

Future Power System Architecture

A report commissioned by the Department of Energy & Climate Change

4. Systems Engineering Methodology



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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.

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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).

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1. Introduction

The project has been tasked to set out, and provide evidence for, the functions that will need to be performed in the future power system as a result of its on-going transformative change. The primary focus is therefore on the functions that will be needed to manage the technical challenges facing the system in 2030 assuming that it achieves the outcome defined by the National Grid's *Gone Green* energy scenario.

The analysis concentrates on the power system technical architecture and does not pre-empt consideration of who should deliver the functions or the governance to be applied. Where commercial considerations have been noted as influential, these have contributed to the identification of relevant functions but do not form part of the formal conclusions in this report.

Project Boundary

For FPSA purposes, the scope of the GB 'power system' includes all electrical generation and inter-connected power networks on the GB mainland and its islands, including national and international inter-connectors and electrical services, industrial and domestic, beyond the meter.

The 'power sector' covers all government, industrial, commercial and public interests in the power system.

The system engineering process applied to the project places functions at the heart of the analysis and considers them in the context of the four dominant time horizons:

- Investment planning
- Operational planning
- Real time operation
- Markets and settlement

Short statements are made (in draft requirement form) to explain why each function of interest is important when considering the way ahead for the power system. The impact of each function and factors affecting the timescales for its introduction are also summarised.

By identifying the functions already in place and comparing the need for extended or new functions, the analysis provides the gap analysis that helps understand the scale of the transformation required.

Functions

'Functions' are central to the FPSA analysis and are a focal point for the conclusions drawn in the report. They are given a broad definition, as follows: hardware or software capabilities, services, tasks, roles or any other action that can be assigned to a system or organisation. They are normally expressed as a verb phrase, such as:

“Confirm remedial action plans for all credible scenarios/faults and implement as necessary.”

It must be possible to implement a function within our real world understanding of the power system. If the function relies on hardware or software, it is usually implemented by a physical system. If it is a service, it usually needs an enterprise to deliver it. If a role, it needs an organisation. Eventual delivery implies procurement and management action of some sort, invariably with cost implications downstream.

Expert consultants have supported a programme of workshops and collated the evidence that demonstrates the need and significance of each function.

2. Context

National Grid's Future Energy Scenario *Gone Green* was assigned as the baseline definition of the challenges to be met by 2030.

Since the conditions represented by *Gone Green* are a target outcome, it has to be shown that the pathway to achieving them is both realistic and capable of withstanding external or emergent factors. 'Consumer Power' was selected as the scenario most representative of the factors against which the functions identified should be stress tested. Under Consumer Power, the power system would experience notably greater solar PV ramp rates and tends to place particular stresses on distribution systems.

A set of high level cardinal characteristics has been compiled using expert experience from earlier projects. As listed below, they provide an overview of the main system development needs and objectives that are expected to influence the pathways to 2030. They have been used as a framework within which the validity and value of the functions can be checked.

Gone Green Scenario

Gone Green is the only one of the 4 Future Energy Scenarios (FES) that meets the Government's emissions targets for 2030 and is considered the most demanding. The use of intermittent renewables (wind and solar) rises to 46% of capacity and 39% of energy generated, a total of 71 GW in 2030.

Significant system changes respond to the growth in distributed generation and the reduction in spinning inertia.

Distributed generation reaches 17% of capacity and becomes part of the balancing mechanism.

The electrification of heat and transport introduces 3.3 million Electric Vehicles (EV) and 6.6 million heat pumps.

Smart meters are installed in 29 million households.

Cardinal Characteristics of the Power System and its Context

- 1. Moving to a low carbon plant portfolio**
Ensure suitable mechanisms to accommodate a generation portfolio compatible with GB carbon reduction targets.
- 2. Designed-in flexibility & agility for identifying and responding to change requirements**
Structure and resource whole-system governance mechanisms, including horizon scanning, rapid change management and a continuous review of functionality, to match customer and policy-maker requirements for continual change at management and technical levels.

3. **Enhancement of existing power network Infrastructure to support the adoption of low carbon technologies and the integration of energy communities**

Facilitate the enhancement of today's power networks using a blend of traditional and smart solutions, to accommodate low carbon generation and new demand technologies.

4. **Resilience of the national electricity system**

Ensure that the national system remains secure against accidental or malicious control mal-operation and has adequate capability for local or national re-starting in emergencies.

5. **Accommodate large numbers of active parties**

Ensure technical and commercial processes can adapt smoothly to massive growth of new social and commercial parties, the services they expect, and the requirements for data.

6. **Seamless response to evolving customer requirements**

Enhance power sector responsiveness to meet new requirements in a way that appears seamless to consumers and other parties.

7. **Establish coherent data and control architectures for distributed technologies and services, including cross vector issues**

Enable the integration of de-centralised arrangements including alternative vectors to work in a federated way with centralised systems where these remain appropriate.

8. **Create open systems for data exchanges**

Establish data interoperability to provide a seamless experience for consumers, encourage competition and new entrants, and to enable the development of new services.

9. **National co-ordination of highly distributed energy resources**

Efficiently co-ordinate the multiplicity of power sources connected to the GB system to ensure balancing and stability of the national system is not compromised.

10. **Aligned financial incentives across customers**

Create financial incentives that reward all customers for making choices that are cost reflective for the GB system and enable them to benefit from providing system support.

3. Aims of the Analysis

The FPSA project has adopted systems engineering techniques (Inset) to develop a ‘whole system’ perspective of the changes by which the power system can achieve the targets embodied in the *Gone Green* scenario.

The project has applied systems engineering principles but rather than formal systems engineering processes, the approach adopted has concentrated on developing simple but coherent models of the technical aspects that need to be addressed as the pace of change advances. The intention throughout has been to enhance communication across a wide stakeholder community and provide a foundation for on-going consultations.

Systems Engineering

Systems engineering is an interdisciplinary culture that thrives on discovering the true nature of a challenge and harnessing its complexities as early as possible in the project life-cycle. This involves taking an open-minded look at all possibilities and evaluating them using practical tools such as the concept engineering applied under FPSA.

As far as possible, the power system is understood without investigating the internal operation of its constituent systems. These are treated as ‘black boxes’ for which their properties and interfaces, as seen externally, are sufficient to define the contribution they make to the power system.

Systems engineering processes often rely on two principles:

- 1) The ‘separation of concerns’ that allows functions to be de-coupled from the various system configurations that might deliver them, the basis of innovation.
- 2) A ‘single point of truth’, based on a project structure that maintains a consistent relationship between all the elements being addressed, allowing stakeholders to ask questions from their own perspective and all receive answers that are consistent with the others.

The first priority has been to understand the issues and challenges that are driving the need for change. Previous work, such as the PNJV report “Handling a Shock to the System”¹, has emphasised the many variables and interests that need to be taken into account. Although a significant number are being addressed already, there are many ways that the power system will have to adapt to introduce the changes needed. Some functionality will be entirely new, others are recognisable today but in the future will need to be undertaken in far greater breadth and at far higher pace. The foundation of the systems engineering process is the ability to de-couple the functions that describe how systems and organisations behave (‘what’ they do) from the systems and organisations themselves (‘how’ they do it).

To investigate the range of possible outcomes for the power system’s technical architecture, concept engineering techniques have been used to build simple, high level models of the power system that allow functions to be mapped onto systems in different ways. This approach considers the main interactions across the power system and avoids entering into the more detailed investigations conducted by projects such as DS2030².

¹IET PNJV: ‘Electricity Networks - Handling a Shock to the System’, position statement and full report, December 2013.

²DS2030 Project Methodologies Stages 4 and 5, Revision 1, Jul 15.

As different ways of addressing each issue have been considered, the functions that emerged have been considered in three broad categories. ‘Existing’ functions are summarised to provide a baseline against which the emergence and evolution of ‘new’ and ‘extended’ functions can be assessed. This gap analysis has helped to clarify the extent of likely changes and the impact they will have on the power system.

Knowledge Area Consultants (KACs) were engaged to support a programme of workshops. The first set explored how issues and challenges could be met individually across the three areas of interest:

1. **Deep Power** - Addressed changes in the way that electricity will be generated, transmitted, distributed, traded and used.
2. **Grid Edge** - Considered the data, control and management systems interfacing with the power system of 2030.
3. **Customers and Communities** - Investigated the potential of physical and virtual community energy schemes and their ability to offer alternative ways of delivering energy.

The workshops allowed expert stakeholders from National Grid, DNO, industry, supplier organisations and others to contribute their experience and build confidence that the functions being collated were both significant and feasible. The second set of workshops continued the themes above but considered whether the functions of interest would be compatible with each other within coherent whole system strategies for the power system. This analysis was the basis for the first formal identification of significant functions within the FPSA Functional Matrix.

The Interim Report included the initial version of the Functional Matrix and the preliminary evidence to support the functions identified. To consolidate the findings for the Main Report, the analysis was extended to provide an overview of the main ways by which the functions could be implemented within four broad strategies, each showing alternative ways by which the power system might evolve. These strategies were modelled as ‘core concepts’:

- Power Sector Adaptation.
- Power Sector Leadership.
- Customer Empowerment.
- Community Empowerment.

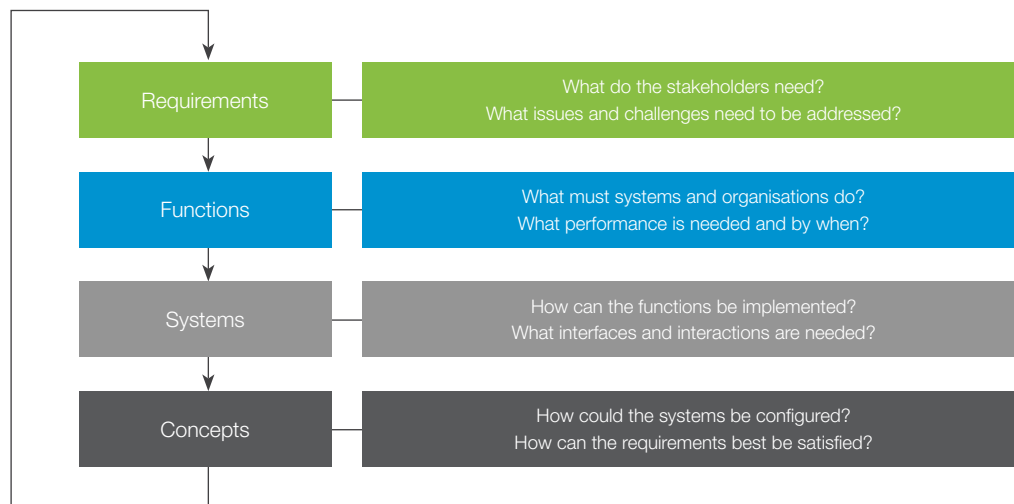
Timescales for the introduction of new and extended functions have been addressed by focusing on the sequence of events and the drivers that would lead to their introduction in the context provided by the four core concepts.

A consultation process allowed the wider stakeholder community to contribute to the Functional Matrix. This was supported by a Stakeholder update event on 28 January 2016 that provided technical briefings on the project’s aims and the derivation of the Functional Matrix. Feedback from the consultation endorsed the direction of the systems engineering analysis and reinforced, in particular, the focus and coverage of the Functional Matrix. An audit trail has been maintained throughout the analysis. The systems engineering pathway leading to the development of the final Functional Matrix is explained below.

3.1. Method applied

The systems engineering process is highly iterative and has been based on the four main elements expanded at Figure 1.

Figure 1: The Iterative Systems Engineering Approach Applied to FPSA



The requirements, functions, systems and concepts have been developed throughout the analysis by answering the questions at Table 1. The items in **bold** text appear in the process summary at Figure 2. The response to each question is developed in the sections below.

Table 1: Questions addressed by the analytical process

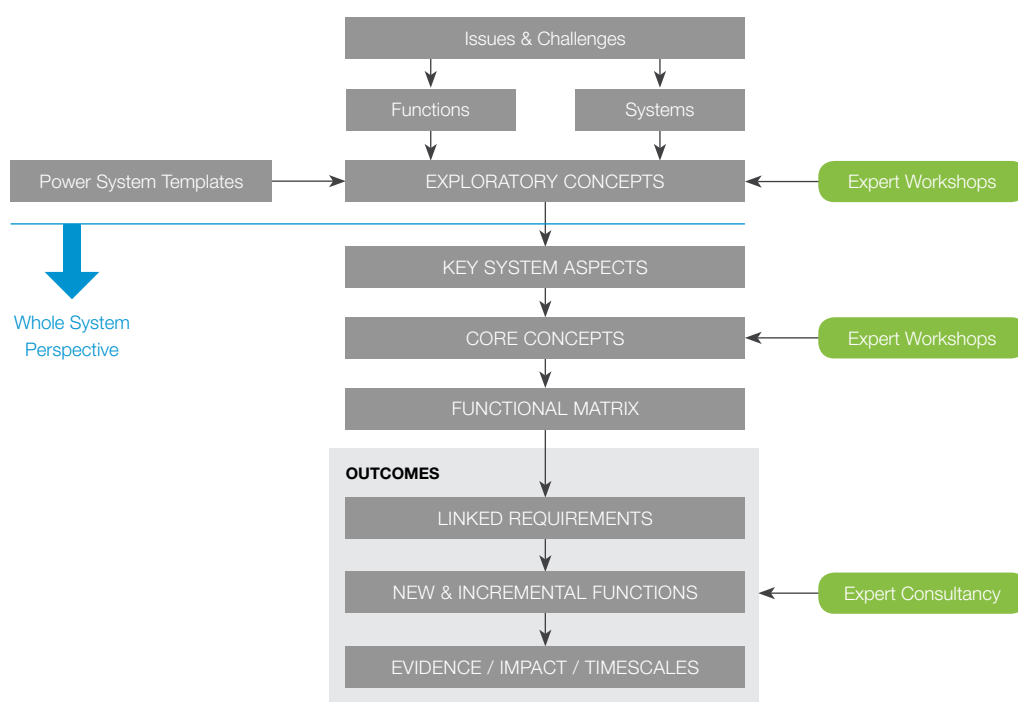
Question Addressed	Response
What issues and challenges demonstrate the need for change?	Use the Issues and Challenges Matrix (Annex A) to act as a partially structured set of requirements and a launch pad for technical investigations. Review earlier reports and stakeholder guidance.
How could the power sector respond to the individual issues and challenges?	Build Exploratory Concepts that consider the functions and systems needed within the power system 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 (See below – Section 3.5) 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 system.
What functions are needed to support realistic transformations for the power sector?	Develop Core Concepts as whole system models of how the power system 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?	Enter evidence and 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 .

Figure 2 shows the process flow, the contribution from expert consultants and the main outcomes.

It is emphasised that the exploratory concepts were set up to encourage free thinking and investigate possible ways by which particular challenges could be solved. All possibilities could be considered and new ideas were actively encouraged, leading to some of the exploratory concepts being similar to each other. A total of 58 exploratory concepts were produced and remain a source of reference for on-going modelling of possible power system transformations.

Thereafter, the process facilitated convergence on strategies that are viable and coherent ways by which the power system may move ahead in practice. The core concepts are simple models of power system configurations that may be viable for 2030 under the National Grid’s Future Energy Scenarios considered, and do not pre-empt future assessments of their relative merits.

Figure 2: Overview of the FPSA Systems Engineering Process



3.2. Issues and challenges

An understanding of the issues and challenges to be addressed was derived from earlier work and by programmes such as National Grid’s System Operability Framework (SOF)³. The issues and challenges matrix (Annex A) provided a first indication of the issues that needed to be addressed and the various capabilities, technologies and risks associated with them. The assessment of this material helped refine the working definitions and terminology that have been applied by the FPSA project.

³Future 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. All FES references in this document are to the 2015 version unless otherwise stated.

3.3. Exploratory concepts

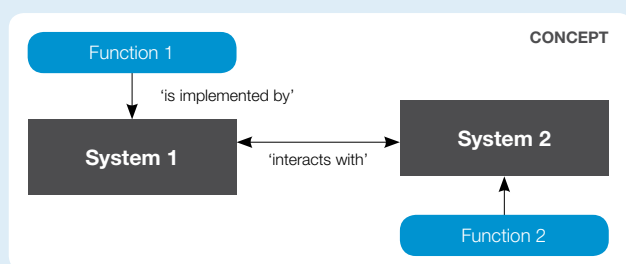
The project considered alternative ways (i.e. exploratory concepts) of addressing current and future requirements. These exploratory concepts were grouped under the categories in the list below (a. to n.). The numbers in brackets show how many exploratory concepts were raised for each category:

- a. Baseline (legacy) and early Strawman for 2030 (2).
- b. Bulk Electric Vehicles (EVs) and Heat Pumps (HPs) (12).
- c. PV micro-generation (6).
- d. Distributed Generation (DG) (5).
- e. High import (via inter-connectors) (1).
- f. Power system flexibility (4).
- g. Capacity management (4).
- h. Private networks (4).
- i. Home automation (4).
- j. Consumer interface (5).
- k. Cold and black start (3).
- l. System balancing (4).
- m. Frequency response (1).
- n. Voltage management (3).

For each exploratory concept (other than the baseline), the 2030 template provided a reference configuration of systems that represented the entire power system, Figure 3. Suitable functions were linked to the systems that would be involved in their implementation.

Concepts

Concepts, as ‘configurations of systems’, explore the various ways by which the systems may be managed and operated.



At the heart of the concept modelling process is the ability to map functions onto systems in different ways, allowing the technical merits of each implementation to be compared. All system interactions have to be compatible for the concept to represent an integrated and realisable approach.

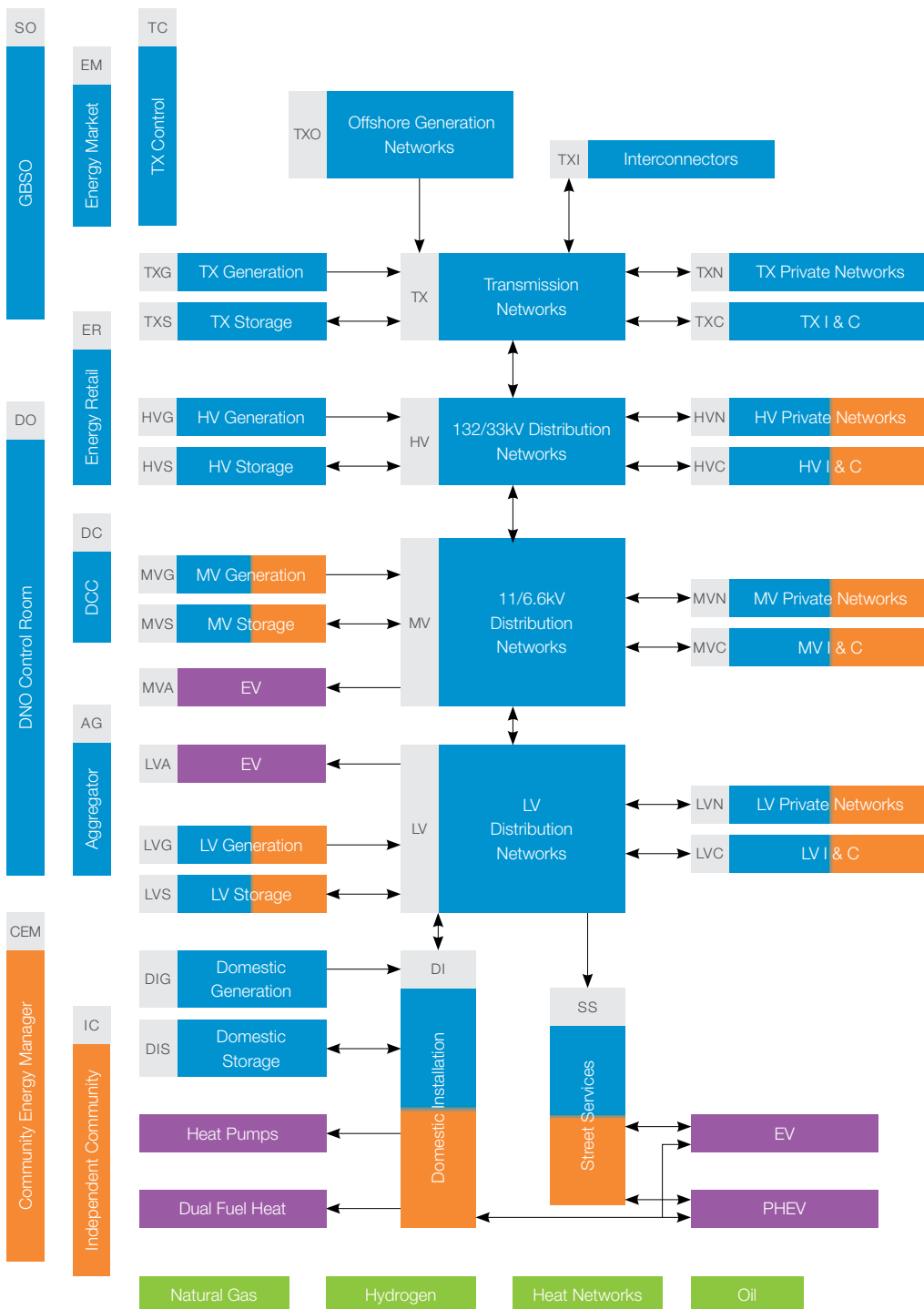
It is important that concepts are based on ‘systems’ because it is eventually the physical system or infrastructure that enters service and that implements functions in the real world.

The FPSA project has concentrated on the power system’s technical architecture but operational, commercial and management aspects must be considered where necessary.

The version of the template shown at Figure 3 has monotone boxes representing the main systems that are expected to make up the future power system. Two tone boxes indicate where the system could be a partial or entirely virtual network.

Black arrows indicate the main energy flows between systems. Each system has a 2 or 3 letter label that provides a simple link to the separate listing of functions. Additional boxes at the base show multi-vector interfaces.

Figure 3: Concept Template for 2030



The development of an exploratory concept is explained under the section ‘Worked Example’, below.

3.4. First set of workshops

The modelling of exploratory concepts supported a series of workshops attended by power sector experts and Knowledge Area Consultants. Exploratory concepts were raised to visualise viable ways by which technical issues could be addressed. The main dependencies were noted.

The discussions provided guidance for the initial evidence gathering by the Knowledge Area Consultants.

3.5. Key system aspects

In preparation for the second set of workshops and as a basis for building whole system concepts, a key system aspects matrix was assembled by the project team. The 8 columns cover the aspects of the power system that need to be resolved when considering how different combinations of exploratory concepts could be adopted to form coherent whole system strategies. They are listed at Figures 4 to 6:

Figure 4: Key System Aspects – Consumer Related

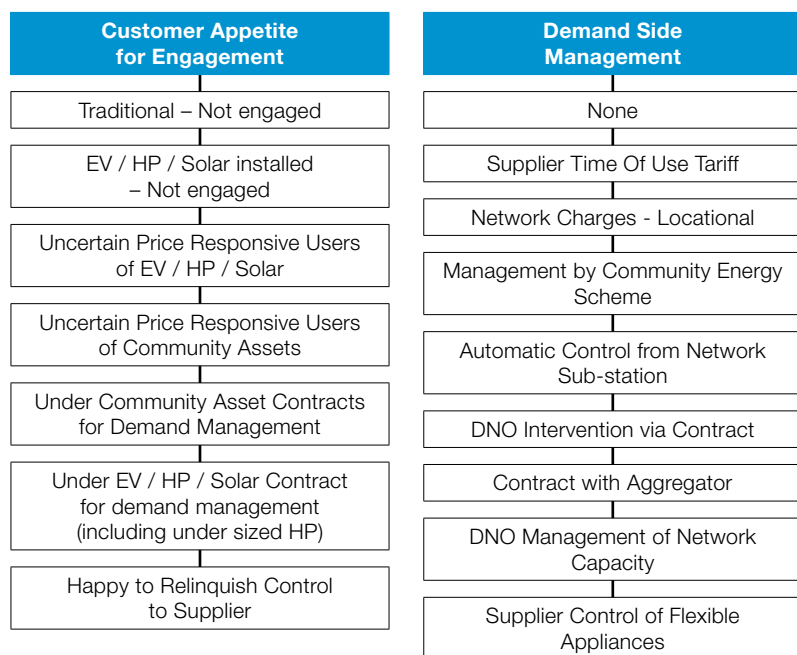


Figure 5: Key System Aspects – Network Related

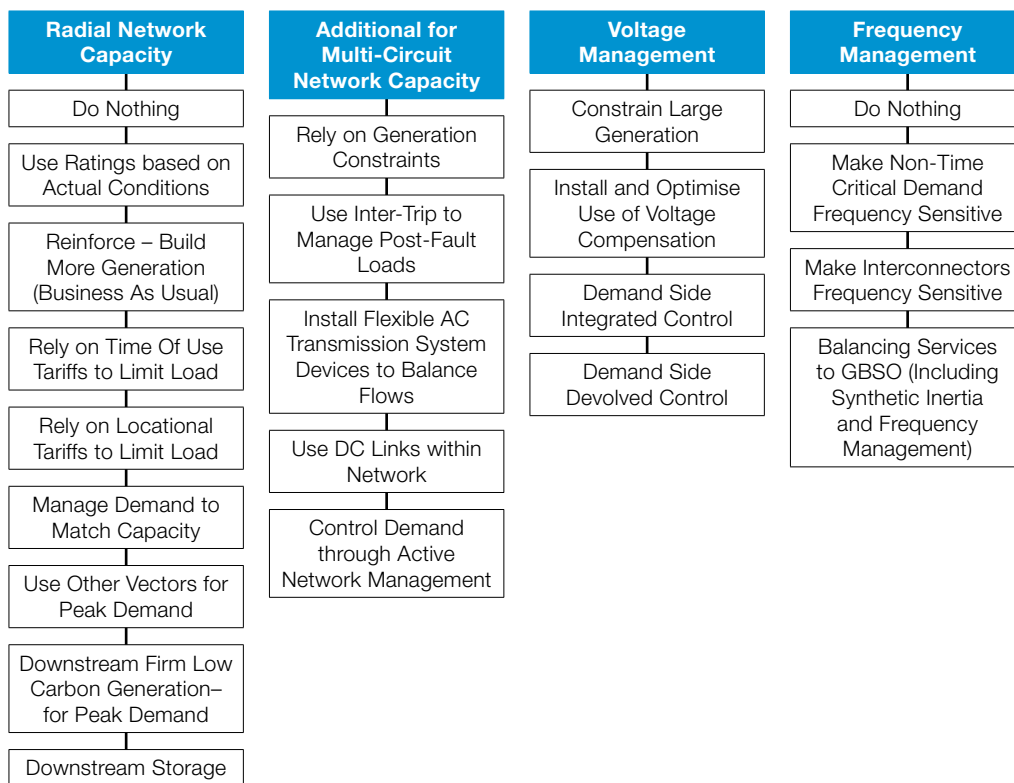
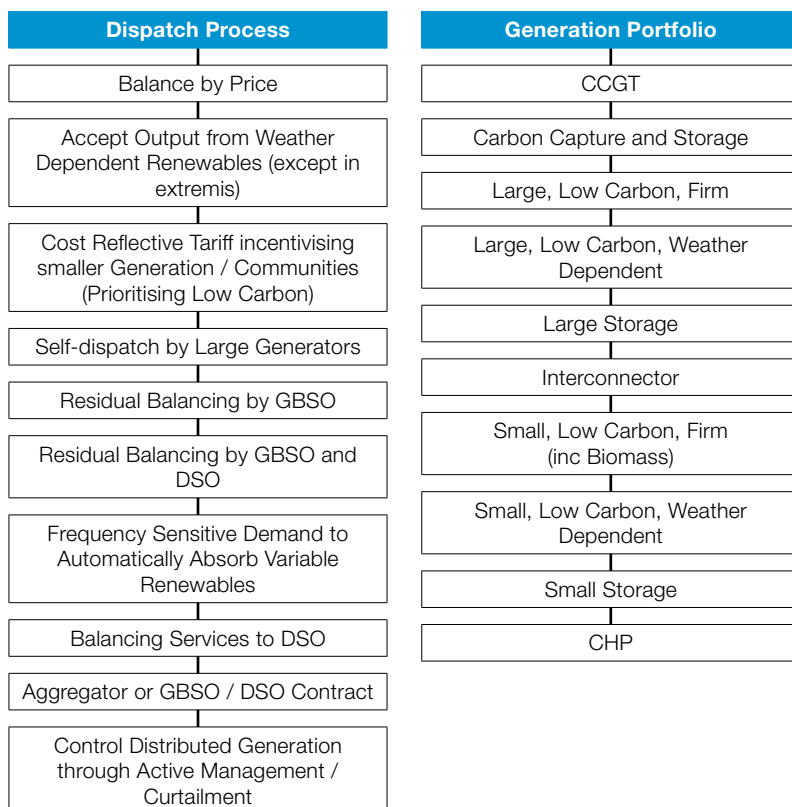


Figure 6: Key System Aspects – Production Related



Key System Aspects

Based on an agreed summary of the power system’s key system aspects (the column headings in the workshop chart), the team considered the main options by which those aspects could be addressed (the boxes in each column). Figures 4, 5 and 6 refer. The most suitable options were selected. To be viable, the selections in each column had to be consistent with those in the other columns.

CUSTOMER		NETWORK MANAGEMENT				PROTECTION	
Customer Specific for Equipment	Customer Role Management	Health Network Capacity	Addressed for Multi-Source Network	Storage Management	Protection Management	Security Services	Operational Functions
Traditional – Not engaged	Active	Use Rating	Relay on Generation	Control Large Generation	Use Ratings	Security by Price	CCSD
EV/HP/Load evolution for equipment	Reduce Power Loss, Self	Use Performance Based Conditions	Relay on Generation	Initial and Control Loss of Network Configuration	Make Non-Time Critical Demand Response Available	Control Output from Renewables (Demand Response in Island)	Control Output and Storage
Operational Role Reassignment	Network Changes – Localised	Resilience – Built into Demand Response (DR) as a Load	Use Meter This to Monitor Peak Load	Demand Load Integrated Control	Make Interconnections Proactive Services	Grid Reliability Self-Optimising (Resilience Low Cost)	Large Low Cost/High Resilience
Control and Management of Community Health	Management to Control Energy Balance	Relay on EV/HP/Load to Load Control	Relay on EV/HP/Load to Load Control	Control Demand Through Active Network Management	Resilience Services to DR (Including Storage, Loss and Peak Mgt)	Self-Optimising to Large Generation	Large Storage
Unproven Community Asset Controls for Demand Management	Active Demand Control	Relay on Localised Self-Reliance to Load Control	Use EV/HP/Load self-Reliance		Resilience Services to DR (Including Storage, Loss and Peak Mgt)	Resilience Services to DR (Including Storage, Loss and Peak Mgt)	Small, Low Cost/High Resilience
Unproven EV/HP/Load Control for Demand Management – providing active demand	Control and Aggregation	Use Other Active for Peak Energy			Resilience Services to DR (Including Storage, Loss and Peak Mgt)	Resilience Services to DR (Including Storage, Loss and Peak Mgt)	Small, Low Cost/High Resilience
Ability to Reassign Control to Supplier	Supplier Control of Flexible Response	Customer/Supplier Low Demand Generation for Peak Demand			Resilience Services to DR (Including Storage, Loss and Peak Mgt)	Resilience Services to DR (Including Storage, Loss and Peak Mgt)	Small, Low Cost/High Resilience

The combined sets of options represented broad and immature strategies by which the whole power system might evolve. They were captured as a set of 6 ‘Derived Concepts’ that, unsurprisingly, were influenced heavily by the focus of the workshops from which they emerged and clearly contained significant areas of overlap.

Extrapolated Business As Usual – Trades high investment for simple operation and low customer engagement. Capacity deficits are addressed by investing in generation and networks to meet the higher peak demands.

Customer Centric – Customers respond to price or contracts to provide balancing services.

Single Optimisation – GBSO and DSO cooperate to optimise the whole system, delivering maximum benefit from the network.

Grid Edge Operation – Customer involvement is maximised by focusing on best use of smart meters, the internet and energy management systems.

City Hubs – A series of diverse Smart Cities develop, each with its own characteristics. Smart Cities would have an identified service territory enabling them to invest in heat networks and other infrastructure.

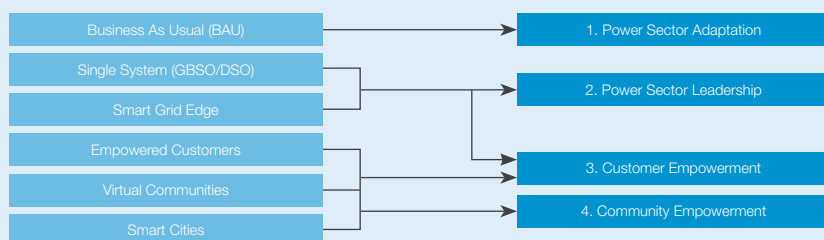
Virtual Communities – Customers have their energy managed by a Community Energy Manager who does not own network assets.

They were rationalised by the project team to drive out related areas of differentiation:

- The level of centralisation and the extent to which the System Operator role may dominate the options open to customers.
- The extent to which customers become actively engaged in the management of energy resources.

Derived Concepts (workshop based)

Core Concepts

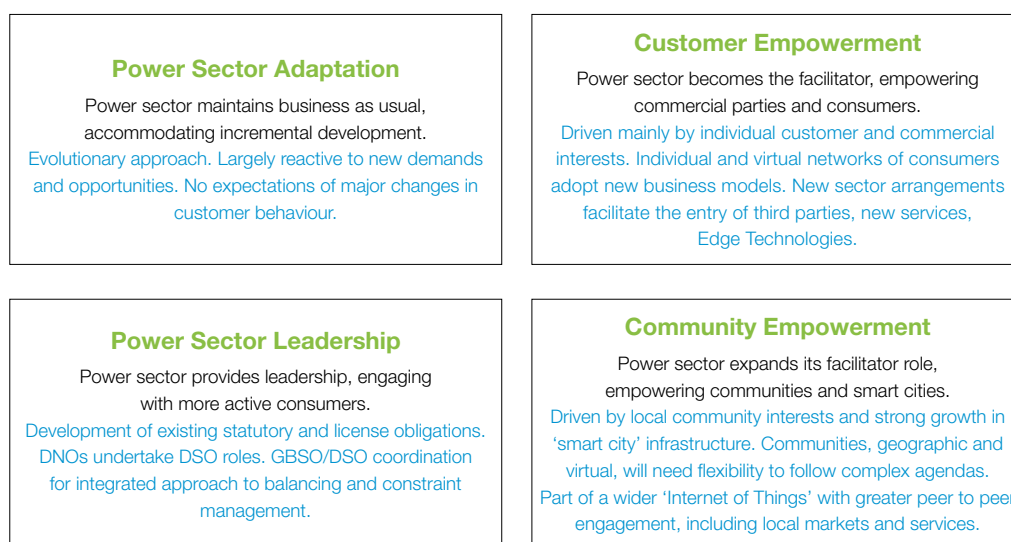


3.6. Core concepts

As an interim step, ‘Derived Concepts’ were built from the threads across the key systems aspects matrix (Inset above). These were a first attempt at identifying whole system strategies. They were compared, filtered and combined within a modelling strategy that looked for clear differentiators between alternative strategies for the power system to follow, rather than specific pathways. An important feature of this analysis was the ‘free play’ that allowed team members to compare approaches on the basis of their experience and expertise, a contribution supported by an on-going review and filtering of the exploratory concepts.

With reference back to the exploratory concepts as sources of specific functionality, it was concluded that four broad strategies were viable.

Figure 7: Overview of Core Concepts



The core concepts represent collectively the range of strategies within which relevant functions can be expressed as control, monitoring, information flows and commercial relationships between the various systems.

The same diagrammatic format was used as for the exploratory concepts (functions mapped onto systems within the power system template as at Annexes B and C) but with four diagrams for each concept allocated to the four time horizons: Investment planning, Operational planning, Real time, and Marketing and Settlement. Annex C refers.

The core concepts act as an assessment tool by which the relevance and applicability of functionality can be assessed. Where functionality has been allocated to some but not all of the core concepts, its value can be assessed against the likelihood that the parent strategy may be adopted. The functionality allocated to all four is considered essential for a *Gone Green* outcome and there is a high level of confidence that it will feature in the way ahead.

3.7. Functional matrix

The Functional Matrix, Annex D, was generated from the information arising in the second workshops.

The headings have been identified at Table 2 (see below) with a brief explanation of the content and purpose behind each. Individual sections are discussed below.

The content of the fully populated Functional Matrix represents the main findings from the project and the main source of the conclusions drawn in the FPSA reports (Main Report).

Table 2: Contents of the Functional Matrix

Heading	Purpose and Content
Function number	Numerical identifier for selected functions.
Cross-reference to Interim Report	Provides traceability back to the Functional Matrix submitted with the Interim Report.
Requirement	A draft requirement that helps explain (in the absence of any formal requirements set) the capability or interest that matters. The candidate requirement allows stakeholder interests to be represented (whereas the remaining columns focus on implementation).
Existing functionality	A short statement indicating the relevant functionality in place to date.
Extended or new functionality	A summary of how the functionality needs to be extended or a statement that new functions are needed.
Function	The formal description of the function itself, expressed as a verb phrase.
Why is the function needed?	Identifies the benefits of introducing the function and the drawbacks of not having it.
Summary of evidence	Collates specific and auditable evidence that the function is relevant, necessary and feasible, including examples of where the function has already been introduced. Where no evidence is available, the reasons are stated.
References	Specific references and links that support the evidence.
Potential implementation challenges	A short summary of the issues that could complicate or delay implementation.

3.8. Requirements

The iterative process at Figure 1 indicates that requirements have a direct relationship with functions and many requirements are functional by nature (others typically relating to quality). The main difference is that requirements are statements of need that express stakeholder interests and that should remain largely solution independent. By comparison, functions are associated with the way that requirements may be implemented in the physical world and form part of the eventual communication with the solution provider. Individual solutions should not be pre-empted, but ultimately a function delivers performance and value by the way it is implemented.

The project has drafted a single covering requirement for each function. This helps to clarify the perceived purpose behind the function and provides working material for any future development of a structured requirement set.

Here the requirement is drafted expressly for the function of interest and the one-to-one relationship allows the requirement to express why the function is important.

3.9. Existing, extended and new functions

The contents of the relevant columns in the Functional Matrix illustrate the gap between the existing functionality and that considered 'extended' or 'new'. A new function is one that has yet to be implemented operationally on a significant scale and that will not be sustained without directed effort within the power sector.

Given the pace of change, it will be noted that the expression of existing functionality can only be related to a broad statement about its contribution to the power system in 2015. This is sufficient to provide a datum for comparison purposes but it is often the case that extended functions arise out of a continuous and on-going response to a wide spectrum of change across the growing range of generation, demand, network management and customer engagement initiatives. The datum will soon be out of date.

3.10. Evidence

Within the Functional Matrix, a short summary statement against each function refers out to a library of evidence documents prepared by the Knowledge Area Consultants. Each document provides a collated body of evidence that is cross-referenced to related functions.

3.11. Sequence of implementing functions

A Function Sequencing Grid has been developed to show how the order in which the functions can be implemented depends upon trigger events and the core concept selected.

4. Worked Example

4.1. Introduction

One of the functions considered fundamental to the transformation of the power system is:

“Automate Demand Side Response (DSR)”

The analysis leading to the identification of this function and the case to address its impact on the power system are summarised below.

4.2. The issue

The electrification of transport and heating will impose additional demands on the electricity network. Heating loads, in particular, will tend to increase peak demand because of daily schedules but are also weather dependent and incur poor load factors, as demonstrated by existing domestic gas demands. DSR has the potential to reduce the peak demand on the network, either by taking advantage of the flexibility provided by better insulation and thermal storage or by matching the heating demand to low carbon generation. This approach has three potential benefits:

- It could reduce the level of investment required in the electricity networks.
- It could reduce the level of investment required in the generation fleet.
- It should enable low carbon generation fleet to operate at a higher capacity factor (i.e. By reducing the need for curtailment).

Related issues were discussed in depth in the early workshops and a clear case emerged for some degree of automated DSR. As the networks experiencing the greater increase in demand are expected to be those supplying domestic premises, the DSR would need to come from domestic as well as industrial or commercial customers. To achieve automated DSR for domestic customers, either price or control signals will be needed but only control signals would provide the necessary assurance that the desired response would be achieved. Since controls cannot be imposed against customers' wishes, it will be necessary for suppliers, community energy managers and other intermediaries to negotiate suitable agreements that customers can sign up to.

There are two main drivers for automation. Firstly, customers may not wish to be actively involved in the process and secondly, the very high number of potential constraints on the LV networks will make it infeasible for the network operators to use a manual approach. For example, some form of automated control of domestic EV charging might be effective in avoiding a large increase in early evening peak demand.

Some level of automated demand response may therefore be anticipated, but there remains a need to resolve the extent to which it is both necessary and feasible. Furthermore, the project has to address whether such a function is compatible with suitable transformations for the power system's technical architecture as it follows a suitable pathway to 2030.

The majority of the cardinal characteristics, in Section 2 above, help build the case for efficient customer DSR.

4.3. Exploratory concepts

DSR features across many of the exploratory concepts but is best illustrated within the family of concepts addressing home automation. One example of the exploratory concepts as shown in Figure 8 below, XI4 'Home automation via internet and control signal', draws attention to the following:

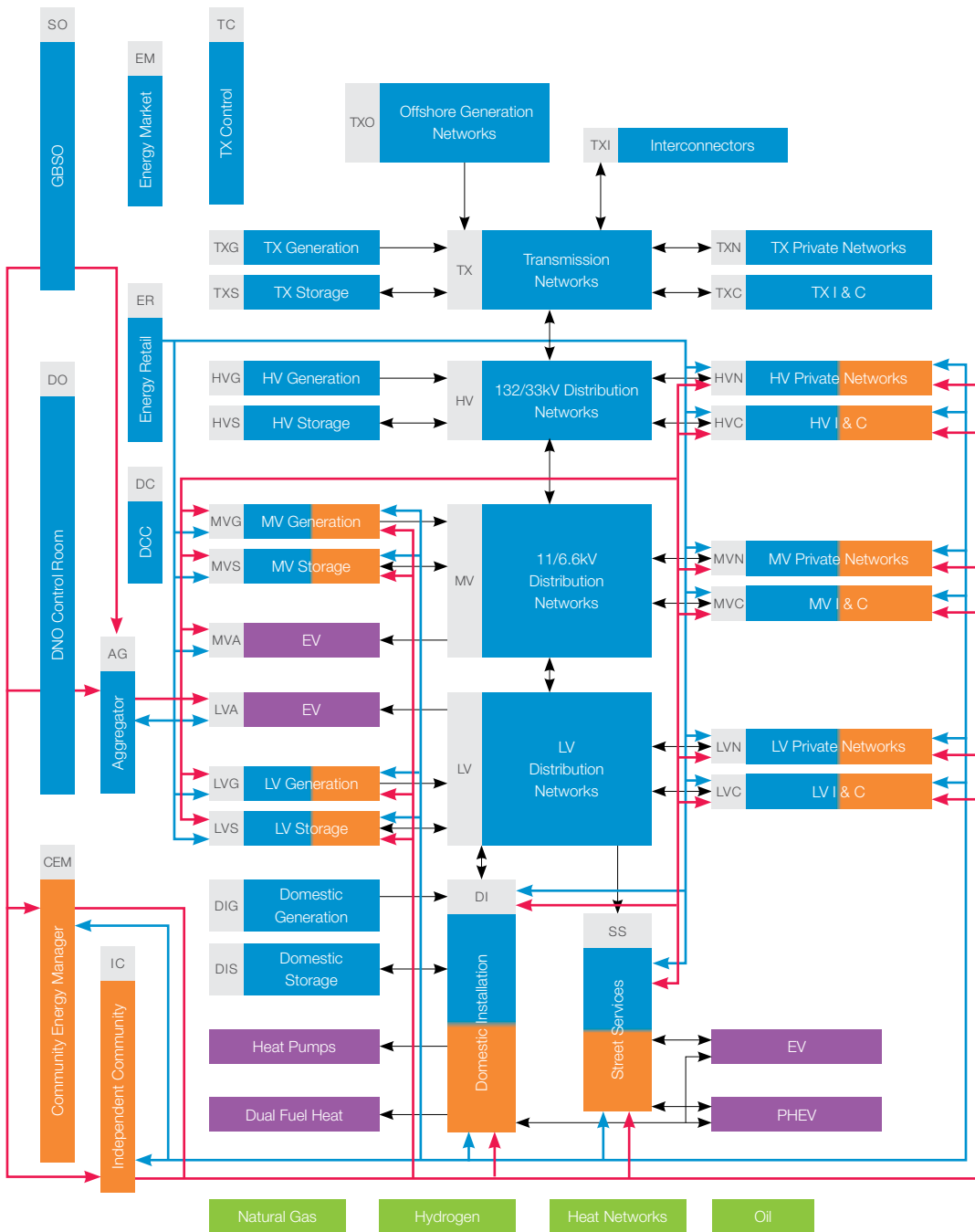
- The end customer will have a contractual arrangement with their supplier, their community energy manager or an aggregator.
- Only the network operator will have visibility of network loadings and the need for intervention.
- Hence, a second contract will be needed, perhaps in conjunction with differential use of system charging, between the network operator and the supplier/community energy manager/aggregator.
- The large number of potential constraints and the desire of the customer for this to happen 'behind the scenes' will drive a need for automation.

The following are examples of the issues that arise:

- It is important that the customer is not significantly affected by the process. Whilst it may be acceptable to delay the charging of an EV that is not required until the following morning, the interruption of heating for more than a few minutes would need to be made good using either locally stored energy or an alternative vector such as natural gas.
- A reliable communication channel will be needed; local security of supply will depend upon this functioning correctly.

The example below is in contrast to concepts that rely on investment in centralised low carbon generation to meet demand. The additional generation capacity would attract the capital costs of the extra plant, the costs associated with poor load factor and the expense of enhancing the transmission and distribution networks to carry peak loads. Any approach that does not include automated DSR will have to make the case that net costs are lower without it.

Figure 8: Example Exploratory Concept – X14 Home Automation



Technical/ Business Issues

- Diagram shows alternative control signals from Community Energy Manager/Independent Community. Currently no standards for the security of these links.

✓

- Use of internet allows any customer data to be collected, e.g. to support remote scheduling.
- SO/DO have certainty of what will be delivered.
- Call off instructions can relate to specific appliances (turn off EV) or network impact (2kW import limit).

SO

- Planning: contract with AG/CEM/IC for balancing services.
- Post Gate: send call off instructions to AG/CEM/CI.

DO

- Planning: contract with AG/CEM/CI for balancing services.
- Post Gate: send call off instructions to AG/CEM/CI.

ER

- Send Time of Use Tariff information to End Customers.

AG

- Planning: contract with end users and SO/DO.
- Post Gate: receive call off instructions from SO/DO.
- Post Gate: send combined call off instructions to end customers.

DCC

DI/SS/MVG/MVS/MVA/LVA/LVG/LVS/HVN/HVC/MVN/MVC/LVN/LVC

- Receive Time of Use Pricing Signal and call off instructions from AG/ER/CEM/CI.
- Determine response to price signals and call off instructions.
- Control Appliances (Arrows omitted for clarity).

Appliances/DIG/DIS

- Respond to control signals.

CEM/IC

- Planning: contact with SO/DO for balancing services if desired.
- Plan operation of community.
- Post Gate: receive call off instructions from SO/DO.
- Translate plan and balancing services into cost and control signal for each participant.
- Send out cost and control signal to participants.

4.4. Key system aspects

The second set of workshops discussed active DSR in the context of whole system strategies. The Key System Aspect ‘Demand Management’ was directly relevant to this debate and included two options that attracted the most interest for whole system strategies:

1. DNO intervention via contract.
2. Contract with aggregator.

These two placed the greatest emphasis on the contractual commitment by which control action could be relied upon when needed. Since customers will avoid unattractive contracts if they can, they also imply a wider process of negotiation by which the level of control relinquished is sufficiently incentivised to be seen as a net benefit to the customers.

For the contract based approach to be realistic, there has to be sufficient interest from customers that will relate to the incentives being offered. Under the key system aspect ‘customer appetite’, the emphasis is on reaching out to those who are in, or would join, those represented by:

1. Community asset contracts for demand management.
2. Under EV / HP / solar contract for demand management.
3. Happy to relinquish control to supplier.

Those unwilling to join these broad groupings would still have a significant contribution to make, if engaged at all, but their unpredictable responsiveness to prices, incentives and other factors would weaken the effectiveness of an automated DSR approach if their numbers dominated where strong DSR is needed.

These considerations drew attention to the impact on the power networks. By preference, the successful introduction of automated DSR would enable an approach based on ‘manage demand to match capacity’ and ‘control demand through active network management’ under a range of voltage and frequency management options.

On the production side, the preferred option for dispatch is identified as ‘aggregator or GBSO/DSO contract’. For the generation portfolio, it needs only to be noted that progress towards automated DSR is a direct contribution to any approach that relies on distributed generation rather than reinforcement of large central generators.

4.5. Core concepts – whole system approaches

The core concepts define the range of likely strategies by which the power system may evolve towards 2030. They use a similar format to the exploratory concepts, showing the functions related to each of the four timescales of interest in separate diagrams.

The functions in the core concepts and applicable to automated DSR can be tracked through the following steps:

1. Applicable cardinal characteristic – ‘accommodate large numbers of active parties’.
2. Applicable exploratory concept – ‘home automation via internet and control signal’
3. Selection of key aspects for typical strategy that includes implementation of automated DSR (See Figures 4,5 & 6):
 - a. **Customer appetite** – ‘under community asset contracts’.
 - b. **Demand side management** – ‘Contract with Aggregator’.
 - c. **Radial network capacity** – ‘manage demand to match capacity’.
 - d. **Additional for multi-network circuit capacity** – ‘control demand through active network management’.
 - e. **Voltage management** – ‘demand side devolved control’.
 - f. **Frequency management** – ‘make non-time critical demand frequency sensitive’.
 - g. **Dispatch process** – ‘aggregator or GBSO/DSO contract’.
 - h. **Generation portfolio** – ‘small low carbon, weather dependent’.

With the exception of Power Sector Adaptation, all core concepts feature high levels of demand side response as a means of limiting peak demand and hence investment. They therefore feature these or related aspects.

Within the core concept models at Annex C, individual functions in the diagrams are cross-referenced, where applicable, to the functions identified in the Functional Matrix (see below Section 4.6). For the power system configuration of each core concept, this highlights the functionality needed to implement the main function of interest. As noted above, concepts are simple models of representative approaches within which suitable functionality can be embedded: they should not be interpreted as definitive ‘solutions’.

4.6. Functional matrix

At this stage, the core concepts, with reference back to relevant exploratory concepts, identify functionality that can be related to the more significant changes associated with the transformation of the power system. It is now possible to express this functionality as high level functions, such as the example here: ‘automate demand side response’, that merit consideration by DECC.

To help refine and express the functions of most interest, a number of basic questions are addressed in the Functional Matrix.

Why does the function matter? The function is important for customers because if the contribution to demand response is vital to the efficient operation of the power system, it is equally important that customers experience a net benefit from their engagement. To implement this function and achieve the performance required

without compromising their interests implies fast and reliable interactions between the systems providing generation and demand. The technological conclusion drawn is expressed as one of many possible requirements that may apply in the future:

- The power sector shall have the capability to introduce Machine to Machine (M2M) automation without compromising the explicit or hidden interests of customers.

Does the function already exist? GB's power system is not currently configured to exploit the potential of energy management systems, although their potential is witnessed by the active development of Home Energy Management Systems (HEMS), Building Energy Management Systems (BEMS) and City Energy Management Systems (CEMS). With the on-going introduction of smart meters and related trials still taking place under LCNF and other programmes, the pathway to automated DSR is not yet resolved. A second aspect to this function is the need to detect that there is an overload on the network and identify what control actions at which locations will remove it with the least impact on end customers. This is therefore treated as a new, rather than extended, function.

Is the function an extension of existing functionality or a 'new' function?

A verb phrase is used to express the function of interest. The wording is intended to be implementation neutral and demonstrate the relevance of the function to changes that need to occur within the power system.

Each function is flagged as new or as an extension of functions that are already in place or under active development.

In this case, it is considered a new function because the full required functionality, in particular any standard control hierarchy or commercial behaviour has yet to be designed. Trials are being undertaken, but not at scale.

Why is the function needed? This question takes a closer look at the functionality needed to operate the power system if DSR is introduced. Once the case is made for demand response itself (as a way to unnecessary investment in new generation plant) the sheer numbers of distribution constraints and related customer demand management actions will be too high to manage manually. Furthermore, many customers will expect these actions to be taken for them in a way that is practically invisible to them. The successful introduction of automated demand side response will provide a range of services that are attractive, affordable and unobtrusive for customers, meeting levels of performance that deliver immediate economic benefits.

4.7. Evidence

What evidence is there to demonstrate that the function is understood, feasible and worth pursuing? The Functional Matrix provides links to collated evidence that focuses on:

1. The need and potential for active network management.
2. The power system development needed to address related security, privacy and communications issues.
3. The benefits of demand side technology, including DSR and energy management.

4.8. References

An extensive list of references is provided at Annex D.

At this point, the analysis has established that automated demand management merits active consideration. The analysis below addresses how it might be implemented within an integrated approach for the power system and the sequence of events to introduce it.

4.9. Timelines

A provisional target of 2020 is identified to reflect the anticipated growth in smart devices and the need to take early advantage of the potential for DSR.

4.10. Implementation and impact

The implementation and impact of the functionality associated with 'automate DSR' can be assessed against each of the core concepts. The analysis is not repeated here but is available in the Main Report.

4.11. Summary

Unless a 'business as usual' approach is adopted and the power system undergoes major reinforcement that meets all future demand for electrical load, automated DSR is identified as a new and fundamental contributor for all viable strategies.

The associated automation, customer engagement, energy management and power system interfaces are areas that merit close attention in the near term as a wide range of smart devices enter the marketplace.

5. Outcomes

The systems engineering process has delivered:

- A library of simple models (exploratory concepts) that visualise how different technical challenges can be met.
- A set of four core concepts that span the range of options for the ongoing transformation of the power system and their possible influence on the power system architecture.
- A matrix of functions that represent the changes anticipated for the power system.
- The evidence to justify the selection of those functions and an assessment of their impact associated with the way they may be implementation.
- A streamlined working process by which further investigations may be conducted if the need arises.
- A technical assessment that provides a foundation for later consideration of governance and commercial issues.

6. Annexes

Annexes available on request

- A Issues and challenges matrix.
- B Library of exploratory concepts.

The 48 Exploratory System Concepts were developed in 12 areas of exploration as identified by the system challenges and issues work earlier in the project (listed below with the number of exploratory concepts in parentheses):

- Accommodating Electric Vehicles and Heat Pumps (8)
- Accommodating Microgen and Distributed generation (11)
- High Import Scenario (1)
- Delivering the required Flexibility (4)
- Interfacing with Private Networks (4)
- Cold Start and Black Start (2)
- Approaches to Balancing the System (1)
- Frequency Response (1)
- Voltage Management (3)
- Home Automation (4)
- Managing Capacity (4)
- Customer Developments (5)

- C Core concepts.
- D Functional Matrix and Function Sequencing Grid (available via www.theiet.org/fpsa or es.catapult.org.uk/fpsa).

7. Acronyms

BEMS	Building Energy Management System
CEMS	City Energy Management System
DECC	Department of the Environment and Climate Change
DG	Distributed Generation
DNO	Distribution Network Operator
DO	Distribution Operator
DSO	Distribution System Operator
DSR	Demand Side Response
EV	Electric Vehicle
FES	Future Energy Scenario
FPSA	Future Power System Architecture
GB	Great Britain
GBSO	Great Britain System Operator
GHG	Green House Gas
GW	Giga Watt
HEMS	Home Energy Management System
HP	Heat Pump
HV	High Voltage
KACs	Knowledge Area Consultants
LCNF	Low Carbon Network Fund
LV	Low Voltage
PNJV	Power Network Joint Vision
SE	Systems Engineering
SO	System Operator
SOF	Systems Operability Framework

Future Power System Architecture

A report commissioned by the Department of Energy & Climate Change

Systems Engineering Methodology

This Systems Engineering Methodology is the fourth in a suite of FPSA documents. It describes how the system engineering process was applied to the project, placing the future functions at the heart of the analysis considered within the context of four dominant time horizons.

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

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