 94% of energy sector executives surveyed predict a "complete transformation or important changes to the power utility business model" as a result of disruptive technology, the changing role of the consumer, and the emergence of distributed generation including PV and storage[16]. More than 56% stated that the fall in solar prices would have "a high or very high impact on their market"[16].

The importance of storage

So far, electrochemical storage in the form of lead–acid batteries has been the most common form of electricity storage for residential PVs. Because of its high costs, it has almost exclusively been used in off-grid applications. Now, with electricity prices increasing in some regions and battery prices decreasing, viable battery storage options are emerging for grid-connected households.

This development is very important from the perspective of global climate change mitigation and sustainable energy supply. Traditional centralized electricity supply systems require instantaneous balancing of supply with demand. Residential battery storage with PVs and smart invertor technology will change this paradigm and allow consumers to shift the times they use electricity, reduce how much electricity they use from the network, or disconnect from the network entirely. Although consumers will choose the configuration most appropriate to their needs, not all options will result in net positive benefits to the system as a whole.

A widespread shift by consumers towards complete grid independence could see network asset use drop, causing electricity prices to increase as network costs are recovered over smaller volumes of electricity[17]. This represents substantial societal cost. Households that cannot afford to reduce electricity from the grid could be locked into a cycle of ever-increasing electricity bills as they become financially responsible for maintaining an under used, capital-intensive electricity network[17].

In contrast, residential battery storage technologies could be configured to support the network and, when deployed in conjunction with subsidies or supportive tariff structures, help to achieve financial outcomes for consumers. For example, time-of-use electricity pricing provides an opportunity for consumers to store electricity when tariffs are cheap and use it during peak periods to avoid higher rates. This reduces demand on the network, resulting in better asset use while reducing system-wide costs. Batteries with smart invertor technology can also be used to help to manage power quality and improve reliability, resilience and diversity of supply across the network. In some instances, carefully managed grid defection on costly-to-maintain networks, particularly in regional and remote areas, could reduce network costs and improve reliability.

The rapidly evolving storage sector

High costs remain the fundamental issue slowing broad market penetration of residential battery storage[18,19]. At present, battery storage is only cost-competitive in some high-value niche markets and in instances where purchasers are motivated by non-economic drivers[19]. At "current cost and performance levels", the IEA questions the transformative impact of storage, stating that it "falls short of delivering the conceptual flexibility potential when compared with competing options"[2]. But a number of factors are coalescing that may trigger a rapid decline in the costs of battery storage while accelerating technology development.

Some governments have developed policy measures to help to drive demand for battery storage. Germany, for example, is offering up to a 30% reduction in upfront costs of residential storage systems[20]. In 2013, more than 6,000 PV battery systems were installed in Germany, with estimates that more than 100,000 residential storage systems could be sold annually in the domestic market by 2018 (ref. 20). Importantly, it was Germany's decision to implement a PV feed-in tariff at the start of the millennium that helped to contribute to the global PV boom by increasing manufacturing scale and driving technology innovation[21]. It remains to be seen whether Germany's action in this regard will enable a similar phenomenon to occur for storage.

Pressure to reduce battery costs is also intensifying as battery manufacturing facilities scale up to respond to increasing demand for electric vehicles (EV). The EV manufacturer Tesla has committed[22] to a US$5 billion manufacturing facility that aims to produce 500,000 EV batteries by 2020 while reducing battery costs by 30% by 2017. Tesla's Model S battery has the capacity to power the average US household for up to 3.5 days (ref. 23). With a global EV fleet of 350,000 vehicles in 2013, and estimates of tens of millions of vehicles on the road in coming decades, there are good prospects for reuse of EV batteries in residential applications in the longer term[2,18].

In response to these developments, forecasts[24–26] suggest that the cost of some battery technologies could halve by 2020. Investment bank Morgan Stanley states that the storage market is larger than predicted and that battery costs will decline more rapidly than previously thought, with a total of 240 GW of residential and commercial storage likely to be deployed in the United States alone[23]. In addition, at least two studies[27,28] have found that PV and storage has already reached grid parity for certain consumers in Hawaii, and with falling battery prices, parity could be achieved in other US markets, such as New York and California, in less than 10 years.

Should battery storage drop in price as forecast, enabling widespread uptake, the impacts could challenge the fundamental assumptions of centralized power system design and the operation of electricity markets[29]. In early 2014, global investment bank Barclays downgraded the corporate bond market for the entire US electricity sector, suggesting that the industry is unprepared for the threat posed by residential PV and storage[28]. Barclays states that costs of residential-scale storage are falling quickly, and with PV, this development will "reconfigure the organization and regulation of the electric power business over the coming decade"[28]. At the same time, Australia's national science agency, CSIRO, predicts that electricity storage could play "a future game-changing role in many aspects of the electricity system" and in one possible scenario it estimates that by 2050, a third of Australian electricity customers could leave the grid entirely[17,30].

Managing the transition

With the world's energy systems on the cusp of unprecedented transformation, it is becoming more important to understand system-wide impacts from disruptive technology to ensure that the delivery of secure and reliable electricity is not compromised. For PV and storage, this will be a difficult objective to achieve. The existing electricity system is complex and characterized by multiple disruptive influences and substantial uncertainty. The emergence of the end-user as a primary driver of change is amplifying system complexity.

Comprehending complexity in the electricity sector and addressing issues with long-term consequences have in the past proven difficult. For example, California's well-known attempt to reform its electricity supply system and lower costs in the 1990s led to higher prices and a financial crisis that saw blackouts, the collapse of the state's largest energy company, declining productivity, job losses and public costs in the billions of dollars[31].

Traditional linear approaches to modelling can be limited in understanding and anticipating change in complex systems over time[32]. Such approaches break a system into its component parts to investigate the linear impact of cause and effect while often ignoring the interactions from which the complexity and the behaviour of the system are derived. A 'systems thinking' approach avoids these pitfalls. It can effectively map and quantify multidimensional causal relationships, while incorporating the impacts of feedback loops and time delays[33].

A key strength of a systems approach is its ability to transcend traditional boundaries between the sciences and humanities to connect often disparate variables[32]. This is particularly relevant for consumer-led transformations in the electricity sector, where large numbers of small end-users with differing motivations have the ability to disrupt an essential service that underpins fundamental social, economic and environmental outcomes.

Figure 1 displays a conceptual framework that demonstrates key variables and important feedback loops that could drive a consumer-led boom in rooftop PV and storage. This framework applies to established, centralized, fossil-fuel-based electricity systems in developed world economies where rising electricity prices, deregulation and new technology are empowering end-use consumers to participate in the electricity market.

This systems model helps to demonstrate the paradigm shift underway in the residential sector where key feedback loops are encouraging energy self-sufficiency and challenging entrenched business models that are reliant on volumetric sales of electricity. Attempts by incumbents to preserve the profitability of existing business models may end up achieving the opposite by reinforcing consumer drivers for grid independence.

Consumer motivation will be central to determining the rate and scale of storage uptake. Although consumers' financial objectives are one of the most important drivers, the pursuit of energy self-sufficiency, frustration with incumbent utilities, and environmental concerns will also influence behaviour[34]. These motivations, along with technology cost and the ability to pay, will drive the type and size of storage that consumers purchase and the way in which they use them. This in turn will determine the system response.

A failure by incumbents to respond to these trends will impact their ongoing competitiveness, allowing new entrants with new business models to cater to consumers' needs. Even with high battery costs, a range of energy service companies around the world are already offering packages that combine storage with other energy efficiency technologies and innovative financing options.

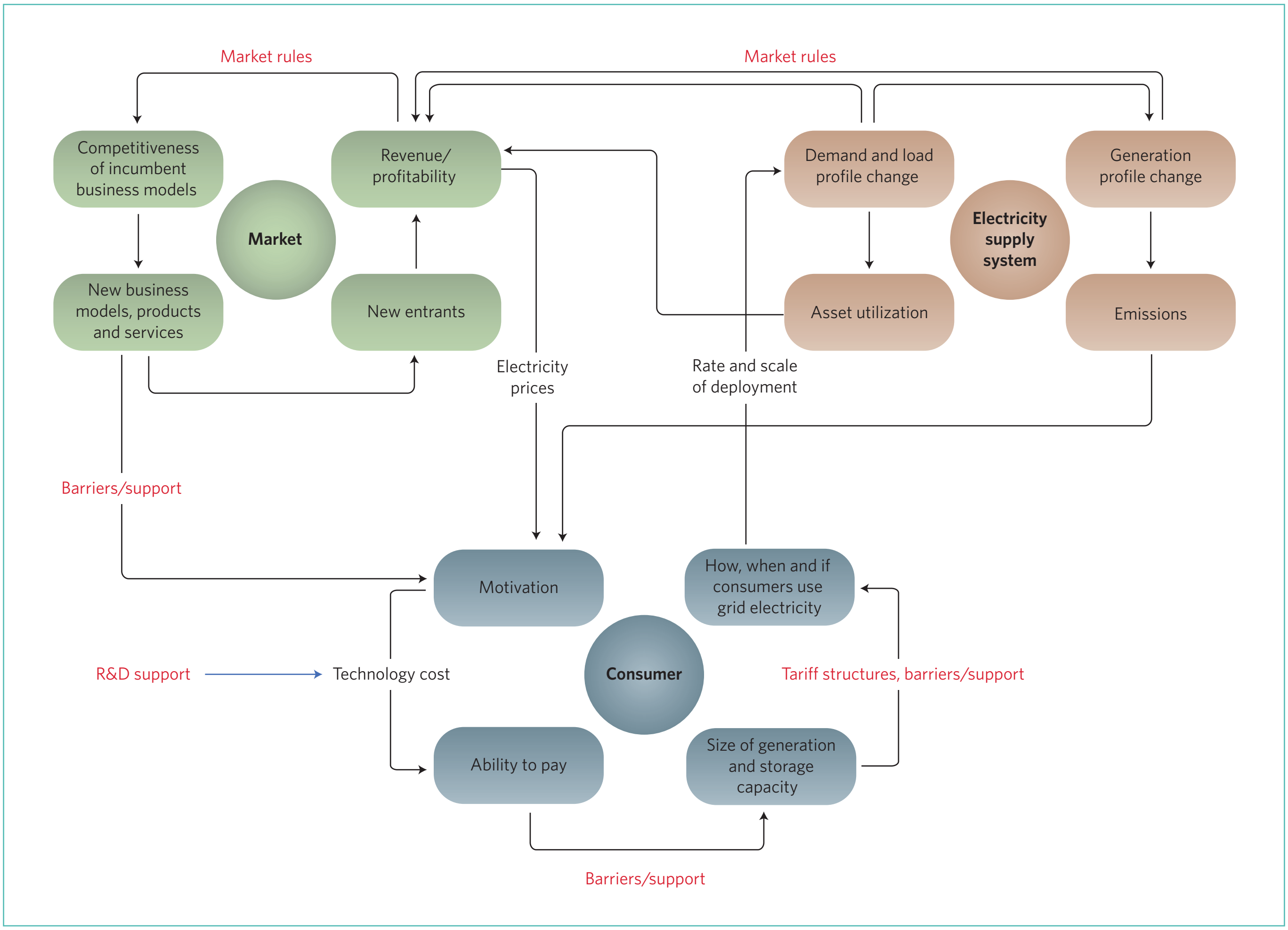

Figure 1 | Factors influencing the rate and scale of solar PV and storage deployment. Red labels represent examples of possible government interventions to achieve good political or social outcomes that could impact storage uptake.

Where next for residential PVs and storage?

Despite the compelling forecasts regarding falling prices and rates of technology improvement, the residential storage market is still very much in its infancy. With sparse empirical data, the extent of future disruption stemming from residential PVs and storage remains uncertain. What is known, however, is that the centralized electricity sector, the form and function of which have remained relatively static for nearly a century, is no longer immune to the power of consumer-led disruption.

For residential storage, this understanding precludes a wait-and-see approach if the problems associated with the PV boom are to be avoided. In this environment, with industry and new entrants mobilizing to maintain or build market share, the risks of suboptimal outcomes along the supply chain and for society more broadly are increased.

A systems modelling approach is well suited to help government and industry plan for, and optimize, the looming market transformation. Once the structure of the system is mapped, multiple simulations can be run to determine the impact of interventions anywhere along the supply system from different stakeholder perspectives. This helps in identifying the key leverage points and can determine where policy resistance may occur; that is, where the initial intervention is comprised by the response of the system to the intervention itself[31].

Should they choose, governments will have substantial power to influence this system to achieve stated environmental, social or economic outcomes. But balancing the diverse expectations of different stakeholders is a challenging task, particularly in the absence of any best-practice policy template or roadmap to address issues such as this[35]. Although incumbent utilities have immense economic and market power, the increasing numbers of households with PVs, in some countries numbering in the millions, wield a different but no less effective type of power.

Ultimately, the extent to which PVs with storage confer net positive or negative outcomes over the coming decades will be influenced by the ways in which the market attempts to realize financial value, and the manner in which governments intervene to achieve political or social good objectives. For market participants with differing strategic and commercial objectives, and for governments, particularly those that retain ownership of electricity infrastructure, this will require a fundamental rethink of the form and function of the existing electricity supply system.

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Author contributions

S.A. researched and wrote the paper. P.D. provided advice on the development of the paper and editorial input.

Additional information

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Competing financial interests

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