IET The Institution of Engineering and Technology

CATAPULT Energy Systems

Future Power System Architecture

A report commissioned by the Department of Energy & Climate Change

1. Summary Report

The Institution of Engineering and Technology

Energy Systems Catapult

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Summary 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.

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

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

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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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 section 2 of the Summary Report and sections 2 and 14 of the Main Report. 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.

1.6 The FPSA project reports and reference material

- **The Summary Report** 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** includes the Summary Report and further 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   **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 of the main report 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:

- o 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.
- o 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.
- o Electrification of heat and transport, with 3.3m electric vehicles (EV) and 6.6m heat pumps.
- o Extensive use of smart meters – installed in 29m households and small businesses.
- o 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:

  - o **Power Sector Adaptation:** business as usual, accommodating incremental development.
  - o **Power Sector Leadership:** sector leads in engaging with customers.
  - o **Customer Empowerment:** sector facilitates, empowering new parties.
  - o **Community Empowerment:** sector empowers energy communities and local markets.

  These are further described in section 6.2 of the Main Report.

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 of the Main Report. A selection of these is described in greater detail in section 5.3 of the Main Report. 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 of the Main Report).
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 of the Main Report).

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 of the Main Report).
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 of the Main Report).

Timeframe	Function
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.
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 of the Main Report).
Real time	Identify available generation and other dispatchable energy resources, and auxiliary services and associated operational restrictions.

"The emergence of smart cities, groups of technology users, aggregators and social enterprises will require new modes of interaction with the power system."

Timeframe	Function
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 of the Main Report).
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 of the Main Report).

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 of the Main Report).

“As the power system becomes increasingly complex, decentralised and more interactive with its customers, major events will become more challenging.”

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 of the Main Report 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 of the Main Report).

- *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.

"The new functions 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 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 of the Main Report), 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 of the Main Report):

- 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 GB's power system architecture.

"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."

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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Future Power System Architecture

A report commissioned by the Department of Energy & Climate Change

Summary Report

This Summary Report forms part of the FPSA project Main Report. It provides an overview of the identified functions and analysis and sets out the project's conclusions and recommendations.

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.

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