Transforming the Electricity System: How other sectors have met the challenge of whole-system integration

Executive Summary

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.

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This is an Executive Summary of the Main Report which can be found at www.theiet.org/pnjv
Part 1: Executive Summary

Transforming the Electricity System: How other sectors have met the challenge of whole-system integration

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.

1.1 The electricity sector – a revolution now approaching?
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”.

Transforming the Electricity System: How other sectors have met the challenge of whole-system integration
1.5 Managing the electricity system

<table>
<thead>
<tr>
<th>Summary of the challenges</th>
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<tbody>
<tr>
<td>■ 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.</td>
</tr>
<tr>
<td>■ 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.</td>
</tr>
<tr>
<td>■ 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.</td>
</tr>
<tr>
<td>■ The increase in inverter-coupled generation and loads will change the spectrum and levels of non-50 Hz currents in the grid.</td>
</tr>
<tr>
<td>■ Inverter-coupled solar PV and wind generators may limit the ability of overcurrent protection systems to detect certain types of fault.</td>
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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.