Big Data Analytics for a Flexible Sharing Energy System Accelerating a Low Carbon Future

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1. Vision for a sharing energy system

The 21st of April, 2017 marked an important milestone in the UK's transition to a low carbon economy. This was "the first ever working day in Britain without coal since the industrial revolution!" The challenge now is to extend the single day to all 365 days in the year.

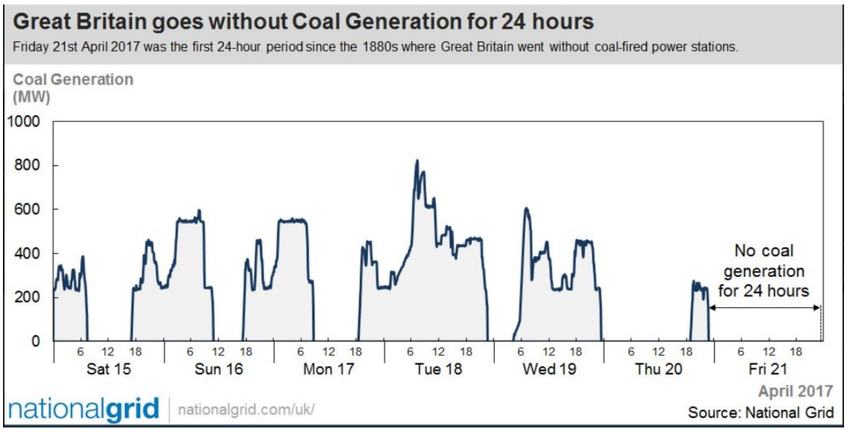

Figure 1 Coal generation of Great Britain from 15th to 21st April 2017

However, increasing the acceleration of this transition is constrained by two significant barriers. The first barrier is the diminishing subsidy for renewable generation. The UK has reduced its financial support for photovoltaic generation by 80% from 2017. The second barrier is a shrinking network capacity, particularly at the distribution level as more low carbon technologies, such as Photo Voltaic (PV) and energy storage or distributed energy resources (DERs), connecting 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. 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 (Uber- connecting passages with drivers) and tourism (Airbnb – connecting guests with home providers). Sharing economies make use of high speed information, communication and Control (ICT) technologies to match supply and demand and increase the utilization of otherwise under-utilized assets through disruptive business models and horizontal peer-to-peer (P2P) trading.

The development of smart grids and the wide-spread 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 the capacity in the existing supply network, deliver major financial value to renewable generation, and ultimately, lead to affordable and clean energy for the current and future energy customers.

This article considers the use of sharing energy systems in two major categories of under-utilized assets:

- *Customer flexibility*: In this context a sharing economy would promote the horizontal supply of energy through P2P transactions. It would allow 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, and thus incentivizing customers to have shared responsibility for maintain network security, and reducing the expensive and exclusive central control when integrating low carbon technologies into the system.

- *Network flexibility*: A sharing economy in the context of a distribution network would require DNOs to give up its exclusive rights to the network. The DNO would be required to lease spare capacity or back up capacity to an independent party. The independent party would be granted a License for System Network Access (SNA) and would act as a secondary DNO. It would exploit the spare capacity in the network so as to provide flexible network services that would match flexible generation and demand. In this manner, it would create extra capacity on the existing network and significantly reduce the network access cost for flexibility.

Table I: 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 under-utilized and not optimized for the whole system	Horizontal peer-to-peer energy trading between prosumers.
Network Flexibility	Reserved for contingencies, idle much of the time	Shared network access: Spare capacity can be leased to accommodate more flexible demand/generation.

Big data and analytics are key enablers for introducing a sharing economy to 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 the real-time information of the current state of energy producers, energy users and the distribution system, and their likely future states. They will form essential ingredients to decisions that will substantially increase the operating efficiency, and inform the most efficient energy transfer between energy producers and consumers, between primary and secondary network operators, and between 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 networks access - new business models in energy networks

2. Current State of play (small data)

The current energy market is a vertical system where local producers and consumers have limited access but aggregated to a reasonable scale to be 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 photovoltaics, electric vehicles, battery storage and heat pumps, rapidly decreasing, they are increasingly being connectedat the edge of the distribution system. Millions of businesses and homes that were traditionally passive energy consumers will become energy prosumers that can store, convert, and generate energy. This will enable them to become active participants in the market.

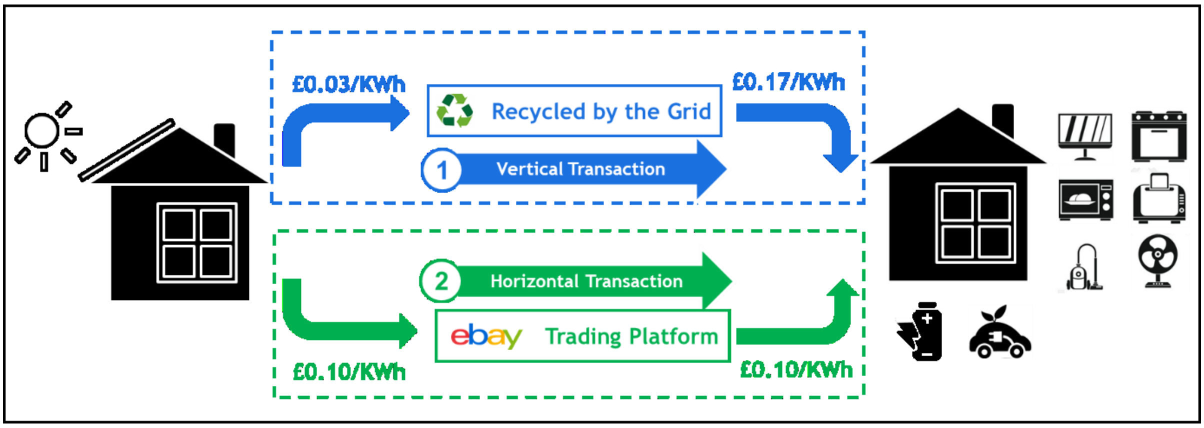

Figure 2. Vertical and horizontal transactions

From a customer perspective, the current vertical business model may disadvantage local energy producers, especially those employing renewable technologies, by providing limited choices of how to utilize their 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 quality of energy supply, i.e. variability of energy outputs The central system then acts as a giant energy store that would increase the perceived supply quality 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 the local wind and photovoltaics (PV) become significant at the distribution level.

At the distribution network level, the current DNO business model is to recover 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 so as 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 the future that does not distinguish flexible demand from fixed, it will diminish the efficiency of asset utilization further by tending to connect flexible resources to the LV networks.

At the market level, the economic principles underpinning current market structures are based solely on price and quantity without any consideration for the quality of energy supply The traditional structure for an electricity market establishes an equilibrium between supply and demand whilst trading only one quality of energy product. All electricity must meet the security and quality standards defined by regulatory bodieswhich generally require near 100% reliability. In the emerging low carbon environment there is an opportunity to utilize the flexibility of emerging loads that have a higher degree of tolerance to the poor quality 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 quality. This will allow low quality of energy supply, such as local photovoltaics (PV) and wind, to be directly traded with a third party in the local area. Such an arrangement has the prospect of providing more choices to users, and to unlock fully the value of local resources.

3. Disruptive technology – Big data analytics and application in a sharing energy economy

A sharing economy mobilizes traditionally underutilized assets that can be in the ownership of individuals or communities, and so enables them to provide services that create a 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 peer-to-peer (P2P) traded market that enables a large number of fragmented energy buyers and sellers (prosumers) to find and trade with each other at a fraction of the grid energy cost. 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 low carbon 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, and thus provide the greatest incentives for the demand side to respond.

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

4. Local P2P energy markets that can track local supply and demand

In a local P2P market, prosumers are envisaged 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.

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 average daily output of a sample PV generator is 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 are not tradable due to uncertainties.

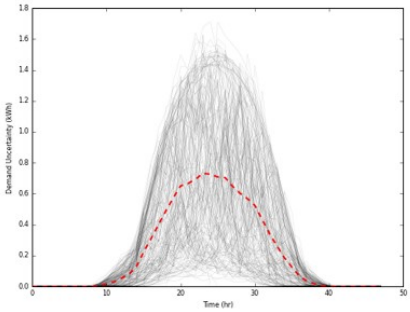

Figure 3: Cumulative daily output of a PV generator over a year; aggregate is the red curve

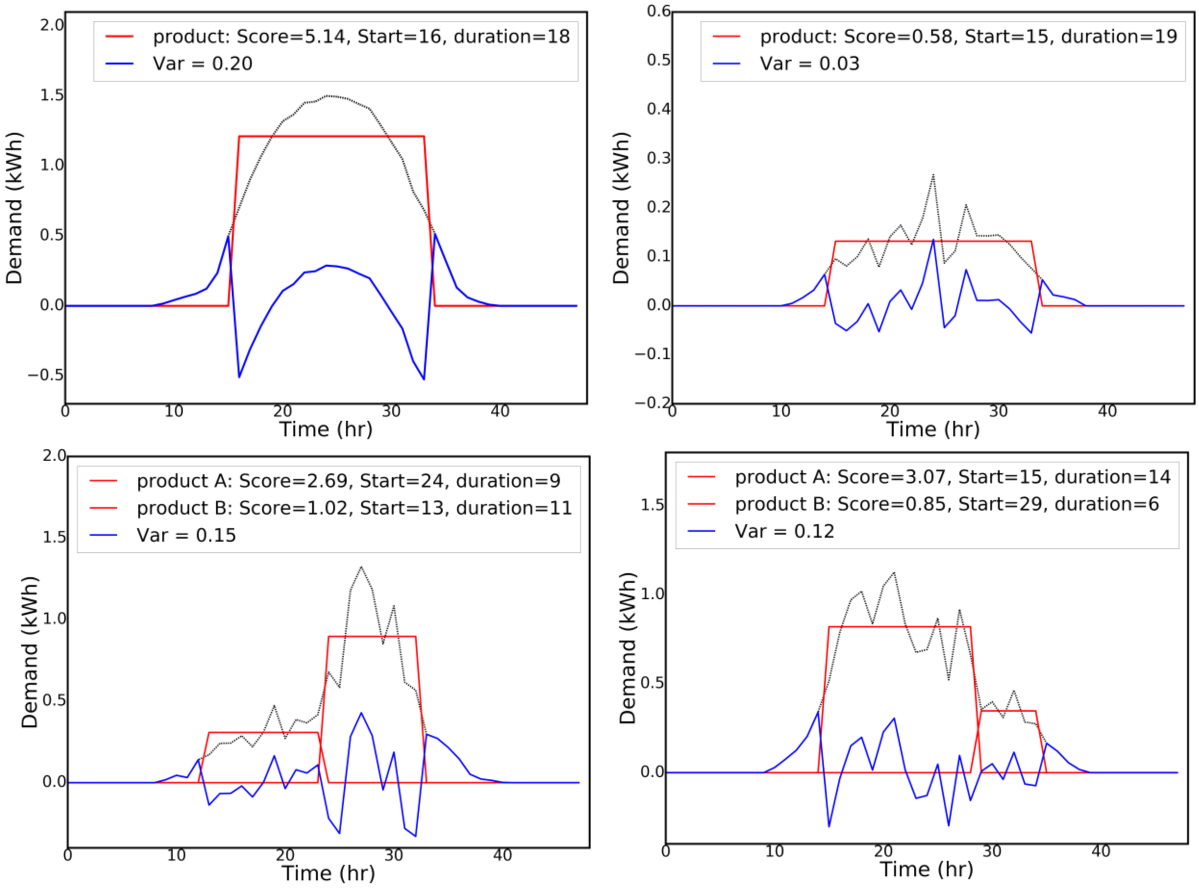

Figure 4: Four typical daily products extracted from annual PV generator output

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

4.1 Market Design – Quality: the third dimension of market equilibrium

The key challenge to developing local P2P markets is to match large numbers of supply and demand customers each with different priorities in terms of quantity, price and, critically, quality of power supply. Trials of small-scale or medium-scale P2P energy trading have already been investigated in other jurisdictions, for example, Vandebron in the Netherlands, Piclo in the UK and Sonnen 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 requirement according to availability of energy ;
- Enabling optimal energy distribution among customers from the local interruptible supply and central traditional supply, and maximizing the utilization of local resources;
- Improving power flows in the distribution networks so as to alleviate congestion levels and reduce the energy curtailment of renewables.

However, none of these approaches distinguish between a high and low quality of energy supply.

To make full use of the sharing system, the third dimension of the market, energy quality, must be introduced so as 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 needed that can extend the traditional theory so that it might account not only for the price and quantity, but also for quality. This would allow a wide range of energy products to be delivered to customers with differing capabilities so as to achieve an economic balance between cost, volume and quality in energy trading.

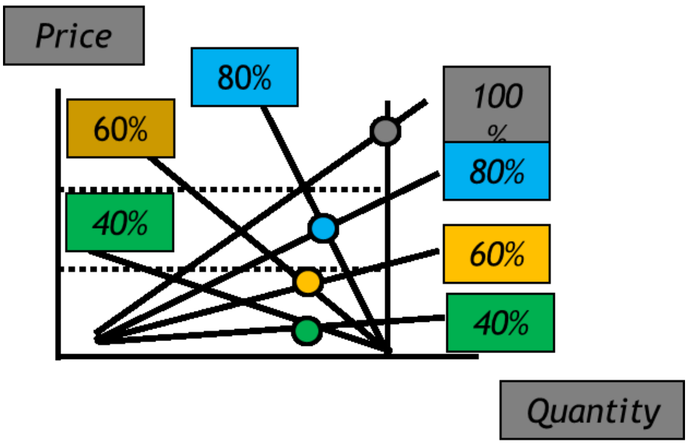

Figure 5 Demand-Supply curves in a local P2P energy market

In figure 5 we have shown the traditional market has almost 0% demand flexibility, whilst the energy product to be traded is almost 100% available at all times. The demand curve for this scenario is shown as being almost vertical. However, if demand flexibility and supply quality 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 quality, and thus less expensive. At the equilibrium points, the customer with higher flexibility will enjoy a much lower price by taking advantage of the local, low carbon and low cost generation instead of relying on the central energy market.

Big data analytics will support the design of local energy markets in the following ways:

- A P2P local energy market would allow energy to be traded in different time blocks (from seconds, minutes to hours), in different quantities and, particularly in different supply quality. Big data analytics would be critical to ensure the multi-time, multi-scale, multi-quality energy trading system optimized for tracking supply/demand level and their variability. Potential applications include:
    - Resource characterization to understand the largest and smallest trading units, largest and smallest time blocks, highest and lowest supply quality.
    - Probabilistic forecasting 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 give a measure of the uncertainty of the estimate.
    - Ultra-fast settlement. Since 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 the fast trading and settlement.

4.2 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 will then find the best matches between the supplies and demands. There is a particular need to improve forecasting, pricing and matching algorithms so as to understand products, flexibility, 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 the pre-requisite to the quality of pricing to ensure that the market would reflect the availability and condition of the offerings. The forecasting and pricing will then determine the quality of matching – the degree of value that can be delivered to local energy resources.

Energy forecasting techniques play a critical role in the traditional centralized market for forecasting generation or demand in volume. The merit of these techniques are challengingat local markets for the following reasons:

i) 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.

ii) In a centralized power market, generators are controllable and can be used to balance demand forecasting error. Contrastingly distributed generators are usuallyintermittent and uncontrollable. The two-way forecasting errors of generation and demand would bring significant uncertainty to the settlement of a local market.

iii) 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 PV and own electric vehicles (EV), and individually have widely varying demand profiles.

In particular, all forecasting techniques rely on the selection of dependent or explanatory variables, which are then used to derive algorithms that can forecast demand from these variables. To support the local market, the selection of variables has to go far beyond the current searching space that 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, whilst household demand is heavily influenced by geo-demographic factors. Life patterns, driving behaviors, and charging locations are likely to be the 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 dominate variables from large volumes of input data and quickly make the prediction with reasonable degree of confidence. Essentially, new variable selection techniques 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 - pricing and matching.

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

5. Shared network access

Shared network access (SNA) aims to integrate flexible demand in a cost-effective manner. As shown in figure 6, the SNA scheme incentivizes the incumbent DNO to give up its exclusive access to the network by leasing the spare capacity or back up capacity to licensed independent parties. The ownership of assets is retained by the incumbent DNO while competition is introduced in the operation of the spare capacity. The independent parties, who are licensed for SNA, will act as a secondary DNO to provide flexible network services using the spare capacity in the network. In this manner they can substantially reduce the network access cost for flexible demand.

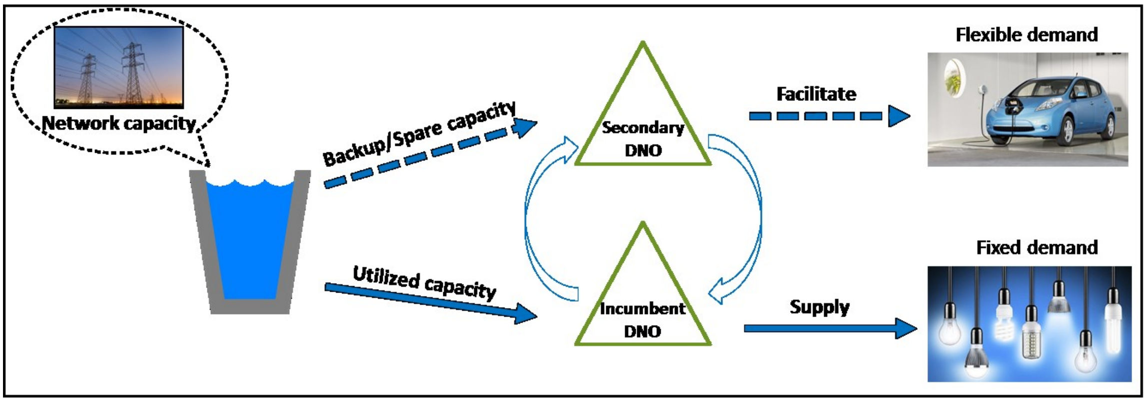

Figure 6 Concept behind SNA DSO business model

The major benefits of SNA over conventional business models are seen by examining the commercial and cash flow relationships among stakeholders. More importantly, the SNA scheme provides an incentive to the incumbent DNO to give up its exclusive access to the network and lease the spare capacity or back up capacity to licensed independent parties. The ownership of assets would be retained by the incumbent DNO, but competition would be introduced through the auctioning or contracting of the rights to the spare capacity. The independent parties who are licensed for SNA would act as a secondary DNO to provided 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 will be returned to the incumbent DNO to ensure the security of supply. It should be noted that there will be significant technical and regulatory challenges in aligning the objectives of primary and secondary operators to ensure the smooth coordination and transition. When the need arises for returning the spare capacity to the primary, this essentially require the secondary operator to interrupt the supply to their flexible demand. The example of telecom industry is when the need occurs, it typically stops all new calls to connect to the existing network but the ongoing conversation is not interrupted. The technical and regulatory challenges must be properly considered to give both primary and secondary operator a higher degree of certainty in the capacity availability, so that they can optimize and coordinate their networks for the interests of both fixed and flexible demand. Fail to be this would lead to much more complicated system with dissatisfied customers.

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

Without “big data” support the DNO oftendesigns 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. This 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 low voltage 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 utilization and the state of the network makes it difficult for a DNO to optimize its network planning and operation. A better understanding of now 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 for planning the security of a future network.

One visualization solution under consideration 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 UK. Inferential statistics, another feature of big data, could be used to visualize the whole system by mining data from small populations. Such a process aims to maximize the values of “small data” so as to 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 UK, a series of projects have been conducted by DNOs 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 low voltage feeders. A set of LV network substation templates was then developed to provide benchmark load and voltage profiles which can be applied across the UK.

Traditional load profiling methods are based on supervised learning techniques and customers mapped into the pre-defined domestic, commercial and industrial classes. As industry has little prior knowledge of LV networks, the project proposes a novel three-stage semi-supervised learning algorithm. The first step is an unsupervised clustering to search for typical substation templates. The next step is then 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. Firstly the templates developed were validated by five out of seven DNOs in the UK, and overall achieved an 87% accuracy. Secondly, 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 of Voltage Reduction Analysis.

Western Power Distribution (WPD) asked the University of Bath to undertake a study into the effects of a voltage reduction scheme for those voltage profiles close to the upper bound of the statutory limits. Bath concluded that such a scheme could significantly reduce demand, customer bills, and carbon emission. WPD adopted the method for customers in South Wales and reduced voltage by 1%. This has saved customers in South Wales approximately £14 million per annum. It is planned 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 GB £315 million and 1.98 million tons of CO_2 each year.

6. Conclusions

Managing flexibility in generation, demand and storage is a requisite towards achieving greater efficiency in electricity supply. Exploiting this flexibility to achieve a higher utilization of the system assets is essential in enabling the UK 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, disruptive business models, and the 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 the extensive analyses of metered data together with socioeconomic and weather information. In this article, we discussed P2P energy markets and shared network access to illustrate the value of embracing a sharing economy in the energy sector. Through these developments, major returns can be delivered to low carbon developers and flexible energy customers by extracting more value from existing generation, network and customer assets.

7. Bio

Furong Li is a professor specializing in power system economics and the Director of Centre for Sustainable Power Distribution with University of Bath

Ran Li is a lecturer with University of Bath specializing in big data analytics

Zhipeng Zhang is a research assistant with University of Bath specializing in new business models for the energy sector.

Mark Dale is an Innovation and Low Carbon Network Engineer with Western Power Distribution, managing high value smart grid demonstration projects.

David Tolley has spent much of his career as a senior manager in the electricity supply industry, a visiting professor at University of Bath, and the proprietor of his own energy consultancy.

Petri Ahokangas is a professor with University of Oulu specializing in business models for a variety of industry, particularly in telecom industry.

Further Reading

Ofgem's Future Insights Series Local Energy in a Transforming Energy System

F. Li, "Incentives for Local Production and Demand Flexibility to Support Community Energy"，New Market Models for Community Energy Conference, January 2015.

R. Li; C. Gu; F. Li; G. Shaddick; M. Dale; "Development of Low Voltage Network Templates—Part I: Substation Clustering and Classification," Power Systems, IEEE Transactions on, 2014

Tao Hong, Shu Fan, Probabilistic electric load forecasting: A tutorial review, International Journal of Forecasting, Volume 32, Issue 3, July–September 2016, Pages 914-938, ISSN 0169-2070, http://dx.doi.org/10.1016/j.ijforecast.2015.11.011.

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H. Shi; M. Xu; R. Li*; F. Li; "Deep Learning for Household Load Forecasting – A Novel Pooling Deep RNN" IEEE Transaction on Smart Grid.