Big data analytics for flexible energy sharing

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The united Kingdom marked an important milestone in its transition to a low-carbon economy on 21 April 2017 (Figure 1). This was the first-ever working day in Britain without coal since the Industrial Revolution. The challenge now is to extend that single day to 365 days a year. However, two significant barriers constrain increasing the acceleration of this transition. The first is the diminishing subsidy for renewable generation: the United Kingdom has reduced its financial support for photovoltaic (PV) generation by 80% from 2017 levels. The second barrier is shrinking network capacity, particularly at the distribution level, as more low-carbon technologies, such as PVs and energy storage or distributed energy resources (DERs), connect to the existing network. If a smart-energy system is to take advantage of widespread DERs in the system, then energy markets should be introduced at the distribution sector to connect energy producers with consumers, delivering financial values so that DERs can thrive in a subsidy-free environment.

Vision for a "Sharing" Energy System

Crucially, a smart-energy system must create additional capacity from the existing network through a substantial enhancement of its operational efficiency, rather than relying on new primary network investment, and thus allow a significant increase in the energy flows of the existing system. Achieving this requires a paradigm shift from the current low-intelligence/high-asset business models of distribution network operators (DNOs).

A sharing economy has delivered enhanced value in many other market sectors such as transportation (e.g., Uber, connecting passages with drivers) and tourism (e.g.,Airbnb, connecting guests with home providers). Sharing economies make use of high speed information and communications technology (ICT) to match supply and demand and increase the use of otherwise underutilized assets through disruptive business models and horizontal peer-to-peer (P2P) trading. The development of smart grids and the widespread deployment of smart meters provide the essential infrastructure for the arrival of a sharing economy in the energy sector.

We foresee that a sharing economy can be one of the critical enablers that will unlock capacity in the existing supply network, deliver major financial value to renewable generation, and, ultimately, lead to affordable and clean energy for current and future energy customers.

This article summarizes our views on the use of sharing energy systems in two major categories of underutilized assets.

- Customer flexibility: In this context, a sharing economy would promote the horizontal supply of energy through P2P transactions (Figure 2), allowing distributed resources to be shared horizontally between energy producers and flexible users. It would also enable customer flexibility to counteract the uncertainty of supply at the local level, thus incentivizing customers to share responsibility for maintaining network security, and reduce the sometimes expensive and exclusive central control of DNO s when integrating lowcarbon technologies into the system.
- Network flexibility: A sharing economy in the context of a distribution network would require a DNO to give up its exclusive rights to the network. The DNO would be obliged to lease spare or backup capacity to an independent party and the independent party granted a license for system network access (SNA) and act as a secondary DNO . It would exploit the spare capacity in the

network to provide flexible network services that would match flexible generation and demand. In this manner, the proposed paradigm would use more existing physical network capacity and significantly reduce the network access cost to create flexibility.

Big data and analytics are key enablers for introducing a sharing economy into a monopoly system. They can access and process large amounts of network, customer, market, socioeconomic, demographic, and environmental data. They can uncover hidden patterns, correlations, and insights into realtime information concerning the current state of energy producers, energy users, and the distribution system, as well as their likely future states. They will form essential inputs for decisions that can substantially increase operating efficiency and inform the most efficient energy transfer between energy producers and consumers, primary and secondary network operators, and network operators and network users.

In this article, we discuss the feasibility of exploiting the flexibility in an energy system through the introduction of two sharing schemes:

- shared energy and flexibility—P2P energy trading in local energy markets
- shared network access (SNA)—new business models in energy networks.

Current State of Play (Small Data)

The current energy market in the United Kingdom is a vertical system (Figure 2), in which local producers and consumers have limited access but, aggregated to a reasonable scale, are able to participate in the central energy or frequency markets. This has worked well since the inception of the electricity market under the traditional structure of the electricity supply system, with generation and consumption separated at both ends of the system. With the cost of low-carbon technologies—such as PVs, electric vehicles (EVs), battery storage, and heat pumps—rapidly decreasing, these technologies are increasingly being connected at the edge of the distribution system. Millions of businesses and homes that have traditionally been passive energy consumers will become energy prosumers, able to store, convert, and generate energy. This will enable them to become active participants in the market.

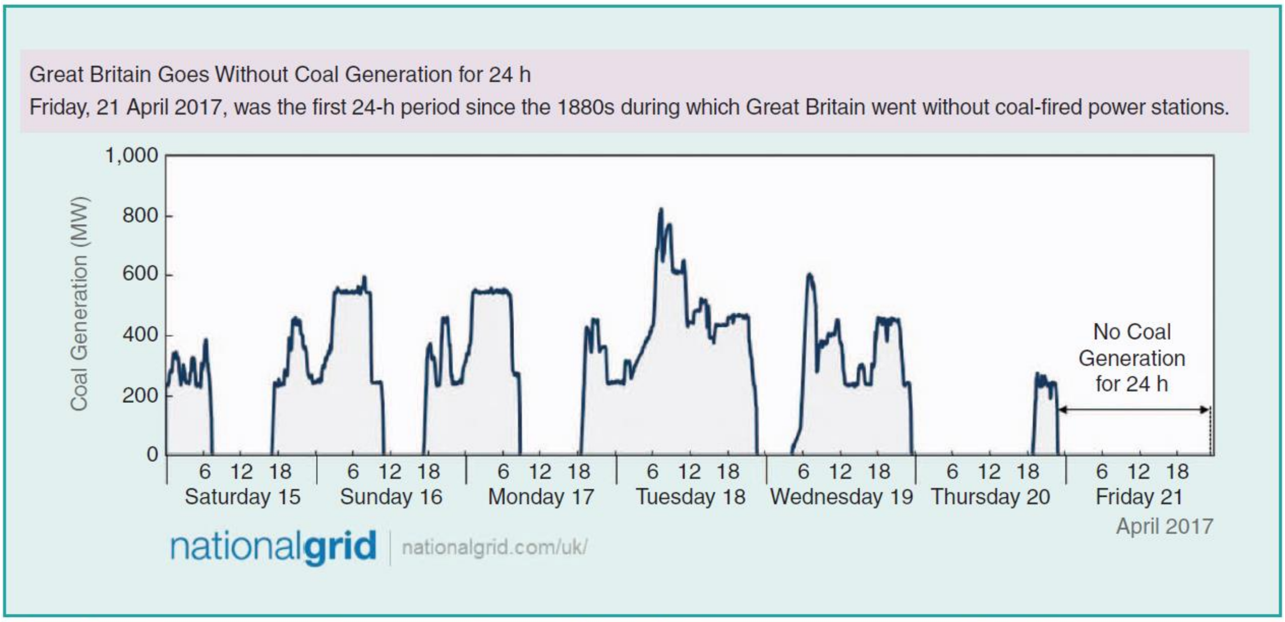

figure 1. Coal generation in Great Britain 15–21 April 2017. (Used with permission from National Grid.)

From a customer perspective, the current vertical business model may disadvantage local producers, especially those employing renewable technologies, by providing limited choices in terms of how to utilize output. Specifically, excess intermittent energy from prosumer renewable resources in its raw form is recycled by the grid at a very low rate: 3 pence/KWh (versus the retail rate of 24 pence/KWh), as it represents an intermittent, low-reliability energy supply, i.e., variability of energy outputs. The central system then acts as a giant energy store that would increase the perceived supply reliability to a level that meets the supply standards. As illustrated in Figure 2, in doing this, it both limits the financial value of the local resources and places an extra burden on the supply system—particularly when local wind and PV become significant at the distribution level.

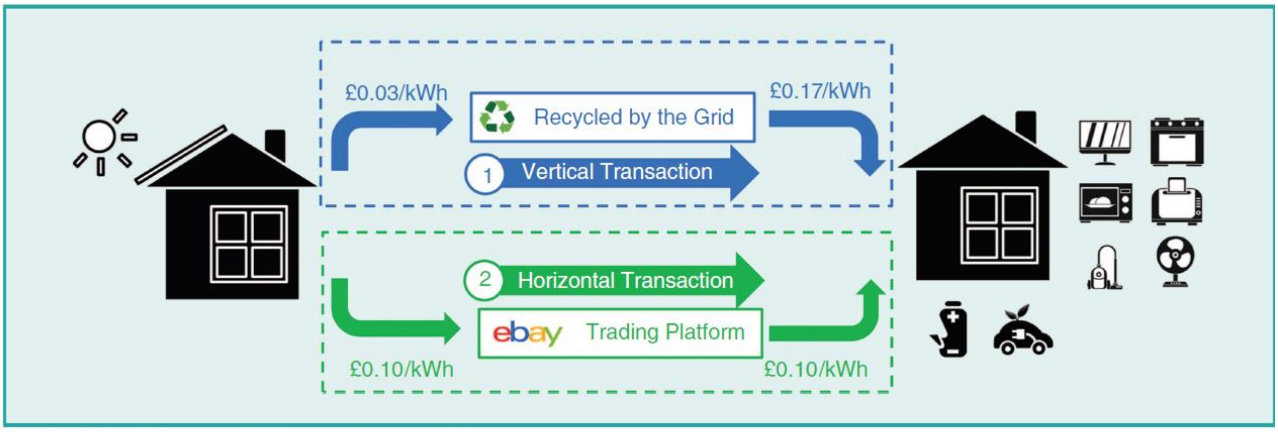

figure 2. Vertical and horizontal transactions.

At the distribution network level, the current DNO business model recovers network operation and investment costs through its use of system and connection charges. Revenues are largely determined by the amount of money spent on its network each year, with investment set to earn a fixed rate of return on capital. Under this business model, a DNO has an incentive to invest in the network to meet forecast load growth on the assumption that all loads require the same level of high reliability. A significant capacity is designed into the network to support the short-duration system peak, with the inevitable consequence that the network remains underutilized for most of the year. The current DNO business model continues into a future that does not distinguish flexible from fixed demand; thus, it will further diminish the efficiency of asset utilization by tending to connect flexible resources to low-voltage (LV) networks.

At the market level, the economic principles underpinning current market structures are based solely on price and quantity, with no consideration regarding the reliability of energy supply. The traditional structure for an electricity market establishes an equilibrium between supply and demand while trading only one level of reliability for energy products. All electricity must meet the security standards defined by regulatory bodies, which generally require near 100% reliability. In the emerging low-carbon environment, there is an opportunity to use the flexibility of emerging loads that have a higher degree of tolerance to the poor reliability of energy supply. These will include loads such as electric heat and transport, smart appliances, and home area energy storage. For this opportunity to be exploited, the current market arrangements need to be extended from cost and quantity to reliability. This will allow low-reliability energy supply, such as local PV and wind, to be directly traded with a third party in the local area. Such an arrangement offers the prospect of providing more choices to users and fully unlocking the value of local resources.

Disruptive Technology—Big Data Analytics and Application in a Sharing Energy Economy

A sharing economy mobilizes traditionally underutilized assets owned by individuals or communities and thereby enables them to provide services that create much greater value for the assets than would otherwise be available. The application of the principle of a sharing economy to local energy markets is through a P2P-traded market that allows a large number of fragmented energy buyers and sellers (prosumers) to find and trade with each other at a fraction of grid energy costs. Electricity prices would be set for an area or a transaction so that local demand can be matched to local generation and thus achieve a "local equilibrium." This local equilibrium can absorb the uncertainty of the impact of lowcarbon supply and demand and thus reduce operational burdens on the DNO and the wider market. Intermittent renewable generating sources would be tracked in real time so that those with the lowest reliability would offer the lowest price, thus providing the greatest incentives for the demand side to respond.

An application of a sharing economy to network access would allow a licensed third party having greater skills in risk assessment and risk mitigation to develop leasing strategies that dynamically match network availability with customer flexibility. Big data analytics is the key enabler to the development of such sharing systems. We next discuss the key technical gaps and prospective big data solutions for each of these arrangements.

Local P2P Energy Markets That Can Track Local Supply and Demand

In a local P2P market, prosumers are envisioned as being able to collaborate horizontally and so trade to bypass the central system. Such local market activities would provide signals and incentives for local customers to change their demand patterns and track the output of local generation, thus absorbing the uncertainty locally.

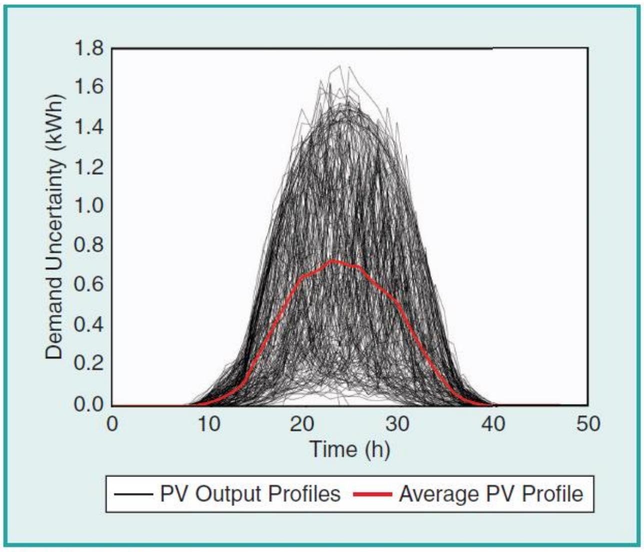

figure 3. The daily outputs of a PV generator over a year; the red curve represents the average diurnal value.

The current half-hourly energy trading system is designed for conventional large-scale generation that can be centrally dispatched. Distributed renewable generators have very different characteristics. Identifying the product a distributed generator can sell over time and space is critical to pricing and matching intermittent generation with demand flexibility. For a typical solar energy producer, the energy products it can offer into a central electricity market vary substantially over time. The daily outputs of a sample PV generator and its average diurnal value are shown in Figure 3, but the typical energy products it could offer to a central market vary greatly from day to day, as depicted in Figure 4. The product is a sampled and quantized profile of similar PV outputs: the “score” indicates the tradable quantity of the product, and “Var” represents the residue quantity, which is not tradable due to uncertainties.

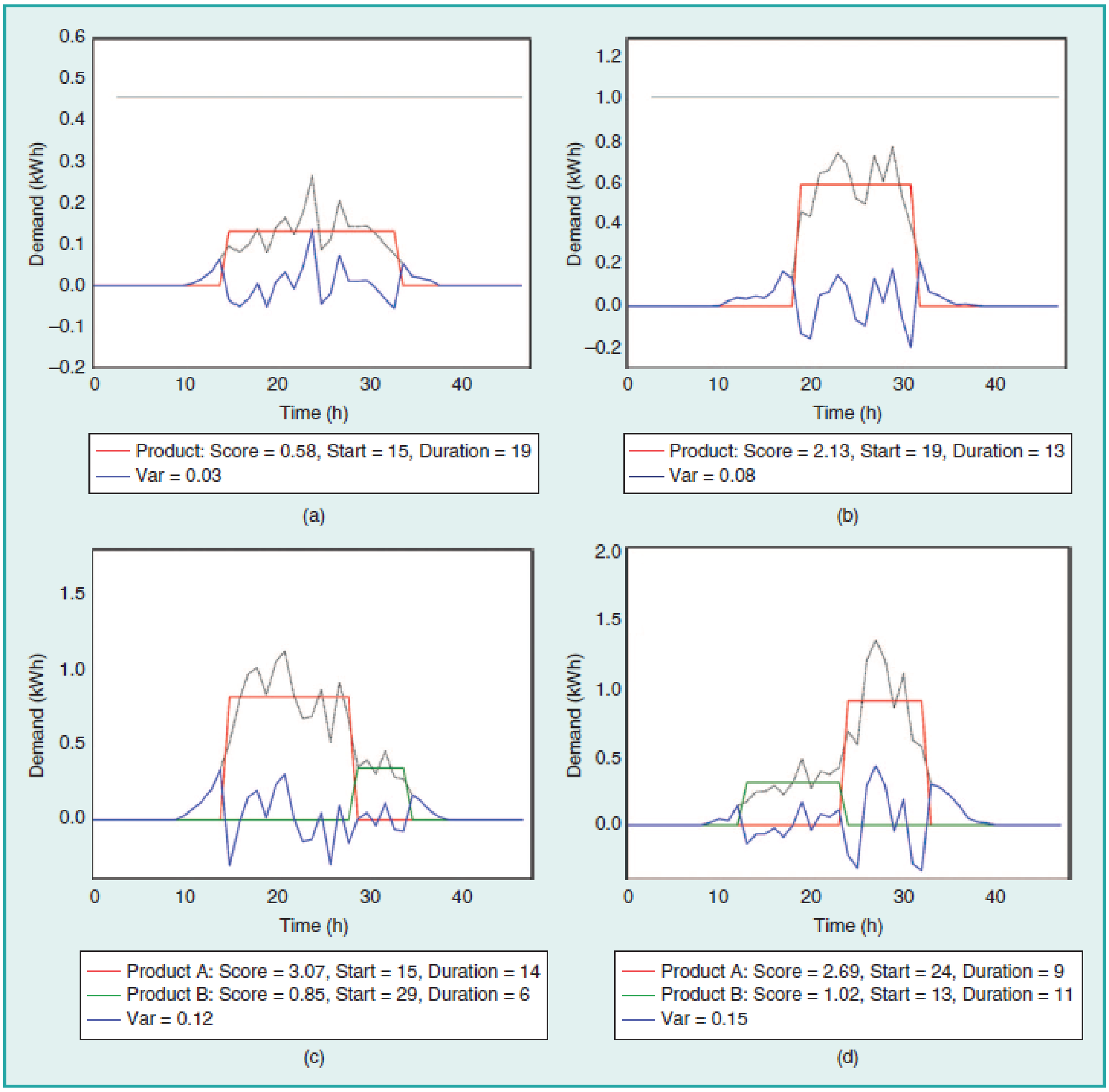

figure 4. Four typical daily products extracted from annual PV generator output.

This suggests a very different market design and operation for distributed low-carbon generation and demand flexibility. The market design must define what, how, and where to buy and sell local renewable-sourced energy products, considering vastly different energy products and their uncertainties. For local markets to compete, market operation must be more efficient than the central half-hourly market.

Market Design—Reliability: The Third Dimension of Market Equilibrium

The key challenge to developing local P2P markets is matching large numbers of supply and demand customers, each with different priorities in terms of quantity, price, and, critically, reliability of power supply. Trials of small- or medium-scale P2P energy trading have already been investigated in other jurisdictions, e.g., Vandebron in The Netherlands, Piclo in the United Kingdom, and the Sonnenbatterie community in Germany. Key innovations that have been considered are

- reflecting surplus and shortage of energy and mobilizing flexible demand to increase or decrease energy requirements according to availability of energy
- enabling optimal energy distribution among customers from the local interruptible supply and central traditional supply as well as maximizing the use of local resources
- improving power flows in the distribution networks to alleviate congestion levels and reduce the energy curtailment of renewables.

However, none of these approaches distinguishes between high and low reliability of the energy supply.

To make full use of the sharing system, the third dimension of the market—energy reliability—must be introduced to allow low and intermittent supplies to be traded and thus unlock the financial value of the local resources. A new P2P energy market theory is proposed that can extend the traditional theory so that it may account not only for price and quantity but also for reliability. This would allow a wide range of energy products to be delivered to customers with differing capabilities to achieve an economic balance between cost, volume, and reliability in energy trading.

In Figure 5, we show that the traditional market has almost 0% demand flexibility, while the energy product to be traded is almost 100% available at all times. The demand curve for this scenario is close to vertical. However, if demand flexibility and supply reliability could be recognized, then the market can be split into many segments with multiple supply/demand interactions and equilibria.

By way of example, in Figure 5, we have illustrated how flexible (0%–60%) demand would respond to energy prices. For local generation, the supply curve slope is flatter than for the central supply because it is intermittent and of lower reliability and, thus, less expensive. At the equilibrium points, the customer with higher flexibility will enjoy a much lower price by taking advantage of local low-carbon and low-cost generation instead of relying on the central energy market.

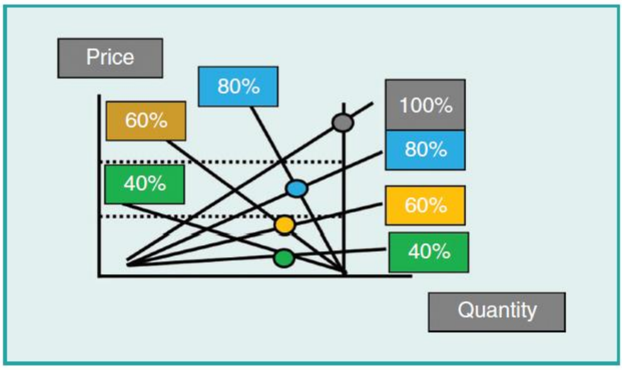

figure 5. The demand/supply curves in a local P2P energy market (Li, 2015).

Big data analytics will support the design of local energy markets by way of the following.

- A P2P local energy market would allow energy to be traded in different time blocks (from seconds and minutes to hours), in different quantities, and, particularly, with different supply reliability. Big data analytics would be critical to ensure a multitime, multiscale, multireliability energy trading system optimized for tracking supply/demand levels and their variability. Potential applications include the following:
    - Resource characterization: This is needed to understand the largest and smallest trading units, largest and smallest time blocks, and highest and lowest supply reliability.
    - Probability forecasting: This will serve to estimate the likely energy (both generation and consumption) over the bidding periods from seconds to minutes to hours. Critically, it will

estimate the probability distribution of each supply and demand level for each bid period to measure the uncertainty of the estimate.

- Ultrafast settlement. Because there is potentially significant uncertainty between predicted energy and real-time trading, the associated surpluses or shortages would need to be reconciled and settled. Depending on the size and time block of the P2P market, big data analytics could support fast trading and settlement.

Market Operation: Forecasting, Pricing, and Matching

During the market operation stage, all potential offers and bids would rely on real-time forecasting and pricing. The trading system would then find the best matches between supply and demand. There is a particular need to improve forecasting, pricing, and matching algorithms to take into account products, flexibility, and uncertainties, and, ultimately, maximize the value of local resources.

Real-time forecasting, pricing, and matching are interdependent, which requires highly efficient data processing to cope with a potentially very large number of offerings. The quality and speed of forecasting are prerequisites for the quality of pricing to ensure that the market reflects the availability and condition of the offerings. Forecasting and pricing will then determine the quality of matching, i.e., the degree of value that can be delivered to local energy resources.

Energy forecasting techniques thus play a critical role in the traditional centralized market. The merits of these techniques are challenging at local markets for the following reasons:

- At the local level, electricity demand is volatile and difficult to predict. At an aggregated level, the diversity between customers makes aggregated demand for a centralized market easier to predict and correlate with explanatory variables such as days of the week and weather.
- In a centralized power market, generators are controllable and can be used to balance demand forecasting error. In contrast, distributed generators are usually intermittent and uncontrollable. The two-way forecasting errors of generation and demand would bring significant uncertainty to the settlement of a local market.
- The deployment of low-carbon technologies will significantly challenge existing forecasting models. For instance, the established average load profiles will become inappropriate when individual households are equipped with PVs, own EVs, and individually have widely varying demand profiles.

In particular, all forecasting techniques rely on the selection of dependent or explanatory variables that are then used to derive algorithms to forecast demand. To support the local market, the selection of variables has to go far beyond the current searching space, which is based on engineering experience. This is because, at the granular level, individual demand and generation are markedly influenced by the explanatory variables. For example, the output from roof solar energy is mostly determined by meteorological factors, while household demand is heavily influenced by geodemographic factors; life patterns, driving behaviors, and charging locations are likely to be key influencing factors for EV demand.

Examining all possible internal and external variables would be far too laborious and time-consuming for real-time applications. Instead, local energy markets require a new breed of forecasting technique that can quickly identify dominant variables from large volumes of input data and make fast predictions with a reasonable degree of confidence. Essentially, new variable selection and forecasting techniques are required to predict key energy information concerning energy availability and variability in a timely manner, thus informing all subsequent market operations, i.e., pricing and matching.

At the real-time trading stage, automatic matching between intermittent generation and flexible demand would maximize the value of local resources. Coping with a very large number of transactions over time and locations requires large-scale and efficient searching algorithms that consider physical uncertainty in forecasting and financial risks in pricing. To this end, prosumer segmentation would enable fast matching processes by controlling similar prosumers as a group to speed up the search algorithms.

Shared Network Access

SNA aims to integrate flexible demand in a cost-effective manner. The major benefits of SNA over conventional business models can be seen by examining the commercial and cash flow relationships among stakeholders. More importantly, as shown in Figure 6, the SNA scheme provides an incentive to the incumbent DNO to give up its exclusive access to the network and lease the spare or backup capacity to licensed independent parties. The ownership of assets would be retained by the incumbent DNO, but competition would be introduced through auctioning or contracting out the rights to the spare capacity. The independent parties who are licensed for SNA would act as secondary DNO s to provide flexible network services using the spare capacity in the network, thus substantially reducing the network access cost for flexible demand. In the case of unforeseen contingencies, the spare capacity would be returned to the incumbent DNO to ensure security of supply. Table 1 summarizes the differences between current models and sharing of energy systems.

table 1. A comparative summary of differences between the status quo and sharing energy systems.

	Status Quo	Sharing System
Customer flexibility	Very limited energy products for customer flexibility; assets are severely underutilized and not optimized for the whole system	Horizontal P2P energy trading between prosumers
Network flexibility	Reserved for contingencies; idle much of the time	SNA; spare capacity can be leased to accommodate more flexible demand/ generation

It should be noted that there would be significant technical and regulatory challenges in aligning the objectives of primary and secondary operators to ensure smooth coordination and transition. When the need arises to return the spare capacity to the primary operator, the secondary operator is essentially required to interrupt the supply to its flexible demand. For example, when necessary, the telecommunications industry typically stops all new calls from connecting to the existing network, but ongoing conversations are not interrupted. The technical and regulatory challenges must be properly considered to give both primary and secondary operators a higher degree of certainty in terms of capacity availability so that they can optimize and coordinate their networks in the interests of both fixed and flexible demand. Failure to do so would lead to a much more complicated system as well as dissatisfied customers.

The key development required to achieve SNA is to make visible the dynamically charging availability of network spare capacity. Generally, in the United Kingdom, the final stage of system monitoring is on the outgoing 11-kV feeders in a primary substation, where current and voltage are both measured. The real-time loading of the distribution substations along the 11-kV feeders is not currently recorded or visible without a site visit. Furthermore, measurements of the maximum demand indicator taken during a site visit exhibit poor accuracy across the loading range.

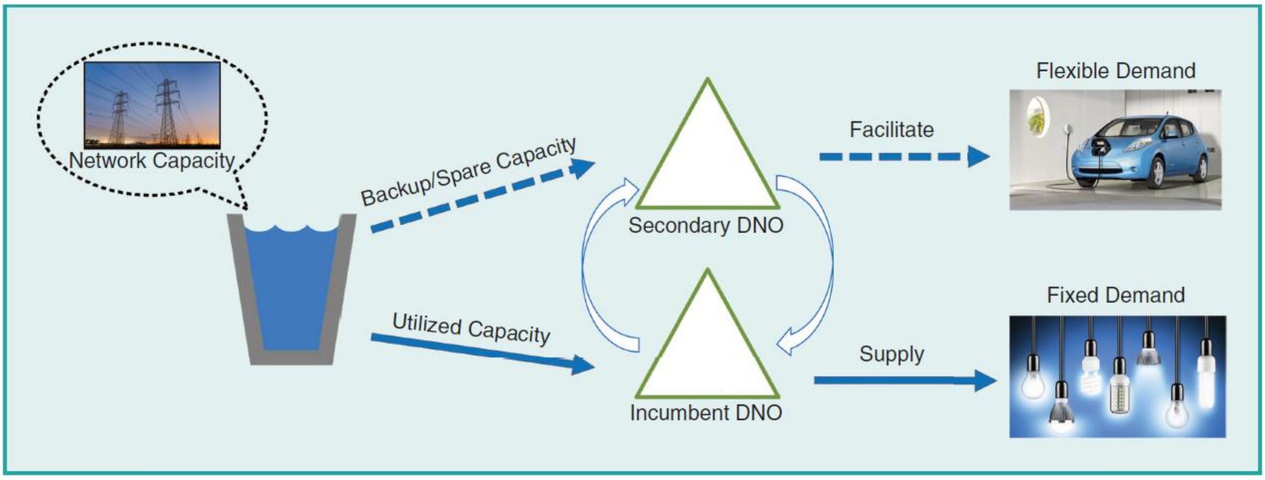

figure 6. The basic concept of the SNA DSO business model.

Without big data support, the DNO often designs the network according to passive "fit and forget" criteria. This ensures that the system can operate within statutory limits and remain resilient under worst-case scenarios, such as the evening peak during the coldest winter period. The approach is based on the assumption that load growth for existing customers will be relatively small, uniform, and predictable. Large-scale adoption of low-carbon technology on LV networks could change this assessment of the worst-case scenario and undermine current load growth assumptions. A key design challenge is to identify when these changes are likely to occur. Limited visibility of asset use and the state of the network make it difficult for a DNO to optimize its network planning and operation. A better understanding of how customer behavior is likely to impact the time-of-day loading and voltage "headroom" available on different parts of the LV network is crucial in planning the security of a future network.

One solution under consideration for situational awareness is widespread monitoring. In practice, such a solution could be prohibitively expensive: it has been estimated that this would cost £2 billion to monitor all the LV networks in the United Kingdom. Inferential statistics, another feature of big data, could be used to observe the whole system by mining data from small populations. Such a process aims to maximize the values of "small" data and thus avoid "expensive" data. The crucial question is whether there is a simple and cost-effective method that can provide the visibility of flows in the LV distribution network.

In the United Kingdom, a series of projects have been conducted by DNO s to answer this question. The LV Network Templates Project was one of these flagship projects. It provides remote monitoring of current and voltage at over 800 distribution substations. In addition, voltage monitors have been installed in approximately 3,500 premises at the end of LV feeders. A set of LV network substation templates was then developed to provide benchmark load and voltage profiles that could be applied across the United Kingdom.

Traditional load profiling methods are based on supervised learning techniques and customers mapped into predefined domestic, commercial, and industrial classes. Because the industry has little prior knowledge of individual LV loads and network states, the project proposes a novel three-stage semisupervised learning algorithm. The first step is an unsupervised clustering to search for typical substation templates. The next step is to assign an unknown substation to the most similar template. The final step is to estimate the loading levels of the LV substations by the use of clusterwise regression.

This has produced two significant outcomes. First, the templates developed were validated by five out of seven DNOs in the United Kingdom and, overall, achieved an 87% accuracy. Second, an even greater and longer-lasting impact of the project has been the learning associated with the voltage profiles. This, in turn, has led to a further project for voltage reduction analysis.

Western Power Distribution (WPD) asked the University of Bath to undertake a study regarding the effects of a voltage reduction scheme for those voltage profiles close to the upper bound of the statutory limits. University of Bath researchers concluded that such a scheme could significantly reduce demand, customer bills, and carbon emission. Adopting the method for customers in South Wales, WPD reduced voltage by 1%. This has saved customers in South Wales approximately £14 million per year. Plans are in place to deploy this approach across WPD ’s four licensed areas, where possible. If rolled out nationally in conjunction with the adoption of voltage tolerances (±10%), it is estimated that the policy could save Great Britain £315 million and 1.98 million tons of carbon dioxide each year.

Conclusions

Managing flexibility in generation, demand, and storage is a requisite for achieving greater efficiency in electricity supply. Exploiting this flexibility to achieve a higher utilization of system assets is essential for enabling the United Kingdom to transition to a low-carbon energy economy. Shifting to a sharing economy is one of the most promising approaches for exploiting flexibility through the use of high-speed ICT, exploration of disruptive business models, and creation of innovative horizontal markets.

A key enabler will be big data analytics that can inform users and market participants, establish prices, and match flexibility in demand with intermittent generation through extensive analyses of metered data together with socioeconomic and weather information. In this article, we discussed P2P energy markets and SNA to illustrate the value of embracing a sharing economy in the energy sector. Through these developments, major returns can be delivered to lowcarbon developers and flexible energy customers by extracting more value from existing generation, network, and customer assets.

Acknowledgement

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For further reading

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