"Prosumage" and the British electricity market

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ABSTRACT

Domestic electricity consumers with PV panels have become known as "prosumers"; some of them also have energy storage and we have named the combination "prosumage". The challenges of renewable intermittency could be offset by storing power, and many engineering studies consider the role and value of storage which is properly integrated into the 'smart grid'. Such a system with holistic optimal control may fail to materialise for regulatory, economic, or behavioural reasons. We therefore model the impact of naïve prosumage: households which use storage only to maximise self-consumption of PV, with no consideration of the wider system. We find it is neither economic for arbitrage nor particularly beneficial for shaving peaks and filling troughs in national net demand. The extreme case of renewable self-sufficiency, becoming completely independent of the grid, is still prohibitively expensive in Britain and Germany, and even in a country like Spain with a much better solar resource.

Keywords: prosumer, electric storage, battery, solar PV, electricity market

https://doi.org/10.5547/2160-5890.6.1.rgre

"It is not possible, until the application of the accumulator or secondary battery—the reserve store of electric power—becomes practicable, to guarantee absolutely against any breakdown of the electric light." *The Times*, 3 October 1881, reporting on the opening of the Savoy Theatre.

1. INTRODUCTION

In 1878, Cragside in Northumbria was the first house to be lit by electricity. The world's first domestic electricity consumer, Lord Armstrong, had to generate his own hydropower. The first theatre to be lit purely by electricity, D'Oyly Carte's Savoy, was powered by his own steam engines. But one month earlier, Messrs Calder and Barrett had started to sell electricity to homes and businesses in Godalming through a public supply system, the world's first. This approach quickly dominated, and small-scale electricity customers became pure consumers, passively turning the switch whenever they wanted power. In the last decade, however, the rapid deployment of small-scale PV panels on rooftops has greatly increased the number of so-called "prosumers" who consume and also produce electricity. Companies are now marketing storage systems, such as the SonnenBatterie and Tesla's Powerwall, as the next step

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Economics of Energy & Environmental Policy, Vol. 6, No. 1. Copyright © 2017 by the IAEE. All rights reserved.

towards energy self-sufficiency. If we add storage to the home, we could perhaps add it to the concept, hence "prosumage."

The aim of this paper is to examine possible consequences of widespread home energy storage for the electricity market of the future, largely by using a model of the system in Great Britain. We deliberately consider self-interested strategies by users who have no commercial interaction with the power system beyond paying their electricity bill. There are many studies that take an engineering perspective on how distributed energy resources (such as rooftop solar PV and domestic batteries) can be controlled in an optimal manner (e.g. Molderink et al., 2010; van de Ven et al., 2013). While this is clearly possible, such studies rarely consider the transactions cost of installing and running the control systems needed for very large numbers of small sources. Leautier (2014) suggests that the benefits from mandating smart meters to enable demand response from small consumers would be low (and could be less than the cost of installing the meters). RTE (2015) uses a more detailed model and shows that the system benefits of demand response from electric heating and electric vehicle charging by households should exceed even a high estimate of the cost of metering and communications equipment. Whether those benefits can be monetised is another question: does a viable business model exist? Pollitt (2016) points out that the householders will want a significant share of the savings, and the net margins available to the companies they would interact with are likely to be very low relative to the cost of customer acquisition and service.

Grubb (2014) points out, furthermore, that many energy consumers' behaviour is dominated by habit, rather than responses to market-based incentives. While the paper in this symposium by Schill et al. considers the benefits of ensuring that prosumage *is* responsive to the needs of the grid, we take an alternative, more pessimistic approach in considering the behaviour of consumers who are oblivious to those needs.

One motivation for installing home energy storage is to self-consume a greater proportion of the owner's PV generation. The growth of PV has largely been due to subsidies, although costs have now fallen to the extent that the average cost of PV in many places is less than the retail price of power (Liebreich, 2015). The true value of the electricity generated is closer to the wholesale price, however, which is lower by the cost of networks and retailing (Ueckerdt, 2013). In European markets, average wholesale electricity costs have stabilised around €50/MWh, but network and retail fees (often including the cost of renewable support) have grown around 50% in the last five years, and now raise the retail price to €200–300/MWh (Liebreich, 2015). To the extent that these costs are recovered by per-kWh charges, self-consumption of PV output reduces a consumer's bill by more than the marginal cost of serving that energy. In some places, net metering regulations mean that all of the household's generation is counted as self-consumption, however mismatched in time. Without net metering, the times of generation and consumption matter when calculating the amount of true self-consumption; however, electricity storage gives the possibility of arbitrage between the price paid for imported electricity and that received for exports (throughout the paper we use import and export from the consumer's point of view). We show the value of this in section 3.

Grid-scale electricity storage, such as the batteries now being commissioned in California and Great Britain (CPUC, 2013; National Grid, 2016; Sandia National Laboratories, 2015), or the pumped storage stations that have existed for decades, can be expected to respond to wholesale market signals and the network's needs. Many electricity consumers face no time-of-day signals and cannot respond to them—instead, they may be motivated by the simple desire to maximise their own self-consumption, or the financial signals explored in the pre-

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ceding section. We explore what this could mean for the power system in section 4, showing that in Great Britain, it is quite possible that it could make the net load on conventional stations peakier, replacing solar exports in high-demand daylight hours with reduced net consumption in lower-demand night-time hours. While the impact may not be economically significant, the example nonetheless shows the importance of making all parts of the power system work together rather than in opposite directions, which becomes harder as control is decentralised.

The extreme case of prosumage is self-sufficiency: the consumer produces all the power their home needs and stores it until the time of consumption. This could allow them to disconnect from the grid and avoid all external charges, although it also forfeits the possibility of back-up supplies in the event of a failure. Nonetheless, the option of independence may appeal to some consumers, and Tesla (2016) describes its Powerwall as "Your path off grid." In section 5, we show that the amount of storage required for complete independence is likely to be prohibitively expensive at many days of consumption, even with enough PV capacity to generate much more electricity than the consumer uses. Before presenting our modelling, however, we review the background and some of the existing work in this area.

2. BACKGROUND

Global solar PV capacity has expanded ten-fold in the six years between 2009 (23 GW) and 2015 (227 GW) (REN21, 2016). 50 GW of new capacity was installed in 2015 (approximately a £50bn value), which is forecasted to rise to around 150 GW/year by 2030, implying that by then approximately 2 TW will have been installed (Liebreich, 2015; IEA, 2014). Solar PV is a prime example of 'learning by doing': since the 1970s module selling prices have fallen by 22% for each doubling of the capacity produced, from around $25 per watt in 1980 to $1 per watt in 2016 (IRENA, 2016).

Australia has the highest rate of household solar installation in the world, with 15% of homes having rooftop PV panels (APVI, 2016), and is discussed further in this symposium by MacGill and Smith. Within Europe, several countries have developed a large installed base of PV panels due to generous subsidies: 40 GW in Germany, 19 GW in Italy and 9 GW in the UK at the end of 2015 (Eurobserver, 2016). Germany hosts 0.49 kW of PV per inhabitant; Italy 0.31 kW and the UK 0.14 kW. The level of German installation is sufficient to bring PV capacity above the minimum level of electricity demand, as shown in Figure 1; the UK is at about half this level.

Electricity networks in many countries are now struggling to accommodate such high levels of intermittent generation. Impacts include depressed and volatile wholesale prices, rising balancing prices, greater difficulty in maintaining system stability and the curtailment of renewable output[1] (Gross et al., 2006; Holttinen et al., 2013; Hirth et al., 2015; Staffell, 2017). Strengthening transmission links within and between countries has been a common response, but this is both costly and politically difficult due to strong public opposition.[2] Storage is another way to ameliorate the impacts of intermittency which has been widely considered

1. Current rates of curtailment are around 5% in Germany (Bundesnetzagentur, 2016) and 7% in Great Britain (Elexon, 2016).

2. Japan, Germany and Britain are investing in new north-south capacity in response to growing PV and wind deployment. Germany is considering underground cables, while Britain had to use offshore 'bootstrap' connections despite their additional cost to minimise landscape impacts.

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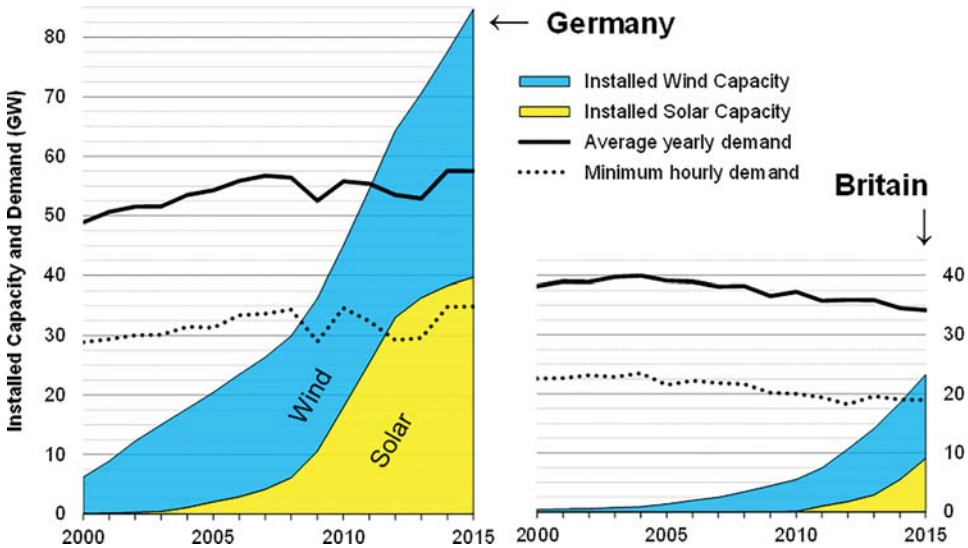

FIGURE 1
Intermittent renewable capacity in Germany and Britain, set against gross electricity demand.
Source: BP, 2016; OPSD, 2016; National Grid, 2016.

from the 'system' perspective (Grünewald et al., 2011; Sisternes et al., 2016). Studies such as IEA (2014) predict a very strong growth in electricity storage, from 40 GW in Europe at the current time to 70–90 GW in 2050 under the 2 Degrees Scenario, and from 20 GW to 80–160 GW in the United States.

Historically, electricity storage has been critically limited by a region's geography, due to the need for mountains suitable for pumped hydro storage. Pumped hydro still comprises around 99% of grid-connected electricity storage, but a variety of technologies are experiencing rapid market growth and reaching the point of materiality (Schlumberger, 2013). Lithium ion batteries are prominent amongst these, not because they are best suited for residential and grid-scale storage, but because they are applicable across multiple sectors (consumer electronics, electric vehicles) and thus have the advantage of increased deployment. Early indications are that the rate of cost reduction for lithium ion and other storage technologies is comparable to that of solar panels (Schmidt et al., 2017). Many in the energy industry are bullish about the future deployment of battery-based electricity storage. Some 34,000 combined PV and solar systems were installed in Germany as of January 2016 (Kairies et al., 2016), and Navigant forecast that worldwide, 4 GW / 12 GWh of residential storage will be installed annually by 2025 (Navigant, 2016).

These projections are driven both by the demand-pull effect of needing to balance the increasing amount of variable renewable generation, and by the technology-push effect of significant cost reductions. They imply that amounts of storage that would clearly not be economic today will be required, and able to pay their way, under future conditions. Nonetheless, the future business cases for storage may depend on its ability to provide multiple services (Strbac et al., 2012): arbitrage between times of low and high prices, reserve capacity for times of high demand and low renewable output, balancing energy to absorb real-time fluctuations in demand and intermittent output; and the ability to relieve network constraints

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by injecting power stored at a time when the network had spare capacity. The task of finding economic and regulatory mechanisms that allow storage devices to sell these multiple and sometimes conflicting services in a coordinated manner is now underway (European Parliament, 2015; BEIS and Ofgem, 2016; FERC, 2016). In this symposium, the paper by Pérez-Arriaga et al. discusses future challenges and recommends regulatory changes.

Focussing solely on the value gained from arbitrage, which is more appropriate for individual households in the present system, yields mixed results. Staffell and Rustomji (2016) find that storage is uneconomical in the near future when participating in the British wholesale market. In contrast, Hoppmann et al. (2014) find that storage would be viable in Germany for customers with the right size of PV systems, even in the absence of subsidies. The viability of storage depends on the specifics of the tariff regime and the interplay between the size of solar panel, storage and demand levels. We go on to explore these in Section 3, considering present-day technologies operating in Britain in the near future.

3. SELF-CONSUMPTION AND REGULATORY ARBITRAGE

The structure of electricity tariffs and support for PV generation varies from country to country. In Great Britain, for example, most retailers charge a fixed fee per day and a price per kWh consumed. The price per kWh only varies between day and night for a minority of customers (around 14%; Lucas and Vincent, 2015). The average cost of electricity therefore falls as consumption increases, although only a small proportion of the typical bill is made up by the fixed fee.[3] In California, retailers instead typically charge increasing block tariffs, under which the rate per kWh rises steeply with consumption.[4] This is not because the marginal cost of that consumption is significantly higher, but as a distributional tool to recover a greater share of network costs from (typically richer) high-volume consumers. This gives these households a greater incentive to reduce the amount they buy from the grid; installing a PV panel is one way of doing this. Borenstein (2015) shows that many households carefully install a panel just large enough, relative to their previous bills, that it mostly displaces high-priced electricity but does not reduce their consumption far into the cheaper bands. The ability to displace particularly high-priced consumption in this way was responsible for 12% of the bill savings made by the average installer in 2014.

The task of displacing high-priced consumption is made easier in California by the state's adoption of net metering—all PV production over the course of a year is deducted from the household's consumption, whether or not it was self-consumed or exported to the grid. Borenstein calculates that net metering was responsible for 15% of the private saving from installing solar panels in 2014, because it treats electricity actually exported to the grid (which would otherwise receive a relatively low price) as if it had been self-consumed. The social value of PV power, measured by the avoided cost of generation, was less than 40% of the bill saving. In short, paying for the network through kWh charges and allowing net metering creates a large part of the private benefits of PV in California.

The UK does not use net metering; households with PV panels receive a feed-in tariff for each kWh generated (whether self-consumed or exported) and they are paid for each kWh

3. For a customer on EdF Energy's standard variable tariff in London (December 2016), 14% of their bill would come from a fixed fee of 18.9p/day, and 86% from a price of 13.93p/kWh, assuming annual consumption of 3,100 kWh.

4. On PG&E's standard rate in San Francisco (December 2016), the first 8.5 kWh per winter day currently cost 18.4 c/kWh; the next 8.5 kWh cost 24.3 c/kWh and anything over that amount averages 40.3 c/kWh.

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that they export to the grid, but at a rate far below the retail tariff for buying electricity. In December 2016, a small system in an energy-efficient home receives 4.18p/kWh through the feed-in tariff for every unit generated and an additional 4.91p/kWh for every kWh exported. The UK does not require the owners of small systems to fit an export meter, but instead assumes that 50% of the electricity produced by the panel (which is metered) is exported; the amount of electricity actually exported is not recorded, as the consumer's import meter is designed not to run backwards. This effectively means that the consumer receives 6.64p/kWh for *all* of their generation, but nothing extra for the units that *are* actually exported, unless they install a smart meter. Those that are self-consumed are worth an additional saving of 13.93p/kWh (based on EdF Energy's tariff) because they reduce the amount of power passing through the import meter. The arbitrage value of avoiding exports and storing electricity until it can offset consumption should be clear—it triples the value of the stored energy.[5]

To explore the economics of this simple kind of arbitrage, and other possible consequences of adopting PV and electricity storage in the future, we need time series of household consumption and PV output. Our consumption series are taken from the DESSTINEE model described in Boßmann and Staffell (2015) and Staffell et al. (2015). DESSTINEE (*Demand for Energy Services, Supply and Transmission in EuropE*) models the European electricity sector in 2050 on the basis of user-specified scenarios for economic growth, technology adoption (e.g. for heat pumps and electric vehicles) and the capacities of generation and transmission. It is available open-source as a set of spreadsheets[6] which project annual energy demands across several sectors within each country, and synthesise hourly profiles of electricity consumption for the major customer classes, including residential consumers. The key assumptions needed to (approximately) replicate several well-known studies of future energy demand have been pre-specified. We used the IEA 2 Degrees Scenario, and interpolated between actual values for 2010 and the predictions for 2050 to give a scenario for 2030. The demands for electric appliances, electric heating and electric vehicles are specified separately, which allowed us to model the profiles for a household with electric heating, one with an electric vehicle and one with neither. The electric vehicle is recharged at the end of each journey, and the heating is resistive; in other words, neither of these large loads is operated with any regard to the needs of the grid. It is important to note that these profiles actually represent the diversified consumption of a large number of households, rather than the behaviour of a single dwelling. Individual profiles would have more variation from hour to hour and from day to day, potentially increasing the amount of power imported from and exported to the grid in particular hours, but decreasing it in others. This implies greater possibilities for storage at some times, but also that it would be needed less at others, and (for a smaller store) that energy or power limits might bind more often. The overall impact on the effects we study here is likely to be limited.

The solar PV output time series are produced by the Renewables.ninja model (Pfenninger and Staffell, 2016). This converts irradiance data from reanalysis and satellite image datasets into the expected output from solar panels, taking into account their location, north-south orientation and inclination (from horizontal to vertical). The model is corrected (by output scaling) to match historic output time series (when available) and allows simulations using 30

5. In the absence of export metering, a unit exported to the grid goes unnoticed and only attracts the feed-in tariff (6.64 p/kWh) while a unit self-consumed also reduces the amount to be paid for from the grid (6.64p/kWh plus 13.93 p/kWh).

6. Available from http://wiki.openmod-initiative.org/wiki/DESSTinEE.

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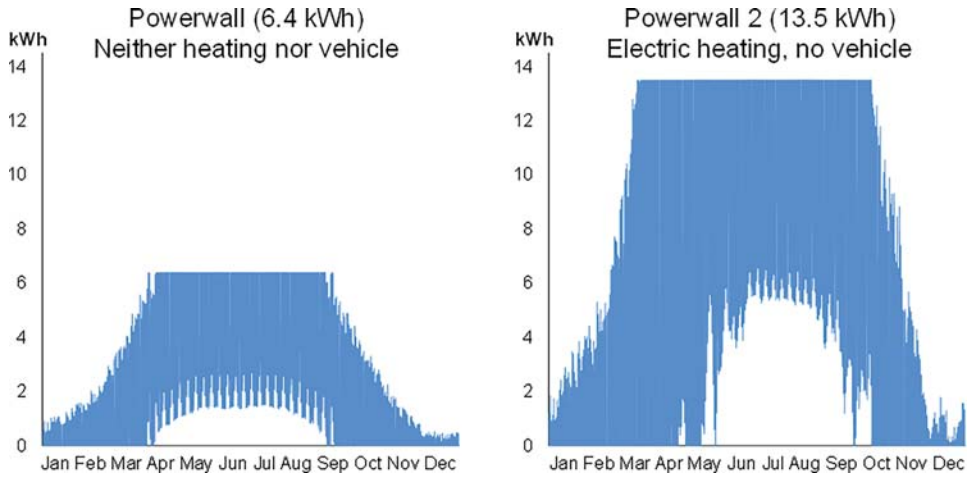

FIGURE 2
State of Charge for a Powerwall in a standard household (left), and for a Powerwall 2 with a household that charges an electric vehicle (right).
Source: Authors' calculations.

years of weather, which can be matched to wind output simulations (Staffell and Pfenninger, 2016) and demand data.[7]

We used the Tesla Powerwall and Powerwall 2 as iconic examples of a home energy storage device. Both devices have a power capacity of 5 kW; the Powerwall has an energy capacity of 6.4 kWh, and the Powerwall 2 an energy capacity of 13.5 kWh. The Powerwall 2 costs $5,500 in the US, with installation from $1,500; the Powerwall (no longer available) sold for $3,000 plus installation. In the UK, it is expected to retail for £6,350, including value added tax and installation (Tesla, 2016). Other devices are available and might offer better value; in particular, Tesla's devices have a power capacity that is much higher than our households will need. We show below that smaller energy capacities can capture much of the value available from a Powerwall. Some households would carry out a careful analysis of their needs before choosing a system; we are modelling the type that goes for an iconic brand.

We assume a deliberately simple operating strategy: that the battery starts to charge as soon as the household's PV panels generate more power than is being consumed, and discharges as soon as demand exceeds generation. It is hard to think of a less sophisticated strategy, but it is (weakly) optimal for any household facing the current UK policy of ignoring actual exports to the grid and an electricity tariff without time of day pricing.

Figure 2 shows the state of charge for two types of household. The one on the left has 4 kW of solar panels, neither electric heating nor an electric vehicle, and a 6.4 kWh Powerwall. The one on the right has electric heating (but no vehicle), 12 kW of panels, and a 13.5 kWh Powerwall 2. Whether these have the optimal storage capacity for each household is discussed below. The panels generate nearly enough electricity to cover each household's consumption over the course of the year, although there is a significant mismatch in timing—generation is far higher in summer than in winter. In the winter months, the battery is fully discharged

7. Time series for national outputs, and a tool to calculate a year's production from a panel or turbine anywhere in the world, are available at https://www.renewables.ninja.

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TABLE 1
Benefits from residential storage under the current UK tariff system, 2030 simulation.

A house with:	Electric Heating	Electric Vehicle	Neither	
	Powerwall 2	Powerwall 2	Powerwall 2	Powerwall
Annual Consumption (kWh)	10,084	6,401	3,794	3,794
Solar PV capacity (kW)	12	7	4	4
Solar PV output (kWh)	9,767	5,697	3,256	3,256
Exports without storage	6,474	3,789	1,842	1,842
(kWh)	66%	67%	57%	57%
Storage capacity (kWh)	13.5	13.5	13.5	6.4
Energy stored (kWh/year)	3,205	2,884	1,386	1,376
	33%	51%	43%	42%
Exports after storage (kWh)	3,269	905	456	465
	33%	16%	14%	14%
Electricity bill before PV (£/year)	1,405	892	529	529
Electricity bill after PV (£/year)	946	626	332	332
Electricity bill after PV and storage (£/year)	544	264	158	159
Saving due to storage (£/year)	402	362	174	173

each evening, and never reaches a high state of charge. In a short period over the spring, however, the battery becomes fully charged, for the panel starts to generate more electricity than the household will consume each day. The home with electric heating cycles its battery between fully charged and fully discharged around 50 times during the late spring when both PV output and heating demand are quite high. Demand falls during the summer, however, and neither battery is ever more than partially discharged. It is only once the autumn sun has weakened enough that the solar panels are no longer generating the households' daily consumption that the batteries' state of charge again falls rapidly towards low levels.

Table 1 shows the key assumptions for our three typical households, and the use they would make of a storage unit. We consider the larger Powerwall 2 in all three households, and compare this to the smaller Powerwall in the house with neither an electric vehicle nor heating. Each household's solar panel is sized to generate most of its electricity consumption, averaged over the year. In practice, however, between a half and two-thirds of the self-generated electricity would be exported to the grid, and the current UK system gives the consumer no benefit for the power actually, as opposed to notionally, exported. Installing the battery would allow these consumers to store between one-third and half of the power they generate, and the amount exported without payment would fall to between one-seventh and one-third of generation. Storing 1 kWh of power that would otherwise be spilled allows it to later displace 0.9 kWh of power from the grid, and the associated share of network and supplier costs (including subsidies to solar panels). Adding storage to a PV system therefore significantly increases the bill savings available, without changing the payments received under the current feed-in tariff rules.

Converting every 100 kWh of electricity that would be spilled and have no value to the consumer into 90 kWh of avoided purchases worth £12.54 might seem to be an attractive

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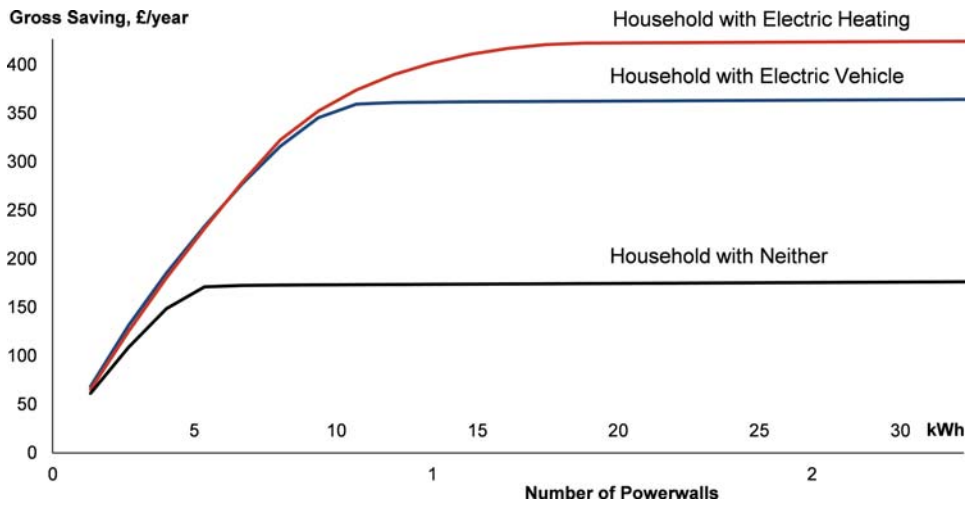

FIGURE 3
Gross Savings as Storage Capacity Varies.
Source: Authors' simulations for 2030.

proposition. Recall, however, that the Powerwall costs £6,350. If we assume a 10-year lifetime and an interest rate of 5% a year, the annual cost in interest and depreciation (calculated as an annuity) is £822. This is at least double the saving from additional self-consumption.

Tesla point out that another advantage of the Powerwall is that it reduces the risk of power cuts—the mean time without power for a British household is just over an hour per year, almost all of it due to network problems. London Economics (2013) estimated the Value of Lost Load for domestic consumers to lie between £7–12 per kWh, depending on the time of the outage. If we assumed the maximum value, and that an outage equivalent to half the Powerwall 2's capacity would be averted each year, this would be worth an additional £80 per year. Note that while the distribution of outage durations is very skewed,[8] saving 6.25 kWh of lost load every year would be far worse than typically experienced in the recent past. Even so, avoiding it does little to close the gap between the cost of the Powerwall and its financial value to the consumer.

The right-hand columns of Table 1 show that for a home with neither electric heating nor a vehicle, there is little difference between the two sizes of store. The smaller Powerwall only needs to export an additional 10 kWh, cycling between empty and full three times over the year, compared to the single cycle of the Powerwall 2. Figure 3 assumes that any scale of system is available, with the same performance and power to energy ratio as the Powerwall 2. The smaller systems would be able to deliver high proportions of the bill savings from the full-sized Powerwall. The gross savings are greatest for a household with electric heating, and flatten off with the largest amount of storage capacity, at about 18 kWh. A household with an electric vehicle has very similar savings up to a capacity of 11 kWh, but has exhausted its savings from that point onwards. The low-consumption household with neither electric heating nor a vehicle needs no more than 5 kWh to use almost all of its arbitrage potential. It

8. During a typical year, most consumers notice no outages, some have short power cuts and a tiny minority experience disruption lasting from hours to days, typically in the aftermath of severe weather.

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should not be surprising to see that for any capacity of storage, this household has the lowest gross savings.

While it is straightforward to show that relatively small storage systems can still obtain a high proportion of the gross bill savings available from a full-scale Powerwall, and the cost of the battery cells should be almost proportional to the store's capacity, there are also fixed costs such as inverters and installation. Tesla's installation charge of £950 implies a ten-year annuity of over £120 per year needs to be earned back (with a 5% discount rate), before paying for the battery, which would tend to make small systems uneconomic.

An obvious technical solution would be to pool several residences together, e.g. the houses on a street or the flats in a block. Ten houses would gain much greater benefits from a single Powerwall than one alone. However, the Powerwall would then be on the wrong side of the customers' meters, exposing it to the many regulations faced by third-party electricity suppliers. Peer-to-peer energy trading must take place over a regulated network, and requires an appropriate mechanism to become a reality (Kelly et al., 2015).

4. SYSTEM-WIDE EFFECTS OF NAÏVE PROSUMAGE

Even though the behaviour in the previous section seems uneconomic, this does not guarantee that it would not occur. In this section, we look at the effect of this kind of "selfish" domestic electricity storage on the overall net load on the system. We continue to take our 2030 version of the IEA 2 Degrees Scenario for demand, but at the national rather than household level. We assume 30 GW of solar PV, and 47 GW of wind capacity—these are the levels predicted for 2030 in National Grid's "gone green" scenario. It should be pointed out that our annual demand—456 TWh—is rather higher than in the National Grid scenario, as the 2 Degrees Scenario assumes greater penetration by electric vehicles and heating.

Wind output patterns come from the Virtual Wind Farm model (Staffell and Green, 2014) via the same method as for solar output, using the Renewables.ninja model described earlier in Section 3. Wind speed data from NASA's MERRA reanalysis was interpolated to the location and hub-height of each existing and anticipated wind farm in Britain, and combined with the manufacturer's power curve to synthesise the output from the national fleet of wind farms.

We assume that there are one million households with PV panels and storage but neither electric heating nor a vehicle, half a million with panels, storage and electric heating, and one and a half million with panels, storage and an electric vehicle. In all, we have 20 GW of domestic PV panels linked to 15 GW / 40 GWh of storage capacity.[9] The other 10 GW of PV panels we assume to be in solar farms with no storage linked to them. We continue to use the same algorithm as in the previous section: consumers start to charge their stores as soon as PV output exceeds demand, and to discharge as soon as PV output is less than demand. In other words, there is no attempt to respond to price signals, or to other information about the needs of the grid, for the reasons given in the introduction. Transactions costs may prevent the coordination of decentralised storage, or consumers may simply continue with existing habits (Grubb, 2014), being unwilling to give up control to a third party (Pollitt, 2016). The

9. We find that this power capacity is far greater than required, since the Tesla batteries have a higher power capacity than the households' needs, as was shown in Section 3. The maximum (collective) outflow from storage is 4.5 GW, and the greatest inflow 7.9 GW.

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use of a deliberately simple algorithm is therefore a pessimistic case, compared to engineering models designed to give a system-wide optimal solution; however, it reveals that ownership and transactions costs can matter.

Figure 4 shows four days of renewable output and the net demand remaining for conventional generators; two winter and two summer. Note that our simulations have enough PV capacity to create a twin peaks pattern for the net electricity demand each day, even in the winter, with a valley between the early morning and late afternoon peaks. Taking electricity into storage as soon as each panel-owning household generates more than it consumes helps to fill in this valley, even though this will raise the net demand for power at a time when that is above-average. Releasing the stored energy later will reduce the net demand: in the winter, this will be at a time of above-average demand, but in the summer, it may deepen the overnight trough.

This particular algorithm does not reduce the very highest net demand on the system, nor raise the level of the lowest minimum, however. Over the course of the year as a whole, this use of storage makes the load-duration curve very slightly flatter—the Gini coefficient of electricity demands falls from 0.2277 to 0.2263. There is also a tendency for the hour-to-hour change in net demand to be slightly smaller, with the average absolute change falling from 2.9 GW to 2.6 GW. These changes will very slightly reduce the average cost of generating power, even though storage losses mean that more now has to be generated. In this symposium, the paper by Schill et al. shows that a more coordinated approach could produce significant savings. To that extent, customer-owned storage that focuses on the customer's own needs is missing an opportunity.

5. SELF-SUFFICIENCY

For some households, the ultimate aim of owning PV panels or other microgeneration is to become independent of the grid (Kemp, 2006).[10] This may meet an emotional need (Hertin, 2015); there could also be an economic impetus if the charges for grid-provided electricity are rebalanced to recover the fixed costs of the grid in a more equitable manner. To recap, most countries recover much of the cost of the network (and support for renewable generators) in per-kWh charges, and consumers who meet part of their demand from self-generation pay a lower share of these costs, despite doing little to reduce them. To avoid the prospect of the "utility death spiral," a number of US utilities have introduced fixed charges for the owners of PV panels, or rebalanced their tariffs towards monthly fixed fees and away from charges per kWh. Becoming disconnected from the grid would allow the household to sidestep these changes: this section asks how much of their production they would need to store to make this feasible.

As before, we take hourly loads for a British household with neither an electric vehicle nor electric heating—the seasonal pattern of heating, which is almost directly opposite the pattern of solar generation, makes self-sufficiency a much harder challenge.[11] A 5 kW solar panel would provide enough energy over the year to meet the household's demand, including the energy lost in storage. Figure 5 shows how the amount of stored energy varies over the

10. While the context is obviously different, Agnew and Dargusch (forthcoming) report that 70% of Australian consumers would ultimately like complete independence from the grid.

11. Air conditioning, in contrast, has a summer-dominated load that is a good match to PV output.

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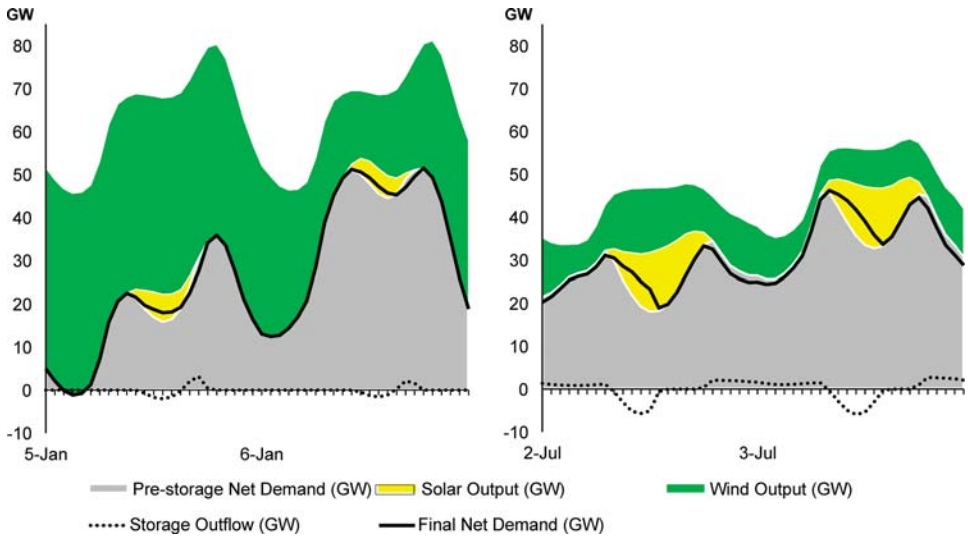

FIGURE 4
Impact of large-scale domestic storage on net loads during typical winter and summer days.
Source: Authors' simulations for 2030.

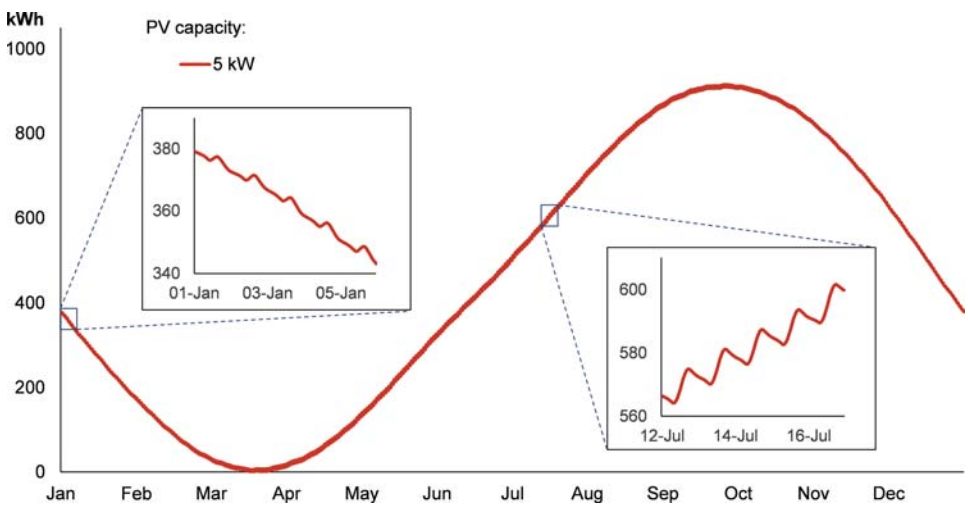

FIGURE 5
Unconstrained storage levels for a self-sufficient household.
Source: Authors' simulations for 2030.

year. The store must be charged over the late spring, summer and early autumn period when solar generation exceeds daily demand, so that it can be discharged over the following months. The left-hand inset shows that even in January, there are a few hours a day when the store is absorbing energy because generation exceeds demand; the right-hand inset shows that in the summer, more than enough electricity enters the store during the day to offset the night-time discharges. Even with perfect foresight and no margin for error, a storage capacity of over 900

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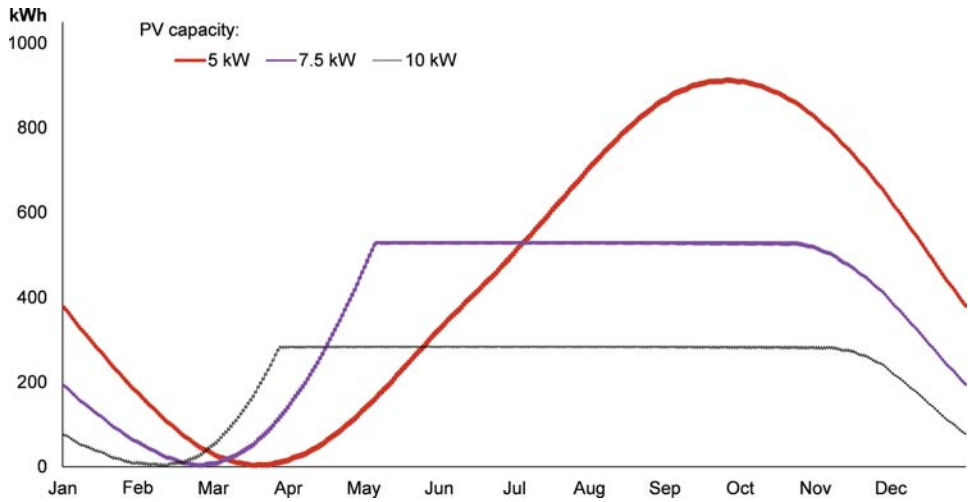

FIGURE 6
Storage levels for a self-sufficient household.
Source: Authors' simulations for 2030.

kWh would be required for a household with an annual demand of 3,800 kWh, or 88 days of average consumption.

The household could reduce the amount of storage required if it was able to generate more of its power during the winter months. Increasing the PV size to 7.5 kW means that only 530 kWh, or 51 days, of storage would be required. Given the relative costs of storage and PV, this is likely to be a less uneconomic option, even though one-third of the power generated would be wasted. Figure 6 shows that from late April to the beginning of November, the store is basically full, with just small overnight variations in its state of charge. The amount of power held in storage falls less steeply in the winter months, because the large panel is generating more of the household's needs, and rises more quickly in the spring.

If the PV panel was even larger, at 10 kW, twice the size needed for self-sufficiency, the storage capacity could be cut further, to 286 kWh, or 28 days' average consumption. Note that this still represents more than 20 Powerwalls, at a current price (before any bulk discount) of £134,000. This seems a high price to pay for independence from the grid.

The UK is of course a notoriously cloudy country in a relatively northerly latitude, factors unlikely to favour the use of PV. Germany, in contrast, was the early leader in large-scale domestic solar; were the policies that led to this chosen because it is more promising territory for self-sufficiency? Figure 7 shows that energy independence there would require a larger store, relative to consumption levels, than in the UK. The vertical axis measures the size of store in days of average consumption; the horizontal axis gives the extent to which the PV panels are over-sized. Note that the lines start with panels able to generate 7% more energy than the household is going to consume, as the excess is lost when it is taken into and then discharged from the store. Germany is less attractive for energy independence than the UK, as there is a slightly bigger mismatch between the seasonal pattern of consumption and that of PV output—German consumers take a slightly lower share of their energy in the summer months than those in the UK, while PV panels in Germany provide a slightly higher share of their annual output. A Spanish household, in contrast, would need much less storage to be

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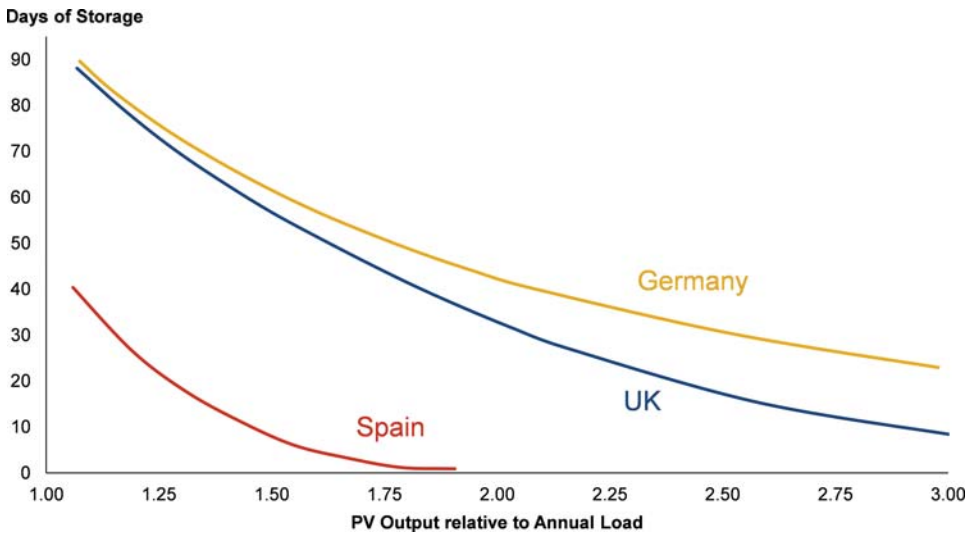

FIGURE 7
Storage capacities required for self-sufficiency in three countries.
Source: Authors' simulations for 2030 using load curves from the DESSTinEE model.

self-sufficient, given a lower variation in both solar output and demand over the year. If the PV panels were over-sized by 50%, just 8 days of storage would be required, and PV panels capable of generating double the household's annual energy consumption could be coupled to less than a day's worth of storage. This suggests that self-sufficiency might be feasible in sunnier climes, but it is not a widely applicable option at the moment.

6. CONCLUSIONS

Networked electricity systems developed for a reason: they exploit diversity in demand and in supply, minimising the need for expensive over-building. Completely rejecting this orthodoxy to become self-sufficient still comes at a very high cost, even with the prospect of cheap electricity storage devices. To quote Ellen Hayes of PG&E: *"Having a solar panel that isn't connected to the grid is like having a computer that's not connected to the Internet."*

We have shown that, even with the unexpectedly low-cost Powerwall, and a pricing system that seems designed to encourage it, energy arbitrage cannot make consumer-based storage economic in Great Britain. The economic case for grid-scale storage is based on the wide variety of services that it can provide, but the complexity of the business models involved is a major obstacle to consumer-led deployment of energy storage. Until storage becomes very cheap (a fifth to a tenth of today's prices), or price swings grow extremely large to make arbitrage profitable, storage units will have to provide a number of separate services, typically to different buyers.

Grid-scale energy storage systems will probably be able to meet these challenges and become commercially as well as technically worthwhile. In principle, aggregators could provide a single interface for the consumer, while controlling their storage devices to provide multiple services. The amount of profit available from each household is likely to be small, and transactions costs (including customer acquisition) will eat in to this—Pollitt (2016) suggests that

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aggregation is unlikely to be a commercially attractive model. Even if an aggregator can keep its costs down, the model is almost predicated on sometimes operating its contracted stores in ways that their owners would not have chosen: will many customers sign up for this? Overall, we fear that energy storage owned by consumers is unlikely to participate in multiple markets, and will thus contribute less than it should to the future energy system.

ACKNOWLEDGMENTS

Research Support from the Engineering and Physical Science Research Council, under grant EP/L014386/1, Business, Economics, Planning and Policy for Energy Storage in Low-Carbon Futures, and the Alan and Sabine Howard Charitable Trust is gratefully acknowledged. We would like to thank Christian von Hirschhausen, Erin Mansur, anonymous referees, and participants in the pre-conference workshop at the 2016 IAEE International Conference, Bergen, for helpful comments.

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