

# Future Power System Architecture

A report commissioned by the Department of Energy & Climate Change

## 2. Main Report



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## **Main Report**

**The Future Power System Architecture (FPSA) project was commissioned by the Department of Energy & Climate Change (DECC) and undertaken through a collaboration between the Institution of Engineering and Technology (IET) and the Energy Systems Catapult.**

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The collaboration has built upon the shared commitment to respond effectively to the challenges presented by the energy trilemma: decarbonisation, security of supply and affordability. The Energy Systems Catapult and the IET have drawn upon their respective strengths and engaged with a broad community of stakeholders and other experts to deliver the project.

The collaboration brought extensive expertise and experience to the project, combining technical, commercial and customer perspectives, including a significant contribution from senior thought leaders within the IET membership. The unique combination of complementary skills has enabled; innovation in the approach, deep analysis and strong evidence building. The collaboration has worked closely on project governance, delivery and commercial management and has applied best practice in all aspects of its work. The position of the IET and the Energy Systems Catapult in the energy sector has assured independence of the outcomes.

### **About the Institution of Engineering and Technology**

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The Institution of Engineering and Technology is one of the world's largest engineering institutions with over 167,000 members in 127 countries. It is also the most multidisciplinary – to reflect the increasingly diverse nature of engineering in the 21st century.

The IET is working to engineer a better world by inspiring, informing and influencing its members, engineers and technicians, and all those who are touched by, or touch, the work of engineers.

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### **About the Energy Systems Catapult**

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The Energy Systems Catapult is the UK's technology and innovation centre set up to support companies and Government for the development of new products and services to address the new commercial opportunities created by the transformation of UK and global energy systems (covering electricity, heat and combustible gases).

The Catapult's mission is to bring the worlds of industry, academia and Government together to encourage and support the development of new technology-based products and services in the energy sector. It is a non-profit, non-partisan company limited by guarantee.

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## Foreword

It gives me great pleasure to commend to you this ground-breaking work. The functionality of the GB electricity system will need to transform over the next decade to allow us to provide affordable, secure and clean electricity to homes and businesses. This is not only to accommodate the renewable energy revolution, but also the parallel and equally revolutionary developments enabled by technology and big data – the rise of the smart consumer, smart communities, smart energy and smart cities.

Much of the drive and innovation within the electricity system is coming from products and services finding application within consumers' premises. This means that developments on the consumer side of the meter, and previously largely ignored by the industry, will be setting the pace of change. There will be much more need for electricity supply, demand and networks to be considered as an integrated whole. This creates an opportunity for a more agile and cost-effective system if we harness the change, or brings new risks to manage if we choose to follow developments as they happen.

To seize the opportunities and manage the clear risks of inadequate responses we need to look afresh at how our industry operates. The work demonstrates how all parts of the system rely on and affect one another. Laws of physics know no commercial boundaries; we need to find ways to govern our industry that can handle this fresh challenge.

The IET and the Energy Systems Catapult have brought together an incredible visionary, yet pragmatic, team, which it has been my privilege to lead. We have engaged widely with the industry and have applied the techniques of systems engineering to view the whole electric power system through an entirely new lens, something I have found personally challenging and highly insightful.

The conclusions are clear. We need to act now to create an industry where we are empowered by this transformation and find new ways to work that release the value and possibilities the new technology brings for us. Such transformation will require focus and urgency and is not without risk. On the other hand, if we choose instead to continue to react to each new situation as it comes to us and manage the emerging risks one by one, we will almost certainly fail to fully realise the opportunities, may struggle in addressing some of the new risks and consumers will end up paying more. While change contains risks and will create winners and losers, there's little doubt about the direction being signposted by the conclusions from this work. The way ahead will have its challenges but if we are prepared to grasp them, I believe it will be in the real interest of future electricity consumers (which means all of us) and of our future prosperity.



**Dr Simon Harrison CEng FIET**

Chair of Future Power System Architecture Project Delivery Board  
Group Strategic Development Manager, Mott MacDonald

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# 1. Executive Summary

## 1.1 The changes facing Britain's power system architecture

The 'power system architecture' is the underlying structure of the electricity system – how its components and its participants are organised and interact. Major policy challenges, advanced technologies and emerging new business models will require transformative change to Britain's power system architecture by 2030.

- **Underlying drivers of change.** These changes are required in order to meet the triple challenge of:
  - (1) maintaining secure and reliable electricity supply;
  - (2) delivering the policy and legal commitment to deep decarbonisation and
  - (3) value for money as new technologies and techniques are integrated at scale.
- **Technology, market and customer drivers.** These include much greater deployment of large scale wind and solar PV farms, smaller scale generation connected to distribution networks, microgeneration in customers' premises, more reliance on interconnectors and growth of domestic and grid-scale storage. On the demand side, electric vehicles, heat pumps and smart appliances will disrupt traditional demand patterns and interact with smart meters, cost-reflective tariffs and automated demand-side response. Meanwhile, new players such as smart cities and community energy schemes will create market opportunities through aggregation of both supply and demand.

## 1.2 The Future Power System Architecture (FPSA) project

The FPSA project was commissioned by DECC to assist ministers, officials and industry professionals to anticipate these developments and to assess their significance. It was led by the Energy Systems Catapult and the Institution of Engineering and Technology (IET). The project uses systems engineering techniques to examine credible evolutionary pathways and new functionality required. The project's analysis draws on National Grid's Future Energy Scenarios, focusing on the *Gone Green* scenario as the one most consistent with established policy objectives.

## 1.3 Project findings – the new functionalities required by 2030

The project has identified *thirty-five* new or significantly modified functions required to meet 2030 power system objectives. The new functions are grouped under seven major drivers and set out in sections 2 and 14. The drivers of new functionality are as follows:

1. **The flexibility to meet changing but uncertain requirements** recognising that the form, magnitude, timing and tipping points of future power system developments are not all predictable far in advance. Changes include uptake of new technologies (e.g. domestic generation and storage, electric vehicles, heat pumps) or active consumer participation (e.g. smart tariffs, home energy automation).
2. **The change in mix of electricity generation** will require new techniques to manage system frequency, stability and reliability as intermittent renewable sources and distributed generation grow to take up a much larger share of total generation.
3. **The use of price signals or other incentives** will enable customers to save money by becoming active participants in the power sector and, in doing so, to contribute to decarbonisation while keeping system balancing costs down.
4. **The emergence of new participants** such as smart cities, groups of technology users, aggregators and social enterprises will require new modes of interaction with the power system to exploit benefits of aggregation while mitigating any risks of destabilisation.
5. **The active management of networks, generation, storage and demand** will facilitate growth of intermittent and distributed generation and new loads such as heat pumps and electric vehicles, without unnecessary network constraints or costly upgrades.
6. **The recovery from major outages** will be far more challenging as the power system becomes more decentralised. Managing prolonged outages will require sophisticated coordination to reintroduce load and to reconnect distributed generation and storage.
7. **The need for some coordination across energy vectors** (electricity, gas, biofuels, petroleum and heat networks) will become inevitable as the UK decarbonisation strategy proceeds with the electrification of heat and transport energy.

## 1.4 Why this agenda is challenging

The new functions have features that challenge the established system architecture:

- They reach beyond the meter and into the home, interacting with consumers' equipment influenced by prices, creating many more active components in the electricity system.



- They bring greatly increased complexity, involving the aggregate behaviour of millions of devices, consumers and businesses, all interacting in more price-sensitive markets.
- They cross current commercial, organisational and governance boundaries, so require a whole-system view from the large power station down to the smart kitchen appliance.
- They introduce new data, IT and communications requirements, bringing design, standardisation, privacy and cyber-security challenges.
- They present new requirements for the forecasting and simulation of whole-system behaviours that are needed to support power system and market processes.
- They will ultimately span all vectors, covering electricity, gas, petroleum and biomass as the electrification of heat and transport energy proceeds.

The 2030 power system will be characterised by greatly increased complexity, interaction and dynamism reaching from within the home to the largest power station with many more engaged participants. The project identifies four credible evolutionary pathways for the power sector over the next 15–20 years, and recognises the need for innovation to address gaps in the available technologies and capabilities required to deliver the new functionality.

### **1.5 Risks or costs may arise if new functionality is not delivered**

Not delivering the identified functionality has potential costs and risks. These include:

- Compromises to the security, integrity and reliability of the power system at physical, operational and data levels.
- Excessive operational costs or avoidable constraints, such as costs of balancing or achieving frequency control, or the emergence of avoidable localised network constraints.
- Inefficient investment, low utilisation of assets or over-engineering – meeting the policy objectives but expensively.
- Impediments to valuable new commercial models and lost benefits to consumers and the economy – the loss of opportunities and barriers to innovation.
- Failure to meet carbon reduction targets if it proves impossible to integrate low-carbon generation and demand-side technologies at scale with adequate reliability and stability.

The implementation of new functionality will also have risks and these should be assessed and managed as part of the implementation regime.

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## 1.6 The FPSA project reports and reference material

- **The Report Summary** comprises the following:
  - o Section 1 is this brief executive summary.
  - o Section 2 provides an overview of the functions identified and summarises the analysis.
  - o Section 3 sets out the project's conclusions and recommendations.
- **The Main Report and Appendices** cover sections 4 to 20, providing the context, methodology, evidence, functional analysis in detail with a deeper analysis for seven of the *thirty-five* functions and summary of stakeholder engagement and consultation responses.

A number of supplementary papers provide further depth and background:

- **International Study** has examined main system level challenges facing the electrical power sectors of Germany, Ireland, the United States and South Korea.
- **Systems Engineering Methodology** provides a detailed account of the systems-engineering methodology used.
- **Functional Matrix** spreadsheet provides detailed analysis and evidence for the functions identified.
- **Function Sequencing** spreadsheet provides analysis of timing and interdependencies.

These materials are available online via the IET and Energy System Catapult websites.

[www.theiet.org/fpsa](http://www.theiet.org/fpsa)

[es.catapult.org.uk/fpsa](http://es.catapult.org.uk/fpsa)



## 2. Report Summary

**Architecture:** *the designed and emergent structure of a system, and the manner in which the physical, informational, operational and economic components of a system are organised and integrated.*

### 2.1 What is Britain's power system architecture and how is it changing?

The Future Power System Architecture project has examined the structural changes to the GB electricity system expected over the next 15–20 years and the challenges that these changes will present to its current architecture. The project has identified the new and extended functions necessary to respond to customer requirements, mitigate risks and exploit the opportunities that lie ahead. We broadly characterise the change of architecture as follows:

- **Current architecture.** For many decades, large, centrally dispatched power stations have produced power as required. Supply is matched to demand via a transmission grid and local distribution networks and through centrally administered power trading and balancing arrangements. Demand is largely predictable and the majority is isolated from short-term price signals.
- **2030 architecture.** The 2030 power system will be a sophisticated and intelligent infrastructure that enables diverse technologies, novel techniques, more active consumers and new business models to flourish with greater autonomy, while utilising assets efficiently and maintaining overall system resilience and stability. This emerging complexity will require system stewardship that takes an entirely new, whole-system perspective to ensure effective and secure integration across multiple parties.

## 2.2 The Future Power System Architecture (FPSA) project

- **Purpose.** The project was commissioned by DECC to assist ministers, officials and industry professionals to anticipate these developments and to determine their significance. The project has been managed by the Energy Systems Catapult and the Institution of Engineering and Technology, involving over fifty specialists with diverse expertise spanning technical, market and social aspects.
- **Method.** The project approach has been to apply a system engineering methodology to establish the new technical functions required by the sector, under credible evolutionary pathways, to meet 2030's power system objectives and to assess their novelty, complexity and urgency. The methodology is described in section 17 and the separate paper included as supplementary material.
- **Future scenarios.** The project has drawn on the National Grid Future Energy Scenarios for planning assumptions for the power system in 2030. The *Gone Green* scenario has been emphasised as it is the scenario that most closely reflects government decarbonisation objectives, and would support an ambitious fifth carbon budget (2028-2032) consistent with the Climate Change Act and international commitments. It provides an effective 'stress test' of the functionality for the power system. *Gone Green* includes the following major trends from 2014 to 2030:
  - The rise of intermittent renewables, wind and solar, from 18 to 46% of capacity rising from 17 GW (2014) to 71 GW (2030) and from 11 to 39% of electricity generated.
  - Distributed generation (not part of the existing balancing mechanism) that reaches 17% of available capacity with microgeneration adding a further 10%. Much of this would form part of the solar or wind power above.
  - Electrification of heat and transport, with 3.3m electric vehicles (EV) and 6.6m heat pumps.
  - Extensive use of smart meters – installed in 29m households and small businesses.
  - Major system changes – reducing system inertia, greater international interconnection.
- **Sensitivity analysis.** In practice, the evolution of the power sector may diverge from the *Gone Green* scenario and that, in turn, might influence the evolution of power system functionality. The project team considered four credible pathways for power sector evolution and the impact these have on project findings. The main findings have been found to be robust and broadly independent of the choice of pathway or energy scenario. Alternative scenarios and pathways may influence the timing and sequencing of individual functions but not the need for the functions themselves.
- **Power sector evolution – core concepts.** The four credible evolutionary pathways are referred to as the *core concepts* for power sector evolution over the next 15–20 years. These pathways are summarised as:
  - **Power Sector Adaptation:** business as usual, accommodating incremental development.
  - **Power Sector Leadership:** sector leads in engaging with customers.
  - **Customer Empowerment:** sector facilitates, empowering new parties.
  - **Community Empowerment:** sector empowers energy communities and local markets.

These are further described in section 6.2.

### 2.3 Project core findings – drivers of new or significantly extended functionality

The project has identified *thirty-five* new or significantly modified functions required to meet 2030 power system objectives. These functions are grouped under seven major drivers and the relevant functions are listed below under each driver. Each function applies to a specific business timeframe and has been assessed in terms both of prerequisites to implementation and trigger points, i.e. the point at which the function must be implemented (see 2.4 below). Some functions may appear to be near duplicates, but they act over different timeframes and are quite distinct.

**Timeframe.** The functions are categorised by the timescale over which they apply. Four different timeframes are considered. Some functions appear over two or more timeframes – they may sound similar but technically they will be quite distinct. The business timeframes considered are as follows:

- Investment planning (typically 3 or more years ahead of commissioning new equipment).
- Operational planning (typically a few days to a couple of years ahead).
- Real time and balancing (on-the-day operation of the system).
- Settlement and market (post real time, typically over a period of weeks).

The *thirty-five* functions are set out in section 14. A selection of these is described in greater detail in section 5.3. The seven drivers and the *thirty-five* new functions required to respond to them are summarised as follows:

#### Driver 1: The flexibility to meet changing but uncertain requirements.

The power sector will need to be capable of identifying and responding to material challenges and tipping points as they emerge (e.g. domestic generation and storage, electric vehicles) and new consumer behaviours (e.g. uptake of smart tariffs, automated control of homes and appliances). We cannot know for sure how the power system will evolve, and what the technologies and business models of the future will be. There is some flexibility in today's power sector arrangements, but it is limited and potentially constraining. Functional requirements include:

Timeframe	Function
All	Continuously review the energy landscape to enable the power sector to respond readily to change and ensure the timely introduction and implementation of new functions (for a detailed description see function 0.1, section 5.3).
Investment	Monitor the impact of changing customer needs on system operability and bring forward effective solutions as necessary.
Investment	Identify emerging threats to operability of the power system from all parts of the sector, both above and beyond the meter.
Investment	Identify and counter cyber threats to operability of the power system originating from inside and outside the power sector.

**Driver 2: The change in mix of electricity generation.** The rise in renewable electricity generation brings with it technical characteristics (e.g. weather dependent intermittency, periodicity, low stabilising inertia) that, at large scales, have the potential to reduce the inherent stability and security of the national power system. New forms of stabilising inertia or ‘frequency response’ capability will be required in future. Functional requirements include:

Timeframe	Function
Investment	Establish mechanisms to ensure the national portfolio of generation and other dispatchable energy resources and auxiliary services delivers carbon, security of supply and affordability policy objectives.
Investment	Plan for the timely restoration of supplies following a national failure (Black Start) (for a detailed description, see function 2.6, section 5.3).

**Driver 3: The use of incentives to enable customers to benefit and the system to operate more efficiently.** Customers will be able to save (or earn) money and contribute to decarbonisation while keeping system balancing costs down by becoming active participants in the power sector through their responses to price or control signals, which will often be software automated. Functional requirements include:

Timeframe	Function
Investment	Provide aligned financial incentives across the power sector, e.g. innovative or flexible tariffs in order to incentivise positive customer engagement in ways that achieve local benefit, without creating national disbenefits.
Operational	Collate and distribute information throughout the power sector on the availability and performance of generation and other dispatchable energy resources and auxiliary services, and any associated operational restrictions that may impact security or quality of supplies.
Real time	Provide a mechanism for peer-to-peer trading with appropriate charging for use of the power system (for a detailed description, see function 15.5, section 5.3).
Settlement	Collate and distribute information throughout the power sector on the performance of demand, generation and other dispatchable energy resources and auxiliary services.
Settlement	Enable settlement for all existing customer profile classes to support flexible tariffs, e.g. on a half-hourly basis using smart or advanced meters.
Settlement	Monitor and settle the delivery of contracted demand, generation and other dispatchable energy resources and auxiliary services.

**Driver 4: The emergence of new parties providing new services to customers.**

The emergence of smart cities, groups of technology users, aggregators and social enterprises will require new modes of interaction with the power system that reflect both the opportunities for their active participation while mitigating the risk that they may create destabilising effects. Functional requirements include:

Timeframe	Function
Investment	Provide the designed-in ability to move between different modes of overall operation in the event or threat of a system emergency.
Investment	Ensure widespread customer engagement by provision of a full range of customer choices including individual, community and smart city services.
Investment	Provide mechanisms by which operational planning can be coordinated between all appropriate parties to drive optimisation, with assigned responsibility for security of supply.
Operational	Collect outage information from all parties of significance within the power sector, coordinate with affected parties, identify clashes and resolve, with assigned responsibility for security of supply (for a detailed description, see function 7.1, section 5.3).
Operational	Engage with all affected stakeholders to support coordinated operation of the system in real time, especially for unplanned or emergency conditions.
Settlement	Coordinate the roles and value propositions of all significant stakeholders across the power sector, including community energy managers and commercial aggregators, to ensure whole system optimisation.
Settlement	Provide a market process that facilitates active engagement of customers, aggregators and smart city schemes to avoid unnecessary investment in networks and generation.

**Driver 5: The active management of networks, generation, storage and demand.**

The rise of intermittent and distributed generation and new loads such as heat pumps and electric vehicles could be inhibited by network constraints or require costly upgrades unless actively managed by intelligent matching of supply, demand and network capabilities. Functional requirements include:

Timeframe	Function
Investment	Forecast (3 or more years ahead) all demand, generation and other dispatchable energy resources and auxiliary services within the power system.
Investment	Plan for the use of smart technologies to maximise the capacity of the power system to accommodate the connection and integration of new demand, generation and other dispatchable energy resources and auxiliary services.
Investment	Ensure monitoring and data quality is in place to support the requirements for application of active system management.

Timeframe	Function
Investment	Review the sector’s developing operational characteristics to validate the assumptions being made during the investment planning process.
Operational	Identify by modelling and simulation, constraints arising from credible events/faults and plan remedial action.
Operational	Forecast (1–2 years ahead) and model all generation and other dispatchable energy resources and auxiliary services with operational, cost and security implications for the power sector.
Operational	Enable the dispatch of generation and other dispatchable energy resources within the power system, such as distributed storage and auxiliary services, to deliver system security and maximise the use of low carbon generation at optimal overall cost.
Real time	Provide automated and secure management of demand, generation and other offered energy resources and auxiliary services, including smart appliances, and building and home energy management systems (for a detailed description, see function 14.1, section 5.3).
Real time	Identify available generation and other dispatchable energy resources, and auxiliary services and associated operational restrictions.
Real time	Coordinate demand, generation and other dispatchable energy resources and auxiliary services within the power system to deliver system security and maximise the use of low carbon generation at optimal overall cost.
Real time	Monitor and control those parts of the system under active management, including network assets, demand, generation and other dispatchable energy resources and auxiliary services.
Real time	Monitor the effectiveness of delivery of demand control, generation constraint and other actions in response to all events/faults and execute remedial action as required.

**Driver 6: The recovery from major events or emergencies.** As the power system becomes increasingly complex, decentralised and more interactive with its customers, anticipating, modelling and managing major events will become more challenging. Recovery from prolonged outages will require much more sophisticated coordination to reintroduce load and reconnect distributed generation and storage. Functional requirements include:

Timeframe	Function
Investment	Plan for the timely restoration of supplies following a pro-longed local failure, termed Cold Start (for a detailed description, see function 2.3, section 5.3).
Real time	Enable the delivery of demand control, generation constraint and other actions in response to all extreme events.



**Driver 7: The emerging need for coordination across energy vectors.** A major pillar of UK decarbonisation strategy is the electrification of heat and transport. As the interactions between these markets deepen, some level of coordination will be necessary across electricity, gas, biofuels, petroleum supply and heat networks. Functional requirements include:

Timeframe	Function
Investment	Assess the impact of gas and other energy vectors when forecasting the volumes of demand, generation and other dispatchable energy resources and auxiliary services on the power system.
Settlement	Collaborate with other energy sectors across multiple sites to make the best use of available energy resources and provide the flexibility to meet environmental and financial priorities (for a detailed description, see function 15.4, section 5.3).

**International experience.** A survey of international experience commissioned under the project shows that other power systems are facing similar challenges driven by the same underlying drivers and that some are beginning to organise to address the challenge (see sections 8 and 20).

## 2.4 Timing and sequencing aspects of the new functions

In the Main Report and supplementary spreadsheets critical aspects of the new functions are set out including the prerequisites for implementation and the trigger points that determine their timing.

**Trigger points** – these characterise the functional requirement according to necessity, risk mitigation or as required to realise opportunities. Section 14 includes the trigger points for the *thirty-five* functions. The classification used in the project is as follows:

- *Trigger point 1:* Should be initiated immediately and developed as required (work may have already begun in the sector).
- *Trigger point 2:* Must be implemented before disruptive generation and demand side technologies, and associated control systems (e.g. electric vehicles, heat pumps, distributed generation, storage, home and building energy management systems) reach a critical level.
- *Trigger point 3:* Must be implemented before the introduction and influence of new players on the system reaches a critical level.

**Prerequisites** – these define co-dependencies and interaction with other functions and are detailed in section 14 of the Main Report and the function sequencing spreadsheet in the supplementary material. These have been characterised as follows, with recognition of some blurred boundaries between them:

- *Prerequisite 1:* None – can be initiated immediately and developed as required.
- *Prerequisite 2:* Requires wider cross-system collaboration, under appropriate governance, which may not be straightforward or possible under current arrangements.

- *Prerequisite 3*: Requires more enhanced metering and monitoring and associated communications to be widespread.

These trigger points and prerequisites create additional complexity and need to be built in to a realistic implementation route map.

## 2.5 Why is implementing these functions challenging and why is a new approach needed?

Four categories of 'challenge' have been identified and their key aspects are set out as follows:

### Challenge 1. Characteristics of the functions.

The new functions have characteristics that will require significant changes to the long-established system architecture (see section 7.3).

- *They reach beyond the meter*, involving interaction with customers' intelligent energy-using equipment influenced by prices, creating many more active components of the electricity system.
- *They reflect greatly increased complexity*, involving the aggregate behaviour of millions of devices, consumers and businesses, all interacting more autonomously in more price sensitive markets.
- *They cross current commercial, organisational and governance boundaries*, so require a whole-system view from the large power station down to the smart kitchen appliance.
- *They introduce new data requirements* with associated IT, communications, data sharing and security obligations.
- *They require new techniques and capabilities for forecasting and simulation*; these are challenging because of the increase in complexity and requirement for a holistic approach.
- *They will ultimately span multiple energy vectors* including electricity, gas, petroleum and biomass; an early requirement for the energy system to become more tightly integrated will be in response to policy drives for electrification of heat and transport.

### Challenge 2. Complexity and interdependence.

Many of the functions interact, are co-dependent or provide for more efficient delivery of other functions. There is a material increase in technical complexity to move from today's predominately passive distribution network to the highly active network of the 2030s. This is in part due to the proliferation of devices beyond the meter (e.g. heat pumps, EVs, smart appliances etc.) that adds a new dimension to the challenge to manage and coordinate the power network in a way that will benefit its users without jeopardising security, or worse, destabilising the whole system. For example, maintaining system stability with rising intermittent and distributed generation is essential given decarbonisation objectives, but it can be delivered more efficiently if a system of responsive tariffs, smart meters and appliances with frequency response can be relied upon to deliver demand-side responsiveness.

**Challenge 3. Multiple stakeholders and complex delivery landscape.** The effort to deliver the *thirty-five* functions will be shared across a large and currently unknown number of stakeholders, ranging from current industry majors to individual consumers and the suppliers of equipment and systems they purchase. These stakeholders will

need to work within agile and forward-looking engineering, market and regulatory frameworks established by government and/or the (whole) industry itself. It is imperative to recognise the technical inter-relationships between the new functionality in terms of how these would be delivered, by whom and in what coordinated timeframe.

#### **Challenge 4. Requirements for Research & Development (R&D) and**

**innovation.** In the more detailed analysis performed for seven representative functions (see section 5.3), a preliminary evaluation of R&D and innovation requirements has been undertaken, indicating that we do yet not have the full range of technologies, techniques and capabilities required to deliver all the functions. Among many requirements, examples include:

- The advanced control systems to balance the use of centralised versus distributed control mechanisms.
- Development of new forecasting and modelling techniques for whole-system and multi-vector applications.
- New protection systems suited to the reducing system strength now emerging.
- The mechanisms for implementing peer-to-peer trading.
- The control and communication regime needed for future Cold Start and Black Start situations.

Achieving this is judged to be within reach, provided the necessary emphasis is given to addressing current gaps in capability.

## **2.6 Risks**

The new functionality described is intended to mitigate risks and realise opportunities. If new functionality is not delivered, or is delivered late, there is potential for several highly adverse consequences (see section 7.4); for example:

- Compromises to the security, integrity and reliability of the power system at physical, operational and data levels.
- Excessive operational costs or avoidable constraints and related costs – e.g. higher than necessary costs of balancing or achieving frequency stability, or the emergence of localised network constraints that, for example, would prevent connection of new distributed generation or a large number of electric vehicles in a local area.
- Inefficient investment, low utilisation of assets or over-engineering – meeting the policy objectives but expensively. For example, smart-grid concepts may provide a lower cost infrastructure to support the electric vehicle population by reducing the need for traditional strengthening of networks to meet predicted demand.
- Impediments to valuable new commercial models, and lost benefits to consumers and the economy – the loss of opportunities and barriers to innovation, for example, if it proved impracticable to implement peer-to-peer trading and the full potential of smart cities or other aggregators.
- Failure to meet policy targets for carbon reduction if it proves impossible to integrate low-carbon generation and demand-side technologies at scale with adequate reliability and stability.

The implementation of new functionality will also have risks, and these should be assessed and managed as part of the implementation regime.



## 3. Conclusions and Recommendations

### 3.1 Project conclusions

The project has drawn four conclusions based on its analysis of the new functions required.

1. Substantial new or extended functionality is required to meet government and power system objectives by 2030. The project has identified *thirty-five* individual new or significantly extended functions; these apply over different timeframes and are interdependent. Their interaction and need for coordination implies that, when taken together, they will amount to a transformative change. Delivering this transformation through a coherent programme rather than by incremental adjustment or piecemeal initiatives would mitigate a number of serious risks. These include: significant extra cost, material constraints on the integration of new technologies, breaching engineering limits, compromising system security and the possibility of failing to meet policy objectives.
2. The new functionality has features that present substantial implementation challenges from a technical, market and commercial perspective. These arise from much greater complexity and technical diversity, far more active users, more smart and responsive demand-side technologies and storage, novel patterns of demand, greater reliance on data and scope for harmful feedbacks and interactions between system components.

3. It is feasible to deliver the changes required for 2030, but the scale and complexity warrant special focus and urgency. These developments are already having an impact on the GB power system and 14 years to 2030 is already a demanding timetable in view of what is involved in defining, designing, developing, risk-assessing and testing solutions prior to introducing them into service. The electricity system is complex and ‘always on’, and the integration of new functionality will need to be undertaken in a systematic way to ensure compatibility and to avoid destabilisation. This will require concerted and coordinated attention in view of the many timing interdependencies, triggers and tipping points.
4. Much new functionality is concerned with interactions that span the whole system – from smart appliances beyond customers’ meters to the largest thermal power stations. This integration runs counter to today’s stratification of system architecture that, to a large extent compartmentalises generation, transmission, distribution and consumers. An effective response will require new organisational and governance capabilities to establish and energise this whole-system approach necessary for transforming Britain’s power system architecture.

### 3.2 Project recommendations

The project proposes six recommendations, based on the conclusions above.

1. Align power system architecture development with major policy commitments. In delivering the fifth carbon budget (2028–2032), the Government should ensure it has a programme and necessary capabilities to deliver the system architecture needed to support the likely mix of technologies required (or that will evolve) to meet the budget.
2. Ensure that there is an implementation framework for delivery of the required functionality, with particular responsibility for end-to-end operability, taking account of other developments in energy sector reform.
3. Deepen and extend the functional analysis through further elaboration and refinement of functional requirements, assessment of barriers to implementation and analysis of timing pressures and interdependencies. Commence work on identifying the technical, market and commercial options for delivery.
4. Develop a transition route map of least-regret actions to ensure market mechanisms are maximised and government intervention minimised to meet the technical requirements identified by the *thirty-five* functions.
5. Extend the evaluation and identification of R&D and innovation requirements to cover all the functionality identified and formulate a supporting innovation programme aligned to the transition route map and coordinated within the existing innovation machinery.
6. Maintain the momentum developed in the FPSA project by formalising and supporting cross-industry and inter-agency working to take this demanding agenda forward, with clear accountability for leading and coordinating change.

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“It will be important to ensure that there is an implementation framework for delivery of the required functionality, with particular responsibility for end-to-end operability, taking account of other developments in energy sector reform.”

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## 4. Project Introduction and Background

### 4.1 Summary

- This report concludes the current Future Power System Architecture (FPSA) project addressing technical functions to deliver the whole power system required for Great Britain (GB) by 2030. This addresses fundamental changes already occurring in the GB power system and power sector.
- The project has not sought to define every requirement or dive down into the technical details of every identified function. However, the analysis and supporting evidence makes a clear case that there is still important work to be done in putting in place various measures to deliver an integrated, whole electricity system to meet security, affordability and climate change goals. Indeed, it may ultimately be appropriate to extend the analysis to consider cross vector issues.
- The project emphasis has been on technical functions that are whole-system relevant and so more challenging for the industry to deliver. The project has also focused on the emerging or anticipated gaps in functionality by way of addressing the existing and future required functionality and also tackling possible function implementations and challenges.
- The project has used National Grid's *Gone Green* scenario as a baseline of the energy developments in the GB power sector to 2030 and has also considered other National Grid scenarios and variants to understand how different system development trajectories influence the required functionality.

- Together, the context and future scenarios present a number of pressing challenges to the GB system development and operation, including multiples of new technologies, integration of Information Technology (IT)/smart solutions across the system, greater activity and dynamism beyond the meter at customer sites, production and consumption technologies of very different characteristics, all this leads to a system with very different characteristics than today.
- The project addresses these emerging trends and challenges through a detailed (yet necessarily high level) study of technical functions required in the GB power sector by 2030.
- A number of credible power sector evolutionary pathways have been considered (known as ‘core concepts’) to test how these might influence the scope of each of the new or enhanced functions and how soon (or in what sequence) these would need to be introduced.
- The project has created a number of detailed resources (see Appendix in section 15) so this report is necessarily contained to a higher level presentation and discussion of the findings.

## 4.2 Structure of the report

This section (section 4) provides the background and context for this project and establishes the high level power system challenges that present the need for new and extended functionality to build and operate a secure, sustainable and economic power system. More detailed background and reference material is presented in appendices and these are referred to in appropriate places in the report.

Section 5 lists the *thirty-five* new or extended technical functions identified, presents a detailed description of seven of the functions as exemplars of seven identified drivers of functionality and introduces the evidence gathered and analysed. Section 5 points to the developed Functional Matrix as the main source of gathered data and evidence on the technical functions, and this is available online at [www.theiet.org/fpsa](http://www.theiet.org/fpsa) and [es.catapult.org.uk/fpsa](http://es.catapult.org.uk/fpsa).

Section 6 presents analysis of the drivers, triggers, dependencies and sequencing of the identified functions as well as the implications of different implementation pathways.

Section 7 sets out the implementation challenges and implications of the identified technical functions.

Section 8 briefly highlights the conclusions of the FPSA International Study – more detail of this is presented in an appendix (section 20) with the full International Study available as an online resource.

Section 9 sets out the main findings of the FPSA project along with the conclusions and recommendations. The conclusions and recommendations mirror those presented above in section 3.

The report aims for factual, evidence-based and concise presentation of the project outcomes so a fair volume of supporting material is presented in appendices with additional supporting material available online at [www.theiet.org/fpsa](http://www.theiet.org/fpsa) and [es.catapult.org.uk/fpsa](http://es.catapult.org.uk/fpsa). Such additional material is referenced clearly in the main body of the report.

### 4.3 Project introduction

The FPSA project was sponsored by the Department of Energy & Climate Change (DECC) and the Energy Systems Catapult. The primary project objective was to establish what new technical functions need to be implemented to plan and operate the power system in response to new customer and user needs, to changing generation technologies and to electrification of heat and transport. The project has used systems engineering techniques and principles to meet this objective.

This Main Report presents the findings of the work. The overall goal of the FPSA project is to establish the key functional requirements for the future (with 2030 as the agreed time horizon), with a focus on the functional ‘gap’ compared with the position today. It is important that these functions are widely supported by all key stakeholders so wide stakeholder engagement and evidence gathering has been a key feature of the project. The identified functions and the challenges to implement them could be used as an input to consider the technical, institutional, regulatory and market developments necessary to ensure that our power sector meets future needs securely and efficiently whilst facilitating sustainability goals.

The FPSA project has examined the structural changes to the GB electricity system expected over the next 15–20 years and the challenges that these changes will present to its current architecture. We use the term ‘architecture’ in the broadest sense, primarily addressing technical matters but, where relevant, extending to commercial and business aspects and their inter-relationships and interactions.

**Architecture:** *the designed and emergent structure of a system, and the manner in which the physical, informational, operational and economic components of a system are organised and integrated.*

The project has identified the new and extended functionalities necessary to respond to customer requirements, mitigate risks and exploit the opportunities that lie ahead. An international review has been undertaken to help inform the project context. This report, its appendices and web-based supplementary material, detail the findings. The overall direction of energy policy has been articulated in a speech by the Secretary of State for Energy and Climate Change<sup>1</sup>, which emphasises the following themes:

- Fundamental transformation required: *‘We need to build a new energy infrastructure, fit for the 21st century’.*
- Primacy of energy security: *‘energy security has to be the first priority – it is fundamental to the health of our economy and the lives of our people’.*
- Cost-effectiveness as the critical imperative in decarbonisation: *‘Our most important task is providing a compelling example to the rest of the world of how to cut carbon while controlling costs’.*
- Reliance on market-based system with declining government intervention: *‘We want a consumer-led, competition focussed energy system’.*
- Intervention reserved for energy security: *‘moving to a new model without risking energy security will require government to continue to intervene’.*

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<sup>1</sup>Rt Hon Amber Rudd MP, ‘A new direction for UK energy policy’, 18 November 2015. Available online at: <https://www.gov.uk/government/speeches/amber-rudds-speech-on-a-new-direction-for-uk-energy-policy>.



- Innovation and openness to new models: *‘Locally-generated energy supported by storage, interconnection and demand response, offers the possibility of a radically different model’.*
- Increasing intelligence and ‘smart’ technology: *‘A fully smart energy system could help us to reduce costs by tens of billions of pounds over the decades ahead’.*
- Encouraging and facilitating new business models in the energy sector: *‘Innovative, new suppliers, which range from start-ups to local authorities, are demonstrating how competition is working for people’.*

These themes are consistent with the government withdrawing from making technology choices, but instead providing a sophisticated open platform and rich enabling architecture on which technologies, innovators and new business models can compete to meet energy system objectives cost-effectively. The project aims to identify the technical functions in the power system required to meet these policy aspirations.

The FPSA project was proposed following a series of studies and stakeholder consultations undertaken by the IET Power Network Joint Vision (PNJV) expert group. In initiating the FPSA project, Prof John Loughhead (DECC) has provided clear instructions to the governance and delivery teams on the required outputs of the project as follows:

*‘What is needed now from this project is to **clearly articulate and provide evidence** for the **specific functions** which will need to be undertaken to **address these challenges**, and why any might not be done under the current system. We are not looking for an exhaustive, detailed study of current systems or a detailed design of a future system, but to understand what **new technical functions** may need to be performed in the light of **current assumptions and practices** and their evolution towards a **secure future system**. The focus should be firmly on the **actual tasks to be undertaken**, and exclude what institutional form they should take; in simple terms to identify exactly what needs doing and approximately when, not the who or how. We will consider whether any institutional reforms are necessary if the findings of this project suggest we should, but that is not itself the purpose of the work.’<sup>2</sup>*

The scope of the project (the transition from the current to the future power system) and the outcomes (specific functions) and approach to be taken (evidence based with linkages to challenges, assumptions and practices) have been communicated and received clearly. Further clarification of the requirement for the FPSA project has also been provided by David Capper (DECC):

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**“What is needed now from this project is to clearly articulate and provide evidence for the specific functions which will need to be undertaken to address these challenges, and why any might not be done under the current system.”**

<sup>2</sup>‘Future Power System Architecture project’, Prof John Loughhead, communication to the IET and Workshop Attendees, 21 July 2015.

*‘The overall project should set out, and **provide evidence** for, what **functions** will need to be performed in the **future power system** as a result of its on-going **transformative change**, and by when. The over-arching goal is not an exhaustive, detailed study of current system or a detailed design of a future system. It should however consider **current assumptions and practices** and their evolution towards a **secure future system**. The project does not need to describe what institutional form those functions will need to take, or which new or existing bodies should undertake them, but should focus on what the **proposed functions** will need to achieve in order to **manage the technical challenges facing the system**.’<sup>3</sup>*

The IET PNJV expert group set out some of the most important technical challenges facing the GB power system in the context of its ongoing transformational change<sup>4</sup>. They further highlighted that not all of these might be adequately addressed through existing industry and regulatory structures. The particular challenges regarding future system architecture were further studied with the conclusion that system architecture was a major issue and that lessons could be learned from other sectors and countries on managing complex system architecture challenges in periods of transformative change<sup>5</sup>.

The FPSA project has applied structured systems engineering methods and a systematic approach to explore potential requirements for new or extended functionality in the GB power sector as it might be in 2030. The methods and approaches used in the project are outlined in an Appendix (section 17) and also supplementary documents available online (the full set of more detailed online resources are listed in the appendix in section 15). The clear project emphasis has been on functions that are whole-system in nature and so more challenging for the industry to deliver. The project has used the National Grid *Gone Green* scenario as a baseline of the energy developments in the GB system to 2030<sup>6</sup>. The project team membership, governance structures, management, wide stakeholder participation and knowledgeable contracted consultants (see the list of project participants in Acknowledgements, section 10) has produced a valuable body of evidence on the future system requirements and functions for the GB power sector in 2030 (see Appendix in section 16 for a fuller project background and a summary of the context and starting points for this project).

The GB electricity sector has responded well to many challenges in recent years including delivering higher levels of supply reliability and cost efficiency whilst managing an ageing asset base, accommodating a rapid growth in onshore renewable generation additional interconnectors to neighbouring countries, offshore generation and grids, and managing new market mechanisms. The sector has also responded well to innovation incentives and is now beginning to roll out a range of new technologies following the completion of a comprehensive and diverse range of innovation projects. The FPSA project is firmly rooted in this context (and has benefited from project team members and contributors active in this domain) but

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<sup>3</sup>David Capper, communication to FPSA Project Delivery Board, July 2015.

<sup>4</sup>IET PNJV: ‘Handling a Shock to the System’, position statement and full report, December 2013.

<sup>5</sup>IET PNJV: ‘Transforming the electricity system: How other sectors have met the challenge of whole-system integration’, October 2014.

<sup>6</sup>IET PNJV: ‘Britain’s power system (the case for a system architect)’, December 2014.

<sup>6</sup>‘Future Energy Scenarios 2015’, National Grid, 15 July 2015, available at: <http://fes.nationalgrid.com/>. The 2015 Future Energy Scenarios are used as the basis for the FPSA project and this report and all FES references in this report are to the 2015 version unless otherwise stated.

looks towards the emerging challenges (adequately explored in *Gone Green* and elsewhere) that will stretch the sector much further in adjusting to a pace, scale and nature of new developments that will impact the operation of the whole system in unprecedented ways.

In order to assure the independence of the study the IET, as a professional body, has played a key role. The Energy Systems Catapult, DECC and the IET form the Joint Sponsors Board. The IET chairs the Project Delivery Board that brings together key stakeholders to steer the work. The project has been carried out in an open way with specific efforts to ensure stakeholder participation and clear communication of outcomes and messages.

The project has addressed the four broadly accepted timeframes of activity in the power sector: investment planning, operational planning, real time and balancing, and settlement (including enabling and administrative activities) and has identified seven core drivers of functionality. As an example, the production of National Grid's Electricity Ten Year Statement<sup>7</sup> is an investment planning function. For real-time operation, balancing the supply of electricity with demand, to maintain a stable power sector, is a key function. Ensuring that the system is secure, affordable and sustainable is fundamental to the work. The project first assessed the functions across the four timeframes as they are carried out today. It then assessed the seven drivers of functionality that can be foreseen, initially through to 2030. The project methodology uses systems engineering techniques to assess the impacts of these drivers and build an evidence base to justify the need for changes and additions to the functions. In essence, the project provides a gap analysis intended to clearly highlight any changes that need to be made to the way we plan and operate the power sector, technically.

It is recognised that there are institutional, regulatory and commercial issues that need to be considered in tandem with technical functions and wider global and societal changes in any significant plan for change to the design, planning and operation of the power system. It is also understood that the inter-relationships between electricity and other energy vectors need to be considered. These wider issues can be very usefully considered from a foundation of clear understanding and consensus about the fundamental technical functions that are the focus of this project. The project has drawn out and noted important issues outside of its technical functions scope for subsequent examination. The background, context and starting points for the project are presented in more detail in an appendix (section 16).

#### **4.4 Project Context: GB power system changes, challenges and ongoing programmes**

The project has captured and assessed the fundamental challenges and changes to the GB power sector already underway, and also those emerging and anticipated. This builds on the growing evidence base that the GB power system is undergoing a significant scale of change, introducing challenges fundamental to its architecture, operation and the commercial and regulatory processes that govern it. Core reference material has included National Grid's Future Energy Scenarios (FES)<sup>8</sup>

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<sup>7</sup>Electricity Ten Year Statement' (ETYS), National Grid, 2015. Available at: <http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/Electricity-Ten-Year-Statement/>

<sup>8</sup>Future Energy Scenarios 2015', National Grid, 15 July 2015, available at: <http://fes.nationalgrid.com/>.

and System Operability Framework (SOF)<sup>9</sup> and the PNJV documents noted previously. To contextualise the technical functions and their implications presented in this report a brief summary of some of the challenges is listed and illustrated below.

Challenges that are already appearing and anticipated in the underlying structure of the GB power system (see Appendix in section 16 for further background):

- Significant and fast growing portfolio of renewables including wind and solar photovoltaic energy sources.
- Anticipated transition to electric Heat Pumps and Electric Vehicles (EVs) for sustainable heating and transportation.
- Growth of decentralised energy and the accompanying challenges for system development and operation.
- Planned roll-out of smart meters and other customer developments (e.g. community energy) providing the opportunity for enhanced customer participation in the power sector.
- Emergence of new actors, participants and stakeholders with ability to disrupt the prevailing technical and commercial arrangements.
- Authoritative scenarios and pathways pointing towards continuation of these trends in the coming 10–20 years with important implications for the development and operation of the GB system.

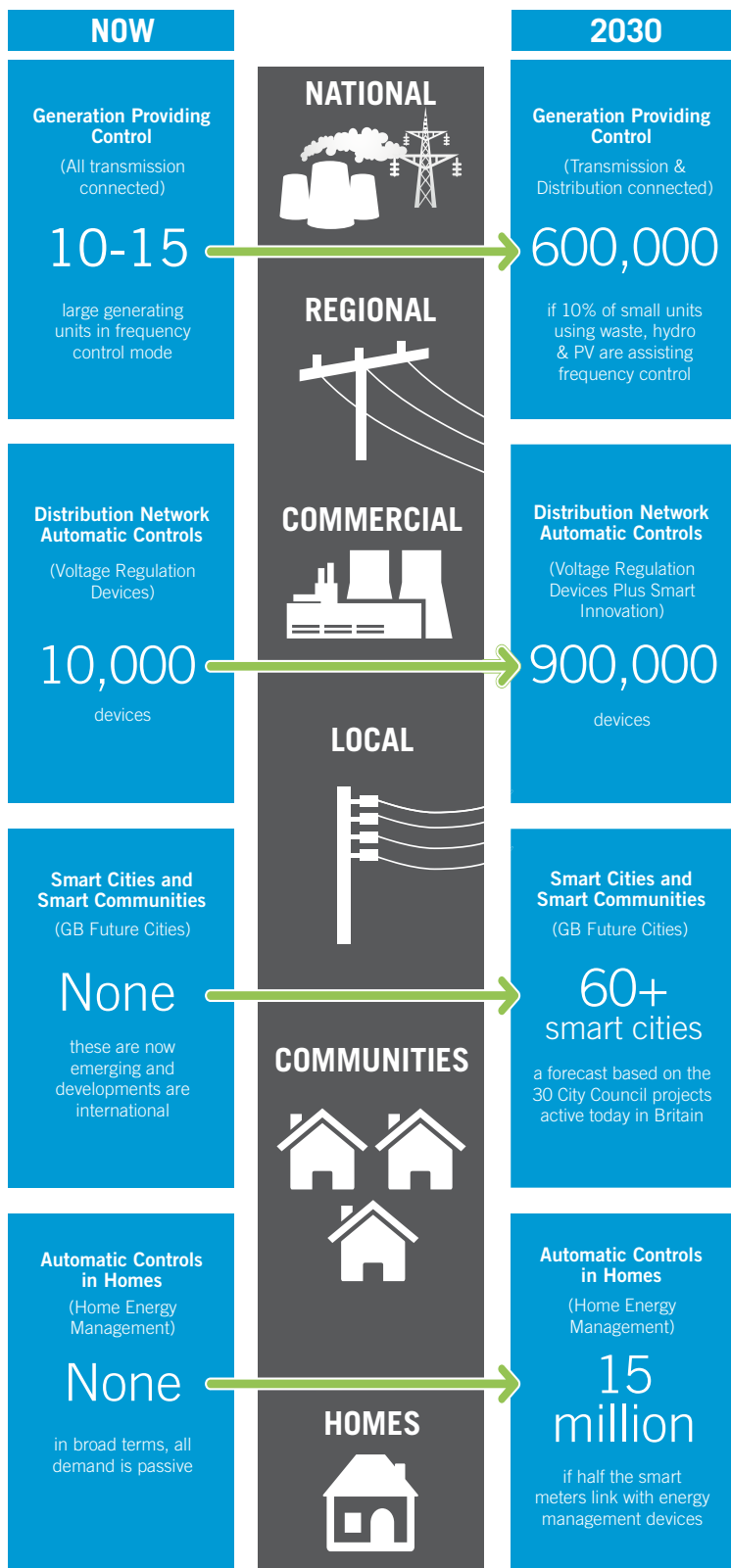
Some of the more striking and challenging of these changes to the GB power system were set out graphically by the IET Power Network Joint Vision initiative and illustrated in Figure 1 below.

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“The project has captured and assessed the fundamental challenges and changes to the GB power sector already underway and also those emerging and anticipated.”

<sup>9</sup>System Operability Framework', National Grid, 2014 and 2015, available at: <http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/>

Figure 1: IET PNJV perspective on changes facing the GB power system<sup>10</sup>



<sup>10</sup>IET PNJV: 'Handling a Shock to the System', position statement and full report, December 2013.

Additional context for the project and the challenges emerging and anticipated for the GB electricity system are set out in the Appendix in section 16.

Given these challenges there has been a plethora of initiatives and work programmes to address specific issues:

- The Committee on Climate Change (CCC) published its proposal for the fifth carbon budget covering the period 2028–2032 – 57% below 1990 levels. The CCC stresses the centrality of power systems modernisation in stating what it believe is required, and feasible, to meet decarbonisation objectives. According to the CCC's supporting material for the fifth carbon budget proposal:<sup>11</sup>
  - o *By the 2030s, around 1 in 7 UK homes are heated using low-carbon sources of energy, helping to reduce emissions significantly and drive further innovation in delivering sources of low-carbon heat.*
  - o *By the 2030s, the majority of new cars and vans bought in the UK are fully or partially electric, removing a significant proportion of emissions from transport, improving UK air quality and potentially boosting UK manufacturing.*
  - o *By the 2030s, the UK is largely powered by low-carbon sources of electricity, delivering power with emissions of below 100 grammes of CO<sub>2</sub> per kilowatt-hour (compared to 450 grammes today). Low-carbon options in the power sector are important to support emissions reduction in other sectors, such as transport and heating, as well as to reduce emissions from the power sector itself.*

An important reason to bring new functionality to the power system is to meet these demanding objectives *with the greatest efficiency*.

- Significant costs or benefits will arise from the decisions made about system flexibility and functionality. Recent work for the Committee on Climate Change showed that the cost of integrating low-carbon generation and demand-side technologies would depend significantly on the level of system flexibility. As demonstrated in the National Infrastructure Commission study, very significant cost savings can be made by increasing system flexibility, reaching £8 billion per year in 2030<sup>12</sup>.
- *Electricity Market Reform (EMR)* – has focused on the need to provide investors in new generation build and the nascent demand side response (DSR) market more certainty on their return on investment, thereby creating a more conducive environment to identify timely market signals, take calculated risks, bring forward investment in appropriate technology and provide incentives in a capacity market for DSR.
- *Ofgem Distribution Network Operator (DNO) to Distribution System Operator (DSO) review* – The fit-and-forget build of the legacy DNO network has been put under increasing strain due to intermittent generation being connected at the lower distribution voltage levels in ever increasing volumes. This has forced DNO's to start to employ similar approaches to managing their network as the Transmission System Operator (TSO). The need for more Active Network Management (ANM) on the distribution network to manage capacity, voltage and power flows has meant that DNOs are now beginning to take on the role of a DSO. The need to be able to balance locally and even employ electricity storage solutions has tested the current governance models. This review is in a very formative stage of thinking.

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<sup>11</sup>Committee on Climate Change, 'Next step towards low-carbon economy requires 57% emissions reduction by 2030'. 26 November 2015.

<sup>12</sup>Imperial College London and NERA Economic Consulting, Value of Flexibility in a Decarbonised Grid and System Externalities of Low-Carbon Generation Technologies, October 2015. [https://documents.theccc.org.uk/wp-content/uploads/2015/10/CCC\\_Externalities\\_report\\_Imperial\\_Final\\_21Oct20151.pdf](https://documents.theccc.org.uk/wp-content/uploads/2015/10/CCC_Externalities_report_Imperial_Final_21Oct20151.pdf)

- *DECC Smart Energy project* – DECC have published their thoughts on the need for a Smart Energy system<sup>13</sup> and will consult on this further this year. Consideration is being given to more fundamental changes that the FPSA project will help to inform and is noted in the report. Again, specific issues, or parts of the whole system are being considered; for instance, the possible role of an Independent System Operator (ISO) (this is often considered as transmission-only system operation). The Flexibility project will inform part of the Smart Energy project as will ongoing thinking on bringing forward and implementing more innovation. The published report confirms: ‘There also appears to be some material barriers to their [smart solutions] deployment, and Ofgem and the Smart Grid Forum have both identified specific areas for further work. As a result, over the coming year, we will work closely with Ofgem on how to manage the transition to a smarter energy system in Great Britain.’
- *DECC/Ofgem Flexibility Project* – With the retirement of large central generation due to carbon emissions and cost considerations, and the increase in intermittent or variable forms of generation, there is a realisation that future generation ‘flexing’ (the ability to turn the base load generation up or down to follow the over or under generation produced by the intermittent sources) is unlikely to be able to fulfil rapidly changing needs of the power system or its users. This is an extremely important requirement to ensure that generation and demand are kept in balance. There has been a global drive to try to access the flexibility of the consumer to respond to price signals to either turn appliances on or off and/or shift the time that they are used to meet the needs of the intermittent or variables output from certain generation sources.
- *Smart Grid Forum Work Streams* – WS1, 2, 3, 6, 7 and 9 – There have been work-streams set up to evaluate the economics of implementing a ‘smart grid’ (WS2 and 3) based on DECC’s 4th Carbon Budget scenarios and future projections of renewable generation, electric vehicles and heat pumps (WS1); there has been another to evaluate if a technical solution with a smart grid is possible with the current technologies available (WS7 – DS2030) and another current work stream (WS9) is accessing the ability of the vendor supply chain to engage and deliver into the current governance structures in order to maximise innovative solutions and competition. Meanwhile WS6 has identified seventeen high-level recommendations that are considered necessary to remove the commercial, regulatory and technical barriers to realising an efficient smart grid in GB.
- *Ofgem’s; Revenue = Incentives + Innovation + Outputs (RIIO), Network Innovation Allowance (NIA), Network Innovation Competition (NIC) and Low Carbon Network Fund (LCNF) initiatives* – have been designed to stimulate and bring forward innovative technologies and new business models to trial on the power networks in order to deliver electricity or gas customer benefits.
- *Ofgem Non-Traditional Business Model Consultations* – Due to the concern that new stakeholders and technologies are starting to appear and have a significant effect on how the grid is operated, Ofgem has consulted to see what other currently unknown disruptive business models are likely to come forward that would need support and accommodation.
- *EU Grid Code harmonisation* – The 28 Member States have their own individual standards relating to the building, running and maintenance of their own national power systems. This has led to challenges when inter-connecting between Member States or providing a supply chain that can deliver to all of them. There has been a

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<sup>13</sup>‘Towards a Smart Energy System’, DECC, December 2015. Available at: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/486362/Towards\\_a\\_smart\\_energy\\_system.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/486362/Towards_a_smart_energy_system.pdf)

European Directive to mandate harmonisation of power system technical and market codes (these are the rules that govern the physical operation of power networks) and each Member State must incorporate these into their own governance legislation. Implementation is currently in progress across Europe. The legislation is necessarily pitched at a fairly high level, in spite of the desire for standardisation, and does therefore leave room for further specification from national and international standards and hence room for national interpretation and differences.

- *National Infrastructure Commission (NIC)* – The National Infrastructure Commission will enable long-term strategic decision making to build effective and efficient infrastructure for the UK and will be established by legislation as an independent body. The National Infrastructure Commission was asked to consider how the UK can better balance supply and demand and has produced a Smart Power report<sup>14</sup>, which investigates just three aspects of this issue; inter-connection, storage and demand flexibility.
- *Security of Supply* – Analysis for the Energy Networks Association Distribution Code Review Panel Working Group (DCRP ER P2) estimates that updating current electricity distribution network infrastructure design standards and increasing the utilisation of the existing assets may deliver additional benefits of £5–10 billion by 2030<sup>15</sup>.

All of the above, along with many other initiatives that have been commissioned at various levels, some with a deep focus on specific aspects relating to the power system, others taking a broader view, have brought valuable insights into how the power system and the power sector generally will need to evolve. However, there has been little explicit and sustained consideration of the holistic impact of the findings or recommendations on those of other projects. As can be seen from the projects/initiatives above, the ability for proposed actions to impact on another area without knowledge of doing so is potentially a high risk.

The PNJV project was unique in its attempt to consider the impact of a lack of coherency across and between:

- Emerging technical and legacy infrastructure;
- Market structures and governance;
- Commercial and economic constructs and
- Societal needs or opportunities.

The PNJV project proposed that the lack of coherency could represent a major challenge in the future to ensuring a power system that was capable of delivering the required flexibility with the required security, unless there was a whole system analysis including all of these attributes. To explore this proposition further, DECC commissioned the FPSA project to analyse new and significantly changed technical functionality that would be needed in future, considered independently from the legal/regulatory/commercial/societal context that would need to be put in place to support it.

With this project background and context in mind, the next section presents the *thirty-five* new or extended functions identified through the FPSA project.

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<sup>14</sup>Smart power: A National Infrastructure Commission report', National Infrastructure Commission, March 2015. Available online at: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/505218/IC\\_Energy\\_Report\\_web.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/505218/IC_Energy_Report_web.pdf)

<sup>15</sup>Imperial College London, NERA Economic Consulting, DNV-GL, Review of Distribution Network Security Standards, DCode DCRP ER P2 Working Group, March 2015. Accessible from: <http://www.dcode.org.uk/dcrp-er-p2-working-group.html>





## 5. New Technical Functionality for the GB System

### 5.1 Summary

- *Thirty-five* technical functions have been identified, consolidated, reviewed and challenged using systems engineering methods that have helped establish robustness, coherency and a strong evidence base. This rigorous approach underpins the assertions made about the real need, feasibility, characteristics and implications of these *thirty-five* identified technical functions.
- Seven drivers of functionality have been identified in the course of analysing and consolidating the functions, and these have been developed further and are a substantive outcome of the project. The presentation of functions is organised according to these seven drivers of functionality to establish exemplars and a clear evidential link between functions and these outcomes.
- The full list of *thirty-five* functions identified is tabulated with a detailed presentation of seven representative functions in this section. Further detail is provided for all *thirty-five* functions in an appendix (section 14).
- The new or extended technical functions for the GB system have been identified in the four broadly accepted time horizons for power system activities: investment planning; operational planning; real time operation and balancing and settlement.
- Analysis of each function in this report shows that some functions are higher level in nature but still dependent on lower level technical functionality while several others are much more overtly technical in nature.

- Wide stakeholder input has been a core part of the functional identification, definition and analysis. Stakeholder engagement has included a specific consultation on the functions with 23 separate formal responses to the Functional Matrix (see 5.2 below) and 72 actioned inputs to the project. The functions are organised and presented in a structured Functional Matrix and this has enabled the evidence to be assembled and further structured analysis of the functions to be undertaken – the Functional Matrix is available as an online resource.

## 5.2 Building the Functional Matrix and identifying the drivers and functionality

The project has had a clear focus on new or extended technical functions for the GB power sector and power system in 2030. These have been assembled in a Functional Matrix which has been developed and tested throughout the project based on the application of the systems engineering principles and methods as described in section 17. The Functional Matrix is available as an online resource accompanying this report (details in an Appendix in section 15).

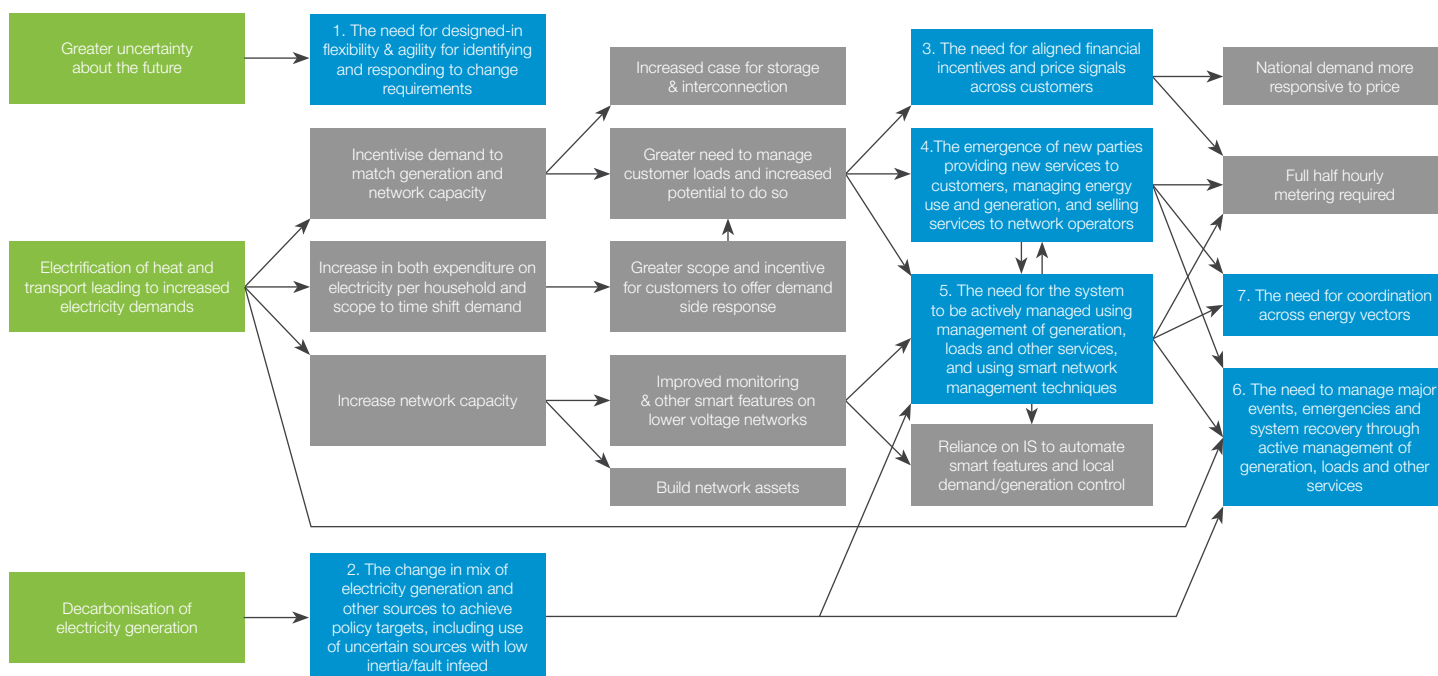
The Functional Matrix is the main source for the analysis presented in this report. It is expected that further development and analysis of the Functional Matrix may be worthwhile and this is picked up in the recommendations. To support this further development and analysis, a 'User Guide' has been embedded in the Functional Matrix.

In parallel to the identification and development of the *thirty-five* functions, seven drivers of functionality have been identified. Figure 2 (below) illustrates how the drivers of functionality were identified. The three green boxes to the left represent the ways in which the future can be expected to be different from the past: there will be greater uncertainty, there will be moves to electrify heat/transport and there will be pressure to further de-carbonise electricity production. The arrows then link to other anticipated consequences of these high level changes or potential mitigating actions and these in turn lead to seven identified drivers of functionality (the blue shaded boxes in the diagram). The *thirty-five* new or extended functions that had been identified were mapped onto these seven drivers according to the most dominant driver in each case.

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“The seven drivers of functionality form a significant outcome of the project and are a consistent thread throughout this report.”

Figure 2: Derivation of Drivers of Functionality



These seven drivers of functionality form a significant outcome of the project and are a consistent thread throughout this report. The seven drivers of functionality follow on logically from the changes in the power system and the challenges already experienced and anticipated. The analysis of the *thirty-five* functions across the timeframes and categories of activities in developing and operating a power system provides a strong evidence base for these drivers of functionality and the need to consider each seriously in any assessment of future power system architecture.

The seven drivers of functionality are described in more detail below:

**1. The enhanced need for designed-in flexibility and agility for identifying and responding to changing requirements.** The future power sector will need to be capable of identifying and responding to material changes as they emerge, including tipping points in technology uptake (e.g. domestic generation, electric vehicles) and consumer behaviours (e.g. adopting smart tariffs, automated control of appliances). The engineering challenge is to have a capability to anticipate and assess both whole-system and localised risks and opportunities and to ensure that the system architecture remains robust as these changes progress. A further requirement is to manage threats that originate outside the power sector such as cyber-attack or extreme weather events. The functions identified by this project are resilient to a wide range of scenarios and feasible evolutions of the power sector, but the timing of their tipping points will depend on many factors that will need to be continuously monitored and evaluated.

**2. *The change in mix of electricity generation to achieve policy targets, including the use of sources that are weather dependent or confer a low contribution to system stability compared with traditional sources.***

The expected change in mix of electricity generation brings with it technical characteristics (e.g. intermittency, periodicity, low inertia) that, at large scale, have the potential to reduce the inherent stability and security of the national power system. Maintaining stable voltage and frequency across the network will become markedly more challenging as coal, gas and nuclear powered plants, with the characteristic stabilising inertia of large synchronous generators, are closed and replaced with solar and wind power and more high voltage DC interconnections. New forms of stabilising inertia or ‘frequency response’ capability will be required in future. Options to provide this include contracts with user communities, use of storage, and appliances such as refrigerators equipped with the means to detect frequency variations and respond by switching on or off, or varying their power consumption. A further engineering challenge is the rise of distributed and devolved systems, and new and diverse participants. Once these sources become substantial in scale relative to the flows in the system in which they are embedded, they can become the source of network constraints, create problematic reverse power flows, cause voltage levels to rise and create sudden and unpredictable calls on the balancing of the national system. Design options to address these challenges include dynamic tariffs (for power import or export), intelligent controls on export to manage constraints and the integration at scale of distributed storage.

**3. *The emerging need for aligned incentives enabling customers to benefit from responding to price signals and the system to operate more efficiently.***

Consumers will be able to save money and contribute to decarbonisation and to keeping overall system costs down by becoming active participants in the power sector. This will require automation and whole-system insight to ensure that local benefits are maximised and not obtained at the expense of national disbenefits. Automation might, for example, ensure power is used when the costs to the consumer and the system are low or, if the consumer has energy storage, by rewarding supply of power to the system to meet local or national needs. New functions and controls are required to enable this more active participation in the power sector, enabling customers and their electrical appliances to respond to price signals that more accurately reflect marginal costs of energy production and network capacity. It will require new settlement mechanisms and contractual forms that guarantee informed consent, fairness and the protection of vulnerable customers.

**4. *The emergence of new parties providing new services to customers.*** New independent communities of energy consumers are beginning to emerge: for example, smart city developments, groups of technology users, aggregators and social enterprises. These communities may exhibit aggregated and coordinated behaviour and could play a significant role in system balancing and provide other essential services such as frequency response. On the other hand, they could have a destabilising effect, nationally or locally, if not suitably coordinated. They are now creating a new class of participants in the power sector. New functions are needed to enable such communities to engage more formally with the power sector when at large scale or aggregated. Customers will benefit from innovative new tariffs and/or contracts and smart control systems, reducing costs for customers while helping them tailor the energy usage to their lifestyle.

5. **The requirement for active management of network, generation, demand and other services using smart network techniques.** A cost-effective, low-carbon and secure power sector will need to achieve high utilisation of its assets by intelligent and responsive matching of supply and demand. The rise of intermittent generation sources, embedded generation and new loads such as heat pumps and electric vehicles presents a challenge and could be inhibited by network constraints or require costly over-engineering if addressed by passive means. The future power system will need to be more actively managed using smart technologies, storage, flexible generation and load management techniques. Benefits will ensue for customers if network constraints are actively managed and greater alignment can be achieved between demand and available low carbon/low marginal-cost generation, including through energy storage. Communication of data across the power sector will be a fundamental enabler of this new functionality and will create a material increase in opportunities, skills requirements and business challenges for the sector. The high penetration of intelligence and active management will require measurement and sharing of data at a material scale, resulting in energy networks being overlaid with communications networks and data management systems. This raises challenging and complex issues of data ownership and privacy, data-sharing protocols and information rights, data quality and reliability, responsibility and liability if damage arises, commercial abuses, contracts and informed consent, security and defence against cyber-attack. This establishes a clear need for effort to be expended in the development and application of innovative systems integration methods, frameworks, tools and skills.
6. **The challenge of managing major events, emergencies and system recovery as the power system becomes increasingly complex and more interactive with its customers.** There will be a continuing need for major power system events to be anticipated, modelled and managed, but this will become more challenging in future. Unlike today, the additional complexity of the 2030 power sector will require a whole-system perspective to secure the stability of the overall national system, while working with greater distributed and devolved energy systems and services. At present, National Grid has restart plans that are largely top-down in nature and are built on relatively few large power stations and rely on cooperation with relatively few distribution network operators. In future, restarting after a major power failure will become more complex and challenging with fewer large thermal stations available and large numbers of electric vehicles, heat pumps, smart appliances and distributed sources. In order not to destabilise the system during restarting, it will be necessary to coordinate recovery among a much larger number of parties and control the reintroduction of load, and both large-scale and distributed generation and storage.
7. **The emerging need for coordination across energy vectors.** A major pillar of UK decarbonisation strategy is the electrification of heat and transport. As the interactions between these three markets deepen, some level of coordination mechanisms will be necessary across electricity, gas, biofuels and petroleum supply to facilitate markets for power, heat and transportation, for example to optimise carbon reductions and to be resilient to price shocks or supply interruptions. Combined Heat and Power (CHP) systems, hybrid heat pumps, heat energy storage and heat networks each have a potential role to play in the

functioning of the power sector and in optimising energy usage across vectors. This further increases the importance of understanding how data will need to be gathered and exchanged. These interactions will involve bringing together parties new to each other and create a significant increase in technical and commercial complexity.

The full list of the *thirty-five* new or extended functions identified by the FPSA project is presented in Table 1 to Table 7 according to the seven drivers of functionality and identifying each function with the relevant power system timeframe (investment planning, operational planning, real time and balancing and settlement).

**Table 1: New or extended functions – The enhanced need for designed-in flexibility and agility for identifying and responding to changing requirements.**

*Comments in italic have been included to provide context and clarity.*

Function	Timeframe
Enable the power sector to respond readily to change and ensure the timely introduction and implementation of new functions <i>This requires significant enhancement to the capabilities of today</i>	Investment Planning
Identify, counter and learn from threats to operability of the power sector from all parts of the power sector both above and beyond the meter <i>There is little or no visibility available today for these threats</i>	Investment Planning
Monitor the impact of customer needs on system operability and propose solutions as necessary <i>More active and engaged customers will have new requirements, unlike any seen today</i>	Investment Planning
Identify and counter cyber threats to operability of the power sector originating from inside and outside the power sector <i>There will be many new parties and automated systems relying on data</i>	Investment Planning

**Table 2: New or extended functions – The change in mix of electricity generation to achieve policy targets, including the use of sources that are weather dependent or confer a low contribution to system stability compared with traditional sources.**

*Comments in italic have been included to provide context and clarity.*

Function	Timeframe
Provide a mechanism to ensure the portfolio of generation and other dispatchable energy resources and ancillary services delivers carbon, security of supply and affordability policy objectives <i>Mechanisms that support a whole-system perspective will become critical in a more highly distributed and devolved sector</i>	Investment Planning
Plan for the timely restoration of supplies following a national failure (Black Start) <i>Black Start will become very much more challenging</i>	Investment Planning
Enable settlement for all existing customer profile classes to support flexible tariffs <i>This will be key to gaining consumer engagement, however it is a non-trivial task at national scale</i>	Settlement

Table 3: New or extended functions – The emerging need for aligned incentives enabling customers to benefit from responding to price signals and the system to operate more efficiently.

*Comments in italic have been included to provide context and clarity.*

Function	Timeframe
Collate and distribute information throughout the power sector on the availability and performance of the portfolio of generation and other dispatchable energy resources and ancillary services, and any associated operational restrictions <i>The number of parties and technologies involved make this a demanding data service</i>	Operational Planning
Collate and distribute information throughout the power sector on the performance of demand, the portfolio of generation and other dispatchable energy resources and ancillary services in order to enable settlement <i>Commercial implications will add challenge to implementing and maintaining data systems of suitable quality</i>	Settlement
Provide aligned financial incentives across the power sector including through innovative or flexible tariffs <i>A whole-system perspective is needed to avoid local sub-optimisation in the sector</i>	Settlement
Provide a mechanism for peer-to-peer trading with appropriate charging for use of the power network <i>Community Energy and Smart City developments are seen to be likely drivers here</i>	Settlement
Monitor and settle the delivery of contracted demand, the portfolio of generation and other dispatchable energy resources and ancillary services <i>This requires material change to today's arrangements so that more active customers and distributed systems can be integrated</i>	Settlement

Table 4: New or extended functions – The emergence of new parties providing new services to customers.

*Comments in italic have been included to provide context and clarity.*

Function	Timeframe
Provide the ability to move between different modes of overall operation in the event or threat of a system emergency <i>This will require multi-party agreement, careful definition of the mode changes, periodic testing, and updating for new developments</i>	Investment Planning
Provide mechanisms by which planning can be coordinated between all appropriate parties to drive optimisation, with assigned responsibility for security of supply <i>This will require joint development and agreement, including many parties who are new or do not currently work closely together in the sector</i>	Investment Planning
Collect outage information from all parties of significance within the power sector, coordinate with affected parties, identify clashes and resolve, with assigned responsibility for security of supply <i>There is potential complexity here where resolving clashes has commercial implications</i>	Operational Planning
Provide an operational planning process that engages with all affected stakeholders <i>In a time of change this will be a 'moving target' and need continual and careful management</i>	Operational Planning
Coordinate the roles and value propositions of all significant stakeholders across the power sector <i>Potential commercial interaction between parties adds to the challenge here</i>	Settlement
Provide a market process that facilitates active engagement of customers <i>This will require new developments, especially for domestic customers and small enterprises at scale</i>	Settlement
Provide a full range of customer choices including individual, community and smart city services <i>Entirely new services need to be defined and accommodated, most likely with continual change</i>	Settlement

Table 5: New or extended functions – The requirement for active management of network, generation, demand and other services using smart network techniques.

Comments in italic have been included to provide context and clarity.

Function	Timeframe
<p>Forecast all demand, generation and other dispatchable energy resources and ancillary services within the power sector</p> <p><i>These will be much less predictable than experienced in today's sector</i></p>	Investment Planning
<p>Ensure that monitoring is in place to support the use of active system management</p> <p><i>Measurement must be accompanied by data, communications, and sharing to agreed performance standards</i></p>	Investment Planning
<p>Use smart technologies to maximise the capacity of the power sector to accommodate the connection and integration of new demand, generation and other dispatchable energy resources and ancillary services</p> <p><i>The potential for smart solutions has been demonstrated but BAU application requires on-going attention</i></p>	Investment Planning
<p>Review the power system's developing operational characteristics to validate the assumptions made during the investment planning process</p> <p><i>In times of change, monitoring of performance is key to detect any deterioration before it causes local or wider disruption</i></p>	Investment Planning
<p>Forecast and model all generation and other dispatchable energy resources and ancillary services with operational, cost and security implications for the power sector</p> <p><i>This becomes a significant challenge as many new parties and technologies become involved</i></p>	Operational Planning
<p>Enable the dispatch of the portfolio of generation and other dispatchable energy resources, of demand, and of ancillary services within the power sector to deliver system security and maximise the use of low carbon generation at optimal overall cost</p> <p><i>This is likely to require a careful blend of technical and commercial solutions</i></p>	Operational Planning
<p>Identify by modelling and simulation constraints arising from credible events/faults and plan remedial action</p> <p><i>This requires an overhaul of today's analytic tools, data sources, and co-ordination</i></p>	Operational Planning
<p>Identify available generation and other dispatchable energy resources and ancillary services and associated operational restrictions in real time</p> <p><i>This will require significant new data collection, communications and open systems agreements</i></p>	Real Time & Balancing
<p>Monitor the effectiveness of, and execute as required, remedial action for the delivery of demand control, generation constraint and other actions in response to all events/faults</p> <p><i>This will involve multi-party new models, data sharing and agreed operational policies</i></p>	Real Time & Balancing
<p>Coordinate demand, generation and other dispatchable energy resources and ancillary services within the power sector to deliver system security and maximise the use of low carbon generation at optimal overall cost</p> <p><i>This is challenging within itself but will also need to accommodate new 'DSO' parties alongside the GB System Operator (GBSO)</i></p>	Real Time & Balancing
<p>Provide monitoring and control of those parts of the system under active management, including network assets, demand, generation and other dispatchable energy resources and ancillary services</p> <p><i>This will require a significant increase in scope and scale of real-time facilities and agreement on open systems for data exchange</i></p>	Real Time & Balancing
<p>Provide automated and secure management of demand, generation and other offered energy resources and ancillary services, including Smart Appliances, Home Energy Management System (HEMS) and Building Energy Management Systems (BEMS)</p> <p><i>This new functionality will require continual validation to ensure security</i></p>	Real Time & Balancing



Table 6: New or extended functions – The challenge of managing major events, emergencies and system recovery as the power system becomes increasingly complex and more interactive with its customers.

*Comments in italic have been included to provide context and clarity.*

Function	Timeframe
Plan for the timely restoration of supplies following a prolonged local failure (Cold Start) <i>This is a serious new challenge for service delivery to customers and differs from Black Start</i>	Investment Planning
Enable the delivery of demand control, generation constraint and other actions in response to all extreme events <i>The extended functionality will require continual validation to ensure security</i>	Real Time & Balancing

Table 7: New or extended functions – The emerging need for coordination across energy vectors.

*Comments in italic have been included to provide context and clarity.*

Function	Timeframe
Assess the impact of gas and other energy vectors when forecasting the volumes of demand, the portfolio of generation and other dispatchable energy resources and ancillary services on the power sector <i>New modelling capabilities will be needed here, with data exchanges between parties who may be new to each other</i>	Investment Planning
Collaborate with other energy sectors to optimise across multiple sites and vectors <i>This will require data exchanges, validation and resolution of disputes, across new commercial interfaces</i>	Settlement

These *thirty-five* functions are also aligned diagrammatically with the seven drivers of functionality and colour-coded by power system activity timeframe (Green for Investment Planning; Light Grey for Operational Planning; Dark Grey for Real Time and Balancing; Blue for Markets and Settlement) as illustrated in Figure 3 to provide a more visual presentation.

Figure 3: Functions by Driver and Timescale.

**Note** - the number preceding the text in the coloured boxes below is the related function number, which can be found in the functional matrix

1. The need for designed-in flexibility & agility for identifying and responding to change requirements.	2. The change in mix of electricity generation and other sources to achieve policy targets, including use of uncertain sources with low inertia/fault infeed.	3. The need for aligned financial incentives and price signals across customers.	4. The emergence of new parties providing new services to customers, managing energy use and generation, and selling services to network operators.	5. The need for the system to be actively managed using management of generation, loads and other services, and using smart network management techniques.	6. The need to manage major events, emergencies and system recovery through active management of generation, loads and other services.	7. The need for coordination across energy vectors.
0.1 Enable the power sector to respond readily to change, and ensure the timely introduction and implementation of new functions.	1.1 Provide a mechanism to ensure portfolio of generation and other dispatchable energy resources and auxiliary services delivers carbon, security of supply, and affordability policy objectives.	6.1 Collate and distribute information throughout the power sector on the availability and performance of the generation and other dispatchable energy resources and auxiliary services, and any associated operational restrictions.	2.4 Provide the ability to move between different modes of overall operation in the event or threat of a system emergency.	3.2 Forecast all demand, generation and other dispatchable energy resources and auxiliary services within the power system.	2.3 Plan for the timely restoration of supplies following a pro-longed local failure (Cold Start).	3.1 Assess the impact of gas and other energy vectors when forecasting the volumes of demand, generation and other dispatchable energy resources and auxiliary services on the power system.
2.1 Identify, counter and learn from threats to operability of the Power System from all parts of the power sector both above and beyond the meter.	2.6 Plan for the timely restoration of supplies following a national failure (Black Start).	14.2 Collate and distribute information throughout the power sector on the performance of demand, generation and other dispatchable energy resources and auxiliary services in order to enable settlement.	5.1 Provide mechanisms by which planning can be coordinated between all appropriate parties to drive optimisation, with assigned responsibility for security of supply.	3.3 Ensure that monitoring is in place to support the use of active system management.	13.1 Enable the delivery of demand control, generation constraint and other actions in response to all extreme events.	15.4 Collaborate with other energy sectors to optimise across multiple sites and vectors.
2.2 Monitor the impact of customer needs on system operability and propose solutions as necessary.		15.1 Provide aligned financial incentives across the power sector, e.g. innovative or flexible tariffs.	7.1 Collect outage information from all parties of significance within the power sector, coordinate with affected parties, identify clashes and resolve, with assigned responsibility for security of supply.	4.1 Use smart technologies to maximise the capacity of the power system to accommodate the connection and integration of new demand, generation and other dispatchable energy resources and auxiliary services.		
2.5 Identify and counter cyber threats to operability of the Power System originating from inside and outside the power sector.		15.2 Enable settlement for all existing customer profile classes to support flexible tariffs, e.g. half hourly using smart or advanced meters.	9.1 Provide an operational planning process that engages with all affected stakeholders.	5.2 Review the power sector's developing operational characteristics to validate the assumptions made during the investment planning process.		
		15.5 Provide a mechanism for peer to peer trading with appropriate charging for use of the power system.	15.3 Coordinate the roles and value propositions of all significant stakeholders across the power sector.	8.1 Forecast and model all generation and other dispatchable energy resources and auxiliary services with operational, cost, and security implications for the power sector.		
		16.3 Monitor and settle the delivery of contracted demand, generation and other dispatchable energy resources and auxiliary services.	16.1 Provide a market process that facilitates active engagement of customers, e.g. aggregators, smart city schemes.	8.2 Enable the dispatch of generation and other dispatchable energy resources and auxiliary services within the power system to deliver system security and maximise the use of low carbon generation at optimal overall cost.		
			16.2 Provide a full range of customer choices including individual, community and smart city services.	9.2 Identify by modelling and simulation constraints arising from credible events/faults, and plan remedial action.		
				10.1 Identify available generation and other dispatchable energy resources and auxiliary services and associated operational restrictions in real time.		
				11.1 Monitor the effectiveness of, and execute as required, remedial action for the delivery of demand control, generation constraint and other actions in response to all events/faults.		
				11.2 Coordinate demand, generation and other dispatchable energy resources and auxiliary services within the power system to deliver system security and maximise the use of low carbon generation at optimal overall cost.		
				12.1 Provide monitoring and control of those parts of the system under active management, including network assets, demand, generation and other dispatchable energy resources and auxiliary services.		
				14.1 Provide automated and secure management of demand, generation and other offered energy resources and auxiliary services, including Smart Appliances, HEMS and BEMS.		

**Key: Time Scale**

Investment Planning
Operational Planning
Real Time & Balancing
Markets & Settlements

### 5.3 Seven functions representative of the challenges and issues facing the GB system

This section provides a detailed description of seven functions. These seven functions, one from each of the seven drivers of functionality identified in 5.2 above, represent a number of different challenges across the four power system activity timeframes. It should be noted that some functions (in the full set of *thirty-five*) may appear similar but this is because they are applicable to different power system timeframes, for example investment planning, operational planning and possible real-time. This is necessary to make sure that the important differences between these related functions are clearly captured and also since the implementation and responsibilities for these functions at different timeframes might reside with different entities.

These seven selected functions are intended to provide a representative and balanced perspective of the issues associated with the full set of *thirty-five* functions identified. The full set of *thirty-five* functions is presented in an appendix (section 14). Note that the function reference number shown in brackets is taken from the Functional Matrix and is provided to enable the reader to refer to the function in the Matrix should they wish to do so.

**Function:** Enable the power sector to respond readily to change, and ensure the timely introduction and implementation of new functions [Function 0.1].

**Function Timeframe:** Investment Planning.

#### **Background**

The power sector has an overall structure that was assumed in law in the 1989 Electricity Act. The Act took the existing highly centralised sector and effectively codified it. So the law expects there to be (generally) only licensed operators generating, supplying, transmitting and distributing electricity. Customers are passive takers of a service. Provision was made for changes to technical and commercial requirements through the licences of operators, and through the industry's codes.

Any changes in society or the sector that do not fit into the current, evolved, structure of the sector are difficult to implement and often require complex code changes, and sometimes even licence or changes to legislation. The current difficulties of the emergence of storage technologies illustrate some of these challenges: nascent technologies are on a trajectory to be economically viable, but the structure of the industry effectively prevents some of the early value propositions from the technologies being realised.

#### **Drivers for new functionality**

The power sector is one of the biggest components of infrastructure that impacts climate change through carbon emissions. The environmental requirements of UK society are currently driving huge change in the power sector, particularly exemplified by the growth of solar photovoltaic (PV) generation and the profound effect that this is having on current power system operations. Another example is the current rapid retirement of thermal power stations, giving rise to significant system operation issues in terms of voltage management, inertia and stability. These current challenges are

being managed by the sector, helped by the inherent and historic capabilities of a well specified power system, but hindered to some extent by lack of foresight and overall planning. Technological and socio-political developments are likely to require accelerating change as to how the power sector responds to these emerging needs. The legacy flexibility of the system cannot be taken for granted, and solutions at scale will, in many cases, take years to implement.

As the future is expected to only provide an increased rate of change and development in technology and customers' needs and expectations, the demands for change placed on the power sector will increase and become more critical. The technology developments are right across the sector, from new aspects of high voltage (HV) DC interconnection with neighbouring systems, to the facilities built into mass market goods used in millions of homes. All these technologies will be part of the Internet of Things.

### **Required functionality**

To avoid frustrating efficient developments across the power sector, it will be necessary to continuously review the current ambitions for the sector, likely future developments, current and future operating environment, policy objectives and likely customer requirement developments. An assessment of the technical capability of the power system and the development path of the sector to meet these requirements should then be made. Such assessment should take account of:

- Government policy objectives – environmental and social are obvious, but the whole spectrum needs considering. For example, policy in respect of telecommunications, data, cyber issues are all likely to have effects on the power sector; some could be profound. The modern power system relies on a mixture of private and commercial telecommunications infrastructure. The growth of smart grids will make increasing use of commercial communications services (even accepting the existence of the smart metering infrastructure). Changes to the systematic behaviour of smart appliances served by such communications based on government or other policy changes could be a threat to the secure operation of the power system. Furthermore, examples of commercial decision-making to withdraw (telecommunication) services have had major cost implications and design considerations that were not foreseen by the electricity utilities. In the future a clarity about the integration between different sectors and which regulator is responsible for which policy area will be more and more difficult to ensure.
- Technological and social change – the interconnected nature of the future means that there is more possibility of unintended simultaneous behaviour across large numbers of devices, which jeopardises the security of the power system.
- Overall systems engineering – there are intelligence and control systems built into all devices connected to the system, including large generators, interconnector converter stations, power system components (e.g. substation equipment), industrial processes, new wind and PV farms, domestic generation, energy storage and modern appliances and devices. All of these have the capability to interact in new and unexpected ways. Appropriate oversight, with clear accountability, will need to be maintained such that likely or emergent threats to stable operation of the system can be considered and mitigated.

- Governance – since the power system operates as if it is a single large ‘machine’, its governance should be such that threats in the very short term (operational planning) or in real time are prevented. This may require specific limits to be applied to what customers of the system want to do. Such actions in the very short term are desirable and necessary for secure system operation. However, the flip side is that those desires should be recognised and accommodated as quickly and efficiently as possible. This requires a flexible and coordinated governance system that is well informed, engaged and inclusive.

### **Implementation**

The objective of the above suggested assessment is not to determine future detailed requirements but to ensure that technical, commercial or other governance issues are sufficiently dynamic and flexible to accommodate their development and deployment. This will need careful oversight from a position that allows all parts of the whole system analysis to be in receipt of the relevant data, information and authority to inform the decisions in different parts of the energy sector. An early example of activity in this area is the development of the System Operability Framework by National Grid as GBSO.

### **Requirements for further research, development and innovation**

The above calls for further research and development, both within and outside the sector. An example is advanced control systems, which will address the balance the use of centralised versus distributed control mechanisms enabled by componentry such as enabled power equipment, power electronics and sophisticated data management and communications. Outside the sector, R&D will drive many of the possibilities for technological and social change and could provide some appropriate early indications of likely future stress points for the sector. Similarly, recognised developments and challenges in the sector will need to have appropriate solutions brought forward and an effective R&D programme within the sector will need to be appropriately supported.

**Function:** Plan for the timely restoration of supplies following a national failure (Black Start) [Function 2.6].

**Function Timeframe:** Investment Planning.

### **Background**

A system Black Start capability is an essential provision to enable electricity supplies to be restored in a systematic way in the unlikely event of a total system shutdown. System Black Start capability is governed through the Grid Code and regularly reviewed to ensure fitness for purpose. It involves coordinated action by all the parties in the power system supply chain. Reviews take account of many factors including: the changing generation portfolio, electricity consumption patterns, the resilience of telecommunications systems (including battery back-up) and the ability of power stations to recommence generation with the external system de-energised. Black Start plans are based on a planned sequence of restoration of supplies on a staged basis as generation, starting with designated ‘Black Start’ stations, is gradually brought back on line and networks are re-energised in selected load blocks, to create temporary power islands prior to full restoration of the transmission system. In terms

of timescales, Black Start stations would typically be operating at full output after 18 hours and whilst the transmission system might be re-energised over a period of typically 12 hours (subject to controlling voltage due to reactive power imbalance) the availability of supplies to DNOs for reconnecting customers will depend on the status of Grid Supply Point substation auxiliary supplies. There are significant technical challenges in rebuilding load on the transmission system: a lightly loaded transmission system during a restart is inherently much less stable than one that is fully interconnected and operating under normal loading conditions.

Any degradation in Black Start capability in terms of the time to re-energise the transmission and distribution networks, bring demand back on line, and achieve full restoration of supplies will be unacceptable, especially given the future increased reliance on electricity for private transport and home heating, mobile phone communications and the internet. Indeed, recent events in the North West of England have revealed the level of modern society's dependence on electricity, and the disruption that occurs in the event of a prolonged supply interruption over a wide area.

The generation portfolio (and the plants that are likely to be running at any given time of day and year) is a critical factor in terms of how a Black Start sequence would be effected, including the time necessary to re-energise the whole system and remove any constraints on demand. For example, xenon poisoning would mean that nuclear plant would not begin to come back on stream for over 24 hours or return to full production for several days, whilst wind and solar PV generation availability will be dependent on weather conditions. Under current winter peak demand conditions, there is the potential for some demand to remain unserved for around 60 hours following shutdown, though some 80% of demand at time of winter peak would be expected to be restored within 30 hours. The impact of unserved demand on consumers would be mitigated through constraint on discretionary (non-essential) demand, the use of standby generation as available and the use of rota-disconnections if necessary.

### **Drivers for new functionality**

Going forward, there are several factors that will have a material impact on how Black Start is effected under future generation and demand scenarios, including under a Slow Progression scenario, but particularly under a *Gone Green* or Consumer Power scenario:

- The fact that the future generation mix is expected to be dominated by non-synchronous generation, which results in lower system inertia, and therefore lower system stability, risking a shutdown and failure during the restart process.
- The growing proliferation of microgeneration that has the effect of creating latent demand – i.e. demand, which is not normally supplied by the transmission and distribution systems (at least during daylight hours in the case of solar PV) and which is both uncontrollable and largely invisible to the system operators.
- The increasing level of Distributed Generation (DG) that will remain either de-energised or disconnected from the distribution system following a total system shutdown, which also creates latent demand from a whole-system perspective.

- The extent to which DG, prior to being resynchronised with the national system, is capable of relieving demand from the wider system by supplying or supporting local power islands.
- Mass deployment of heat pumps and EV charging, which in future will increase the level of demand to be restored and (depending on weather conditions and the length of the supply interruption) present zero diversity when re-energised and until normal cycling is restored.
- The reduced availability of warm thermal generating plant that can be brought on load quickly, especially under light demand conditions and/or when wind and/or solar PV generation output is high and few Combined Cycle Gas Turbine (CCGT) stations will be on-line. By 2030, under a *Gone Green* or Consumer Power scenario, less than 2 GW of traditional thermal plant might be running during periods of minimum load. Thermal generating plant has the inertia and other operating characteristics most suited to re-energising an unstable, lightly-loaded transmission system. At present, the bulk of the stations equipped to initiate a Black Start are coal or gas fired.
- The need to ensure adequate system stability is retained as generation is brought back on stream, the system is gradually re-energised, and load is progressively restored: this might for example limit the reconnection of available wind or solar PV generation until sufficient thermal plant (e.g. CCGT stations) has reached stable operating conditions.
- The availability of new nuclear plant: out of all synchronous generation resources, new nuclear power plant is expected to be uniquely available at all times and across all Future Energy Scenarios (FES) scenarios (SOF 7.4.1.4. states that under Grid Code provisions, new nuclear build should be capable of islanding with a load of at least 55% of its registered MW capacity).

### **Required functionality**

This function meets the requirement to have a Black Start capability under all credible future 'real time' generation portfolio and demand scenarios, and addresses the material changes that are needed to enable Britain's system Black Start capability to be able to continue to deliver timely restoration of supplies following a total system shutdown. A critical factor going forward will be how frequency is regulated between designated Black Start stations and distributed generation following the restoration to any block of load. If the DG protection and control responses are not appropriately specified this may lead to instabilities in the temporary power islands when frequency and voltage can be expected to vary beyond limits defined in the Grid Code and Security and Quality of Supply Standard. DG and microgeneration protected by G59/G83 over/under frequency protection might repeatedly disconnect and reconnect, exacerbating frequency variations within the power island and creating a hunting condition that might ultimately result in loss of the power island forcing multiple attempts to restart.

### **Implementation**

It follows from all the above that there will be many challenges associated with the availability of traditional Black Start resources. The implementation challenges arise from the greater degree of coordination required across the power sector and the wider distribution of energy sources that will need to play a future role in providing Black Start services. This can be expected to require licence and code changes.

The coordination of self-dispatching generation managed by Energy Communities will be critical but complex, requiring a new level of information sharing across investment planning, operational planning and real-time timeframes. Further measures will also be required to review DG protection in relation to block load instability concerns, to ascertain the role that energy storage might play and the role that DNOs might play in a future bottom-up Black Start system restoration. Consideration will also need to be given to the telecommunications infrastructure that will be required to function during this process.

### **Requirements for research, development and innovation**

Transmission System Operators within ENTSO-e (European Network of Transmission System Operators for Electricity) are driving the creation of an Emergency and Restoration Code, which seeks to standardise best practice process in the management of inter control area Black Start. Another objective of this code is to complement the Cooperation of Electricity System Operators (CORESO) security assessment role, with clarity of the ability of various power islands developed as part of an emergency restoration scenario to reenergise external grids. In GB, the Voltage Source Converter (VSC) High Voltage Direct Current (HVDC) links between Ireland and Mersey and continental Europe could form part of a Black Start approach. So although there is a new legal imperative to address one aspect of the issue, there remains the need to design and implement practical mechanisms across a wide range of stakeholders and across current governance bodies, and for the provisions to change as the sector itself continues to change. The complexity and importance of this issue indicates that ad hoc mechanisms will be inadequate.

**Function:** Provide a mechanism for peer to peer trading with appropriate charging for use of the power system [Function 15.5].

**Function Timeframe:** Markets and Settlement (but applies in all timeframes).

### **Background**

The power sector has an overall structure that was assumed in law in the 1989 Electricity Act. The Act took the existing highly centralised sector and effectively codified it. So the law expects there to be (generally) only licensed operators generating, supplying, transmitting and distributing electricity. Customers are passive takers of a service; they are not expected to trade with anyone apart from licensed suppliers.

### **Drivers for new functionality**

Many current factors make this structure inappropriate for the future. Taking two of these, the growth of domestic scale generation provides an opportunity for its domestic owners to seek the most advantageous commercial terms for its production and similarly the growth of communities interested in becoming self-sufficient, or other objectives, in energy provides a spur for novel energy trades. The rest of the description of this function assumes that existing commercial and economic approaches do not block the development of Peer-To-Peer Traders (PTPT).

Elaborating on the above, there is no reason, for example, why a family having the ability to generate more solar electricity than it consumes should not sell its output



to other customers of its choice, for example the school (or even university) that its children attend. Equally, a group of consumers with solar PV generation could form a community trading with another community perhaps with a different generation technology such as a local wind farm, in which case surpluses might occur at different times. If either community had a storage facility that would release further options. Clearly, there are many economic and commercial issues associated with the development of such trades. However, if the motivation, whatever the driver, is strong enough the power sector will have to accommodate these trades.

In the current power sector, if such trades were to occur in a minor way with only a few instances, the effect will be invisible, i.e. business as usual. However, if this becomes an activity of any significance it has the ability to disrupt the operation of local and national networks unless the activity is appropriately coordinated. At scale this will have profound effects on networks. For example, any number of physical parties could group together to become a single PTPT entity, and indeed merge into a community energy scheme. Power flow management between the PTPT and DNOs' (and GBSO's) systems will need to accommodate all the appropriate variations. It is also a working assumption that the ingenuity and drive to create such trades will also create appropriate management tools for those trading to forecast, to plan and to manage the trades in real time. It is most unlikely that such trading, if it is to become a significant feature of the sector, will rely much on human intervention.

### **Required functionality**

This function will need to allow a variety of systems that peer-to-peer traders (PTPT) have to adopt to interface with the management systems used by the rest of the sector. It is most likely that the prime interface will be with local DNOs – although of course these trades might well cross the asset boundaries of one or more DNOs. From an operational perspective, DNOs (including 'independent' DNOs) do not yet have advanced systems for managing active distribution networks. This is currently development work in progress, with the marrying of energy management systems and distribution network management systems starting to appear in the market for distribution control systems. It is not obvious that a single interface design would be appropriate or desirable, but there needs to be a set of open standards created for interfacing PTPT activities to DNO systems. It is also a current expectation that DNOs' systems will aggregate all such activities in planning timeframes (and in real time in the case of actively managed networks) and communicate appropriately with the GB transmission system operator's management systems and with those of other DNOs, appropriately. It is worth noting that these systems may also need to cover other large users who are not engaged in PTPT, but whose variations in load could affect the operation of the network.

The interfaces described above are based on the technical need to predict, understand and ultimately control flows of power. However, there is an equal need to develop systems for dealing with the commercial consequences and effects. A particular challenge here will be designing trading systems that ensure appropriate sharing of costs between PTPT and non-PTPT parties. For example, PTPT parties might reasonably claim that power flows do not extend to the transmission system, nor necessarily beyond the local Low Voltage (LV) distribution system. As such, it might be considered appropriate for PTPT Distribution Use of System (DUoS)

(only) charges to be based on a smaller subset of the distribution network. On the other hand, there are likely to be times when local generation within a PTPT group is unavailable or insufficient to meet the PTPT group demand. DUoS charges will therefore need to embrace the provision of top-up and standby services. Interfaces will need to be two-way, with a flow of PTPT intentions matched by a flow of price information the other way. Coordination will be needed to establish open systems. Intended PTPT activity should be appropriately influenced by the cost of accommodating those flows both in terms of network effects and legitimate cost effects on other users of the power system. Revised PTPT planned activity will then need to be recommunicated to the power sector. All such trades might involve iterative planning loops to determine the economic level of trade PTPTs wish to conduct.

### **Implementation**

The key challenges for PTPT are developing and implementing the open standards for interfaces between PTPT parties and DNOs, and also for the interfaces between PTPT parties and other settlements systems. PTPT can design whatever trading systems they want to use between themselves, but it will be necessary to allow for settlements overall and payment for any network services etc. that support the PTPT activities. These requirements suggest a more comprehensive level of metering to establish temporal traded volumes for reconciliation with the overall settlements system.

### **Requirements for research, development and innovation**

There is a significant requirement for development of systems integration methods and technologies to address this function. For the interaction between DNOs' systems, settlements systems and PTPT systems further research, development, deployment and end-to-end testing will be necessary in order to detect any potential malfunctions, adverse interactions or suboptimal outcomes, and hence determine the necessary standards, specifications and codes of practice that will need to be implemented.

**Function:** Collect outage information from all parties of significance within the power sector, coordinate with affected parties, identify clashes and resolve, with assigned responsibility for security of supply [Function 7.1].

**Function Timeframe:** Operational Planning.

### **Background**

The planning of network outages within the power sector historically has been an almost exclusive preserve of transmission and distribution system operators, ranging from extensive contingency analysis for transmission and higher distribution voltages, to basic load checks at 11 kV and just assumptions at LV.

For transmission systems the effect on load flows and other technical parameters is studied in detail for all critical load periods during the outage, with the key contingencies for other forced outages analysed. The studies can be extensive and may take hours or days to plan and execute. These studies depend critically on forecasts of demand and generation that historically have been known and/or

predictable. The same approach has been taken on 132 kV systems and on 33 kV systems with the complexity of analysis becoming proportionally less given the scale of the impact of events during the outages and the limited effect at lower voltages on overall system stability. At 11 kV the planning is generally much simpler and based on a few simple measurements of loadings and, at LV, because DNOs have historically had no telemetry on the LV system, any planning or consideration has been based solely on assumptions.

Given the historic slow change in the networks, network companies have come to know where the pressure points are and have generally tailored the depth of study depending on the known stress on the networks at relevant points. The companies have made a virtue of only collecting sufficient data both internally and from customers to undertake the minimum study analysis necessary. At distribution voltages historically this has been a small subset of the theoretically available data. The practicality of this is obvious given that distribution systems historically, not least because of the ageing Engineering Recommendation P2 planning standard, have been designed to be fit-and-forget, capable of being operated through any single contingency (i.e. outage) without further intervention.

### ***Drivers for new functionality***

In the future, smart distribution systems will no longer be designed on a fit-and-forget basis, with demand and generation following a mixture of price and other signals to maximise the utilisation of the distribution network and minimise reinforcement investment in it. DNOs will therefore have to collect forecast data from customers and their own systems much more extensively to plan and manage the operation of their systems, to ensure reliability and safety in not allowing customer demands and/or generation to cause dangerous overloads. It is expected that the forecasting and scheduling will be an integral part of customers' smart devices and appliances for both domestic and small industrial and commercial customers.

### ***Required functionality***

The challenges for the GB system operator are similar and there will be a continuing need to model power flow and stability. However, the new smart behaviour by customers en-masse is not likely to be predictable using historic tools and statistical approaches. The GB system operator will need to have access to more granular data and forecasting from further down the system, probably via DNOs aggregating their forecasting and planning assumptions. Although small customers do not generally present outages that need to be managed, distribution connected generation and storage will, and as well as collecting forecasting loading etc. data for outage planning, DNOs will also need to know the outage plans of such customers because of the significant effects on local flows. Again, DNOs will need to aggregate this information on their systems to be able to communicate a complete picture to the GB system operator.

In terms of interfaces between customers' appliances and systems and the DNOs, the smart metering system will provide a basic infrastructure for the necessary interfaces and commercial offerings such as Hive and Nest have demonstrated the feasibility of autonomous home management, which could interact directly with DNOs' future management systems. Hive and Nest are examples of a 'system within

a system'; i.e. their communication and control systems have become a de facto part of the overall control system for the power sector, the materiality of which will depend on their scale of penetration. However, all the communications systems employed by such offerings and systems must be secure from accidental or malicious intervention and any data generated must be securely held to protect privacy.

### **Implementation**

The very wide interests and grouping of interested stakeholders in the GB power sector makes for a particular implementation challenge, not least because their interests are not necessarily aligned, are naturally uncoordinated, and could even be in commercial and technical competition with each other. A key grouping is the current and future domestic appliance manufacturers in the global market. The current GB Code structure does not address these challenges. Code Panels are constrained to consider the narrow remit of each particular code; there are no defined obligations or practical mechanisms to work collectively to deliver commercial and technical developments that enable widespread autonomous smart behaviour.

Moreover, the ability to fully exploit these widely distributed energy resources, will depend critically on the adoption of open standard specifications that provide the requisite degree of interoperability, compatibility and security whilst not adversely constraining innovation and development. Particular attention will need to be given to communications systems and the extent to which they should be integrated, paying particular attention to reliability, cyber security and data privacy. Clearly defined operational standards and comprehensive commissioning test regimes will also be required, as will an ongoing monitoring regime to identify and rectify any emerging adverse characteristics (e.g. indications of hunting or instability). It follows that a strong presence is required in appropriate standards-making activity. This needs to be a two-pronged approach: ensuring that the GB power sector is able to extract the most value from the future development of smart devices conforming to appropriate open standards and at the same time influencing standards to maintain the maximum opportunity for the current and future GB power system to continue to develop efficiently.

### **Requirements for research, development and innovation**

Although limited pilot trials have been conducted (e.g. as part of LCNF or NIC projects) deploying elements of this function, there is little experience of incorporating customers' management systems or using smart appliances, Home Energy Management Systems (HEMS) and Building Energy Management Systems (BEMS) at either the scale or level of integration that will be necessary to provide a coordinated system-wide service capability sufficient to meet the challenges envisaged for 2030 under a *Gone Green* (or especially Consumer Power) scenario.

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“The ability to fully exploit these widely distributed energy resources will depend critically on the adoption of open standard specifications that provide the requisite degree of interoperability, compatibility and security.”

A good example of the current state of development of the necessary interfaces is the UKPN 'KASM' project. This project plays into this in terms of contingency analysis and understanding how export from two offshore wind farms (Kentish Flats and Thanet) and a solar PV farm (Owl's Hatch) could be constrained due to either distribution, transmission, or even interconnector outages. Without such tools the consequence is that renewable output might be unnecessarily pre-fault constrained, or tripped off post-fault. Similarly, for planned outages it is necessary to understand the power flows under generator output and demand variations, and the impact of a second fault outage during the planned outage. Clearly this involves multiple parties sharing information in operational planning timescales – including of course the generators in terms of short-term production forecasts and also the Met Office in terms of short-term weather forecasts – and undertaking numerous contingency studies.

To ensure that the challenges of this function are appropriately understood, further research, development, deployment and end-to-end testing of this function will be necessary in order to detect any potential malfunctions, adverse interactions or suboptimal outcomes, and hence determine the necessary standards, specifications and codes of practice that will need to be agreed with multiple parties, validated and implemented.

**Function:** Provide automated and secure management of demand, generation and other energy resources to provide ancillary services, including through Smart Appliances, HEMS and BEMS [Function 14.1].

**Function Timeframe:** Real Time and Balancing.

### **Background**

The power system has traditionally relied on the availability of ample sources of synchronous generation associated with coal, gas and nuclear stations to supply relatively predictable levels of demand. The balancing mechanism surrounding bids and offers, coupled with reserve services provided primarily by part-loaded generation and aggregators contracting with business customers for DSR, has been sufficient to ensure that the power system remains in balance with sufficient reserve in hand to restore the balance following a major event such as a sudden unexpected loss of generation.

### **Drivers for new functionality**

The ongoing displacement of synchronous generation associated with thermal power stations with converter-connected generation or DFIGs (Doubly-Fed Induction Generators) typically associated with solar and wind generation, gives rise to three increasing challenges for the power system:

- The ability to accurately forecast total national production in operational timescales (even 4 hours ahead – the time typically required for a CCGT station to be in full production from an instruction to start) due to periodic and less predictable output from weather-dependent generation.
- Falling levels of system strength (loss of inertia and falling fault levels) giving rise to increasing rates of change of frequency in the event of a loss of infeed or a

large step-change in demand, and increasing depth, duration and dispersion of voltage dips arising from system faults or large step increases in demand. This phenomenon is exacerbated by the planned increase in the size of nuclear units supplying base load since in the event of an unexpected loss of a large nuclear powered synchronous generator when the GB system is lightly loaded, the loss of infeed will be coupled with a significant loss of inertia.

- The increasing penetration of heat pumps, electric vehicles and microgeneration is likely to create higher network peak demands, reverse power flows and voltage management challenges, potentially giving rise to costly and disruptive network reinforcement, which might be mitigated by the managed use of distributed energy resources.

In order to address these challenges economically (e.g. minimising the need to retain a level of synchronous generation supplying demand and/or on spinning reserve and/or preventing network overloads) it will be important to secure new sources of system reserve and other ancillary services.

### **Required functionality**

This function will enable homes and small businesses to participate fully in a smart power sector, by exploiting the potential for demand side response and provision of ancillary services such as system balancing and frequency response. Trials have demonstrated that manual interaction by consumers, for example in response to tariff price signals, can be helpful in terms of reducing peaks demand and/or minimising the requirement to dispatch low merit order (high carbon/high marginal cost) generation. However, in order to fully exploit the potential for flexible demand from electrical appliances such as refrigeration and other 'white' goods, small/microgeneration, EV chargers and storage – to support real-time requirements such as system balancing, frequency response and network constraint management – an automated and secure response capability is required.

Smart Appliances, which are able to respond to external price or control signals, and home or building Energy Management systems (HEMS and BEMS), which can manage electrical energy usage in response a range of inputs, provide a means of automated response. The smart metering system will provide a basic infrastructure for time-of-use tariffs and remote switching of appliances and commercial offerings such as Hive and Nest have demonstrated the feasibility of autonomous home management. Hive and Nest are examples of a 'system within a system'; i.e. their communication and control systems have become a de facto part of the overall control system for the power sector, the materiality of which will depend on their scale of penetration. However, all the communications systems employed by such offerings and systems must be secure from accidental or malicious intervention and any data generated must be securely held to protect privacy.

### **Implementation**

Given the complexity of the technical issues of managing national, regional and local balancing, frequency control, local voltage rise, network constraint management and reactive power management, a highly sophisticated automated hybrid application that runs both centrally and in a distributed architecture will be required to ensure whole system stability is maintained. Otherwise, the likelihood of inappropriate interventions

at different control levels (transmission, distribution and beyond the meter) could lead to automated control interactions leading to hunting or instability of the entire system. For example, if a large number of devices collectively responded to correct an under-frequency event, it would be important to prevent an over-correction leading to a high frequency event and hence a further corrective action. Similarly, a large number of devices simultaneously responding to a price or control signal could give rise to a voltage or frequency step-change requiring rapid corrective action and potentially triggering the operation of protection systems leading to a loss of local generation.

The very wide interests and grouping of interested stakeholders in the GB power sector makes for a particular implementation challenge, not least because their interests are not necessarily aligned, are naturally uncoordinated and could even be in commercial and technical competition with each other. A key grouping is the current and future domestic appliance manufacturers in the global market. The current GB Code structure does not address these challenges. Code Panels are constrained to consider the narrow remit of each particular code; there are no defined obligations or practical mechanisms to work collectively to deliver commercial and technical developments that enable widespread autonomous smart behaviour.

Moreover, the ability to fully exploit these widely distributed energy resources, will depend critically on the adoption of open standard specifications that provide the requisite degree of interoperability, compatibility and security whilst not adversely constraining innovation and development. Particular attention will need to be given to communications systems and the extent to which they should be integrated, paying particular attention to security and data privacy. Clearly defined operational standards and comprehensive commissioning test regimes will also be required, as will an ongoing monitoring regime to identify and rectify any emerging adverse characteristics (e.g. indications of hunting or instability). It follows that a strong presence is required in appropriate standards making activity. This needs to be a parallel approach: ensuring that the GB power sector is able to extract the most value from the future development of smart devices conforming to appropriate open standards, and at the same time influencing standards to maintain the maximum opportunity for the current and future GB power system to continue to develop efficiently.

### **Requirements for research, development and innovation**

Although limited pilot trials have been conducted (e.g. as part of LCNF or NIC projects) deploying elements of this function, there is little experience of using smart appliances, HEMS and BEMS at either the scale or level of integration that will be necessary to provide a coordinated system-wide service capability sufficient to meet the challenges envisaged for 2030 under a *Gone Green* (or especially Consumer Power) scenario. To achieve that objective, further research, development, deployment and end-to-end testing of this function will be necessary in order to detect any potential malfunctions, adverse interactions or suboptimal outcomes and, hence, determine the necessary standards, specifications and codes of practice that will need to be developed with multiple parties, validated and implemented.

**Function:** Plan for the timely restoration of supplies following a prolonged local failure (Cold Start) [Function 2.3].

**Function Timeframe:** Investment Planning.

### **Background**

The design of electricity distribution systems is governed by various requirements under Electricity Safety Quality and Continuity Regulations (ESQCR), Distribution Code, Grid Code, Distribution Licence and various other code provisions and statutory instruments. Design requirements include:

- Ensuring components operate within safe thermal limits (under peak loading and fault conditions);
- Maintaining statutory voltage limits;
- Meeting various standards relating to power quality (including harmonic distortion and voltage flicker) and
- Ensuring sufficient fault level for protection systems to clear faults.

Anticipated peak loading conditions for distribution systems have traditionally been based on the concept of ‘after-diversity maximum demand’ (ADMD). ADMD takes account of the fact that under normal conditions, the electrical loading presented to the distribution system will be the aggregate of many consumers’ loads that, over any given half-hour period, will be highly diversified. For example, for a modern gas heated residential estate, a DNO would typically assess the ADMD presented at a local distribution substation to be around 1–1.5 kW per dwelling. This is despite the fact that the actual maximum demand of any given property might regularly and significantly exceed that level over periods of the day.

For example, at breakfast time in a residential property it is quite feasible that a 3 kW kettle, a 3 kW toaster and a 1 kW microwave cooker might be operating simultaneously, along with lighting, refrigeration, possibly a TV and perhaps a central heating ‘wet system’ circulating pump. However, the kettle, toaster and microwave will typically be operating for only 1 or 2 minutes and hence the likelihood of many local households operating such appliances at exactly the same time is extremely low. Even if that did occur, the very brief period over which the abnormally high aggregate demand was presented to the network would present few problems due to the inherent thermal inertia of the network cables and the fusing characteristics of the circuit protection fuses at the substation that are such that a very brief period of high loading, well in excess of the nominal fuse rating, would not result in the fuse blowing.

### **Drivers for new functionality**

The electrification of residential heating through heat pumps, and of transport through electric vehicles, fundamentally changes the concept of ADMD or even means it is no longer a valid statistical approach. EVs and heat pumps will impose significant additional electricity demands on the distribution system and on the power system as a whole. For example, home EV chargers are readily available that draw 7.5 kW and a domestic air source heat pump will present a load typically of around 3 kW. Moreover, such additional loads may be presented over several consecutive hours. Whilst these appliance ratings might seem comparable to the combined rating of domestic



appliances in a typical home, such as the examples mentioned above plus washing machines, tumble dryers, dishwashers, electric showers etc., the difference is that these traditional appliances exhibit an inherently high level of diversity in terms of the times of day, or days of the week, when consumers in a given residential area will use such appliances.

EV chargers and heat pumps, on the other hand, might exhibit very little diversity – for example at around 6 pm on a winter weekday evening, it is conceivable that many EV chargers and heat pumps will be operating simultaneously in any given residential area and indeed across the country – i.e. at the very time that system peak demand occurs today. The problem is further exacerbated by the potential for local clustering, whereby a concentration of heat pumps and EV chargers might present a particularly high demand at the local distribution substation.

It is conceivable that, with appropriate attention to incentives through the introduction of time of use tariffs, or cheaper flat-rate tariffs where a supplier controls an element of the consumers 'flexible' demand, some degree of diversity might be introduced to EV charging and/or between heat pump and EV charging demand. High levels of building thermal insulation, built-in for new-build properties or retrofitted for existing properties, along with domestic hot water storage, might also enable some degree of diversity in terms of the operating cycles for domestic heat pumps, as would the adoption of hybrid heat pump alternatives. This could be significant in terms of mitigating the need for local network reinforcement and the peak capacity requirement of the power system as a whole.

However, there remains an issue that is unresolved by the above measures. In the event of a prolonged supply interruption over a given area, normal levels of diversity of demand in relation to certain electrical appliances will be lost. For example, the thermostats controlling the cabin temperatures of refrigerators and freezers (which normally exhibit a highly diversified demand to the power system due to the cyclic nature of their operation) will all be calling for cooling. Hence, when the supply is restored, all refrigeration demand will be presented simultaneously. This phenomenon is known as 'Cold Start' or 'cold pick-up' demand and is well understood, but hitherto the level of domestic demand subject to this effect has been relatively small.

### ***Required functionality***

The advent of EV charging and heat pumps raises the Cold Start issue to a completely new level. Taking heat pumps alone, a local distribution system originally designed on the basis of (say) 1.5 kW per dwelling would experience an aggregate Cold Start heat pump demand of 3 kW per heat pump supplied by that part of the power system, on top of any traditional domestic demand such as refrigeration and lighting (and not improbably, an abnormal number of kettles simultaneously operating shortly after the supply restoration). Should the supply be restored at a time when EVs are connected to their chargers, that would further add to the Cold Start demand. Not only would this coincident demand present a risk of thermal overloading and abnormally low voltage being experienced by consumers, the simultaneous starting of heat pumps and/or EV charging might cause a significant voltage depression. Initial loading, exacerbated by high starting currents of heat pumps and refrigeration compressors, might be sufficient to cause local network protection fuses to operate

resulting in an almost immediate re-interruption of supply. Under these circumstances it will be apparent that in the event of a re-interruption of supply following a Cold Start due to a local substation fuse operation, any attempt to replace the fuse is simply likely to result in a further fuse operation shortly afterwards. Whilst it would be possible to reinforce the distribution system in order to deliver this cold-start demand, the scale of investment would be prohibitive in terms of cost and public disruption (e.g. street excavations and temporary shutdowns).

One possible resolution to the problem would be to restore supplies to sections of the local network on a sequential basis, after allowing time for diversity of demand to be regained for the section of re-energised network before attempting to extend the restoration. This may be feasible for local networks equipped with isolation points (known as link boxes on underground LV networks) but many LV networks cannot readily be sectioned in this way. In such cases, there might be a need to manually remove cut-out fuses at the meter positions of domestic services so that only a portion of consumers are restored initially. Clearly, this would be a highly disruptive and frustrating process for consumers who had already suffered a prolonged supply interruption and, being an essentially manual process, would greatly extend the time taken to fully restore supplies.

The smart metering system offers a potential solution to this problem in that the possibility exists for the smart meter load switch to be operated remotely via the Data Communications Company (DCC) communications system. So, for example, in the above circumstances it would be technically feasible upon restoration of supplies to immediately open the load switches for sufficient numbers of customers to enable the Cold Start demand to be accommodated (the load switches cannot be opened until supply to the smart meter communications hub is restored, but provided this action is taken promptly, the thermal inertia of the network and fusing characteristics referred to above would be sufficient to prevent any immediate problem). After sufficient time had elapsed, a proportion of the load switches could be reclosed and, after a further delay, further switches closed. The extent to which supplies would need to be restored in this manner would need to be determined in advance so that a planned sequence of supply restoration could be enacted as and when required. Using the smart metering system to monitor the level of demand fall-off following supply restoration could further inform the speed at which supplies could be restored. A potential refinement to this procedure would be to use smart meter auxiliary load control switches to de-energise specific appliances. This could, for example, enable domestic lighting to be restored initially, prior to full restoration of supply.

Whilst the above might appear to resolve the problem, in practice it does so only to a certain extent, and even then only if concession is granted under the Smart Energy Code for DNOs to issue critical commands – i.e. directly controlling smart meter load switches or auxiliary load switches. Under current provisions, the above sequential supply restoration procedure would rely on Suppliers performing the load switch operations on behalf of the DNO. Given that, for any given local network, that might involve several, or many, Suppliers, the current restriction on DNOs might render the process impractical. A further issue (or opportunity) is that well before 2030, it is likely that a range of communications systems, including the internet, will be used to control domestic appliances.

### **Implementation**

The above describes the required functionality in high-level and largely conceptual terms. However, a great deal of further consideration will need to be given to the relevant codes, licence conditions, Cold Start capability assessment modelling and communication channels between the many parties to the power sector. These provisions will need to be in place before the level of heat pump and EV charging demand reaches critical levels in terms of Cold Start capability. The complexity of the task indicates that ad hoc arrangements will be inadequate to establish, monitor and maintain this important new functionality.

Under the 2015 National Grid *Gone Green* scenario, some 8.5m domestic heat pumps will be installed by 2035 of which around 6.5m are expected to be air source heat pumps and the remaining 2m hybrid heat pumps (numbers of ground source heat pump installations are not expected to be significant). *Gone Green* also assumes around 7m EVs by 2035. These volumes represent around 25–30% of GB domestic households. However, an element of clustering of these technologies at 2035 is likely, meaning that some local distribution substations might experience much higher ratios of heat pump installations and electric vehicle chargers and, hence, more onerous Cold Start conditions.

### **Requirements for research, development and innovation**

It follows from all the above that the future means of ensuring Cold Start capability is likely to depend on a sophisticated real-time communication strategy involving numerous power sector parties. A mechanism will also need to be established whereby a DNO would have the authority under the Smart Energy Code to take control of smart meter load switches (i.e. issuing command signals through Data Communications Company – DCC) under Cold Start conditions where an assessment demonstrated the likely need for a sequential supply restoration in the event of a prolonged supply interruption (which would depend on several factors including time of day, day of week, time of year, ambient temperature etc.) This would mean the DNO having systems consistent with the authority to issue critical commands over the DCC system, for example systems with the necessary security to prevent misuse of commands to smart meter load switches, auxiliary load control switches or Home Area Network (HAN) connected auxiliary load control switches.

**Function:** Collaborate with other energy sectors to optimise across multiple sites and vectors [Function 15.4].

**Function Timeframe:** Settlement (but applies to all timeframes).

### **Background**

The power sector today is, to a large extent, only loosely integrated with other energy sectors (gas, heating and cooling, transport, coal, nuclear, lighting, white goods appliances etc.) by historical evolution, and has become polarised into generation fuels or demand side load with little concern for how best to optimise between these various segments, other than by market price signals. The technical challenge has been to ensure connection, rather than integration or cross vector optimisation. Examples of this cover all timeframes (investment, operational, settlement etc.):

- Regulatory price reviews are carried out in isolation to each other – electricity transmission, electricity distribution, gas transmission, gas distribution etc.
- No distinction is made between generation types when self-dispatching, for example taking carbon emissions into account (there is an inherent and questionable assumption that the market will have factored that in).
- Heating and cooling is run asynchronously to the condition of the electricity networks thereby wasting an opportunity to use the flexibility of these loads.
- In settlement there is no ability to share excess electricity generation or heating between neighbours in a bilateral agreement.
- Electric vehicles have no way to trade excess storage back to grid (e.g. they do not qualify for Feed-In Tariff (FIT) payments) etc.

### ***Drivers for new functionality***

The above examples are not theoretical or aspirational applications to be considered in the future; all of these are openly being discussed today as needs and therefore the driver for change is clearly defined. These are but a small subset of the various combinations and inter-relationships that will require coordination in the future to optimise across the energy sector for cost and price across market structures, environmental impact, technical deployment and societal needs.

The functionality required to address the above issues will need to be developed in a collaborative manner to achieve understanding of the impacts each sector places upon the other, and to provide consistent and coherent market structures that deliver integrated technical and commercial solutions with the lowest overall cost of meeting energy needs. Agreement on data sharing between the sectors is likely to be key and development of standards, protocols and frameworks for communications and data management will be necessary. This raises issues for ownership of systems, confidentiality requirements placed on the system operators and accountability for their secure operation and evolution.

### ***Required functionality***

The technical challenges that are raised by these examples are partially catered for today by individual products and service offerings. The real challenge is the integration of these multitude of products and services into coherent applications that can interface across energy sector boundaries. An example of this is the challenge of dual-fuel (hybrid) heat pumps, already available on the market, where neither the gas or electricity network has any visibility of the switching that takes place between fuels. Therefore, if a synchronous event (e.g. a local weather report that triggered all heat pumps in a localised cluster to turn on and switch from gas to electricity (due to a price signal)) caused an already congested area of the electricity network to suddenly receive a very large load demand without notice, the stability of the grid could be compromised. There are no sensors, data collection or management systems to understand this relationship. In this example the customer may have an instantaneous price benefit but the cost of providing the infrastructure to manage this is not factored into that cost on either side of the equation – gas or electricity. There are many more examples where this is the case between different parts of the energy sector.

### ***Implementation***

Going forward, the decarbonisation of heat and transport to levels that satisfy GB's

2050 obligations will require a far more holistic consideration of the roles of the various energy (and transport) vectors and their inter-relationships. Heat networks, gas or hybrid heat pumps, CHP, micro-CHP, Carbon Capture and Storage (CCS), the role of hydrogen, energy storage systems involving multiple vectors, will all play a vital role in resolving the energy trilemma: keeping GB economically competitive and energy-secure whilst meeting its Green House Gas (GHG) emission obligations. Energy policy cannot therefore limit its horizon to 2030 since that is merely a stepping stone to a far more challenging need for energy vector optimisation. Instead, the pathway to 2050 must determine the strategy for cross-energy vector optimisation at 2030 and hence implementation of the new functionality described here is a vital first step.

### **Requirements for research, development and innovation**

Research is required to understand the potential touch points and interactions between vectors and to determine the associated costs and benefits. This functionality is also likely to require innovation, R&D and trials to understand how best to structure the markets, technical integration and commercial contracts that will meet customers' needs.

## **5.4 Evidence base for GB System 2030 functionality**

A body of evidence has been gathered and presented in summary form alongside each of the *thirty-five* technical functions. In addition, a Functional Matrix has been prepared and is available as an on-line resource accompanying this report (details in an appendix in section 15). This sets out the propositions and assertions that can be made about the power sector change and challenge, the requirements that these bring, the technical functions that would be required and the experience and challenges in implementation of the new or extended technical functions.

Evidence gathering and collation has progressed iteratively throughout the project, from referencing and building from key industry documents and then fully aligning more detailed and focused research and evidence capture with the consolidated Functional Matrix.

The evidence gathering and collation approach aims have been to:

- Provide evidence of the need for the incremental/new functionality.
- Ensure evidence gathered is robust and demonstrable.
- Ensure evidence gathered is not exhaustive, but is sufficient to demonstrate its existence and supports the need for the associated function(s).
- Provide high level summary for inclusion in the matrix, backed up by further detail.

The methodology for evidence gathering and collation has been to:

- Summarise evidence needed against each function (as noted in section 5.2).
- Compare function topics and summarise.
- Gather evidence for each identified topic.
- Write an evidence summary with references for each function.

The evidence supporting the technical functions identified has been constructed as a reference list linked to each function in the Functional Matrix and then explored in a more detailed theme-based format in a separate evidence document.

Evidence gathering was targeted at diverse and authoritative sources including the most recognisable international comparators to the GB system and provides the basis for: the need for the function, which existing agencies provide related functionality now, the feasibility (including any relevant deployments) and likely timing and triggers for the new functions.

The evidence that has been considered appropriate is in the form of: examples of implementation or proposed implementation in other countries; studies and modelling that have demonstrated the need for new functions and innovation trials that have explored and evaluated means of supporting functions. Evidence gathering has supported the categorisation of functions as incremental and new. Although thinner evidence for very new and challenging areas is expected, evidence is available for why new functionality might not be implemented. The extensive portfolio of network operator LCNF, NIC and NIA projects, learning and closedown reports provide evidence of successful implementation and many of the difficulties in implementation of extended and new functionality addressing the challenges facing the GB power system. Diversity of evidence (e.g. LCNF/NIC/NIA reports, academics studies, DECC/Ofgem reports, international sources etc.) is regarded as an important aim and also an important indicator of the strength of evidence.

The International Study provides good evidence for similar challenges in Germany, Ireland and the US, and highlights a number of key learning points for architecting the future GB system including the need for a whole system and integrated approach to planning, operating and markets. Integrated coordinated whole system architectures are emerging and Independent System Operators (ISO) and other supervisory agencies are already taking a wider responsibility for whole system coordination than currently in GB. Interoperability and standardisation already have more prominence in other countries.

The next section analyses the identified functions and evidence with a view to identifying the triggers, dependencies and sequencing issues.



## 6. Function Triggers and Sequencing

### 6.1 Summary

- The functions have been analysed to understand better the prominent learnings and their implications. These analyses provide an underpinning evidence base for the functions identified and the evidence supporting them through assessment of the triggers, implementation challenges and implications of the functions.
- Further analysis of the Functional Matrix has provided strong indications of the drivers and triggers for the new or extended functionality and the system context in which they would play essential and valuable roles (the outcomes were presented in section 5.2 above).
- Analysis has been undertaken to determine how the need for new functionality is triggered – along with prerequisite developments necessary for new functionality to be introduced. This in turn has enabled a broad indication of the likely sequencing of new functionality under different power sector development pathways or ‘core concepts’. While there are differences in sequence and triggering of functions under different core concepts (and the inherent uncertainty in the pathways to get there), there is significant evidence that the full set of technical functions recommended by this work will be required under all of these core concepts.
- The drivers, triggers and sequencing of the technical functions have been analysed through linkage of functions to the power system concepts and assessment of the triggers for the function in the context of those concepts. The results of that analysis are presented below.

## 6.2 Function triggers and sequencing

The methodology for creating the four power sector evolutionary pathways (core concepts) is described in Appendix (section 17) but in summary, the four core concepts considered are as follows:

- Power Sector Adaptation: The power sector maintains business as usual accommodating incremental development, largely reactive and no expectations of major changes in customer behaviour (a more likely pathway under a future ‘No Progression’ energy scenario).
- Power Sector Leadership: The power sector takes a lead in engaging with customers; DNOs evolve to DSOs who coordinate with GBSO (or ISO) for system balancing and constraint management (more consistent with a *Gone Green* scenario).
- Customer Empowerment: The power sector becomes a facilitator empowering the emergence of new commercial parties, new business models, and new services (consistent with *Gone Green* but leaning towards ‘Consumer Power’).
- Community Empowerment: The power sector expands its facilitation role, empowering smart cities and energy communities with local markets and peer-to-peer trading (consistent with *Gone Green* but even more consistent with a ‘Consumer Power’ scenario).

Table 8, Table 9, Table 10 and Table 11 illustrate the high level outcome of detailed analysis of triggers and sequencing of the required implementation of the identified technical functions for each of the identified four core concepts. The four GB system concepts presented were developed by the project team as a means of creating coherency and consistency across the functions when placed in a whole system context.

Table 8: Sequencing analysis for ‘Power Sector Adaptation’ concept

<b>Power System Adaptation</b>	Power sector maintains business as usual, accommodating incremental development.
Sequencing approach assumed for this concept	<p>Functions will be implemented only when impacts of issues are detected in operating the system. Changes are reactive rather than proactive.</p> <p>The functions are adopted after the ‘needed by’ event, potentially causing operational issues, necessitating temporary ad hoc solutions and delaying benefits gained from innovation.</p>
Advanced Metering:	Being introduced, will be widespread relatively soon. Less important as much of the network will still be managed passively.
New Technologies:	Being adopted, but will not reach critical mass until a little later. Impact managed mainly be reinforcement rather than active network management.
New Players:	Not being greatly encouraged, and will not become a major impactor until later. Less important as little active network management.
Cross-system Collaboration:	Not being actively sought, so not occurring until much later. Less important as little active network management.

**High level sequencing of the implementation of the functions:**

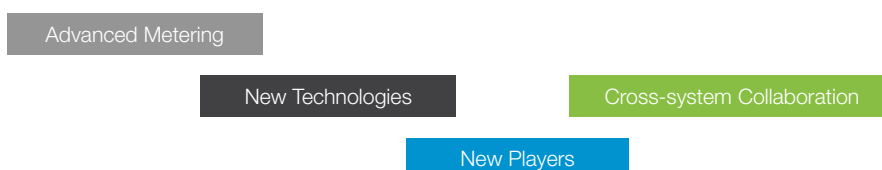




Table 9: Sequencing analysis for ‘Power Sector Leadership’ concept

<b>Power Sector Leadership</b>	Power sector provides leadership, engaging with more active consumers.
Sequencing approach assumed for this concept	<p>Functions will be implemented to ensure continued operation of the system and then to enhance customer choice.</p> <p>Functions are adopted a little earlier and generally pro-actively, meaning that more functions are implemented before the ‘needed by’ event. However, the delay in cross system collaboration means that there are still timing issues.</p>
Advanced Metering:	Being introduced, will be widespread relatively soon. Vital for settling customers who participate in active network management.
New Technologies:	Being adopted, but will not reach critical mass until a little later. Deployment will stall without active network management: requires advanced metering and new parties.
New Players:	Not being encouraged by the power sector, so not reaching critical mass until much later. Vital unless DNOs engage directly with customers – putting suppliers out of balance.
Cross-system Collaboration:	Is being sought to enable more efficient running of the system, but still not implemented until a little later. Need will grow as new players gain scale and GBSO/DSO work more closely.

**High level sequencing of the implementation of the functions:**



Table 10: Sequencing analysis for ‘Customer Empowerment’ concept

<b>Customer Empowerment</b>	Power sector becomes the facilitator, empowering commercial parties and consumers.
Sequencing approach assumed for this concept	<p>Functions will be implemented to enable customers to be able to adopt technologies quickly and be engaged.</p> <p>Triggers are reached much sooner and therefore functions implemented earlier. This enables benefits of innovation to be realised sooner, but indicates a period of very rapid change, which will need careful management.</p>
Advanced Metering:	Being introduced, will be widespread relatively soon. Vital for settling customers who participate in active network management.
New Technologies:	Significantly accelerated by engaged customers, so critical mass soon. Deployment will stall without active network management: requires advanced metering and new parties.
New Players:	Accelerated by the take-up of new technologies, so critical mass relatively soon. Vital unless DNOs engage directly with customers – putting suppliers out of balance.
Cross-system Collaboration:	Is being sought to enable cross working with new players, but still not reaching critical mass until a little later. Need will grow as new players gain scale and GBSO/DSO work more closely.

**High level sequencing of the implementation of the functions:**



Table 11: Sequencing analysis for ‘Community Empowerment’ concept

<b>Community Empowerment</b>	Power sector acts as a comprehensive facilitator, empowering communities and smart cities.
Sequencing approach assumed for this concept	Functions will be implemented to enable communities to develop and act in the interest of their members. Triggers are reached much sooner and therefore functions implemented earlier. This enables benefits of innovation to be realised sooner, but indicates a period of very rapid change that will need careful management.
Advanced Metering:	Being introduced, will be widespread relatively soon. Vital for settling customers who participate in active network management.
New Technologies:	Significantly accelerated by communities and engaged customers, so critical mass soon. Deployment will stall without active network management: requires advanced metering and new parties.
New Players:	Significantly accelerated by the increase in communities, so critical mass soon. Vital unless DSOs engage directly with customers – putting suppliers out of balance.
Cross-system Collaboration:	Is being sought to enable cross working with new players, so critical mass relatively soon. Need will grow as new players gain scale and GBSO/DSO work more closely.

**High level sequencing of the implementation of the functions:**

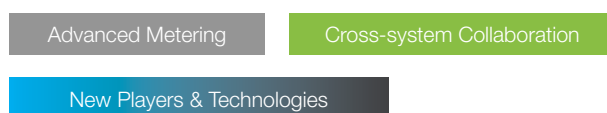


Table 8 to Table 11 above provide a high-level illustration of the sequencing of categories of functionality under each power sector core concept. Full mapping of functions to trigger points under each core concept has been undertaken and is accessible as an on-line resource accompanying this report (details in Appendix section 15). The main outcome of this analysis is that whilst, to a greater or lesser extent, all functions are relevant to each of the power sector evolutionary pathways (and future energy scenarios) considered, there are likely to be differences between core concepts in terms of sequencing of functions and timing of trigger points. It follows that the actual evolutionary pathway of the power sector and the energy scenario that materialises will need to be closely monitored, and the impact on sequencing and trigger points for functions carefully analysed, such that due emphasis can be given to developing those functions that appear on the critical path. This emphasises the need for a flexible and agile approach to power sector planning as well as to operating the power system. The next section further analyses the functions to identify key implementation challenges.

“The four GB system concepts are a means of creating coherency and consistency across the functions when placed in a whole system context. This emphasises the need for a flexible and agile approach to power sector planning as well as to operating the power system.”



## 7. Implementation Challenges and Impacts of the Functions

### 7.1 Summary

- Analysis of the implementation challenges and sector impacts has been undertaken on the *thirty-five* functions and seven drivers of functionality.
- Themes emerging from this analysis are a significant requirement to extend existing functionality to cope with and exploit the emerging system trends (common across different scenarios and system concepts) as well as the need for completely new, cross-cutting, whole system functionality and overall compatibility of different interventions that sit across the boundaries of the existing industry and governance structures.
- It is clear from the analysis that there are options and choices between implementations of the new functions (including where in the system and by which participants they are delivered) but that the different options need to be implemented in a coordinated manner. The functions identified are required broadly and commonly across all the scenarios and sector evolutionary pathways (core concepts) identified.

### 7.2 Analysis of implementation challenges

The following analysis focuses on the common threads and broader implications drawn from analysis of the potential implementation challenges of the *thirty-five* power system functions, identified by the FPSA project. These points have been drawn as

observations directly from the Functional Matrix, which is the core deliverable of the FPSA activities. The observations differ in terms of both extent and profundity. The conclusions have been grouped to identify:

- **Points of commonality between the different functional implementations:** looking to group common implementation themes between different functions, different core concepts and each of the four planning timescales.
- **Points of difference between the functional implementations:** looking to highlight unique or distinct implementation approaches required within a function, core concept or planning timescale.
- **Particular implementation challenges:** features of complexity or significant costs that are likely to present challenges to the power sector's ability to deliver.

It is important to note that the analysis has not been limited to just one scenario or evolutionary path for the sector (i.e. only the *Gone Green* scenario or only one power sector core concept). Rather, the project has sought to embrace the range of credible pathways to ensure that any functionality that might be a unique (or stronger) requirement under a different pathway has not been missed. The range of core concepts developed and used as a tool in the analysis of technical functions should prove adequate to accommodate any of the National Grid Future Energy Scenarios.

### 7.3 Implementation challenges identified

This section presents the high level implementation challenges identified from the analysis conducted:

- ***All functions cross current commercial, organisational and company boundaries***

One of the initial aims of this FPSA project was to develop a functional set that was, as far as possible, institutionally and organisationally neutral. This is reflected in the fact that all of the functionalities listed, to a greater or lesser extent, cut across current boundaries. This correlates well with the identified drivers of functionality and triggers/sequencing analysis that highlights the requirement for improvements to the scope and approaches to collaboration within the power sector in order to deliver the required functions.

Organisational barriers take many forms. Power sector roles include those of the government and regulators, generators, suppliers, network (transmission and distribution) operators, and system operators, as well as 'new' players such as aggregators and energy community managers (these already exist to some extent, but are considered 'new' as they are not yet widespread and considered 'Business as Usual' (BAU)). In fact, customers, by nature of the interaction with their appliances and devices, are also considered by the FPSA project as part of the power system. Collaboration across these roles will also take several forms from 'light touch', such as sharing ideas and innovations, through to legally-mandated interworking throughout the investment planning, operational planning, real time and settlement timescales. At present, mandated arrangements are established through mechanisms such as the Distribution Code, Grid Code, Balancing and Settlement Code and Smart Energy Code – each of these has oversight from Ofgem and they are enshrined within licence obligations. With new parties

becoming active in the sector (parties who do not need to have a licence and are not under Ofgem purview), current arrangements are potentially inadequate for the emerging challenge.

It is noted that crossing organisational boundaries, particularly in ways that are not currently enabled, can be a significant barrier to achieving change. Though boundaries in themselves are not a technical challenge, they can be a significant barrier to the development and implementation of new technical functions, especially where flexibility and responsiveness is called for. It also presents a challenge in regard to ensuring the all-important adoption of new protocols, procedures or technical characteristics that form part of a whole-system strategy to ensure resilience and security of the evolving power system.

- ***Many of the functions have significant technical complexity requiring reliable interaction of a large number of devices and cooperation of a large number of players***

Many of the functions require active Energy Management of generation, loads, storage and other energy services. It is accepted that this activity has significant potential advantages to the system as a whole. However, implementation poses significant technical challenges due to the need to have reliable interaction of a large number of devices and the cooperation of a large number of players.

The scope and scale of available DSR, storage and distributed generation needs to be tracked and understood in order to enable the system to take advantage of the potential benefits, and to guard against potential threats to operation. This will necessitate coordination between the relevant parties, significant additional monitoring and the data and IT systems will be required. New tools will be needed for forecasting and analysis. The processes for developing and utilising these services at scale will need appropriate validation, implementation planning and monitoring as they will have an element of probabilistic behaviour, unlike today's systems that are largely deterministic. The processes for using these services will need appropriate testing and implementation planning.

It is likely that the offering, dispatch, implementation and settlement of much of this activity will be automated. This is likely to require development of standards for mass market appliances, which can be used for Energy Management. There will be significant lead times in creating appropriate open standards frameworks including working with manufacturers, international standards bodies etc.

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**“All functions cross current commercial, organisational and company boundaries which can be a significant barrier to achieving change.”**

- **Many functions require significant additional telecommunication, monitoring and IT systems**

A feature of the complexity highlighted is that many functions require additional data and associated telecommunications, data management and machine to machine (M2M) communication to deliver them. This is especially true for the Customer Empowerment and Community Empowerment core concepts that envisage a much greater participation and system role for customers and communities. Wide scale deployment of these technologies establishes an unprecedented set of threats and challenges to the power system including:

- o The requirement to prevent 'hunting' issues due to the unstable interactions of autonomous distributed control systems.
- o The requirement to provide a secure system with a potentially large number of individuals with divergent approaches and technologies.
- o The importance of respecting data privacy.
- o The requirement for a coordinated approach to cyber security across whole sector, including customers.

The body of engineering knowledge for monitoring and controlling these threats is immature. The tools, techniques and approaches have not converged around a set of internationally accepted standards and best practice. There is likely to be a significant lead time to develop and implement appropriate open standards frameworks with international standards bodies.

- **Many of the functions require sharing of data**

Many of the functions require active management of the power system, including generation, loads, storage and other energy services, and some specifically refer to the need for additional monitoring with the need to share data across the sector.

The volume of data that will be needed to support these functions is likely to be significant, and this in itself generates a technical challenge in communicating, collecting, storing and processing that data in order for it to be in a useable format, to acceptable levels of quality control and readily available to appropriate parties. This requirement evidently crosses many boundaries and raises questions in regard to end-to-end responsibility for its delivery, cost-sharing and periodic upgrading for new services or to address new cyber threats.

There is also a key challenge to ensure data security and confidentiality. This includes both commercially sensitive data around the performance of privately owned equipment, or of forecast volumes that could enable market manipulation by other parties and also personal data about the energy use within domestic properties. This is sensitive as it is possible to infer a significant amount of information about the activities within a property from only its energy data. Managing this risk and protecting the privacy of the customers within the system is a vital consideration when implementing these new functions.

- **Many of the functions require the development of new modelling and simulation tools and techniques**

Current power system modelling approaches have evolved in a largely unstructured

manner. This has taken place over many years in response to the requirements of individual stakeholders and therefore does not reflect the breadth of modelling approaches that are required to develop, design, analyse and assure the functions identified by the FPSA project. Whole systems modelling is an underdeveloped area of analysis within the power sector and is likely to be required to manage complexity and assess the risks of undesirable emergent behaviour within the future power sector.

- **Many functions require the development of new forecasting capabilities**

A high penetration of intermittent sources of generation, aggregated demand profiles (e.g. for EVs and heat pumps) and the use of these resources to provide system services represent new sources of variability that challenge the power system requirement to balance sources of demand and generation at local, regional and national levels. This new variability is both temporal and locational and therefore reliable and accurate forecasting is required in both of these domains.

In particular, local weather forecasting (temperature, wind speed and cloud cover) is identified as important under many functions and core concepts. Today's forecasting methods for system demand generally achieve a very good accuracy, but the emerging and future changes are likely to undermine the validity of the methodologies used currently. For example, today's methods take a 'top-down' approach using data from large generating stations and substations, and apply automated corrections on a rolling basis to recognised 'turning points' (maxima, minima and plateau points) on the 'daily load curves'. These turning points are likely to be modified by either Time-of-Use tariffs that will trim the peaks and fill the troughs, or by dynamic tariffs that take account of forecast weather patterns and intermittent generation availability to set day-ahead prices. Hence, the sources of variability will no longer be tracked by 'top-down' measurements. This indicates a very substantial shift being needed to 'bottom-up' analysis, drawing data from all sources of variability and is a 'Big Data' challenge of considerable proportions.

- **Many functions reach beyond the meter**

A significant feature of many functions is the anticipated and required interaction with customers' intelligent energy-using equipment influenced by prices, creating many more active components of the electricity system. This creates significant challenges to operating a coordinated, economic and secure system but also in anticipating, designing and implementing the required information and operational systems to support the volume and complexity of a power system based on customer interaction.

- **Some functions will ultimately span multiple energy vectors**

There are already cross-energy vector interactions (e.g. gas used for electricity production) but the anticipated interactions in future will likely include electricity, gas, petroleum and biomass as primary fuel sources. In addition, there is likely to be an early requirement for the energy system to become more tightly integrated in response to policy drives in electricity usage for heat and transport and co-dependencies on interactions with the communications sector.

#### 7.4 Implications and risks of non-delivery of functions

The new functionality described is intended to mitigate risks and realise opportunities. If new functionality is not delivered, or is delivered late, there is potential for several highly adverse consequences:

- Compromises to the security, integrity and reliability of the power system at physical, operational and data levels.
- Excessive operational costs or avoidable constraints and related costs – for example, higher than necessary costs of balancing or achieving frequency stability, or the emergence of localised network constraints that, for example, would prevent connection of new distributed generation or a large number of electric vehicles in a local area.
- Inefficient investment, low utilisation of assets or over-engineering – meeting the policy objectives but expensively. For example, smart grid concepts may provide a lower cost infrastructure to support the electric vehicle population by reducing the need for traditional strengthening of networks to meet predicted demand.
- Impediments to valuable new commercial models and lost benefits to consumers and the economy – the loss of opportunities and barriers to innovation. For example, it could be impossible to implement peer-to-peer trading and the full potential of smart cities or other aggregators.
- Failure to meet policy targets for carbon reduction if it proves impossible to integrate low-carbon generation and demand-side technologies at scale with adequate reliability and stability.

The implementation of new functionality will also have risks and these should be assessed and managed as part of the implementation regime.

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“The volume of data is likely to be significant, which generates a technical challenge in communicating, collecting, storing and processing it. This activity crosses many boundaries and raises questions in regard to end-to-end responsibility for its delivery, cost-sharing and periodic upgrading for new services or to address new cyber threats.”





## 8. International Comparison

The International Study has looked at the main system level challenges facing the electrical power sectors of Germany, Ireland and the United States (US) (with a high level desktop study on South Korea). They correlate strongly with those facing the GB system around key changes including:

- Integration of large renewable generation sources (and a corresponding reduction in system inertia).
- The growth in distribution-connected energy resources (distributed generation, electric vehicles, heat pumps, demand side response, energy storage).
- The trend towards microgrids, community energy systems and engaged customers.
- Greater interconnection with neighbouring grids, both AC and DC.

It is widely recognised across the studied regions that the effects of these represent both threats and opportunities to the successful planning and operation of the respective power system. The potential scale of the changes and their materiality has led to greater system-wide thinking for those power systems from both technical and policy perspectives.

It is evident that a business as usual approach has been discounted as each of the countries (or regions in the case of the US) has developed new thinking to meet these challenges. They vary from a highly collaborative working forum with strong governance (Ireland) through to a radical overhaul of regulatory frameworks and markets (New York). Germany and other regions in the US are taking a broader systems-wide perspective to identify areas where roles and responsibilities need to evolve to meet these challenges.

These approaches are highlighting new functions required and identifying those that need to be significantly enhanced. For example, in New York a formal Distribution System Operator function is being created whereas California's DRP (Distribution Resource Plan) calls for a significantly enhanced distribution planning function that forecasts and models distributed energy resources for inclusion in long term planning. All share the same purpose: to ensure their electrical power system remains resilient while incorporating technology evolution and maximising clean energy resources.

The key messages from this International Study are that:

- The challenges faced by the GB electricity sector are similar to those faced in the other countries reviewed however none of them face all of them to a similar extent if we assume National Grid's *Gone Green* scenario. For many varied reasons, not all of these challenges appear in any particular country to the same extent. This indicates that the scale of the change anticipated on the GB system is greater and potentially poses a greater coordination and integration challenge.
- Many experts consulted expressed the need for greater system wide planning and indicated that they believed the scale of changes anticipated represented a real risk to system resilience and reliability if not fully coordinated, the value that Distributed Energy Resources (DERs) can bring is being accepted, policies in the countries reviewed are aimed at promoting and encouraging the adoption of DERs.
- This review has identified a number of significant change programmes happening in these countries to meet these challenges. The approaches are varied, though all are pro-active and consistent in aiming to incorporate the challenges identified into their power systems. There is no evidence of inaction.
- There is evidence of greater central coordination and planning in the countries examined to ensure that system security is preserved and the value of DERs is fully realised. In California and New York that greater coordination is coming from the Independent System Operators and Public Service Commissions. In Ireland it is through an SO/TO led cross industry working group.
- Distribution systems are highlighted as facing the greatest challenges in defining and implementing comprehensive distribution management systems. In addition, these will need to integrate with ISO systems, Home Area Networks. Microgrid controllers, SCADA systems and market mechanisms to name a few. While many of these have detailed architectures and defined interfaces, there is an absence of a system of systems overview. This is beginning to be actively discussed, with Pacific Northwest National Laboratory (PNNL) and Electric Power Research Institute (EPRI) both being cited as thought leaders.
- There are many new functions that are being developed across the sectors that will need to be incorporated, either into existing functions or through developing new ones. Examples include modelling of DERs, interconnection rules and standards, situational awareness, data exchange and common information models.

The International Study can be downloaded via [www.theiet.org/fpsa](http://www.theiet.org/fpsa) or [es.catapult.org.uk/fpsa](http://es.catapult.org.uk/fpsa)



## 9. Project Findings

This section presents the high level findings based on the detailed functional development and analysis presented in the report and the appendices.

### 9.1 New or extended functions

The project has identified *thirty-five* new or significantly modified functions that, together, are required to meet power sector objectives as the GB power system transitions in the coming years. The functions should be viewed as a collective set of inter-related functions that are required to effectively plan and operate the emerging, more complex, more challenging system.

Analysis of the functions has identified several high level findings including:

- The identified function set is diverse, spanning different: parties (existing and new), timeframes, levels of technical complexity, types of system tasks, starting points, and scales of activity (e.g. from managing a set of smart cities to engaging potentially millions of new smart devices or actively participating customers).
- There is uncertainty with respect to the triggers, pathways, priorities and sequencing of the system changes anticipated and hence the timing of the introduction of the identified technical functions.
- The lead times to implement the set of functions widely and fully across the sector are expected to be long (with some functions at very early R&D stage and with low Technology Readiness Level: TRL) so there is some degree of urgency to start developing and implementing the new functionality. Expected innovation, research and development topics were set out under each of the seven detailed function descriptions in section 5.3 above, and these will be required to be coordinated across funding programmes to ensure solutions for function implementation are available when the system needs them.

### 9.1.1 International comparators

- The international comparators to the GB system are experiencing similar challenges and have ongoing programmes to embrace the challenges and respond accordingly. The programmes that have been initiated to respond to the challenge are different in form, scale, maturity and leadership in keeping with the sector arrangements in those territories but greater coordination, embracing new stakeholders and opportunities, an emphasis on active distribution systems of varying sorts, and an early emphasis on planning are all evident. It should be noted that some of these changes being implemented in those territories cross the technical-commercial-regulatory-legislative boundaries so cross-cutting programmes are evident in those comparable power systems.
  - o The FPSA assessment of international developments confirms that the challenges are faced elsewhere and viewed as material and significant.
  - o Others are addressing and have various programmes/activities underway.
  - o Though not all are taking a systems engineering view that we have, it is evident that new and enhance functions are being conceived and implemented already to meet similar challenges that the GB has.
  - o Given the similarities, it can be concluded that the GB system should take appropriate steps to ensure that the power sector develops to meet these challenges, preserve system resilience and actively supports UK policy to move to a low carbon economy.

### 9.1.2 Challenges and risks

- The scale and pace of change to the power system along with the nature, implications and challenge of implementing the required functions could overwhelm the current sector capabilities to respond if not monitored and managed in an active and coordinated manner – there are opportunities that could be missed and national and customer value that could be inhibited if the functions are not implemented in a timely manner beginning soon.
- The analysis of function implementation challenges shows that there is a very significant programme of work cutting across many domains, involving significant new technology research and development, requiring the sector to innovate and implement the outcomes of innovation at a different scale and pace compared to today, and involving unprecedented application of information, communication and data technologies and systems.
- The challenges and risks associated with the functions cannot be managed in isolation since there is a high level of interdependency across the functions and also between the participants and stakeholders in the emerging power system. This requires new levels of cooperation across existing and new technical and organisational boundaries.

### 9.1.3 Interdependencies and the need for coordination

- The GB power system changes and the required functions that follow on from that are not independent of each other so joined up, whole-system approaches are more likely to deliver the coordinated, secure, economic system desired.

Whole system approaches, system integration capabilities and the use of systems engineering methods are required to adequately manage the power system transition into a much more integrated, interdependent system.

- The services and products/value propositions for customers are growing in number and sophistication and many of the new functions, enhanced functions or new integrations of existing functions will provide opportunities (and accompanying risks of various sorts) for customer participation, value delivery, choice and competition. This emphasises the need for thorough, systemic, multi-party, coordinated thinking to ensure that GB energy customers are empowered and enriched by the transition to a smarter, low carbon system rather than frustrated by it.
- Migration from existing functions and introduction of new functions (and their integrations) can be expected to be complex and challenging so the sector capability to embrace new techniques, disciplines, ways of working, etc. requires attention as much as the end solutions to the functional challenges themselves.
- The triggers and sequencing analysis has identified various common dependencies underpinning the functions such as advanced metering, new information/control technologies, new participants and cross-sector collaboration. This emphasises the mix of technology, infrastructure and ways of working across the sector required to deliver the functionality identified as well as the interdependency across the set of functions on these enabling frameworks and platforms.
- The clear linkage from electricity to other energy vectors (e.g. heating systems, transport systems, energy storage/conversion systems) is becoming more apparent so the need for systems thinking and 'system of systems' integrated solutions is likely to become more crucial.
- The diversity of the identified functions and the new participants in them along with new responsibilities and a much higher expected volume of active devices emphasises the need for technical compatibility and interoperability as well as commercial coherency as these new functions are added to the existing system functionality.

#### 9.1.4 Related work

- The project highlighted ongoing work and emphasis on system flexibility and the FPSA project has independently (and, to an extent, in parallel) identified flexibility as a major driver of functionality and characteristic of future system architecture. The set of functions identified provide the technical means of delivering flexibility in the system (from system investment planning through to real-time operations, with supporting settlement functions) so should prove valuable in moving the related programmes on flexibility forward.
- The project also notes the ongoing work on SO, ISO and DSO questions and such enquiry mirrors either existing arrangements or new programmes in the international comparator jurisdictions. One of the threads evident in the International Study was that of the best allocation of responsibility between existing and new entities for identification, definition, development, implementation and operation of the new functions. This is clearly a line of thought that follows on logically from the identification of new functions in this FPSA project and is evident in the discourse in the GB power sector currently.

## 9.2 Drivers of functionality

The *thirty-five* functions and their analysis highlighted seven drivers of functionality to which the functions have been linked through this report. The seven drivers of functionality are developed in section 5.2 above and are consistent with the findings presented immediately above in section 9.1. Like the collective set of *thirty-five* functions, these drivers of functionality appear to be common across the different scenarios, concepts and pathways against which the GB power system might develop:

1. The enhanced need for designed-in flexibility and agility for identifying and responding to changing requirements.
2. The change in mix of electricity generation to achieve policy targets, including the use of sources that are weather dependent or confer a low contribution to system stability compared with traditional sources.
3. The emerging need for aligned incentives enabling customers to benefit from responding to price signals and the system to operate more efficiently.
4. The emergence of new parties providing new services to customers.
5. The requirement for active management of network, generation, demand and other services using smart network techniques.
6. The challenge of managing major events, emergencies and system recovery as the power system becomes increasingly complex and more interactive with its customers.
7. The emerging need for coordination across energy vectors.

These drivers of functionality not only create the need for *thirty-five* functions identified but also are features of the architecture of the future system (e.g. flexible in both planning and operation, interacting with more participants than today, depending on many new services, requiring new forms and extents of active management, crossing energy vectors and infrastructures). These architectural features need to be seriously considered as roles and responsibilities for their consideration and implementation crosses existing boundaries of responsibilities within the power sector.

To fully and properly address these drivers of functionality and system architecture requires new approaches.

The conclusions and recommendations building on these findings have been presented in section 3.

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“The drivers of functionality not only create the need for the *thirty-five* functions identified, but also are features of the architecture of the future system. Serious consideration is needed here as implementation crosses existing boundaries of responsibilities within the sector.”

## 10. Acknowledgements

This project has been delivered with the essential inputs of a wide range of contracted and volunteer participants. The IET and the Energy Systems Catapult acknowledge these valuable contributions.

The lists below provide the full set of contributors to March 2016. The following individuals have contributed their time and expertise to this project. Their participation does not necessarily imply endorsement of the findings of the project by the organisations they are affiliated to. The report is by the IET and the Energy Systems Catapult and addressed to DECC and to relevant stakeholders.

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The following list of organisations had representatives at the FPSA project workshop(s) and/or stakeholder engagement activities. These individuals either represented themselves or the organisations they work for. This list is provided to give the reader an understanding of the breadth of engagement across the industry. This report is not representative of the views of the organisations listed below:

ACS, Alcatel Lucent, Analysys Mason, Andromeda Capital, Atkins, Bath & West Community Energy, BEAMA, BMT Hi-Q Sigma, BSRIA, Carbon Trust, Cardiff University, Centrica, CGI, Chiltern Power, CIBSE, Counterfactual Consulting Ltd, DECC, Digital Systems Catapult, DNVGL, E4Technology, EA Technology, EDF Energy,



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## 12. Document Control and Approval

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B	22/03/2016	FPSA Project Team	FPSA Steering Group	FPSA Steering Group	Revision including substantial ongoing drafting and responses to stakeholder inputs and PDB (18/03/16) feedback.
C	29/03/2016	FPSA Project Team	FPSA Steering Group	FPSA Steering Group	Revision based on DECC input, PDB review at meeting on 24/03/16 and wider discussion.
D	07/04/2016	FPSA Project Team	FPSA Steering Group	FPSA Steering Group	Revision based on DECC feedback on draft versions to date.
E	08/04/2016	FPSA Project Team	FPSA Steering Group	Project Delivery Board	Revised and approved at final PDB review.
F	12/04/2016	FPSA Project Team	FPSA Steering Group	Joint Sponsors Board	Revised and approved at final JSB review.

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# 13. Glossary

## 13.1 Key terms

Phrase	Definition
Active Management	The means by which real-time interactions with, or between parts of, the power system are undertaken in order to ensure that the network operates satisfactorily. The alternative is passive management whereby the network is designed to cater for all credible scenarios.
Aggregators	Parties that enter into contractual arrangements with clients to assemble portfolios of dispatchable energy resources (e.g. flexible generation, demand and/or storage) in order to provide system balancing, constraint management and other ancillary services to a system or network operator.
Ancillary Services	Technical services provided to a system or network operator in order to support the real-time operation of the power system.
Asset	Any physical part of the power system (including but not limited to generation and network assets) including customers' assets, which affects the capacity of the system (or part of that system) to deliver power.
Black Start	The procedure to recover from a total shutdown of the power system without access to external electricity supplies. It can also be used to speed the recovery from a partial shutdown of the network.
Cold Start	A procedure to restore supplies to a part of a power system that has suffered an interruption of supplies where latent demand and/or loss of demand diversity precludes all supplies being restored simultaneously.
Community Energy Managers	Managers of either geographically bound (physical) or virtual energy communities whose role is to manage the demand/generation of community members and possibly the trading of energy/ancillary services on behalf of the members. The objective could be energy cost minimisation, maximising revenue opportunities or include broader issues such as lowering carbon emissions or providing social benefit.
Concept	Any configuration of systems that can be explored as a means by which the GB power system may be shaped for the future. (See exploratory concepts, derived concepts and core concepts for each stage in the process).
Constraints	A limitation on the capacity of any part of a power system to transport power, for example due to an asset rating limitation, stability consideration or network outage.
Core Concepts	A concept emerging from the final down selection of derived concepts and representing an option for the FPSA that is sufficiently mature to merit active consideration by DECC. Collectively, the four Core Concepts identified are intended to cover the range of viable approaches for the power sector to take and therefore provide a framework within which all functions of interest should be defined. There are four core concepts: see list an end of glossary.
Cross Vector	A matter which takes into consideration the impact of the electricity power system on other vectors (e.g. gas, heat, transport etc.) or vice-versa.

Phrase	Definition
Curtailement	A form of Active Management to automatically reduce load, either imported or exported, to a level that the power system can accommodate at a given moment in time. Curtailement contracts with distributed weather dependent generators can reduce costs or delays in providing a connection and permit higher levels of generation capacity to be connected the network.
Derived Concepts	A concept built from combinations, or down-selection, of exploratory concepts to build consistent, coherent and complete high level models of viable strategies by which the FPSA could realistically be implemented by 2030.
Dispatch	An action requested of, or undertaken by, a party to the power sector to assist in the operational management of the power system (for example increasing generation output or reducing demand).
Demand Side Response (DSR)	The actions of a customer or group of customers in response to a command or signal (including price signal) to reduce or increase demand taken from the power system, including through dispatch of the customer's own generation or storage.
Exploratory Concept	An early concept that explores the implications of one or more issues or study cases, concentrating on the impact they create and making no attempt to consider realistic options for the FPSA.
Function	The purpose, roles, capabilities, etc. of the power system discharged by one or more parties to the power sector in order to fulfil an identified requirement. Functions are distinct from both the systems that implement them and the requirements identified. Collectively, the functions will deliver the requirements identified.
Extended Function	A function that is either not currently implemented or will need to be extended to cover new requirements and will not be sustained without directed effort from the power sector.
Future Energy Scenarios	Scenarios updated annually by the National Grid to assess the impact of the main drivers affecting the future generation mix and demand characteristics. There are four, see the list below.
Generation Portfolio	All the sources of generation of electrical power supplying the GB interconnected electricity system, including generation and storage connected to all networks and consumers' installations.
Incident	An occurrence of a set of circumstances that give rise to local or national stress in the power system that requires specific management actions (including autonomous) to resolve.
Operating Environment	The socio-political, economic and technical realities, current and future.
Peer to Peer	Between similar parties or actors; denoting an activity operating freely within a broad rule set, and where the nature and volumes of interaction are mutually agreed between the parties (e.g. two domestic customers in close proximity agreeing to trade electrical energy between themselves).
Power Network Joint Vision	An IET cross sector initiative to establish a joint view of change, challenges and potential solutions for the emerging and transitional issues in the GB power system.
Power Sector	All actors who have an interest in the production and consumption of electrical energy, including government, regulators, producers, consumers and intermediaries, acting collectively or individually.

Phrase	Definition
Power System	All physical assets directly associated with the generation, transmission, distribution and storage of electricity, including meters, communication, control and monitoring systems, and customer owned appliances that respond to controls or tariff price signals and/or provide power system services including DSR and frequency response.
Private Network	A network of discrete assets that are under a single ownership but operated without a formal legal electricity transmission or distribution licence.
Public Network	A network of discrete assets that is operated under one or more formal legal electricity transmission and/or distribution licence(s).
Requirement	A statement of need that expresses the interests of a stakeholder.
Smart City Operators	An actor who coordinates multi-vector energy use and the associated trading across a defined geographic region. The SCO may or may not have effective operational control of generation and demand and of private network assets. A SCO might operate a Virtual Network.
State Estimation	A means to derive an estimated value for a network variable (e.g. load flow) from direct measurements made elsewhere on the system or to detect and correct suspect data.
System Emergency	An incident, or related incidents, that give rise to a significant challenge to the power system nationally or locally, and where unusual steps need to be taken to protect the power system and to preserve supplies or to restore them as quickly as possible.
System Operability	The ability of one or all of those actors responsible for scheduling consumption and demand to achieve a forecast operating point that does not violate any physical limits of assets, does not subject any actor to inappropriate security risks and is appropriately affordable.
System Operability Framework	A GBSO annual publication based on internal analysis and external stakeholder input that sets out the challenges, initiatives and potential solutions for existing, emerging and anticipated system operability challenges.
Virtual Network	A set of energy production and consumption devices in common or various disparate ownership that can be scheduled by a single actor, irrespective of their physical location.

## 13.2 Abbreviations

The following abbreviations are used in this report and expanded in full at first usage:

AC	Alternating Current
ADMD	After-Diversity Maximum Demand
ANM	Active Network Management
BAU	Business As Usual
BEMS	Building Energy Management System
CAISO	California Independent System Operator
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage (or Sequestration)
CEC	California Energy Commission
CHP	Combined Heat and Power
CORES0	Cooperation of Electricity System Operators
CPUC	California Public Utilities Commission

DC	Direct Current
DCC	Data Communications Company
DECC	Department for Energy & Climate Change
DER	Distributed Energy Resources
DFIG	Doubly-Fed Induction Generator
DG	Distributed Generation
DMS	Distribution Management System
DNO	Distribution Network Operator
DRP	Distribution Resource Plan
DSR	Demand Side Response
DSO	Distribution System Operator
DSP	Distribution System Platform
DUoS	Distribution Use of System (pricing)
EMR	Electricity Market Reform
ENTSO-e	European Network of Transmission System Operators for Electricity
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas (Texas ISO)
ESCO	Energy Services Company
ESQCR	Electricity Safety Quality and Continuity Regulations
EV	Electric Vehicle
FES	Future Energy Scenarios
FIT	Feed-In Tariff
FPSA	Future Power System Architecture
GB	Great Britain
GBSO	Great Britain System Operator
GHG	Green House Gas
HAN	Home Area Network
HEMS	Home Energy Management System
HV	High Voltage
HVAC	Heating, Ventilating and Air Conditioning
HVDC	High Voltage Direct Current
IET	Institution of Engineering and Technology
IOU	Investor Owned Utility
ISO	Independent System Operator
IT	Information Technology
LCNF	Low Carbon Network Fund
LCT	Low Carbon Technologies
LV	Low Voltage
M2M	Machine-to-Machine
MV	Medium Voltage
MW	Mega Watt
NIA	Network Innovation Allowance
NIC	Network Innovation Competition
NIC	National Infrastructure Commission
OT	Operations Technology
Ofgem	Office of Gas and Electricity Markets
PNNL	Pacific Northwest National Laboratory
PNJV	Power Network Joint Vision
PTPT	Peer-to-Peer Traders (or Trading)



PV	(Solar) Photovoltaic
R&D	Research & Development
RIIO	Revenue = Incentives + Innovation + Outputs (Ofgem price control mechanism)
RFP	Request For Proposal
SCADA	Supervisory Control and Data Acquisition
SO	System Operator
SOF	System Operability Framework
T&D	Transmission and Distribution
ToU	Time of Use
TO	Transmission Operator (sometimes Owner)
TRL	Technology Readiness Level
TSO	Transmission System Operator
UK	United Kingdom
US	United States
V2G	Vehicle to Grid
VSC	Voltage Source Converter

## 14. Appendix: Presentation of the *Thirty-Five* Identified New or Extended Functions for the GB System

This section presents the remaining twenty-eight identified new or extended technical functions for the GB power system, these can be found in the Functional Matrix available online via [www.theiet.org/fpsa](http://www.theiet.org/fpsa) or [es.catapult.org.uk/fpsa](http://es.catapult.org.uk/fpsa) and are summarised in Figure 3 of this report.

**Driver of Functionality:** The enhanced need for designed-in flexibility and agility for identifying and responding to changing requirements.

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This section presents the remaining functions most closely linked to this driver of future power system functionality and architecture.

- **Function:** Enable the power sector to respond readily to change, and ensure the timely introduction and implementation of new functions [Function 0.1]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o Should be initiated immediately and developed as required (work may have already begun).

This function is needed because the rate and extent of change within the power sector and its operating environment is driving the need for a more responsive and flexible system in order to harness opportunities and manage threats as they arise. These require the power sector to continuously monitor its objectives and operating environment, and manage necessary changes across the sector including by introducing additional functions beyond those identified by this report. This new functionality will need to address the requirements presented by the prevailing scenarios and policies, the growth of smart solutions, the prevalence and scale of demand side intelligence/participation, disruptive technologies etc. A strong horizon scanning and R&D agenda along with interaction with the sources of a wide array of potential new participants and solutions in the GB system is anticipated. A core, growing modelling and analysis capability<sup>16</sup> is expected to play a role in the implementation of this function. This might create new requirements and new technical and commercial processes that need to be adopted seamlessly across the whole sector to match customer and policy-maker requirements for change and the changing external landscape and shifting background assumptions underpinning the prevailing/legacy approaches adopted in the power sector.

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<sup>16</sup>IET GB Power System Modelling Capability Reports. Available online at: <http://www.theiet.org/sectors/energy/resources/modelling-reports/>

- **Function:** Identify, counter and learn from threats to operability of the power sector from all parts of the power sector both above and beyond the meter. [Function 2.1]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o This function requires wider cross system collaboration and coordination.
- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to pre-empt and assess future threats and challenges to enable the GBSO, DNOs and any other operators and stakeholders to take the necessary action in a timely manner. For example, new flexible business models are developing, effectively extending the boundaries of the power system beyond the customer meter. These can have major impacts on the power system so addressing these new challenges of scale and complexity at investment planning stage is necessary. If not considered these may have detrimental effects in the planning and operation of the future system and frustrate new generation, storage and demand technology integration as well as consumer and community freedom and system flexibility opportunities. The SOF has identified issues that arise from lower and more variable system strength (fault levels and inertia) leading to prolonged disturbances, deeper voltage dips and lower-order harmonic resonance across Transmission and Distribution (T&D) systems, as well as increased rate of change of frequency on loss of a major infeed and potential protection coordination issues. All of this requires the identification and management of threats to system operability. This new functionality will extend the analysis to cover the distribution networks and 'beyond the meter' impacts arising from microgeneration, storage, heat pumps, electric vehicle charging and new electricity usage patterns, in the same depth as currently undertaken for transmission.

- **Function:** Monitor the impact of customer needs on system operability and propose solutions as necessary [Function 2.2]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o This function requires wider cross-system collaboration and coordination.
- o Should be initiated immediately and developed as required (work may have already begun).

This function is required because the power sector needs to coordinate and harmonise interventions by market participants in order to exploit synergies and avoid conflicts that could threaten whole system operability (including security, efficiency and sustainability drivers). Aggregators, Community Energy Managers and other new entrant participants could cause demand and production transients by allowing or initiating unmanageable step changes in demand and production. New services such as NEST (a form of HEMS) are currently able to develop and operate without taking account of system

issues. Problems could be caused by uncoordinated/deliberate actions or maloperation of implemented control schemes at different scales and locations. If the correct relationships and coordination is developed these stakeholders could provide a substantial benefit to the operation of the power system. The requirement is to ensure the operability of the system whilst minimising the constraints placed on customer/user flexibility. This new functionality would track developments in customer behaviour (e.g. responses to changing prices) and developed assets and infrastructure, predict when this might challenge operability and propose solutions.

- **Function:** Identify and counter cyber threats to operability of the power system originating from inside and outside the power sector [Function 2.5]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.

This function is needed to identify the needs and develop a plan to provide much higher levels of detection, protection and response to cyber security threats and incidents. The extents of power systems IT systems are expanding in areas such as critical command and control systems, and for systems used to exchange commercial information necessary for the operation of the power system. There are likely to be many more potential sources of cyber-attack as the power system develops and becomes increasingly interdependent. These controls include management measures such as incident response plans, as well as technical controls such as firewalls. A successful attack on critical network control systems, active demand or generation management systems, or price/control signal-based demand response systems could lead to major disruption and prolongation of system outages of different scales. However, it is important to recognise that there is no fail safe: for example, a firewall blocking valid data in error could also compromise system control. This requires the power sector to have the capability to foresee threats and their sources (e.g. beyond traditional power system boundaries), detect, protect from, and respond to incidents which impact the confidentiality, integrity, and availability of critical control and commercial functions, including the data required for those functions. This new functionality involves identifying and delivering the cyber security requirement for each new element of information and communication technology implemented.

**Driver of Functionality:** The change in mix of electricity generation to achieve policy targets, including the use of sources that are weather dependent or confer a low contribution to system stability compared with traditional sources.

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This section presents the remaining functions most closely linked to this driver of future power system functionality and architecture.

- **Function:** Provide a mechanism to ensure the portfolio of generation and other dispatchable energy resources and ancillary services delivers carbon, security of supply, and affordability policy objectives [Function 1.1]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed as a planning measure to forecast the emissions, costs and security levels of the proposed system (network, generation fleet and portfolio of service contracts) to create the frameworks and mechanisms to ensure investment in the most appropriate assets. The decisions for generation procurement are expected to be market based but with ongoing government policy intervention for different types and scales of production assets. The function to forecast the emissions for a particular generation portfolio must be based on data and analysis managed within the power sector. Modelling and planning are core components of understanding the impact of possible generation portfolios and their interactions with other resources such as responsive demand and energy storage. A key requirement is to assemble a national portfolio of generating plant, distributed energy resources and ancillary services that can be called on to deliver lower carbon and higher security objectives, and provide the ability to manage it in operational timeframes whilst maintaining the operational integrity of the whole power system. Final decision making on procurement may be external but the power sector needs to be able to influence the selection and delivery processes. This requires the power sector to be able to influence, deliver and manage the future generation portfolio and other resources and predict the greenhouse gas emissions, security and likely economy-wide and energy retail costs for future generation portfolios. This extended functionality covers existing and new players including government and regulators, DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators, and consideration of storage and new services. This extended functionality needs to be sufficient to deliver adequate volumes of energy sources, and to incorporate carbon, cost and security.

- **Function:** Plan for the timely restoration of supplies following a national failure (Black Start) [Function 2.6]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.

This function is needed to counter threats effectively, including planning for Black Start capability, which is essential for security of supply purposes. The current means of providing Black Start will need to be reviewed. It is expected that the load factor of thermal stations will fall and so ensuring that a critical number of them are kept warm will have increasing financial and environmental costs. The coordination of self-dispatching generation and virtual communities will be complex. There is also likely to be an increasing reliance on VSC connected DC interconnectors and these present

new system electrical characteristics but also create new opportunities in the stable operation of the system. This requires securing Black Start capability under all credible future generation portfolio and demand scenarios. This new functionality would deliver the Black Start plans needed to take account of: reduced quantities of controllable, readily available synchronous generation; new potential sources of capability and managed flexible loads; and growing levels of heat pumps and EV charging having low or zero diversity upon restoration.

- **Function:** Enable settlement for all existing customer profile classes to support flexible tariffs [Function 15.2]

**Function Timeframe:** Settlement

**Trigger Points and Prerequisites:**

- o This function requires enhanced and widespread metering, monitoring and communications.

This function is needed to align the financial incentives for customers with an enlarged portfolio of different types of energy sources and the mechanisms and systems to support this. This requires the capability to recognise, record and reward customer responses to cost-reflective incentives such as tariff price signals. The continuation of settlement by profile class is a disincentive to suppliers to depart from traditional flat-rate or simple two-rate tariffs since settled volumes would not reflect actual usage patterns or provide the tools and incentives to unlock required customer flexibility. This new functionality would provide the incentive for suppliers to introduce new innovative tariffs that reward flexibility and align with overall system operation requirements. Delivery of the function would require the active use and overall system integration of advanced half-hourly or smart meters to unlock demand response across all customer types.

**Driver of Functionality:** The emerging need for aligned incentives enabling customers to benefit from responding to price signals and the system to operate more efficiently.

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This section presents the remaining functions most closely linked to this driver of future power system functionality and architecture.

- **Function:** Collate and distribute information throughout the power sector on the availability and performance of the portfolio of generation and other dispatchable energy resources and ancillary services, as well as any associated operational restrictions [Function 6.1]

**Function Timeframe:** Operational Planning

**Trigger Points and Prerequisites:**

- o This function requires wider cross system collaboration and coordination.

- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to ensure that all relevant power sector stakeholders have current information of assets and services that can influence system operations and that will support operational decision making by multiple stakeholders. It is difficult to imagine effective operational planning in a more complex/diverse future system without enhanced information flows to enable it. This requires having appropriately complete and timely information on the availability of physical assets, their operational capability and commercial flexibility to system operational needs. This extended functionality covers new players including DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators and consideration of storage and new services and so is a considerable upscaling and also significantly enhanced scope (in terms of types, location and ownership) from current approaches.

- **Function:** Collate and distribute information throughout the power sector on the performance of demand, the portfolio of generation and other dispatchable energy resources and ancillary services in order to enable settlement [Function 14.2]

**Function Timeframe:** Settlement

**Trigger Points and Prerequisites:**

- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is closely aligned with the requirement for information to support operational planning so could involve similar participants and common information infrastructure. This function is needed to address the sheer number of customer demand management actions that will likely become too high to manage through existing approaches, if the full benefit is to be achieved. Also, many customers will expect these actions of settling their commercial positions to be taken for them in a way that is practically invisible to them while other new participants will make it their business to navigate and provide services in settlement. This requires the capability to introduce secure, automated M2M information exchange without compromising the explicit or hidden interests of customers. This new functionality, in particular any standard control hierarchy or commercial behaviour, has yet to be designed. Trials of aspects of such enhanced settlement mechanisms are being undertaken, but not at scale. With a significantly larger scope and scale of energy and system services settlement across many new participants (as well as existing) completely new means of settlement are envisaged.

- **Function:** Provide aligned financial incentives across the power sector including through innovative or flexible tariffs [Function 15.1]

**Function Timeframe:** Settlement

**Trigger Points and Prerequisites:**

- o This function requires wider cross system collaboration and coordination.
- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.

This function is needed so that customers, both demand and generation, have controlled exposure to the variable prices on the system and so have appropriate incentive to modify their production and consumption behaviours. Limitations due to low (economic) elasticity of electricity demand will require meaningful price signals (based on marginal cost of network or generation capacity/output) for price signalling alone to be effective as well as specific commercial vehicles for specific system services. This requires the means to align financial incentives across generation and demand, transmission and distribution, licensed and non-licensed participants, and energy storage flexibilities by using innovative or flexible tariffs that better align prices with marginal costs and value. This new functionality would create the financial incentives needed by the system but that have yet to be established and also the means of aligning and coordinating financial incentives to achieve overall whole system objectives across all stakeholders.

- **Function:** Provide a mechanism for peer to peer trading with appropriate charging for use of the power sector [Function 15.5]

**Function Timeframe:** Settlement

**Trigger Points and Prerequisites:**

- o This function requires wider cross-system collaboration and coordination.
- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to address the anticipated significant interest in peer-to-peer trading so it is in the interests of the power sector to establish attractive and common processes for doing so. This requires the enablement of peer-to-peer trading for individuals and communities and mechanisms to share use of system costs equitably. This new functionality, which would deliver a suitable peer to peer trading scheme, has yet to be made widely available to customers.



- **Function:** Monitor and settle the delivery of contracted demand, the portfolio of generation and other dispatchable energy resources and ancillary services [Function 16.3]

**Function Timeframe:** Settlement

**Trigger Points and Prerequisites:**

- o This function requires wider cross system collaboration and coordination.
- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to provide an appropriate level of certainty that the required energy and system services will be delivered if System Operator, Network Companies, Suppliers, Aggregators etc. are relying on demand management in lieu of capacity. This requires confirmation that contracted demand, generation and other dispatchable energy resources and ancillary services commitments are being met with remedial action taken where they are not. This new functionality would extend to all customer types including domestic (although action or penalty associated with non-delivery would likely be proportionate to commercial value and system impact). As with other significantly scaled up information dependent functions, this function would likely share information infrastructure with a number of other functions. With new system actors, participants and stakeholders, it is envisaged that information sharing, system service delivery monitoring and assurance, financial settlement and dispute resolution will be significantly different from prevailing approaches.

**Driver of Functionality:** [The emergence of new parties providing new services to customers.](#)

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This section presents the remaining functions most closely linked to this driver of future power system functionality and architecture.

- **Function:** Provide the ability to move between different modes of overall operation in the event or threat of a system emergency [Function 2.4]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o This function requires wider cross-system collaboration and coordination.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to prevent loss of supplies and restore the system following a major outage/Black Start in a timely manner utilising actions from a significantly greater

and wider set of system participating parties. This requires planning the emergency procedures to be used to either avoid the loss of supplies or speed restoration resulting from anticipated and secured events (that might also have a wider scope than today). This new function would involve emergency procedures taking account of new parties (e.g. Community Energy Managers), smart technology on distribution networks and at customer sites, and issues associated with Cold Start. This may require the suspension of normal commercial processes as incidents are managed in an ‘emergency mode’ of operation. The transition to ‘emergency modes’ of different types and scales and transition back to ‘system normal’ state will likely require numerous new and enhanced control functionalities across the system and its participants if material disruption and economic loss are to be avoided from more complex disruption events in a more complex power system.

- **Function:** Provide mechanisms by which planning can be coordinated between all appropriate parties to drive optimisation, with assigned responsibility for security of supply [Function 5.1]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o This function requires wider cross-system collaboration and coordination.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to better coordinate planning across relevant parties and so improve accuracy of forecasting and whole system optimisation of planned investments and developments of the GB system. This requires having the capability to coordinate planning across all engaged stakeholder organisations in timeframes sufficient to allow effective investment planning. This new functionality will integrate new players into the planning process including DSOs, Community Energy Managers, Private Networks, Smart City Operators and Aggregators. This will also properly include consideration of new energy sources, new customer demand flexibility, energy storage and other new services. Complexities are expected from multiple competing value streams, licensed/unlicensed and regulated/unregulated participants and stakeholders and distinctly different planning options and alternative asset investments aimed at the same objectives, as well as increased levels of planning uncertainty.

- **Function:** Collect outage information from all parties of significance within the power sector, coordinate with affected parties, identify clashes and resolve, with assigned responsibility for security of supply [Function 7.1]

**Function Timeframe:** Operational Planning

**Trigger Points and Prerequisites:**

- o This function requires wider cross-system collaboration and coordination.
- o This function requires enhanced and widespread metering, monitoring and communications.

- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to ensure that all relevant power sector stakeholders have up to date knowledge of planned outages of assets that can influence system operations in order to support operational decision making. This requires maintaining visibility of the planned availability of significant network assets, generation, demand side resources, storage capacity and ancillary services. This extended functionality needs to properly address new players including: DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators and consideration of storage and new services.

- **Function:** Provide an operational planning process that engages with all affected stakeholders [Function 9.1]

**Function Timeframe:** Operational Planning

**Trigger Points and Prerequisites:**

- o This function requires wider cross system collaboration and coordination.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to share plans appropriately across system operation participants and stakeholders in support of coordinated operation of the system in real time. This requires visibility of operational planning processes across all relevant parties in relevant timeframes ahead of real time control and system balancing. This extended functionality could build from existing approaches but will need to properly integrate new players including DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators and consideration of storage and new services. The available and/or required responses from all participants will need to be shared and assessed with planned preventive and corrective actions identified to ensure secure and economic system operation. This function is expected to be technically challenging especially with larger scale and scope of system participation with new actors and devices/technologies playing a role in the future system. The functionality to share information, assess operability and optimise planned/scheduled responses across these new devices and participants does not exist, nor does the information, communication and control infrastructure.

- **Function:** Coordinate the roles and value propositions of all significant stakeholders across the power sector [Function 15.3]

**Function Timeframe:** Settlement

**Trigger Points and Prerequisites:**

- o This function requires wider cross-system collaboration and coordination.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to coordinate the otherwise unilateral and uncoordinated commercial/market driven actions by parties that could compromise whole system optimisation. This requires coordination of commercial arrangements between energy retailers, Aggregators and Community Energy Managers so that contracted positions from diverse participants and production/storage/consumption technologies align with each other and with an overall whole system economic outcome. This new functionality clarifies and coordinates the roles and value propositions of Suppliers, Aggregators, Smart Cities and Community Energy Managers. This requires that the technical means of this coordination is aligned with the commercial and market functions and that new roles and responsibilities are recognised and facilitated in regulation and relevant stakeholder licenses.

- **Function:** Provide a market process that facilitates active engagement of customers [Function 16.1]

**Function Timeframe:** Settlement

**Trigger Points and Prerequisites:**

- o Must be implemented before the introduction and influence of new players on the system reach a critical level.

This function would provide the necessary technical integration of active customers, aggregators, community/municipal energy managers etc. into overall system operation through appropriate interfaces and information infrastructure. This function is needed to prevent unnecessary investment in network and generation capacity through failure to fully leverage the demand management capability of customers. This requires facilitating the active engagement of customers by, for example, enabling smart city and community energy schemes to participate appropriately in the overall system commercial arrangements and thus contribute through energy, balancing, flexibility and other services. This new technical functionality would support accompanying market mechanisms that fully leverage the demand management capability of customers. There are challenges in implementing this function through the scale and diversity of active customer and participant types, the timeframes involved and the many technical services and commercial arrangements to be supported.

- **Function:** Provide a full range of customer choices including individual, community and smart city services [Function 16.2]

**Function Timeframe:** Settlement

**Trigger Points and Prerequisites:**

- o Should be initiated immediately and developed as required (work may have already begun).

This function is needed as customer engagement will be more widespread if customers have access to a diverse range of system and market integration mechanisms. This requires allowing all customers to have choices, e.g. individual, city, community and independent schemes, and then being able to integrate those customer choices into a

coordinated system. This new functionality would create customer access and freedom of choice that includes smart city and community energy schemes.

**Driver of Functionality:** The requirement for active management of network, generation, demand and other services using smart network techniques.

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This section presents the remaining functions most closely linked to this driver of future power system functionality and architecture.

- **Function:** Forecast all demand, generation and other dispatchable energy resources and ancillary services within the power sector [Function 3.2]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.

This function is needed as transmission and distribution network constraints will arise in unforeseen ways if forecasting models are unable to predict the peak demand impact of Low Carbon Technologies (LCT), reverse flows due to DG and demand shape impact of ToU tariffs and DSR. The accuracy of these forecasts will need to be monitored, implying the measurement of generation and demand across public and private networks and the application of advanced data and analytical techniques. This requires the capability to forecast generation and demand across public and private networks. Virtual networks will be picked up via their physical connection points, as happens for large generating companies in current system arrangements. This new functionality will draw in active participants and more active management of the distribution networks, so more parties will need to be included such as Community Energy Managers, Virtual Network Operators, Private Network Operators and Smart City Operators. Additional complexity arises from the many new technologies and operating modes to be forecast but also from the different smart grid control arrangements that will govern their operation and hence impact on system planning.

- **Function:** Ensure that monitoring is in place to support the use of active system management [Function 3.3]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o This function requires enhanced and widespread metering, monitoring and communications.
- o Should be initiated immediately and developed as required (work may have already begun).

This function is needed as distribution network designs based on traditional After Diversity Maximum Demand (ADMD) principles are likely to be inadequate to accommodate LCT demand or have unused/stranded capacity. More granular monitoring of voltage and network flows will be required to support real time control and system balancing and this will need to be planned and implemented ahead of requirement so adding to the system planning challenge. This recognises that a range of new types of participants with control over distributed energy resources (and some of which have primary objectives not linked to optimising the wider power system) are emerging and have the potential to grow with accompanying impact on the power system. At scale, such new participants would form significant parts of the whole power system and would be involved in operational control. New generation and demand-side technologies being developed and deployed within the power system confer new opportunities and challenges to the operation of the system but will need to be integrated with data, communications and control infrastructure to enable the benefits to be realised. This new functionality would access additional data to enable the assessment of capacity and surpluses/shortfalls as an input to load forecasting and identification of emerging local network constraints. Smart metering will play a key role in delivering this function.

- **Function:** Use smart technologies to maximise the capacity of the power sector to accommodate the connection and integration of new demand, generation and other dispatchable energy resources and ancillary services [Function 4.1]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o Should be initiated immediately and developed as required (work may have already begun).

This function is needed as traditional reinforcement solutions will need to be augmented with techniques for managing national, regional and local peak system demands and/or DG/DER exports and temporary capacity shortfalls. This will include commercial instruments, active network management and plant rating enhancement techniques. This requires development of the power system to accommodate changes in both generation and demand, using both network assets and active management of distribution systems. This extended functionality would incorporate active management of distribution networks (and similar smart solutions) into forward investment planning options. This will consider an economic mix of network assets, smart technologies, innovative tariffs and demand control contracts.

- **Function:** Review the power system's developing operational characteristics to validate the assumptions made during the investment planning process [Function 5.2]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.

- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed to ensure that any deficiencies with planned network and system interventions are identified and rectified. This requires review of investment plans when significant differences emerge between the data used in the planning process and current expectations and observed system behaviours. This extended functionality addresses the greater reliance on control of customer demand and new sources of flexibility and will require engagement with customers, Community Energy Managers, Private Networks, Smart City Operators and Aggregators, as well as consideration of storage and new services to ensure that relevant information is available when required. New techniques for analysing the prevailing system operation against the planned system characteristics and new remedial solutions (including non-wires solutions) will be required.

- **Function:** Forecast and model all generation and other dispatchable energy resources and ancillary services with operational, cost and security implications for the power sector [Function 8.1]

**Function Timeframe:** Operational Planning

**Trigger Points and Prerequisites:**

- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.

This forecasting function is needed to ensure that all relevant power sector responsible licensees and stakeholders have necessary current and forecast future information of system status to ensure optimal operational decision making and remedial action planning. The greater uncertainty of future generation and demand requires that network security is tested for a full range of credible outcomes expected to be greater in number and more complex than today. It will also be important to identify and manage the potential range of costs from transmission, distribution and other system constraints as an essential part of operational forecasting. This requires having the capability to forecast generation, storage, demand and other services within operational planning timescales, across all public and private networks and with the technical characteristics as well as economic profiles of different assets and services included. Virtual networks will be picked up via their physical connection points, as happens for large generating companies now. Existing functionality needs to be extended to cover new players including DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators and consideration of storage and new services.

- **Function:** Enable the dispatch of demand, other dispatchable energy resources and ancillary services within the power sector to deliver system security and maximise the use of low carbon generation at optimal overall cost [Function 8.2]

**Function Timeframe:** Operational Planning

### Trigger Points and Prerequisites:

- o This function requires wider cross-system collaboration and coordination.
- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.

This function is needed to address the growth in distributed and variable energy profile assets and the need to optimise their operation and reconcile that with system operational requirements in order to meet overall policy objectives of security, sustainability and affordability. This requires being able to dispatch power and energy flows across the GB system for optimal reconciliation of national, regional and local needs and likely to include self-dispatch coordinated with organised market dispatch. Existing functionality needs to be extended to cover new players such as DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators and consideration of storage and new services.

- **Function:** Identify by modelling and simulation constraints arising from credible events/faults and plan remedial action [Function 9.2]

**Function Timeframe:** Operational Planning

### Trigger Points and Prerequisites:

- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.

This function is needed to ensure that operational timescale plans for emergency response are put in place. This requires planning of remedial actions for all credible scenarios and faults and the application of new techniques to model the operation of a more complex system with new technologies, participants, commercial mechanisms, smart control infrastructure and 'latent' operational arrangements behind the meter.

This is an extension of existing functionality to cover new players in the power sector including DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators and consideration of storage and new services.

- **Function:** Identify available generation and other dispatchable energy resources and ancillary services and associated operational restrictions in real time [Function 10.1]

**Function Timeframe:** Real Time and Balancing

### Trigger Points and Prerequisites:

- o This function requires wider cross system collaboration and coordination.
- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.



This function is needed to ensure that all relevant power sector stakeholders are integrated into real-time control and balancing and that system operational responsible parties have access to current information of the system assets available for operations in real time and the flexibility these afford to whole system operation. This requires being able to confirm availability of physical assets and operational capability against operational plans and then track and respond to system requirements and operational dynamics as they develop in real time. Existing real time control and balancing functionality needs to be extended to incorporate new players including DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators and consideration of storage and new services.

- **Function:** Monitor the effectiveness of, and execute as required, remedial action for the delivery of demand control, generation constraint and other actions in response to all events/faults [Function 11.1]

**Function Timeframe:** Real Time and Balancing

**Trigger Points and Prerequisites:**

- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.

This function is needed to implement active management of the whole power system with the anticipated additional degrees of operation and possible normal and corrective responses to real-time requirements. Without appropriate real-time controls with monitoring and correction of the operational outcomes, the ‘fit and forget’ system management philosophy would prevail and investment in current system operational headroom would have to be retained, requiring significant expenditure in reinforcement. This requires putting in place market mechanisms and smart capabilities to ensure an effective real time response to system events or faults across the power system. This extends existing functionality to cover new players including DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators and needs access to the full range of options including smart capabilities, commercial actions and customer demand management.

- **Function:** Coordinate demand, generation and other dispatchable energy resources and ancillary services within the power sector to deliver system security and maximise the use of low carbon generation at optimal overall cost [Function 11.2]

**Function Timeframe:** Real Time and Balancing

**Trigger Points and Prerequisites:**

- o This function requires wider cross system collaboration and coordination.
- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand side technologies and associated control systems reach critical levels.

This function is needed to coordinate otherwise unilateral action by individual parties, which would likely be detrimental to the optimal reconciliation of national, regional and local system needs and overall objectives of economy, security and sustainability. This requires being able to dispatch power across GB for optimal reconciliation of national, regional and local needs. This new functionality will enable responsible system balancing and control authorities to be able to dispatch power across the whole power system for 'optimal' delivery of security of supply and carbon output in real time. This would likely require taking the engineering challenge of integrating the existing energy production and consumption assets and their controls with new assets and participant systems into overall coordinated real-time control and system balancing infrastructure with delegations of control responsibilities as appropriate.

- **Function:** Provide monitoring and control of those parts of the system under active management, including network assets, demand, generation and other dispatchable energy resources and ancillary services [Function 12.1]

**Function Timeframe:** Real Time and Balancing

**Trigger Points and Prerequisites:**

- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.

This function is needed to provide effective monitoring and state estimation to enable the power system to be actively managed. Without such monitoring a 'fit and forget' philosophy must be adopted, possibly requiring additional expenditure in reinforcement. This requires effective monitoring and state estimation of generation, demand, energy storage and multiple other asset types across the power system to provide responsible control authorities with the necessary information on system real time state to enable effective control in a much more complex, diverse and dynamic system. New functionality is required to provide monitoring and state estimation throughout the 11 kV and 400 V networks in order to enable active management and the appropriate aggregation and information exchange to relevant system control stakeholders. Smart metering data has a role to play here.

- **Function:** Provide automated and secure management of demand, generation and other offered energy resources and auxiliary services, including Smart Appliances, HEMS and BEMS [Function 14.1]

**Function Timeframe:** Real Time and Balancing

**Trigger Points and Prerequisites:**

- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.

This function is needed to address the number of customer demand management actions being too high to manage manually, if full benefit is to be achieved. Also, customers will expect these actions to be taken for them in a way that is practically invisible to them. This requires having the capability to introduce secure M2M automation without compromising the explicit or hidden interests of customers. This new functionality required, in particular any standard control hierarchy or commercial behaviour, has yet to be designed. Trials of aspects are being undertaken, but not at scale.

**Driver of Functionality:** The challenge of managing major events, emergencies and system recovery as the power system becomes increasingly complex and more interactive with its customers.

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This section presents the remaining functions most closely linked to this driver of future power system functionality and architecture.

- **Function:** Plan for the timely restoration of supplies following a prolonged local failure (Cold Start) [Function 2.3]

**Function Timeframe:** Investment Planning

**Trigger Points and Prerequisites:**

- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.
- o Must be implemented before the introduction and influence of new players on the system reaches a critical level.

This function is needed as temporary cold pickup demand, exacerbated by latent demand and loss of diversity following a prolonged interruption, may exceed network ratings leading to thermal overloading and potentially partial voltage collapse. This requires a Cold Start capability under all credible future generation portfolio and demand scenarios. This new functionality would deliver Cold Start capability to restore services after long outages to cope with zero diversity of heat pumps/EV.

- **Function:** Enable the delivery of demand control, generation constraint and other actions in response to all extreme events [Function 13.1]

**Function Timeframe:** Real Time and Balancing

**Trigger Points and Prerequisites:**

- o This function requires enhanced and widespread metering, monitoring and communications.
- o Must be implemented before disruptive generation, demand-side technologies and associated control systems reach critical levels.

This function is needed to provide effective response to system emergencies, to provide the means of all parties and all potential actions to be coordinated to minimise the impact and hasten the recovery by changing the mode of operation of the overall system and cascading this modal change through all relevant integrated sources of event response. This requires being able to coordinate all relevant assets and system participants to minimise the consequences of a system incident and to restore the system in a timely manner. Existing functionality needs to be extended to cover new players in the power sector including DSOs, Community Energy Managers, Private Networks, Smart City Operators, Aggregators and consideration of energy storage and new services. There is a challenge in integrating the many new potential participants in contingency response but also potential benefits to be gained in mitigating many of the impacts of major events through additional means of response.

### **Driver of Functionality:** The emerging need for coordination across energy vectors.

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This section presents the remaining functions most closely linked to this driver of future power system functionality and architecture.

- **Function:** Assess the impact of gas and other energy vectors when forecasting the volumes of demand, the portfolio of generation and other dispatchable energy resources and ancillary services on the power sector [Function 3.1]

**Function Timeframe:** Investment Planning

#### **Trigger Points and Prerequisites:**

- o Should be initiated immediately and developed as required (work may have already begun).

This function is needed to properly and effectively consider relevant dependent energy infrastructures in planning the power system so as to avoid overinvestment and stranded capacity in the power sector. If forecasting underestimates the use of dual fuel heating (e.g. hybrid heat pumps) or the arbitrage effect of reducing electricity peak demands, then the planned system would not be efficient. Network constraints may also arise if power flows increase due to higher than anticipated CHP output or use of the system from other related energy sources of use (e.g. other energy vectors used for energy storage or transportation or related to new uses in heating and transportation). Interactions between the power system and heat networks will also need to be considered. This requires having the capability to consider potential cross-vector impacts on electricity demand across physical and virtual networks. This new functionality could enhance the existing System Operability Framework and Future Energy Scenarios (FES) to include cross-vector aspects, e.g. dual fuel heating.

- **Function:** Collaborate with other energy sectors to optimise across multiple sites and vectors [Function 15.4]

**Function Timeframe:** Settlement

**Trigger Points and Prerequisites:**

- o This function requires wider cross system collaboration and coordination.
- o Should be initiated immediately and developed as required (work may have already begun).

This function is needed as there is likely to be major interest in peer-to-peer trading and it is in the interests of the power sector to establish attractive and common processes for doing so. This requires enabling peer to peer trading for individuals and communities. This new functionality would deliver a suitable peer-to-peer trading scheme that has yet to be made widely available to customers.

## 15. Appendix: Supplemental Online Resources

The following project resources have been developed and are core to the identification and development of the technical functions and their analysis. These supplemental resources are hosted online on the Institution of Engineering and Technology and the Energy System Catapults' websites [www.theiet.org/fpsa](http://www.theiet.org/fpsa) and [es.catapult.org.uk/fpsa](http://es.catapult.org.uk/fpsa):

- Systems Engineering Methodology
- Functional Matrix
- Function Sequencing Grid
- International Study

## 16. Appendix: Detailed Project Background

This FPSA project was commissioned to determine the technical challenges and potential functional requirements to inform the design and operation of the future electricity system in GB. It considers new risks, impacts and emerging innovation, and the implications, if any, for achieving a satisfactory future physical architecture of the system.

The project sets out, and provides evidence for, what functions will need to be performed in the future power system as a result of on-going transformative changes and by when. A horizon of c2030 has been considered.

The objectives for the project were agreed with DECC and the over-arching goal is to gain a representative view of future requirements, rather than an exhaustive, detailed study of the current system or a detailed design of a future system. It has considered current assumptions and practices and their evolution for maintaining a secure system into the future.

The project did not examine what institutional form will be required to support those functions, or which new or existing bodies should undertake them, but focused on what the proposed functions will need to achieve in order to manage the technical challenges facing the system. The wider context may well be relevant to addressing the technical issues, so institutional and commercial aspects have been noted where they arose.

The project has been systematic and has sought robust conclusions. Structured requirements-based systems engineering methods (also termed system engineering formal methods) are viewed as a key part of the methodology. A holistic approach, considering the end-to-end power system is a core requirement of the work.

The emphasis in the FPSA project has been on a sufficient, rather than exhaustive analysis of future system requirements and functions and on the end-to-end electrical system with a horizon year of 2030.

The project builds on the work over the last 2 years by the IET's Power Network Joint Vision (PNJV) expert group. The timescales for delivery of this current FPSA project were constrained and a compressed approach to this stage of the work has been adopted. To assist this, the successful working arrangement used for the IET's work with the Council for Science and Technology (CST) is being adopted. This approach brought together the best available specialists and integrated their work through a synthesis process<sup>18</sup>.

The IET's PNJV expert group has helpfully set out some of the most important technical challenges facing the GB power system in the context of its ongoing transformational change<sup>17</sup>. They further highlighted that not all of these might be adequately addressed through existing industry and regulatory structures. The particular challenges regarding future system architecture were further studied with the conclusion that system architecture

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<sup>17</sup>IET PNJV: 'Handling a Shock to the System', position statement and full report, December 2013.

<sup>18</sup>The academic papers from this IET work for CST are at: <http://www.theiet.org/sectors/energy/resources/modelling-reports>.

was a major issue and that lessons could be learned from other sectors and countries on managing complex system architecture challenges in periods of transformative change<sup>19</sup>.

### 16.1 IET Power Networks Joint Vision (PNJV) work completed to date

The IET has led the way in bringing together power sector expertise to deliver projects that have cut through issues of importance for the power sector in Britain.

- The IET 'Shock to the System' report established an authoritative and comprehensive set of challenges facing the GB power system and came to the view that these emerging challenges go beyond the normal pace and scale of change and should be classed as major transformative change that requires an appropriate significant response.
- A further IET study explored how other sectors have dealt with the type of whole system integration issues that face the electricity sector with the conclusion that there are highly pertinent lessons to be learned and experience to be gained in the area of system architecture and its governance.
- The IET study into the case for System Architect function to be developed in the GB power systems sector acknowledged the organisational and governance challenges with system architecture but presented the case for a system architect function (not a person such as a Chief Engineer or necessarily a new body) to be seriously considered given the scale of the challenge faced.
- A further IET study (this time for the UK Government's Council for Science and Technology (CST) examined the emerging and future power system modelling challenges and set out an agenda for modelling capabilities to be developed to meet the challenges.

This body of previous work sets the background and creates a foundation for the FPSA project. The wide expertise gathered in the resources created by these IET projects has provided useful contributions and reference points in the delivery of the FPSA project.

The issues with PV, heat pumps electric vehicles and decentralised energy, and the System Operability Framework responses to these issues, are presented below.

### 16.2 Specific new challenges to the power system

#### **Photovoltaics (PV)**

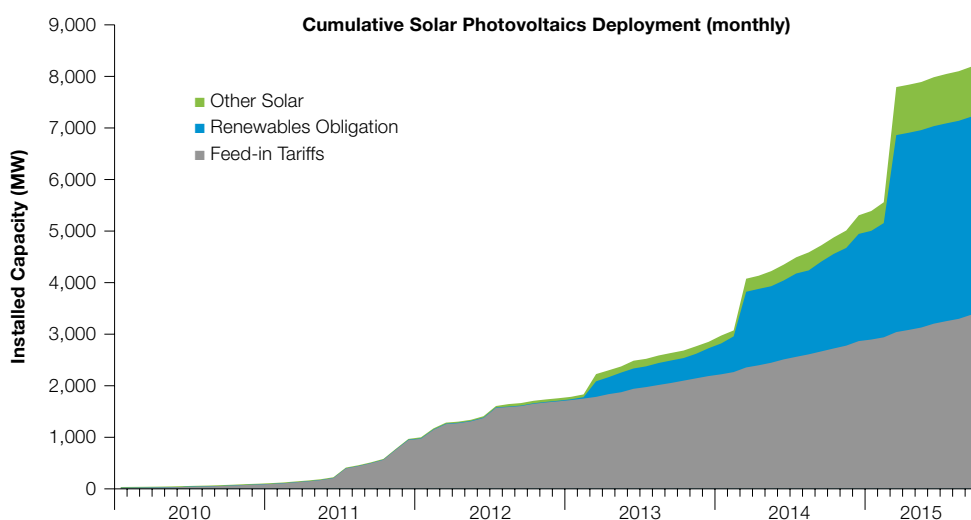
Solar PV has experienced rapid growth in the last 2–3 years and scenario projections have increased to reflect continuation of this trend into the future. The 2013 *Gone Green* projections were 6.0 GW by 2020 and 13.5 GW by 2030 and in FES 2014 this had risen to 7.5 GW by 2020 and 15.6 GW by 2030. The installed PV as at November 2015 already exceeds 8 GW and this serves to illustrate the pace of change in such developments. [Source DECC: Installed Capacity PV Publication URN: 15D/430].

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<sup>19</sup>IET PNJV: 'Transforming the electricity system: How other sectors have met the challenge of whole-system integration', October 2014.  
IET PNJV: 'Britain's power system (the case for a system architect)', December 2014.



Figure 4: Cumulative Solar PV deployment in UK, 2010–2015<sup>20</sup>



The DECC currently predicts 12 GW by 2020 (c.f. 13.8 GW in FES 2015 *Gone Green* rising to 23.3 GW by 2030). Not illustrated are the similar growth rates for Electric Vehicle (EV) and electric Heat Pumps (HP) to 2020 with much more expected by 2030 (12 million EVs and nearly 8 million residential HPs).

### Heat pumps

Domestic ground and air source heat pumps can be installed with conventional heating controls. However, smart home and heating systems (e.g. Nest and Hive) are becoming more popular and when these are implemented into homes with heat pumps then these become controllable loads.

FES 2015 *Gone Green* indicates that 5.1m Domestic Heat Pumps (mostly air source but with a modest amount of ground source) would be installed by 2030.

If we assume that:

- The average heat pump is rated at 1.7 kW.
- Approximately 30% of the installed domestic heat pumps are connected to a Smart Home or Smart Heating System.
- On average, approximately 30% of the heat pump load can be flexed.

Then approximately 1.0 GW of domestic heat pump demand can be seen as controllable and dispatchable load.

This is 2% of the predicted peak demand in 2030 according to National Grid's scenarios.

### Electric Vehicles (EVs)

It is assumed the all modern electric vehicles are sold with remote charging management capabilities as standard. In practice, this means that the user will have an application or similar that will display charging and other data and they will be able

<sup>20</sup>Installed Capacity PV Publication URN: 15D/430

to schedule charging. This capability can be easily extended to enable the back-end system to manage charging directly.

*Gone Green* projects that 3.3m electric vehicles will be in use by 2030.

If we assume that:

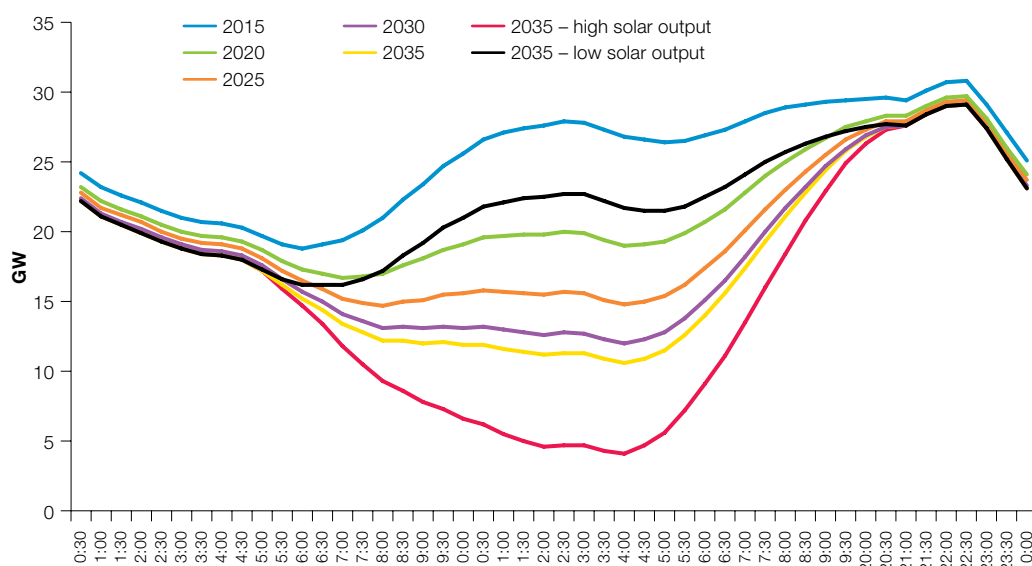
- The average EV charges at 3.5 kW.
- EVs are ‘available’ for an average of 10% of the time (plugged in and not fully charged).

Then 1.2 GW of EV demand can be seen as controllable and dispatchable load. This is 2% of the predicted peak demand in 2030 according to National Grid’s scenarios. (Note: these impacts are similar to those for Heat Pumps according to the assumptions made in the analysis.)

### Managing distributed energy

Solar PV (mostly micro and distributed), with the associated cloud transient phenomena, is projected to be responsible for ~17 GW of swing in system load within a single day by 2030 (See Fig. 5 below or Fig. 96 in the 2015 FES – ‘Consumer Power’ scenario, p. 183–184).

Figure 5: GB system demand ‘swing’ projection for 2030 from National Grid’s Future Energy Scenarios (2015) – Consumer Power scenario<sup>21</sup>



The 2015 SOF expands on the scale of the challenge in operating a system where many of the controllable and responsive resources are connected to distribution networks, and the Active Network Management (ANM) schemes deployed to manage and control distributed energy are adding further unpredictability and complexity to system operation.

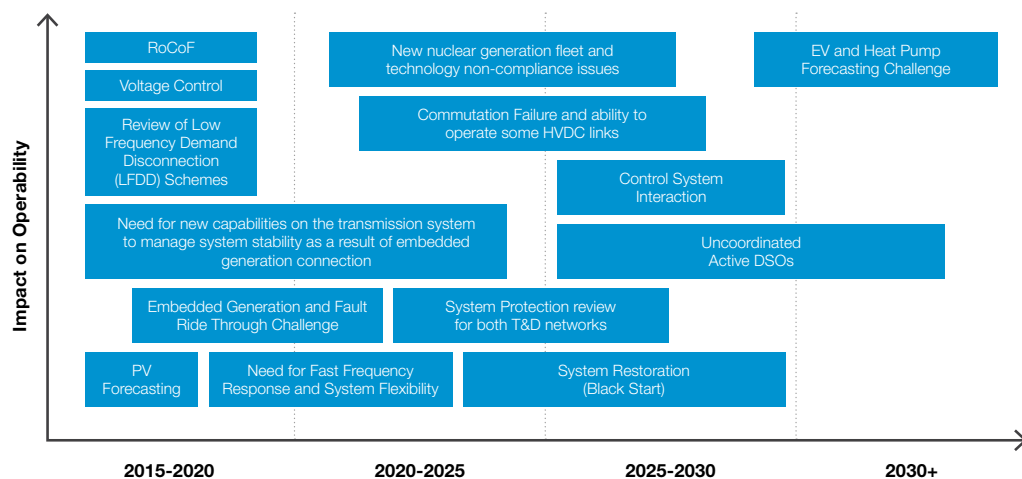
<sup>21</sup>‘Consumer Power’ scenario, Fig. 96, p. 183–184, 2015 National Grid’s Future Energy Scenarios.

‘Without sufficient coordination between the System Operator (SO), transmission, and distribution companies, the immediate impact of ANM schemes on the overall system operation is the increased uncertainty for short-term demand forecasting and interactions between SO and ANM actions. In the longer-term, as explained in the System Inertia section, it may be expected that a large proportion of the fast frequency response requirement will be provided by the distributed service providers embedded within the DNO networks, therefore the interaction between these and the ANM schemes that may be active in the same area will need to be understood and defined.’

### The GB system challenges in the SOF 2015

The System Operability Framework (SOF) noted above is a helpful document and identifies a number of important operational challenges for the GB system (the diagram below is from the 2015 SOF Summary published in Nov 2015 alongside the full SOF). Furthermore, the document demonstrates that many of these will require a whole-system approach. Evidently the solutions to many of the challenges will involve multiple parties through the GB supply chain, including National Grid, the DNOs, Generators, Customers and Communities. It will be important to explore the matters that arise here, such as who is accountable for ensuring coordinated solutions where they span multiple parties and, where detailed work is necessary, who will fund and resource the necessary research, development, modelling, analysis and interfacing with external parties who are not established parties in today’s sector and its institutional arrangements.

Figure 6: Timeline of System Operability Framework Challenges<sup>22</sup>



### 16.3 Relevant other work and inputs from the sector

In addition to the prior work of the IET PNJV Expert Group and the commissioned projects delivered as set out above, there are other highly relevant sector activities that provide excellent foundations for this project on Future Power System Architecture. The Project Delivery Board members were asked<sup>23</sup> to suggest the most relevant projects and these are briefly summarised below:

<sup>22</sup>Timeline of System Operability Framework Challenges, System Operability Framework Summary, National Grid, November 2015.

<sup>23</sup>Future Power System Architecture (FPSA) Project Delivery Board (PDB) Meeting Minutes, 22 July 2015.

- **Smart Grid Forum Work Stream 3 – ‘Transform Model’<sup>24</sup>**: The findings are that emerging distribution network challenges can be economically addressed with the deployment of alternative, non-traditional, innovative, smart solutions. The volume and pace of roll-out of the new solutions increases to substantial levels in the period to 2030. The architecture of the system to integrate the new solutions was not in the scope of this work.
- **Smart Grid Forum Work Stream 7 – ‘Distribution System 2030’ project<sup>25</sup>**: Findings provide a technically detailed engineering insight into the operability of the future distribution network, selected whole-system issues and identify smart solution integration technical challenges. The project governance, wider stakeholder consultation and deeper analytical approach are distinguishing features of this project.
- **National Grid Future Energy Scenarios 2015<sup>26</sup>**: The annual cycle of capturing stakeholder inputs, developing scenarios and consulting on findings is now well established. The findings from the recently published 2015 scenarios are that decentralised energy is causing major challenges for transmission system operation, but that large-scale (transmission bulk capacity, interconnectors, offshore) developments are a plausible parallel system development track along with the decentralised energy agenda. A slow progression in system impacting developments is also noted as a plausible but also challenging outcome in future years. The use of scenarios in this FPSA project is further explained in section 16.3.
- **National Grid System Operability Framework (SOF) 2014 and 2015<sup>27</sup>**: This recently initiated, and widely welcomed, annual process sets out the major challenges, both current and emerging through to 2035, in the operation of the GB transmission system and the new solutions required to stabilise, secure and address the emerging challenges. The challenges captured in the SOFs provide strong evidence for the system operational changes already starting to take place and point towards a set of possible directions and some solution that would form components within the future system architecture.
- **Innovation Projects**: The large portfolio of relevant, recently completed and ongoing innovation projects in the power sector form a valuable resource to this FPSA project. Notably, the innovation projects led by the power network operators<sup>28</sup> which point towards the implementation of innovative new solutions to meet the emerging challenges to the power system.

A call for interested partners, collaborators and suppliers<sup>29</sup> invited sector stakeholders to suggest further sources of relevant evidence for consideration in the delivery of the project and these have been used in the development of the project. Furthermore, the responding stakeholders and experts have become key to project delivery as Knowledge Area Consultants, Project Delivery Board members, Technical Working Group members and wider consulting stakeholders.

## 16.4 Future power system scenarios

To provide the contextual starting point for this FPSA project it was agreed that the National Grid’s Future Energy Scenarios (FES) 2015 be used as the point of reference for the project. National Grid’s FES is based on five primary drivers that underpin the

<sup>24</sup>Smart Grid Forum Work Stream 3 – ‘Transform Model’ findings (various documents available from Energy Networks Association).

<sup>25</sup>Smart Grid Forum Work Stream 7 – ‘Distribution System 2030’ project – Final Report signed off by WS7 in Mar 2016.

<sup>26</sup>Future Energy Scenarios 2015’, National Grid, 15 July 2015, available at: <http://fes.nationalgrid.com/>.

<sup>27</sup>‘System Operability Framework’, National Grid, 2014 and 2015, available at: <http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/>.

<sup>28</sup>Energy Networks Association, ‘Smarter Networks Portal’, <http://www.smarternetworks.org/>.

<sup>29</sup>FPSA: Future Power System Architecture (FPSA) Project - Call for Interested Partners, Collaborators and Suppliers’, 7 Aug 2015.

range of modelling inputs; these drivers are: political, economic, social, technological and environmental.

Figure 7: National Grid's Future Energy Scenarios 2015<sup>30</sup>



As Figure 7 illustrates, four scenarios are presented based on permutations (high/low) of green ambition and prosperity. Although both Slow Progression and Consumer Power make progress towards low carbon transition, only *Gone Green* achieves current targets for renewable energy and carbon emissions on time.

For the purpose of the FPSA project, *Gone Green* was used as the core scenario. Because it is anchored on delivering the challenging UK renewable energy targets, *Gone Green* will generally present the most challenging circumstances for the electricity system and give rise to the most demanding functional requirements over the period to 2030. However, in order to test sensitivity, it is proposed to also consider specific issues created by the Consumer Power scenario that assumes greater interaction with the electricity system by consumers and higher levels of distributed generation and microgeneration. For example, Consumer Power gives rise to more acute system balancing and stability issues in summer time, with the majority of electricity production entering the distribution system directly rather than via the transmission system. Table 12 illustrates the nature and the scale of the challenge of the *Gone Green* scenario for the 2030 GB system and provides further evidence of significant changes to many aspects of the overall system structure and that point towards the new or extended functionality explored in this project. Table 12 shows the main areas of GB power system development in the first column and quantification of the scale of that challenge in the second column.

<sup>30</sup>'Future Energy Scenarios 2015', National Grid, 15 July 2015, available at: <http://fes.nationalgrid.com/>.

Table 12: Quantifying the scale of the *Gone Green* scenario challenge for the 2030 GB system

The *Gone Green* scenario in 2030

Significant power system developments and challenges	The <i>Gone Green</i> scenario ( <i>National Grid, 2015</i> )
Increased reliance on intermittent generating sources such as wind and solar above the level that is easily assimilated.	Wind and solar capacity increase from 17 GW to 71 GW by 2030 – an increase from 18 to 46% of the total available capacity (GW) and from 11 to 39% of the electricity generated (TWh).
More decentralised power generation embedded in the distribution network or in individual properties, with microgeneration growing in prominence.	42 GW of distributed and micro-generation by 2030 (cf. 15 GW in 2014) – an increase from 17 to 27% of the total generating capacity.
More interconnection to other countries and grids – providing stability and flexibility but with some risks.	Interconnector capacity rises from 3.8 GW in 2014 to 17.7 GW in 2030, with electricity supplied rising from 7 to 13% of the GB total over the same 2014–2030 period.
Declining physical stability as heavy generating sets are decommissioned and power electronics is more widely used.	Coal and nuclear decline from 29% of installed capacity to 7% following coal phase-out.
Electrification of space and water heating: more heat pumps creating high demand and winter peak demand.	5 million air source heat pumps installed by 2030 – 1 in 6 of the 2030 housing stock – with a further 1.5m hybrid heat pump/gas boiler systems.
Electrification of transport: more electric vehicles creating new ‘tidal’ patterns of charging demand and high peak demands.	An increase from 19 674 (2014) to 3.3m electric vehicles by 2030.
Pervasive use of smart meters, making consumers more responsive to pricing, control of ‘smart appliances’ and easier switching between suppliers.	Rising from 12 000 smart meters installed in 2014 to 29m by 2030.
Time-of-use tariffs and smart appliances, and the behavioural response to these technologies.	These are expected to reduce peak residential demand by 3 GW by 2030.
More storage – either through new technology or through exploiting storage capacity in electric vehicles.	Not quantified in <i>Gone Green</i> . [If 5% of homes had a Tesla Powerwall or equivalent (7 KWh) in 2030, the storage capacity would be equivalent to the 1800 MW/10 GWh Dinorwig pumped storage facility].
The rise of smart cities, community energy schemes, virtual energy communities etc. These can create aggregated and coordinated synchronised behaviour.	Not quantified in <i>Gone Green</i> .

As a further sensitivity test, consideration was also given to the No Progression scenario that is the most benign in terms of challenges to the electricity system over the period to 2030. Although this scenario is inconsistent with low carbon transition, it presents a baseline against which the scale of the system challenges and functional requirements due to low carbon transition (as opposed to other drivers) can be gauged.

In summary, whilst other scenario sets could have been used, there are a number of advantages in selecting National Grid’s FES for the FPSA project:

- The FES rationale is comprehensive and supported by informative dialogue.
- The FES is public domain and freely available (free web download).
- The scenarios are developed with wide stakeholder input.
- The scenarios are derived ‘bottom-up’ rather than goal-driven.
- There is no (electricity) market sensitivity surrounding the scenarios.
- The scenarios are refreshed annually and hence always present a current best view.
- The scenarios are produced as a NG license condition and require wide industry engagement and support, including from Ofgem.
- The proposed FPSA scenario (*Gone Green*) meets UK’s renewable energy and carbon emission targets in the required timescale.
- Each scenario presents projections for overall electricity consumption, ACS peak demand and generation mix.
- Each scenario presents projections for electric vehicles, heat pumps, distributed generation and microgeneration, enabling distribution as well as transmission impacts to be assessed.
- The scenario projections track from 2005/06 through to 2035/36 and hence comfortably embrace the time horizon for the FPSA project.

# 17. Appendix:

## Project Approach and Methodology

### 17.1 Summary

- The FPSA project has used systems engineering methods in a structured and systematic approach to explore potential requirements for new or extended functionality in the GB power sector as it might be in 2030.
- This has involved extensive stakeholder inputs and independent evidence gathering including an International Study of systems with common challenges and characteristics to GB, Germany, Ireland and selected US states.
- The goal of the project has been to identify technical functions that predominately challenged the current institutional arrangements for delivery in the future and the project has succeeded in identifying and testing a number of new or extended system functions that are fully contextualised and justified through the systems engineering approaches (including requirements, functions, systems, and overall GB system concepts for 2030).
- The overall project methodology is supplemented by additional online resources as listed in an appendix in section 15.

### 17.2 Overall project methodology

The FPSA project developed and followed a structured approach to build a solid, evidence-based foundation for analysis of the challenges facing the power sector through analysis of technical functions. The main elements of the project methodology were:

- Establish key project inputs – scenarios, issues, international references and challenges including:
  - National Grid Future Energy Scenarios, 2015
  - IET PNJV Report ‘Transforming the Electricity System’, Oct 14
  - System Operability Framework (SOF) 2014 and 2015
  - Smart Grid Forum, WS7, ‘Distribution System 2030’ (‘DS2030’) Final Report, Mar 2016.
- Develop and analyse the base case and drivers for change.
- Apply systems engineering methods to create requirements, functions, systems and concepts with the main purpose of identifying new or extended functionality for the GB system in 2030.
- Structured and systematic evidence gathering and analysis methodology.
- International Study to provide another layer of evidence to further contextualise, justify and enhance the functional analysis and project outcomes.
- Analysis of the identified technical functions to produce the project findings.



### 17.3 Systems engineering principles applied in the FPSA project

The project has developed an overall project methodology, governance and stakeholder engagement mechanisms (set out initially in the Project Definition Document and also in the Initial Findings Report) based on systems engineering principles.

Some terminology used in this report has a specific meaning in systems engineering methods as follows:

- **Requirement** – a required outcome, such as controlling frequency – preferably solution independent.
- **Function** – an action to deliver a requirement or operate the system. Not all functions are requirements driven. Some are ‘enablers’. Many functions at a high level can be thought of as ‘services’.
- **Systems** – solutions to implement specific functions.
- **Concept** – a set of systems designed to facilitate functions to deliver a requirement.

Figure 8 illustrates the core systems engineering constructs that have been used in an iterative approach through the phases of the FPSA project.

Figure 8: The iterative systems engineering approach applied to the FPSA project

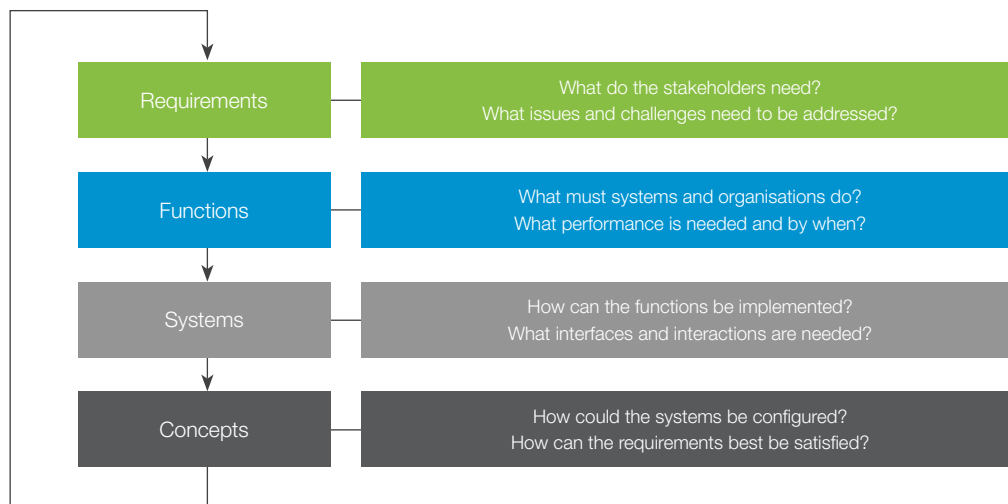
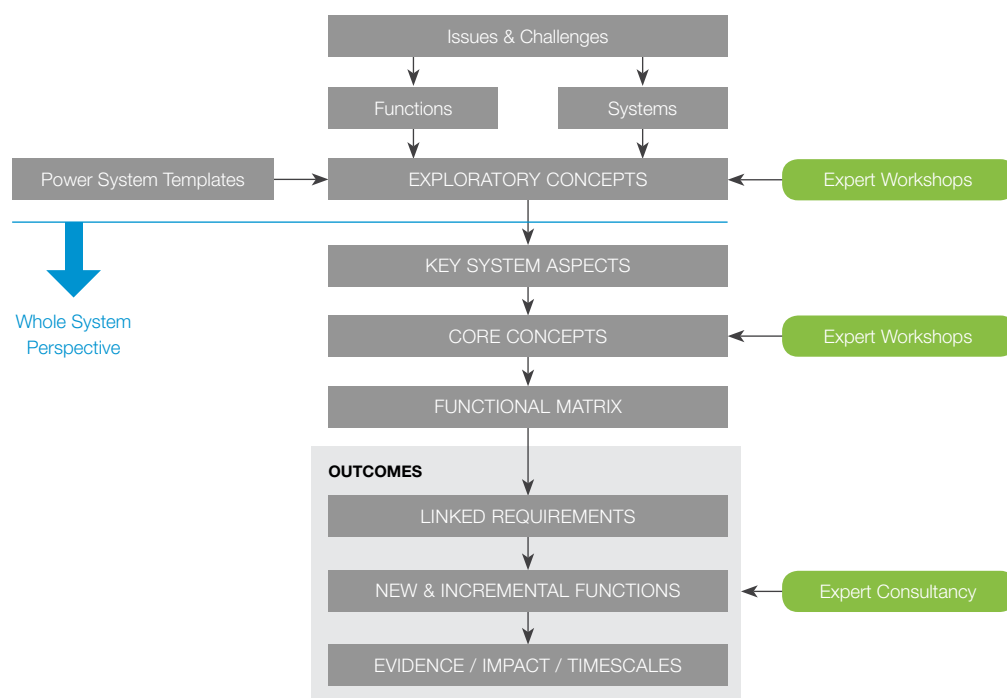


Figure 9 illustrates the broader systems engineering based approach adopted in the FPSA project and highlights the transition from the exploratory, individual challenge based activities to whole system thinking (i.e. assessing the technical functions in the light of the whole system) and then to the production of the project outcomes through consolidation, evidence gathering and analysis. This approach to the project is described in greater detail in a separate System Engineering Methodology document, which is available as an additional online resource as detailed in the Appendix in section 15.

Figure 9: Overview of the FPSA Project Methodology



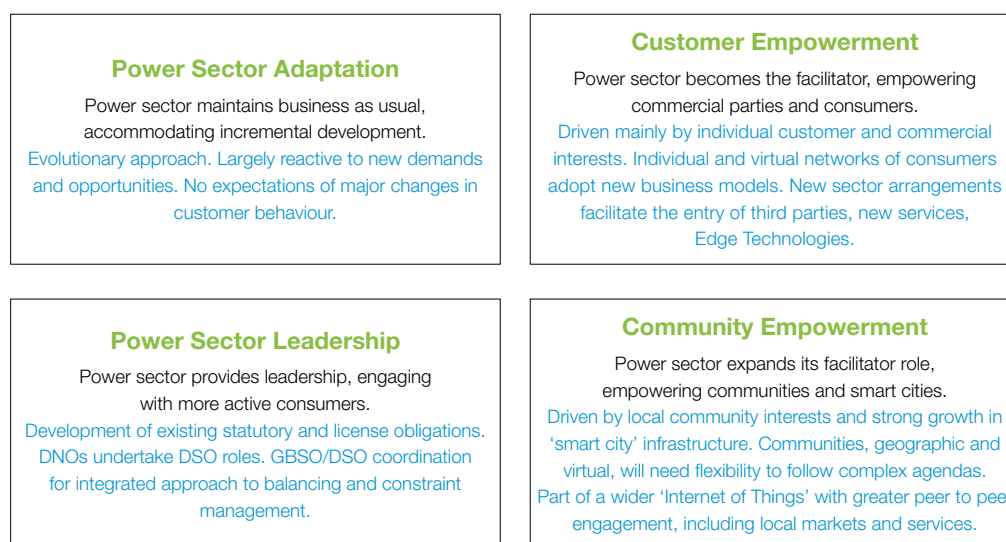
The questions addressed in the FPSA project and the approach taken (with the artefacts developed) is set out in Table 13. This illustrates the rigour in the methods deployed in delivering the project outcomes.

Table 13: Addressing key questions in the FPSA project

Question Addressed	Response
What issues and challenges demonstrate the need for change?	Use the Challenges Matrix to act as a partially structured set of requirements and a launch pad for technical investigations. Review earlier reports and stakeholder guidance.
How could the power sector respond to the individual issues and challenges?	Build exploratory concepts that consider the functions and systems needed within the power sector to address each technical issue.
What are the main aspects of the power sector that the functions need to support?	Develop the Key System Aspects matrix to span the range of production, consumption and network management considerations.
What options are there for addressing the main aspects?	Build themes linking related options in the Key System Aspects matrix to build a coherent pathway for the evolution and transformation of the power sector.
What functions are needed to support realistic transformations for the power sector?	Develop core concepts as whole system models of how the power sector could evolve to address all significant issues across the four time horizons.
What evidence is there to support the need and viability of the functions?	Research evidence of examples of need for and/or implementation of functionality (including trials) including through an International Study. Summarise findings with covering requirements in the Functional Matrix.
What is the impact of the most likely implementations?	Summarise the range of possible implementations with an impact statement in the Functional Matrix.
When and in what order do the functions need to be implemented?	Enter the sequence of events and the main triggers for function implementation in the Functional Matrix.

Core concepts are useful outcomes of the Systems Engineering methods that enable testing of the coherence of the new or extended functions and the analysis of the role, triggers and impacts/implications of the functions. The core concepts developed in the project are presented in Figure 10.

Figure 10: Overview of core concepts developed in the FPSA project



#### 17.4 Analysis of the identified functions

Several forms of analysis were conducted to further refine the Functional Matrix as well as to develop the project findings:

- Evidence Analysis
- Drivers, Triggers and Sequencing Analysis
- Functional (Deep Dive) Analysis
- Gap Analysis to produce assessment of new/extended functions
- Implementation Challenges Analysis
- International Comparison.

The results of these analyses are presented in the subsequent sections of this report.

#### 17.5 Stakeholder participation and contribution

Stakeholder engagement, participation, contribution and consultation have been a major feature of the FPSA project. An appropriate balance has been struck between the complexity and scale of very wide stakeholder participation and the breadth, quality and seriousness with which stakeholders have contributed and challenged the progress and outcomes of this work.

A significant input has been received on the project consultation around the Functional Matrix. An overview of the consultation on the Functional Matrix and a summary of the responses is provided in the Appendix in section 18.

The project has benefitted greatly from a range of inputs throughout the project (through bilateral conversation, stakeholder events and the consultation exercise) including:

- General project comments and direction
- Clarifications and definitions
- Updates to functional coverage and scope
- Suggested evidence
- Examples of implementations
- General and specific inputs to the Functional Matrix.

# 18. Appendix: Summary of Stakeholder Consultation on the Functional Matrix

## 18.1 Consultation overview

The stakeholder consultation consisted of the then current version of the Functional Matrix, background information on the project, a summary of the initial findings and a short consultation paper. In the consultation paper stakeholders were asked these four questions:

- QUESTION 1 The **first question** we would like stakeholders to consider is whether there is any key future function of the overall power system that is not represented in the matrix, or where that representation is critically deficient. In other words, are there any new rows of functions that are required, or do any existing rows require significant modification?
- QUESTION 2 The **second question** relates to the collection of evidence to support the future functions, and specifically, seeks confirmation that the evidence collected so far against the functions, and is summarised in the matrix in columns J and K, is appropriate and the best available.
- QUESTION 3 The **third question** also relates to the collection of evidence and comprises an invitation for stakeholders to contribute their own knowledge of evidence, i.e. to populate blank cells in columns J and K.
- QUESTION 4 The **fourth and final question** is to seek any comments on the functions, but particularly the timescales and impacts in columns L and M. Clearly, these include necessarily broad assumptions in some cases, but please indicate if you have a significantly different view from that expressed in the matrix.

The consultation was published on 21 January 2016, with responses requested by 11 February. Twenty-three written responses were received. The majority were from stakeholder organisations, although a small number were from individual expert stakeholders.

As might be expected stakeholders returned their comments in various forms, some using the templates provided and others in free format text. These responses were split into seventy-two separate points for consideration by the FPSA project.

## 18.2 Consultation responses

### **Question 1**

Approximately half the points related to the functions identified in the matrix, and of these the majority were underlining aspects that the project was already considering. There were a couple of helpful prompts from half a dozen stakeholders. The first was to recognise that the boundary between current DNOs and future community energy operators could become blurred over time, with new parties having a similar local role. A couple of respondents also reminded the project that there are existing activities, such as the production of the FES and SOF by National Grid, whose importance is likely to grow in more complex and uncertain futures.

Other salient points, although not necessarily directly new functions, included the effects of other energy vectors and the continual need to ensure that smart solutions represent value for money over 'traditional' solutions.

Several respondents made points, that seem to the FPSA project team to be points of detail, related to the implementation of functions, rather than the functions themselves.

These points included:

- The interaction between energy vectors is important as this could drive clustering of new Low Carbon Technologies (LCT) developments
- Better local forecasting is required
- The trade-off between reinforcement and active management
- Carbon intensity drivers
- Security of Supply Standards
- The need for appropriate planning tools
- Appropriate tariff structures and incentives are required
- Other existing components of functions, such as National Grid's Ten Year Statement and the DNOs' Long Term Development Statements
- The need to address power quality issues
- The effects of increased interconnectors to Ireland and the continent.

Many of the points suggest the need to have effective planning within the wider power sector such that changes in the sector did not adversely impact on any part of the sector to the detriment of customers.

### **Question 2 and 3**

Six respondents offered between them twelve specific examples that supported functions in the matrix, largely drawn from recent and current Low Carbon Network Fund (LCNF) projects that they suggested. Two of the six respondents suggested where additional evidence could be sought. These suggestions have been added to the collation of evidence associated with the relevant functions.

#### **Question 4**

A small number of respondents addressed the issue of timescales, although all via commentary rather than amendments to those in the matrix. These comments tended to underline the importance of understanding the sequencing of and triggers for functions, rather than produce concrete material that can be added to the Functional Matrix.

#### **Other points raised by respondents**

A variety of other points were made by respondents. Some of these, such as those relating to the supply of skills and trained staff, and the implications for losses, are out of scope of the project as they are not technical functions. Nevertheless, they are still important points and are alluded to in the final report.

A number of responses contained helpful suggestions for the implementation of future and existing functions. However, as these generally are solutions rather than functions, they have not been directly incorporated into the Functional Matrix.

One respondent offered the view that the Functional Matrix approach was already too prescriptive and comprehensive, leading to a constrained ability to innovate and change. A number of the comments (ten) provided direct or indirect advice on how to present the final report, or aspects of it.

One respondent provided compelling background evidence of the change in customer behaviour as seen by network companies, once demand-side behaviour and local generation is taken into account. The implications of this for how network companies plan and operate the system are profound, adding complexity to a number of functions.

One respondent made some pertinent observations about skills and capabilities in the wider power sector, particularly in non-traditional power sector players. Whilst the project team notes this concern, it is a matter for implementation, not for the validity of functions, so beyond scope.

A couple of respondents were not convinced that the *Gone Green* scenario was appropriately likely, and was therefore unsuitable.

A number of respondents offered other comments along the lines of suitability or otherwise of central planning versus market solutions. As the scope of the project is limited to identifying future functions rather than their method of implementation, these comments were noted as being out of scope.

### **18.3 Outcomes**

In the main, all the comments have either been addressed in the production of evidence, in the construction and wording of the Functional Matrix, or in the presentation of the final report.

A number of comments are not appropriate to accommodate, as outlined above.

All respondents will receive an individual response explaining broadly how the FPSA project has used their input.

## 19. Appendix: Summary of Evidence Collated and Linked to Functions

In addition to the high level summary of evidence linked to each function in the Functional Matrix the project has created a summary available as a supplementary online resource as detailed in the Appendix in section 15 of the evidence gathered according to the following categories. The evidence statements made under each area of evidence are aligned to appropriate functions in the Functional Matrix.

### ***Pace of change***

- Threats to power sector:
  - The new technologies, services and behaviours developing within the power sector present new, emergent and unpredictable threats to system operation.
- Existing 'horizon scanning' approaches:
  - Many players within the power sector already undertake their own activities to mitigate these threats.
  - These activities may fall short of what is required to assure whole power sector future operability and coherency.
- The importance of system resilience and flexibility:
  - Resilience to the emergent threats is best provided through increasing flexibility with the power sector.

### ***New business models and new players***

- The emergence and enabling of new business models:
  - A range of market players utilising new business models are responding to demands for a range of new energy services, and have the potential to present both threats to the status quo and opportunities to create new sources of value for stakeholders. Consultation suggests a need for more agile and flexible market design and regulation to enable these new business models.
- New players overview:
  - A range of new types of player, which have control over distributed energy resources, and some of which have primary objectives not linked to optimising the wider power sector, are emerging and have the potential to grow. New players include smart cities, social as well as commercial aggregators and virtual energy communities of various types, community energy schemes, and both off-grid and grid-connected private networks, in addition to DSOs. At scale, such players would form significant parts of the whole power sector and impact on operational network challenges.



- Distribution System Operators:
  - System operations at a distribution network level are increasingly needed to manage distributed energy resources, driving work to define the scope of Distribution System Operators.
- Aggregators and Community Energy Managers:
  - There is a significant number of community energy projects and virtual energy communities of various sorts in Great Britain already that in general will be attempting to optimise their own operations, and are likely to have other drivers beyond optimisation of the power sector.
- Private networks:
  - A range of different types of private network exists for a range of different reasons, with both off grid and grid-connected examples.
- Smart cities:
  - City initiatives, under the broad banner of Future Cities and Smart Cities, may well increase to a scale that becomes significant in the power sector, such that coordinated planning and operation will become increasingly important.
- Risk of unexpected demand shifts:
  - Large numbers of consumers using the same automated machine to machine (M2M) interfaces may present risks to the system in the form of unexpected shifts in demand.

### ***Customer engagement***

- Benefits of customer engagement:
  - There are significant potential benefits to be gained from an increase in customer engagement in the electricity system.
- Customer pull for engagement:
  - There is evidence of increasing activity and aspiration in customer engagement in the power sector.

### ***Innovative tariffs***

- Benefits of innovative tariffs:
  - There are significant potential benefits to be gained from the implementation of innovative tariffs.

### ***Peer-to-peer trading***

- Benefits of peer-to-peer trading:
  - Peer-to-peer energy trading has the potential to deliver greater returns for local generators, greater choice for consumers, social benefits from community engagement, and is broadly aligned with wider developments in the collaborative economy.
- The emergence of peer-to-peer energy markets:
  - Services to enable distributed energy to be directly traded in peer-to-peer marketplaces are beginning to emerge.
- Limitations of existing licensing options:
  - Increased local energy generation and new business models are part of the expected changes in the period to 2030. Successful local supply and local distribution arrangements are needed to support this.

### ***Growth of renewable and distributed generation***

- Operational threats to power sector:
  - o The new generation technologies being deployed en-masse within the power sector present new, emergent and unpredictable threats to system operation.
  - o Much work has been done under the LCNF and other innovation funding programmes to understand and mitigate these new risks and to benefit from the collaborative opportunities.
- Challenges to standard assumptions:
  - o The growth of low carbon generation technologies presents a challenge to the fundamental daily and seasonal predictability of the power sector. Standard planning assumptions, including the timing and magnitude of peak demand, may be challenged.
- Low carbon generation opportunities:
  - o A significant and growing portion of renewable, intermittent sources of electricity are connected as microgeneration beyond the meter.
  - o Intermittent and renewable generation deployment is a key feature of the development of new players and business models with the power sector.

### ***Growth of demand-side technologies***

- Demand-side response – advantages and existing technologies:
  - o There are significant potential benefits to be gained from demand side technology, such as demand-side response and Energy Management.
  - o Demand side response and ancillary services are already in operation within the system, including National Grid's balancing services and commercial aggregation service providers.
  - o Innovative demand side technology is being developed and implemented within the system already, including some demand side response and Energy Management.
- Uptake of low carbon technologies:
  - o There will be increasing uptake of low carbon technologies such as heat pumps and electric vehicles.
  - o Increase in low carbon technologies will have a significant impact on the system.
  - o Demand side technologies, such as smart meters, demand-side technologies and low carbon technologies, can support stability of the wider system.

### ***New network management***

- Opportunities:
  - o By reducing peaks on the transmission and distribution networks, DSR can reduce reinforcement costs for the TOs and DNOs.
- Threats:
  - o A future smart grid will lead to a massive scale-up in smart technologies and automated equipment in distribution networks to regulate voltage, fault current, power and reactive flows, and to dynamically reconfigure networks.

### **Multi-vector energy**

- Benefits of multi-vector:
  - o The benefits of multi-vector energy techniques are well accepted within the industry, and include flexibility, resilience and carbon reduction.
- Existing multi-vector activity:
  - o Some multi-vector thinking has taken place for local and city-wide planning and small, local multi-vector systems exist already.
- Limitations on development:
  - o Unchangeable features of the gas network may impinge on the power sector's abilities to de-carbonise.

### **Communications**

- Opportunities:
  - o The convergence of traditional power systems and operations with information and security technologies will provide an optimal data platform and framework that will fundamentally alter the future of our digital day-to-day life. The benefits are both holistic and discrete with many yet to be realised.
- Threats:
  - o New communications approaches have the potential to create new and emergent threats to the operability of the power sector. They also present vectors for the disruption of power sector operation by both accidental and deliberate mal-operation.

### **Modelling and simulation**

- Existing modelling and simulation approaches:
  - o Modelling and simulation of power flow and the stability of conventional power grids is a well understood and mature discipline.
  - o There are areas of significant strength in modelling other aspects of grid performance (carbon emissions, security of supply and cost to consumers) within current modelling practice, especially in relation to investment and operations planning.
  - o Current power system modelling approaches have arisen in an unsystematic manner, in response to the requirements of individual stakeholders, and therefore don't reflect the breadth of modelling approaches that will be required by the future power sector.
- Future modelling requirements:
  - o New models, and potentially new modelling approaches, are required in order to simulate the level of complexity in the future power sector.
- Modelling leadership:
  - o Concerted effort is required by the power sector to ensure that modelling and simulation is commissioned and conducted in line with established best practice.

## 20. Appendix: Summary of Evidence from the International Study (fact-finding)

An International Study (fact-finding) was commissioned within the project with the purpose of exploring electrical power sectors in other countries that are known to be facing similar system challenges to those we might envisage in future impacting the national GB power sector. The full report is available online, listed under the appendix in section 15.

A precise comparison between the countries and regions is not entirely straightforward, however, balancing individual viewpoints, programmes, declared issues and future plans in Table 14 below provides a correlation with the issues facing the GB system. Three ticks (✓✓✓) indicate a very strong correlation in that those issues are very relevant through to a cross (✗), which indicates that that challenge area is not particularly relevant or not expected at any notable scale.

Table 14: Comparison of drivers and challenges in the international comparator territories

Challenge Areas	Ireland	Germany	United States			GB (Gone Green Scenario)
			New York	Texas	California	
Distributed Generation	✓	✓✓✓	✓	✓	✓✓✓	✓✓✓
Heat pumps	✓	✓	✓	✗	✗	✓✓✓
Electric transportation (BEVs & PHEVs)	✓✓	✓	✓	✓✓	✓✓✓	✓✓
Microgrids and Community energy systems	✗	✓	✓✓	✓	✓✓	✓✓
Interconnections	✓✓✓	✓✓	✓	✗	✗	✓✓✓
Large scale renewables and inertia challenges	✓✓✓	✓✓✓	✓✓	✓✓✓	✓✓✓	✓✓✓

It was not the purpose of the International Study to advocate approaches adopted in other countries, or to recommend if, or how, initiatives or policies adopted for their electricity power sectors should be applied to the GB system. (Table 15 illustrates that quite different forms of industry structure and governance prevail in each of the chosen international comparators.)

Table 15: Industry structure and governance in international comparator countries

Power Sector Component	Ireland	Germany	United States		
			New York	Texas	California
Large Scale Generation	Competitive (privately owned)	Competitive (privately owned)	Competitive with some state owned	Competitive (privately owned)	Competitive (privately owned)
System Operations	Independent, though state owned	Performed by 4 privately owned Transmission companies	State owned independent system operator	State owned independent system operator	State owned independent system operator
Transmission	Owned and operated by two state owned companies	Monopolies, private ownership unbundled from generation	State owned and private/ competitive	Private - competitive	Private owned and regulated monopolies
Distribution	Owned and operated by two state owned companies	Largely owned by municipalities (circa 860)	Mainly private ownership with some municipals	Mainly private with some municipalities	Primarily through 6 IOUs and circa 55 municipalities
Metering	Distribution companies	Responsibility of distribution companies	Responsibility of distribution companies	Utility (DNO) led	Utility (DNO) led
Electricity Retail (Supply)	Competitive	Competitive	Competitive – ESCO or incumbent Utility	Competitive, DNO can also supply electricity	Decoupled regulated rates from utilities cover majority of the state
Customer engagement and Energy Efficiency	Supplier led	Energy Retailers	The DNOs, though there is an internal revenue decoupling	Energy retailers and utilities	Utility led

While the industry structures and governance arrangements are important context (in selection of the territories and proper understanding of the challenges and ways of addressing the challenges), the purpose of the study was to:

- Provide evidence of challenges currently being faced, or anticipated elsewhere.
- Discover how the relevant industry players and authorities in those countries are addressing or proposing to address those challenges; and
- Identify initiatives and policies that might be particularly relevant to the GB context.

Care has been taken to establish contact with reliable sources of information within the countries studied, and to ensure that the findings captured are factually accurate. By way of further assurance, peer reviews of the findings have been conducted where practicable. The International Study has looked at the main system level challenges facing the electrical power sectors of Germany, Ireland and the US (with a high level desktop study on South Korea). They correlate strongly with those facing the GB system, namely around:

- Integration of large renewable generation sources (and a corresponding reduction in system inertia).
- The growth in distribution-connected energy resources (distributed generation, electric vehicles, heat pumps, demand side response, energy storage).
- The trend towards microgrids, community energy systems and engaged customers.
- Greater interconnection with neighbouring grids, both AC and DC.

It is widely recognised that the effects of these represent both threats and opportunities to the successful planning and operation the respective power system. The potential scale of the changes and their materiality has led to greater system-wide thinking for those power systems from both technical and policy perspectives.

It is evident that a business as usual approach has been discounted as each of the countries (or regions in the case of the US) has developed new thinking to meet these challenges. They vary from a highly collaborating working forum with strong governance (Ireland) through to a radical overhaul of regulatory frameworks and markets (New York). Germany and other regions in the US are taking a broader systems-wide perspective to identify areas where roles and responsibilities need to evolve to meet these challenges.

These approaches are highlighting new functions required and identifying those that need to be significantly enhanced. For example, in New York a formal Distribution System Operator function is being created whereas California's Distribution Resource Plan (DRP) calls for a significantly enhanced distribution planning function that forecasts and models distributed energy resources for inclusion in long-term planning. All share the same purpose: to ensure their electrical power system remains resilient while incorporating technology evolution and maximising clean energy resources.

These approaches towards architecting the power sector are highlighting new functions required and identifying those that need to be significantly enhanced. For example, in New York a formal Distribution System Operator function is being created whereas California's DRP calls for a significantly enhanced distribution planning function that forecasts and models distributed energy resources for inclusion in long term planning. All share the same purpose: to ensure their electrical power sector remains resilient while incorporating technology evolution and maximising clean energy resources. The new functionality being implemented in New York is:

- **Distribution planning** – enhanced planning to incorporate DERs, value those resources and improve coordination with transmission planning.
- **Distribution grid operations** – improvements to load and network monitoring including effective multidirectional power flow to improve value from DERs.
- **Distribution market operations** – administer RFPs (Requests for Proposals), run auctions, commercial agreements, performance management of DERs and participants
- **Data access** – collection and provision of customer and distribution system data to facilitate a DER market and spur investment (respecting data privacy and security)
- **Platform technologies** – it is recognised that the different Investor Owned Utilities (IOUs) are at different technology advancement, this function sets a minimum standard to be met to enable a functioning DSP, namely the DER management system, geospatial system, optimisation tools and a communications network.

It is clear that the functions highlighted by the FPSA study resonate closely with the challenges faced in the reviewed countries and it seems accepted that wide ranging functional changes are going to be required to accommodate the evolution of the power sector to meet technology developments. A summary across the comparator countries of the functional and system architectural changes being made to address the challenges is presented in the following table.

Table 16: Response to power sector challenges in international comparator countries

Country	Changes
Ireland	<i>Changes:</i> Focus on ensuring system resilience as renewable penetration grows and technical issues become acute.
	<i>How:</i> Creation of a new collaborative programme (DS3) to bring together industry participants to discuss, analyse and agree on market and industry changes. Covers wide ground and although not ‘architect’ in name is considering a whole systems approach. The programme designed to be temporary but may pivot into a more formal role. All existing industry roles and responsibilities remain unchanged. Changes executed through established bodies and codes and updates to market mechanisms.
Germany	<i>Changes:</i> The energy transition that sets a policy of moving to a renewable economy phasing out fossil fuel and nuclear generation. It also aims to promote distributed generation and community energy systems.
	<i>How:</i> Primarily through long term generation and transmission planning with new investments, wholesale and balancing market developments and continued support for distributed generation through a variety of supportive feed-in-tariff type commercial and community ownership type arrangements.
US – New York	<i>Changes:</i> Creation of a formal DSO entity which will have greater responsibility for long term planning and integration of a variety of DERs.
	<i>How:</i> structural changes to the distribution and end user community involving creation of new markets, new entities and easier access for new market entrants all covered by new regulatory framework. Solutions and long term development of the networks will be largely market driven with greater long term planning to encourage innovation and system development. Begins to ‘unbundle’ the distribution network and allow market forces to prevail. Significant change to distribution companies’ role.
US – California	<i>Changes:</i> Focus on ensuring system resilience with growth in renewables and EV adoption. A number of change programmes in the sector assessing impacts and recommending solutions.
	<i>How:</i> California Energy Commission (CEC), California Public Utilities Commission (CPUC) and California Independent System Operator (CAISO) taking a greater role in guiding/ shaping the market to encourage more renewable generation and enabling distributed resources (storage, DER, DSR etc.). Main IOUs developing and implementing very broad demonstration programmes to prove technical and operational capabilities with changing resource mix. No plans for single or coordinated architecture. More decisive actions to guide solutions to manage system security in light of growing renewable penetration (e.g. storage mandate). Requirement for IOUs to produce longer term detailed plans (DRPs) explicitly valuing and accommodating DERs.
US – Texas	<i>Changes:</i> Greater penetration of renewables (primarily transmission connected wind) driving system operator challenges.
	<i>How:</i> No structural changes to industry roles envisaged. Greater planning and coordination between Electric Reliability Council of Texas (ERCOT) and regulator being taken forwards. No substantial structural changes to the distribution networks outside of implementation of smart grid technologies being taken forward by the IOUs following their own strategies. Creation of DSO still in early stages of discussion.

The key messages for the FPSA Study project and/or GB system considerations from the International Study are:

- The challenges faced by the GB electricity sector are similar to those faced in the other countries reviewed, however, none of them face all of them to a similar extent if we assume National Grid’s *Gone Green* scenario. For many varied reasons, not all of these challenges appear in any particular country to the same extent. This indicates that the scale of the change anticipated on the GB system is greater and potentially poses a greater coordination and integration challenge.

- Many experts consulted expressed the need for greater system-wide planning and indicated that they believed the scale of changes anticipated represented a real risk to system resilience and reliability if not fully coordinated. Equally the value that Distributed Energy Resources (DERs) can bring is being accepted, policies in the countries reviewed are aimed at promoting and encouraging the adoption of DERs.
- This review has identified a number of significant change programmes happening in these countries to meet these challenges. The approaches are varied, though all are pro-active and consistent in aiming to incorporate the challenges identified into their power systems. There is no evidence of inaction.
- There is evidence of greater central coordination and planning in the countries examined to ensure that system security is preserved and the value of DERs is fully realised. In California and New York that greater coordination is coming from the Independent System Operators and Public Service Commissions. In Ireland it is through an SO/TO led cross-industry working group.
- Distribution systems are highlighted as facing the greatest challenges in defining and implementing comprehensive distribution management systems. In addition, these will need to integrate with ISO systems, Home Area Networks. Microgrid controllers, SCADA systems and market mechanisms to name a few. While many of these have detailed architecture and defined interfaces, there is an absence of a system of systems overview. This is beginning to be actively discussed, with PNNL and EPRI both being cited as thought leaders.
- There are many new functions that are being developed across the sectors that will need to be incorporated, either into existing functions or through developing new ones. Examples include modelling of DERs, interconnection rules and standards, situational awareness, data exchange and common information models.



# Future Power System Architecture

A report commissioned by the Department of Energy & Climate Change

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## Main Report

This Main Report includes the FPSA project Summary Report with additional sections which provide the context for the work, the methodology followed, the evidence gathered and the detailed functional analysis carried out (for seven of the *thirty-five* functions identified) with a summary of the stakeholder engagement process and consultation responses.

The full set of FPSA documentation including the Summary Report, Main Report and supplementary papers are available online via the Institution of Engineering and Technology and the Energy Systems Catapult.

[www.theiet.org/fpsa](http://www.theiet.org/fpsa)

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