The Institution of Engineering and Technology

Transforming the Electricity System:

How other sectors have met the challenge of whole-system integration

Executive Summary and Main Report

A report from the IET expert group: Power Network Joint Vision







www.theiet.org/pnjv

About This Report

This report supports the discussion that was initiated by The IET in December 2013 by the report 'Electricity Networks: Handling a Shock to the System'.

The IET identified the emerging challenge for maintaining essential technical co-ordination across the power system, for example, as generation becomes distributed and consumers become active parties.

To avoid any misunderstanding, the use of the engineering term 'system architect' refers primarily to a technical co-ordination role, not a 'central buyer' or market activity.

This report was written with the assistance of Innovate UK, the new name for the Technology Strategy Board, the UK's innovation agency. Innovate UK (www.innovateuk.org) provided advice and a financial contribution. It was supported by the IET Energy Sector and Energy Policy Panel, and is informed by the IET Power Network Joint Vision (PNJV) expert group.

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First published 2 October 2014

This report is also available on the IET website:
www.theiet.org/pnjv

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1 Executive Summary

1.1 The electricity sector – a revolution now approaching?

For over 100 years, the principles behind Britain's electricity sector have remained largely unchanged. The steam turbine was demonstrated by Sir Charles Parsons in 1884 and, before the First World War, Charles Merz had established the world's first alternating current (ac) distribution grid in Newcastle-upon-Tyne.

The last decade has seen the beginnings of a revolution: this is an international trend and one that will change the way established power systems operate. In Britain, the Climate Change Act 2008 and similar regulations have triggered a paradigm shift in the way electricity will be produced. So far, we have seen relatively small changes, but phasing-out coal-fired power stations and the widespread adoption of renewable energy will change the power system radically.

Power flows through the grid are also changing: rather than all power flowing from central power stations to passive consumers, electricity is being generated by solar PV panels on houses and businesses, and by community scale renewable energy connected to the distribution grid. This can result in the reversal of power flows that may not be within the capability of today's networks. There are also substantial new types of load coming on the system, including chargers for plug-in vehicle batteries and electrically-powered heat pumps.

Some of the most significant changes are in the control individuals have over their electricity use. We are beginning to see mobile phone apps that allow consumers to control their heating remotely; smart meters, which will be rolled-out over the coming five years, will be enablers that allow consumers to schedule electricity use; and, during the past year, Google and Apple have announced plans for "smart homes" where heating systems and white goods respond to users' lifestyles. Demand response takes place at the consumer level, but its impact when adopted at scale will affect the national as well as local power networks.

All these factors influence the way in which the electricity system operates; taken together, they represent a fundamental shift in the industry structure. Effective technical co-ordination across these multiple parties is an engineering prerequisite if unintended consequences are to be avoided and if costs and supply resilience are to be assured.

1.2 The structure of this report

The technical developments necessary to implement the changes to the electricity supply system have been discussed in previous reports produced by the IET.

The main objective of this study has been to determine how other industries are structured to deal with complex system changes and the extent to which these technical integration activities are relevant to the electricity supply sector. To make valid comparisons, it was necessary to identify the scale of the system engineering challenges faced by the electricity sector so they can be compared with the challenges faced, and solutions adopted, by other sectors.

The early parts of the main report therefore concern the electricity sector. These are followed by sections on each of the industries investigated.

1.3 What is a system architect?

The original meanings of *architect* and *architecture* may have related to the design of buildings, but the words are now widely used in relation to the structure of any complex system. Thus, John Maynard Keynes has been described as the *architect* of the Bretton Woods financial system, and we talk about the *64 bit architecture* of personal computers.

For many large systems there is often a gap between the stakeholders who specify what the complete system has to achieve and the plethora of contractors, design authorities, operators, and other technical specialists who provide the hardware, software, and skills to construct and run the many sub-systems that together form the whole. This is a gap that, in engineering projects, is commonly filled by a body known as the *system architect*. In different sectors of the economy these bodies may be known as system designers, consultant engineers, system authorities or strategic planners, but the role is much the same. They are neither the stakeholders who set the objectives for the system, nor the organisations that design, build and operate the hardware.

Britain has a free-market economy and the default assumption is that “the invisible hand of the market” shapes the structure, supply chain and “system architecture” for goods and services. However, there are certain sectors of the economy that cannot be left to the market alone, either because they are integral to the democratic processes of the state, they are natural monopolies, or they cannot be allowed to fail. The national electricity supply system falls into the last two categories.

The proposed system architect role for the electricity system is a body that provides the co-ordination and the “glue” between both established parties and new entrants, including generators, network operators, and users, thereby facilitating the technical operation and the market mechanisms in a multiple-party, complex world.

1.4 The Internet revolution

Summary of the challenges

- The power network is becoming more closely integrated with the Internet and telecommunications networks. A failure in one could impact the others, as it is likely these networks will be used to control both distributed generation and time-shiftable loads.
- Home energy control systems are being developed to manage domestic heat pumps, EV battery charging, and other loads. These control systems, designed to minimise consumers' bills, might contribute to wider power network stability or might act as a destabilising influence on other network control systems.
- New smart networks and systems will produce very high levels of data. Converting this data into useful information, sharing it with relevant parties, and redesigning control systems to respond to "real time" information, rather than predictions based on historic data, will be major engineering tasks that include agreed open protocols for data transfer.
- The smart meter network is being installed before its role in a future Internet-connected energy system has been fully determined. Although steps have been taken to pre-empt these requirements in the smart meter specifications, there remains a credible risk that the necessary functionality, resilience, and safety integrity level for the smart grid will not be available from the metering network.

For the system architect, the coming-together of intelligent systems, telecoms, IT, and electrical generation/distribution, will define the essential competences in the role. It is likely that the dominant challenges for the system architect to resolve over the coming two decades will be related to these new disciplines, which were almost unknown during the CEGB-managed expansion of the network in the 1960s and 70s, and which will be essential to manage the new smart networks and appliances and high and variable levels of distributed generation.

Resolving the Internet revolution challenges will require large numbers of engineers and technicians who are able to understand not only power systems engineering but also the application of digital electronics to real time control systems and the way in which those systems interface with the millions of individuals in whose homes they will be installed. Because houses and families are different and there are different ownership models (private landlords, social housing, shared ownership, community energy participants, owner occupation, etc.) this is not a project where "one size fits all".

1.5 Managing the electricity system

Summary of the challenges

- The switch from the traditional load and frequency control to one based on millions of independent generators and consumers will represent a paradigm shift in the way the grid is managed.
- As presently configured, the grid relies on synchronous rotating generators to maintain constant frequency. In theory, it would be possible to design a network that is dominated by power infeeds from power electronic inverters with few synchronous machines. However, this would represent a radical redesign of the GB power system with no international precedent, and major challenges in both final design and the transition path.
- Synchronous generators can provide reactive power for voltage control on the network in a way for which wind turbines and solar PV are not designed. With a decarbonised power system there will be a need to manage reactive power and voltage control in new ways.
- The increase in inverter-coupled generation and loads will change the spectrum and levels of non-50 Hz currents in the grid.
- Inverter-coupled solar PV and wind generators may limit the ability of overcurrent protection systems to detect certain types of fault.

Each of the above issues is a systems engineering challenge. Taken together, they represent an aggregate challenge far greater than any in the history of electricity supply.

One of the most pressing is frequency regulation, which is influenced by system inertia and managed at present by the large steam turbine generators used in coal, CCGT and nuclear stations. Electricity generation from renewable sources typically does not have an intrinsic ability to control frequency. There are solutions, such as requiring the output of solar panels to be frequency sensitive or incorporating synthetic inertia in wind turbine control systems, but they are untried in Britain and represent a major departure from current practice.

1.6 Market challenges ahead

Summary of the challenges

- The electricity market was designed for an industry where the price of electricity was dominated by fuel costs. We are moving to a situation where costs will be dominated by capital and, at times, operating costs will approach zero.
- The future electrical load is not known with any degree of certainty. Scenario analysis has shown that by 2050 the peak demand on the system might reach more than twice that in 2014, or could be much the same as today. The difference between summer and winter will be more significant and it is possible that some generation assets will be unused for long periods of the year.
- Community energy groups may form the core for more resilient networks, such as micro-grid operation under disruptive storm conditions. It is not yet clear how such a structure could be compatible with the present market arrangements.

The evolution of the market structure is not a responsibility of the system architect, but will be an important consideration for ensuring whole-system operating integrity. For various reasons, a completely free market in electricity would not satisfy the requirements for decarbonisation, security and affordability, and so it has to be heavily regulated.

This problem has been recognised by the government as part of the EMR, in that the Contracts for Difference (CfDs) which have been agreed for new nuclear, on-shore and off-shore wind, and will, almost certainly, be required for CCS, effectively bypass the market for low-carbon generators.

By 2030, we can expect to see an electricity “market” fed predominantly by nuclear power, renewables, and CCS. This will be a market largely in name only as prices paid to generators will be pre-determined by CfDs.

Understanding the commercial framework is important in analysing possible roles of a system architect, as technological solutions have to be compatible with the likely outcome of whatever market structure exists, and be capable of accommodating market changes. A political decision to change the market or regulatory structure can be implemented more quickly than changing the technology that underpins stable grid operation.

1.7 Comparing electricity with other sectors

The study has looked at the way the system architect function is handled in other sectors, namely Telecommunications, Internet, Satellite Navigation, Air Traffic Control, Highways, Rail, Military, Healthcare, and Water. Three basic models have been identified to characterise the system architect roles:

Project companies and joint ventures

In private-sector project companies, the system architect is often closely associated with the project engineering or system engineering group reporting to the main contractor or the joint venture management team. Similar business models have been found in the telecoms, aerospace, and rail sectors – a small team of multidisciplinary engineers who interpret the commercial requirements into technical requirement specifications for different subsystems and components and are also involved in defining the integration tests on the complete system.

A successful example of a systems architect was that used for the DBT (design-build-transfer) contracts for light rail systems in the 1980s. Although these were state-funded and subject to competitive bidding, they were bought against system functional requirements specifications and the customer took a hands-off approach during the design and build phases. The system architect was a subsidiary of the main contractor working to a fixed-price contract and thus had an important incentive to finish on-time and within budget. This arrangement works well when the project is easily defined, which is the case for “greenfield” developments. However, it is not a model that has been widely used in the re-engineering of complicated legacy systems.

A unified industry

The traditional structure of a nation-wide, state-owned industry (e.g. BR, CEGB or BT) had a central management team with a technical director or equivalent, working with other members of the team to develop a technically-coherent business strategy and then taking responsibility for the integration of the various engineering components, with the support of heads of the technical departments. This can work effectively in the context of a vertically integrated organisation. The Highways Agency is an organisation that operates in a similar way.

In the *System of Systems Approach* (SOSA) used by the MoD, a systems architect is appointed within the MoD organisation. The architect can review assets that are planned to be connected to its data networks and has the authority to veto contracts that are non-compliant. However, its scope is more limited than would be needed in the electricity sector as the assets are owned by the MoD, or allied military organisations, and the SOSA is only concerned with the information system integration, not the functionality of the assets themselves.

A similar unified model is seen in air traffic control where NATS is a single body responsible for the operation and development of all air traffic services and has an internal system architect function responsible for the integration of the myriad of data systems that allow the safe operation of aircraft within the UK airspace.

London Underground Ltd. operates a similar system for managing change on its network and has an in-house systems engineering group performing a similar role to the SOSA team. The water companies, which have defined geographical areas and a clearly defined responsibility within them, also have similar structures. Comparable engineering structures can be seen in several (vertically integrated) European utilities and transport undertakings.

Committee-based system architect

The world-wide web (www) has a clearly identified system architect – the World Wide Web Consortium (W3C). Consortium membership covers a large number of businesses, including all the large software and computer system companies. Representative committees confirm all major decisions. However, it is not simply a committee-based organisation as it has many full-time technical staff, including the www founders. It is quite different to a standards committee, such as JPEL/64, that approves the IET Wiring Regulations, BS 7671.

Other industries that consist of a number of independent companies have interface and interoperability committees. In the telecoms industry, committees allow service providers to agree standardised interfaces with equipment suppliers. Similarly, in the European rail industry, international committees define TSIs (Technical Standards for Interoperability) that ensure safe operation of international trains and allow cross-border trade in railway hardware. However, these are not system architects, in that they agree the interfaces of the system building blocks rather than designing the systems from those blocks.

This type of committee structure works where decisions are largely technical; where the industry is not subject to radical change, where industry players have a common interest in a successful outcome (such as computer manufacturing companies needing a ubiquitous and consistent web interface), and where failure to comply with the recommendations of the committee result in being unable to connect to the Internet or not having trains approved for operation on the rail network. However, this research has not found successful examples of rapid, large-scale system change being managed by a committee – particularly where the industry participants have close commercial relationships with each other, as in the GB electricity sector.

Comparison with the GB electricity sector

It can be seen from the examples that a system architect function is common practice in industries where a number of autonomous parties have to cooperate to achieve an end result that no single party could achieve.

Comparing electricity with the other sectors studied, it has become apparent that the challenges are more demanding than in any other sector that has been researched during the study. The scale of change will be as great as that seen in the Internet and telecoms sectors over the last two decades. However, there are fundamental differences – while the consumers of telecoms have seen dramatic changes to available services (e.g. sophisticated mobile phones, on-demand television, mobile Internet, multi-player gaming, downloading movies, cloud storage) which excite consumer interest and justify new charges, the electricity available from a 13A socket is identical to that provided for the past 70 years.

This research has identified that there is not currently an overall system architect for the sector, other than DECC, which has the role by default rather than intent. The scale of the challenge means that a system architect function is likely to be of considerable benefit and there are risks of continuing without such a role being adequately defined and resourced.

1.8 The present system architect function and how it might change

At present the operation of the transmission and distribution systems is managed by two key documents – the Grid Code and the Distribution Code, each kept up-to-date by code review panels including representatives of the bodies responsible for operation of the transmission systems and the distribution systems. However, many new bodies and groups are becoming involved in the electricity system. Figures 1 & 2 (on pages 12 and 13) highlight the changes: Figure 1 represents today's landscape with the coloured boxes showing the major players and the representation at the two Code panels. Red circles indicate bodies currently represented at the Grid Code Review Panel and blue triangles are those represented at the Distribution Code Review Panel. Figure 2 shows the likely participants in the industry by the mid-2020's and reveals the multiple players and the inadequacy of coverage by the present arrangements.

In terms of an ability to manage change of the scale identified in this report, the current structure has the following limitations.

1. The Grid Code and Distribution Code Panels have a narrowly defined remit – they cannot take a comprehensive view of the whole electricity system. The remit of the Panels is purely technical, yet most real world solutions will work best with the technical, operational and commercial impacts treated together.

2. "Smart loads", such as the electric vehicle charging infrastructure, Internet-connected white goods, and heat pumps, will have a major impact on the system but are not represented on either panel.

3. Today's code change procedures work reasonably well for small incremental changes, but there is doubt about their ability to implement large, rapid, or complex changes.

4. Ofgem now has significant code review powers. However, it is not clear whether these arrangements are wide enough for the future, or may be constrained in other ways.

5. The Codes refer to the "System", but not in the sense of "whole-system" as used in the context of "system architect"; the Distribution Code definition of System is simply, "An electrical network running at various voltages".

6. New European network codes being prepared for the Commission by ENTSO-E (the European Network of Transmission System Operators for Electricity) are likely to influence future arrangements.

7. The code panels have essentially short-term time horizons, but many system architect issues are in the domain of a strategic planning activity.

These diagrams avoid the over-simplification of putting a large circle round the whole picture and labelling it "system architect role"; it is important to recognise that this is a complex sector having many parties, priorities and accountabilities, and developments. The creation of an effective system architect function would need to be undertaken with care and full consultation.

Figure 2 shows the parties likely to be active in the electricity system sector by the mid-2020's. Note that while many of these are potentially "GB industry" parties that might fit within a revised model of today's panels, there are others that are key external parties (for example overseas consumer product manufacturers) where technical integration would need to be achieved by facilitation, rather than by direction under a Code.

Figure 1: TODAY - Networks sector participants, with main players highlighted

Today's Technical & Operational Co-ordination: the red and blue shaded areas show the principal focus for the remit of the respective Panel. The coloured dots and triangles indicate the membership of these panels (Blue triangles – Distribution Code Review Panel and Red dots – Grid Code Review Panel). Parties without coloured symbols are linked to the Panels on an ad hoc basis only. Orange boxes show other industry panels, likely to need closer integration for future developments.

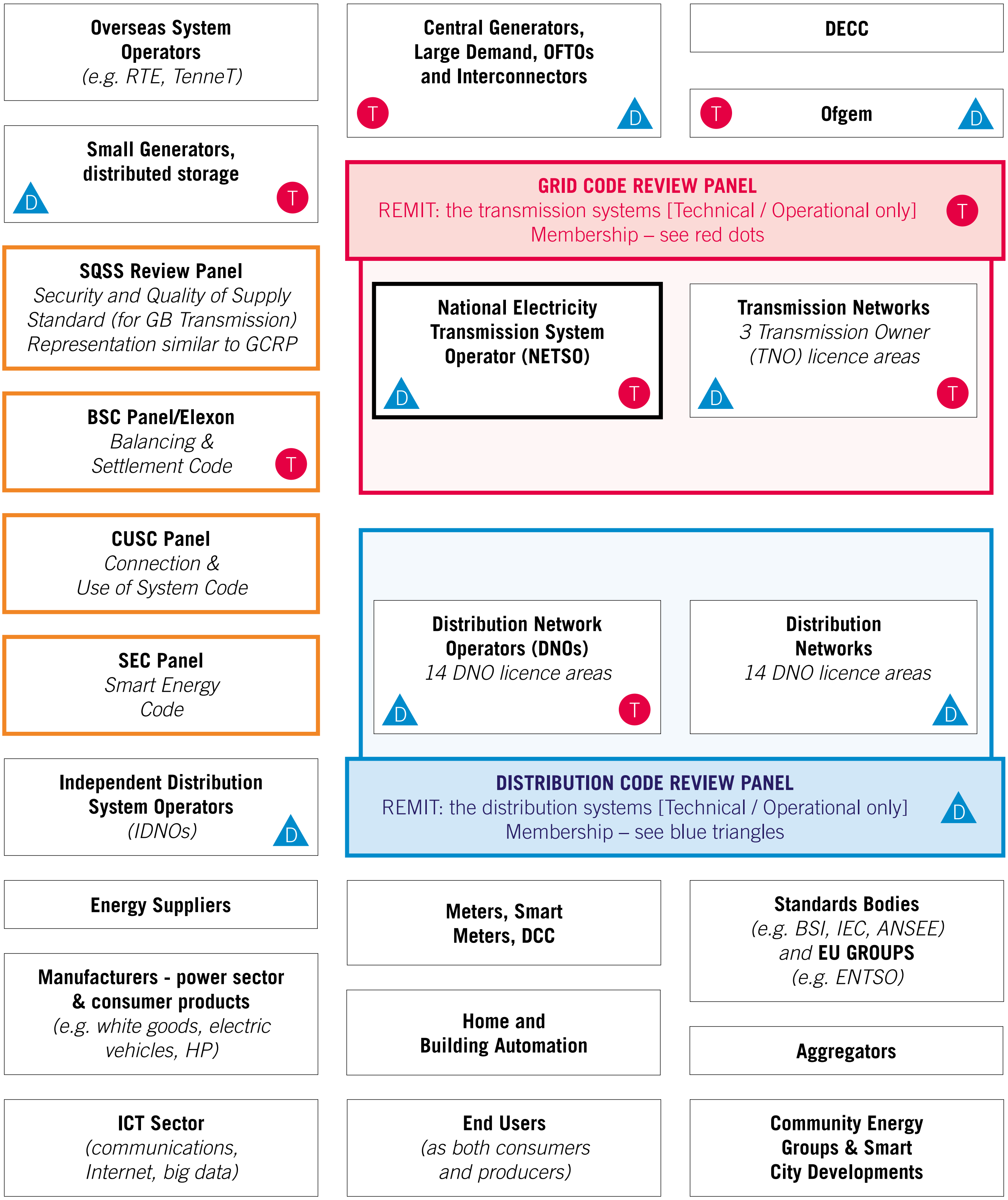
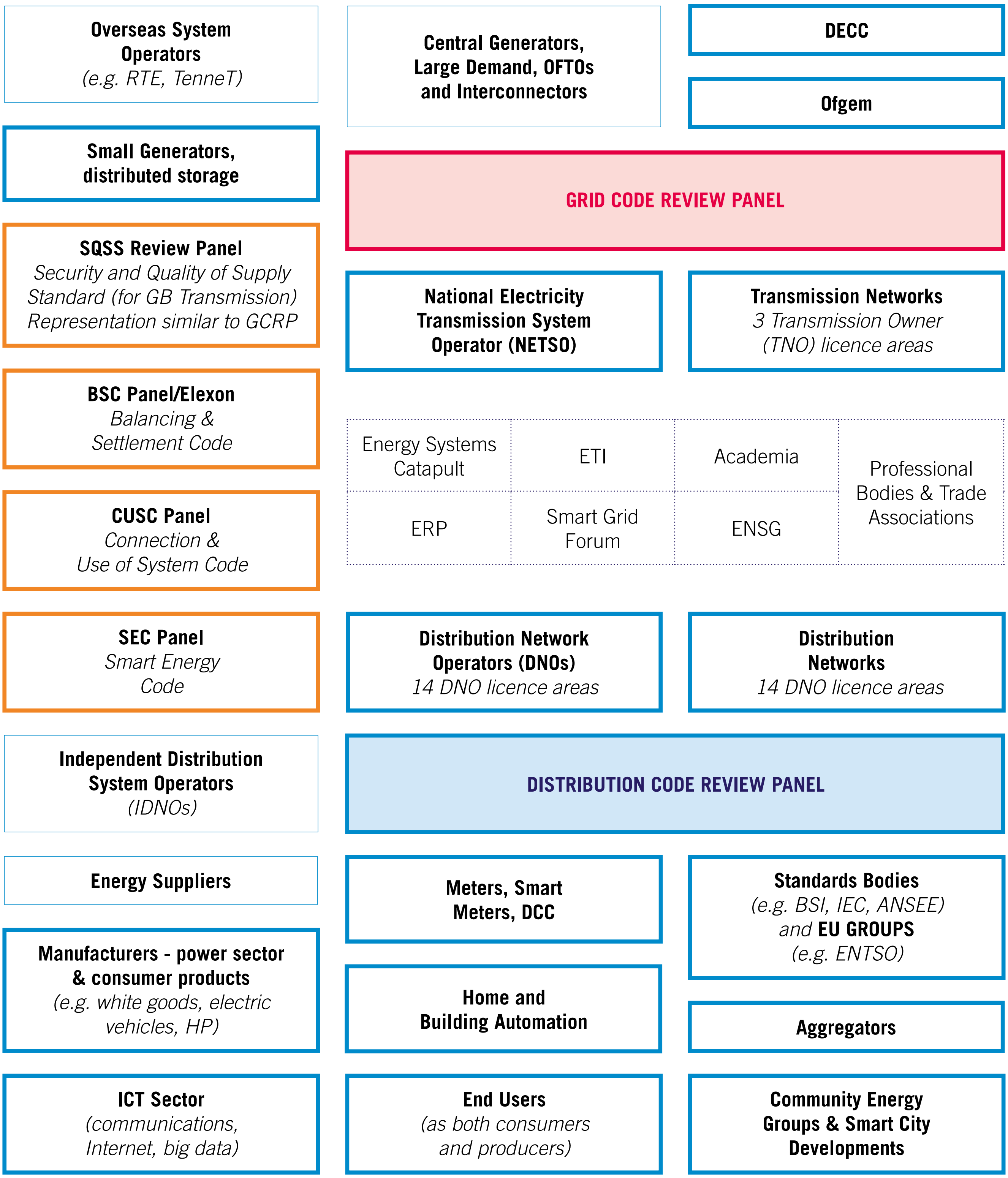


Figure 2: FUTURE - Major networks sector participants in mid-2020s, revealing the multiple active parties

This diagram outlines the potential landscape for a system architect role – highlighted boxes indicate the principal areas requiring systematic co-ordination, either through influence or control as appropriate.



1.9 Models for a system architect

This research has not discovered a model for a system architect that could be adopted unchanged by the electricity sector, however there are several models that provide ideas that could contribute to the design of a system architect function. Three alternative models are described below that are representative of the wide range of those that could be considered:

Model 1: Unified industry

The "agency as main contractor" model, as used by the Galileo satellite system or the Highways Agency, is one that could be adapted to the electricity sector. In both cases, the central body has a technical team that has competence in the architecture of the system but passes responsibilities to other bodies for major activities, such as road maintenance, large-scale research, or launching satellites.

Model 2: Maximum subsidiarity

The "maximum subsidiarity" model used by the water industry could not be adopted directly, but, in an environment with large amounts of distribution-connected generation, frequency-sensitive loads, and a high uptake of "smart" load management, might provide a model leading to DNOs having a commercial relationship with end-users and distribution-connected generators in regional networks, as well as the main responsibility for short-term load balancing. This would leave the Transmission System Operator managing inter-regional balancing, correcting "clock error", and relationships with larger generators. In this model, which would radically change the commercial structure of the industry, the systems architect function would be distributed between the central TSO and the DNOs, depending upon whether a specific issue was "whole system' or "local" in character.

Model 3: A standards-based system architect

The system architect model of the world-wide web, in which underlying principles of operation and interfaces are agreed by a Technical Architecture Group (TAG) reporting to a central board, is one that could form the basis of a standards-based system architect function. A TAG that included representatives from National Grid, the DNOs, and major generators, could agree the system architectural principles, which would then be implemented by detailed standards. However, this would have a much wider scope than the existing code panels, would need to embrace new third party stakeholders, and would require changes to governance and regulation of the industry if the arrangements are not to fall foul of competition and other laws.

Models to be avoided

The experience of the rail industry suggests that a government department attempting to fulfil a system architect function in addition to its normal activities carries conflicts of interest and may not be an ideal solution.

A second model to be avoided is to spread the system architect role between several bodies in an unstructured way, as appears to have happened in the NHS National Programme for Information Technology (NPfIT) where different companies were required to produce interoperable systems without an overall system architect or an adequate specification of the transition plan from the multitude of existing systems that had been tailored to the specific needs of different medical specialities.

1.10 Conclusions

1. **The systems engineering challenges of the GB electricity industry are at least as complicated as those in any other sector of the economy, if not more so.** The industry has been operating to the same basic system model since the early part of the 20th Century and, to meet the targets of the Climate Change Act and the Industrial Emissions Directive, will need to re-engineer its systems and technologies over the coming decade. This will require more than simply tuning the present arrangements.

2. **The timescale for delivering transformational change in the industry is very short in comparison with asset lifetimes and recent experience of technological innovation**. Managing the transition will be at least as difficult as determining the end state.

3. **At present the industry is based on a one-way flow of energy from large central power stations to millions of consumers connected to distribution networks**. If present targets and aspirations for renewable energy sources are met we can expect to see periods of the day, particularly in summer, when solar PV and wind energy generation could provide the full load. If this situation materialises we will be faced with the situation where system voltage and frequency regulation will migrate from a handful of large power stations to millions of customers who will be both consumers and generators. This will represent a paradigm shift in the operation of the grid that has not yet been achieved anywhere else in the world.

4. **With the development of electric vehicles, electrically-driven heat pumps, home energy management systems, smart grids, and local energy networks, the electricity network will become more interdependent with the telecoms network.** This represents another ground-breaking shift in technology, new transformational relationships between suppliers and consumers, and new risks that must be managed to ensure that resilience and security is maintained.

5. **It is challenging to define the role of a system architect for the electricity sector when the decarbonisation trajectory of the rest of the energy sector is uncertain**. While the electricity sector needs to be able to plan on levels of penetration of plug-in vehicles and heat pumps, and the growth in distributed renewables, these will be determined by customer take up, not central planning. Flexibility will be an important attribute of the future energy system and of its system architect.

6. **The transformation of the energy network is likely to have only limited success unless consumers buy-in to the concept and the system design**. The system architect function needs to have an agenda that is wider than technical issues alone and needs to include the interface with IT and communications systems as well as the human factors.

7. **A spectrum of possible models for a system architect has been identified and three examples have been proposed**. One is based round an agency model, another based on the principle of maximum subsidiarity, and a third being a standards-based structure. The objective of this report was not to propose a particular solution and these are therefore included simply as examples of a wider continuum of what would be possible.

8. **The implementation of an effective system architect role will require government to recast its relationship with the industry**. To deliver commitments on decarbonisation, there will be a need to define output targets, such as a trajectory for decarbonisation of the sector, rather than specifying the means to the delivery of those targets, such as the number of solar PV panels.

9. Based on what has emerged from this research, it would be useful to undertake a modest extension of this study to investigate international experiences of managing the system architect role in electricity sectors.

2 The main report

2.1 Contents

2.2 Summary and scope of report

2.2.1 Objective

The objective of this report, commissioned by the steering group in February 2014, is to undertake comparative research of *system architect* roles in different industries. This report, which is one of a number of studies, covers:

a) How the system architect role is fulfilled in the present electricity system;

b) An overview of the systems engineering challenges that will have to be addressed as new technologies are introduced to decarbonise the sector;

c) How other sectors in UK undertake the system architect role, how successful these approaches have been and any lessons that can be learned.

2.2.2 Structure of the research

The investigation of other industries was based round desktop research and (lightly structured) interviews with a small number of key players in each. The objectives of each of these was to understand:

- The structure of the system architect (SA) role in the industry, the vision, objectives, size and responsibilities of the organisation(s) undertaking the role, and a brief history of how the SA role became established;

- The systems engineering challenges in the industry; how are these challenges identified, and how research is conducted;

- Governance, authority, responsibility, accountability and funding of the SA body and its relationship with stakeholders (including regulators and standards bodies);

- Any indications of the successes of the arrangements, and learning points from where it has failed.

2.2.3 Acknowledgements and referencing

The report discusses the structure and SA roles in several sectors of the economy. The people listed in Appendix B have provided much of this information, without whose contributions the report could not have been produced. Individual, oral or email contributions are not attributed so it is not possible to see who contributed which ideas. This is not an oversight, but was to allow individuals to be more frank than would have been possible were observations to be attributed. However, the published material in Section 8.3. Appendix C is referenced using the *Harvard Referencing System* [indicated by the author's name and publication date in square brackets].

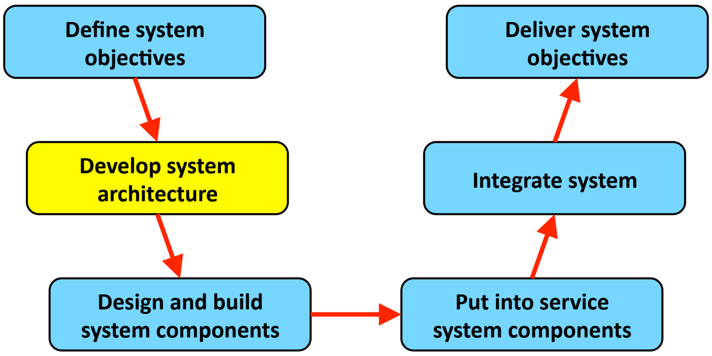
2.3 A system architect

2.3.1 What is a system architect?

A SA is needed when a system[1] is undergoing change. The change could be the development of new activity, such as building a network of international space stations; more usually, it is where an existing system is subjected to significant changes, either to its objectives, the environment in which it operates, or to the technology it uses.

Developers of computer software refer to a V-diagram for software testing [Sommerville, 2010]. A variation of this diagram can be used for defining the role of system architect:

Figure 3: How a systems architect fits into project delivery



Starting at the top left, the objectives of the system are defined. For restructuring the accident and emergency (A&E) services in a region these might include: emergency service response times, waiting times in hospital, death rates, ability to cope with an epidemic, patient confidentiality, cost and so on. The objectives are defined as desired outcomes, not how those outcomes are achieved.

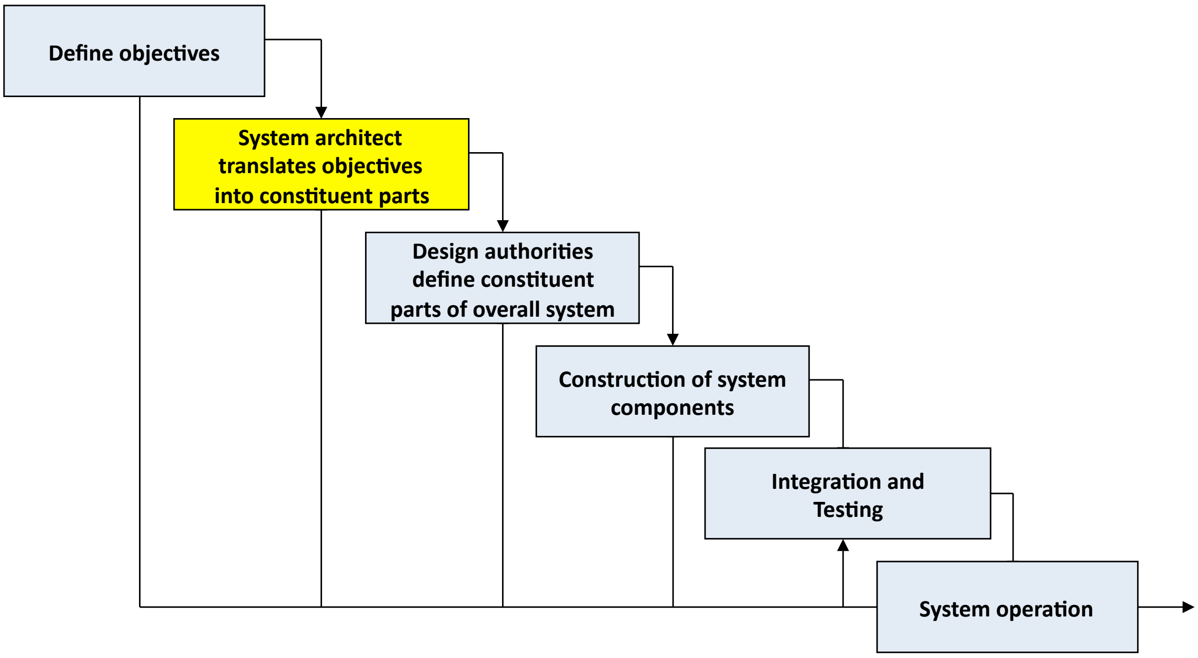
The SA body takes these objectives, analyses different options and produces a system architecture that will satisfy the outcomes. For the A&E example, the architect might analyse possible combinations of walk-in centres, computer-based diagnostics, regional hospitals, community nurses, mobile treatment centres, and extended GP facilities. The SA's outputs are recommendations of what facilities are needed and how they would interact. The design authorities for these facilities use the SA's guidance when designing and building facilities. The right hand side of the diagram is about putting into service the various components of the system. At the top right the system objectives are delivered.

SAs are not responsible for everything that happens – within their domain of interest they will have control of some things, influence over others, and will be aware of others. It can be seen as a collaborative role, rather than a detached central planning function.

An alternative way of looking at an SA's role is a version of a *waterfall diagram*, also used in the software industry. In Figure 4, the SA takes the objectives, which are expressed in terms of performance, and translates them into a series of concrete recommendations that can be used by bodies responsible for providing the component parts of the system. These might be related to hardware, such as the construction of a dc-dc link between two electrical networks, or could relate to soft system components, such as the choice of data formats or operational protocols.

In both examples, the SA does not act in a vacuum – it works closely with whatever body or group of stakeholders is defining the overall requirements of the system and with the bodies that are responsible for the design and operation of the various component parts of the total system.

Figure 4: Waterfall diagram



The diagrams differentiate between the roles of a *system architect* or *system authority* and *design authorities*. The former are responsible for the structure of a system, for defining the functional specifications of its various subsystems, and for ensuring that the designs of those are properly validated. On the other hand, *design authorities* are responsible for designing the component subsystems and managing their long-term configuration. Both roles are essential.

System authorities are responsible for:

- understanding the objectives of the client(s), users, and other system stakeholders;
- analysing the various operating conditions under normal, abnormal, and partial failure conditions;
- producing the system architecture and the top-level sub-system functional specifications;
- ensuring that the complete system and its component subsystems function as intended.

SAs ensure emerging disruptive threats to the system are researched, either by themselves or by industry parties, establish the feasibility of the architecture to cope with these threats, and recommend actions to industry players. The SA is the body that is expected to underwrite the safety and efficacy of the total system to meet the objectives of the stakeholders.

By contrast, *design authorities* are responsible for the design (and, in some cases, operation) of particular sub-systems. With reference to the complete electricity system, a sub-system could be a major item of capital plant, such as a nuclear power station or an offshore windfarm.

In many complex systems, the various bodies involved may lack a common agreement on what constitutes “the problem”, and there may exist many different perspectives, values, and beliefs around what aspects of the situation are most important and how to address them. The SA function needs to be able to address a range of highly interrelated non-technical issues, one technique for doing so being *Soft Systems Methodology*. [Checkland, 1999]

Within a large sub-system it is likely that there will be lower-level systems engineering teams, with similar roles to the overall SA to interpret the overall design requirements, who work alongside project managers and the other specialists.

2.3.2 Managing change in an existing system

An architect designing a new hospital on an empty site has a task that is reasonably easy to specify. Rebuilding a working hospital that is still admitting patients and where staff are carrying out operations is altogether more challenging!

The same consideration applies to the SA role in other sectors. Designing a new road junction to carry 100,000 vehicles/day is reasonably straightforward; producing a design that can be implemented while 50,000 vehicles/day are passing along the route is far more difficult and it is likely that the final design will have to be adapted to allow it to be constructed without too much traffic disruption. In this, the SA group is not an “island”. They have to work closely with other stakeholders to produce a design concept that provides the planned benefits but that can be implemented in stages on a working system.

In the refurbishment type of project, in addition to the final design, the SA needs to produce a “roadmap” (or *capability release programme*) showing how the new technology will be phased-in, how it integrates with the existing technology and eventually replaces it, moving securely and safely from today’s technology to the target architecture. The transition plan can be the most challenging part of a project.

2.3.3 When is a system architect needed?

The UK is a free market economy and there is an underlying assumption, both domestically and in the EU, that markets are used to organise the exchange of goods and services. A market can undertake most transactions in such a society. Paul Seabright writes of the puzzlement of a delegate from a newly liberalised country when told that there is no-one in charge of the supply of bread to the population of London. [Seabright]

However there are activities within most businesses that, for a variety of reasons, the directors consider to be “core business” that have to be carried-out in house and cannot be outsourced to third parties. Similarly, there are areas of national life in which markets cannot be left to define all outcomes – defence, parliament, and the administration of justice are considered off-limits in most countries. In addition, there are some sectors of the economy that are natural monopolies, such as regional water supply and sewerage, where it is impracticable for a householder to seek offers from competing suppliers.

In sectors which, for whatever reason, cannot be left to the markets, there is usually a need for a central function to establish the overall architecture of the activity and how various “players” interact to produce the goods or services, particularly during periods of non-evolutionary change. This function can be described as the SA. There is no need for a SA to define the production and distribution of bread in London, but there probably is a need for it to set out a structure of how the army, navy and air force establish a joint mission on the other side of the world.

2.3.4 Definition of system requirements

It is useful to categorise system requirements into three groups: *functional* requirements, *non-functional* requirements and *domain* requirements:

Functional requirements are some of the most straightforward to specify as they represent the purpose for which the system is being constructed.

Non-functional requirements cover a wide range, including defining the users, operator skills, the organisation within which the system has to be operated and maintained, and specific legal requirements, including safety approval processes.

Domain requirements cover issues that may seem obvious to a specialist in a particular area but are not necessarily known by someone designing a new system. To a librarian, that professional journals can be classified by *Volume* and *Number* or by *Date* may be second nature and not worth mentioning, but software designers building a new filing system for a library may not be aware of this, so it has to be specified.

Accurate definition of domain requirements will be particularly important in a future electricity system that will rely on an integration of IT, telecoms, and consumer engagement with electrical engineering.

2.3.5 Characteristics of a successful systems architect

Systems engineering is a specific competence that is different to the competences necessary to design or build a particular component or sub-system. It is a numerate discipline involving the simulation of steady-state and dynamic relationships between system elements. For example, in a health service the SA might be expected to simulate the speed and geographical spread of an epidemic, to estimate the probability of different growth scenarios and then to specify an infrastructure of ambulances, treatment centres, vaccination stockpiles, and staffing levels necessary to meet the targets set by its client organisation.

SAs cannot work in a vacuum; they need a client prepared to specify or agree quantitative targets and objectives for different phases of the project. In the above example, the “client” is likely to be a national or regional health service and the targets would have to include the probability of the system not being able to cope and thus being unable to treat critically ill patients. Without a clear frame of reference, agreed assumptions and targets and a roadmap of how the business expects to progressively implement the system, a SA is unlikely to be able to do a good job.

Although systems engineering is a specific competence, the SA team needs to understand the design and operation of sub-systems sufficiently so as not to place inappropriate demands on them. This is similar to the role of an architect in the design of a building. In many industries, multidisciplinary systems engineering teams have members who previously worked in the major sub-systems or in operations. As an example, the system engineering team for a metro development might include people with experience of civil engineering, passenger behaviours, vehicle design, ergonomics, communication systems, HV electrical systems, and operations. However, their role is not to “double guess” the specialist design/delivery parties but to make sure the systems engineering team understands the domain requirements and the limits of these specialisms and that they can “speak the same language”.

End notes for Part 2

[1] The word **system** has many uses and definitions. In this paper, it is taken to mean “An organised structure that consists of interconnected and interdependent elements (often the responsibility of different organisations) built to achieve a defined objective. System elements can themselves be subsystems, each consisting of further sets of elements. Systems display emergent properties not seen in the individual elements.”

3 Challenges in the electricity sector

3.1 How the system architect role is fulfilled in the GB electricity system

3.1.1 Under nationalisation

The Central Electricity Generating Board (CEGB), which replaced the Central Electricity Authority in 1957, oversaw the last major expansion of the electricity network in England and Wales. In the post-war boom, electricity demand grew rapidly and the CEGB duty, laid down by government, was to provide an adequate and secure electricity supply, rather than pursuing the cheapest generation route. Thus the CEGB had the duty to ensure sufficient power stations and grid capacity; the Area Electricity Boards similarly were required to buy sufficient power to supply customers, and to maintain adequate local distribution networks.

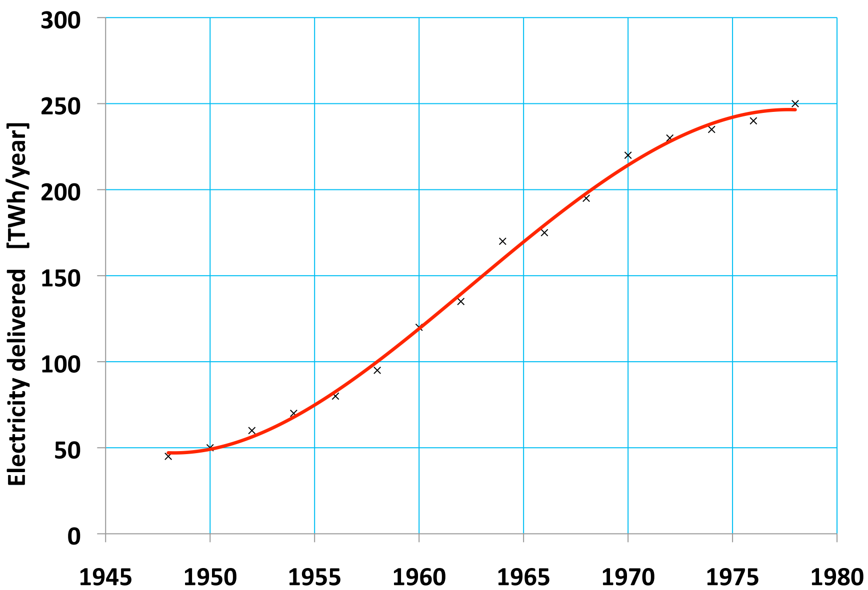
The CEGB was a largely technocratic organisation, led by engineers, and the SA role was undertaken by its strategic planning function, supported by senior management. However, the government, by its representatives on the boards of the nationalised industries, the appointment of senior directors, and its relations with the supply industries – such as the National Coal Board or the Gas Council – had considerable influence over the development of the sector.

In the area boards, there was also a strategic planning role that could be described as an SA function. The CEGB undertook an overall SA role through its ”development plan” mechanisms, involving annual consultation with generation, transmission, and distribution parties. The Electricity Council and its Chief Engineers' group addressed technical matters on a cross-industry basis. These mechanisms resulted in the publication of some 500 engineering recommendations and guidance documents that are still extant today and under the ownership and management of the Energy Networks Association (ENA), with oversight of continuing developments being addressed by Ofgem.

3.1.2 Systems engineering challenges for the post-war expansion

Between 1950 and 1970 the output of Britain's electricity system quadrupled, as shown in Figure 5. [Wikipedia]

Figure 5: Post-war growth in electricity supply



However, although there were impressive developments in the technology of turbines, generators, circuit breakers, and other equipment, the principles on which the grid operates had been well-established for several decades. The steam turbine was first demonstrated by Sir Charles Parsons in 1884; by 1900 the largest steam turbo-generator produced 1.2 MW and, by 1910, units of more than 30 MW were being built.

Before the First World War, Charles Merz had established the world's first ac distribution grid in Newcastle upon Tyne, based round Neptune Bank power station and distributing power at 5.5 kV, three-phase. By the mid-1920s there were more than 600 local electricity grids, supplied by coal-fired power stations, which were rationalised by the Electricity (Supply) Act 1926 setting up the Central Electricity Board. The 132kV grid started as a number of disconnected networks in 1933 and, by the outbreak of the Second World War, it was operating as a national system with 9 million consumers. [Wikipedia]

The ratings of steam turbo-generators continued to grow from 50 MW in 1930, to 100 MW by 1950 and 500 MW by 1970, responding to economies of scale. The technology of the associated control systems also changed over that period from electromechanical control systems using liquid resistors to regulate generator excitation to electronic systems using power semiconductors. However, the concept of steam turbine generators feeding a high-voltage grid, progressively stepped-down to low-voltage feeders supplying individual streets, was largely unchanged for the 30 years before the CEGB expansion. This is completely different to the scenario we face now, described in section 3.2, which represents a fundamental re-engineering of the electricity system.

3.1.3 Privatisation of the industry

By the 1980s, the large-scale rebuilding of infrastructure by the CEGB and the unexpected drop in the rate of increase of demand caused by the rapid exploitation of North Sea gas led to an over-generous capacity margin.[2] Privatisation was seen as a way of reducing costs for consumers, as well as part of an ideological policy to "roll back the frontiers of the state".

The principle of privatisation was set out by Nigel Lawson in a speech on energy policy [Lawson, 1982]. It provided a clear break with the tradition of state control and was the start of the process that led to the Electricity Act 1989 and privatisation of the industry:

> *"I do not see the government's task as being to try to plan the future shape of energy production and consumption. It is not even primarily to try to balance UK demand and supply for energy. Our task is rather to set a framework which will ensure that the market operates in the energy sector with a minimum of distortion and energy is produced and consumed efficiently."*

However, as Dieter Helm wrote [Helm, 2002], "It is apparent that any attempt to describe the energy market as a competitive one, just like any other industry, is mistaken. The government is a major player in the energy market – indeed in many respects it is the dominant one, influencing price, outputs and capital structure. Privatisation did not change this feature; it changed the form of interventions, and the mechanisms of influence shifted from the boardrooms of nationalised industries to more explicit policy instruments and regulatory control. But the idea that governments could simply retreat from the scene and leave it to competitive markets is an illusion – energy is just too important to the economy and society."

3.1.4 The electricity sector today

In the 12 years since Helm wrote these words, government intervention in energy policy has become more intrusive, dominated by the 2008 Climate Change Act. Since 2010, the IET Energy Policy Panel has responded to a dozen government consultations a year and there has been a plethora of initiatives on renewable energy, fuel poverty, the *Green Deal,* smart metering, feed-in tariffs, new nuclear stations, electricity market reform, etc. It is difficult to avoid the conclusion that the government has, in recent years, moved towards becoming the system architect (SA) of the electricity sector, perhaps without realising it and arguably without having considered the full implications.

It has been helpful that, for the period since privatisation, the system architecture developed by the nationalised industry was adequate to accommodate many incremental extensions to the system. It is now becoming apparent, as identified recently by the IET in their statement *Handling a Shock to the System* [IET, 2013c], that the changes ahead are disruptive to the long-standing architecture. In a later section of this report, Figure 15 shows how relationships in the industry might develop over the coming decade. Increasingly the tools and techniques used for the last three decades are becoming less appropriate.

3.2 Systems engineering challenges for the electricity sector

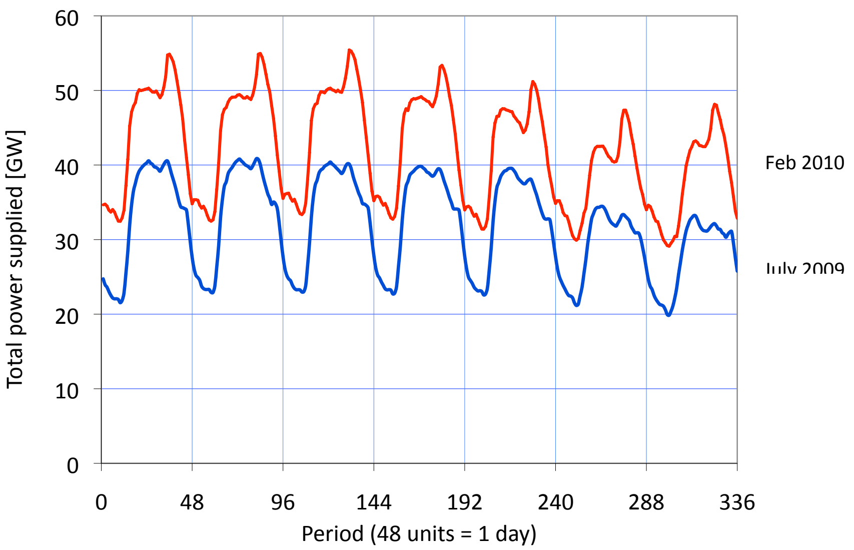
This section, which has been informed by previous work by National Grid, the ENA and the IET PNJV project, [NG, 2014b; ENA, 2012; IET, 2013c] summarises the challenges in the electricity sector to allow a comparison with those in other sectors reviewed later in this report. In researching this section, it has been assumed that the targets for the proportion of energy met from renewable sources and for system decarbonisation are unchanged from those in the 2008 Climate Change Act and other current legislation.

Conclusions are summarised in sections 3.5 to 3.7.

3.2.1 Increased demand

The present demand for typical weeks in summer and winter is shown in the following graph:

Figure 6: Load on National Grid in summer and winter



It can be seen that the summer load varies between around 20 GW and 40 GW while the winter load varies between 30 GW and 55 GW with peaks up to 60 GW.[3] Demand will increase with the expected electrification of heat and transport; but it is not clear by how much or how quickly.[4] Making the assumption that 20% of domestic heating and of travel by car/taxi will have switched to electricity by 2030, the additional load represents an increase of around 20% in total electricity demand – an additional 60 to 70 TWh compared with the total demand in 2012 of 320 TWh.

However, this demand would not be constant throughout the year. Two thirds of the increase will be heating load that is concentrated in the winter months and, in particular, in the early morning and early evening [RAEng, 2012]. Transferring 20% of domestic heating from gas to heat pumps, plus the likely additional direct electric heating,[5] might be expected to increase the peak electrical load by up to 30 GW, an increase of 50% on the present peak load.[6] Predictions of the peak load in 2050 can only be tentative but, if the objectives of the 2008 Act are met in the manner presently envisaged by the Climate Change Committee and without effective load smoothing by demand response, the peak could be more than twice the current maximum. National Grid takes a more optimistic approach to improvements in energy efficiency and the smoothing effect of energy management, as well as a lower estimate in some scenarios of the penetration of heat pumps and electric vehicles. [NG, 2014c] The *Gone Green* scenario shows peak electricity demand in the mid-2030s of only 69 GW.

While the heat pump load would be concentrated at certain times of the day and year, the plug-in vehicle battery charger load will be much the same summer and winter but the load will be spread rather differently over the day. Without time-of-use tariffs, the EV/plug-in hybrid load would be expected to peak in the early evening when the day shift ends for commercial users and commuters return home and plug in their cars. With appropriate incentives, much of this load could be shifted to the early hours of the morning when other loads on the network are at a minimum.

At present, most EVs charge at 16A so the theoretical peak load of 6 million chargers in 2030 could be 20 GW, but, because of diversity, this is never likely to be seen. However, it is anticipated that 32A will soon be the norm for battery chargers for medium/large cars and many commercial vehicles and, by 2050, the CCC expects most cars to be electric. This could, in theory, represent 100 GW of load, which to prevent excessive peaks will have to be scheduled by smart charging systems, probably utilising smart meters and time-of-use tariffs. These smart systems will require new sensors, measurement data, communications, processing and commercial frameworks to be seamlessly integrated with the power grid.

In summary: the divergence of estimates illustrates that the future electrical load is not known with any degree of certainty. By some forecasts, by 2050 the peak demand on the system might reach more than twice that in 2014; alternatively it could be little more than today. Depending on the way electricity use develops, it is possible that some generation assets will be unused for long periods of the year. This scale of impact would be disruptive and would require the smart control and management systems to be highly effective, robust, and user friendly. This issue affects the whole system, raising loading concerns for distribution networks, transmission networks, and, of course, national generation capacity.

3.2.2 System effects of renewable generation and energy-efficient loads

Although there is not a formal target for the rate of new build of wind turbines, a recent study [RAEng, 2014] concluded that, from an average of different estimates, Britain could have about 26 GW of installed wind capacity by 2020, split roughly equally between onshore and offshore, and 50 GW by 2030, of which 30 GW could be offshore and much of the rest onshore in Scotland, some distance from the major loads on the network.[7]

A recent policy document [DECC, 2014b] sets out a strategy to increase the amount of solar power to 20 GW by 2023 and to concentrate this on medium/small installations which would feed into the LV or MV distribution systems,[8] rather than into the high-voltage grid, like conventional power stations or “agricultural scale” solar farms.[9] The load on the electricity system on a bright summer morning can be as low as 25 GW, which could, at least in theory, be completely provided by solar panels and wind turbines.

These changes impact upon several system engineering issues, discussed below.

Frequency stability

As the national transmission system operator, National Grid is responsible for a sophisticated and closely managed power network that maintains a regular supply of electricity at an alternating current frequency of between 49.8 and 50.2 Hz. As electricity users, we are oblivious to this but an excursion from this narrow band can be highly disruptive and result in large-scale shutdowns. Change of system frequency is a measure of the balance between supply and demand at any time. To manage frequency, the power demanded from a group of larger generators is increased or decreased to speed-up or slow-down the grid to stay within this frequency band. Wind already operates within this system but, as the level of penetration of wind increases, the way in which it is managed will have to change.

Wind turbines have less inertia and thus a shorter electro-mechanical time constant than conventional turbo-generator plant. This means that, with a high proportion of generation from wind power, the frequency of the grid responds more quickly to a sudden reduction or increase in demand or supply.[10] The Irish grid is reporting wider frequency fluctuations and higher rates of change of system frequency since the widespread adoption of wind power. [EirGrid, 2012]

Although modern designs of wind generator, coupled to the grid by electronic converters, have negligible intrinsic inertia,[11] it is possible, in principle, to simulate system inertia by "gearing up" short term variations in grid frequency to correspond to larger variations in turbine speed – so called "synthetic inertia". [Cutululis, 2011] This is not done at present in the UK and will require development and proving.

The increase in numbers of solar panels will also result in a reduction in the power system time constant. PV panels produce dc power that is fed into the distribution network by an inverter, so contribute no inertia to the power system.[12]

A move from fossil fuel generation to wind turbines and solar power is not the only influence on frequency stability. Traditionally most mechanical loads were supplied by induction motors running just below synchronous speed. For many loads, such as fans or pumps, a reduction in supply frequency resulted in reduced power demand which, in turn, improves grid stability. Modern drive systems, designed to reduce energy consumption, use electronic inverters to allow a partially-loaded motor to run more slowly, and thus take less power. This type of drive is used on nearly all modern heat pumps. These electronic control systems decouple the load taken by the motor from the frequency or voltage of the supply. If the frequency changes, the load stays the same; if the voltage drops, the current increases. Electronically controlled motors are helpful for the consumer as regards energy use, but can be detrimental to the stability of system frequency.

In summary: as presently configured, the grid relies on synchronous generators to control frequency. In theory, it would be possible to design a network fed entirely from inverters, with no synchronous rotating machines – the 3-phase auxiliary systems on some aircraft, trains and ships are supplied in this way. However this would represent a radical redesign of the entire power network with no international precedent and major challenges in final design, the transition path, and ensuring adequate resilience.

Harmonic content

Another common factor of inverter-coupled generators and loads is an increased harmonic content on the grid waveform. Harmonics are a cause of waveform distortion, departing from the 50Hz sinusoidal shape, and can result in power losses, reduction of network capacity, and the maloperation of network equipment and consumer loads. This is an important issue addressed by Engineering Recommendation G5/4 which has evolved over the last 50 years since it was conceived to cope with the high levels of harmonics produced by mercury arc rectifiers in industry. [ENA, 2005]

Since the Recommendation was last revised in 2005, there have been significant and accelerating changes in the scale and type of electronic converters on the system. While the focus of concern used to be on 5th, 7th and 9th harmonics, modern inverters produce little low frequency waveform distortion but wide-spectrum electrical noise in the 15 – 25 kHz range.

In summary: the increase in inverter-coupled generation and loads will change the spectrum and levels of non-50 Hz currents in the grid. Whether this will be detrimental to system operation will be determined by the detailed specification and design of the inverters and is likely to require investment in waveform filtering devices and adaptive control systems on the distribution networks. This is an issue that potentially spans vendor products, GB and EU standards, distribution networks, and transmission networks.

Fault levels

Short-circuit and earth fault protection on the LV and much of the MV distribution networks relies on overcurrent protection. Typically, the source impedance of the network is 5% near a substation to 15% at the end of a feeder, so a short-circuit results in a current between 6 and 20 times normal which trips circuit breakers and/or blows fuses within a few seconds. Well-established protection discrimination rules are in place to minimise the number of subcircuits tripped by a single fault.

Inverter-controlled generation or loads have a current limit to protect the semiconductor devices, so a fault on the network can result in a current only marginally above normal which cannot be relied on to initiate the clearance of a network fault.

In summary: inverter-coupled solar PV and wind generators and drive systems limit fault currents and thus the ability of traditional protection systems to detect certain types of fault. Undetected faults can result in extensive damage to networks and to consumer equipment, long-duration shutdowns, and safety risks for the public and network company staff. Changes in fault level can also impact the operation of other equipment connected to the network and thus this issue potentially affects many parties, not just the network operator.

Reactive power

Many loads consume reactive power, including household appliances such as fridges, phone chargers, computers, and TV sets. The electrical grid also contains many components that consume reactive power, such as the magnetic fields in transformers and the inductance of circuits.

Although it adds to their losses, synchronous generators, as used in thermal power stations, are able to provide reactive power; inverter-coupled generators, such as solar PV panels, are generally not.

In principle, there is no reason why inverter-coupled generation should not provide reactive power, but most current designs of wind turbines are not designed to do this and there have been reports of the Danish grid relying on Germany to provide reactive power under conditions of high wind penetration. There is much international research in this area that could help mitigate the problem. [Chen et al, 2012; Barth et al, 2013]

In summary: with a decarbonised network, there will be a need to manage reactive power in new ways. This could be done by redefining the interface with PV and wind turbine inverters but is likely to require sophisticated control connections. An alternative would be the provision of specific power factor correction equipment on the network, managed under automatic control. Reactive power management is key to network voltage control and integrated solutions potentially involve generators, large consumers, distribution networks, and transmission networks.

3.2.3 Increased complexity and randomness

The PNJV Position Statement [IET, 2013b] identified some of the additional complexity that could be introduced into the GB electricity network by 2030, on the assumption that GB meets its decarbonisation targets and aspirations by the means currently envisaged. A large proportion of the electricity demand will be met by flow renewables, available only when the wind is blowing, the sun is shining, or the tide is flowing. Weather forecasts and tide tables will become a significant component of generation planning which will have to cope with increased randomness in generation as well as demand. Forecasting of generation and demand conditions closer to real time is likely to become increasingly important.

At the domestic level, we can expect to see at least 15 million homes with energy management systems,[13] responsive to price signals from the smart meter network, many of which will control heat pumps and/or EV battery chargers taking the much higher loads discussed earlier. Many of these will be controlled by systems of which network operators have no direct visibility.

In summary: the switch from the traditional load and frequency control to one based on millions of independent generators and consumers will represent a paradigm shift in the way the grid is managed. There is no doubt that it can be done, but there is currently no detailed engineering strategy or plan for the transition. Determining and implementing effective solutions will require integrated working across all parts of the supply chain, including third parties providing energy management facilities, and power network operators across the distribution and transmission companies. To meet the challenging climate change targets, it will be necessary for the electricity industry to embrace independent energy management companies, but, if not integrated effectively, these bodies could exacerbate system instability.

3.2.4 Merger of power and IT systems

For many years, power networks have used SCADA (supervisory control and data acquisition) systems for remote measuring of electrical parameters and control of circuit breakers, tap-changers, and other equipment. Traditionally, these have used bespoke and reasonably simple software with a separate link to each device being controlled. Subsequent generations of equipment used PLCs (programmable logic controllers) that allowed a single data link to be used to control several geographically separated devices. These used special purpose industrial data networks which, because they were used in environments isolated from public access, had little or no security against hacking or other malicious intervention.

Later generations of remote control systems are more likely to use conventional Ethernet data links and transmissions protocols, bringing them closer to the technology used by millions of businesses and individuals world-wide. Rather than provide separate data links to remote locations, control systems are using commercial wired and wireless data networks.

Between now and 2020 energy suppliers will be responsible for replacing over 53 million gas and electricity meters with devices connected to a new wireless data network [DECC, 2014a]. A significant proportion of these smart meters could be connected into home energy networks, almost certainly using the same technologies that are used for current wired and Wi-Fi networks and probably sharing routers and cabling. It is likely that many home energy networks will use software provided by companies such as Google,[14] Apple,[15] or Microsoft,[16] designed to optimise the consumer's energy bill, rather than to enhance the stability of the network. It may be that these will work in harmony with the despatching and frequency regulation systems of the transmission system operator (TSO). Alternatively, because they are optimised with very different objectives, they may work against the TSO's systems. With large numbers of installations using the same software, there is a risk of "herd effects" when thousands, or even millions, of home energy systems decide to take the same action, in response to an external stimulus, thus causing large load swings and nullifying assumptions of diversity.

The implications of the plans for 20GW of solar energy by 2023 are that some means will have to be found to integrate this source of energy (equivalent to a dozen nuclear power stations) into the electricity network.[17] It is possible this will use a smart grid network of some type.

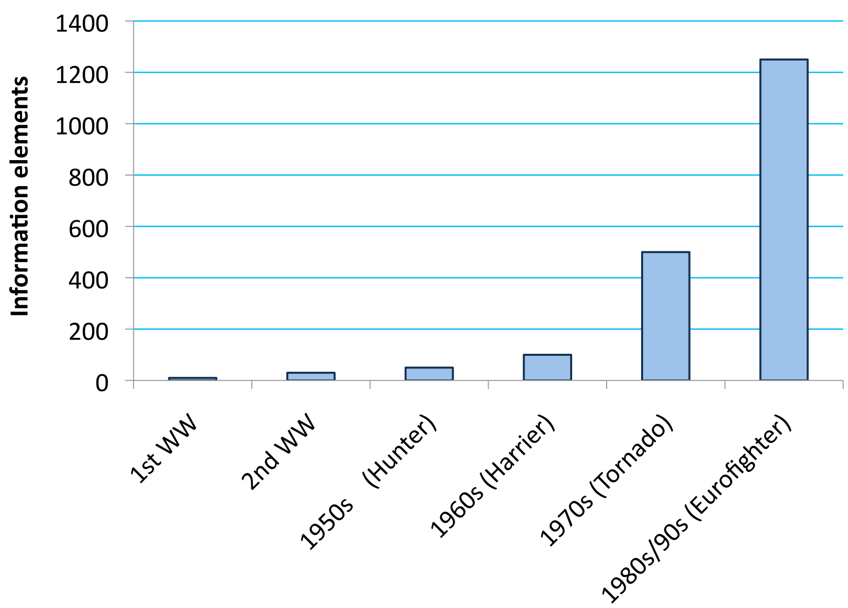
In summary: third-party suppliers are increasingly offering energy monitoring and management systems that link into telecoms networks allowing consumers to schedule their domestic heating and appliances remotely via the Internet or Apps on their mobile devices. These will interface with the smart meter/smart grid infrastructure, so we will be in a situation where the monitoring and control of the electricity network is integrated with mobile telephony and the Internet. As now, a failure of the electricity grid could seriously disrupt the Internet and telecoms networks, but, in the future, a failure of those networks could have serious implications for the grid.

This challenge to system resilience will require thorough analysis to ensure that weaknesses are not introduced to the national power system; it will involve parties across the power supply chain, together with ICT providers and specialists in cyber security (including government agencies). It may be necessary to engineer "fail-safe" mechanisms into controllable loads, such as frequency-sensitive over-rides to demand control signals. This would require a whole-system approach to design its operation and co-operative action (or policy mandate) to implement it on the demand side.

3.2.5 Information overload

There are integration challenges (operational as well as technical) that arise from the increased importance of ICT identified earlier. Power station control rooms have used analogue electronic control systems since the 1960s, but the change to digital systems in the 1970s resulted in an increase in sources of information. A similar trend has been seen in other industries; Figure 7 shows the number of cockpit information elements available to pilots in different generations of combat aircraft.

Figure 7: Cockpit information elements [BAE Systems[18]]

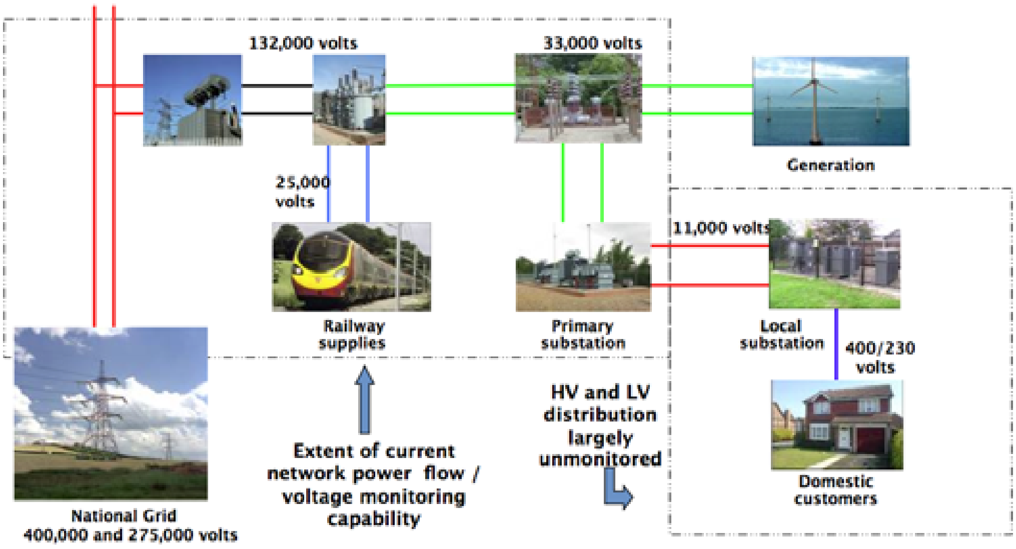


While the control room instrumentation in a conventional power station can cope with a few thousand feedback elements from different parts of the plant and can carry out a root cause analysis of fault messages to avoid overloading operators, the situation will be more complicated in the future. A 2 MW wind turbine connected to the 33 kV or 11 kV networks could transmit 120 signals to the owner's control room, of which a dozen could be fed through to the DNO. If by 2030 we have 2000 turbines, either singly or in small groups, connected to DNO networks, that could represent 20,000 data inputs, as well as a few thousand control signals to modulate their output under conditions of low demand and high wind.

Solar PV panels will be far more numerous. If the government aspirations are met, [DECC, 2014b] it will be necessary to include some arrangement to modulate generation under low-load conditions, which could involve data links. Additionally, with widespread distributed generation, it will be necessary to monitor voltages and currents at various points in LV networks, for example to manage variable loads and adjust tap-changer positions.

The situation at present is that LV substations and circuits are largely unmonitored, as shown in Figure 8 [UK Power Networks, 2013]. Even with a minimal level of monitoring, it is likely that MV and LV monitoring will involve many hundreds of thousands of data inputs.

Figure 8: Extent of existing data monitoring



Installing data monitoring and transmission systems is relatively straightforward. In systems engineering terms, the challenge is how to extract useful information from this data and then use that to control the increasingly complex power networks and their interface with millions of home energy computers and industrial energy management systems.

In summary: new smart networks and systems will produce very high levels of data. Converting this data into useful information and redesigning control systems to respond to "real time" information, rather than predictions based on historic data, will be a major engineering task. Sharing of information will become increasingly important to enable the wider picture to be seen and improve forecasting; this will be between the Transmission and Distribution operators, between the Distribution operators, and with third parties such as the smart metering DCC, aggregators, and operators of EV charging facilities. Standardisation of protocols and formats will be essential to ensure all parties "speak the same language" and to ensure that data can be summated and information extracted efficiently. With increasing complexity and interconnectedness, unforeseen risks to system resilience are likely to emerge if not addressed in a systematic and robust way.

3.2.6 Distribution networks and community energy

An earlier section described the increased load that is expected on the network. This will impact all three groups of assets – generation, transmission, and distribution – as well as the appliances and energy automation systems of consumers. At present, it is not clear what future loadings will look like on the distribution network. If the heating systems in a quarter of the houses in a street are converted from gas boilers to heat pumps, the peak electrical load in winter could double. However, if they also have solar PV panels installed, the daytime load in summer could be halved.

The ability of a local distribution network to cope with these increased loads depends, to some extent, on when it was built. After the Clean Air Act 1956, the domestic burning of coal was largely banned; for the following 20 years many houses were fitted with electric storage heaters, supplied from baseload coal and nuclear power stations as well as direct electric heating. Distribution networks were sized to cope with these loads. With increased exploitation of North Sea gas in the early 1970s and the conversion of the network, natural gas became the fuel of choice for most domestic consumers, electricity consumption reduced, and more houses could be supplied from a single substation with tapered LV feeders.

The simple way of dealing with a doubling of load would be to dig up the streets and double the number of cables and transformers; however, this would be expensive and highly disruptive to the public. In principle, smart grid technologies could obviate or off-set this need and allow the control of load on the grid down to the level of each subcircuit – in fact to a “postcode level”. This would be undertaken with the agreement of consumers, who would be rewarded for the service they provide. Within that postcode, the home energy management computers and local network management computers could prioritise loads and determine how best to allocate capacity while not causing serious inconvenience for any individual consumer. Current smart grid projects, funded through Ofgem’s Low Carbon Network Fund, are starting to validate such approaches and are already providing encouraging results. [ENA, 2014]

Recent years have seen growth in Community Energy Networks that could provide up to 3 GW of energy by 2020. [DECC, 2014a] Although some community energy projects are off-grid, most are grid connected. These are, in effect, “postcode level” networks where communities owning generation and flexible demand manage their load internally and negotiate supply and feed-in contracts with energy suppliers.

The establishment of community energy groups could strengthen community focus and encourage energy awareness and efficiency. These may also form the core for smarter and more resilient networks, such as micro-grid operation under disruptive storm conditions, and for means of managing distribution feeder loading. Widespread community energy groups, or equivalents run by a distribution network operator (DNO), could reduce the need to upgrade LV distribution circuits by time-shifting the load within a neighbourhood. However, it is not obvious how a future smart grid system would interface with these groups. To manage the loading on a local substation, their relationship needs to be with the DNO but smart meters have an interface with a central Data and Communications Company (DCC), based on the assumption that the consumer interface is with a national electricity retailer, not with the local DNO. Although DNOs can be given access to consumer data, there appears to be no provision for active interaction and the latency delays in transmission may limit this type of interactive control. Alternative arrangements have been considered in an ENA discussion paper. [ENA, 2012] and the Smart Grid Forum, Workstream 4, but the proposals have not been adopted for the current roll-out of smart meters.

In summary: it is not yet clear whether the smart meter infrastructure could support this type of operation, how compatible the necessary close collaboration with the DNO would be with a market based round national energy retailers, and how potentially conflicting calls for demand management actions will be resolved. Community energy groups and, indeed, smart city developments, will result in important new players coming into the electricity sector and this will require new co-ordination mechanisms to ensure effective integration and development of common best practices and standards to avoid adverse system interactions and ensure cost-effective and consumer-friendly solutions. This is one of the areas where integration with other energy vectors may need to be addressed, sooner rather than later.

3.2.7 Smart grids – managing the security risk

The GB smart meter network and its potential to interface with controllable loads will provide an important opportunity to balance the increased demands of heating and transport with less-predictable sources of energy. However, it could also represent a major new source of risk. If, at 19:00 on a winter's evening in the 2030s, a software fault, either in the smart meter network or one of the systems connected to it, were to send a "cheap electricity now" signal to all homes with EVs, it could trigger a sudden increase in demand of up to 20 GW as home energy management systems respond to the erroneous price signal. Since April 2014, grid management has assumed that the maximum step change in demand or load is 1.8 GW, so an event of this nature could theoretically represent more than 10 times the present worst case assumption.

With multiple connections to the Internet and telecoms network there appears to be a credible risk that the control of assets connected to the grid could be affected by viruses and other malware, such as the Stuxnet virus used against Iranian nuclear centrifuges or the Cryptolocker "ransomware" that has attacked unprotected computers in the UK. A system crash would have serious implications, so there is an essential requirement for end to end systems integrity and resilience. Risk management may be assisted by incorporating "defence plans" into controllable loads, such as frequency sensing to initiate or disable demand response actions.

The computer industry uses the concept of Safety Integrity Level (SIL) defined in IEC 61508[19]. [IEC, 2010] The specification, design and validation of software-managed control systems for a SIL 3 or SIL 4 system is a far more arduous undertaking than for a SIL 1 system. The system architecture must be constrained to avoid certain types of fault or ambiguity, code has to be assessed and validated and the whole system is tested against a far greater range of potential faults. There are specific procedures for using COTS (commercial off-the-shelf) equipment, which would include smart meters and their associated equipment.

While smart meters are used simply for remote meter reading, demands on system reliability and integrity are not high, although there could be more stringent requirements for customer data confidentiality. However, if the network is used for real-time control, capable of causing large and rapid changes in power flows, a high SIL would probably be justified. Engineering experience has shown that it can be extremely difficult to uprate the SIL of a network that was not designed for high integrity and resilience *ab initio*. It may be the case that the smart meters and associated data networks being installed over the next 5 years are compatible with the use of smart grids for domestic demand response and the management of distributed generation, as a means of balancing load and supply and reducing carbon emissions, but this cannot be taken for granted without rigorous analysis. The IET has consistently put the case that the deployment programme for smart meters should be designed and implemented as part of a wider plan for smart energy grid infrastructure as part of a whole-system approach to energy supply and demand. [IET, 2013a]

In summary: the smart meter network is being installed before its role in a future Internet-connected energy system has been determined in full. Although some efforts have been made to pre-empt these requirements in the smart meter specifications, there remains a risk that the necessary functionality, resilience and safety integrity level for smart grid will not be available from the metering network. Addressing this as smart meter utilisation grows and new features are integrated, together with any defence plans for demand management devices, will require co-ordinated effort between Meter Owners/Suppliers, distribution network companies, the Transmission Operator, the DCC and ICT providers.

3.3 Electricity too cheap to meter?

When the electricity industry was privatised, there was an over-provision of generation, much of which had been in service since the 1960s and 70s and was therefore fully depreciated. The transmission network was also well-established. Thus the cost of electricity was largely determined by fuel costs. The additional costs of providing the infrastructure represented an "add on" to the fuel bill, generally recovered by a standing charge and/or charging more for the first few hundred kWh of electricity.

Over the coming 15 years this will change. To meet targets for decarbonisation and industrial pollution, existing coal-fired plants will have been phased out before 2030 and unabated gas will be reserved for peak lopping. The bulk of electricity generation is likely to be provided by nuclear and renewables, supplemented during the winter by coal power stations fitted with carbon capture and storage (CCS).

Refuelling and operating costs of nuclear power stations are low and operating costs of wind and solar power are effectively zero. However, the costs of the generating assets and associated infrastructure will be substantial. Because of the difference in load between summer and winter, the present arrangements whereby operators of wind and solar renewables can assume that there will always be a customer for their electricity whenever the wind blows or the sun shines is unlikely to last. In addition, operators of nuclear power stations may find their output restricted at certain times when there is insufficient load. In these circumstances, the concept of *levelised cost of generation*, used for many economic comparisons, becomes largely irrelevant.

In a situation where marginal energy costs (per kWh) could be almost zero and capacity charges (per kW) are very high, it is difficult to see how an electricity market based an auction of energy (per kWh) is possible. Bid prices would no longer be related to operating costs and there must be a risk that it would be closer to a game of poker, where the bid is based on an assessment of the competition, rather than on cost. A free market for electricity would be likely to produce the politically unacceptable result of extremely high prices in winter, particularly at periods of peak demand, but very low prices at times when the demand can be met entirely by renewable energy.

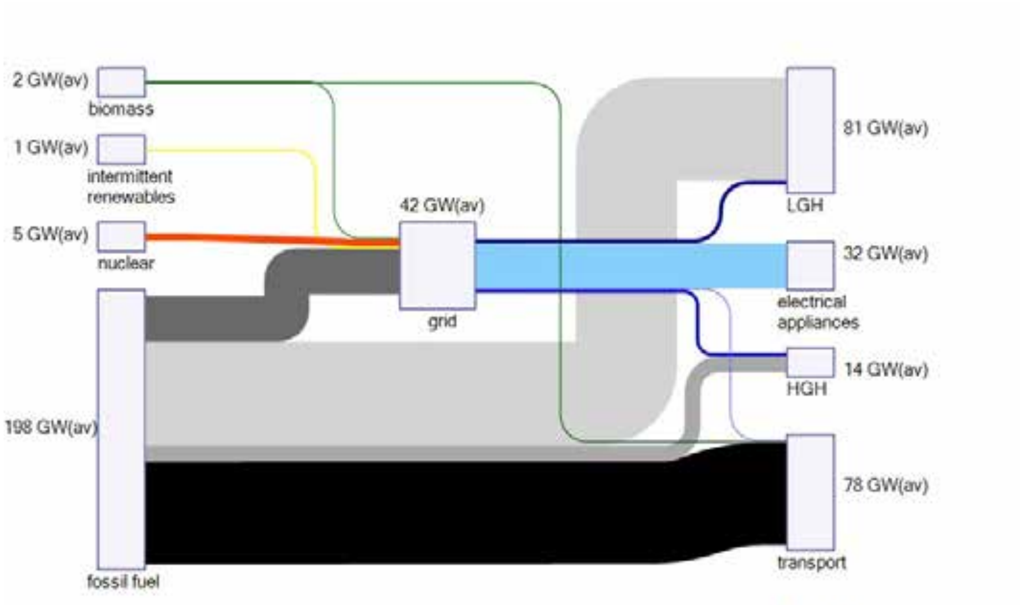
It is not obvious that present market arrangements will continue to work in a stable and transparent manner. This has impact not only for the working of the wholesale market but also for the planning and secure operation of the networks which are highly sensitive to the geographic location of the generation that runs and to its particular technical characteristics.

3.4 Political uncertainty

Earlier sections discussed the actions that will have to be taken to meet the targets of the 2008 Climate Change Act, as interpreted in the Fourth Carbon Budget and EC emissions directives. These imply a large increase in electrical load from heat pumps and plug-in vehicle charging systems, more or less offset by improvements in efficiency. Almost all solutions to meeting the targets also require a significant increase in distributed generation that would require network reinforcement. However it is not clear that this is what will happen and, to avoid the risk of stranded assets, Ofgem is very cautious about supporting investment to meet environmental targets until developers put forward specific plans for specific sites.[20]

Figure 9 is a greatly simplified chart[21] showing energy flow from sources on the left (fossil fuel, nuclear, intermittent renewables and biomass) to the major loads (transport, high-grade heat, electrical appliances and low-grade heat) on the right. (Data is for 2008, the date of the commitment to reduce CO_2 emissions by 80% by 2050.) It can be seen that the two largest energy users are transport (primarily oil fuel) and low grade heat (primarily natural gas). While the extent to which these demands will transfer to the electricity network is unclear and as pre-emptive investment is discouraged, it is difficult to identify a roadmap for the electricity sector.

Figure 9: Energy flow chart for 2008 [RAEng, 2010a]



In comparison with the timescale for establishing a UK supply chain for wind farms or tidal flow turbines or for the design and build of nuclear reactors, political decisions can change very quickly. In November 2013, Section 115 of the renewable energy roadmap update said "the Government will continue to provide a stable long term investment framework for the [onshore wind] sector." [DECC, 2013] Five months later the *Daily Telegraph* reported "David Cameron wants to go into the next election pledging to "rid" the countryside of onshore wind farms." [DT, 2014]. The solar PV strategy [DECC, 2014b] was announced with little forewarning and, if the objectives are met, will have a major effect on electricity networks.

Even larger changes are on the horizon: a decision in 2017 to leave the EU could make commitments to meet the Industrial Emissions Directive 2010/75/EU less relevant.

In 1974, Lord Carrington was Secretary of State for Energy. Since then, energy policy has been the responsibility of 20 Secretaries of State, several of whom have introduced major changes. During 2013, the largest proportion of electricity (41%) was produced by coal-fired power stations, almost all of which were operating in Lord Carrington's era. The challenge for a SA will be to retain sufficient organisation flexibility to accommodate the inevitable policy changes in an industry with plant lifetimes that are many times longer than the political cycle.

3.5 Integration of power engineering with telecoms, the Internet and active consumers

Summary of the challenges

- The power network is becoming more closely integrated with the Internet and telecommunications networks. A failure in one could impact the others as it is likely these networks will be used to control both distributed generation and time-shiftable loads.
- Home energy networks are being developed to manage domestic heat pumps, EV battery charging, and other time-shiftable loads. These control systems, designed to minimise consumers' bills, might contribute to network stability or might act as a destabilising influence on other network control systems.
- New smart networks and systems will produce very high levels of data. Converting this data into useful information, sharing it with relevant parties, and redesigning control systems to respond to "real time" information, rather than predictions based on historic data, will be major engineering tasks that include agreed open protocols for data transfer.
- The smart meter network is being installed before its role in a future Internet-connected energy system has been fully determined. Although steps have been taken to pre-empt these requirements in the smart meter specifications, there remains a credible risk that the necessary functionality, resilience, and safety integrity level for the smart grid will not be available from the metering network.

For the SA, the coming-together of intelligent systems, telecoms, IT, and electrical generation/distribution will define the essential competences in the role. It is likely that the dominant challenges to the SA over the coming two decades will be related to these new disciplines, which were almost unknown during the CEGB-managed expansion of the network in the 1960s and 70s, and that will be essential to manage the new smart networks and appliances and high and variable levels of distributed generation.

In Britain's 1970s de-industrialisation, many of the large national companies that had been involved in the post-war growth of the energy industries either closed, merged or were taken-over. The message to teenagers was that power engineering was not an attractive career path. University departments scrapped power engineering laboratories and the numbers of students studying the discipline, either at university or in further education (FE) colleges, dropped.

Implementing the technologies discussed in this paper will require large numbers of engineers and technicians who are able to understand not only power systems engineering but also the application of digital electronics to real time control systems and the way in which those systems interface with the millions of individuals in whose homes they will be installed. Because houses and families are different, and there are different ownership models (private landlords, social housing, shared ownership, community energy participants, owner occupation, etc.), this is not a project where "one size fits all".

3.6 Managing the electricity system

Summary of the challenges

- The switch from the traditional load and frequency control to one based on millions of independent generators and consumers will represent a paradigm shift in the way the grid is managed.
- As presently configured, the grid relies on synchronous rotating generators to control frequency. In theory, it would be possible to design a network that is dominated by power infeeds from power electronic inverters with few synchronous machines. However, this would represent a radical redesign of the GB power system with no international precedent and major challenges in both final design and the transition path.
- Synchronous generators can provide reactive power for voltage control on the network in a way for which wind turbines and solar PV are not designed. With a decarbonised network, there will be a need to manage reactive power in new ways.
- The increase in inverter-coupled generation and loads will change the spectrum and levels of non-50 Hz currents in the grid.
- Inverter-coupled solar PV and wind generators may limit the ability of overcurrent protection systems to detect certain types of fault.

Each of the above issues is a systems engineering challenge. Taken together, they represent an aggregate challenge far greater than any in the history of electricity supply. The problems are soluble and many techniques that are already being developed, such as active network management or quadrature boosters [UKPN 2013] or rapid frequency response, [NG 2014] could contribute to a solution.

One of the most fundamental questions that is typical of those in the new energy system,relates to GB frequency regulation, which could be managed centrally, sending instructions to controllable demands and to distributed generation. Alternatively, both distributed generation and time-shiftable loads (such as heat pumps, air conditioning, EV charging, water heating, and freezers) could individually be made frequency-sensitive so a deviation above, say, 50.05 Hz, would result in a progressive reduction in distributed generation and a deviation below, say, 49.95 Hz, a progressive reduction in load. The most suitable combination of centralised control and frequency-responsive loads will depend on an analysis of the GB system characteristics, the different types of renewable generation and time-shiftable loads, and the capabilities of the IT structure (including the smart meter network) that could be used to implement load and generation control. This will impact generators, network operators and consumers; it is typical of a problem that would benefit from a whole-system approach, such as could be provided by a SA function that provides a co-ordinating and integrating role across the industry, including engagement with new third party entrants.

3.7 Market challenges ahead

Summary of the challenges

- The electricity market was designed for an industry where the price of electricity was dominated by fuel costs. We are moving to a situation where costs will be dominated by capital and, at times, operating costs will approach zero.
- The future electrical load is not known with any degree of certainty. The winter peak load could increase by 50%, even allowing for load-smoothing by smart tariffs. Analysis shows that by 2050 the peak demand on the system might reach more than twice that in 2014 or could be much the same as today. The difference between summer and winter will be more significant and it is possible that some generation assets will be unused for long periods of the year. This scale of impact would be disruptive and would require the smart control and management systems to be highly effective, robust, and user friendly.
- Community energy groups may also form the core for more resilient networks, such as micro-grid operation under disruptive storm conditions. It is not yet clear how compatible the necessary close collaboration with the DNO is with a market based around national energy retailers and how potentially conflicting calls for demand management actions will be resolved.

The evolution of the market structure is important in examining the role of a SA. Economists define a free market as one in which economic agents interact freely and price emerges as the outcome to the interaction between supply and demand. Such an idealised state emerges only if agents are numerous (on both sides of the market), information is widely disseminated, firms are similar in size (typically small relative to the size of the market), there is interchangeability in the products they produce, entry and exit are relatively easy, and prices fluctuate smoothly and quickly in response to changes in conditions.

In addition, markets rely on the principles of *diminishability* and *excludability*. That is to say that as the availability of a commodity diminishes the price rises, which incentivises other players to enter the market and, if potential consumers cannot or will not pay the price asked, they are excluded from the benefit of that commodity.

By the above definition, GB electricity supply is a much tighter, less flexible, “oligopolistic” industrial structure, in which firms are large in relation to the market, entry is expensive, heavily regulated and time-consuming, economies of scale dominate, and the products on offer can vary across potential suppliers in terms of important secondary characteristics, such as CO_2 emissions. In such situations, the traditional, competitive market of textbooks is replaced by the potential for collusion (between both suppliers and those who sell and those who buy), for strong “bargaining” relationships between buyers and sellers, and for the establishment of long-term relationships that diminish the importance of “price” as the allocative mechanism.

Additionally, diminishability and excludability present problems in that it would be politically unacceptable for a seasonal shortage of electricity to drive up prices to the extent that it excluded significant sectors of the population from its use. And without the prospect of high prices, it would be impossible for investors to justify investment in assets that are used infrequently.

This problem has been recognised by the government as part of the EMR, in that the Contracts for Difference (CfDs) which have been agreed for new nuclear, on-shore and off-shore wind, and will, almost certainly, be required for CCS, effectively bypass the market for low-carbon generators. By 2030 we can expect to see an electricity "market" fed predominantly by nuclear power, renewables, and CCS. This will be a market largely in name only as prices paid to generators will be pre-determined by CfDs.

Understanding the commercial framework is important in analysing the possible roles of a SA as technological solutions have to be compatible with the likely outcome of whatever market structure exists. A political decision to change the market or regulatory structure can be implemented more quickly than changing the technology that underpins stable grid operation.

End notes for Part 3

2 Capacity margin – the difference between the maximum available supply capacity and the maximum demand. [RAEng, 2013]

3 NB: These data, taken from the NETA website, relate to the load on the transmission system; loads provided by distributed generation connected to the distribution system are "netted off" and do not appear in these data.

4 The Climate Change Committee (CCC) has discussed a doubling of the load on the electricity network by 2050, as a result of almost complete electrification of domestic heating and transport. Although the 4th Carbon Budget, aiming for decarbonisation of the grid by 2030, was accepted by Parliament on 17 May 2011 [Hansard 2011] it is neither clear how firm this commitment is nor what trajectory is envisaged for a switch to electric vehicles or electrically powered domestic heating.

5 Conventional wisdom is that heat pumps should be installed in well-insulated buildings and should be operating most of the day. Under these conditions a 6 kW (thermal) heat pump could replace a 20 kW gas boiler. However, many buildings are difficult to insulate and thus heat pumps are likely to be operated only when heat is required. Because their instantaneous output is less than a gas boiler, at cold times of the year their output is likely to be supplemented by direct electric heating, that is not necessary when using a gas or oil boiler.

6 This represents an additional load around 5 kW for a typical house fitted with a heat pump.

7 In 2013, the Government updated plans for renewable energy and wrote "The UK has some of the best wind resources in Europe, and onshore wind is one of the most cost-effective large-scale renewable energy technologies. The Government is committed to onshore wind as part of a diverse energy mix contributing to our security of supply and carbon reduction targets". [DECC, 2013]

8 As defined by IEC 60038

9 At present half a million homes are fitted with solar PV panels and the maximum output of solar power in GB is 2.7 GW. In round numbers we can expect 3 million installations as the domestic contribution to the 2013 target.

10 Rate of change of frequency (ROCOF) is an important parameter in operation of the grid as the protection system on many power stations includes a ROCOF relay that trips out the power station if a rate of change greater than a set value (typically 0.125 Hz/s) is detected. This is because a failure of the lines connecting a power station to the national transmission network is likely to result in a mismatch of supply and load resulting in acceleration or deceleration of the generator. ROCOF protection guards against "islanding" when part of the network is disconnected from the rest but continues to operate in an uncontrolled manner.

11 Different types of wind generator have different effects on frequency stability. Some designs of small wind turbines use induction generators with fixed-ratio gearing in which the inertia of the mechanical system is coupled to the electrical system through the reasonably "stiff" connection of generator slip speed. Larger turbines traditionally use doubly-fed induction generators (DFIGs) in which the rotational speed of the generator can be decoupled from the frequency of the grid so the mechanical inertia does not influence the frequency response of the grid. Recent designs of large turbines using permanent magnet synchronous generators are coupled to the grid via back-to-back semiconductor inverters that completely isolate the rotational speed of the turbine from the grid frequency. How doubly-wound and converter-fed generators affect the overall electromechanical time constant of the grid is thus no longer a function of the characteristics of the machinery but is determined by the control algorithms built into the converter control circuits.

12 Grid standards G83/2 (for small units) and G/59 (for larger units) allow the inverter to feed into the grid as long as the grid frequency is within particular limits – 47 to 52 Hz for lower power devices. If the grid frequency remains within these limits, feed-in power is constant and thus solar PV contributes nothing to system inertia or frequency regulation.

[13] Assuming most consumers with plug-in vehicles use time-of-use tariffs to reduce their transport costs.

[14] In January 2014 Google purchased Nest Labs for $3.2 bn. The latter's smart thermostat system is intended to integrate a homeowner's habits and comfort preferences into a home heating regime that helps reduce energy use.

[15] In May 2014 the Financial Times reported that Apple is preparing to announce a new software platform that would turn the iPhone into a remote control for lights, security systems and other household appliances, as part of a move into the "Internet of things".

[16] A July 2013 blog by Microsoft says they are working with a public-private collaborative of downtown Seattle property owners and managers to achieve a reduction of 50% in energy use by 2030. The cloud solution will collect data from the myriad systems in those commercial buildings and use data analytics to provide a prescriptive approach to how the building management systems can be tuned to improve energy efficiency.

[17] One way would be to make all devices frequency-sensitive, so they reduce power if the frequency exceeds 50 Hz and increases it if the frequency drops, but this could reduce the power unnecessarily at times of moderate load. A connection via the smart metering network would allow the system operator to switch-on frequency responsiveness only under low-load conditions when it is needed. With the incentive of higher average output, most owners of solar PV systems are likely to support connection.

[18] Human Factors Shared Service, BAE Systems Warton

[19] Oversimplifying, control systems including programmable devices are categorised from SIL 1 to SIL 4; the latter are systems (such as nuclear reactor control, railway signalling or aircraft control surface actuators), where a fault could result in multiple fatalities, while the former are systems where a fault is unlikely to result in more than consumer annoyance or limited financial loss. SILs 2 and 3 are intermediate levels. The following table shows the worst-case failure probabilities for systems of different SILs that have to be validated by rigorous analysis and tests. For occasionally used systems, the rates are expressed in probability of failure on demand, for continuously used systems in probability of failure per hour.

	Occasional use system	**Continuous use system**
SIL	Failure on demand	Failure per hour
1	10–1 - 10–2	10–5 - 10–6
2	10–2 - 10–3	10–6 - 10–7
3	10–3 - 10–4	10–7 - 10–8
4	10–4 - 10–5	10–8 - 10–9

[20] James Veaney, Head of Distribution Policy, Ofgem, speaking on 6 June 2014.

[21] DECC produces a more comprehensive Sankey Diagram that show import and export of energy vectors and system losses, but that was considered unnecessarily complicated for this application.

4 Experience in other industries

4.1 Telecommunications

4.1.1 Fixed line telecoms

From 1912 to 1981, British Telecom was a monopoly supplier of telephone services. The network had developed from operator-connected local exchanges; each telephone was wired to a local telephone exchange, and the exchanges were wired together with trunks. Networks were connected in a hierarchical manner until the public switched telephone network (PSTN) spanned cities, countries, and continents. In the early 20th Century, automation, using dials on phones and electromechanical Strowger equipment in the exchanges, introduced pulse dialling between the phone and the exchange, and then among exchanges. This was supplanted by electronic systems.

The functions of system architect (SA) during the growth of the PSTN was embedded in the Post Office Research Station at Dollis Hill, London. This was established in 1921 and in 1968 began the move to a new site at Martlesham Heath in Suffolk.

Following the ending of BT's monopoly in 1981, a consortium of Barclays, BP and Cable & Wireless set up Mercury Communications in competition with BT to meet some of the unmet demand for phone lines. However, this did not change the architecture of the system that had developed over many years.

Increasingly, the telecoms business is moving closer to the Internet and, with the growth of on-demand services, to broadcast TV. BT's Chief Architect group is currently part of BT Technology, Service & Operations (TSO). They focus on the technology of all IT platforms, networks, and infrastructure, including the technical delivery for BT's TV business. [BT]

4.1.2 Mobile telecoms

The coming of cellular mobile phones at the end of the 1980s dramatically changed the architecture of the telecoms networks. From the 1930s there had been radio-telephone connections to fixed networks operating over limited urban areas, along with "walkie talkie" services for the military, taxis, and emergency services. Analogue cellular services were introduced in the 1980s, but had significant deficiencies and their development has been described as chaotic (not unusual with the rapid introduction of a new technology). In 1991 the first 2G GSM digital network was launched in Finland and this quickly spread throughout Europe.

Cellular phones offered significant benefits compared to fixed-line telephony, for which customers were prepared to pay, and there was a rush to develop services. Initially, there were various incompatible standards, but these have consolidated into a common set of standards for all equipment manufacturer and operators.

The main standards body is ETSI, the European Telecommunications Standards Institute, a not-for-profit organisation with more than 750 member organisations drawn from 63 countries world-wide. ETSI publishes between 2,000 and 2,500 standards every year. Since its establishment in 1988, it has produced over 30,000. These include the standards that enable key global technologies such as GSM, 3G, 4G, DECT, smart cards, etc.

There is no GB national SA, but every major telecoms company has a SA team. When installing or upgrading a mobile network in a particular geographic area, the SA investigates different ways of achieving coverage, decides how many frequencies are needed, where switches, land lines or base stations should be placed, and so on.

Because hardware is bought from recognised manufacturers to defined technical standards, the role is largely about constructing cost-effective systems from well-understood building blocks. The size of the group working on each project depends on its size and complexity – a large project might have a SA, 4 or 5 section leaders dividing the work into networks, coverage, base stations, etc. with each having a supporting team of engineers.

Inter-company co-ordination is also promoted by the GSM Association. This body is an association of mobile operators and related companies devoted to supporting the standardising, deployment and promotion of the GSM mobile telephone system. The GSM Association was formed in 1995 and represents the interests of mobile operators worldwide. Spanning more than 220 territories, it links some 800 of the world's mobile operators with 250 companies in the broader mobile arena, including handset and device makers, software companies, equipment providers and Internet companies. It also works with organisations in industry sectors such as financial services, healthcare, media, transport and utilities. This is an example of a highly competitive industry sector that works co-operatively where matters of mutual interest make this a sensible course of action and where there is no conflict of interest commercially. Its operation can be seen as a mark of sector maturity.

4.2 The world-wide web (www)

Before discussing the world wide web (www) it is worth looking at the hardware systems on which it runs. Following the Russian launch of Sputnik in 1957, the USA established the Defense Advanced Research Projects Agency (ARPA, later renamed DARPA). This agency, with a budget of $3bn p.a., was intended to give the US superiority in various technological sectors.

The Advanced Research Projects Agency Network (ARPANET) was one of the world's first operational packet switching networks, the first network to implement the Transmission Control Protocol/Internet Protocol, commonly referred to as TCP/IP. The network was initially funded by ARPA within the U.S. Department of Defense for use by its projects at universities and research laboratories in the US. The packet switching of the ARPANET, together with TCP/IP, was developed into the backbone of the Internet.

4.2.1 The Internet Assigned Numbers Authority

A TCP/IP link is only useful if there is an unambiguous set of machine-readable addresses to allow communication. The Internet Assigned Numbers Authority (IANA) is responsible for coordinating the Internet's globally unique identifiers, and is operated by the Internet Corporation of Assigned Names and Numbers (ICANN).

The IANA functions are key technical services critical to the continued operations of the Internet's underlying address book, the Domain Name System (DNS). These include coordination of the assignment of technical protocol parameters, administration of country code Top-Level Domains and allocation of Internet numbering resources.
It works with an Internet Architecture Board (IAB) that provides oversight of aspects of the architecture for the protocols and procedures used by the Internet, oversight of the process used to create Internet Standards, and an appeal board for complaints of improper execution of the standards process.

ICANN originally performed its IANA functions under a US Government contract. However, technological governance of the Internet, which includes establishing standards and management protocols, has been handed off to non-profit organisations, including the Internet Engineering Task Force, the World Wide Web Consortium (W3C), and the Internet Corporation for Assigned Names and Numbers (ICANN). Although ICANN was initially a creature of the U.S. government and nominally under its jurisdiction, in 2009 the United States gave up its oversight function. ICANN is currently covered by an international board made up of academics, businesses, and civil society interests. All the above organisations are, at least in theory, open for anyone to take part in, yet because of their highly technical nature, it is generally people with technical expertise who make decisions about management operations by consensus. [Rifkin, 2014]

4.2.2 The World Wide Web Consortium

Consortium structure[22]

As a result of these agreements, W3C is the systems architect for www. It is an international community with about 400 (mainly institutional) members where a full-time staff and the public work together to develop web standards. Led by Web inventor, Tim Berners Lee, and a management team of about 20 people, W3C sees its mission as "to lead the Web to its full potential".

W3C is administered via a joint agreement among *Host Institutions*: Massachusetts Institute of Technology (MIT), the European Research Consortium for Informatics and Mathematics (ERCIM), Keio University in Minato, Tokyo and Beihang University (BUAA) in Beijing, China. The W3C staff (many of whom work physically at one of these institutions) are led by a Director and CEO. A small management team is responsible for resource allocation and strategic planning on behalf of the staff.

Much of the work is done by the Advisory Committee, composed of one representative from each member, a Technical Architecture Group, which primarily seeks to document Web Architecture principles, and the chartered groups populated by Member representatives and invited experts, which produce most of W3C's deliverables, such as interface specifications.

W3C is not currently incorporated. For legal contracts, W3C is represented by "Host" institutions. Within W3C, the Host institutions are governed by joint sponsorship contracts; the Hosts themselves are not W3C Members.

The Technical Architecture Group (TAG)

The TAG undertakes the core systems architect role for W3C. Interestingly, considering the www was invented 20+ years ago, it was created only in February 2001. The mission of the TAG is defined as *stewardship of the Web architecture*. There are three aspects to this mission:

1. to document and build consensus around principles of www architecture and to interpret and clarify these principles when necessary;

2. to resolve issues involving general www architecture brought to the TAG;

3. to help coordinate cross-technology architecture developments inside and outside W3C.

The primary activity of the TAG is to develop *Architectural Recommendations*. An *Architectural Recommendation* is one whose primary purpose is to set forth fundamental principles that should be adhered to by all www components. Other groups within W3C may include cross-technology building blocks as part of their deliverables, but the TAG's primary role is to document cross-technology principles.

The TAG does not just document what is widely accepted; it is also required to anticipate growth and fundamental interoperability problems. Elaborating the intended direction of the www architecture is intended to help resolve issues when setting future directions, help establish criteria for starting new work at W3C, and help W3C coordinate its work with that of other organisations.

The TAG also acts as an "appeal court" for *Member Submission Requests* that have been rejected for reasons relating to web architecture. A *Member Submission Request* is a proposal from one of the members for a development of the web. This is then considered by one or more working groups and may be accepted, in which case changes are made to specifications and protocols, or rejected.

The TAG's scope is limited to technical issues about www architecture. The working documents are clear that the TAG should not consider administrative, process, or organisational policy issues of W3C, which are generally addressed by the W3C Advisory Committee, Advisory Board, and Team.

Detailed web specifications

The nature of a digital communications system is that addressing has to be 100% correct or the communications fails. If a power system operator specifies a limit on negative phase-sequence (NPS) currents, a consumer who draws NPS currents a few percent above that limit is unlikely to be noticed and suffers no immediate and catastrophic consequence. By contrast, anyone who has mistyped a web address will be well aware that the likely outcome is a complete failure of communication. The sensitivity to precise compliance with standards will increase in the electricity sector as energy automation and smart systems become more widely established.

It is essential in a complex environment that standards are precise and detailed. The W3C website contains hundreds of pages setting out in great detail what is acceptable and what is not acceptable in terms of the interface with other www users. The following extract from the W3C document "*Resource Description Framework (RDF): Concepts and Abstract Syntax*" is included to give a flavour of the style of some of these documents:

> "For example, the IRI http://www.w3.org/1999/02/22-rdf-syntax-ns#XMLLiteral would be abbreviated as rdf:XMLLiteral. Note however that these abbreviations are not valid IRIs, and must not be used in contexts where IRIs are expected. Namespace IRIs and namespace prefixes are not a formal part of the RDF data model. They are merely a syntactic convenience for abbreviating IRIs."

4.2.3 Characteristics of the www systems architect

It can be argued from the above that W3C is unambiguously the SA for the www. It has a mission to make the www widely available and universal in its application; it sets addressing protocols, interface specifications, and all the other standards necessary for the www to work effectively for the millions of people who connect to it each day; it resolves technical interface problems, it has a forward-looking mission to anticipate future requirements, and it has in-house competence and a strong governance process.

The structure of W3C is such that it does not compete with major technology companies, such as Microsoft, Nokia or Sun Microsystems, and these are all members of the group.

Funding

W3C is funded mainly by membership subscriptions which, to promote a diverse membership, are dependent on organisation type, size and country. For UK organisations in the current year, these are between €2,000 and €68,000. Realistically, €68,000 for a company in the largest category (turnover >€€800 million), is insignificant. There is no official category of individual member and, although individuals may join at the same rate as a small "not for profit" organisation, this is not encouraged.

Challenges

Some of the most important challenges for W3C are political, not technical. Many countries block certain websites and even well-intentioned censorship, such as the porn filter supported by the Prime Minster, strikes at the heart of open access communication. The US domination of ICANN is being challenged with the objective of making this an international body.

Rifkin cites the 2011 case where Russia, China, Uzbekistan, and Tajikistan submitted a proposal to the UN General Assembly calling for an international code of conduct for the information society. The proposal, which had no provisions for a multi-stakeholders approach, would have the effect of increasing government control of the Internet.

The preamble to the proposal states unequivocally that the “policy authority for Internet-related public issues is the sovereign right of States”.

The private sector is also beginning to stray from the three-party stakeholder alliance, seeking increased income and profits by way of price discrimination—a move that threatens to undermine network neutrality, one of the guiding principles of the Internet, the hardware platform on which the www runs. This is the principle that assures a non-discriminatory, open, universal Communications Commons in which every participant enjoys equal access and inclusion.

There are thus increasing challenges from attempted “Balkanisation” of the www and its communications carrier, driven by the political desire to establish ring fences around particular functional or geographical activities, by the desire of commercial organisations to extract greater rents, by the fallout from the disclosures of NSA and GCHQ interception, and by the increased use of spam and malware to extract information or money from users and/or to sabotage Internet-connected equipment.

Technical challenges include bringing together standards for www content and broadcast TV. These developed in separate silos and each represent £ billions of investment. With TV increasingly being viewed on the www, greater commonality of standards is clearly important, but it would be publically unacceptable for it to be achieved at the cost of making obsolete recent investment in either.

Within the industry, some large companies are developing parallel systems that could lead to radical departures from the open TCP/IP model. In addition, many researchers are working on software-defined networks that could be superimposed on the existing www. [e.g. Gutz et al., 2012] These challenge the W3C consortium dominance.

4.3 The Galileo navigation system

Galileo is a €5bn global navigation satellite system being built by the EU and European Space Agency (ESA). One of the aims of Galileo is to provide a high-precision positioning system upon which European nations can rely, independently from the Russian GLONASS, the American GPS, or the Chinese Compass systems, which, despite assurances to the contrary, might be disabled in times of tension. The headquarters of the Galileo project is in Prague and it has ground operations centres, near Munich in Germany and in Fucino in Italy.

On 21 October 2011, the first two of four operational satellites were launched to validate the system. The next two followed on 12 October 2012, making it “possible to test Galileo end-to-end”. Once this In-Orbit Validation (IOV) phase has been completed, additional satellites will be launched to reach Initial Operational Capability (IOC) around mid-decade. The first determination of a position relying on signals emitted only from Galileo satellites was achieved on 12 March 2013. Full completion of the 30-satellite Galileo system (27 operational and three active spares) is expected by 2019. [Wikipedia]

The use of basic (low-precision) Galileo services will be free and open to everyone. The high-precision capabilities will be available for paying commercial users and for military use. Galileo is intended to provide horizontal and vertical position measurements within 1 metre precision, and better positioning services at high latitudes than other positioning systems. It will also provide an emergency call system.

In terms of project structure, the European Commission is, in effect, the customer for the system with the European Space Agency as the prime contractor. The team working in ESA is around 100 people with a system architecture team of around 30 people. Much of the system engineering work was subcontracted to specialist subcontractors, as are the satellites and their launch vehicles.

Apart from determining the basic architecture of the system, a significant part of the system architecture work concerns how Galileo relates to GPS and other satellite arrays. Several years into the project, the management of the project agreed to switch to a different type of carrier modulation to allow the coexistence of both GPS and Galileo and the future combined use of both systems.

4.4 Air traffic control

4.4.1 Structure of the industry

Air traffic control for commercial flights in the UK started in 1920. Croydon was first used as London's air terminal, but the controller's actions were limited to giving a pilot a red or green light for take-off and acknowledging reports by radio. After the war, ATC became the responsibility of the Ministry of Civil Aviation. [CAA & NATS websites]

The National Air Traffic Control Services (NATCS) was established in December 1962. It covered civil ATC but liaised with the MoD (RAF) in areas where military traffic needed to cross civilian routes. When the Civil Aviation Authority (CAA) was established in April 1972, NATCS became part of it, shortened its name to NATS and became a wholly owned subsidiary of the CAA, which was privatised in 2001.

NATS is divided into two parts – one is the regulated monopoly service provider part (with similar conditions to equivalent parts of National Grid), the other is a consultancy arm that undertakes work in 30 countries around the world.

4.4.2 Challenges to the industry

The European Commission's "Single European Sky" project is seeking to improve air traffic management (ATM) performance, increase integration, improve network performance, and ensure that European developments are aligned with the NextGen programme in the USA. This will require operators to squeeze maximum use out of runways and airspace. At the same time, changes to International Civil Aviation Organisation (ICAO) standards, European legislation, and network technology, will mean that airports, airlines, and air navigation service providers (ANSPs) will need to change both technology and operating methods.

The biggest technological challenge is to reduce the size of the safety zone (possibly, more accurately, the "zone of uncertainty") around an aircraft to allow more planes to land and take off from a single runway, and to simplify and reduce the width and separation of air corridors.

4.4.3 The Systems Architect

Within NATS there are two groups undertaking a SA function – one is concerned with the operational side of the Future Aerospace Strategy, the other with the system architecture of the technology platforms necessary to support that strategy. The latter has about 20 people, but implementation of the SA's plans rests on several hundred engineers responsible for the various systems.

Changes to the air traffic control system are invariably slow to take effect. Modifications to an aircraft require certified type-tests; there are dozens of different aircraft operators, flying aircraft built over several decades, using British skies and there are many international treaties and standards with which aircraft must comply.

Short term systems architecture projects are those that are likely to be operational by 2020; medium term are expected in the mid-2020s, and longer-term are beyond that timeframe.

4.5 The road network

The Highways Agency (HA) operates, maintains, and improves the strategic road network in England on behalf of the Secretary of State for Transport. The strategic road network in England is some 4,300 miles long and is made up of motorways and trunk roads — the most significant being “A” roads. Other UK roads are managed by local and regional authorities. While the HA network represents only two per cent of all roads in England by length, it carries a third of all traffic by mileage.

The HA is the standards authority for the road network. The Design Manual for Roads and Bridges is a comprehensive 15-volume document providing requirements for the design of different aspects of the road network. As an example, Volume 1, Section 3, Part 14 is a 118-page section on loads for highway bridges, methods for calculating wind loading, and similar.

The construction or major improvement of a section of the trunk road network is handled through a standardised process. [HA website]

- During the **Options Phase**, a number of options are investigated in order to determine the preferred solution (or route) to the transport challenge the scheme is seeking to tackle. The scheme option(s) are then subject to public consultation and at the end of the Phase the preferred route announcement is made.
- In the **Development Phase** the preferred route is designed in detail. If the scheme requires a new line of the road, side road changes, associated compulsory purchase of land and similar provisions, a planning consultation is held. Otherwise, this is straightforward design process.
- The scheme is built during the **Construction Phase**, following which it can be opened to traffic.

Of these, the options phase involves the nearest to what might be called a SA function. It is during this phase that HA staff and consultants explore the different options for modifying or building new roads or the possibility of introducing ramp metering or a smart motorway, such as has been implemented on the M42. During this phase the HA can work with road users, Local Enterprise Partnerships, local authorities and other interested bodies.

Where a smart motorway is introduced, it is usual for the HA to set the overall objectives but to use a consultant to undertake detailed design. This is compatible with the HA being the SA of the road network but using specialist contractors for particular subsystems.

4.5.1 Autonomous vehicles

In 1953, RCA Labs successfully built a miniature car that was guided and controlled by wires that were laid in a pattern on a laboratory floor. In 1958, a full size system was successfully demonstrated by RCA Labs and General Motors on a 120 metre length of public highway in Lincoln, Nebraska.

Inspired by this demonstration Central Power and Light Company launched an advertorial (Figure 10) that was used by many newspapers throughout 1956 and 1957 predicting autonomous cars:

> *ELECTRICITY MAY BE THE DRIVER. One day your car may speed along an electric super-highway, its speed and steering automatically controlled by electronic devices embedded in the road. Highways will be made safe – by electricity! No traffic jams ... no collisions ... no driver fatigue. [Wikipedia]*

Figure 10: Vision of autonomous car 1956 [Wikipedia]

Over the past 10 years there have been more realistic approaches to autonomous vehicles. Google has demonstrated a driverless car in a design that eliminates all conventional controls including the steering wheel. There are plans to build 100 of the vehicles for testing with the eventual aim of "bringing this technology to the world safely". [*Guardian*, 2014]

At the end of the 20th Century, it was assumed that control systems for autonomous road vehicles would be similar to those for moving-block railway signalling – large infrastructure-based computers sending signals to individual vehicles. This implied an architecture based around central control with the inevitable question of which body would take responsibility for the safety and integrity of vehicles and the (international) approval processes that would be necessary prior to a vehicle being accepted into the system. This also raised the question of who would be the SA and/or who would find themselves in court in the event of an accident caused by system failure.

The 1968 Vienna Convention covers road traffic safety regulations and as such establishes principles to govern traffic laws. One of the fundamental principles of the Convention has been the concept that a driver is always fully in control and responsible for the behaviour of a vehicle in traffic. Under this view, every vehicle is the responsibility of an individual and there is no "architect" for the resulting interactions of traffic.

There has been some erosion of this principle with the widespread introduction of ABS and, more recently, vehicle stability programmes. It is being further eroded by technologies such as Volvo's City Safety system: an automated brake system that contributes to avoiding or reducing the consequences of an accident by detecting the movements of people or vehicles and braking automatically. However, a centrally managed convoy of autonomous vehicles would require a radical change in responsibilities with a SA (who would "carry the can" for any accidents caused by system failures).

Current thinking on autonomous vehicles is moving in the direction of the control systems and most of the "intelligence" being in the vehicles themselves. [Parry-Jones, 2014] Interfaces between vehicles and the fixed infrastructure would be defined by appropriate interface standards and on-board systems would have the responsibility for reading messages from sensors, from other road users, and via the infrastructure. From this data, they would decide what route to take and the acceleration, braking, and steering necessary to avoid other vehicles, people or other obstructions. Under this model of autonomy, there would not be a central systems authority but individual drivers would remain responsible for the behaviour of their automated vehicles.

4.6 The railways network

4.6.1 Under nationalisation

Until nationalisation in 1948 Britain's railways operated as 4 independent companies – Great Western (GWR), London Midland and Scottish (LMS), London North Eastern (LNER) and Southern (SR). These had been formed under the Railways Act 1921 from the myriad of smaller railways built to serve particular routes and markets.

Initially there was little strategic vision in the nationalised industry. The network was regionalised – GWR became the Western Region; SR became the Southern Region and so on.

The 1954 Railways Modernisation Plan introduced new technology but did not ask searching questions about the future so, for example, it introduced new large freight marshalling yards, just as the lorry was taking over much low-volume wagonload traffic. It updated the technology, replacing like-with-like, which resulted in the overprovision of shunting locomotives and low-power diesel freight locos, which replaced the tank engines used in goods yards and on branch lines, just as the business on these lines was disappearing.

The first attempt at the implementation of a SA function was represented by the two reports written by Dr Richard Beeching: *The Reshaping of British Railways* (1963) and *The Development of the Major Railway Trunk Routes* (1965). He is generally remembered for the first report that identified more than 2,000 stations and 8,000 km of track for closure, representing 55% of stations and 30% of route kilometres.

Under the subsequent organisation, the technical side of the SA role was undertaken by joint working groups of engineers from the major engineering departments: Chief Mechanical & Electrical Engineer (CMEE), Chief Civil Engineer (CCE), Chief Signal and Telecommunications Engineer (CSTE) and, where relevant, the Chief Operating Manager (COM). As an example, the introduction of thyristor-controlled trains (part of the APT programme) was overseen by a joint team from CSTE, CMEE and the BRB Research Department, with invited engineers from the CEGB. A programme of analysis and tests was agreed; track tests were undertaken with technical staff from all three departments in signal relay rooms, feeder stations, and the test train. Technical papers were written and the introduction of phase-angle thyristor control went reasonably painlessly, and without excessive bureaucratic paperwork.

In the 1980s a "business-led railway" was introduced with the sectors – InterCity, Suburban, and Freight – being treated as separate profit centres. As a result, the central rolling-stock engineering function was split into separate groups. At a superficial level, the railway moved further from a model having a SA, but practically there was sharing of resources between sectors and a degree of integration was retained.

4.6.2 Post privatisation

When the industry was privatised there was a general assumption that the integration of the network would be achieved by a safety framework and a commercial framework. The safety framework was to be provided by Railtrack's Safety and Standards Directorate (SSD), the commercial framework by the franchising operation, and commercial relations between Railtrack and the Train Operating Companies (TOCs).

In retrospect, this system did not work well. The process for obtaining approval of standards was complicated and bureaucratic; most related to the detail of particular interfaces and there was no process for looking forward to where the railway and the technology were going, as opposed to dealing with day-to-day interface issues.

In this phase of GB's mainline railway, TOCs had a free hand at defining to Rolling Stock and Leasing Companies (ROSCOs) what type of train they wanted, which resulted in a proliferation of train types. There was little standardisation so that, for example, TOCs purchased different designs of tilting train with different tilt system performance. This has resulted in different speed limit profiles for different types of tilting train, even when running over the same track. There was no SA to set out a standard tilt system performance that could be incorporated into the Tilt Advisory and Supervisory System (TASS).

4.6.3 The wheel-rail interface systems authority

The nadir of this phase of railway engineering integration in Britain was the Hatfield train crash on 17 October 2000. In the 1970s and 80s, work had been undertaken by BR Research Centre and Cambridge University on the causes of rolling contact fatigue on railway rails. [Bower & Johnson, 1991] This had been forgotten during subsequent privatisation of the industry and there was no adequate specification of the interface between wheels and rails.[23]

At the same time, Railtrack was moving to on-condition maintenance and was reducing track inspections. Consequently Railtrack did not know how to respond to this problem. Because most of the engineering skills of British Rail had been privatised into various engineering consultancies, Railtrack was not able to estimate whether this was a one-off or how many other incidents were waiting to happen. The emergency speed limits introduced as a panic measure almost brought the railway to a standstill.

Following the accident, Canadian consultants were brought in (ironically including engineers who had worked at the BR Railway Technical Centre two decades earlier) and the industry relearned the science of rolling contact fatigue. The need for a SA was identified and the industry set up several "system authorities", including the Wheel-Rail Interface System Authority (WRISA). The objective of this body, which included representatives from operators, the infrastructure manager, manufacturers, and consultants, was to define best practice for the wheel-rail interface, which would act as guidance both to rolling stock operators/manufacturers and to the infrastructure manager.

WRISA was not successful. It had no power to make things happen and potential members, aware of the catastrophic implications of getting the interface wrong, were reluctant to be involved. As a non-official body involved in collaboration between nominal competitors, it was difficult to establish a constitution for the committee that did not fall foul of competition law. Members also found difficulty in obtaining professional indemnity insurance. Eventually, it was absorbed into the RSSB Vehicle-Track Interface Committee[24], which makes recommendations to a Standards Committee that are, in turn, used by Network Rail to inform their rail inspection and grinding programme, and in rolling stock procurement.

4.6.4 Current arrangements for systems architect on the national railway

The initial publicity for privatisation spoke of giving passengers a competitive market with TOCs free to offer the service using whatever rolling stock they feel will give them a competitive advantage. Since then, top-level systems specification has vacillated between the Department for Transport (DfT) and other bodies. From 2001 to 2006 the Strategic Rail Authority was given the role, but not the power or the funding to implement its decisions. The pendulum has swung the other way and, over the last decade, the DfT has taken more of a hands-on interest in rolling stock, even producing (using consultants) the detailed procurement specification for the new Intercity Express (IEP) trains.

As there is no other body with a vision that encompasses trains and infrastructure, and with the power to influence outcomes, it is difficult to avoid the conclusion that, in some of its technical specification activities, the DfT is the *de facto* SA for the GB rail system. Commentators in the specialist press have questioned whether this is an appropriate role for a government department in a privatised industry.

4.6.5 Light rail systems

In the 1980s a number of light rail systems were built in the UK. These used a very different form of construction contract to that of the national rail network. The examples of London Docklands Light Railway is discussed below and compared with the more conventional contracting used for the Edinburgh tramway.

London Docklands Light Railway (DLR)

The DLR initial system was designed to provide a transit link between London's central business district, the high-rise office developments in Canary Wharf, and a transport hub at Stratford. [Kemp, 1987] Contracts for construction were placed in 1984 and the first passengers were carried in 1987. Before the Initial System was even complete plans were in hand both for major extensions and a complete rebuilding of the original system. Ironically, it was the success of the initial system that led to its replacement within eight years of first carrying passengers.

Rejuvenation of the area had been entrusted to a new corporation, the London Docklands Development Corporation (LDDC). The area was developed, and the infrastructure paid for, mainly by private finance on the back of public sector pump-priming. LDDC needed a showpiece transport system to demonstrate that things were happening. The three criteria for the system were that it should be visible, that it should be different, and that it should be up and running very quickly. Government approval was obtained on the basis that the whole system would cost less than £100m (including consultants' fees, service diversions and land acquisition), that it would be operational in three years, and that the private sector would carry the risk.

The requirements specification for the trains, signalling, and other systems was barely 20 pages in length. This was to be a turnkey system and the client specified the number of passengers to be transported and the standards of service required (e.g. maximum waiting times, maximum percentages of standing passengers, service reliability, facilities for the disabled, and the passenger environment). The contractor was responsible for deciding not only technical details but also how many vehicles would be needed to provide the service. At the time, this form of contracting was a revolutionary concept, but it paid off and allowed competing contractors the freedom to offer cost-effective systems and equipment.

Following an international call for tenders, the performance contract was placed with a Joint Venture, the GEC-Mowlem Railway Group. GEC Transportation Projects Ltd. (later subsumed into Alstom) undertook the systems architecture role on behalf of the JV and managed the trade-offs and compromises between the different electrical and mechanical systems.

Stray current control, acoustic noise management, interference between traction and signalling systems, complaints from neighbours about radio-frequency interference, and loading gauge calculation are just some of the issues that have delayed other transportation projects, provided work for teams of expensive consultants, and generated additional costs to the client. On DLR, a specification, a timescale ,and a price were agreed at the outset between client and contractor, which focused the SA's mind on delivering effective compromises, resulting in the system being delivered on time and without price increase.

Edinburgh tramway[25]

The first phase of the Edinburgh Trams project consists of a 15-station, 14 km link between York Place in the New Town and Edinburgh Airport. Construction began in 2007, but suffered many delays and contractual disputes. Only two-thirds of the originally planned line has been built, with the extension to Leith postponed. A second line running from Haymarket to Granton Square has been postponed indefinitely and a line serving the Southside was not approved.

Initially, the Scottish Executive earmarked £375m, indexed for inflation, for the proposed tram routes linking the city centre with both Leith and Edinburgh Airport. It was hoped trams would be operational by 2009.

Approval was given by the Council in December 2007 for Transport Initiatives Edinburgh (TIE), a company wholly owned by the City of Edinburgh Council, to sign contracts with CAF for the supply of the vehicles and BBS (a consortium of Siemens and Bilfinger Berger) for the design and construction of the network. Initial construction work commenced in July 2007, with the diversion of underground utilities in preparation for track-laying in Leith. These works followed a plan by System Design Services (SDS), a joint design team led by Parsons Brinckerhoff and Halcrow Group Limited. [Wikipedia]

The first part of the tram system was originally scheduled to open in February 2011. By March 2010, project delays had resulted in the prime contractor revising their estimated completion date to 2014. The whole scheme was originally costed in 2003 at £375 million. Present estimates are that it will cost £776 million, plus £228 million of interest payments on a 30-year loan to cover the funding shortfall. Work on the tramway's infrastructure was complete by October 2013, and passenger service started on 31 May 2014.

Edinburgh City Council Chief Executive, Sue Bruce, is reported as saying the project had been a "shambles" and that there were "big questions to be asked over the original due diligence of the programme", and the council had to be "held to account" over what had gone wrong. [BBC, 2014]

Although it is too early to write the definitive history of the tramway, it appears that the structure of the contract neither set up TIE (as a surrogate for the City Council) as the undisputed SA, nor did it appoint an engineer or a main contractor that could carry the SA architect role. It appears that the SA role was shared between TIE, SDS and BBS.

4.6.6 European overnight stock (EONS)

The European Overnight Stock (EONS) is included as an example of a project that failed, at least partly because of inadequate definition of the SA responsibility. It was a contract placed in 1992 for a fleet of sleeping cars to run from British cities via the Channel Tunnel to cities in Continental Europe. The project was handled by British Rail (BR) on behalf of the railway organisations in Belgium (SNCB), France (SNCF), Germany (DB), the Netherlands (NS), and the UK.

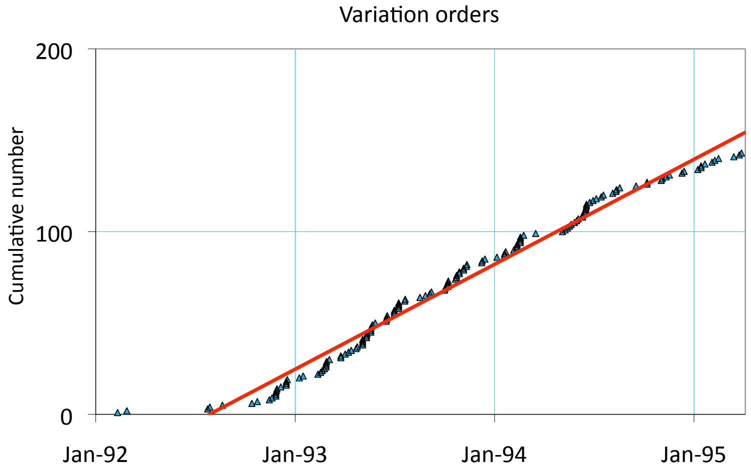
The *Invitation to Bid*, dated 21 December 1990, said, "The specification is complete, except for the sections relating to catering and Control Authority requirements". Specification 90/014 Issue A weighed 2.5kg, called up more than 200 other specifications, and lasted less than 2 months, when it was completely rewritten.

The vehicles were specified to be hauled over several European networks and therefore had to be compatible with 7 different train auxiliary supply voltages from a variety of locomotives, including 750 V dc in Britain, 3000 V dc in Belgium and ac supplies at 50 Hz and 16€Hz. A fundamental problem, flagged-up by the vehicle contractor in their bid, was that some of these supplies were not powerful enough to run the energy-hungry hotel services to which the project was committed.

It became clear during the contract that the specification was really only a wish-list. The client organisations had no more than a vision of what the project was intended to achieve and, more relevant from the SA perspective, none had both an understanding of an architecture of vehicles and systems that would allow the trains to meet their commercial and political objectives, or the authority to propose solutions that would resolve the problems.

As the client team tried various ways of solving an insoluble problem, without compromising on their incompatible objectives, it issued a stream of variation orders to the vehicle builders: Figure 11.

Figure 11: European Overnight Stock - variation orders



The original date for passenger service (June 1993) came and went and the project had not solved the essential dilemma of how to provide the energy-hungry hotel services on a 400 m train from the inadequate power output of a locomotive running on the British 750 V network. The problem was not admitted publically and, 18 months after the trains were supposed to have been in service, a Parliamentary Under-Secretary of State listed them, then in manufacture, as part of the success story of the government's rail strategy. [Hansard, 1994]

The trains never went into service in Europe. For several years they were stored in a MoD depot, out of public view, and were sold for sleeping car services in Canada.

4.7 Military projects

4.7.1 System architects for capital projects

One of the UK's largest military contracts is for two aircraft carriers, HMS Queen Elizabeth and HMS Prince of Wales, ordered from the Aircraft Carrier Alliance (ACA). The ACA has four members, three of which are industrial; Babcock, BAE Systems, and Thales UK. The fourth, the UK Ministry of Defence, has a dual role, acting as a member of the Alliance as well as the customer. [ACA website]

BAE Systems is described as "the lead member of the Aircraft Carrier Alliance" [BAES website] and Thales UK is described as the design leader of the QE Class programme. [Thales UK website] Thales claims skills in "Whole warship design and systems integration, naval prime contract management, systems integration and command information systems", as well as various specialist subsystems. Although the websites do not describe it as such, Thales appears to be the SA of the project (as the term is used in this paper) and has responsibility for integration of the other systems and subsystems on the vessel.

The Major Projects Authority annual report for 2014 says, "Of the eight projects that we rated red in September 2012, only one was still rated red in September 2013, the Queen Elizabeth Class Aircraft Carrier project. However, since September 2013, the Ministry of Defence has reported that a new contract has been agreed with the Aircraft Carrier Alliance." [MPA, 2014] However, reports suggest that the cost and time overrun problems referred to by the MPA were caused mainly by changes in functional specifications, such as whether the vessels were to be designed for vectored-thrust aircraft or conventional aircraft requiring catapults and arrestor wires, rather than the structure of the SA function.

The aircraft carriers will form part of an integrated defence operation, discussed in the following section.

4.7.2 The System of Systems approach (SOSA)

For many years the Ministry of Defence (MoD) has been involved in the integration of different systems on a "platform" – examples include the integration of radar, sonar, communications and weapons targeting on a warship or flight data, radar, electronic countermeasures, and weapons control on an aircraft.

More recently, the MoD recognised that the nature of warfare was changing and there was a need to move to "network centric warfare" where the (information) network would increasingly be at the heart of managing (i.e. commanding and controlling) different defence assets on the battlefield and their support logistics. It termed this "Network Enabled Capability". At the same time it recognised that the command and control networks that did exist were being allowed to evolve "bottom-up" with no overall control of system architecture and were, consequentially, sub-optimal in terms of performance and cost. This included aspects such as security and safety of the network where there was no single authority to understand, control and underwrite these aspects on an "end-to-end" basis. [MoD website]

Flexibility is a crucial requirement for the systems acquired by MoD. Operational flexibility is required to enable agile mission groups to configure and reconfigure available assets to meet rapidly changing operational requirements. Technical flexibility is required to enable more rapid and effective upgrade of systems, especially in terms of technology insertion. Commercial flexibility is required to achieve value and innovation in procurement. Open systems has been seen as an enabler of this required flexibility.

The MoD buys many and complex defence systems (ships, planes, submarines, vehicles, soldier systems, etc.) and each is required to interact with others through the network in increasingly connected and complex ways. For years, the MoD had applied some systems engineering (SE) at individual "platform" level (eg to a ship) but recognised it was not applying SE to the network as a whole – conceptually it was not applying system engineering at the "system of systems" level to manage the "glue" that linked all the other system together into an effective (interoperable) defence capability.

To address this, they created an initiative called the "Systems of Systems Approach" (SOSA), which was about applying best practice systems engineering and related approaches such as Enterprise Architecture to the design and management of the network. It recognised it could not achieve this by centralising all design, development and management of the network under one roof, so instead it came up with the concept of a "federated approach" where design/development/operating activity was allowed to "lie where it fell" but a number of central roles were created to design and control the network from a top-down basis.

4.7.3 Structure of SOSA

The System of Systems approach (SOSA) created two new types of body:

a) **Network Technical Authority (NTA).** This body has 3 primary roles: To Architect, Ensure and Assure the network. The *Architect* role is all about mapping the "as-is" architecture and designing a "to-be" target architecture that meets the requirements that will be placed on the network in a particular timeframe. The *Ensure* role is then about ensuring that the individual network "projects" (e.g. planned upgrades to the network and new additions to the network) "add-up" to deliver the required target architecture in the defined timeframe (including aspects such as safety and security). The *Assure* role is about setting architectural standards for anyone wanting to either connect to the network or deliver changes/additions to the network and then "policing" these to make sure they are complied with.

b) **Network Operating Authority (NOA).** This body "owns" the live network (fixed & mobile) and is responsible for managing and restoring the network as a whole as a response to any faults. It also is the "release authority", acting as the gatekeeper for any changes to the network or anyone wanting to connect to the network. For example, they set up a "Global Operations Service Centre" where all the contractors who were managing their part of the network were grouped together to collectively manage and optimise the service performance of the whole network.

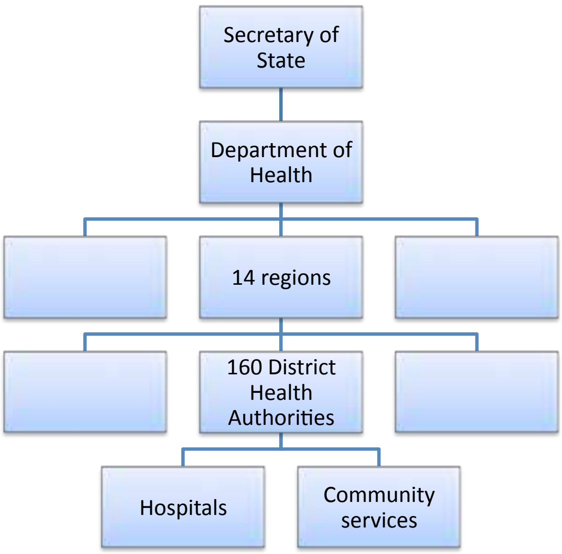
It is important to note that SOSA is about more than the technical role of a SA. The MoD learned from the experience of attempting to set up a Technical Integration Authority that the authority had to have the technical competence to define the system architecture and also the authority to ensure that the recommendations of the architect are acted on. This has been incorporated in the concept of Domain Authority, and approval for new projects is now only given if they are compliant with the approved system architecture. In addition, the NOA has the power to enforce "joining rules" to ensure the network is not degraded by non-compliant systems connecting to it. It is important that power comes with responsibility. A system of systems has to be covered by a safety case and the Domain Authority can be held accountable in the event of an incident.

4.8 Healthcare

4.8.1 The health service prior to 1999

Prior to 1999, the NHS was organised on a regional and district basis, as shown in Figure 12. It could be argued that the district was the key management level and the District Health Authority was the SA for all the services in that district.

Figure 12: Pre-reorganisation health service

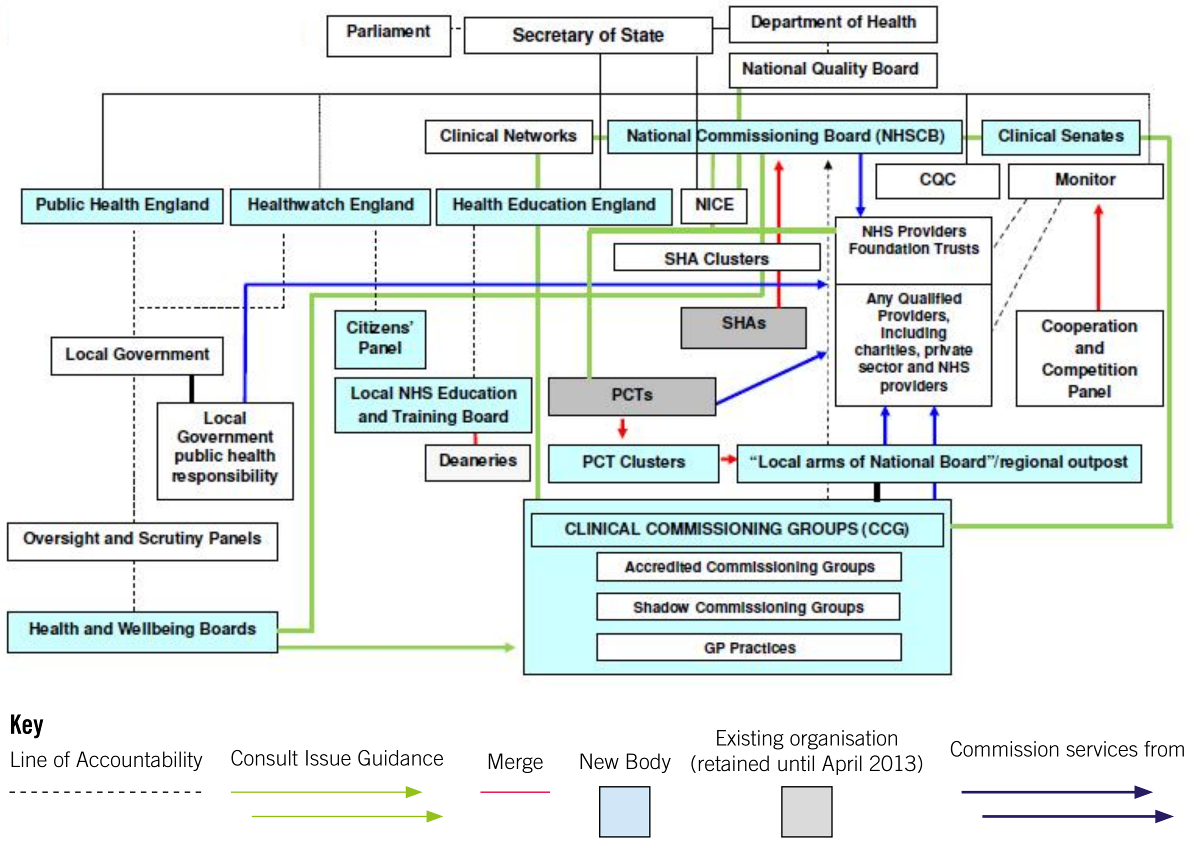


Funding was provided centrally to regions and districts based on a funding formula that took account of the population of each district and their health needs measured by deprivation and similar metrics.

4.8.2 The health service today

The idea that market forces, not public planning, should shape the English NHS has been a cornerstone of government strategy since Labour's NHS Plan in 2000. The approach was taken further by the current government, culminating in the Health and Social Act 2012, which moved away from the system of planning services for geographical areas that had underpinned the NHS since its creation in 1948. Under the Act, the government's statutory duty to provide or secure a comprehensive health service was repealed and strategic health authorities and primary care trusts, which had been responsible for implementing that duty, were abolished. [Pollock, 2013] The present organisation is shown in Figure 13; interestingly, despite the complexity of the diagram, a member of a Health Trust, to whom it was shown, pointed out that it does not identify the responsibilities of the Chief Medical Officer who, one might have thought, was a key member of the organisation.

Figure 13: Post reorganisation health service



http://blogs.ft.com/westminster/2011/08/organograms-show-nhs-becoming-even-more-complex/

The Clinical Commissioning Groups (CCGs) are now, in theory, the decision-making bodies that define the services available to patients registered with one of their GP partnerships from various trusts. However CCGs are not responsible for services over a particular geographic area.

As explained by Paul Burstow MP, in a recent parliamentary debate, "The first principle is that, in the absence of failure in the arrangements set up by local commissioners, decisions about what services should be provided at an NHS trust or an NHS foundation trust should be taken by local commissioners working within their local health economies, and should not be foisted on the local NHS from outside. This autonomy principle is reflected in the absence of any general right for the Secretary of State or NHS England to direct local commissioners about the discharge of their functions. The second principle is that commissioners who have successfully managed the quality and demand in their area should not have decision making taken away from them. Decision making can be removed from the trusts that are failing, and this may mean that commissioners of such bodies have to accept unwelcome changes. But local decision making should remain in place where a local commissioner and provider are working successfully together." [Hansard, 2014]

An amendment to the Care Bill (which obtained Royal Assent on 14 May 2014) would provide trust special administrators (who are sent in to manage trusts that have large deficits) with the power to reconfigure neighbouring services as well as those of the trust that is in trouble. However, the special administrators would have no complementary duty to plan health services for the population of that area on the basis of need; their responsibility is simply to ensure that trusts can pay their debts.

4.8.3 Who is the system architect?

Under the new arrangements it is difficult to identify a SA. The CCGs can commission services from various autonomous trusts, but they have no authority to set up facilities, such as an A&E department, to meet a particular need of the patients registered with their GP practices, and no powers to prevent the facilities being closed.

4.8.4 The NHS Computer system

In September 2013, the House of Commons Public Accounts Committee (PAC) reported on the NHS national programme for IT (NPfIT). [PAC, 2013] Press reports suggested the problem areas identified were not unique to the NHS and quoted a member of the Committee who said that the project was, "evidence of a systemic failure in the government's ability to draw up and manage large IT contracts". It went on to make comparisons with IT failures in the Child Support Agency, the Passport Agency, and other departments.

The focus of the PAC report, and of most of the press, was on the financial and contractual management of the project, but some publications have attempted to analyse the technical reasons for the lack of success; one author identified six issues [Maughan, 2013]:

- **Top down project** – the NPfIT was conceived by ministers and their advisors as a bold project to update the NHS. While the motives were laudable, it was not designed by professionals who understood the complexities of health service data management.
- **Time pressure** – there was pressure to award contracts for NPfIT as quickly as possible. Consequently the scope and deliverables were sometimes unclear and had to be renegotiated during the contract phase.
- **Buy-in** – successful ICT projects need good consultation with all stakeholders involved – particularly end-users. Because of the way the NPfIT was conceived, many key stakeholders, especially hospital doctors and GPs, had had doubts about the system.
- **Procurement** – the NPfIT procurement model called for a significant reduction in timescales.
- **Contract scope** – was unclear and much work needed to be done after contract award to agree key contract parameters such as scope and deliverables.
- **Common interfaces** – NPfIT was innovative in that it required different service providers to work to common interfaces so that, in the event of failure of one contractor, another could step in. While helpful in principle for risk management, this had the disadvantage that it placed a much greater system interface management role on the client body.

The analysis of stakeholder objectives and user requirements, and their translation into a system definition, is a key function of a SA. Another is the specification of interfaces between different subsystems. There appear to have been deficiencies in both areas pointing to a failure in the arrangements for the SA function.

4.9 Water supply

4.9.1 Industry structure

Traditionally, a city's water supply was the responsibility of the city corporation. As an example, prior to the Industrial Revolution, Manchester was supplied by local springs and wells. In the early 19th Century, reservoirs were built at Gorton but these were soon inadequate. In 1846, the Manchester Corporation appointed John Bateman to advise on improving the town's water supply. His plan took water from the Longdendale Valley in the West Pennines – at the time it was the biggest water supply project ever undertaken in Europe.

The 150 km Thirlmere Aqueduct was constructed by Bateman for the Manchester Corporation Water Works to carry 250,000 m³/day from the Lake District to Manchester. It was opened in 1894 and is the longest gravity-fed aqueduct in the country.

Other cities carried out similar work. Liverpool Corporation developed the Vyrnwy Valley, a tributary of the River Severn with a reservoir at Llanwddyn, and an aqueduct to Liverpool. Birmingham Corporation also developed reservoirs in Wales on the upper portion of the Rivers Elan and Claerwen.

In 1975, the various corporation and town water works were incorporated into ten Regional Water Authorities, along with the river authorities, organised on a river catchment basis and responsible for surface water quality, river pollution control, fisheries management, land drainage, and flood prevention and sewerage boards that were generally defined by local authority boundaries.

In 1989, the industry was privatised and there are now 26 water and sewerage authorities, including 16 small, water-only authorities.

4.9.2 A systems architect for water?

The water industry in England & Wales now consists of regulated regional monopolies. Discussions with the industry players for this report could not identify any one body that could be considered as a national SA. Each water company has responsibility for balancing the supply and demand for water in its area. They are required by statute to prepare 25-year Water Resource plans every five years which have to be approved by Defra. These plans set out the companies' forecasts of expected demand and how each company expects to meet it in the light of many factors (including the vagaries of a changing climate). This is a little like the "predict and provide" model operated by the CEGB, but the water industry has the advantage of being able to store water in a way that the electricity industry cannot – although the extent of storage is measured in days rather than months or years. In effect, the strategic planning groups in the various water companies act as SA for that area. Discussions have suggested that the industry is very traditional in its approach; data on how much water is provided to whom is very limited and important issues, like the scale of losses, can only be estimated as the difference between two poorly-known numbers.

End notes for Part 4

22 Most of this section was taken from the W3C website, listed in Appendix C

23 To meet then-current specifications, recent types of train had been designed to run without hunting (i.e. the establishment of self-sustaining oscillatory movements) over track with a high conicity at the wheel-rail interface. This required bogies with stiff primary yaw suspension characteristics which, in turn, resulted in high longitudinal creep forces, exacerbating rolling contact fatigue cracking.

24 The remit for SICs is to: (1) Identify opportunities for improving efficiency at the interface between vehicles and infrastructure and consider how to develop and implement them, (2) Commission studies or research or use other methods to seek solutions to interface issues, and to develop opportunities where appropriate; (3) Identify solutions to issues, and make recommendations to the Technical Strategy Leadership Group, industry (including RSSB), or Department for Transport on the best solutions. In so doing, recommendations should take into account the benefits to the industry as a whole, where the specific benefits will fall and the cost of implementing the recommendations; (4) Promote agreement on how solutions could be implemented.
For each issue, a SIC will determine solutions based on technical and economic evaluation and identify which is in the best interest of the industry as a whole. Some of these solutions may be implemented unilaterally where it is in the commercial interest of individual organisations to do so. Existing processes (such as vehicle or network change) will be used as far as possible to balance instances where the benefits and costs of a given action may not lie in equal measure with the same parties. Where such processes are unsuitable, the regulators may act to ensure that parties are appropriately incentivised to implement optimal system-wide solutions. [RSSB]

25 Despite several requests, it has not been possible to arrange interviews with relevant people involved in this project. This section is thus based on press and Internet reports.

5 Discussion of findings

5.1 The nature of projects

Three months after this project was started, the UK Government's Major Projects Authority[26] issued its Annual Report 2013-2014. [MPA, 2014] Although the MPA is more concerned by the delivery and financial outturn of projects than by the detail of how the systems architecture is managed, there were remarkable parallels between the challenges identified by the MPA and by those identified by this research. Some of the opening paragraphs of the section entitled, *Being open about the challenges*, are copied below:

"Given the number, complexity and scale of the challenges facing major projects, it is essential that we are realistic about what we can achieve, which means developing a culture of realism about these challenges. This kind of approach allows teams to find solutions before problems spiral out of control. Among the challenges are:

- **Technological complexity**. Many of our major projects incorporate some of the most innovative and technologically advanced engineering in the world. For example, the Department of Energy and Climate Change's Carbon Capture and Storage Project will support the development of new technologies to lead the fight against climate change, while the Astute and Successor class nuclear submarines being designed and built by the Ministry of Defence are amongst the most technologically advanced machines that have ever been created.
- **New information technology**. Our digital transformation agenda aims to provide world-class digital services; typically, this involves redesigning public services involving millions of people and hundreds of millions of transactions.
- **Scale**. There are more than 10 projects in the portfolio with costs of over £10bn, while many will have impacts across the whole of the UK, for example national vaccination projects, the electoral register, or national tax and benefit reform.
- **Multiple delivery partners**. Most of our major projects have many delivery partners spanning both the public and private sectors, while a high proportion involve complex private sector procurement exercises. In the context of health, for example, developing new IT programmes requires hundreds of semi-independent organisations and trusts across public health and social care to work together to share information.
- **New organisational structures**. Because they are not "business as usual", managing and delivering major projects usually requires the development of new temporary structures, either within government or in collaboration with partners. On occasion these may be entirely new organisations such as the Olympic Delivery Authority."

All of the above issues are significant in the definition of the role of system architect (SA) for the electricity sector and are discussed later in this paper. The parallels, for example in regard to addressing increasing complexity, are striking. Some have also been discussed by a paper produced by a joint team from Imperial College and Cambridge University. [Strbac et al., 2013]

5.2 System architects: what works?

Most of the sectors studied have a SA function of some sort, although not always given that name. Three successful business models have been identified; it should be noted that some are more suited to a “greenfield” development while others are more suited to an evolutionary development:

5.2.1 Project companies and joint ventures

For private-sector project companies, the SA is often closely associated with the project engineering or system engineering group, reporting to the main contractor or the joint venture management team. Similar business models can be found in the telecoms, aerospace and rail sectors – a small team of multidisciplinary engineers who interpret the commercial requirements into technical requirement specifications for different subsystems and components, generally as illustrated in Figure 3, and are also involved in defining the integration tests on the complete system.

A successful example of a SA was that used for the DBM (design-build-maintain) contracts for light rail systems in the 1980s. Although these were state-funded and subject to competitive bidding, they were bought against system functional requirements specifications and the customer took a hands-off approach during the design and build phases. In these projects, the SA was a subsidiary of the main contractor working to a fixed-price contract and thus had an important incentive to finish on-time and within budget. However, although the JV or the project company undertook the SA function, the client organisation was ultimately accountable for the project and for having delegated the responsibility to them.

A key success factor of this type of structure is that the SA has the unwavering support of the senior management of the project and the authority to define the technical performance and interfaces of component parts of the total system. The arrangement can work well when the project is easily defined, which is the case for “greenfield” developments; it is not a model with a successful track record in re-engineering complicated legacy systems.

5.2.2 A unified industry

The traditional structure of a nation-wide, state-owned industry (e.g. BR, CEGB or BT) had a central management team with a technical director or equivalent, working with other members of the team to develop a technically-coherent business strategy and then taking responsibility for the integration of the various engineering components, with the support of heads of the technical departments. This can work effectively in the context of a vertically integrated organisation. The Highways Agency operates in a similar way.

The *System of Systems Approach* (SOSA) used by the MoD, appoints a systems architect within the MoD organisation. The architect can review assets that are planned to be connected to its data networks and has the authority to veto contracts that are non-compliant.

London Underground Ltd. operates a similar system for managing change on its network and has an in-house systems engineering group performing a similar role to the SOSA team. The water companies, which have defined geographical areas and a clearly defined responsibility within them, also have similar structures. Comparable engineering structures can be seen in many European utilities and transport undertakings.

A variant of this model is seen in air traffic control where NATS is a single body responsible for the operation and development of all air traffic services and has an internal SA function.

5.2.3 Committee-based system architect

For the www, the SA is the World Wide Web Consortium (W3C), a body that represents a large number of businesses, including all the large software and computer system companies. Decisions are confirmed by a group of members. However, W3C is a SA body in its own right with full-time staff, including the www founders; it is quite different to a standards committee, like JPEL/64 that approves the IET Wiring Regulations, BS 7671.

Other industries that consist of a number of independent companies with limited contractual links between them use committee-based system authority functions. In some areas of the telecoms industry, committees allow service providers to agree standardised interfaces with equipment suppliers. Similarly, in the European rail industry, international committees define TSIs (Technical Standards for Interoperability) that are enforced to ensure safe operation of international trains.

This type of system engineering function works where decisions are largely technical, where the industry is not subject to radical change, where industry players have a common interest in a successful outcome (such as computer manufacturing companies needing a ubiquitous and consistent web interface) and where failure to comply with the recommendations of the committee result in being unable to connect to the Internet or not having your trains approved for operation on the rail network. It may not work so well if large players see commercial advantage in "cornering the market" for particular services or where non-compliance does not result in immediate functionality failure. This research has not found successful examples of the architecture of rapid, large-scale change being managed by a committee – particularly examples where the industry participants have close commercial relationships with each other, as in the GB electricity sector.

5.2.4 Summary of what works

From the examples investigated, it is possible to draw the following conclusions:

1. A SA function is essential in a "change project" that affects a "system" comprising multiple elements (this may involve a greenfield development or may create significant changes to an existing system). The need for an architect must be recognised at an early stage in the project and its responsibilities and authority clearly defined.

2. For a project involving the upgrading of an existing system, the SA function must include the transition plan and not just the design of the final system.

3. A SA should hold ultimate responsibility for the correct functionality of the complete system, but is neither responsible for the detailed design of the component parts nor acts as a quality control department of a main contractor. Discharging this responsibility requires well-designed systems and governance if the role is not to become confused with other contract management functions.

4. A SA must have power to influence the design of the system and, where necessary, veto the integration or connection of particular subsystems.

5. A SA should be part of a competent and suitably resourced organisation with a strong interest in the success of the total system. The role can be part of a private sector company managing a network (such as a mobile phone operator), attached to a client organisation (such as an agency reporting to a government department), to a company fulfilling a comprehensive role in a defined geographic area (such as a regional water company), or to a main contractor undertaking a new build or major refurbishment project.

5.3 System architects: what doesn't work?

This research has found a number of examples where the SA role did not work well. One was the experience of WRISA, the wheel-rail interface systems authority. The reasons for its lack of success include that it had no power to implement its decisions; it was a free-standing group without a corporate interest in success; it was faced with a high level of ill-defined technical risk, over which members had little control; membership of the group carried a large potential liability for unfavourable outcomes but no group benefit, other than to the wider industry, from a successful outcome.

Another unsuccessful structure was adopted by the Edinburgh tram project. This appears to have had a confused responsibility for system design: the project was initially overseen by a company wholly owned by the City of Edinburgh Council, who were project managers and, presumably, carried responsibility for system architecture; some of the system design was undertaken by a design team led by two large consultancies and contracts to build the system were let to an international consortium with parent companies in Germany.

Some of the best known project failures have been associated with large IT projects, including the NHS computer system, which is reported to have been structured in such a way as to require a heavy SA responsibility, but with no effective organisation to take on that role. This has some similarities to the European Overnight Stock project that failed because the contract was let against an incomplete specification, which was internally contradictory and forever changing. Thus the design organisation never had a proper specification against which to work.

5.4 Responsibilities of a system architect

This research has identified that there are almost as many definitions of a SA as there are sectors investigated. There is a huge difference between a SA for a DBT (design-build-transfer) project on a greenfield site and for an upgrading project. In the former, typified by a new light rail network, the architect has a responsibility that is clearly bounded in both scope and duration. In the latter, typified by the upgrading of the West Coast Main Line, there is an on-going responsibility for the performance of the system before, during and after the upgrading works, and the responsibility can cover any number of "heritage" systems in a better or worse state of repair that have to be kept working during the transition.

For the former type of project, a SA can select almost any technology. To continue with the light rail example, the project could use a monorail, magnetic levitation, rubber tyres, or any other suspension technique. However, for the WCML upgrade, there is no choice but to retain two steel rails at 1435 mm spacing, both to ensure continued passenger service during the decade-long upgrade and to comply with the EU Railway Interoperability Directives. The challenges for a SA are very different in these two environments and the structure and size of the organisation reflects this difference.

When planning the upgrading of an existing system, one of the major tasks of a SA is to establish a detailed roadmap for the project showing how technologies are phased-in so the service can be maintained while existing assets are retired and new ones are commissioned. This is not the same as the Gantt charts produced by project managers but would be a key input in the production of those documents.

End notes for Part 5

[26] The Major Projects Authority (MPA) is tasked with improving project performance for the taxpayer. It aims to address the findings from the National Audit Office's report Assurance of high risk projects and from the Major Projects Review 2010. It is a collaboration between the Cabinet Office, HM Treasury and departments and has the fundamental aim of significantly improving the delivery success rate of major projects across central government. It was launched in 2011.

6 System architect: lessons for the GB electrical system

6.1 A comparison with other sectors

When considering models for a system architect (SA) function that might be helpful to consider for the GB electricity industry, it is worth summarising the systems engineering challenges described in Chapter 3.2. This identified six separate groups of challenges:

1. A major change in technology: the switch from fossil-fuel generation to renewables, nuclear power, and carbon capture and storage, each having very different characteristics.

2. The integration of power engineering with the automation, electronics and telecoms industries, and widespread adoption of "smart" controls and active consumers.

3. An evolving commercial structure involving massive financial investment and different relationships between market players.

4. Fundamental technical challenges concerned with the design and operation of networks, for which there are no international precedents.

5. Undertaking the transformation of the electricity sector while "keeping the lights on" and maintaining a reliable electricity supply.

6. Ensuring flexibility to accommodate the inevitable political uncertainty about future policy for low carbon sources, particularly onshore wind, unconventional gas, the applicability of EU directives post 2017, and strategies for decarbonising domestic heat.

Taken together, these are more demanding than in any other sector that has been researched during the study. The scale of change will be as great as that seen in the Internet and telecoms sectors over the last two decades. However, there are fundamental differences – while the consumers of telecoms have seen dramatic changes to available services (e.g. sophisticated mobile phones, on-demand television, mobile Internet, multi-player gaming, downloading movies, and cloud storage) which excite consumer interest and justify new charges, the electricity available from a 13A socket is identical to that provided for the past 70 years.

Although the quality of the electricity available to consumers is identical, the price of all domestic energy has increased. [House of Commons Library, 2014] The main incentives for consumers to become involved in new technology are thus to save money by reducing energy use, or procuring energy at a more favourable tariff, perhaps by time of day, or to engage more closely with energy, such as through demand management, distributed generation and storage, or community energy schemes. This is fundamentally different to the situation in many of the other sectors studied.

6.2 How large might be the task of a system architect?

This research has identified that there is not currently an overall SA for the sector, other than DECC, which has the role by default rather than intent. The scale of the challenge means that a SA function is likely to be of considerable benefit and there are risks of continuing without such a role adequately defined and resourced.

Since 2009, the Climate Change Committee (CCC) has established the broad direction of travel towards decarbonising the economy. However, neither the CCC nor DECC has been specific about the balance of generating technologies that can be expected on the system. If at least 40% of the generation mix, even in summer, is fossil/CCS or nuclear power using conventional synchronous generators, then present methods of system balancing could continue to be used and the task of the SA is not difficult to quantify.

DECC's 2013 update of the renewable energy roadmap showed almost 20 GW of onshore wind and 16 GW of offshore wind, either constructed or in the planning pipeline, which is compatible with their central range forecasts for 2020 [DECC, 2011] of 10-13 GW onshore and 11-18 GW offshore. Add to these estimates the 2023 target for solar energy of 20 GW [DECC, 2014b] and a possible contribution from marine current turbines, and we face a situation where, for several months of the year, the daytime electrical load could be provided by flow renewables (if the wind is blowing). In this case there would be a far more important and challenging role for a SA function.

Because of these new sources of energy, all exhibiting different technical characteristics and having different contractual arrangements, the most complicated task of the SA is likely to be about the real-time control systems needed to match the loads on the system with the best combination of generation assets, taking into account cost, emissions, frequency stability, system resilience, and all the other issues discussed in Section 3.2, some of the most challenging of which are:

- Integration of power engineering, smart meters, automation, the Internet and telecoms. Full utilisation of the capabilities of the new smart meter network will need particular attention to ensure adequate system integrity and resilience, so avoiding the introduction of risks to the integrity of the wider energy system.
- Migration from traditional load and frequency control by central power stations to a system that, by a combination of frequency sensitive loads and control signals, involves millions of independent generators and consumers.
- Accommodation of the changing generation and demand characteristics where, for much of the day, most generation and many loads will be inverter-coupled to the grid by power electronic devices, providing no intrinsic inertia or ability to generate reactive power, and contributing increased non-50 Hz currents and reduced fault levels.
- Adapting to the likelihood of high EV charging loads capable of being scheduled by load-shifting and a large increase in winter energy demand that could result in some generation assets being unused for long periods of the year.
- Integrating new structures for local energy networks including micro-grids to provide resilient networks capable of "islanding" under disruptive storm conditions, and setting out a pathway that can accommodate developments in other energy vectors (e.g. heat systems), and work in conjunction with the smart communities and smart cities now being conceived and developed.

Even without the complexities of an electricity market designed for an industry where the cost of electricity (in £/MWh) was dominated by fuel costs moving to a situation where the main costs are capital (£/MW) and operating costs are close to zero, together with an industry structure based on nationwide retailers who have no responsibility for the distribution networks by which they supply their customers, these are major challenges.

Moving towards a network dominated by information technology that allows peer-to-peer energy exchange outside the established centrally managed structures would be a disruptive transformation of the existing infrastructure. Jeremy Rifkin argues that "a distributed, collaborative, peer-to-peer, later¬ally scaled communications medium is ideally suited to manage renewable energies that are distributed in nature, are best organised collaboratively, favour peer-to-peer production, and scale laterally across society. Together, Internet communications and renewable energies form the inseparable matrix for an infrastructure whose operating logic is best served by Commons management." [Rifkin, 2014]

However, a power system so closely integrated with the Internet and a myriad of community groups and third-party energy management systems could result in serious and unforeseen risks to resilience if not addressed comprehensively. A systems architecture team needs to be able to understand not only the power systems but also the human factors and IT issues involved in what is likely to be a rapidly evolving system.

6.3 How the function is discharged today

This section seeks to address, at a high level and in non-technical terms, answers to the following questions:

- "How is technical co-ordination achieved today in the electricity system?"

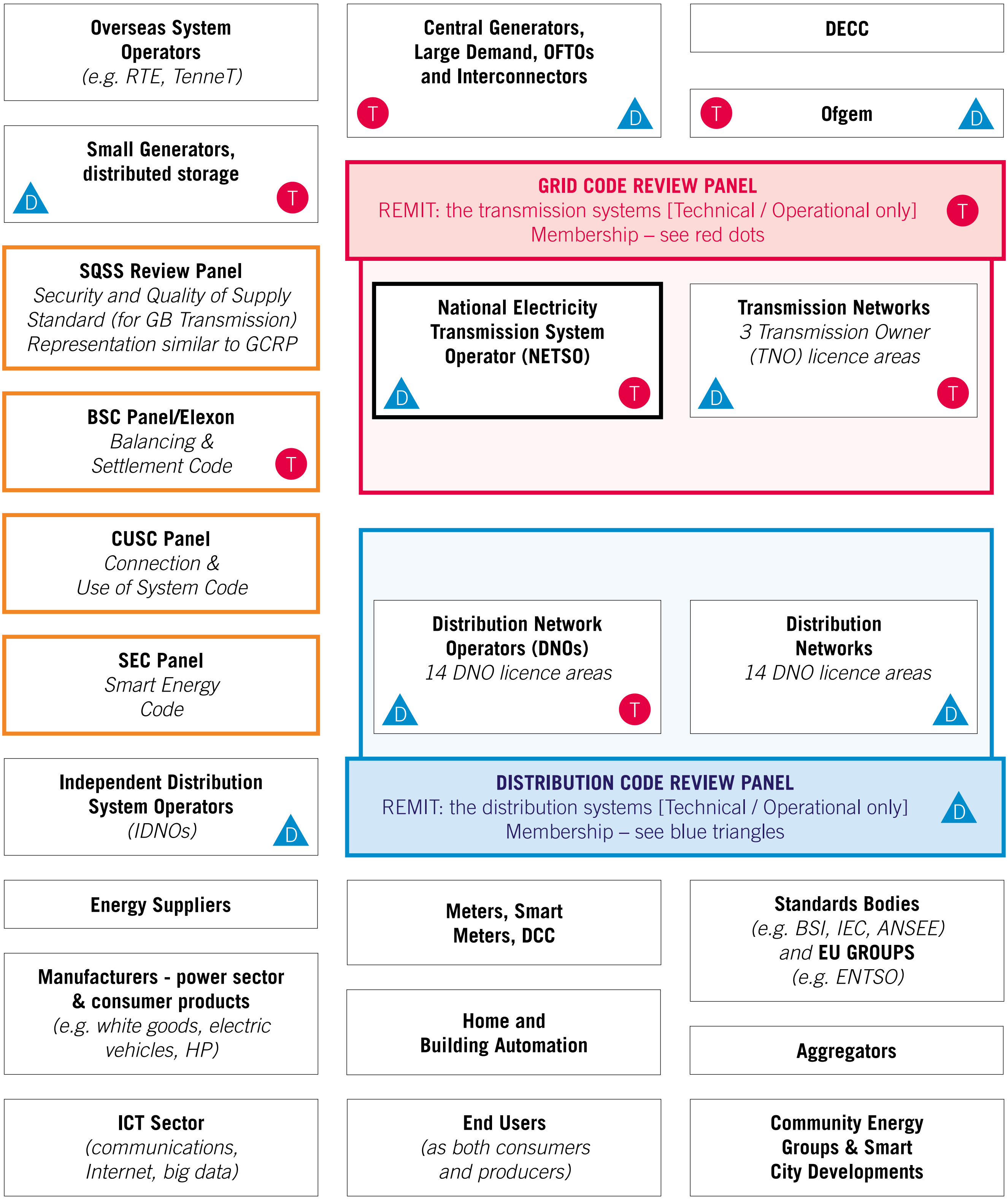
  and

- "Looking to the power system changes ahead, where might the gaps be in current arrangements?"

It includes key messages that have been drawn from industry observers, including those involved at first hand with today's arrangements.

Figure 14: TODAY - Main technical coordinating parties and forums for GB electricity networks

Today's Technical & Operational Co-ordination: the red and blue shaded areas show the principal focus for the remit of the respective Panel. The coloured dots and triangles indicate the membership of these panels (Blue triangles – Distribution Code Review Panel and Red dots – Grid Code Review Panel). Parties without coloured symbols are linked to the Panels on an ad hoc basis only. Orange boxes show other industry panels, likely to need closer integration for future developments.



6.4 Summary of key features and gaps in today's arrangements:

1. **The Grid Code and Distribution Code Panels have a narrowly defined remit, defined by Licence, and cannot take an holistic view**. Their constitutions limit their remit to considering "better furthering the objectives of their respective Codes". Neither Panel can take a whole electricity system view, and certainly not a whole energy system view. An element of common sense applies here to addressing cross-cutting issues (such as RoCoF relays recently) but this is at the margins and is confined to technical matters only. The remit of the Panels is purely technical, yet most real world solutions will work best with the technical, operational and commercial impacts treated together. For example, in regard to Demand Side Response the Code Panels can address the technical framework – but without a matching commercial framework, the technical framework can't be used ... or won't be, because the incentives are wrong.

2. **Important new influences are not represented on either panel.** "Smart loads" such as the electric vehicle charging infrastructure, Internet-connected white goods, and heat pumps, will have a major impact on the system but are not represented on either panel.

3. **Today's code change procedures** work reasonably well for small incremental changes, but there is doubt about their ability to implement large or complex changes. Recent big changes (BETTA and gas distribution network sales), have taken the route of designating a whole new code.

4. **Ofgem now have significant code review powers** – i.e. to co-ordinate just those code changes that otherwise would get mired in the silos of applicable objectives. However, it is not clear whether these arrangements are wide enough for the future, or may be constrained in other ways. To enable big changes to be made effectively, a clear change mechanism with strong political support needs to be in place.

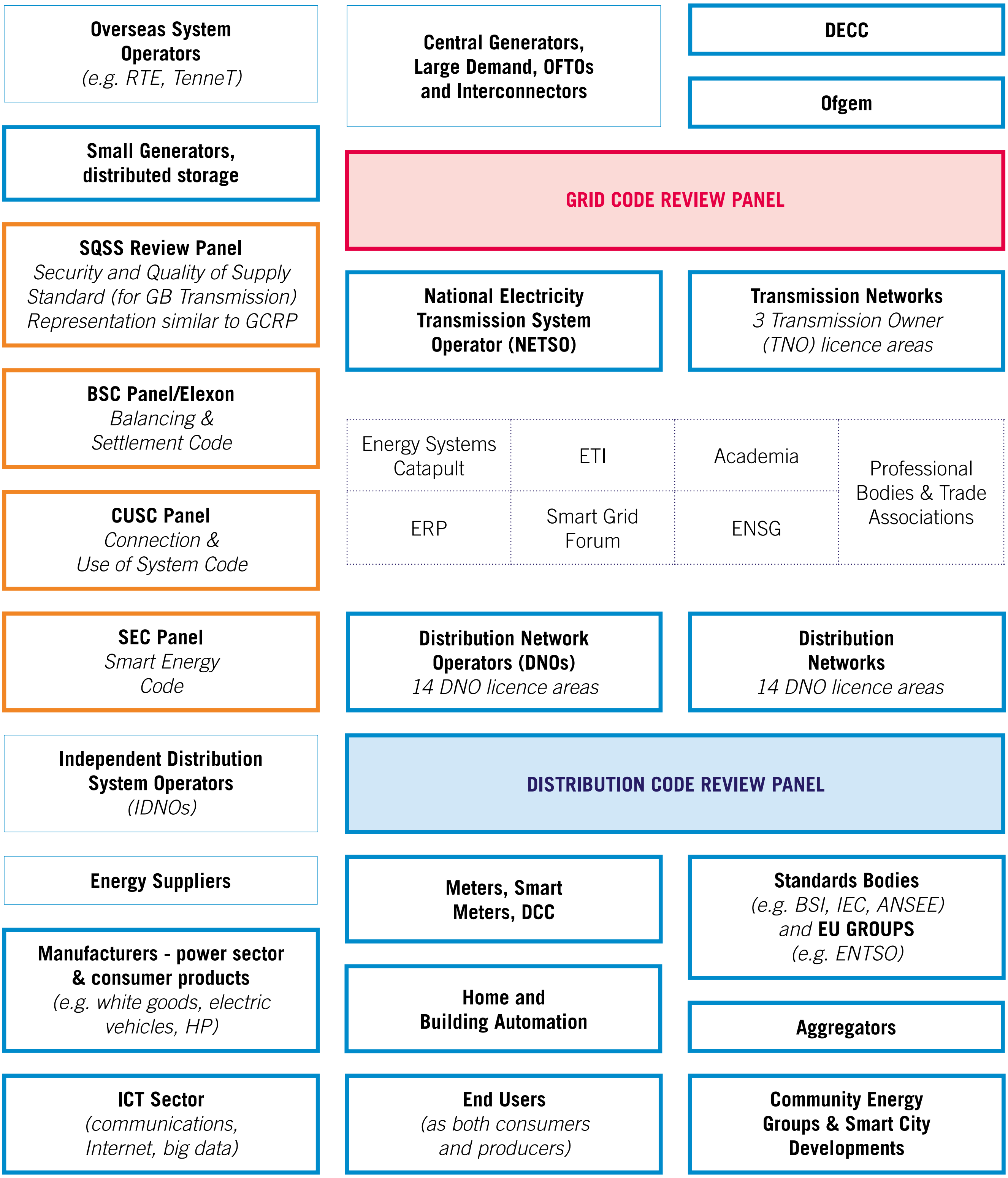
5. **The Codes refer to the "System", but not in the sense of "whole-system"**, as used in the context of "system architect"; the Distribution Code definition of System is simply "An electrical network running at various voltages".

6. **New European network codes are soon to be introduced**. These European Codes, being for the Commission by ENTSO E[27] are likely to influence future arrangements.

7. **There is lack of clarity in regard to the time dimension**. While it can be argued that the number one priority is to make sure that the system is renewed/expanded so that it remains fit for purpose on a continuous basis, there is also the longer term strategic planning aspect to consider, especially in times of disruptive change. It remains a priority to ensure that the system operates in a safe and efficient manner, however many SA issues are in the domain of a strategic planning activity; SA issues could however extend into operation.

Figure 15: FUTURE – mid-2020's

This diagram outlines the potential landscape fowr a system architect role – highlighted boxes indicate the principal areas requiring systematic co-ordination, either through influence or control as appropriate.



1. Figure 14 **identifies the parties that will need to be closely engaged** in delivering whole-systems solutions for the anticipated changes in the GB electricity system. It uses the same format of diagram as Figure 14, and is not intended to be exhaustive but rather be representative of key aspects.

2. **The bold blue boxes** show the players that are envisaged to have leading roles in the future and will need to work in an integrated way, the lighter edged boxes show the parties that can be expected to be involved from time to time on specific matters.

3. **The diagram continues to show the current industry mechanisms**, such as the Code Panels and other elements of today's governance framework; it is premature to comment on whether these would remain largely unchanged, be modified in some way, or whether it would make best sense for their activities to be undertaken in a different way.

4. **Some of the relevant industry organisations and committees** have been added in dotted boxes. Likewise, a further level of detail would need to be examined before the scope of relationships with these parties could be defined.

5. **The diagram avoids the over-simplification** of putting a large circle round the whole picture and labelling it "system architect role"; it is important to recognise that this is a complex sector having many parties, priorities and accountabilities, and developments to create an effective SA function would need to be undertaken with care and full consultation.

6.5 Models for a system architect

This research has not discovered an existing model for a SA that could be adopted unchanged by the electricity sector, however there are several models that provide ideas that could contribute to the design of a SA function. Three alternative models are described below that are representative of the wide range of those that could be considered:

6.5.1 Model 1: Agency as main contractor

The "agency as main contractor" model, as used by the Galileo satellite system or the Highways Agency, is one that could, in theory, be adapted to the electricity sector, but would involve a significant change of responsibilities of incumbent parties. In both cases, the central agency has a reasonably small technical team that has competence in the architecture of the system but passes responsibilities to other bodies for major activities, such as road maintenance, large-scale research or launching satellites.

Although the self-contained design-build-transfer contract for a new light-rail system is very different to the major re-engineering of a complex and historic electricity network, some aspects of the structure of the SA function could read across. In this case, the consortium acted as an agent for the ultimate client and undertook the systems engineering activities to provide the "glue" between the various subsystems.

6.5.2 Model 2: Maximum subsidiarity

The "maximum subsidiarity" model used by the water industry could not be adopted directly but, in an environment with large amounts of distribution-connected generation, frequency-sensitive loads, and a high uptake of "smart" load management, might provide a model leading to DNOs having the main commercial relationship with end-users and distribution-connected generators in regional networks, as well as the main responsibility for short-term load balancing. This would leave the Transmission System Operator managing inter-regional balancing, correcting "clock error" and relationships with larger generators. In this model, which would radically change the commercial structure of the industry, the SA function would be distributed between the central TSO and the DNOs, depending upon whether a specific issue was "whole system" or "local" in character. However, integration would have to be achieved between the respective DNOs and in collaboration with the TNOs, the GBSO, and external parties. This would be likely to require a measure of industry restructuring and would present significant challenges.

The “system-of-systems approach” (SOSA) used by the MoD operates in a very different commercial organisational environment to the privatised electricity industry, in that it integrates various engineering systems that are owned by the MoD or its allies. Also, it relates only to the real-time control of the assets, rather than to their provision or to their adequacy to satisfy the strategic needs of the MoD in any given situation. However, one could see similarities between a SOSA structure and a model of the electricity system in which the DNOs were considered as individual “systems” and a central TSO provides the SOSA integration into a complete system.

6.5.3 Model 3: a standards-based system architect

For the last 20 years, the electricity industry has used a standards-based system in which the Grid Code and the Distribution Code have provided the framework of technical regulation that has allowed the evolutionary growth of the network. Today’s code change procedures work reasonably well for small incremental changes, but not for large complex changes, and the codes relate only to the operation of the transmission and distribution networks, not to the operation of the complete electricity system or the closer engagement of third parties such as smart communities.

The SA model of the www, in which underlying principles of operation and interfaces are agreed by a Technical Architecture Group (TAG) reporting to a central board, is one that could form the basis of a standards-based SA function. A TAG that included representatives from National Grid, the DNOs, and major generators could agree the system architectural principles, which would then be implemented by detailed standards. However, this would be very different from the existing code panels, would need to embrace new parties such as non-GB heat pump manufacturers, and would require significant changes to governance and regulation of the industry if the arrangements are not to fall foul of completion and other laws.

The distributed intelligence model for the control of autonomous vehicles would have a variant of a standards-based SA. However, this is not yet at a development level to allow it to be used as a reference.

6.5.4 Models to be avoided

While it has been difficult to identify a pre-existing SA model that matches the complicated needs of the electricity sector, it has been less difficult to identify models that are unlikely to be satisfactory. The experience of the rail industry suggests that a government department attempting to fulfil a SA function in addition to its normal activities carries conflicts of interest and may not be an ideal solution.

A second model to be avoided is to spread the SA role between several bodies in an unstructured way, as appears to have happened on the Edinburgh tram project, without a logical structure of how responsibilities are divided. A similar problem has been identified in large computing systems, including the NHS National Programme for Information Technology (NPfIT), where different companies were required to produce interoperable systems without an overall SA or an adequate specification of the transition plan from the multitude of existing systems that had been tailored to the specific needs of different medical specialities.

6.5.5 The importance of the requirements specification

A common factor of many of the sectors studied has been the failure of the client (typically a national or regional government department) to produce an adequate requirements specification setting out in detail what the system has to do, what the priorities are, which requirements are essential, and which are “nice to have”, how it has to behave under both normal and abnormal conditions, and how its introduction is to be phased-in. Earlier sections of this paper have defined the SA role as interpreting the needs of the stakeholders into specific requirements for the many participants in the industry. Without clarity of definition of the needs and objectives of the client organisation (the stakeholders), there is little chance that the SA, however it is structured, will operate successfully.

Most importantly, the client specification has to be "*do-able*" – the client body does not need to specify how the objective should be attained (and there are good reasons why it should not be too specific) but, possibly with the assistance of consultants, it needs to be absolutely sure that the objectives are attainable. The contract for the European Overnight Stock (EONS) is an example of a project that was doomed from the start because the objectives were mutually exclusive.

The NHS National Programme for Information Technology (NPfIT) is an example of a project that appears to have been started without a clear specification of everything that was required from the system and with no clear definition of the functionality of the system it was replacing. More recently, the DWP Universal Credit programme, which has been "reset" by the MPA, appears to be in a similar situation. [MPA, 2014]

End notes for Part 6

[27] ENTSO-E: The European Network of Transmission System Operators for Electricity

7 Conclusions

It was never intended that this research, which is part of a wider investigation into the system architect (SA) role in the electricity sector, would come out with a set of conclusions recommending a particular arrangement of system engineering responsibilities for the industry and a detailed structure of the SA. However, the following conclusions can be drawn from the work:

1. **The systems engineering challenges of the GB electricity industry are at least as complicated as those in any other sector of the economy, if not more so**. The industry has been operating to the same basic system model since the early part of the 20th Century and, to meet the targets of the Climate Change Act and the Industrial Emissions Directive, will need to re-engineer its systems and technologies over the coming decade. This will require more than simply tuning the present arrangements.

2. **The timescale for delivering transformational change in the industry is very short, in comparison with asset lifetimes and recent experience of technological innovation.** Managing the transition will be at least as difficult as determining the end state.

3. **At present the industry is based on a one-way flow of energy from large central power stations to millions of consumers connected to distribution networks**. If present targets and aspirations for renewable energy sources are met, we can expect to see periods of the day, particularly in summer, when solar PV and wind energy generation could provide the full load. If this situation materialises we will be faced with the situation where system voltage and frequency regulation will migrate from a handful of large power stations to millions of consumer/generators. This will represent a paradigm shift in the operation of the grid that has not yet been achieved anywhere else in the world.

4. **With the development of electric vehicles, electrically-driven heat pumps, home energy management systems, smart grids and local energy networks, the electricity network will become more interdependent with the telecoms network**. This represents another ground-breaking shift in technology, new transformational relationships between suppliers and consumers, and new risks that must be managed to ensure that resilience and security is maintained.

5. **It is challenging to define the role of a SA for the electricity sector when the decarbonisation trajectory of the rest of the energy sector is uncertain**. While the electricity sector needs to be able to plan on levels of penetration of plug-in vehicles and heat pumps and the growth in distributed renewables, these will be determined by customer take up, not central planning. Flexibility will be an important attribute of the future energy system and of its SA.

6. **The transformation of the energy network is likely to have only limited success unless consumers buy-in to the concept and the system design**. The SA function needs to have an agenda that is wider than technical issues alone and needs to include the interface with IT and communications systems as well as the human factors issues.

7. **A spectrum of possible models for a SA has been identified and three examples have been proposed**. One is based round an agency model, another based on the principle of maximum subsidiarity, and a third being a standards-based structure. The objective of this report was not to propose a particular solution and these are included as examples of a wider continuum of what would be possible.

8. **The implementation of an effective SA role will require government to recast its relationship with the industry**. To deliver commitments on decarbonisation there will be a need to define firm output targets, such as a trajectory for decarbonisation of the sector, rather than specifying the means to the delivery of those targets, such as the number of solar PV panels.

9. Based on what has emerged from this research, it would be useful to undertake a modest extension of this study to investigate international experiences of managing the SA role in electricity sectors.

8 References and Appendices

8.1 Appendix A: Author and potential conflicts of interest

Roger Kemp is a part-time Professorial Fellow at Lancaster University. Prior to joining the University in 2003 he was UK Technical and Safety Director of Alstom Transport. Earlier he was Systems Engineering Manager of GEC Transportation Projects, part of the joint venture that designed and built the London Docklands Light Railway initial system. He spent several years in Paris working on the design and construction of the Eurostar trains and, on his return, was asked to carry out a review of the contract for the European Overnight Stock.

He is a Fellow of the Royal Academy of Engineering and was involved in researching, writing or peer reviewing the five reports referenced in Appendix C. He is a member of the IET Energy Policy Panel.

The author's only paid employment in the electricity supply industry was as a graduate trainee when he spent a few months working with South of Scotland Electricity Board research department on the dynamics of coal-fired power stations.

8.2 Appendix B: Individual contributions

Many members of the Steering Group contributed to the research and spent hours in face-to-face meetings, on Skype and on the phone. They provided long e-mails and commented both on draft chapters and on multiple drafts of the whole report. Their contributions have been essential to the work – particularly in understanding the present electrical system.

In addition, the following people contributed to this research – including by interview, by answering questions on e-mail, or by reviewing various drafts. Interviews took place either face-to-face or by phone or Skype. The contributions of all the interviewees are greatly appreciated. As discussed in the introduction, a version of the *Chatham House Rule* has been adopted and their inputs have not been attributed.

Malcolm Bingham, Head of Road Network Management Policy, Freight Transport Association
John Butcher, Regional Water Supplies Manager, United Utilities.
Simon Daykin, Chief Architect, NATS
Dr Chris Elliott FREng, Barrister, and previously board member of Strategic Rail Authority.
Professor Anne Garden MBE, Head of Lancaster Medical School
Brendan Harnett, Airbus Defence and Space
Professor David Hutchison, Professor of Computing (networked and distributed systems), Lancaster University.
Anson Jack, Deputy Chief Executive (Commercial and Strategy) RSSB
Mike Kay, Networks Strategy and Technical Support Director, Electricity Northwest
Ian Llewellyn, Science & Innovation, DECC
David Liversidge, Principal Consultant, BMT Hi-Q Sigma Ltd
Keith Mason, Senior Director of Finance and Networks, Ofwat
Peter Morgan, Smart meter programme delivery team, DECC
John Morris, Technical Director – Rail, Parsons Brinckerhoff Ltd.
Richard Peckham, Business Development Director, Airbus Defence and Space
Professor Allyson Pollock, Professor of Public Health Research and Policy, Queen Mary, London
Professor Bob Rothschild, Emeritus Professor of Economics, Lancaster University.
Dr Mike Short, Vice-president, public affairs, Telefonica,
Cliff Walton, Executive Director, PPA Energy, Visiting Professor Imperial College

Speakers at the *Energy Systems Conference, When Theory Meets Reality*, held 24-25 June 2014, provided useful information, and several members at the joint Cambridge Energy Policy Research Group / UK Power Networks meeting on 6 June 2014 contributed ideas that have been incorporated. Discussions at the IET Energy Policy Panel and PNJV Steering Group meetings have also provided an important input, as did speakers at the *Control 2014* conference, held at Loughborough University in July 2014.

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