Delivering future-proof energy infrastructure

Report for

National Infrastructure Commission

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Executive Summary

1. Context

The UK electricity system is facing exceptional challenges in the coming decades in order to achieve the ambitious climate change mitigation objectives:

- **Limited ability to accommodate low carbon generation**
  Significant penetration of variable and difficult to predict renewable generation in combination with inflexible nuclear generation will radically increase the complexity of real time demand-generation balancing, which may significantly limit the ability of the system to integrate low carbon technologies. Furthermore, wind and solar generators do not currently contribute to system inertia, and this will limit the system's ability to accommodate renewables. The necessity to deliver increased levels of ancillary services, supported by conventional generation, may lead to *significant curtailment of renewable output* and greatly increase the cost per unit of renewable generation actually delivered.

- **Degradation in asset utilisation**
  Wind generation and other low carbon distributed generation technologies will displace energy produced by conventional plant, but their ability to displace capacity will be very limited. In addition, decarbonising the broader energy system through electrification of segments of the heat and transport sectors will lead to increases in peaks that are disproportionately higher than the corresponding increases in annual electricity demand. These peaks will require *significant reinforcement of generation and network infrastructures*.

- **Offshore network infrastructure**
  An unprecedented amount of network investment will need to take place in the coming decades in order to accommodate the large volume of low-carbon generation, primarily offshore generators. It will be important to undertake this development in a coordinated manner in order to ensure that *offshore transmission network infrastructure is developed at minimum cost*.

In this context, the objective of this report is to bring together available evidence and set out the challenges, opportunities and next steps for facilitating a cost-effective evolution to a lower carbon electricity system. Key topics discussed include (a) *the role and value of flexible technologies* (b) *future system integration, operation and design*, (c) *enhancement of commercial and regulatory arrangements* needed to support delivery of least-cost future infrastructure.

2. Role and value of flexible technologies

Operational flexibility will be at the core of facilitating a cost-effective evolution to a low-carbon electricity system. In the future, there will be an increased need for operational flexibility to deal with growing variability in supply. Studies suggest that in an inflexible UK electricity system, with 30GW of variable renewables and inflexible nuclear generation, up to 25% of wind energy may need to be curtailed due to the increased need for fossil fuel generation to operate part-loaded in order to provide required ancillary services [2]. Clearly, flexibility requirements will grow substantially in order to cost effectively integrate low-carbon generation and demand technologies and the cost associated with the business-as-usual operating paradigm would be very high. In response to this challenge, novel flexible technologies that can make more efficient use of the existing infrastructure are emerging. In particular, four technologies have been identified as key:

- **Flexible generation**
  Advances in conventional generation technologies with enhanced flexibility that can operate at lower levels of power output and provide enhanced frequency regulation and balancing services, which will *improve the ability of the system to accommodate increased amount of variable renewables and inflexible nuclear generation*.

- **Interconnection and flexible network technologies**
  Further investment in cross-border interconnectors with continental Europe will be important for enabling *large-scale sharing of energy and back-up resources*. In addition to this, the deployment of novel network technologies aimed at improving controllability and utilisation of existing assets will be necessary to *release latent network capacity* to users, ensuring optimal use of available resources across all voltage levels.

- **Demand Side Response**
  Demand-side response (DSR) schemes that can re-distribute consumption and engage demand-side resources for balancing can *enhance system flexibility* without compromising the service quality delivered to end customers. These schemes have a significant potential to provide a range of flexibility services across multiple time frames and system sectors, from providing primary frequency response to facilitating network congestion management.

- **Energy storage**
  Energy storage technologies can also contribute substantially to services such as system balancing, various ancillary services and network management.

Recent analysis [9] demonstrates that savings in operating and investment costs from the application of flexible technologies could reach £8bn/year in 2030[1].

Within a number of pilot projects funded by Ofgem’s Low Carbon Networks Fund (LCNF), demand- and generation-led DSR, energy storage and novel flexible network technologies are being successfully trialled at the distribution level. In this context, an important role is fulfilled by the DECC/Ofgem Smart Grid Forum (SGF), a platform for industry, government

[1] This analysis is based on the scenarios of the Committee on Climate Change

and other key stakeholders to engage on the significant challenges and opportunities posed by GB's move to a low-carbon energy system, particularly for electricity network operators.

Furthermore, it is important to note that *developing innovative smart grid solutions*, particularly in the area of demand-side response, *may potentially present a significant opportunity for GB, not only to respond to domestic system integration challenges, but also to provide leadership at the international level* in novel smart grid applications, advanced data and system management and novel business models. For example, successful deployment of DSR in the UK may create valuable know-how expertise in an area which will be in high demand worldwide in the coming decades.

3. Future system operation

In order to deliver a cost-efficient, secure and low carbon electricity system, it will be critical to move beyond historical operation and design principles. Recent advances in the area of Information and Communication Technology (ICT), the increasing instrumentation at all system levels and the potential of novel technologies create a unique opportunity to implement fundamentally new operation paradigms. There is a crucial opportunity to move from security delivered through costly asset redundancy to smart corrective control measures that will enhance the utilisation of existing infrastructure and enable cost effective integration of low carbon technologies. In particular:

- **Improving system control**
  New network technologies such as Special Protection Schemes, Dynamic Line Rating and various forms of power electronics-based devices, can enhance network controllability and stability and increase power transfers through the application of advanced, technically-effective and economically-efficient *corrective control* actions. Significant evidence from research and demonstration projects shows that the ability to intelligently increase asset utilisation will release significant amounts of latent capacity, increase operating efficiency and reduce the need for infrastructure reinforcements.

- **Big Data**
  The growing amount of data that is becoming available to system operators can be used to develop innovative energy management platforms that would enhance system condition awareness and facilitate *a shift from the current redundancy-in-asset to intelligent-operation-based delivery of security* and hence facilitate effective decision-making, ultimately leading to improved system operation and investment performance. Big data supported with appropriate intelligence can be leveraged for substantial efficiency gains across many activities, from building more accurate prediction models that more precisely forecast demand and renewable outputs, to facilitating asset management by identifying pending asset failures.

- **Integration of transmission and distribution**
  Strengthening interactions through sharing data and resources for *control between transmission and distribution systems* will be a key enabler for significant cost savings. The large number of distributed energy resources can be pooled together in the form of a controllable *Virtual Power Plant* (VPP) which will be fundamental in rendering distribution-connected flexibility more accessible and enable distributed energy resources to participate in both local and nationwide service markets.

- **Decentralised control**
  The emerging concept of Smart Cities and Communities presents a significant opportunity to optimise the use of local resources and assets while increasing resilience to supply interruptions. This will lead to consumer choice driven system operation and design. For example, deployment of smart metering will increase the reliability of supply by giving the opportunity of prioritisation of load curtailment in the events of system stress. Instead of fully interrupting electricity supply across an entire area, it will be possible to continue supplying *essential loads* through novel control techniques, rather than indiscriminately disconnecting consumers. This intelligent control capability would *radically enhance security of supply* as seen by end consumers.

4. Future system design

Another key issue regarding system evolution is how the processes, standards and codes that govern network operation, planning and security can deliver cost-effective and secure future-proof infrastructure, while taking advantage of the emerging smart grid and information technologies and data. A number of opportunities have been identified:

- **Revisiting the current design principles**
  Distribution and transmission network operation planning standards should reflect the increasing capability of smart post-fault corrective control including the contribution of flexible technologies, such as generation- and demand-led DSR and energy storage. Similarly, there is significant evidence that relaxing present voltage standards may release significant latent network capacity and enhance the reliability performance experienced by consumers. *The historical distribution network planning and voltage standards are currently being fundamentally reviewed* and the Energy Networks Association (ENA) is coordinating these processes. Updating these standards may deliver significant benefits to end consumers.

- **Moving beyond 'like-for-like' replacements**
  In view of potentially very significant amounts of investment required for network reinforcement in the coming decades, it would be appropriate to consider moving beyond the current '*like-for-like*' incremental replacement philosophy and consider potentially *strategically* different designs. It is imperative to understand whether certain design

decisions made in the past are still fit-for-purpose or may unduly constrain future system evolution; such examples could include changes in voltage levels at which networks would operate and coordination in the development of onshore and offshore transmission and interconnection infrastructure.

- **Strategic investments**
  Similarly, the degree to which economies of scale can be leveraged effectively will very much determine the cost-efficient delivery of future infrastructure. In cases of investments with large fixed costs, such as in large offshore transmission or undergrounding cable in urban environments, a *strategic infrastructure planning paradigm may bring very significant benefits*.

- **Managing uncertainty**
  Future network developments are characterised by increased uncertainty across a number of topics such as future capital cost and uptake levels of different low carbon generation and demand technologies, energy storage, or the future uptake of demand-side schemes. Current planning practices largely ignore uncertainty and plan against specific scenario developments. In response, the planning process must be reformed to allow a portfolio approach that considers technologies that would bring *flexibility to deal with uncertainty* and delay large infrastructure projects until their construction can be justified.

- **Improving resilience to high impact events**
  Current network design standards designate reliability-driven investment needs on the basis of the system being capable to deal with "credible" events. In order to increase resilience against high-impact low probability (HILP) events, such as extreme weather events and a range of common-mode failures (and potentially also driven by ICT failures that may affect multiple assets), it may be appropriate to *consider resilience in future distribution and transmission network planning*.

5. Integration and coordination

Beyond expanding the assets and leveraging intelligent control there is an increasing need for coordination and integration of system operation and planning across different sectors of the industry. In particular:

- **Transmission coordination**
  Currently, there are three distinct transmission regimes; onshore, offshore and cross-border. Given that future investment in these networks may be very significant, *harmonizing* these can bring very significant savings and create the opportunity for *multi-purpose projects* to emerge. Such projects would cut across regimes and will be fundamental in creating a cost-effective North Sea offshore grid infrastructure.

- **Whole systems approach**
  A key challenge towards future infrastructure development will be to move from the currently fragmented approach, where each sector is planned on an individual basis, to a *whole-systems approach that orchestrates planning activities at different system levels* so as to holistically consider energy delivery, emissions, losses and needs for ancillary services and security of supply.

- **Coordination across energy vectors**
  It is well understood that the scope of interactions between electricity and other energy vectors is bound to increase substantially; *multi-energy system planning will become highly relevant* particularly in the area of heat and transport sector decarbonisation and to take account of the growing interaction between gas and electricity systems.

In the context of whole-systems approach to future system operation and design, the *Future Power System Architecture* (FPSA) project is very relevant. The overall goal of the FPSA project is to establish the key functional requirements associated with future system operation and planning, with a focus on the functional 'gap' compared with the present practices. The conclusions drawn from the analysis of the functions are clearly pointing towards increased complexity in functionality with implications for business frameworks along with stakeholder roles and responsibilities. Related to this is National Grid's *System Operability Framework* (SOF), which provides a holistic view of how changes in the energy landscape will impact the operability of the GB transmission network. The SOF outlines operability challenges facing National Grid in their role as GB system operator and wider whole industry impacts on the basis of technical assessments, a review of operational experience and extensive stakeholder engagement. The SOF outlines a future operability strategy and development opportunities for new technology and service solutions to enhance system operability in line with system requirements and stakeholder needs.

6. Improving current commercial and regulatory arrangements

In view of the challenges and opportunities identified above related to flexible technologies, novel operation and planning paradigms and coordination, a series of recommendations are made to ensure that the regulatory and market environment can successfully deliver future-proof electricity infrastructure.

- **Changing role of the regulator**
  In the view of the growing system complexity and the plethora of competing solutions, there is consensus developing worldwide that the regulator's role should shift from detailed investment evaluation and *focus instead on setting commercial incentives* and ensuring that market designs and business models are fit for purpose in view of technological advances and underlying system reality. Network owners should not negotiate investment plans with their regulator; instead a trusted, well-informed third party (such as an Independent System Operator), or market arrangements where network

users reveal their willingness to pay for improvements should guide investment decisions.

- **Incentives for the smart grid**
  Reform in the way transmission and distribution network investment is incentivised is necessary. There is a need to move beyond an asset-biased regulatory philosophy towards a setup that directly rewards innovation, the more intelligent use of existing infrastructure and the application of flexible technologies to enhance system utilisation. To achieve this aim, it may be appropriate to consider *increasing the rate of return to projects that deliver lower cost solutions* (e.g. cost-efficient DSR measures) compared to more costly conventional upgrades, and ensure that system planners pursue such measures proactively.

- **Establishing level playing field markets**
  Level playing field markets must be established to ensure that the different services provided by *non-traditional flexible technologies are appropriately rewarded*, particularly in the context of the Capacity Mechanism and delivery of network infrastructure reinforcements. Also, introducing a real time market for flexibility may be critical for cost effective operation and development of the future system, given that the value and the volume of ancillary services needed will substantially increase. Furthermore, it will be important to develop a regulatory framework that would recognise the *option value of investment* in flexible assets and technologies to manage uncertainties. Again, independent scrutiny and the ability of third parties to propose solutions is needed to prevent the process being captured by incumbents.

- **Integration of wholesale and retail markets and cost-reflective charging**
  Development and implementation of cost-reflective energy and network pricing will be fundamental to ensure that the right price signals are sent to market participants, and ensure that consumer choices will drive future system development. In this context, *full integration of wholesale and retail markets will be essential*. The rollout of smart meters opens an unprecedented opportunity to finally realise this integration. This is critical, as beyond 2030, for example, energy bills of flexible consumers may be significantly lower than for inflexible consumers, *if they were fully cost-reflective*. This means that end user costs will be driven by the way their electricity is consumed, potentially more than by the amount of electricity consumed. Similarly, network use of system charges and the allocation of Capacity Mechanism costs need to better reflect the drivers for investment.

- **Changing the role of system operators**
  The proposition of moving towards the concepts of an Independent System Operator (ISO) and Distribution System Operators (DSOs) that no longer own the network assets would potentially deliver significant benefits. Beyond the resolution of perceived conflicts of interest and the problems created when different regulatory regimes apply to

similar assets performing similar functions, such institutional arrangements could greatly facilitate whole-system operation and planning, substantially *strengthen coordination across different sectors and timescales*, and take a holistic approach towards strategic decision-making while also managing long-term uncertainty. This will require taking more account of the needs of future (as opposed to existing) consumers, and allocating costs accordingly, rebalancing the allocation of infrastructure cost between existing and future consumers. In addition, by decoupling asset ownership from operation, the introduction of competition in the delivery of infrastructure can increase cost efficiency and induce innovative solutions beyond the reach of incumbent institutions.

- **Acknowledging the increased risk of smart technologies**
  Deployment of *new technologies inevitably creates significant risks* for the system operators. Risks associated with the application of new technologies and solutions are not fully recognised by the current regulatory framework, and stronger incentives may be needed to make their introduction worthwhile.

- **Extending integration with EU**
  Improving interactions and coordination with other EU Member States is an important priority. There are significant opportunities to optimise the decarbonisation effort at a European level, by *locating renewable generators at locations with high resource quality*. In addition, *trading of ancillary services and flexibility cross border* should be enabled. Furthermore, in the interest of developing of cross-border links and offshore grids, the issue of asymmetric cost-benefit allocation should be addressed.

It is important to mention that Ofgem and DECC have shown significant interest in flexibility and a whole-systems approach to facilitating coordination in control and operation between distribution and transmission networks, while enabling a level playing field in the delivery of system services.

As mentioned above, there are a number of important initiatives aimed at reviewing present regulation and the rules that govern the electricity sector, indicating a clear understanding of the number of significant challenges and opportunities associated with future infrastructure operation and planning. Given the scale of the decarbonisation task, *there is an urgent need to integrate evidence from these initiatives, trials, studies and stakeholder engagement across the industry and government and to develop a concrete set of recommendations that will create a regulatory framework and develop new market designs that are fit for delivery of future-proof infrastructure on the basis of sustainability, security and cost effectiveness*.

1 Role of flexible technologies in the future electricity system

In this section we describe the main factors that will be driving requirements for electricity infrastructure in the future, focusing on the growth of renewable sources of energy and electrification of the segments of transport and heating sections. The increased need for operational flexibility is highlighted by pinpointing specific challenges that arise in the new system paradigm. Four key flexible technologies are considered and their potential contribution is discussed. The importance of possessing operational flexibility in response to long-term uncertainty is also highlighted along with the opportunity to render UK a world-leader in the deployment of innovative solutions.

1.1 Drivers for change

The UK electricity system is facing exceptional challenges in the coming decades in the effort to meet the government's target of reducing carbon emission levels by 80% below 1990 levels by 2050. This will be largely achieved through decommissioning carbon-intensive plants, primarily aging coal plants; increased integration of low-carbon generation, such as wind and nuclear; and the gradual electrification of the transport and heating sectors. These changes across the supply and demand sides of the electricity system will require substantial investment in new generation and transmission and distribution network assets. The total cost for realising this transition will greatly depend on our capability to make efficient use of the infrastructure and be flexible about electricity consumption and generation. The evidence suggests that substantial savings could be made through leveraging flexibility; the UK will be able to meet its decarbonisation target cost effectively, by maximising the use of existing assets and minimising the need for additional investment in energy infrastructure.

Increasing penetration of low-carbon generation

The primary means for decarbonising the electricity system will be to replace carbon-intensive generation with low-carbon sources such as offshore and onshore wind, solar and nuclear generation. Integration of significant intermittent renewables and inflexible nuclear in the UK electricity system in 2020 and beyond will impose a very considerable demand for additional flexibility, particularly ancillary services associated with balancing demand and supply across all time horizons, from seconds, hours, days, seasons. Increased requirements for real time ancillary services, if provided by conventional generation running part-loaded, will not only reduce efficiency of system operation but will significantly undermine the ability of the system to accommodate low carbon generation, increase emissions and drive up cost for the consumer.

There is significant evidence that operational flexibility will be a key driver for the efficient integration of low-carbon technologies. Flexibility can be provided by different sources. One such source is flexible generation; plants that have low minimum stable generation levels, high ramping rates and increased capability for ancillary service provision.

In Figure 1 we demonstrate how the flexibility of conventional generation in the future UK electricity system will affect its ability to cope with intermittent renewables and inflexible nuclear generation. This is quantified in terms of the level of wind energy curtailment driven by the lack of flexibility. Two systems are analysed and compared; a system that has flexible conventional plant and an inflexible system equipped with conventional generators possessing operational limitations similar to the current UK fleet.

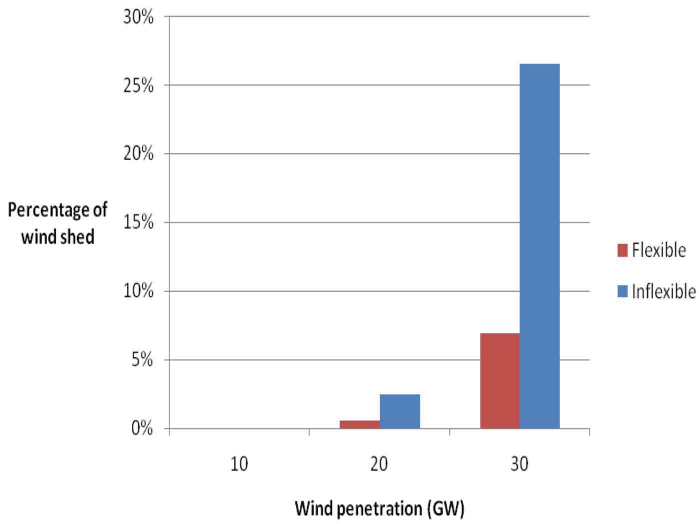

Figure 1: Amount of wind generation curtailed as function of wind penetration and system flexibility.

As can be seen above, for low level of wind penetration, the difference in the amount of curtailed renewable energy is modest. However, for 30 GW of wind generation, the curtailment could exceed 25% of annually available wind energy, in case the system is characterised by less flexible generators. This analysis highlight that the impact of operational flexibility on the system's ability to integrate intermittent renewable output will be significant.

This is also driven by the increased frequency regulation requirements. Due to plant characteristics, wind and solar generators do not currently contribute to system inertia. Conventional generation plant on the other hand regulates the frequency of the UK grid by providing system inertia as well as the fast frequency regulation which provides the rapid increase in generator output (within seconds) required to compensate for a possible loss of the largest plant operating at any particular point in time. In order to meet this requirement, an increased number of conventional generators will need run part-loaded when providing frequency response to maintain the system frequency within the required range. Therefore as more intermittent renewables are added to the system, more conventional plant running part-loaded will be required to provide frequency response. This is problematic in the context of meeting a decarbonisation target, as demand that could otherwise be met by renewables will instead be met by part-loaded conventional plant that is required to operate, thereby curtailing renewable output.

Offshore network infrastructure

An unprecedented amount of network investment will need to take place in the coming decades in order to accommodate the large volume of low-carbon generation. This relates greatly to onshore and offshore generators which are typically located away from the load centres. It is expected that investment in onshore, offshore and cross-border transmission capacity will reach between £23bn and £50bn by 2030[2]. This represents a substantial expansion of GB transmission assets, whose current value is less than £13bn. Recent research demonstrated that by a pursuing strategic rather than incremental approach to development of onshore and offshore transmission infrastructures and by recognising the interaction between interconnection and offshore wind connections, very significant cost reductions can be achieved. Analysis of the future development of North Sea Grid infrastructure [24] suggests that coordination in connecting offshore wind farms could deliver significant savings between £1.5bn and £10bn.

Degradation in asset utilisation

From the system integration perspective, one major concern is associated with *degradation in generation and network asset utilisation*, as wind generation and other low carbon distributed generation will displace energy produced by conventional plant, but their ability to displace capacity will be very limited. Our analysis suggests that the average utilisation of generation capacity could reduce significantly, from 55% at present to below 35% by 2030. In addition, decarbonising the broader energy system through the electrification of segments of heat and transport sector would require substantial investment in additional generation, transmission and distribution assets to achieve the carbon emission targets while ensuring security of supply. The key concern is that this integration will lead to increases in peaks that are disproportionately higher than the corresponding increases in annual electricity demand (even if radical energy efficiency measures are undertaken). This will potentially require significant reinforcement of the generation and network infrastructures. In particular, studies on the UK system have verified that peak demand driven by electrification of segments of transport and heat sectors beyond 2030 could increase from about 60GW at present to more than 120GW [1]. Consequently, massive distribution network reinforcement may be required, costing up to £30bn by 2030 if passive distribution network operation and the existing network design standards are maintained. On the other hand, a coordinated application of smart demand technologies, and innovative network technologies, can significantly reduce this cost. Appropriate policies and regulatory frameworks should be developed to facilitate the development and timely deployment of such technologies. In this context the process of reviewing network planning and design standards and voltage standards may be particularly

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[2] The expected investment ranges have been established by considering minimum and maximum investment scenarios from a number of sources. These include the RIIO-T1 final proposals (available at: http://www.ofgem.gov.uk/Networks/Trans/PriceControls/RIIO-T1/Pages/RIIO-T1.aspx), the National Grid Electricity Ten Year Statement and Imperial College analysis (Imperial College and NERA Consulting, 2012, Understanding the Balancing Challenge, Analysis conducted for DECC, available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48553/5767-understanding-the-balancing-challenge.pdf

relevant, so that distribution network operators are able to consider the contribution of new flexible demand categories when making network reinforcement decisions. In the current regulatory framework, which typically remunerates asset-based network reinforcement, network operators are not fully incentivised to take advantage of smart control solutions as an alternative to strengthening the grid. Similarly, review of the voltage standards may be very relevant in this context. If all these measures are undertaken, the cost of distribution network reinforcements could be reduced by more than 50%.

1.2 The role of flexibility

The future electricity system will be characterised by large volumes of intermittent renewable generation that increase the need for back-up reserves and ancillary services. In addition, decarbonising the heating and transport sectors through electrification will lead to increases in peaks that are disproportionately higher than the corresponding increases in annual electricity demand, even if radical energy efficiency measures are undertaken. Under this new reality, operational flexibility will be increasingly important for a number of reasons.

A lack of operational flexibility limits the system's ability to accommodate output from intermittent renewable technologies. This is a major concern since the decarbonisation effort will be based on replacing conventional plant with inflexible nuclear generation and intermittent wind and solar units. Naturally, more expensive low-carbon plant will be required to meet environmental targets under lack of operational flexibility if the system is not capable of fully absorbing renewable output.

In addition, attempting to meet the new system peaks resulting from electrification of segments of transport and heating sectors, while exhibiting a lack of operational flexibility, will lead to substantially increased capital costs in terms of new generation, transmission and distribution assets. Analysis has demonstrated that asset utilisation could significantly reduce by 2030, meaning that a large portion of new investments will be undertaken solely for the purpose of being used very few hours per year; a clearly uneconomic development. In contrast, if we are flexible towards our electricity consumption, much less infrastructure will be required allowing us to meet decarbonisation targets at a severely reduced cost.

It is clear that *system flexibility* will be at the core of facilitating a cost-effective evolution to a low-carbon energy future. Flexibility can be provided by different technologies, as shown in Figure 2.

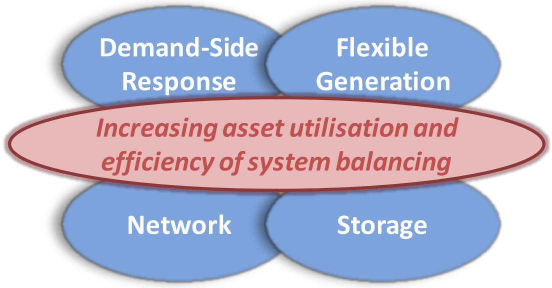

Figure 2: Flexible technologies

The key flexible technologies that can enhance the utilisation of the assets and efficiency of operation of future low carbon systems are:

- Deployment of **energy storage technologies** that can deliver ancillary services (e.g. reserve and response) thereby reducing the need for part-loaded plant, additional back-up generation and network infrastructure reinforcement.
- **Demand-side response (DSR),** which entails demand reduction, shifting or engagement of demand-side resources at no compromise of customer utility, is useful for providing primary and secondary frequency response, short term operating reserve, services for network congestion management services and security of supply [4].
- **Network solutions** such as reinforcements in the transmission and distribution network for the resolution of energy transfer constraints as well as increased cross-border interconnection (e.g. with mainland Europe) increasing system flexibility via sharing of reserves and backup generation with other countries.
- More efficient and more **flexible generation technologies**: conventional plant that can operate stably at lower levels of output (and therefore less likely to push renewables out of the system) and provide faster frequency response (requiring less overall thermal plant to balance the system).

In the analysis carried out using Committee on Climate Change scenarios [9], it was demonstrated that the level of system flexibility will significantly affect the cost-optimal low-carbon generation mix. The analysis revealed markedly different generation mixes, depending on the level of inherent flexibility that may be available from sources such as DSR, interconnection and storage. The optimal generation mixes for the cases of having low, medium and high flexibility, as defined by the assumed penetration levels of storage and DSR resources and availability of flexible gas-fired plants, are shown in Figure 3.

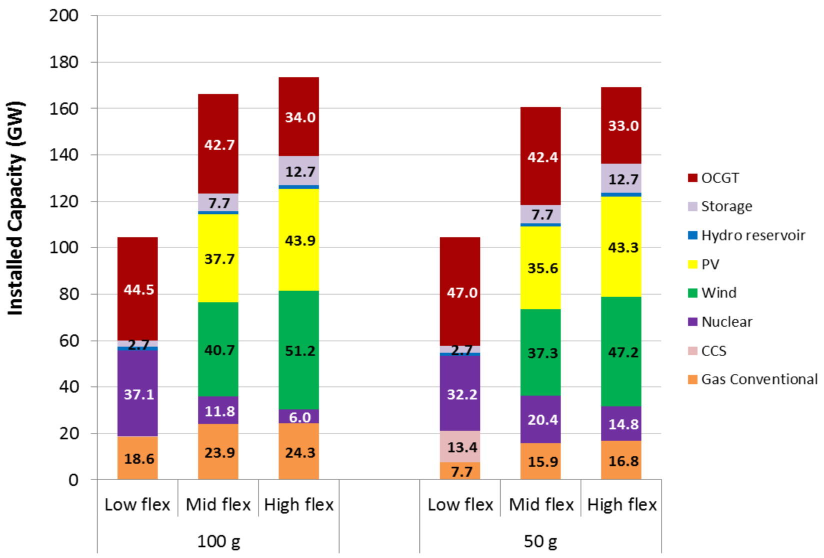

Figure 3: Impact of inherent system flexibility on optimal generation mix for 50 and 100 g/kWh average power sector emissions in 2030.

The optimal generation mix in terms of achieving two decarbonisation levels, 50 gCO2/kWh and 100 gCO2/kWh, at minimum investment and operational cost have been determined. In the figure above we observe that with a low level of inherent flexibility, the technologies chosen to deliver a decarbonised electricity system are primarily nuclear and to a lesser extent Carbon Capture and Storage (CCS). As much as 37GW of nuclear is built in the 100g/kWh low-flexibility scenario, while 32GW of nuclear and 13GW of CCS are built in the 50g/kWh. Most notably, no wind or Photovoltaic (PV) generation is selected as part of the optimal generation portfolio, suggesting that although these options have lower levelised capital costs, their whole-system cost is comparatively higher than that of nuclear. In the other extreme case, where a high level of inherent flexibility is available, we observe a massive shift in the generation mix towards renewable technologies, with more than 90GW of wind and PV capacity, reflecting the reduced integration cost of renewable generation technologies enabled by enhanced flexibility. Nuclear capacity is still present, although with a far lower volume, while CCS is not selected at the assumed technology costs, given that the additional system flexibility makes wind and PV more cost-effective due to reduced integration costs. In the medium-flexibility scenario, reducing emissions from 100gCO2/kWh to 50 gCO2/kWh is achieved by increasing the amount of nuclear plant capacity, while in the high-flexibility scenario this is achieved by increasing the capacity of renewable generation. The gross benefits of flexibility are reflected in the reduced investment and operation cost for reaching a given emissions target. The total savings in terms of reduced operational and capital costs when comparing between low and high-flexibility systems have been quantified to £4.5bn per annum for the 100 gCO2/kWh scenario and around £6bn per year for the 50 gCO2/kWh scenario[3].

[3] Note that these savings refer to the optimised generation portfolio (in contrast to the £8bn/year savings found for CCC scenarios that did not optimise the generation mix)

In summary, one of the key observations from this study is that operational flexibility can significantly reduce the integration cost of intermittent renewables, to the point where their whole-system cost makes them a more attractive expansion option than CCS and/or nuclear. However, sufficient operational flexibility must be available to ensure that the system can cope at times of stress (e.g. lots of wind, very low wind over several days, unexpected nuclear outages, low fuel prices, high demand).

Additional analysis carried out to quantify the potential regret of pursuing a more flexible power system, against a business-as-usual evolution with limited operational flexibility Even in a system that is less decarbonised (e.g. reaching 200 g CO2/kWh in 2030), increasing flexibility was found to be a low-regret option, reducing the overall cost while maintaining security of supply requirements. For example, the analysis shows that gross benefits of flexibility for reaching the 50 g CO2/kWh intensity level are between £7.1-8.1bn per annum, while the corresponding benefits for the 100 g/kWh target amount to £3-3.8bn annually (savings in the system with 200 g CO2/kWh would also be significant at around £2.9bn per annum).

In additional studies carried out on DECC scenarios, the analysis demonstrates that flexibility could reduce the amount of low carbon generation that would need to be built to meet the carbon targets. In the core DECC scenario, the presence of non-generation flexibility can reduce the amount of nuclear and wind generation to be built between 2030 and 2050 by 14GW and 15GW respectively, while still meeting carbon targets of 25g/kWh. Gross benefits of flexibility in these scenarios could reach £10bn/year. This demonstrates that flexibility does not only assist in accommodating renewables output but results in significant savings in investment in low carbon generation (a decarbonisation target can be met by building less low carbon plant).

To summarize, the above evidence shows that achieving deep decarbonisation at efficient cost will require a significant increase in system-wide flexibility from the current levels, alongside the expansion of low-carbon capacity. Analysis demonstrates that the value of ancillary services market, if supplied by conventional plant only, would increase about 10 times, which should provide strong incentives for non traditional technologies and solutions to compete[4]. However, currently there are no market structures in place to fully reward the providers of this flexibility, thus offering insufficient incentives for the deployment of flexible solutions. In response, appropriate policies and regulatory frameworks should be developed to facilitate the development and timely deployment of such technologies.

Furthermore, the present review of network planning and design standards may enable network operators to take into account the contribution of new flexible technologies when

4 F Teng, G Strbac, *Assessment of the Role and Value of Frequency Response Support From Wind Plants*, IEEE Transaction on Sustainable Energy, 2016

making network reinforcement decisions. These issues are further discussed in Sections 2 and 3.

Demand-Side Response

There are a number of potentially flexible loads that could deliver *demand-side response*, such as flexible industrial and commercial (I&C) loads, flexible heat pump or Heat Ventilation and Air Conditioner (HVAC) systems, electric vehicles following smart charging strategies, smart domestic appliances [10] etc. DSR can support the integration of low-carbon generation by providing both energy arbitrage over time (load shifting or peak load reduction) and ancillary services. It is important to note that utilisation of many forms of DSR generally would not involve any compromise on the services delivered to end customers (e.g. internal temperatures achieved by heat pumps or the ability of consumers to use their electric vehicles). Also, some DSR technologies are able to dampen frequency fluctuations (i.e. provide synthetic inertia) or provide the frequency response service, which will reduce the need for synchronised generation capacity and in turn increase the ability of the system to absorb more renewable output.

Within a number of Low Carbon Network Funding projects [36], significant trials have been undertaken to understand the potential benefits and costs of implementing DSR in commercial buildings. In particular, the trials carried out were mostly based on control of the building's HVAC systems. The work demonstrated that the main factors influencing the building's thermal demand, the operation of HVAC systems and ultimately the amount of demand response that may be available are specific to location, height and orientation of building, insulation level, outdoor temperature profiles, humidity, solar radiation and other weather factors, design of HVAC systems and equipment used, activities taking place in the building and demand payback, given that demand reduction periods will be normally followed by load recovery periods, which lead to increase in demand that would need to be accommodated. Overall, the DSR potential of I&C consumers in the UK has been estimated to be between 4% and 30% of their corresponding peak demand [11]. Importance of DSR from I&C consumers is expected to grow greatly in importance and may constitute as much as 15% of flexible demand resources by 2030.

Deployment of DSR schemes at the domestic level in today's system is still at the trial level, but with the planned rollout of smart meters in the UK, it is expected that the technical barriers to deploying DSR schemes will be largely removed. The additional cost associated with the introduction of DSR schemes, in particular the cost of engaging customers, is at present highly uncertain with no reliable cost estimates available. Therefore, the cost of deploying and operating DSR schemes is not included in total system cost. Nevertheless, it is likely that the benefits of DSR would significantly outweigh the cost of deployment. A similar approach has been adopted in [2].

In the future system the cost of supplying customers with electricity will increasingly depend not only on the volume of energy consumed, but also on the way energy is used. It is therefore critically important to have cost-reflective pricing mechanisms that that dynamically reflect the changes in the value of electricity depending on the circumstances in the system, including ancillary services. Achieving this will require the integration of retail and wholesale markets. The importance of DSR has been recognised by the Government and Ofgem, which is currently considering ways to address barriers to effective DSR implementation, as discussed in [4] and [44]. In this context, development of efficient market mechanism that would appropriately reward flexibility will be critically important for facilitating cost-effective decarbonisation of the GB electricity system. This is critical, as beyond 2030, for example, energy bills of flexible consumers may be significantly lower than for inflexible consumers. In other words, consumers' electricity bills in future may be very driven by the way their electricity is consumed, not only by the amount of electricity consumed. In this context the integration of whole-sale and retail markets, that can be achieved by the roll-out of smart meters, will be essential as end consumers will, by making choices, essentially drive the development of the energy industry.

Flexible generation

The operating flexibility of a generator is dictated by its operational limitations, such as its minimum stable generation, the ability to provide balancing services including frequency response and reserve, ramping rates, minimum up and down times as well as the degree of efficiency reduction when running part-loaded. Although more flexible versions of conventional gas generators are already available today at a moderately higher cost than its less flexible alternatives[5], the relatively low value of flexibility today does not generate a very high demand for this type of generation. In a study carried out with DECC in 2012 "Understanding the balancing challenge" [2] it is demonstrated that more flexible generation would potentially bring significant benefits. In this context it may be important that the new gas plants that will be built in the coming decades are more flexible than existing ones. The study concluded that the scale of the balancing challenge would increase very significantly beyond 2030, with flexible conventional generation being very beneficial.

The present GB Grid Code does not require renewable generators to provide any balancing services; however this may change in the future. In order to provide balancing services, renewable generators would also need to run part-loaded, which is not economic if the marginal value of their energy output is greater than the marginal value of providing the service. However, at high penetration levels the marginal value of energy may become lower than the marginal value of balancing services, rendering the partial curtailment of renewable output for the purpose of providing balancing services, justified[6].

Interconnection and flexible network technologies

The benefits of cross-border *interconnection* include (i) the enhanced efficiency of system operation due to the provision of access to more efficient resources, (ii) improved security of

5 Based on recent communication with generating equipment manufacturers, it is estimated that a flexible version of CCGT plant would cost about 15% more than the standard less flexible version.

6 F Teng, G Strbac, Assessment of the Role and Value of Frequency Response Support from Wind Plants, IEEE Transaction on Sustainable Energy Systems, 2016

supply due to the ability of the interconnected markets to share secure generation capacity (iii) as well as ancillary services, and (iv) enhanced ability to accommodate intermittent renewable generation by taking advantage of geographical diversity of renewable output. It has to be noted though that the decisions to deploy interconnection capacity are highly sensitive to conditions prevailing in GB and the neighbouring markets, in particular with respect to decarbonisation policies (EU-wide versus member state focused delivery) and policies towards sharing security and balancing services across borders. Benefits of sharing balancing services are estimated to be between £0.6bn/year and nearly £4bn/year, depending on the amount of renewable generation on the system. In section 3.7, the challenges and opportunities for future coordination with other European countries through cross-border network infrastructure is discussed.

There would be also significant benefits in the application of novel power electronics based network technologies, such as Flexible Alternative Current Transmission Systems (FACTS), Soft Open Points (SOPs) etc., applied at the transmission and distribution network levels. These technologies could enhance the utilisation of the existing network infrastructure and postpone reinforcements. For example, our analysis demonstrates that smart voltage control, facilitated by these technologies, could potently save about £6bn by 2030 in avoided capital investments across distribution network reinforcements that would otherwise be necessary for the integration of heat pumps and electric vehicles [11].

Electricity storage

Since the discovery of electricity, effective ways for storage have been sought to enable its use on-demand. Over the last decades, significant technological progress has been made in this area, giving rise to various cost-effective solutions at the transmission and distribution level. Understanding the potential of electricity storage to reduce the costs of electricity generation in our future system is critical in guiding policy in this area. A whole-systems model was employed to capture the impact that bulk and distributed storage can have along the electricity value chain, including savings in terms of generation, transmission and distribution investment as well as operational cost savings including externalities such as reduced emission levels. [9].

Figure 4 presents the effective deployment volume of storage for different capital cost levels, expressed in terms of £/kW of storage. Three curves are shown, related to economic deployment levels in 2015, 2030 and 2050. The inset table shows the value of whole-system benefits for a cost of £1000/kW.

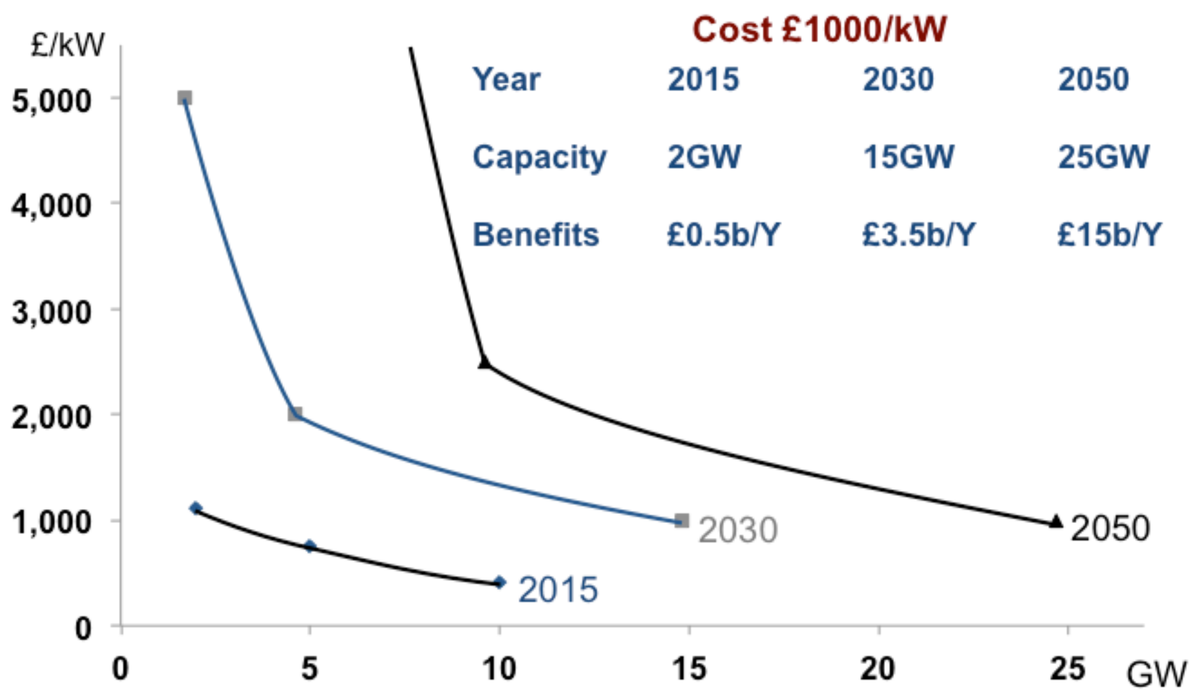

Figure 4: Optimal storage deployment levels for storage (x-axis) for different storage capital cost scenarios (y-axis) in the years 2015, 2030 and 2050.

As it can be seen, the value of storage increases very significantly in the future - for example, assuming the cost of 1000£/kW it would be economic to have 2GW of energy storage in 2015, 15 GW in 2030 and 25GW in 2030. The *net benefits* of energy storage increase from £0.5bn/year in 2015, over £3.5bn/year in 2030 to finally reaching £15bn/year in 2050. By observing the curve shapes, it is evident that the system will be facing an increasing need for storage; it can be seen that even if the cost of storage is doubled, i.e. to £2,000/kW, it would be efficient to install 5GW in 2030 and about 13GW in 2050.

Operation patterns and duty cycles imposed on the energy storage technology are found to vary considerably, and it is likely that a portfolio of different energy storage technologies will be required, suited to a range of applications. Short-term storage primarily provides highly-beneficial services in terms of peak shaving and reserve provision; energy storage over longer durations such as a week, would bring marginal additional value (in the scenarios analysed). The efficiency of storage (the ratio of energy output to energy input) has been found to affect its value modestly and only becomes more relevant with higher levels of deployment.

This analysis demonstrates that the value of energy storage technologies in low carbon energy systems with a large contribution of renewable and nuclear generation may be very significant; it will therefore be important to ensure that energy policy and market frameworks do not impose a barrier but rather facilitate the application of cost-effective energy storage technologies. It is well-recognised that energy storage can bring benefits to several sectors in the electricity industry, including generation, transmission and distribution, while providing services to support real-time balancing of demand and supply, network congestion management and reduce the need for investment in system reinforcement. These "split benefits" of storage pose challenges for policy makers to develop appropriate market mechanisms to ensure that the investors in storage are adequately rewarded for delivering these diverse sources of value.

Synergies and conflicts between flexibility options

The range of scenarios considered in these studies, including different levels of generation flexibility, interconnection, DSR and energy storage, show that some of these flexible options are complementary and some compete more directly. In cases of conflicting technologies that address similar system needs, we observe that in the majority of cases, when a particular option faces competition from other alternatives, the net benefit generated reduces, and the optimal level of deployment drops. For example the range of storage volumes deployed in the presence of flexible generators reduces slightly (in the order of 10-15%) for the assumed range of storage cost values, when compared to the baseline scenario. Similarly, the volume and value of storage deployed decreases when it competed with interconnection; this occurs on a similar scale for both bulk and distributed storage across the different ranges of costs of energy storage. On the other hand, the volumes of storage deployed with a high penetration of flexible demand are significantly reduced compared to the baseline case, suggesting that the installed capacity of storage is sensitive to the presence of competition from flexible demand. Comprehensive analysis of synergies and conflicts of different flexibility options can be found in [2].

1.3 Option value of smart technologies

In this section we discuss another chief aspect of smart technologies; their substantial strategic value towards adapting to a wide range of future system development scenarios. This is in stark contrast to asset-heavy capital commitments, such as reinforcing a large transmission corridor, which may possess significant economies of scale and resolve constraints in a long-term fashion, but suffer from very substantial stranding risks until their construction is fully justified.

Until now, network planning at the transmission and distribution level has mainly been an exercise of meeting future demand growth projections at minimum cost while ensuring adequate security of supply. This landscape is changing significantly due to the increased uncertainty that surrounds future generation and demand developments, preventing planners from making fully informed investment decisions. In this environment, there are significant risks of asset stranding, premature commitment to suboptimal investment paths and lack of adaptability to adverse scenario realisations, ultimately leading to increased costs for consumers. The increasing uncertainty that surrounds future electricity system development, coupled with the irreversible nature of capital investments, indicates that attractive investment opportunities should not be identified solely on the basis of net benefit, but also on the *option value* that they provide. The concept of option value refers to the strategic value placed on the ability to utilize an asset in the future and constitutes an important element of the total economic value of a project.

The option value concept is very applicable when evaluating the adoption of 'interim' asset-light solutions, such as energy storage or demand response. This is because the benefit of such solutions lies not only in the provided service (e.g. better utilization of available resource etc.) but also in how these can facilitate and de-risk subsequent decisions.

Such solutions can 'buy time' until some uncertainty is resolved, after which capital-intensive commitments are well-justified. It has recently been shown that smart assets such as energy storage and FACTS type technologies may grant planners the ability to react swiftly to the unfolding uncertainty while deferring the need for long-term investments until fully justified [12]. This ability is further enhanced in cases of assets that are relocatable. It is imperative that future planning frameworks consider these aspects to fully capture the diverse benefits stemming from smart technologies.

1.4 Opportunities for innovation

Another important aspect that pertains to new technologies is that the system benefits they can provide are characterised by decision-dependent uncertainty. In particular, the benefit that they can bring to the system is highly dependent on their early deployment levels in order to reach cost maturity, induce public participation and become attractive long-term investment options. There is wide consensus that relying on traditional valuation frameworks to decide the optimal path to decarbonisation while disregarding the potential for future technological improvements can lead to a technological lock-in, potentially leaving many promising technologies unexplored. To this end, developing novel appraisal models to tackle optimal investment under endogenous uncertainty is an active research area of high priority.

Initial findings obtained from analysing the value of DSR in Great Britain, which is characterised by very high levels of uncertainty with respect to eventual deployment, consumer participation levels and associated costs suggest that preliminary investment in order to resolve the initial information gap that exists is potentially an attractive strategy. As soon as this uncertainty begins to be partially resolved, more informed decision can be made. In many cases, the value of resolving this information gap can be shown to be substantial and can justify investment in pilot DSR programmes even if demand-side resources eventually prove to be less attractive than other competing technologies. Further study in this field should be highlighted as an important topic in order to inform policy decisions regarding long-term innovation funding at the national level in a strategic manner.

Another important aspect related to the benefit of smart technologies is that their early adoption and successful integration in the electricity system can create significant externalities related to the know-how expertise obtained. Given that the balancing change in the UK will be significant, shift to fundamentally new operation principles and technologies will be beneficial and necessary well before this will be needed in other jurisdictions, such as in the US and mainland Europe. In this context, this problem that UK is facing could be potentially turned into opportunity for the UK to possibly lead innovation in some disruptive technologies and concepts (such as DSR) at the international level[7]. In particular, this could include areas of system integration, IT platforms and infrastructure, legislation, development of novel commercial arrangements for integrated distribution and transmission operation, including the development of novel business models for enabling technologies such as energy storage and DSR as well as the implementation of promising new operational and planning concepts such as Virtual Power Plants and whole-system development. The transition to the smart grid era presents economic opportunities for the UK at the international level, in addition to facilitating decarbonisation of our electricity system.

7 In this context, Low Carbon Network Funding projects, although focused on the benefits to UK consumers, have provided some insights for development of smart grid business proposition that are relevant internationally.

2 Operation and planning of future electricity infrastructure

Context

In this section we outline the opportunities and challenges pertaining to the principles of future electricity system operation and design. These changes are driven by the growing penetration of low carbon generation technologies including intermittent renewables and inflexible nuclear, and electrification of segments of heat and transport sectors. There is also a very significant uncertainty that surrounds future energy system development that will need to be dealt with effectively.

In order to facilitate a cost effective transition to lower carbon system it will be important to take advantage of emerging flexible technologies and optimise infrastructure utilisation though novel intelligent control. To achieve this, significant changes will be required in the way the system is operated, designed and the way different sectors interact.

There is a number of initiatives that addresses specific challenges associated with technical, commercial and regulatory aspects of operation and development of future energy system.

In this context, important role is fulfilled by DECC/Ofgem Smart Grid Forum (SGF), which is a platform for industry, government and other key stakeholders to engage on the significant challenges and opportunities posed by GB's move to a low-carbon energy system, particularly for electricity network operators. In this context, Low Carbon Network Fund supported projects that enabled Distribution Network Operators to try out new technology, operating and commercial arrangements. Network operators have been exploring how networks can facilitate the take up of low carbon and energy saving initiatives such as electric vehicles, heat pumps, micro and local generation and demand side management. These projects provided valuable learning for the wider energy industry and policy makers.

Furthermore, National Grid's System Operability Framework (SOF) provides a holistic view of how changes in the energy landscape will impact the operability of GB power networks. The SOF outlines operability challenges facing National Grid in their role as GB system operator and wider whole industry impacts involving technical assessments, review of operational experience and extensive stakeholder engagement. The SOF outlines a future operability strategy and development opportunities for new technology and service solutions to enhance system operability in line with system requirements and stakeholder needs. The SOF has clearly demonstrated that a whole-system approach is necessary to achieve our future energy objectives. Evidently, the solutions to many of the challenges will involve multiple parties across the GB supply chain, including National Grid, the DNOs, generators, customers and communities. It is recognised that ensuring coordinated solutions across multiple parties will require novel technical and institutional arrangements. SOF also demonstrates that in order to maintain the stability of the transmission system, coordination of services between transmission and distribution networks will be critical.

The Future Power System Architecture (FPSA) project [37] is particularly important and it has identified new technical functions that will need to be implemented to plan and operate the future power system. The project is addressing the four key time horizons in power systems; investment planning, operational planning, real-time operation and markets. The overall goal of the FPSA project is to establish the key requirements for the future, with a focus on the functional 'gaps' compared to the status quo. The conclusions drawn are clearly pointing towards *increased complexity* in functionality with implications for business frameworks along with stakeholder roles and responsibilities. Another consideration that is growing in importance is the inter-relationship between electricity and other energy vectors.

Additionally, Ofgem has clearly indicated the increasing role that flexible technologies are expected to play in the future system, recognising the need for new regulatory rules and business models to facilitate their uptake [44]. Similar views are shared by DECC in their recent paper on future challenges and increasing need to shift towards a flexible smart grid paradigm, recognizing the role of storage, DSR and other new technologies.

Furthermore, Engineering Recommendation P2/6, governing network planning and operation, is undergoing a fundamental review to ensure that the security contribution of novel technologies and intelligent operation measures are formally acknowledged [51].

In section 2.1 we discuss some key aspects of future design and operation that will enable the delivery of a secure, affordable and low-carbon electricity system. The main theme is that novel technologies and operational practices could enhance cost effectively utilisation of existing assets. In section 2.2 we discuss important principles that will guide system design in the future. First, we highlight the need to move beyond the 'like-for-like' design philosophy and re-think some fundamental aspects of the electricity system in light of the emerging technologies and new business models. The need for strategically integrating smart interim measures with large-scale projects is also essential in order to take advantage of economies of scale while remaining flexible to respond to uncertainties. Finally, we discuss the need to strengthen the transmission-distribution interface, as well as increase coordination across different transmission regimes and energy vectors. In this light, whole-systems analysis is put forward as key for the optimal development of the GB electricity infrastructure.

2.1 Future Infrastructure Operation

Improving system control

The cost-efficient transition to a smart grid will require fundamental changes in the historical system operation paradigm in order to ensure cost effective integration of low-carbon generation and demand technologies through the use of new information and communication technology (ICT) and flexible technologies that can significantly enhance utilisation of existing electricity infrastructure.

New technologies could reduce network redundancy in providing security of supply by enabling the application of a range of advanced, technically effective and economically efficient corrective (or post-fault) actions that can release latent network infrastructure capacity of the existing system. For example, the deployment of advanced communication and information technologies along with recent developments in Special Protection Schemes, Wide-Area Monitoring and Control Systems, Dynamic Security Assessment techniques, Dynamic Line Rating, grid-friendly controllers for Demand Response etc., could substantially increase system robustness to faults while relying less on capital-intensive traditional infrastructure assets.

System security against specific disturbances is currently ensured primarily through redundancy in assets and the concept of preventive control. This results in low utilisation of network assets, higher operating cost and potentially increased emissions. Given the recent developments in ICT and control technologies, decision-making can be moved much closer to real-time thus enabling a shift towards a corrective control paradigm. By relying on post-fault corrective measures, operators can drive the system closer to its limit without unduly restricting its operation to ensure recoverability in the event of a fault. This ability would result in significant savings in network infrastructure investment, reduction in generation operating costs and corresponding emissions. Power electronic devices that have already been deployed in GB such as Phase Shifting Transformers (PSTs), Flexible Alternative Current Transmission Systems (FACTS), Special Protection Schemes (SPS) and High Voltage Direct Current (HVDC) networks etc., have a significant potential for enhancing real-time system controllability, thus reducing the need for preventive security measures. In a similar manner, the future development of DSR and energy storage solutions present an important opportunity for introducing a range of novel corrective actions to the operator's arsenal.

Delivering carbon targets cost effectively, will require fundamental changes in the historical philosophy of network operation and investment. However, before the need for new network investment can be established, it is critical to ensure that the rules used to determine the volume of network capacity that should be released to network users, are efficient. Establishing the optimal level of network capacity that should be made available by network operators in real time should balance (i) the value that users attribute to the level of network capacity released, against (ii) the cost of reserves, losses and expected costs of interruptions (caused by forced outages of generation and network facilities) that is associated with the volume of network capacity released. The optimal level of network capacity that should be released to users corresponds to the equilibrium when the marginal value to users of the network access equals the marginal costs associated with its provision. This equilibrium position is different across different system boundaries and depends on the specific network characteristics and system conditions.

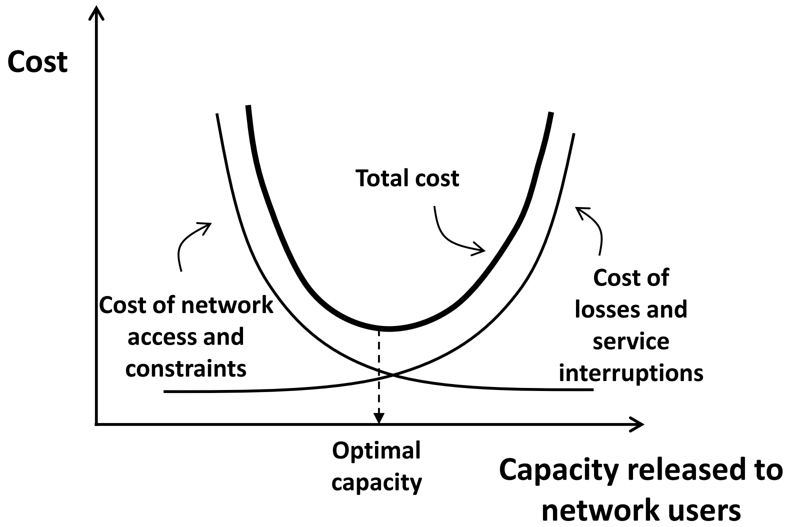

Figure 5: Impact of releasing latent network capacity on system cost elements.

As shown in Figure 5 above, as the network capacity released to the users increases through the introduction of intelligent operation measures, naturally the cost of network access and constraints falls. However, the cost of losses and service interruptions increases since higher utilisation will increase losses and also that network outages may lead to more severe consequences. Striking the right balance between releasing latent network capacity through intelligent operation and expanding the system capacity through network infrastructure reinforcement is one the key challenges the future electricity system is facing.

Leveraging big data

The increasing amount of information and data that is starting to become available to system operators along with expanded opportunities to exert system control at various levels and timeframes are rapidly changing the landscape of system operation. Advanced state estimation in combination with increased amounts of real-time measurements obtained via Phasor Measurement Units (PMUs) and smart metering, will increasingly be used to enhance visibility and improve real-time situational awareness. The current challenge pertains how the trend of increasing instrumentation and resulting abundance of different data feeds can be leveraged to improve system security and carbon performance and increase robustness at reduced cost to consumers.

One promising application area is the enhancement of situational awareness for system operators. It is envisaged that having a high-resolution view of the underlying physical reality of the grid will facilitate decision-making leading to improved cost, carbon and security performance. This will ultimately enable operators to move beyond conservative rules drawn empirically on worst-case assumptions towards cost-efficient use of available resources. Sophisticated decision-support models are being developed worldwide (e.g. see [47]). Another way of leveraging system monitoring data lies in constructing an ever-expanding database of past system states. By comparing past forecasted and realised system states, the statistical characterisation of the different uncertain variables and the corresponding prediction errors becomes possible. Such information will be instrumental in gaining a deeper understanding of the way different sources of uncertainty are correlated as well as of the operator's ability to forecast these. Statistical characterisation of uncertainties at the operational timescale is of paramount importance, particularly because the share of intermittent generation will increase. Finally, another application of big data is asset monitoring. Ultimately, asset owners would be able identify pending failures enabling their prevention through timely repair/replacement and substantial mitigation of impacts.

It is important to note all the above functionalities would be enabled through intelligent use of data, most of which is collected at all system levels. As such, leveraging this information could enhance the utilisation of the existing infrastructure and facilitate cost-efficient evolution to a decarbonised smart grid.

Enhancing reliability of supply

Currently, in situations where the stability of the grid is compromised, system operators resort to load curtailment. This is carried out in the form of full interruptions to consumer service and indiscriminate demand curtailment without prioritization or selective disruptions. With the advent of smart meters at the household level it is envisaged that future load curtailment would be prioritised, ensuring that essential loads will be supplied. For example, instead of fully interrupting electricity supply across a number of feeders during network congestion, it may be possible to partially disrupt a larger number of feeders while providing each consumer with sufficient capacity to sustain some basic functionality to supply essential loads such as lighting and information appliances. The highly non-linear nature of utility related to electricity dictates that the discomfort experienced by the overall population would be much lower in the second case despite the larger number of customers affected due to their ability to supply their essential loads. The ability to prioritise load curtailment is an exemplary way of utilising intelligent control to increase the level of network reliability without the need for network asset investment, but with a more informed use of the existing infrastructure.

Network users at present can exercise very limited choice with regard to their security of supply. Implementing this type of bottom-up approach will be increasingly facilitated by advanced instrumentation and embedded control technologies at the lower system levels. Over a longer time scale, the introduction of smart metering will facilitate reliability-based choices of consumption. Different types of consumers place different value on their security of supply; some customers (e.g. businesses and commercial) may be willing to incur higher costs to ensure their continued supply after a fault while some other consumers (e.g. domestic) may be willing to accept some of their non-critical demand to be curtailed for a short period and in return pay significantly lower charges for the use of the network (and generation capacity through Capacity Mechanism), as investigated in [52]. Allowing consumers to communicate their own valuation of electricity supply will provide an equitable outcome and also inform the DNO on the investment needed to deliver the required levels of reliability.

Co-ordinated operation across transmission and distribution networks

As the UK system evolves to a low carbon energy system characterised by variable renewable generation and inflexible nuclear, the resource of controllability of the system through conventional generation will significantly reduce. While it is expected that the bulk of energy flows will continue being from the grid to the end consumers, PV technologies deployed at the distribution level are reversing the power flows. Flexible demand will be supporting the operation at local level managing network constraints while also facilitating balancing at the national level. As such, there are significant opportunities for embedded resources such as demand- and generation- led DSR and distributed energy storage to provide multiple services to different sectors of the electricity system. Beyond the provision of voltage support, congestion management, and security services to the local distribution network, embedded resources could also be bundled in intelligent ways so as to provide various forms of ancillary and balancing services at the national level. In addition, evolving non-network technologies (demand- and generation- led DSR and distributed energy storage) connected to distribution networks could provide services to support real-time balancing of demand and supply and network congestion management. In the future, following the electrification of segments of transport and heat sectors, interactions between transmission and distribution will become even more important and may start encompassing other energy vectors as well. For example, it may be possible to use the thermal capacity stored in district heating systems to manage an unexpected fluctuation in wind energy output in the North Sea. Strengthening interactions at these different levels is a fundamental requirement for the emergence of the Smart City and community energy system concept, where multiple technologies are seamlessly integrated to optimally manage a community's assets and resources.

However, the conventional power system was designed around a transmission network transporting bulk electricity from a small number of large stations to demand centres. As shown in the left panel of Figure 6, large generators are currently the main providers of control to the demand-supply balance and to the power flows over the transmission network. The multiple benefits that can be generated by flexible technologies at the distribution level cannot currently be exploited to their full potential due to the lack of an appropriate two-way interface between system levels, as shown in the right panel of Figure 6. If smart technologies are to be deployed at efficient levels, it is necessary that service providers are rewarded according to the benefits they can provide across the entire electricity supply chain. Smart grid assets should not be constrained to contributing solely at the local network level, but also be capable of participating in the provision of balancing and ancillary services at the national scale. If unresolved, it is likely that the costs of network investment and system real-time balancing costs will increase. Currently, transmission and distribution networks are operated by different organisations, resulting in limited levels of visibility and coordination across the boundary; the interface between transmission and distribution system operation needs to be enhanced significantly.

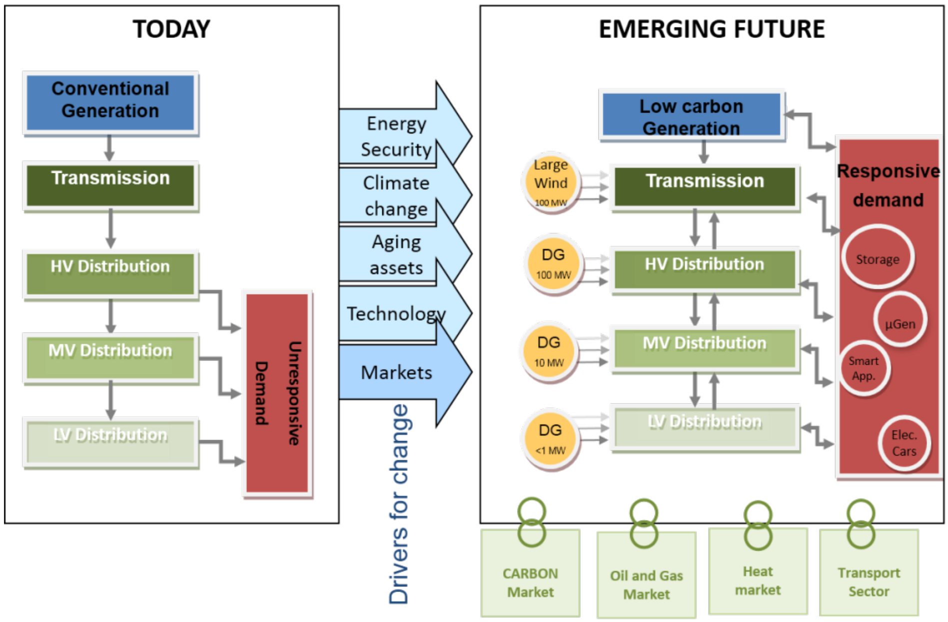

Figure 6: Schematic of conventional power system and electricity markets (left) and the emerging paradigm of increased integration.

Given the diverse type of resources that may be embedded at the distribution level, concepts such as Virtual Power Plants (VPPs) are envisioned to become critical instruments capable of abstracting system controllability across different system levels and locations, enabling unhindered visibility and access to embedded energy resources. A VPP is a flexible representation of a portfolio of embedded resources that can be used to make contracts in the wholesale market and offer services to the system operator – subject to firmness of access to distribution networks. A VPP describes the capability of different resources such as DSR and DG by creating a single operating profile from a composite of the constituent parameters while also incorporating spatial (i.e. network) constraints. The VPP is characterised by a set of parameters usually associated with a traditional transmission-connected generator, such as scheduled output, ramp rates, voltage regulation capability, etc. In this way, the VPP can be used to facilitate trading of embedded resources in the wholesale energy markets (e.g. forward markets and the Power Exchange) and can provide services to support transmission system management (e.g. reserve, frequency and voltage regulation) as well as to contribute to the active management of distribution networks.

Enhancing the role of decentralised control

Given the above discussion, it is evident that the amount of energy and flexibility resources embedded in the distribution level is going to increase, especially with the advent of electrified transportation and heating. Along with the concept of aggregating and offering services to the upstream network, another idea is the shift to a decentralised control paradigm.

The shift from a centralised to a more decentralised operation model will open new opportunities for enhancing cost effectiveness and security performance of future electricity system. In stark contrast to the present approach, control algorithms deployed within a fully decentralised paradigm will be meeting dynamically changing objectives while the network topology, network conditions and control infrastructures are also changing, with the aim to deliver a truly integrated self-controlling, self-optimising, self-healing and self-protecting electricity network. In this context, “microgrids” with appropriate enabling technologies, may facilitate the paradigm shift in delivering resilience and security of supply from redundancy in assets and preventive control to more intelligent operation at the Low Voltage (LV) and High Voltage (HV) level through corrective control actions supported by a range of enabling technologies and ICT. Local district / community networks (enhanced through “web of cells” concepts) would mitigate grid disturbances, serving as a grid resource for faster system response and recovery, and ultimately strengthening the overall supply resilience seen by end consumers. It is important to stress that the development of resilient district networks is in line with the concepts focused on the planning, construction, operation, and management of smart districts and cities’ energy infrastructure. This is driven by multiple challenges posed by the need to enhance the energy supply resilience in response to growing concerns associated with vulnerability to energy supply interruptions. As a result, there is growing interest in making full use of various forms of local generation (backup generation) in public or private institutions, combined with various forms of demand-side response and energy storage technologies, as integrating these resources within local district / community networks would significantly enhance the security of supply delivered to local communities.

However, implementing decentralised control will be a challenging task; coordination of a large number of resources will require sophisticated algorithms to achieve its goals. In order to ensure that the different system constituents can communicate so as to provide their resources and support where most needed, appropriate signals are necessary to convey service value information. For example, dynamic pricing constitutes a promising approach for the realisation of the significant potential of demand side response in future distribution networks, particularly in the case of electrification of transport and heat sector. A suitably designed set of time- and location-specific power prices will be transmitted to the users that would, with support of their smart energy management systems, determine a set of actions that would minimise their electricity costs, taking into account their preferences and constraints. However, application of a simple price based control approach may lead to significant loss of diversity and concentration effects, resulting in new peaks which have similar patterns to those of today. The new demand peaks created by this concentration effect might breach the voltage and/or thermal limits of the distribution network -requiring expensive demand shedding (and increase the losses in the network as the latter are proportional to the square of the power demand). Non-linear pricing approaches have been demonstrated to successfully flatten the demand profile and render it amenable to a management signal for achieving different objectives.

2.2 Future Infrastructure Design

Revisiting the current design principles

Electricity networks designed and operated in accordance with deterministic security standards have historically delivered reliable supply to customers. In accordance with the conventional reliability criteria, electricity systems are expected to withstand the occurrence of any one of a defined set of credible outages (e.g. a loss of one or two circuits in accordance with N-1/N-2 criterion) without causing overloads or inadequate voltages on any remaining circuits/busbars, and without violating system stability limits. Post-fault network overloads, following credible contingencies, are avoided by preventive operational measures such as engagement of back-up services and energy dispatch re-adjustments to ensure the network is recoverable at all times. Currently, security of supply is delivered through asset redundancy and there is limited use of corrective control measures. A key issue regarding future system evolution is how the planning standards should be adapted to make efficient use of the existing network infrastructure while taking advantage of emerging smart grid technologies to increase their utilisation.

In this context, historical practices and standards, mostly developed in the 1950's, are now being reviewed in order to take full advantage of new emerging technologies and facilitate transition to a smart grid paradigm. Traditional deterministic rules, relying on a binary measurement of risk are fundamentally problematic when addressing the above concerns since the balance of reliability benefits and associated costs is not explicitly considered on a case-by-case basis. Additionally, the present standards do not deal explicitly with common mode failures and do not provide guidance for dealing with high impact low probability (HILP) events such as floods. New network design frameworks may also take advantage of appropriately balancing network investment against non-network solutions. The key general concerns associated with this traditional network operation and design philosophy are related to economic efficiency and the ability of this concept to balance the cost of operation and network infrastructure against the security benefits delivered to network customers. Furthermore, given that network security is provided mainly through asset redundancy, this approach may create a barrier against innovation in network operation and design and prevent the implementation of technically effective and economically efficient solutions that could enhance the utilization of the existing network assets and maximize value for the users of the network. In the last several years in particular, significant investigations have questioned this historical approach to electricity network operation and design, and provided growing evidence that a radically different paradigm may be needed to facilitate a cost effective delivery of energy policy objectives, particularly in relation to integrating low-carbon generation, and the application of smart grid technologies.

It is important to highlight that in the UK, Engineering Recommendation P2/6, the code governing design and operation of distribution networks, is currently undergoing the fundamental review to facilitate cost effective decarbonisation.

Improving resilience to high-impact events

Resilience refers to the ability of the system to reduce its vulnerability to multiple failures, due to temporary outages or permanent damages of network and control equipment caused by external hazards or common-mode failures (CMF) of system components. The alarming importance of improving resilience of the electricity system was recently stated by the Science and Technology Committee [46]. In the light of climate change and the possible increasing frequency of extreme weather, it would appropriate to ensure that the critical electricity infrastructure is resilient to certain HILP events. A spectrum of preventive measures including flood mitigation, use of insulated overhead line conductors, rebuilding lines to a heavier construction specification, increasing lightning surge withstand capability, and automated switching to isolate faults and restore supplies, can been considered to increase resilience to extreme weather events. Similarly, it would be appropriate to consider cyber-physical systems (CPSs): failures of ICT infrastructure may cause CMFs potentially leading to severe supply interruptions.

The present security standards do not provide explicit guidance regarding CMF/HILP events. To effectively mitigate the impact of such events, it may be appropriate to consider if/how network resilience should be considered, which is discussed within ENA led fundamental review of the distribution network security standards.

Moving beyond 'like-for-like' replacements

New network transmission and distribution assets have very long lifetimes of several decades. If the current trend of pursuing 'like-for-like' asset replacement persists, the UK is running the risk of perpetuating design inefficiencies that were decided many decades ago based on completely different objectives and constraints. Below we outline some specific examples where the electricity system could potentially benefit by contemplating a departure from the status quo philosophy.

On such example is the re-consideration of appropriate transformer density at the distribution level. Rather than following like-with-like network reinforcement due to uptake of low-carbon technologies, it may be more cost effective to consider changing transformer density. Increasing the density of secondary distribution transformers/substations (where this is feasible) may enhance the ability of distribution networks to cost effectively integrate low carbon generation and demand technologies. This would reduce the length of LV feeders in the longer term and hence reduce exposure to voltage and thermal constraints driven by load growth. A relevant analysis recently demonstrated that distribution network reinforcement costs, driven by the uptake of low carbon technologies due to electrification of transport and heat, are dominated by LV network reinforcement. A network replacement strategy that involves inserting additional distribution transformers could be very cost effective when compared with reinforcing the LV underground network [32].

Another example pertains to rationalising voltage levels. The design voltage levels chosen by network operators many decades ago are potentially sub-optimal to support future requirements. Network companies have developed long-term strategies for progressive changes to network voltages, driven largely by optimising the investment costs to meet the required levels of network utilisation. For example, many of the historical 6.6kV networks in GB have been replaced or uprated to 11kV over the past decades. In some GB distribution networks, especially in areas of high load density, direct transformation has been the preferred means of electricity distribution, e.g. 132kV to 11kV. As network demand increases and reduced losses become more desirable, there is the potential for greater application of the direct transformation approaches. More recently in Ireland, ESB has replaced large sections of their 10kV system with plant and equipment operating at 20kV in order to accommodate increased wind generation [43]. In a similar vein, a recent study with the Energy Networks Association examined the benefit for adopting fewer voltage transformations [32]. In the case of semi-urban network semi-rural networks, the overall cost reduction would be about 18% and 12% respectively, in the direct transformation designs.

Another highly topical discussion that should be undertaken is the definition of voltage limits on distribution networks. Under the current standard, voltage does not deviate beyond ±5% of the nominal values. Violations of these voltage limits are on the rise due to the deployment of DG sources, resulting in high voltages at times of high output and low demand, and increasing the need for network reinforcement. At the same time, the makeup of residential load has changed significantly, due to the proliferation of different types of household appliances, lighting sources and widespread use of electronic devices that use a DC source. Many of the modern devices are capable of operating across a much wider voltage range without any degradation of the service provided. It is possible that continuing to abide to the historic voltage limits would result in a large volume of unnecessary investment which could be deferred or even avoided without substantial impacts on the level of supply security and quality of service.

The above examples indicate the potential gain in re-thinking system design with a strategic outlook to facilitate unconstrained long-term growth without being hindered by an unnecessary commitment to past decisions.

Identifying opportunities for strategic investments

Large electricity infrastructure projects are characterised by economies of scale; in most cases fixed costs outweigh variable cost components. In offshore transmission, laying a cable on the seabed is substantially insensitive to the size of the cable. Distribution network investment is largely similar; cable undergrounding cost is much more significant than the cost of cable itself. In order to take into account future investment needs in an efficient manner, it is necessary to engage in strategic investments in an anticipatory manner. Anticipatory investments refer to network developments for which firm user commitment is not obtained at a particular point in time. However, anticipatory transmission investment may be efficient when there are material economies of scale at play, constraints associated with establishing additional transmission corridors or developing new rights-of-way in the future due to environmental or social constraints. On the other hand, given the significant uncertainty and the difficulties in predicting future developments, the risk of investing in assets that become stranded can be material and should be taken into account when making such decisions.

The issue of strategic investment is prevalent at all system levels. In the case of transmission infrastructure, it pertains mostly to the accommodation of offshore wind, which will require very large amounts of new transmission capacity connecting the remote offshore sites to load centres onshore. As such, there are substantial opportunities to undertake pre-emptive large investments in anticipation of the growing need to accommodate increasingly large energy transfers from UK offshore hubs with large offshore potential. This appetite for a strategic vision is shared by industry and was highlighted by Ofgem in the conclusions of the Offshore Transmission Co-ordination Project [42]. This is supported by evidence of substantial benefits regarding the potential for exploiting scale economies in accommodating offshore wind in the North Sea [24]. Savings in terms of infrastructure cost calculated across four different offshore generation deployment scenarios over the next 30 years were found to be between £1.5bn and £10bn. This highlights that a strategic rather than incremental approach to development of onshore and offshore transmission infrastructures as well as recognising the interaction between interconnection and offshore wind connections, could lead to further cost reductions.

Significant strategic opportunities to exploit economies of scale are also present at the distribution level[8]. Overall, electricity demand is expected to increase in the long term due to the connection of new consumers and the envisaged electrification of transport and heat sectors. Although the utilisation of existing network should be maximised, once reinforcement is required, the new network should be significantly oversized. Recent work [27] demonstrated that, in the long term, the capacity of distribution networks would need to be *significantly above the peak demand requirements* in order to reduce losses, given that the savings in losses exceed the extra cost of oversizing the network. For example, studies have shown that an optimally sized LV circuit, considering the Ofgem capitalisation guidelines with 3.5% discount rate and up to 45-year lifetime, would be operated at maximum demand no higher than 11-25% of its thermal rating. In other words, the capacity of optimally design LV circuit would be at least four times larger than the peak demand. Similarly, HV circuits would be subject to a maximum loading no higher than 13-27% of the thermal rating. Loss-inclusive network design clearly leads to network assets of *significantly greater capacity*, considerably above the peak loading level. Loss inclusive network design will reduce the amount of energy needed to supply losses in distribution networks, which is equivalent to the energy production of a nuclear plant.

The above points indicate that important decisions will need to be made regarding the way we reinforce the existing network and/or replace aging assets and how we accommodate renewable sources of energy, typically located far away from the load centres. Success in

[8] Pudjianto, D., Djapic, P., Kairudeen, S. and Strbac, G. (2014) "Strategic Investment Model for future Distribution Network Planning, report for the Flexible Plug and Play Project: Imperial College London

leveraging economies of scale in the interest of future consumers will largely determine the cost-efficiency of the decarbonisation effort.

Managing uncertainty

Although taking advantage of economies of scale makes economic sense, an issue that is becoming more and more relevant is the fact that future developments are characterised by increased uncertainty. This uncertainty pertains to the future cost of generation, network and smart technologies, the amount, location and type of generation that profit-maximising investors will choose to build as well as a plethora of other commercial and political factors such as fuel costs, willingness of public to own an electric vehicle etc. As such, although large-scale projects may be desirable due to their long-term outlook and economic efficiency, the benefits they will ultimately deliver throughout their lifetime are highly uncertain with potential for downside risks. For example, in the case of offshore transmission, if the wind capacity foreseen to come online at an offshore hub does not materialise, the system will be facing a strategic investment undertaken ahead of need that resulted in no benefit, at the expense of consumers. As such, there are a number of aspects that must be carefully considered if we are to effectively balance between existing and future user needs.

One fundamental consideration pertains to the importance of exploring alternative scenarios that may unfold in the medium to long-term. Gaining a common understanding of alternative future scenarios across stakeholders has already been recognised by the System Operator, however more developments are required in this field to effectively capture all critical evolution paths and their branching points from the ‘business-as-usual’ trajectory. Another aspect relates to the fact that the presence of uncertainty renders flexible technologies that focus on increasing utilisation of existing assets highly attractive. This is because keeping options open without committing to capital-intensive projects is highly valuable in an uncertain decision environment. For this reason it is also important to highlight the critical role of commissioning times; the smaller the building time of a particular project, the more flexible it becomes for managing uncertainty. Consider the extreme case where a reinforcement project can be built instantaneously; under this assumption uncertainty is much less relevant since the planner can optimally adjust his response to the unfolding reality.

Following the above points, it is clear that in order to manage uncertainty effectively, the system planning process should be viewed as a portfolio optimisation task. The investment portfolio should consider many different asset classes with fundamentally different performance characteristics in terms of cost, rating/energy capability and flexibility. Most importantly, this investment portfolio must be drawn on a comprehensive ‘what-if’ analysis where important branching points are identified and the possibility for resorting to recourse actions considered. Such an approach will enable the identification of cost-efficient and robust investment strategies that entail flexibility-driven elements to manage uncertainty resolution in the interim as well as long-term strategic commitments, which could be deployed once uncertainty has been resolved and the appropriate opportunity arises.

There are different methods to undertake such an analysis; regret-based methods are attracting attention due to their suitability for assessing capital investment projects. A recent study [25], based on the concept of min-max regret on the uncertainty characterising offshore wind deployment in the North Sea, demonstrated that it would be preferable to over-design the offshore grid in the first stages in anticipation of a potentially large rollout of offshore wind rather than taking a conservative stance in anticipation of a low-offshore wind future. However, one critical aspect that balanced the risk of the over-design approach was the incorporation of some flexibility-driven investments in the investment portfolio. These flexible projects were capable of transforming large offshore-onshore links, which could potentially become stranded, to cross-border interconnectors between countries essentially providing alternative functionality for assets that would otherwise be stranded and face low utilisation. For the scenarios considered, the benefits for the UK if such a strategy was adopted, expressed as a reduction in terms of the regret experienced in the worst case due to foregone capital and operational savings, were estimated to be between £0.5 to £3.5bn by 2030.

In addition, as mentioned in section 1.3, flexible assets such as storage and power electronic devices such as phase-shifting transformers have been shown to constitute valuable strategic investments in cases of increased uncertainty [12]. In the case of distribution networks, Soft Open Points (SOPs) which enhance flexibility though topological changes and increased control over the network have also been shown to be capable of deferring costly re-conductoring of distribution feeders until such an undertaking is fully justified [33]. The above studies highlight how some flexibility-driven investments can enhance the adaptability of an otherwise inflexible investment plan and transform it to a strategy aimed at adjusting to possible deviations from the envisioned future at minimum cost while successfully delivering cost-efficiency to future users through exploitation of scale economies.

2.3 Co-ordinating energy system planning activities

Enhancing coordination across transmission regimes

An unprecedented amount of transmission investment will take place in the coming decades. Indicatively, these investments will be the largest transmission network reinforcements since the post-WWII expansion. It is expected that investment in onshore, offshore and cross-border transmission capacity will potentially range from £23bn to £50bn by 2030. This is very substantial given that the Regulated Asset Value (RAV) of the existing GB transmission assets is less than £13bn. Currently, the GB transmission system is comprised of three distinct regimes; onshore, offshore and cross-border. Most importantly, each regime is subject to its particular set of regulatory rules. It is important to bear in mind that these distinctions are artificial, since all assets should be used for social welfare maximisation. Given the limited amount of offshore and interconnection assets at present, there is currently modest interaction between the regimes with respect to co-ordinated transmission planning, delivery and operation [28]. However, there has been growing evidence of benefits in transmission projects that cut across regimes, also known as multi-purpose projects. Examples of such projects include offshore wind farms connecting to interconnectors, and the connection between two offshore clusters to form an undersea transmission bootstrap for reinforcing an onshore boundary. Such developments are bound to increase in relevance due to the significant economies of scale; a meshed offshore grid in the Northern Sea has been set as one of the main infrastructure priorities for Europe [41].

There have been several studies quantifying the net benefit of an integrated North Sea grid. A recent study carried out for E3G [24] demonstrated that the net benefit of integrated development offshore infrastructure will range between £17bn and £35bn depending on the deployment volumes of offshore wind. Most interestingly, a very large portion of these savings will be enjoyed by the UK. For example, under the high deployment scenario, the total volume of onshore-to-offshore connections in the UK is reduced from about 68 GW (business-as-usual case) to 58GW (integrated design). This shows that it is more cost effective to export UK offshore wind directly to continental Europe, driven by the large amount of offshore wind capacity in UK waters. Instead of importing wind to the main UK grid and then distributing energy via cross-border links to France, Belgium and Netherlands, which entails reinforcement of the onshore network, three large offshore-to-offshore links are built that connect Hornsea, East Anglia and Dogger Bank to a large Netherlands offshore cluster and subsequently to mainland Europe. This is another clear demonstration of the potential benefits and synergies that arise when full onshore, offshore and international integration is made possible.

Present policy arrangements cannot facilitate such developments, potentially leading to inefficient operation and investment. The government is fully aware of the national importance of offshore developments for the UK and the regulator is consulting with industry on the matter, investigating novel ways to plan and deliver ambitious infrastructure projects spanning onshore, offshore and cross-border assets [34].

Enhancing interactions with other energy vectors

Multi-energy systems are becoming particularly relevant given the growing interactions between electricity, heat, transport, gas, hydrogen, and water sectors, as driven by the decarbonisation targets. The interfaces between different energy vectors and corresponding infrastructures are becoming increasingly important as the integrated approach is likely to deliver significant savings when compared with the traditional approach of considering individual energy sectors in isolation. For example, as research has demonstrated, the heat sector may present substantial opportunities for energy storage and thereby support a more cost effective integration of intermittent and inflexible electricity generation [35]. Similarly, pumping operations in the water sector, aimed at filling reservoirs, could potentially provide very valuable flexibility and enhance efficiency of the real time balancing tasks in a future low carbon electricity system. Furthermore, recent research has clearly demonstrated that interaction between gas and electricity infrastructures may be significant and that an integrated approach to operation and infrastructure designs could bring significant benefits [40].

Whole systems approach to electricity system planning

Managing the synergies and conflicts between the transmission and distribution network, energy supply and the EU interconnection infrastructure when planning the development of the UK electricity system is a very challenging task due to the complexity and multitude of interfaces. An important aspect to appreciate is that DNO-centric or transmission-centric operation and planning approach is suboptimal. In response to the challenges associated with decarbonisation, a whole-systems approach that considers energy, emissions, losses, needs for ancillary services while having a clear view of transfer constraints at both the transmission and distribution levels is necessary to ensure that different system planning activities are carried out in an orchestrated manner and goals are achieved at the minimum cost possible.

This is particularly relevant for various forms of smart technologies that may be able to provide a variety of services across multiple system levels. As such, a whole-systems planning approach is necessary to recognise the full benefit these technologies can offer across the entire system. For example, a number of studies have been carried out to investigate and quantify the role and value of DSR and energy storage applications using the whole system approach. This framework allows holistic assessment of the value of DSR in reducing the system operational cost by reducing wind power curtailment and maximising the utilisation of other low carbon generators as well as reducing the infrastructure cost including the capital cost of low carbon generation and network assets needed to achieve a particular CO2 target.

3 Improving current commercial and regulatory arrangements

This chapter discusses various commercial and regulatory challenges that must be resolved to enable the delivery of a low-carbon electricity system in a cost-effective manner encompassing the operation and design principles discussed in section 2. Issues that could be addressed in the short to medium term are first presented, followed by suggestions pertaining to the longer-term evolution of the GB system.

3.1 Changing role of the regulator

In light of the increasing complexity that characterises system planning and operation, the wide range of candidate solutions, the expanding scope for system-wide and cross-sector synergies and the increasing number of stakeholders involved, it is evident that cost-efficient decarbonisation of the electricity system entails several challenging aspects [60]. To this end, the present regulatory framework is focused on assisting Ofgem in its role as appraiser and proxy buyer of network services by requiring detailed business plan submissions by TSOs and DNOs, which include comparisons of candidate options and full justification of the proposed capital and operating expenditure.

In view of the growing system complexity and the plethora of competing solutions, there is consensus developing worldwide that a regulator's efforts may be better-placed in the design of an incentive framework so that the most cost-efficient solutions emerge endogenously without the need for extensive scrutiny of the propositions on an individual basis. With such a framework in place, the regulator's role can shift from detailed investment evaluation to process due diligence, enduring oversight and administration of the investment framework itself as well as focusing on ensuring that commercial incentives, market design and planning process are fit for purpose in view of technological advances and the underlying system reality. Examples of such streamlined regulatory processes in the area of transmission network investment include the Regulatory Investment Test held in Australia [20]. In the same vein, FERC recently introduced Order 755 [21], which aims at remedying undue discrimination against energy storage solutions in providing system services, showing a clear appetite for incentivising advanced operational measures through suitable market mechanisms. The UK regulator stands to gain from adopting some of the advanced regulatory practices applied worldwide.

3.2 Aligning the incentive frameworks for investment and operation

The revenue business model that currently applies to both DNOs and TSOs, which is biased towards capital expenditure to raise the Regulatory Asset Value (RAV), creates insufficient incentives for planners to proactively pursue asset-light solutions based on intelligent control of existing assets. As recognised in [38], historically there has been a tendency supported by the RAV-based approach to favour capital investment over other asset-light alternatives. The new RIIO approach used by Ofgem treats capital and operational spending equally during the eight years of each price control period, but if companies perceive (rightly or wrongly) that capex will raise their future RAV, they will still be inclined to favour investment over alternative solutions. The earlier parts of this report have shown why revenue models that favour asset-based solutions are not capable of driving cost-efficient system planning in the face of the looming smart grid system transition. For this reason, it is important to begin recognising and directly rewarding the adoption of new smart operation practices by focusing on their strategic value when constituting a medium-term solution in the face of high uncertainty, and recognising the value of learning-by-doing while acknowledging the increased exposure to technical and commercial risks – which are bound to decrease as large-scale deployment gets under way. To achieve this aim, it may be appropriate to consider increasing the rate of return associated with projects that deliver lower cost solutions (e.g. cost-efficient DSR measures) compared to more costly traditional network reinforcement, and ensure that system planners pursue such measures proactively. These policy measures will level the playing field, remove commercial distortions that may be hindering direct comparison between competing technologies and encourage TSOs and DNOs to proactively develop cost-efficient advanced operational measures where appropriate.

3.3 Establishing level-playing-field markets

A key concern associated with the evolution of the future energy system relates to the need for fair and cost-reflective market mechanisms that can induce efficient investment and operational decisions and foster competition between established and emerging technologies.

Market for flexibility

Currently the System Operator procures a number of different ancillary services products through contracts covering periods of several months. Introducing a real time market for flexibility may be critical for cost-effective operation and development of the future system, given that the value and the volume of ancillary services required will substantially increase. Establishing consumers and suppliers of various flexibility services in such a market would be important step forward. This would also provide more cost reflective signals for emerging technologies, such as DSR and energy storage, to deliver the spectrum of flexibility services needed for cost effective decarbonisation of the electricity system.

Capacity Mechanism

It is critical that the Capacity Mechanism (CM) is technology-neutral and that embedded resources such as demand side response, distributed generation (both back-up and CHP type) and energy efficiency measures are able to compete against large conventional generation on equal terms. This is important for facilitating competition in security provision to reduce the corresponding cost to GB consumers, as well as to ensure that owners of non-conventional assets are appropriately rewarded for the system services they can provide. This is a necessary prerequisite for incentivising the roll-out of new flexible technologies which will ultimately enable cost-efficient decarbonisation of the electricity system. However, in the GB CM, the contract length for new central generation is 15 years, while for new Demand Resources the contract length is only one year. This is especially relevant given that the international experience, particularly in the US, clearly demonstrated significant and very successful participation of embedded resources in the capacity markets, which led to security procurement at reduced cost. Similarly, energy efficiency measures are excluded from the GB CM, while in the New England and PJM markets this form of demand resource is eligible for participation. There is a fundamental requirement to ensure that the adoption of new technologies is rewarded when it is the efficient choice. Furthermore, the current approach to allocating cost of GB CM is inefficient, as it does not provide signals to consumers to react when it matters. Hence there is no real opportunity for consumers to reduce their bills by responding to actual system needs and, in turn, reduce the future demand for capacity to be auctioned.

3.4 Integration of wholesale and retail and cost-reflective charging

The large-scale deployment of smart meters presents an unprecedented opportunity to integrate wholesale and retail markets, which will eventually allow network users to drive operational and planning decisions across the electricity system. However, utilities currently have pre-specified customer charging profiles which are not cost reflective; this prohibits user participation. In order to leverage demand-side flexibility, it is imperative that end users access wholesale prices that reflect real-time resource availability. In the future beyond 2030, for example, energy bills of flexible consumers may be significantly lower than for inflexible consumers, if they were fully cost-reflective. This means that end user costs will be driven by the way their electricity is consumed, more than by the amount of electricity consumed. In this context the integration of wholesale and retail markets, including markets for flexibility, would be essential for efficient development of the energy industry. Similarly, network use of system charges and CM cost allocation need to better reflect the drivers for investment.

3.5 The changing role of system operators

Independent System Operator

In the last years, there have been several initiatives exploring alternative governance setups and arrangements to ensure the efficient long-term delivery of the future UK electricity system. Ofgem recently consulted on the identification of weaknesses related to the current regulatory regime in order to understand and mitigate some key concerns related to that regime, given that it shared many of those concerns [34]. The possibility of establishing alternative governance structures, with a particular focus on the potential form and role of an Independent System Operator (ISO) at the transmission level was examined [28]. The ISO could replace National Electricity Transmission System Operator (NETSO) as the system operator and would be responsible for overall co-ordination across regimes. A key distinction to the current NETSO structure would be that instead of relying on profit maximization incentives the majority of the ISO functions would be dictated through grid codes and rules and a broad mandate to maximize social welfare.

Overall, the responsibilities and actions of the ISO would broadly match those of the NETSO, implying that this option would not require substantial market code changes. In line with the international experience elaborated in [38], the ISO should be a not-for-profit entity, managed by a board of directors and could be supported by an advisory board representing the interests and expertise of all market participants and TOs. Grid codes, well-defined process and rules, supporting decision making through transparent cost-benefit analysis (CBA) targeting social welfare maximization (all of which would be reviewed regularly against best international practice), should ensure that the ISO maximises the efficiency of system operation.

Distribution System Operator

In view of the need to establish suitable interfaces between transmission and distribution systems, the concept of establishing a DSO has been gaining attraction worldwide. For example, the centrepiece of the 'Reforming the Energy Vision' (REV) programme, a regulatory review project that aims to redefine electricity market rules in New York [59], is the development of a DSO that will be the integrator of various distributed generation and demand-side services, including energy efficiency, demand response, energy storage and electric vehicles. Proposals such as this acknowledge that novel arrangements are in high need to foster market integration and fully monetise the potential benefits of the smart grid concept.

Advantages and concerns

Implementing an ISO/DSO structure has the potential to address a significant number of issues that currently hinder the cost-effective system evolution. In particular:

- Resolution of the perceived conflicts of interest
- Further integration of transmission and distribution sectors
- Enabling strategic and flexibility-driven investment
- Introducing competition in delivery of infrastructure
- Enabling constructive engagement processes for user-driven investment

However, there are concerns that would need to be addressed. One concern pertains to the ISO and DSO's inability to optimise between operation and investment in the sense of making the best use of an asset's lifetime; if different entities own and operate an asset, it may be difficult to balance operational choices against their effect on degradation. Furthermore, there are concerns that that the ISO and DSO may choose a risk-averse operational paradigm, foregoing the opportunity to deploy novel technologies and operational methods due to a limited upside gain compared to the increased effort and complexity. These concerns highlight the need to develop a framework that will ensure that optimal planning and operational decisions are pursued by the ISO and DSOs.

Resolving perceived conflicts of interest

Concerns about perceived conflicts of interest arise in the UK system due to the System Operator having interests in cross-border interconnectors and being a Transmission Owner. Having the same owner designing and building the transmission assets and benefitting from interconnections facilitated by such transmission investment can create the concern that potential entrants might be deterred by the perception that they would be relatively disadvantaged. Similar concerns could also apply if it was decided that competitive delivery should extend to onshore assets. In addition, there exist perceived informational advantages related to NGET's role for EMR delivery as well as its engagement with ENTSO-E. This is important given the role that European institutions are expected to play in the development of the future transmission system through the inclusion of projects (and the associated funding) in the EU ten-year development plans. Resolution of any perceived conflicts of interest is essential to opening the market to as many participants as possible.

Further integration of transmission and distribution sectors

As discussed in section 2, in the future, resources at the distribution level will be supporting the operation of the national system in managing network constraints and balancing. Establishing an ISO and DSOs will facilitate the effective control of these embedded resources by providing an appropriate interface so as to move beyond the current sector-specific operation and planning practices[9]. It could also avoid the inefficiencies that can arise when similar assets performing similar functions are subject to different regulatory regimes, as is presently the case for onshore and offshore transmission.

Enabling strategic and flexibility-driven investment

An issue that currently affects the design of transmission and distribution networks is the increasing need to balance between existing and future user needs. As discussed in section 2, there is an increasing need to identify strategic large-scale projects as well as interim measures for uncertainty management. However, given that the current regulatory framework places considerable importance on cost reduction over the regulatory period and requires a demonstrable need case for all projects, strategic investment programmes are not in scope at present and several areas of improvement can be identified, pertaining to both the transmission and distribution levels. New planning frameworks are necessary to identify attractive opportunities for cost-efficient strategic investments in response to the reality of increased uncertainty. It is envisaged that the institution of ISO and DSO will assist in this matter by developing novel planning methodologies fit for a world of increasing uncertainty and optimally exploiting novel technologies

Systems run by ISO structures are leading developments in this field. A prominent example of how option value can be included in the planning framework is that of Australia, where the benefit of each candidate investment in the transmission system is appraised according to the Regulatory Investment Test for Transmission (RIT-T) [13]. Another example related to distribution investment deferral under uncertainty through deployment of smart assets can be found in New York, where the regulatory framework is being reviewed to accommodate 'no-regrets' near-term solutions [14].

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9 I. Konstantelos , D. Papadaskalopoulos, D. Pudjianto, M. Woolf, G. Strbac, "Novel commercial arrangements for smart distribution networks", Report D5 for the "Low Carbon London" LCNF project: Imperial College London, 2014.

Competition in delivery of infrastructure

Another potential advantage of differentiating between system operation, planning and ownership by implementing an ISO will be the possibility to have multiple parties participate in the procurement of system services. Overall, evidence from jurisdictions that implement competitive tendering for the delivery of transmission projects shows that competition can apply downward pressure to the cost of project delivery. Such arrangements already apply to the offshore regime, but potential savings when applied to onshore transmission and distribution could be substantial. The point is not about competitive tendering for a given design of, say, transformer, but opening up the question of what assets are actually needed to provide the services required by consumers; and indeed, what consumers actually want.

Constructive engagement for user-driven investment

Although network investment in the UK is carried out in a top-down manner, where the TSO and DSOs define investment requirements, there are international examples where the need for investment in electricity infrastructure is driven in a bottom-up manner by the network users. This user-driven approach to network investment reduces the risk that users are exposed to inefficient investments and corresponding high long-term tariffs. A form of user-driven investment, through stakeholder engagement, has been applied with great success in Argentina, Brazil and Chile [19] as well as in some regions of North America and Australia [20]. The main ideas of this arrangement are constructive engagement with all stakeholders that may be influenced by candidate projects as well as the use of transparent cost and benefit allocation rules to ensure that all influenced parties have long-term tariff visibility. It is envisaged that moving to an ISO/DSO structure will encourage user-driven initiatives, which are beyond scope under the current top-down regulatory regime.

3.6 Increased risk and complexity of new smart technologies

Delivering adequate levels of infrastructure will benefit significantly from the deployment of novel cost effective smart technologies and solutions that would displace conventional network reinforcements. However, the deployment of new technologies, such as those associated with smart grids, into actual transmission and distribution networks will inevitably create additional risks for the system operators. It is unclear how these risks and the associated cost would be managed, particularly with respect to the application of more disruptive technologies. Risks associated with new technologies are not fully recognised by the current regulatory framework, which may present an impediment to their widespread adoption and potentially lead to an increase in network investment costs. Smart grids will also increase considerably the complexity of network operation compared to the traditional solutions, given that significant ICT infrastructure will be needed in addition to advanced Energy Management Systems applications, all necessary to make use of available information and control in real time management of distribution networks. Similar concerns have been identified in a report for the Committee on Climate Change [9].

3.7 Challenges and opportunities for the future EU market design

Enhancing coordination across EU

The EU Renewable Energy Directive sets out a methodology for allocating the EU renewables targets between individual Member States. The Directive's 'flexibility mechanisms' are designed to allow Member States with lower renewable generation potential or higher costs to partially fulfil their renewables targets in or with other countries through statistical transfers, joint project co-financing and joint support schemes. These mechanisms are aimed at providing incentives for investments in renewable power generation at the most resourceful locations, and thereby facilitating a cost-effective decarbonisation of the European electricity system. A recent analysis [55] has shown that by siting a higher proportion of generation in areas with high load factors, it would be possible to get the same level of renewable energy output using 15% less capacity. The total net benefit of deploying renewable generation in the most resourceful locations in the EU may exceed €200bn by 2030. This is particularly relevant for the UK, given the growing amount of interconnection with EU member states as well as the significant offshore wind resources available in the North Sea. However, there are significant challenges to overcome before such a coordinated deployment can be possible.

Cross-border energy, capacity and reserve trading

Benefits of moving from the current member state-centric to a pan-Europe wide market design would be very significant. Analysis demonstrated that the benefits of fully integrating EU energy and capacity markets would be €12-40bn/year and €7-10bn/year respectively by 2030, while integration of the EU balancing market would save an additional €3-5bn/year. These savings go far beyond the €2.5-4bn/year that the EU has saved through its existing measures to integrate its electricity markets through day-ahead energy arbitrage.

Under high levels of penetration of intermittent renewable generation, the operating reserve requirements and need for flexibility increase significantly. In particular, the allocation of the reserve portfolio between spinning and standing products is vital to operate a congested network efficiently. This is because the commitment of spinning reserves in areas with significant wind generation can be very costly due to potential wind curtailment events. In such cases, the commitment of standing reserves should be preferred over spinning reserve, even if these are located in neighbouring states and may require reduction in network energy transfers leading to increase in constraints cost. In such cases, the need to access the optimum portfolio of reserves has to be balanced against the need to access low-cost energy sources, leading to the allocation of interconnection capacity between energy delivery and reserve services. Although the question of allocating network capacity between energy and reserve is a key issue, it is not facilitate by the current market coupling arrangements.

In Figure 7 below, an example of a two-area system is presented – Area A with significant penetration of renewables (e.g. UK) and Area B with significant penetration of low cost generation, such as nuclear, but also flexible standing generation (e.g. France). If we ignore the reserve requirement, the interconnector capacity will be used for transport of energy from Area B to Area A. However, if the interconnector capacity is optimised between energy and reserve, we observe that flows between the two areas will be radically different.

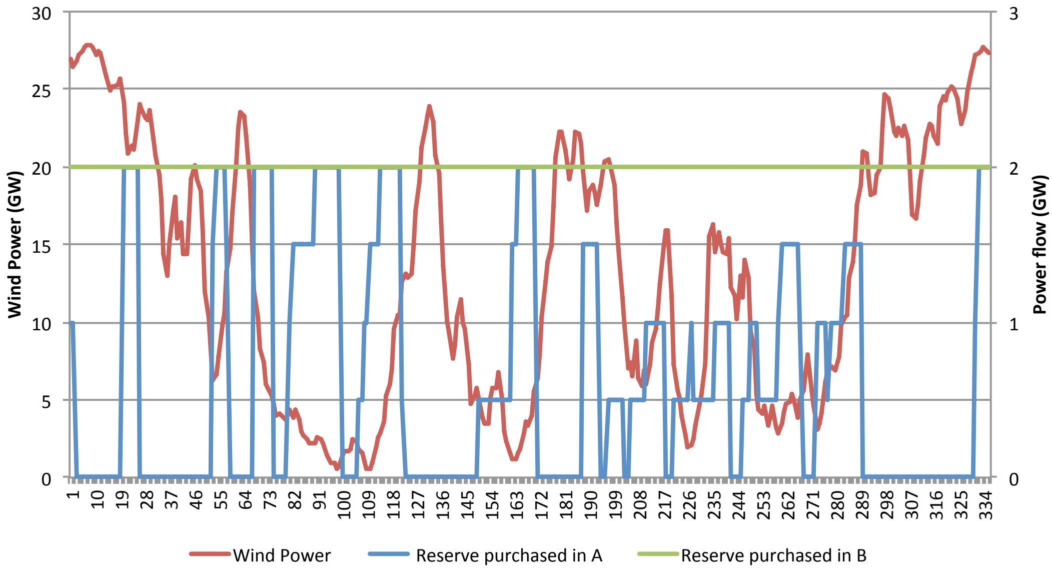

Figure 7: It is efficient to constrain energy flow in order to facilitate cross-border access to flexible generation.

Clearly, the development of new trading arrangements for sharing reserve between member states would bring significant benefits, particularly to the UK as demonstrated in [2]. It will be important to optimise allocation of reserve products across regions, as there are potentially significant benefits of sharing flexibility that can be achieved by shifting the requirements to provide reserve from areas with high renewable production (exporting areas) to areas with low production or demand-dominated areas (importing areas) by making use of cross-border transmission. Furthermore, given the increased diversity in demand and renewable output across interconnected areas, when reserve products are shared across member states, rather than every member state providing reserve services for its own needs, the total reserve requirements are bound to decrease substantially. Recent analysis of the annual operation of the EU system shows that regional sharing of frequency regulation and reserve services using cross-border capacity reduces operating costs by about €3bn/annum, when compared with a policy where each member state provides the services to meet their own requirements. When considering carbon impacts, these benefits can be very significant for the UK [2].

However, the present market arrangements do not facilitate the optimal allocation of interconnection capacity between energy and reserve services. Transmission capacity in Europe is currently allocated by power exchanges trading energy, while separate institutions deal with reserve and balancing. This is an issue of high priority that should be resolved at the European level through design of efficient market mechanisms to ensure optimal resource sharing across all Member States.

Harmonizing benefit distribution

In light of Europe's goal of increased market integration between Member States, cross-border interconnection is envisaged to become increasingly important for the purpose of sharing back-up and balancing services in order to manage the substantial intermittency introduced by large volumes of renewables.

However, one major concern pertaining to the development of cross-border interconnectors and an integrated grid is that the benefit generated may be distributed asymmetrically between countries. This is a well-known aspect of trading; prices in the importing countries decrease, while prices in the exporting country decrease. In the absence of appropriate compensation rules, it is possible to foresee countries refusing to go ahead with the construction of cross-border links for political reasons. The Agency for Cooperation of Energy Regulators, ACER, has already highlighted the need to review cross-border compensation between member states [21].

The NorthSeaGrid project [18] carried out extensive analysis in order to shed more light on the materiality of such distributional effects. In particular, two hypothetical (yet very probable) UK-related interconnection case studies have been analysed in detail to probe further into potential implementation barriers; a connection between the UK and Norway and a connection between UK, Belgium and The Netherlands. The main finding of this analysis was that although both projects presented significant cost savings if undertaken in an integrated fashion compared to their radial-connection counterparts, the adoption of existing allocation rules results in asymmetric cost-benefit allocation between the participating countries. Given that not all participating countries would stand to gain by pursuing an integrated network, it follows that it is very difficult for such projects to reach the consensus and progress until the final investment decision has been made under the current regulatory framework. A cross-border allocation method consistent with the 'beneficiary pays' principle [20], where countries that face negative net benefit are compensated by parties accruing positive net benefit, was found to be necessary for the resolution of asymmetric benefits. The above examples highlight the increasing need for appropriate cross-border cost-benefit allocation schemes in order to facilitate the optimal development of interconnection infrastructure in Europe.

4 References

[1] D. Pudjianto, P. Djapic, M. Aunedi, C.K. Gan, G. Strbac, S. Huang and D. Infield, "Smart control for minimizing distribution network reinforcement cost due to electrification", *Energy Policy*, vol. 52, pp. 76-84, 2013.

[2] G. Strbac, M. Aunedi, D. Pudjianto, P. Djapic, S. Gammon and R. Druce, *Understanding the Balancing Challenge*, DECC, 2012. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48553/5767-understanding-the-balancing-challenge.pdf

[3] http://www2.nationalgrid.com/UK/services/Balancing-services/Reserve-services/

[4] Ofgem, "Creating the right environment for demand-side response: next steps", December 2013, https://www.ofgem.gov.uk/publications-and-updates/creating-right-environment-demand-side-response-next-steps

[5] Committee on Climate Change, Building a low-carbon economy, December 2008.

[6] The UK HM Government, The UK Renewable Energy Strategy, July 2009.

[7] Department of Transport, National Travel Survey 2014, September 2015.

[8] Carbon Trust, Micro-CHP Accelerator Interim Report, 2007.

[9] Imperial College London and NERA, "Value of Flexibility in a Decarbonised Grid and System Externalities of Low-Carbon Generation Technologies", Report for the Committee on Climate Change, October 2015.

[10] M. Aunedi, P. A. Kountouriotis, J. E. Ortega Calderon, D. Angeli, G. Strbac, "Economic and Environmental Benefits of Dynamic Demand in Providing Frequency Regulation", IEEE Transactions on Smart Grid, vol. 4, pp. 2036-2048, December 2013.

[11] Imperial College London and Element Energy, "Infrastructure in a low-carbon energy system to 2030: Transmission and distribution - Final report for the Committee on Climate Change", April 2014.

[12] I. Konstantelos and G. Strbac, "Valuation of Flexible Investment Options under Uncertainty", *IEEE Transactions on Power Systems*, vol. 30, no. 2, pp. 1047-1055, Mar. 2015.

[13] Ofgem, "Real Options and Investment Decision Making", March 2012.

[14] State of New York – Department of Public Service, "Developing the Rev Market in New York: DPS Staff Straw Proposal on Track One Issues", August 2014.

[15] Ofgem, "Offshore Transmission: Non Developer-Led Widen Network Benefit Investment", January 2014.

[16] Ofgem, "Conclusion of Consultation on the Evaluation of OFTO Tender Round 1 Benefits", 19 September 2014.

[17] T. Greve and M. Pollitt, "Designing electricity transmission auctions: an introduction to the relevant literature", EPRG Working Paper No. 1221, 2012.

[18] P. Klemperer, "The Product-Mix Auction: a New Auction Design for Differentiated Goods", *Journal of the European Economic Association*, vol. 8, pp. 526-536, 2010.

[19] S.C. Littlechild and C.J. Skerk, "Transmission Expansion in Argentina 1: The Origins of Policy", *Energy Economics*, vol. 30 no. 4, pp. 1491–1526, 2008.

[20] AER, "State of the energy market", 2009.

[21] FERC, *Order No. 755: Frequency Regulation Compensation in the Organised Wholesale Power Markets*, October 2011.

[22] Directorate General for Energy, 'Energy Infrastructure priorities for 2020 and beyond – A blueprint for an integrated European energy network', European Union, November 2010.

[23] S. Cole, P. Martinot, S. Rapoport, G. Papaefthymiou and V. Gori, "Study of the benefits of a meshed offshore grid in Northern Seas region", report for European Commission, July 2014.

[24] Strbac G., Moreno, R., Konstantelos, I., Pudjianto, D., Aunedi, M., 2014. Strategic development of North Sea grid infrastructure to facilitate least-cost decarbonisation. Available at: http://e3g.org/showcase/North-Seas-Grid/

[25] NorthSeaGrid, Final Report on the NorthSeaGrid project, 2015. Available at: http://www.northseagrid.info/

[26] Hogan, W., 2011, Transmission Benefits and Cost Allocation, Harvard University, Cambridge, MA.

[27] ACER, 2013. Recommendation No 07/2013 regarding the cross-border cost allocation requests submitted in the framework of the first union list of electricity and gas projects of common interest.

[28] Imperial College London and Cambridge University, Integrated Transmission Planning and Regulation Project: Review of System Planning and Delivery, June 2013.
[29] IET, Britain's Power System – The case for a System Architect, December 2014. Available at: http://www.theiet.org/factfiles/energy/brit-power-page.cfm
[30] HM Government, The UK Renewable Energy Roadmap, July 2011.
[31] S. Grenard, D. Melovic, G. Strbac, "Effect of losses on design and regulation of distribution networks," CIRED – 17th Intl. Conf. on Electricity Distribution, Barcelona 12-15 May 2003.
[32] Imperial College, ENA, "Benefits of Advanced Smart Metering for Demand Response based Control of Distribution Networks", Report by Centre for Sustainable Electricity and Distributed Generation, March 2010.
[33] Giannelos, S.; Konstantelos, I.; Strbac, G., "Option value of Soft Open Points in distribution networks," in PowerTech, 2015 IEEE Eindhoven , vol., no., pp.1-6, June 29 2015-July 2 2015
[34] Ofgem, Integrated Transmission Planning and Regulation project, https://www.ofgem.gov.uk/electricity/transmission-networks/integrated-transmission-planning-and-regulation
[35] Sansom R. and Strbac G. (2012) The Impact of Future Heat Demand Pathways on the Economics of Low Carbon Heating Systems, 9th BIEE Academic Conference, Oxford, U.K.
[36] https://www.ofgem.gov.uk/electricity/distribution-networks/network-innovation/low-carbon-networks-fund
[37] Future Power System Architecture (FPSA) project http://www.theiet.org/sectors/energy/resources/fpsa-project.cfm
[38] M. Pollitt," Lessons from the History of Independent System Operators in the Energy Sector", Energy Policy, 47 (Aug): 32-48.
[39] Ofgem (2013a), "Electricity System Operator Incentives: Final Proposals", May 2013, available at: https://www.ofgem.gov.uk/ofgem-publications/39898/electricity-system-operator-incentives-final-proposals-scheme-2013.pdf
[40] M. Qadrdan, M. Chaudry, J. Wu, N. Jenkins, J. Ekanayake, "Impact of a large penetration of wind generation on the GB gas network." *Energy Policy* 38.10 (2010): 5684-5695.
[41] Directorate General for Energy, 'Energy Infrastructure priorities for 2020 and beyond – A blueprint for an integrated European energy network', European Union, November 2010.
[42] Ofgem, Offshore Transmission Coordination Project: Conclusions, Mar. 2012.
[43] http://www.seai.ie/Renewables/Wind_Energy/Regional_Wind_Workshops/Delivering_a_21st_century_electricity_infrastructure_ESB_Networks.pdf
[44] Ofgem, "Making the electricity system more flexible and delivering the benefits for consumers" September 2015, https://www.ofgem.gov.uk/sites/default/files/docs/2015/09/flexibility_position_paper_final_0.pdf
[45] F. Teng, V. Trovato and G. Strbac, "Stochastic Scheduling with Inertia-Dependent Fast Frequency Response Requirements", IEEE Transactions on Power Systems, accepted for publication.
[46] House of Lords' Science and Technology Committee, First report – The Resilience of the Electricity System, 24 Feb 2015.
[47] iTesla project, http://www.itesla-project.eu/
[48] Smart Grid Task Force EG3, "Regulatory Recommendations for the Deployment of Flexibility", January 2015.
[49] IET, Future Power System Architecture Project: Initial Findings Report, December 2015.
[50] DECC, Towards a Smart Energy System, December 2015.
[51] Energy Networks Association, Review of Engineering Recommendation P2/6. http://www.smarternetworks.org/Project.aspx?ProjectID=1723#project-details
[52] M.O. Oseni, M.G. Pollitt, D.M. Reiner, L. Richter, K. Chyong and M. Baddeley, "2013 EPRG Public Opinion Survey: Smart Energy Survey – Attitude and Behaviours", EPRG Working Paper no. 1327, December 2013. Available at: http://www.econ.cam.ac.uk/research/repec/cam/pdf/cwpe1352.pdf
[53] National Grid, Future Energy Scenarios, 2015.
[54] G. Strbac, R. Moreno, D. Pudjianto, M. Castro, "Towards a risk-based network operation and design standards", IEEE General Meeting 2011, Detroit, July 2011.
[55] R.J. Green, D. Pudjianto, I. Staffell and G. Strbac, "Market Design for Long-Distance Trade in Renewable Electricity", The Energy Journal, forthcoming, 2016.
[56] Ofgem, Project Transmit, Available at: https://www.ofgem.gov.uk/electricity/transmission-networks/charging/project-transmit
[57] G. Strbac, C. Vasilakos, R. Moreno, D. Papadaskalopoulos, S. Gammons, R. Druce, and P. Davies, Assessing the cost reflectivity of alternative TNUoS methodologies, February 2014.

[58] Transition Pathways project, “Transition pathways for a UK low carbon electricity system: Comparing scenarios and technology implications”, December 2013.
[59] Pollitt, M. and Anaya, K., ‘Can current electricity markets cope with high shares of renewables? A comparison of approaches in Germany, the UK and the State of New York’, The Energy Journal, 2016, Volume 37, Bollino-Madlener Special Issue, doi://10.5547/01956574.37.SI2.
[60] Pollitt, M.G., ‘The future of electricity network regulation: the policy perspective.’ In: Finger, M. and Jaag, C. (eds.) *The Routledge companion to network industries.* (2016) Oxford: Routledge, pp.169-182.