The Institution of
Engineering and Technology

Modelling Requirements for GB Power System Resilience
during the transition to Low Carbon Energy

IET Report for the Council of Science and Technology

Part 2: Commissioned Papers Summary

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Energy

About this report

The Institution of Engineering and Technology was commissioned by the Council of Science and Technology (CST) to research the emerging challenges for modelling electricity systems and how Britain's capabilities would need to be adapted to assess electricity system resilience as GB makes the transition to a low carbon electricity system.

This project commissioned, and received, fifteen individual papers from GB-based specialists of international standing in power system modelling. The authors of the papers worked with a wide stakeholder base of network companies, academics and others, who provided review and challenge. Professor Graham Ault CEng FIET was contracted to provide technical co-ordination and drafting. The emerging conclusions were further validated by means of an industry and academic workshop sponsored by Government Office for Science. The entire project was conducted under the direction of an independent steering committee composed of senior IET Fellows, two of whom were also CST nominees.

The report is composed of three parts:

- Part 1: Main report
- Part 2: Summary of Commissioned Papers
- Part 3: IET Special Interest Publication – Academic & Industry Papers

All three parts of this report are available from the IET website at:

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1 Introduction

This report provides a summary of the findings of the fifteen papers commissioned from subject experts for the IET project on modelling capability requirements of the GB Power System for CST (Energy) and GO-Science. The overall project objective is to assess the modelling capability required to enable a full understanding of the behaviour of the electricity grid as it is adapted to meet the challenges of low carbon transition. The project reviews the currently available modelling capabilities and identifies new challenges and accompanying modelling gaps that need to be addressed in order to fully understand and manage the performance and resilience of the electricity system in GB.

Fifteen papers were commissioned to address the full spectrum of power system modelling challenges and specialist domains. The commissioned papers (listed under References in Section 3) draw on relevant industry practice, developments already underway, emerging and future issues, and recommendations to tackle the main challenges for modelling the GB power system, to manage the emerging and future risks to resilience and performance.

The authors were provided with project background information, including the overall project briefing and objectives, and were asked to prepare papers describing the emerging modelling and simulation capability to address known challenges and gaps, and to provide a view as to the state-of-art and state-of-practice in the specific topic area. The topic areas for the papers were generated from the original CST project scope, Steering Group discussions and review of documents generated to commission the fifteen papers.

The authors were requested to provide a comprehensive, referenced and concise description of the power system modelling landscape in the specific topic area, along with an evaluation of the power system modelling capability and its adequacy, future suitability (given the challenges emerging and anticipated), any gaps, as well as the emerging challenges or concerns related to input data and assumptions.

This report presents a summary of the key points from each paper to form a concise and accessible evidence base, on which the project will draw conclusions and generate recommendations. The words of the authors are presented verbatim in several places to capture the significance of their review, conclusions and recommendations and to maintain the independence and significance of those views.

The objectives for this summary document are:

- To provide a broad view of GB power system challenges and the consequent emerging and anticipated modelling challenges.
- To summarise the evidence base for the IET/CST Steering Group to base their discussion, conclusions and recommendations on GB power system modelling capabilities.
- To provide an access point to detailed technical papers.
- To provide a high level reference point or agenda for modelling capability development following on from this project.

Some observations on the summaries of the papers are presented below as a guide to key points and to create a reference point for topics of likely interest to the IET/CST project Steering Group, GO-Science, CST (Energy), and the wider stakeholder groups.

- There is a clear view presented of a **nature, scale and pace of change** emerging in the GB power system that requires a new approach to harnessing the available power system modelling capabilities and developing new capabilities.
- There is a clear view from the authors that there is a **significant modelling challenge** that extends beyond and cuts across current capabilities, resources, governance, etc. The numbers of new devices expected (both in type and in their population and distribution in the power system) present a variety of planning and operational challenges to be supported by new modelling capabilities.
- There is strong view created across the papers that several issues of modelling capabilities need to be addressed, in order to deal with the **threats posed by developments emerging in the GB power system**.
- There is an excellent level of **technical detail** based on the literature (with a full GB and international sweep) which cannot be summarised easily, but should be considered at the stage of implementing recommendations, to address the modelling capabilities challenge and the undertaking of the modelling development work itself.
- There is a strong sense of a need for **coordinated direction and effort** to meet the requirements of the challenge. Even though there is a high level of international awareness and connectivity of the subject, there is still a clear call for coordinated action on topics that require buy-in and contribution across the sector in GB.
- With the volume of issues and challenges identified, there is a need to **prioritise the issues** based on both **timing and seriousness**. Some of the papers point to the urgency of these issues, but there is a clear need to map the challenges and actions required to address the challenges and provide a clear roadmap of coordinated activity.
- The **resources and responsibilities** for identifying, specifying, developing, deploying and maintaining the modelling capabilities required to support the transition of the GB system are a common theme across the papers.
- **Availability and development of skilled analysts** is noted by several of the authors as a concern, at a time when more sophisticated modelling capabilities need to be developed and deployed.
- **Data and model collection, management and controlled/shared access** are also common themes across papers, with existing modelling techniques dependent on access to new data sets or opportunities to model in new valuable ways not possible because of data access issues.
- While the **management of risk** is implicit in the existing modelling activities of responsible network and system operation companies, several authors mention risk-focused modelling activities as an explicit branch of modelling capability that needs to be developed and exploited.
- Several authors note the **application of more sophisticated modelling tools and techniques** to new areas of the power system as needs dictate, so signalling a transition to a more complex fabric of modelling to deal with already emerging challenges. Examples include more harmonics issues associated with renewables and power flow analysis, in lower voltage networks, with more distributed generation.

- Many **whole system challenges** (top to bottom in the electrical systems, as well as inter-dependence with other infrastructure systems) are highlighted across the papers with emerging issues and modelling requirements highlighted.
- A **wide spectrum of different modelling techniques and tools** for different purposes is clearly set out across the papers, but it has always been the case that the application of even the most general of techniques (e.g. power flow analysis) is carefully targeted and managed. While it is expected that a number of new techniques will be developed and applied, along with new applications of existing techniques to new problems and with new models and data sets, the same careful targeting and appropriate application of techniques to the problems should continue.

The project Steering Group identified several high level modelling themes from the gathered evidence as follows:

- **Power system models that span both transmission/distribution networks and active consumers,** enabling the modelling of more facets of power system behaviour in one analysis package or at least compatible interoperable packages.
- **Markets and commercial externalities** that have a direct bearing on technical performance and its modelling, noting the potential for active demand responding to time of use prices.
- **New ranges of data** required to support advanced modelling treatment, yet which might be hard to access for reasons of commercial confidentiality or lack of operational experience; and whose accuracy needs to be assured (e.g. GB connection application status/register, operational notifications, effectiveness of smart grid solutions, characteristics of power electronics converters (e.g. harmonic distortion), EV charging behaviour (impact on demand curves), heat pumps (impact on demand curves) and DG fault ride-through capability).
- **Transitioning to a less predictable, stochastic world** that can no longer be based upon deterministic system ‘givens’, such as parameters that will vary depending on wind and sun forecasts, but which will depend on consumer choices, behaviours and temperament.
- **Optimising demand interaction** with the power system to fully integrate this valuable whole system resource while providing greater flexibility and usability for system users.
- **Modelling intra-day conditions** and much more frequently changing system conditions, noting that long-established load curves and ‘cardinal points’ are likely to change significantly and be far less predictable.
- **The dynamic business and operational context** which will be characterised by continual change, new commercial models and services, and new devices and upgrades entering service and changing behaviour at a faster pace than previously experienced.
- **The requirement for interoperability** between power system equipment including a greater dependency on ICT technologies and infrastructure.
- **The interaction between energy vectors:** planning and operating energy-delivery and energy-using infrastructure in an efficient resilient way (e.g. electricity, gas, transport and heat).

- **Interaction with smart cities and communities** with multi-faceted public and commercial services infrastructures and systems.
- **Interaction with new third parties**, typically from the ICT and data sectors, but also including micro-generators, independent micro-grid operators, and new power network service providers.

These are captured, prioritised and expanded in the project Final Report.

2 Commissioned paper summaries

This section presents a summary of the main points in each of the fifteen papers commissioned to inform the IET project for CST and GO-Science on modelling capability requirements of the GB Power System.

Paper One: Power system modelling issues and requirements identified by the IET Power Network Joint Vision project

[1] presents a critical assessment of the modelling implications of the main findings of the IET PNJV Position Statement and Technical Report (published in December 2013) and concludes the following:

- Power system modelling has played a crucial role in supporting the delivery of a secure and efficient power supply system in GB. Power system modelling provides visibility of the implications of decision made by power system planners and operators at various stages of the power production and delivery cycle.
- A number of new challenges are emerging and can be expected to have greater implications in future as the sources of power generation transition towards renewable and distributed sources and the uses of electrical power increase particularly in heating and transportation applications. Furthermore, the introduction of energy storage along with enhanced measurement, monitoring, automation and control technologies presents substantial new areas for model development and application. Each of these new developments needs to be modelled fully and embedded into new planning and operational processes and procedures.
- The scope of power systems modelling needs to increase to capture a variety of new generation, network, storage and consumption equipment and systems as well as market, customer and regulatory issues in a whole system context, and more responsive/stochastic approaches in the context of a far less deterministic, predictable power system.
- The challenges and opportunities of the available, future, diverse power systems data sets have yet to be fully explored and exploited to enhance power system planning and operations. There are numerous capture, access, security, analytics and application challenges to be overcome to exploit not only the possible, but also the necessary uses of new and diverse data and information sources. Shared data protocols, and data repositories among power network companies and their stakeholders and agreed governance models for data as potential modelling inputs will likely be an area for further development. The sheer volume of input data (and results) will itself require fresh thinking (commonly captured under the banner of ‘big data’ and ‘data analytics’). This will also likely raise serious data privacy and security aspects not previously encountered by power system modellers. Access to, for example, smart meter data and EV location and charge status information, brings with it entirely new responsibilities.

- Cross industry support and coordination (including internationally) is required to address the modelling challenges and in particular to bring forward proposals to support the development of the required power system modelling skills to underpin the development of the modelling platforms, tools and capabilities required to underpin the continuance if not improvement of current levels of security and performance in the GB power system. The future complexity and subtlety of power system modelling, interactions between models, and responses to new developments and devices, will require a depth and continuity of expertise that the network companies might be unable to sustain. Furthermore, this multi-component tool set would need to span users in more than the network companies, and link up seamlessly with modelling of other energy vectors. There are important skill, knowledge and resource questions to address.
- The System Architect role proposed by the IET's expert group would include leading the specification and development of power system modelling tools to address the whole-system aspects of the emerging and future challenges to GB system security and performance. The System Architect might also be a key user of the power system analysis tools.

[1] concludes as follows:

The implications for network modelling of the issues outlined above are potentially very large and cross-cutting with issues of many new devices and technologies to be integrated into the GB power system in the coming years, new models and modelling capabilities to be developed and harnessed, exploitation and management of new data sets, the coordination and cooperation of multiple stakeholder groups, the need for clear and strong governance of modelling processes from existing bodies and the potential for now stakeholder groups and governance to be introduced. It is clear that the nature, pace and scale of change in the GB power system in the coming years is very challenging. The response in developed and deployed modelling capabilities must lead the change to fulfil the role of modelling of providing visibility and understanding of key issues to enable effective decision making on planning, design and operation of a more sophisticated but also more complex power system.

Paper Two: Existing Capabilities and Anticipated Challenges for Power System Modelling in the GB Network Companies

[2] addresses the existing power system modelling capabilities deployed by the GB network operators and the GB System Operator for planning and operating the GB system. The paper authors conducted a background literature review and conducted interviews with network and system operator representatives. The review focused on both long and shorter term planning as well as operational objectives for power system modelling.

Power system modelling conducted by the network operators and the system operator to support planning and operations have the aim of checking planned system compliance and system operability against the relevant codes and standards: Grid Code, Distribution Code, SQSS (Security and Quality of Supply Standard), Engineering Recommendation (ER) P2/6, as well as various other Engineering Recommendations.

Analysis to support network and system planning is carried out to study outage and maintenance schedules, network reinforcement options and new generation or demand customer connections.

The main techniques currently used include steady-state analysis, fault analysis, dynamic simulation and harmonic analysis.

Table 1 sets out the analytical tools used by DNOs and shows the range of platforms deployed to study network by voltage level. Several analysis platforms are often in use within the same DNO.

Voltage Level (applicable number of DNO regions)	Power System Analysis Software (used by number of DNO regions)
Below 11 kV (14)	DINIS (2), PSS Adept/PSS Sincal (2), WinDebut (4), No modelling (6)
11 kV (14)	DINIS (8), PSS Adept/PSS Sincal (2), GROND (2), IPSA (1), DIgSILENT (1)
33 kV (14)	DINIS (1), IPSA (3), PSS/E (6), DIgSILENT (4)
132 kV (12)	DINIS (1), IPSA (3), PSS/E (5), DIgSILENT (3)

Table 1: Power system planning software packages used by GB Network Operators (number of DNO users in parenthesis).

In current distribution planning, power flow analysis is conducted routinely for EHV (132kV) networks and then as required in other networks where there is sufficient uncertainty in power flows under various credible conditions to warrant full power flow analysis. The same is often true for power flow analysis on 33kV networks associated with interconnected groups, meshed/ring systems, and where intermittent generation is significant. 11kV networks will also be subject to power flow studies as required by the complexity or uncertainty of the prevailing or anticipated conditions.

Arithmetic assessment of ‘group capability’ (based on contingent conditions) against peak demand generation maximum and minimum export conditions plays a role in planning general network capability in cases where the network complexity is lower and so power flows more obvious without recourse to power flow analysis.

The full set of power system analytical tools used by DNOs includes power flow analysis, fault analysis, voltage step analysis (using power flow simulation), transient analysis (for EHV networks) and harmonics analysis. Dynamics as greater numbers of dynamic/active components are connected to distribution networks and their impact (especially larger plant) has more impact on a lower inertia system. Required transient and harmonic analysis is often conducted by external consultants to the DNOs.

Whole energy system models (which take account of parameters such as gas, heat and carbon as well as electricity), and economic models for the purposes of planning and scenario testing based on prospective outlooks and backgrounds are also utilised for specific purposes.

Some of the techniques listed for network and system planning are also used to support operational planning with the addition of supplementary modelling capabilities including demand forecast models and market models.

Within the GB network companies, forecasting is generally undertaken using models created and developed internally. National Grid has developed and deployed an Energy Forecasting Tool to provide a greater accuracy to wind power forecasting for System Operation. Currently DNOs do not routinely forecast renewable energy variation as their System Operation role is contained to network switching and emergency response. However, it is expected that additional system operational modelling capabilities will be developed to meet future requirements as their System Operator role increases as a result of the development of active networks.

The real time operation and management of power systems is carried out on software platforms known as Network Management Systems (NMS). These NMSs are utilised at both transmission and distribution voltages, and are operated from within the control centres. The management of the power system is achieved through interaction with the topology models built within the NMS which are linked to the ICT (information and communication technology) and SCADA (supervisory control and data acquisition) infrastructure out on the network which updates measurements and the status of equipment in real time.

There are several ongoing innovation and developmental projects (e.g. LCNF and NIC) addressing modelling challenges and these anticipate many of the challenges faced by network operators. Relevant transmission projects that address some of the significant modelling challenges for system planning and operation in the context of the emerging and future challenges are:

- The System Operating Framework (SOF) project in National Grid to develop the modelling tools and processes to underpin overall system operability in the context of the changing system characteristics.
- The VISOR project that is developing system operation models that utilise phasor measurement unit (PMU) data to provide a much enhanced visibility of system state and emerging dynamic and transient issues.
- The Multi Terminal Test Environment (MTTE) project that aims to provide the means to model HVDC interconnections and interconnected systems to de-risk HVDC developments in system planning and system operation.

- The WholeSEM project aims to address some of the whole energy system modelling challenges to address concerns of interactions between the different inter-dependent energy systems.
- WPD and National Grid and separately ENW and National Grid are working on an operational data link between their control centres to share data and models. The purpose of these initiatives is to enhance system state visibility and provide additional control response options to underpin secure, within limits system and economic system operation.

The modelling challenges identified in this paper are:

- Visibility and sharing of information between the System Operator and the DNOs
- Wind forecasting
- Harmonics
- Ongoing review of the P2 Security of Supply Standard
- Modelling of HVDC and FACTS devices
- Modelling of IT and communications
- Dynamics in distribution systems
- New power system modelling techniques and capabilities to address the changing GB power system
- Reliability and risk management in the emerging system

The highlighted modelling capability gaps of greatest concern to the network operators and system operator are:

- Data availability and accuracy in areas including:
    - Steady State Data and Modelling
    - Dynamic Data and Modelling
    - Harmonic Data and Modelling
    - Data sharing between network operators and with the system operator
    - Geographical Information Systems (GIS) data and its integration with other data sets and models
- Skills gaps in existing and new analysis personnel
- Integrating modelling platforms for consistency, productivity and to address wider system issues
- Voltage management in distribution networks
- Statistical and probabilistic tools
- Usability of modelling tools and platforms

Paper Three: A Review of Power System Modelling Platforms and Capabilities

[3] captures the modelling platforms used by the network operators and system operator and these are summarised in Table 2.

Type of Modelling	Purpose	Study Types	Examples of Software Packages
Steady state power system analysis	Assessment of voltage and thermal conditions, fault levels	Load flow, voltage step, fault level contribution of DG	DIgSILENT, DINIS, ERACS, ETAP, IPSA, Power World, PSS/E, SKM Power Tools, OpenDSS
Dynamic power system analysis	Assessment of the transient and dynamic behaviour of equipment e.g. generators, DFIGs, and/or the network	Transient stability, critical clearing time, dynamic voltage step/ control, fault ride through	DIgSILENT, DINIS, ERACS, ETAP, IPSA, Power World, PSS/E, SKM Power Tools
Harmonic analysis	Assessment of harmonics, distortion levels and identification of resonances	Impedance scan, harmonic load flow (including impact of VSC)	DIgSILENT, ERACS, ETAP, IPSA, PSS Sincal, SKM Power Tools
Electro-Magnetic Transient (EMT) Analysis	Assessment of electro-magnetic transients and phenomena	Insulation coordination (lightning, switching), HVDC/FACTS equipment design, sub-synchronous resonance (SSR)	ATP-EMTP, EMTP-RV, PSCAD/ EMTDC
Real Time Simulation (RTS)	Closed loop and scenario testing in real time	Real time simulations, protection testing, control system testing	RTDS, Opal-RT
Hybrid Simulation	Assessment of multiple models/ programs in the same dynamic simulation environment	Dynamic analysis of the interaction between two systems	ETRAN (PSS/E and PSCAD)
Multi-Domain Analysis	Assessment of multiple systems and their interactions	Study of interactions between electrical, power electronic, mechanical and fluid dynamic systems	MATLAB (including Simulink and SPS/Simulink), DYMOLA

Table 2: Power System Analysis Platforms in Common use by GB Network Operators.

Table 2 shows a diversity of specialised power system analysis tools available to network operator companies. Potential for isolation and divergent paths in modelling capabilities across companies and modelling platforms is highlighted as a risk at a time when more integrated modelling for more challenging and complex systems is an emerging requirement.

Table 3 sets out the additional models in use or coming into use in the network operator companies. Again, the diversity and capability is encouraging but the breadth of use, the needs for specialist skills (and this residing with relatively few people) and the potential for isolation and isolation of issues across modelling platforms is a risk.

Type of Modelling	Purpose	Study Types	Examples of Software Packages
Whole Energy System Models (design tools that integrate power, heat, transport and infrastructure with energy resources and demand scenarios)	Study the long term evolution of energy systems	Scenario testing of future power systems taking account of various energy vectors	MARKAL-based modelling (International Energy Agency), Energy System Modelling Environment (ESME) developed by ETI, NGET's Future Energy Scenarios
Power Network Economic Models	Assessment of the economics of planned developments	Cost vs. Benefit analysis	Smart Grid Forum WS3 "Transform" model, Scenario Investment Model (SIM) from the FALCON Low Carbon Network Fund (LCNF) Project
Market, pricing, demand and customer models & Dynamic resource and supply model	Inform on regulatory issues, optimise generation dispatch	Price forecasting, generation dispatch, transmission investment planning	Commercial Models: PLEX-OS (used by National Grid), AURORAxmp, Ventyx PROMOD IV. Non-commercial: BID3 (incorporates BID2.4 and Zephyr – Pöyry), ECLIPSE (IPA)
Generation and demand forecasting	Forecasting for system balancing (may also feed into trading tools)	Forecast modelling to optimise network operation whilst minimising costs	Network operators use internal modelling tools. Commercial wind and solar forecasting models include AWS Truepower, Garrad Hassan – GH Forecaster, 3Tier – PowerSight Wind Forecasting System, Element Energy's Forecasting Tool, Grid Scientific's Load Profile Modelling

Table 3: Overview of additional power system models used by GB network operators.

Power system modelling for operations purposes is carried out by each of the network operators and the system operator to ensure control engineers can monitor and manage their networks in real time. This is achieved using NMS platforms which are fully integrated with the communications and SCADA networks. Engagement with a number of the GB network companies revealed that all but one of the DNOs use the GE products ENMAC or PowerOn Fusion DMS (where PowerOn Fusion is an upgraded and rebranded version of ENMAC), while NGET use the GE PowerOn Reliance EMS product.

The GE PowerOn Fusion DMS encompasses monitoring and control of distribution networks, fault management and outage planning, and performance optimisation through a range of integrated modules. It also offers a platform where smart grid technologies can be implemented and deployed, and tools to make managing vast LV networks more efficient.

The PowerOn Reliance EMS is an open-standard, distributed architecture tool which focuses on grid situational awareness and reliability as is required for the transmission network. Emphasis is also placed on security, with a comprehensive layered approach to provide a 'defence-in-depth' strategy.

Other NMS platforms used in GB are the Thales NMS at distribution, and the Alstom (previously Areva T&D) e-terra product at transmission. The Thales product is a SCADA system designed to manage infrastructure and provide real-time control, and also to provide the core capability in the control room. There is also an emphasis on security to protect data over the communications links. The Alstom e-terra product also a widely used NMS platform.

The issues identified in the review of power system modelling platforms in this paper are:

- Consistency in the use of modelling platforms within and across network operators
- Shift in modelling timeframes with more sophisticated models being explored for use in operational timeframes as well as more multi-period studies required.
- Unbalanced power flows requirement
- Modelling of emerging and future devices and
- Modelling and co-simulation of power system, control and communication networks

The paper concludes with additional recommendations in the areas of modelling platform consistency, modelling emerging and future devices and technologies, modelling multiple interdependent networks and the need for harmonised processes to underpin effective modelling of the emerging GB power system.

Paper Four: Forecasting and Probabilistic Methods for Power Systems: A Review of UK Research

[4] describes the established role that probabilistic methods have in the following aspects of system modelling and analysis:

- Generation adequacy assessment where the publication in the last three years of the 'GB Capacity Assessment Study' presents the outcome of analysis of frequency and severity of generation shortfall against demand.
- Network planning where the SQSS and P2 standards capture probabilistic features of connected generation and demand along with network equipment. Both standards allow for full exploration of the economic case for system development based on analysis of likely planned and unplanned system behaviours.
- Short term forecasting and system operation where National Grid procures weather and wind forecasting services to support operations and also has an active R&D programme to support its activities in this area. Demand forecasting is a core part of system operation activity and there is significant (i.e. internationally award winning) academic activity in this area with Peter Grindrod and the Counting Lab. Stochastic unit commitment is an area of significant international development in response to operating power systems with variable and non-dispatchable generation sources an demand and Imperial College has notable expertise in this area.
- System reliability assessment has long used probabilistic techniques to explore the nature of unexpected, random failures of equipment and there are new areas that this might develop into as the nature of the power system changes.

[4] notes that probabilistic methods can be further developed in a number of areas to address existing and emerging random system characteristics, stochastic external factors, development uncertainty and risk but further work is required to fully develop and then exploit the benefits of probabilistic approaches, for example:

- Short term forecasting by system operators in the face of greater variability in renewable resource production and changes to demand profiles.
- Reliability analysis scope will need to broaden to capture new devices and technologies connected to the network that have an impact on overall system reliability and security.
- Greater use of Monte Carlo simulation to capture a broader set of operating conditions. The application and the input data should be carefully considered.

Enhancing model availability to a wider stakeholder group is suggested as a means of broadening the modelling capability base and an enabler for methods development and enhanced insight and therefore confidence in the models and the results of the simulations.

Model validation and governance where a wider set of device models is required and used is noted as an important issue.

Positive confirmation that the power system planning standards framework (SQSS, P2 and their supporting documents) is appropriate for emerging and future challenges in the GB power system would provide a solid foundation for their application.

The paper ends with four broad conclusions regarding future development of the field:

- The UK has a number of existing centres of excellence in probabilistic modelling applied to power systems, spread across a number of research communities including power systems, mathematical sciences and meteorology, and these should be encouraged.
- Even where probabilistic methods can provide major benefits in planning and operating real systems, a major challenge in broad deployment is that the relevant skills are not widespread in the industry. Where such deployment is deemed important, a significant training or hiring programme may be necessary, as if methods are to be applied well it is critical that staff involved have sufficient understanding of them.
- Collaboration between relevant research communities should be encouraged. The relevant skills are spread across multiple research communities, in addition to power systems engineering, and both academic and industry funding schemes should be designed to bring together the right interdisciplinary teams where this is required.
- Access to the necessary data is vital for any modelling project. In areas where it is unduly challenging or expensive for one organisation or project to produce its own high quality validated datasets (e.g. spatially and temporally disaggregated historic renewable resource data), there are great potential benefits to creating national datasets which are broadly available to all relevant modelling projects.

Paper Five: Methods and Tools for planning the Future Power System: Issues and Priorities

[5] addresses the use of models and power system analysis in support of system planning and highlights several areas for consideration. The paper notes that transmission planning tools, methods and processes have largely been developed to reflect the criteria of the planning standards and codes so this has an implication that incentives and drivers for change in the modelling tools might be created through changes to planning standards. Legislation in the form of system and network licenses and regulatory incentives also drive the development of tools to plan a system of a particular form that delivers particular outcomes. This difference in standards also partly explains the difference in planning approaches between transmission and distribution in the UK. Planning tools on the market have a range of features but few have all required features in a single package.

Figure 1 is presented to capture the context, role, inputs and outputs of the planning process and it relationship to system operation.

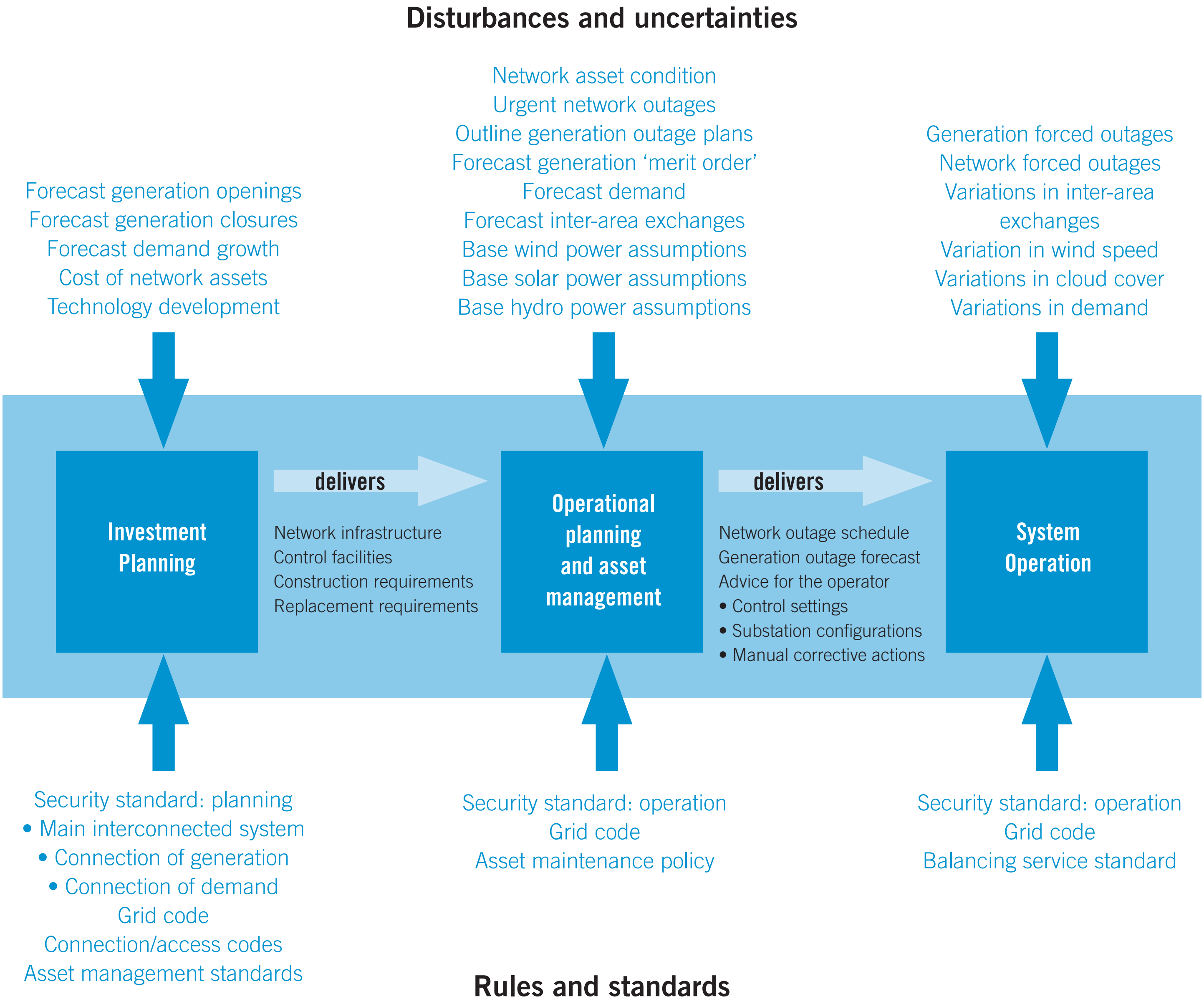

Figure 1: The context of investment planning as a facilitator of operation.

The transmission planning criteria against which a transmission system is considered adequate vary across international jurisdictions with single case, demand peak conditions and a single generation merit order for dispatch common and with seasonal static equipment ratings and a defined set of contingent conditions. Use of multiple factors, through year assessment, scenarios for generation and demand, and a full sweep of contingencies are resource intensive and not always used by transmission planners. Some of these advanced features of transmission planning studies are used in GB along with specialised models and studies for non-conventional equipment (e.g. special protection schemes for inter-tripping and embedded HVDC circuits). Facilitation of outages should be considered in planning stage as system will be run closer to the limit so providing less opportunity for outages.

[5] notes that there is generally a reliance on a few highly skilled planners and analysts for complex whole transmission system studies integrating multiple scenario generation and demand backgrounds (sometimes developed in ancillary software packages) and that there is limited openness of the planning models and data sets to third parties.

[5] highlights the specific transmission planning challenges in relation to the exploitation of new technology and approaches in the development of the system are the limitation of what smarter approaches are allowed in the planning standards and how they are implemented where they are allowed (e.g. inter-tripping, dynamic ratings) and where there are no planning tools in the NETSO to exploit the capabilities of other smarter solutions (e.g. optimal tap settings on phase shifting transformers in system operation support tools).

[5] notes the main drivers of distribution network planning as asset replacement, demand growth but more recently the fast growth in generation connections. The planning and operation of active distribution networks is likely to present a significant number of challenges to Distribution Network Operators (DNOs) and, to a large extent, will require them to translate system modelling methods and tools used in transmission systems. These might be expected to include contingency analysis, constraint management, optimal scheduling of resources, operational forecasting, etc.

[5] draws attention to international experience and notes a CIGRE working group consensus on the top three improvements in analytical capability from a survey as:

1. Robust and transparent input data
2. Complicated (sophisticated) probabilistic analysis of variable generation, especially intermittent forms such as wind and solar
3. More sophisticated modelling of electricity pricing and demand.

[5] concludes and makes recommendations in four areas as follows:

Management of and access to data:

- Although current methods for management of and access to key data for the support of planning of the future power system have been largely though not entirely adequate to date, they are inadequate for dealing with new challenges such as greater penetration of renewable energy, the extended use of corrective actions and the increased utilisation of, for example, real-time thermal ratings, HVDC, phase shifting transformers and scheduling of flexible demand. The expected huge increase in the number of individual active participants in the power system also presents challenges in terms of access to and management of data.

- Even without the new challenges, it is possible that significant improvements could be made in respect of the efficiency and accuracy of data management and exchanges between different units within a company and between different companies including in respect of assumptions about generation patterns and system operation.
- Time series, at suitable spatial and temporal granularity, should be made available to investment planners in respect of power available from wind and solar generation in such a way as to adequately represent temporal and spatial correlations. Distribution planners should have access to suitable demand time series and patterns of operation of embedded generation. Transmission planners already have access to time series of net demand but should also have access to data describing the behaviour of embedded generation.
- Of particular importance for transmission planners is access to adequate models of generators and HVDC converters including correct control system parameters; this access should be improved and the models made available within standard analysis packages.
- Network utilities at both transmission and distribution levels should invest more in the collection of asset reliability data and its processing not only for asset management but also for system reliability assessments. This is particularly important for new types of asset and for equipment involved in facilitating corrective actions.
- In future, distribution asset data should be maintained in such a way as to make the construction of system models more convenient. The business case for conversion of legacy data sources into more efficiently manageable forms should be explored.
- The characteristics of loads with respect to dependency on voltage and system frequency should be assessed and made available to network planners and operators.
- The main parameters of the GB transmission network are already available to independent researchers. The main parameters of distribution should be equally easily accessible. The main parameters of transmission connected generators and HVDC converters should also be made available to independent researchers but, in order that sensitivities around commercial confidentiality are respected, cost data withheld except in respect of outturns of final outputs and accepted bids and offers from GB balancing mechanism at a unit level and other outturn data necessary to inform ancillary service markets.

The provision of new methods and tools:

- Analysis tools for such applications as load flow, short circuit analysis and stability assessment exist and are generally adequate. However, matching of data between different applications and different users is sometimes difficult and there can be significant problems with the implementation of models of new equipment, in particular wind farms and HVDC converters.
- Methods and tools used in distribution planning are generally unsophisticated and have changed little in many years. Established methods are not yet evident in respect of voltage and reactive power and evaluation of curtailment of generation. However, a number of Low Carbon Networks Fund (LCNF) projects promise useful progress.
- Useful new methods and tools applicable at transmission levels have been developed in Britain and elsewhere that have many of the features that seem to be required to facilitate planning of the future power system against an uncertain background. However, they are either not yet sufficiently mature (in particular in respect of user interfaces and access to data) or the capability to use them has not been maintained.

- New and emerging power system challenges require development of new methods and tools.
- A better understanding of long-term influences on growth (or otherwise) of demand should be gained along with interactions with different energy systems such as those for gas, heat and transport.
- Work should be undertaken to articulate an appropriate trade-off between model simplification, precision and the burden of managing large volumes of data and computational complexity.
- Improved methods for identifying bad data in respect of historic distribution network performance and using the cleaned data to inform planning should be further developed and then adopted.
- In addition to what is emerging from some LCNF projects, further work should address ways of dealing, with confidence, with lack of observability on distribution networks and allowing planners to make reasonable assumptions.
- Understandable and effective methods should be developed for planners to evaluate real-time thermal ratings and flexible demand.
- Understandable and effective methods should be developed for distribution planners to evaluate storage, curtailment of generation and voltage issues and potential solutions.
- Different data sources should be better integrated and maintained and new tools developed for the efficient formation of models and operational scenarios to allow the operational implications of planning decisions to be evaluated, including in respect of automated responses, real-time ratings, re-scheduling of flexible demand, HVDC and phase shifting transformers.
- Tools should be developed to allow the more efficient processing of applications by small generators to connect to the distribution network.
- Effort should be invested in development of Monte Carlo tools capable of dealing, in a convenient way, with variations in generation and demand and planned outages as well as unplanned disturbances.
- Aids to the interpretation of power system analysis results should be developed and made available to investment planners.

Decision making frameworks:

- Progress has been made in recent years in respect of evaluation of options for transmission development under uncertainty and new technologies are being deployed. However, some approaches, such as system to generator inter-trips, are precluded in investment planning timescales, guidance is scant on the management of ‘complexity’, the facilitation of planned outages is not always clearly addressed in respect of the main interconnected system and methods for assessment of risk of major interruptions have not yet been widely established.
- Approaches at a distribution level for decision making under uncertainty and the evaluation of options for active network management are quite immature.
- Access to current industry standards should be made easier by applying the example of publication of the Security and Quality of Supply Standard (SQSS) and Grid Code on the web also to distribution standards including ER P2/6, ER G59/3 and ER G83/2 thus enabling contributions to discussion of appropriate revision of standards to better facilitate the future power system in customer’s best interests.

- A framework should be developed that allows a more explicit quantification and use of 'risk', i.e. the impact of different uncertainties including reliability of service to network users, as an informer of investment planning.
- Acceptable levels of risk should be defined and, where necessary, standards revised to drive action to satisfy those levels.
- Different methods should be evaluated for using risk to make decisions.

Provision of adequate skills and expertise:

- There has been understandable pressure on network utilities to reduce 'headcount' and dependency on specialists.
- There is increased pressure on DNOs in respect of processing of generation connection applications.
- The development and retention of power systems expertise and specialists in the methods and tools associated with planning the future power system are crucial to realising the benefits of new approaches to operating the system and new technologies employed on it.
- Investment planners and their superiors should develop their understanding of the nature of 'risk' and its analysis. This should include an understanding of average outcomes, e.g. in respect of reliability of supply over a period of time, and rare events that may cause major loss of supply, and will depend on some familiarity with basic statistics.
- A sufficient pool of power systems experts should be maintained within a network utility capable of assessing new technologies, verifying the appropriateness of models, writing equipment specifications and evaluating system behaviours not seen before.
- An understanding of methods for decision making under uncertainty should be developed.
- Utilities, not only consultancies, manufacturers and research institutes, should commit to the development of staff such that they can understand and make full use of new analysis methods and tools.
- A commitment should be made to the retention of skills and knowledge within universities in order that education of future power engineers can be achieved and research carried out to inform the industry on emerging risks and opportunities in the planning and operation of power systems. Funding of universities by industry should not be entirely dependent on specific 'innovation projects' but should contribute to the underpinning of capability and the ability to inform regarding future opportunities and threats.

Paper Six: Emerging Modelling Capabilities for System Operations

[6] introduces this key topic of modelling in support of system operations as follows:

The current modelling tools used by transmission system operators have been designed for an era characterised by conventional generation technologies, high predictability of generation and demand patterns and a limited number of control actions to be determined and executed close to real-time. The traditional security provision philosophy has been to adopt a preventive stance and rely on preventive measures with security of supplied being delivered through redundancy in assets rather than through real-time control actions. In a similar vein, operation of distribution networks has been based around one-way flows and a limited scope for resource optimization and control, except post-fault network restoration.

Furthermore, the integration between transmission and distribution network operation has been very limited thus far.

However, the transition to a low-carbon economy is rapidly changing the reality of electricity system operation in GB. In the light of increasing penetration of renewable energy sources at the transmission and distribution level, together with expected de-carbonisation of transport and heat sector demands, the traditional operational doctrines are becoming out-dated; security through asset redundancy will have to give way to smart operational approaches and achieve higher degree of service quality at lower costs.

Along with the challenges that arise in contemporary electricity system operation, new opportunities are enabled by novel technologies. Devices such as Phase-Shifting Transformers (PSTs), Flexible AC Transmission Systems (FACTS), System Protection Schemes (SPS) and HVDC grids promise to increase operational flexibility through corrective security provision. Furthermore, the large-scale deployment of Phase Measurement Units (PMUs) along with the introduction of a pan-European common information exchange standard will enable System Operators to have improved visibility over their network. The introduction of novel concepts such as Virtual Power Plants (VPPs) promises to further integrate electricity operation across the transmission and distribution boundary, further enhancing the value of controllability of distributed energy sources. The above create a significant opportunity for a paradigm shift in system operation to make full use of real-time measurements, advanced pre and post fault control in order to maximise cost effectiveness and security performance of the system while making of use of emerging flexible technologies.

The use of appropriate modelling tools is at the core of this transition and will be an essential pre-requisite for effectively navigating the new landscape of system operation. However, the existing modelling capability is lacking in a number of key aspects. Intense effort has to be directed towards developing tools to increase network visibility by making use of new data streams that are starting to become available. Furthermore, it is imperative to move beyond deterministic models towards tools that optimise operational decisions such as system balancing and allocation of ancillary services on the basis of the uncertainty present in the system. The scope of these tools should be extended to consider all control actions that are being added to operators' arsenal, such as the possibility to provide corrective post-fault control through FACTS, the ability to shift demand etc. In addition, such actions would need to be abstracted in such a way to maximize their effective contribution and controllability from a whole-system perspective and be considered on a probabilistic basis to account for non-delivery events. Also, in order to hedge the system against the range of disturbances, it is becoming important for operators to consider multiple timeframes, from micro-seconds to hours. In the longer term, the shift from centralised to distributed operation model will open new opportunities for enhancing cost effectiveness and security performance of future electricity system.

[6] identifies and develops the case for the developing new modelling capabilities in the following areas:

1. Enhancing the Whole-system Visibility and Predictability:

- Supporting Coordinated Control of Distribution and Transmission Network through Enhanced Measurements and Advanced State Estimation
- Informing Relevant System Operation Scenarios from Historical Data

2. Optimising Short term Operation of the System Under Uncertainty

- Stochastic Generation Scheduling
- Security-Constrained Dispatch Models
- Modelling of Corrective Security
- Multi-time Scale Modelling
- Defence Plans and System Restoration Models

3. Modelling Requirements for Decentralised System Operation

- Modelling of Operation of Future Distribution Networks
- Modelling Requirements for fully Autonomic Power Systems

[6] summarises the four main trends towards operational modelling as:

- The shift of operational doctrine from empirical practices based on comfortable security margins and drawn a priori for generic states of the system to the development of operational platforms capable of providing bespoke recommendations tailored to the real-time operating point and the envisaged short-term uncertainty.
- Further integration between the transmission and distribution systems so as to make optimal use of all energy and flexibility resources and network assets available across all voltage levels; upstream and downstream systems are not treated as passive elements, but proper interfaces are established in order to reach global optimality.
- Operational models that take advantage of all available control choices on the basis of cost efficiency and adequate security.
- The shift from centralised to more decentralised operation paradigm will open new opportunities for enhancing cost effectiveness and security performance of future electricity system. In stark contrast to the present network control standard, control algorithms deployed within this concept will be meeting dynamically changing objectives while the network topology, network conditions and control infrastructure are also changing.

[6] concludes:

A number of modelling developments are needed for this vision to materialize in the coming decade. First of all, system operators must increase visibility to their networks by making appropriate use of new data streams becoming available through the deployment of PMU and smart-metering devices along with state estimation techniques. This data will not only be useful in informing real-time operational decisions but can also serve in characterizing the different uncertainty sources at a high temporal and spatial resolution. Furthermore, models will need to be synthesized to represent distribution-embedded resources and novel demand-side management schemes rendering them controllable from a systems viewpoint. The combination of the above can lead to the development of holistic stochastic optimization models that can operate on a rolling multi-horizon basis along with recommendations for preventive and corrective actions to secure the system against all credible disturbances. To this end, recent advances in the fields of mathematical programming, statistics, machine learning, agent based modelling and power system simulation will need to be leveraged to construct such novel modelling tools and propel GB system operation to the smart grid era.

Paper Seven: Modelling and Software Platforms for Extensive Power System Studies of Distribution Networks with Low Carbon Technologies and Smart Solutions

[7] describes the modelling activities being undertaken in the Smart Grid Forum (SGF) Workstream 7 (WS7) study of the Distribution System in 2030 (DS2030). This project will develop and demonstrate modelling approaches and provide valuable indicators to types of modelling, models and data required to plan and operate the distribution system for the year 2030.

Some of the developments that distribution networks will be subject to will have whole system implications and Levi notes the following:

- Whole system balancing and frequency response is a crucial element for deciding whether distribution network owners (DNOs) could become distribution system operators (DSOs). The NG reduced transmission network will be used for this purpose and DNO equivalent demands will be replaced with several new objects: equivalent distributed generator (DG) with frequency response characteristics, demand side management (DSM) load which can be curtailed, demand side response (DSR) load which might contribute to load reduction (stochastic in nature) and an unmanaged load.
- Impact of the large scale penetration of distributed generation (DG), such as solar and wind, connected at different voltage levels, on the thermal capacities, voltage – reactive powers and stability of the transmission network. Of particular interest are winter peak regimes when spare transmission capacities can be created, as well as summer minimum regimes whereby already present excessive transmission voltages can be further increased.
- Impact of new demands, such as, electric vehicles (EVs) and heat pumps (HPs) on the transmission network. Different EV charging patterns and profiles will be modelled at the 11(6.6)kV and 0.4kV voltage levels and new annual half-hourly load profiles will be suggested. The impact of air- and ground-source pumps will be assessed in a similar way.
- Impact of energy storage, DSM and DSR will be further investigated at all distribution voltage levels.

It is noted that new modelling approaches, processes, models and data will be required to properly address these developments. The WS7 DS2030 project is tasked with conducting modelling to address these future requirements and that will likely deliver some strong pointers on the existing modelling capability and then what would be required to fully address the new challenge sin distribution networks. The DS2030 project will examine new capabilities required under any transition from DNO to DSO and some of the new modelling capabilities for distribution currently conducted for transmission networks could be required in distribution networks in future, for example:

- Sequential power flow analysis, optimal power flow.
- Dealing with substantial volumes of active generation units, demands, customers, etc.
- Data on DG dynamics is not routinely gathered so this poses a challenge to modelling.
- Contingency analysis to cope with more complex running arrangements and the use of preventive and corrective controls to resolve issues in operational time frames.
- Distribution System Operator requirements to schedule, contract ancillary services efficiently, manage interface with active customers and the transmission system.
- Managed (public) access to data and analysis and the use of Geographical Information Systems (GIS) to aid this.

[7] concludes as follows:

1. Future DNOs will need to do the whole suite of power system studies, namely sequential load flow, optimum power flow, fault/short-circuit analysis, frequency response and balancing, reliability analysis, dynamics simulations, harmonic/power quality analysis and protection study. Some of the studies will be done for development and operations planning, some within (extended) real-time control. Both planning and control staff will need to be trained to fulfil new commitments.
2. Identified modelling and data gaps in load flow studies are: sequential load flow will be required to study annual demand and generation profiles obtained from the DMS; new functions, such as network reconfiguration & restoration, optimum power flow with ‘adequate’ objective function and multi-stage models are required; development of new LCT models, such as EVs, HPs, energy storage and DSM/DSR is required; low-voltage networks should be studied within GIS.
3. Identified modelling and data gaps in fault/short-circuit study are: calculation method shall be compliant with the UK legislation; models of new LCT components, such as energy storage, EVs and DSM-DSR motor contribution shall be developed; fault levels of converter connected generators and motor fault contribution of general loads need to be established; low-voltage networks should be studied within GIS.
4. Identified modelling and data gaps in frequency response and whole system balancing studies are: several component models required for quasi steady-state balancing need to be developed; dynamic models of EVs, HPs, energy storage, converter connected generators and under-frequency load shedding are required; different control concepts are missing.
5. Identified modelling and data gaps in reliability study are: currently available reliability calculation engines seem inadequate, a Monte Carlo based simulation method shall be developed; reliability of communication, automation and protection systems shall be integrated within reliability analysis; there is no reliability modelling for equipment approaching its end-of-life; currently used reliability indices may be inadequate.
6. Identified modelling and data gaps in dynamics study are: DNOs do not have dynamic models of various controls and do not do transients studies; dynamic models of new LCTs and some of ‘smart’ solutions are not available; angle, voltage stability and electromagnetic studies shall be addressed in greater detail.
7. Identified modelling and data gaps in harmonic/power quality study are: there is no data on background harmonic injections and harmonic injections of new LCTs and some of ‘smart’ solutions; approach to determining the network of interest to be studied needs to be developed.

The following recommendations are made:

1. DNOs should establish internal processes to gather various types of modelling data which are required for both steady-state and dynamic studies. New steady-state modelling data are required for LCTs and some of ‘smart’ network solutions, whilst dynamic modelling data are needed for existing and new control devices because DNOs will need to start doing dynamic analyses. Particular attention should be paid to the data required for frequency response and whole system balancing studies. All required data should be obtained from developers (new connections), equipment manufacturers and other relevant third parties.

2. DNOs should critically assess currently used software platforms for power system analyses. It is recommended to use a single platform for 132kV, 33kV, 11kV and 6.6kV networks. Where the network model is of ‘huge’ size, 11kV and 6.6kV network model can be stored separately. It is also recommended to use ‘smart’ GIS for planning studies of low-voltage (i.e. 0.4kV) networks, with the essential power system analysis functions built in. Real-time measurements available in control room DMS should be made accessible to the selected software platform, because future analyses cannot be based on representative operating regimes. In that respect, DNOs need to be encouraged to invest into measuring and tele-communicating data from the network, and in particular from distribution substations 11/0.4kV and 6.6/0.4kV.
3. The selected software functionality should be critically assessed in light of future power system components (e.g. LCTs and ‘smart’ solutions) and operational requirements. It is recommended to consider development of new multi-stage load flow and OPF models, OPF models with voltage-reactive power objective functions and/or security constraints, new network equivalencing models for steady-state and dynamic studies, distribution network reconfiguration and restoration models for 11kV and 6.6kV voltage levels, new reliability analysis model possibly based on sequential Monte Carlo simulation and a new steady-state voltage stability tool.
4. DNOs should participate in the whole system restoration following system emergencies. This applies above all to frequency response, (spinning) reserve and voltage-reactive power services (note that a new ‘inertia service’ may be introduced shortly). The hierarchical control principles between NG and DNOs control centres need to be established first, which should be followed by detailed specification of technical and commercial data that need to be exchanged on a regular basis. It is envisaged that the data exchange will be required for short-term operations planning and (extended) real-time control.
5. Development of models of new network components, such as EVs, HPs, different types of storage, different types of DSM and DSR, under-frequency & under-voltage load shedding, etc. is required. Reliability models of communication, automation and protection systems need to be developed and integrated into the power system reliability module.

The paper also highlights the following issues for modelling campaigns across modelling platforms:

- Unification of diverse modelling platforms: with so many modelling challenges and requirements there is a need to invest in coordination and unification of modelling capabilities (platforms, models, data, etc.).
- Models and data can be translated across platforms and shared by different users in different organisations but the task is time and skill intensive so streamlining this is an important future objective.

Paper Eight: Emerging Capability on Power System Modelling: System Security, Resilience and Recovery Modelling

[8] highlights that one of the major current system operation challenges is to develop robust recovery strategies to bring the power system back to normal status in case of large disturbances. The problem of bulk power system recovery following a complete or partial collapse has always existed and electricity industry companies have developed methods, tools and procedures to cope with the system recovery issues. However, it is necessary to review the existing methods, tools and procedures and understand the challenges ahead and hence it is absolutely useful to understand the gaps for the development of new recovery methods and tools under the new environments with massive distributed energy sources and smart grid controls.

[8] provides a succinct overview of the topic and the initiatives on defence plans and system restoration procedures in the major interconnected system by ENTSO-E (Europe), the US, Brazil and in China for comparison.

The analytical and modelling tools used to support system restoration are:

- Power Flow (PF) Program: Sustained overvoltage control; Reactive power balance; Line and transformer thermal limits.
- Transient Stability (TS) Program: Subsystem stability; Under-frequency load shedding; Low frequency isolation scheme; Intentional islanding.
- Long-Term Dynamic (LD) Program: Frequency response of prime movers; Response reserve; Load frequency control.
- Voltage Transient (VT) Program: switching surges; Insulation coordination.
- Short Circuit (SC) Program: Minimum source currents; Breaker interruption ratings; Relay coordination.
- Electromagnetic Transient Program (EMTP): Insulation coordination and switching surge; Harmonic resonance and ferro-resonance, SSR, and Magnetizing transformer inrush over-voltages.
- Standing Phase Angle (SPA) Program.
- Cold Load Pickup (CL) Program: Heuristic approach; Physical modelling.
- Restoration Coordination Program (CPM): Allocation of resources; Scheduling of restoration tasks; Estimation of restoration duration; Evaluation of restoration process.

These modelling tools and the underlying capabilities will need to address HVDC, FACTS, Demand Response, Energy Storage, Electric Vehicles and Phasor Measurement Units. [8] makes the case for the development and use of highly sophisticated modelling tools and presents the following conclusions:

1. Current simulation tools for system recovery largely rely on power flow algorithms or extended power flow algorithms (simplified stability simulation algorithms), which are neither adequate nor versatile.
2. Current power grid modelling and simulation efforts are often piecemeal, usually focusing on a narrow set of issues. The recent report by the IET has indicated that we will need to address the broader issues; the scope of such modelling and simulation efforts has yet to address national concerns.

Recommendations are presented as follows:

Near term objectives (next 1-3 years)

1. Development of real-time simulators for 10,000-bus system of RMS type phenomena and 1000-bus system of EMT type phenomena.
2. The system would provide, for instance, a high-fidelity simulation environment for testing new models and evaluating the grid system's performance.
3. Identification of risk scenarios such as automatic control system failure and loss of communications, cyber security attacks, etc.
4. Investigation of smart recovery strategies using distributed resources such as EVs and Energy Storage, and the impacts of heat pumps on the system recovery.
5. Dynamic power islands with distribute resources, smart controls and energy storage.

Mid-term objectives (next 3-5 years)

1. The simulator should have very powerful interfacing capabilities to support wide area measurement based applications, power electronic applications including FACTS and other power electronic converters and complex protection systems.
2. The simulator should provide full featured simulation capability over different phenomena as shown in Figure 2.
3. The system would provide functionalities of market operations.

Long-term objectives (next 5-8 years)

1. A whole energy system with real-time simulation capability: A next generation national power grid simulator should focus on UK electric power grid modelling and simulation in the contexts of whole energy system approach, which will have connections with other critical infrastructures, such as transportation, oil and natural gas, water supply, and communications.
2. The system would provide functionalities of market operations.
3. Such a capability would provide a simulation framework and suite of integrated simulation tools to support needs for security, reliability, and resiliency as well as market operations of the UK national power grids.
4. The simulator should provide the opportunities to understand the operating challenges otherwise these would not be recognised easily.

Paper Nine: Modelling Requirements for Low Carbon Electricity Systems: New Robust Models of Demand, Generation, Energy Storage and Demand Side Management in Static and Dynamic Studies

[9] provides an overview of the modelling gaps and challenges in relation to Low Carbon Technologies (LCT) with implications for the GB power system as follows:

- Demand and generation profiles will change due to electrification of transport (EVs) and heating (HPs) and connection of large amount of solar and wind generation. It is envisaged that variation of demand and generation is going to be significantly faster in future, and the GB power system will become substantially more dynamic.
- The power system stability and security will be adversely affected by new types of load and large proportion of intermittent generation. Furthermore, reliability of new ‘smart’ solutions is still unknown and it can further aggravate system stability and security. Here, reliability of software, communication and automation systems will play vital role.
- Operation of the electricity network will have to change in order to cope with the new LCTs and ‘smart’ solutions. System control engineers will have to cope with the substantially increased burden of system balancing under rapidly changing operating conditions.
- Processing of smart meter data in (near) real-time will further increase burden in control centres. Real-time and short-term operational procedures that make use of smart meter data will need to be developed taking into account realistic capabilities of control centres.
- The future permissible generation mixes will have to be carefully established on a locational basis using operational planning principles and system constraints. It is likely that generation constraining in both operation and planning/connection will happen.
- Amounts of the frequency response, emergency spinning and non-spinning reserve will have to be recalculated using new methods which can take into account high intermittency of wind and solar sources. The higher the intermittency of generation, the more reserve is needed.
- Low system inertia will become reality following connection of large amounts of fully converted generation, HVDC connected off-shore wind-farms and HVDC interconnections. It will be dealt with by very fast converter connected generation and/or storage and fast load shedding. The rate-of-change-of-frequency settings on generation protection will need to be changed.
- The conventional ‘critical’ operating regimes used in system planning are likely to change due to changed load and generation profiles. More specifically, sequential planning studies will need to be performed in future. For example, excessive voltages are already experienced on the transmission network during summer low-load conditions and adequate controls are needed to reduce them.
- DNOs will be faced with distribution systems of ‘transmission type’. They will have to cope with new technologies with shorter time constants, larger amounts of data that need to be processed in (near) real time and in planning stages, new software platforms and tools, etc. An example is new voltage control schemes, which will need to be developed and installed on DNO networks.
- DNOs will need to take part in system balancing, at least during system emergencies. In that respect, hierarchical control principles between National Grid and DNOs will need to be established and corresponding data exchanges initiated.

- ‘Appropriate’ market framework will need to be developed to allow the development of a more integrated system. For example, ‘low inertia auxiliary service’ can be introduced independently from the frequency response service. Participation of DNOs in different markets also needs to be developed.
- New ‘smart’ solutions can distort the existing auxiliary service markets. For example, large-scale compressed air storage could drive out of business existing pumped hydro storage.
- Developing the analytical base is one of key challenges.

[9] concludes with a summary of the identified gaps in modelling capabilities for LCT:

1. **Electric Vehicles:** there are neither dynamic models of EV batteries, nor dynamic models of frequency response of EV charging, nor aggregated dynamic models. Steady-state models based on EV battery (I-V) characteristics do not exist, and there are no hourly load profiles for different charging regimes. Data on harmonic current injections of EV loads and reliability data are not available.
2. **Heat Pumps:** there are neither full thermo-dynamic models of different HP types, nor reduced dynamic models in which thermal processes are simplified. Aggregated models of several HPs and dynamic frequency response models accounting for thermal processes are also missing. The steady-state hourly profiles of HPs need to be developed and applied in sequential studies. Data on harmonic current injections and reliability data are not available.
3. **Demand side management and response:** there are neither dynamic models of DSM/DSR, nor frequency response models associated with DSR/DSM. The full and/or aggregated load and DSM/DSR models should have a frequency response module. Furthermore, steady-state hourly profiles of DSM/DSR taking into account load recovery need to be developed.
4. **Solar Generation:** dynamic models of solar generation in the form of equivalent circuits, whose voltage/current sources are dependent on non-electric parameters, do not exist in power system analysis tools. Similarly, there are neither models for ‘cloud transients’, nor dynamic frequency response models, nor methods for calculating solar fault contribution. Existing reliability methods cannot adequately model solar generation. Data on harmonic current injections and reliability data are not available.
5. **Wind Generation:** the existing dynamic models make use of simplified aerodynamic and mechanical sub-systems. Dynamic models of fully converted machines are not available; there are neither frequency control blocks (e.g. ‘synthetic inertia’ models) in the software tools. Fault level contribution of ‘static’ wind generators needs to be established. Currently available reliability engines are not capable of adequate wind-farm modelling. Data on harmonic current injections and reliability data are not available.
6. **Energy Storage:** identified gaps are discussed by storage types:-
    a. **Compressed Air Storage:** there are no dynamic models that take into account thermo-dynamic properties of the system. Models for frequency control are neither available. Similarly, steady-state models with thermo-dynamic parameters, as well as load and generation profiles are not available. Currently available reliability engines cannot model thermodynamic cycle of these systems.

b. **Pumped Hydro Storage:** there are neither dynamic models of pumped storage hydro plants, nor of its components, such as water reservoir, water tunnel with penstock and hydro turbine. Similarly, there are no 'hydraulic' frequency control blocks in the software tools. Adequate steady-state models for sequential analysis by hourly intervals do not exist. Existing reliability methods cannot adequately model plants with hydro storage, nor pumped hydro storage.

c. **Flywheel Storage:** there are no models of the frequency response characteristics. It is not clear whether steady-state models are required.

d. **Battery Storage:** there are neither dynamic models of different types of batteries, nor frequency response models of battery systems in the software tools. Steady-state models based on (I-V) characteristics and the state-of-charge are not available; the corresponding hourly profiles need to be developed for sequential studies. Data on harmonic current injections and reliability data are not available.

e. **Super-capacitor Storage:** dynamic models considering frequency response during emergency operating regimes are not available. There are no data on harmonic current injections of super-capacitor storage systems.

f. **Superconducting Magnetic Energy Storage:** frequency control models are not available. There are no data on harmonic current injections.

[9] makes the following recommendations:

1. Development of dynamic and steady-state models of new network components, such as EVs, HPs, solar and wind generation, under-frequency and under-voltage load shedding, as well as different types of storage and DSM & DSR is required. Reliability models of new components together with communication, automation and software systems need to be developed and integrated within the new power system reliability engine.

2. Some of the models will have to be developed outside the power system analysis tools using the 'in-house' approach. Coordination of the model development among DNOs, National Grid and other relevant parties (e.g. academia and software providers) is of prime importance. A common database of these models should be established, so that DNOs and National Grid can share the models and avoid unnecessary development costs.

3. It is likely that 'scripts' associated with currently used software tools will have to be developed to perform certain types of studies (e.g. sequential analyses). A common database of scripts should be established, and that scripts shared between DNOs and National Grid.

4. New models will have to be populated with real-life data. DNOs and National Grid should establish internal processes to gather and store various types of modelling data, which are currently missing. All required data shall be obtained from developers (new connections), equipment manufacturers and other relevant, third parties.

5. The new models will be applied within the whole suite of power system studies, namely sequential load flow, optimum power flow, fault/short-circuit analysis, dynamics simulations, frequency response and balancing, reliability analysis, harmonic/power quality analysis and protection study.

6. New functionality of power system analysis tools will be required in future. Some of the envisaged new functions are multi-stage load flow, optimum power flow with 'appropriate' objective function and/or security constraints, new network equivalencing models for steady-state and dynamic studies, distribution network reconfiguration and restoration functions and new reliability analysis model based on sequential Monte Carlo simulation.
7. Both DNOs and National Grid should go for a common software platform that will have desired functionality and models of new components. Unification of diverse power system analysis tools among DNOs is of prime importance.
8. The existing staff will need to be trained to perform new studies with new component models; however, it is likely that DNOs and National Grid will have to employ new, 'properly educated' generation of young engineers. In that respect, GB academia shall provide adequate education of students in power engineering. Specialised courses, delivered by academia and consultants, will be highly appreciated.

Paper Ten: Electrical Models of New Network Technologies and Devices including Power Electronics and supporting ICT Infrastructure

[10] introduces the issues for modelling power electronics in power systems as follows:

There are substantial fundamental differences between the characteristics of the electro-mechanical machines at the heart of a conventional power system and new technologies such as power electronic power converters and digital communication systems. The main differences concern the time-horizons over which the defining characteristics emerge but also in the dependence on control loops rather than physical parameters as the dominant features and in the discrete time nature of the systems.

For steady-state and time-series sequential application of steady-state models, there are few difficulties. Challenges arise in modelling fast dynamic effects for various forms of stability and protection studies.

There are challenges in system-of-system and disparate time-step modelling but these are not insurmountable. Detailed models based on underlying physics for checking performance in time domain are mostly in place. Main issue, and it is large, is whether convergence and agreement on control systems will be achieved between vendors and whether data to tune models/controllers will be available. The comparison is with, say exciters for synchronous generators where the various types have been classified and typical ranges for time-constants and gains are known. There needs to be a major sector-wide and international effort to ensure that this is done for new technologies. Although raised here for transient (time-step) and steady-state models, this is a pervasive point.

A notable feature of modelling synchronous generators is that there is wide-spread (and well-founded) agreement on when the dynamics of various elements (damper windings, shaft compliance, exciter, PSS, governor) can be ignored as being too-fast or too-slow to be relevant to a particular type of study. We do not have that maturity of view for small-scale inverter interfaces or communication systems and arguably not for VSC HVDC. Possibly that is now in place for wind turbines, if not for aggregate wind farm models.

For the specific analysis of stability and protection there are some outstanding issues for power electronic model. For small-signal stability study, linearization of a complex and strongly non-linear physical system can be problematic and emerging power converter circuits take time to appear in commercial software in an appropriate form. There is also a lack of consensus on what level of detail or model order is appropriate. In large-signal studies (post fault recovery etc.) there is a strong dependence on the control structure and signal-limit functions used by each vendor and a need to agree on standard ways to represent behaviour. In turn, the large-signal models need to be reduced to simple source-plus-impedance models for inclusion in fault flow algorithms. This is an immature topic and bedevilled by variation in control approach between vendors.

Even when the stability models of individual power electronic devices are settled there is still an issue of how to form aggregate models for use in large system studies, which with exception of perhaps wind turbines, is not well covered.

Power electronics is always a concern in the analysis of harmonics although not always for the right reasons. There is a large variety of harmonics emissions from nominally similar equipment and this makes forming aggregate models difficult. There is also an under-researched topic of the response of power electronic loads and sources to distorted voltage (which can range from damping to anti-damping). For power electronic equipment, low-order harmonics are not the only, or even primary, concern. Current emissions in the kilohertz range are hard to assess both in terms of aggregate levels and impact on other equipment.

The application areas for power electronics are presented by [10] as follows:

- Wind Turbine Generation Interfaces
- DER Interfaces and Micro-grids
- HVDC
- FACTS
- Distribution FACTS
- Loads

[10] illustrates and describes the modelling challenge for power electronics in power systems with reference to the classifications of types of HVDC models for power electronic devices in Table 4. While this is relevant to HVDC it highlights the modelling challenge for power electronics that is replicated across the application areas listed above.

Type of model	Description	Simulation Tools
1 - Full Physics Based Models	Switches are represented by differential equations	Not suitable for grid models
2 - Full Detailed Models	Switches are modelled by a nonlinear resistor	EMT
3 – Detailed Model	Switches represented by two-value resistors	EMT – faster than type 2 but loss of switching details
4 - Detailed Equivalent Circuit Models	Use Thevenin/Norton equivalent to reduce the number of nodes	EMT – faster than type 3 but loss of device details
5 - Average Value Models (AVM) based on switching functions	AC and DC sides modelled as controlled current and voltage sources with harmonic content	EMT – faster than type 4 but loss of sub-system details
6 - Simplified Average Value Models	AC and DC sides modelled as ideal controlled current and voltage sources	EMT and phasor-domain – much faster but loss of converter internal details
7 - RMS Load-Flow Models	Load flow models will use steady-state converter outputs	Load flow – no transient details

Table 4: Classification of the types of Modular Multilevel Converter (MMC) models.

In addition, the different FACTS applications and devices are detailed in Table 5 which illustrates a variety of device types and applications and the challenge for network operators in integration design, planning and operation of systems with FACTS.

Function	Non-FACTS solution	FACTS solution
Voltage Control	Generators Synchronous condensers Transformer tap-changer Shunt (series) Capacitor/Reactor	Static Var Compensator (SVC) Static Synchronous Compensator (STATCOM) Battery Energy Storage Systems (BESS)
Active/Reactive Power Flow Control	Generator Schedules Transmission line switching Series capacitor (switched/Fixed)	Thyristor controlled series compensator (TCSC) Static Synchronous Series Compensator (SSSC)
Transient Stability	Corrective Action (Special Protection Scheme) Braking Resistor	SVC, STATCOM, TCSC, BESS, SSSC
Dynamic Stability	Power System Stabilizer	SVC, STATCOM, TCSC, BESS, SSSC

Table 5: FACTS solutions.

A series of challenges for the integration of communications networks into power system planning, design and operation are explored by [10] with a clear message about this being an emerging area of challenge and solutions in power systems. The challenges highlighted are:

- Co- simulation: power/ communications networks
- Networked control, Information management and planning
- Reliability aspects and Cyber security
- Communication infrastructure evolution/networked control
- Monitoring and state estimation
- Co-design and co-simulation

The general conclusions in [10] are:

- While there is still much innovation in underlying power electronics technology some areas are relatively mature.
- Generally, models emerge quickly in academic literature but take time to become part of commercial suites, especially outside of time-step models.
- Black-Box models are difficult to trust.
- Techniques to handle disparate time-steps are known but there is a penalty in complexity, convergence and computation time in modelling with comprehensive bottom up models.
- Vendor specific and commercially secret control details.
- Tuning and data difficulties are present even when the form of control is known.
- Reducing order of models systematically with confidence.
- Aggregate models need development and validation.
- Fault modelling is immature.
- Standardisation, verification, acceptance.

Paper Eleven: Emerging Capability on Power System Modelling: HVDC Systems

[11] provides an overview of the two main HVDC technologies: Line Commutated Converters (LCC) and Voltage Source Converters (VSC) and the modelling required to analyse their role and impact in power systems. The merits of desktop simulation, transient network analysers and real time digital simulation environments for modelling and analysing HVDC systems is discussed with the following conclusions:

1. Benchmark EMT models for HVDC: It is highly recommended that benchmark models for HVDC systems including the emerging MMC HVDC Grid should be developed. The models being used in different simulation tools should be harmonised. The models for HVDC with different levels of details should be compared and then general guidelines should be given on how to use these models. In addition, the interoperability of a multiple terminal MMC HVDC grid will need to be considered in the modelling of the DC grid in the situation of multi-vendor multiple terminal DC grid. It is desirable to set up multiple terminal MMC HVDC grid test systems as a benchmark to understand the basic characteristics of DC grid, validate control and protection algorithms, develop new control strategies, etc.

2. Standardised simulation scenarios: There is a lack of standards and consistent simulation scenarios that can be conducted at different stages such as equipment design, network design, and system operational planning where different levels of risks from failure of a single component to complete shut-down of the HVDC system.

3. HVDC control parameters: Satisfactory operating performance of MMC HVDC Grid relies on the well-designed control systems and associated parameters. As far as modelling is concerned, detailed model of MMC HVDC Grid and associated control parameters are extremely important. However, due to issues of confidentiality, manufacturers may not be able to provide requested detailed model parameters. This will in turn lead to difficulty in understanding the operating characteristics of the HVDC grid and affect the system performance being maximised. Suitable protocols should be established to ensure that all the essential DC Grid model and control parameters will be provided to system operators.

4. “Multi-Terminal Test Environment (MTTE) for HVDC Systems”: The facility “Multi-Terminal Test Environment (MTTE) for HVDC Systems” led by SSE in collaboration with National Grid and Scottish Power will house: a real-time simulator system (which simulates HVDC schemes), IT infrastructure and accommodation for replica HVDC control panels. In collaboration with suppliers, it is likely that the facility will be helpful to facilitate multi-vendor HVDC schemes and de-risk control interactions and hence maximise the benefits of utilisation of multiple terminal HVDC technologies.

5. High frequency small signal stability models: Normally for power system small signal stability analysis, network dynamics can be neglected if the frequency of interest is between 0.1 - 2 Hz. However, if the frequency of interest is higher than 5Hz, network dynamics cannot be neglected.

6. Large scale power system simulation with HVDC grid: In terms of the development of HVDC technologies, there is a big gap in terms of R&D in large scale power system simulation. With the advances in computing and electronic technologies, new large scale simulation technologies will need to be developed.

Paper Twelve: Future GB Power System Stability Challenges and Modelling Requirements

[12] addresses the issues of system stability and highlights the significant issues of system inertia, Distributed Generation, Series Compensation, AC-DC system interaction and maximum expected single infeed loss are the challenges to system stability.

The paper highlights the conventional view of power system stability replicated in Figure 2:

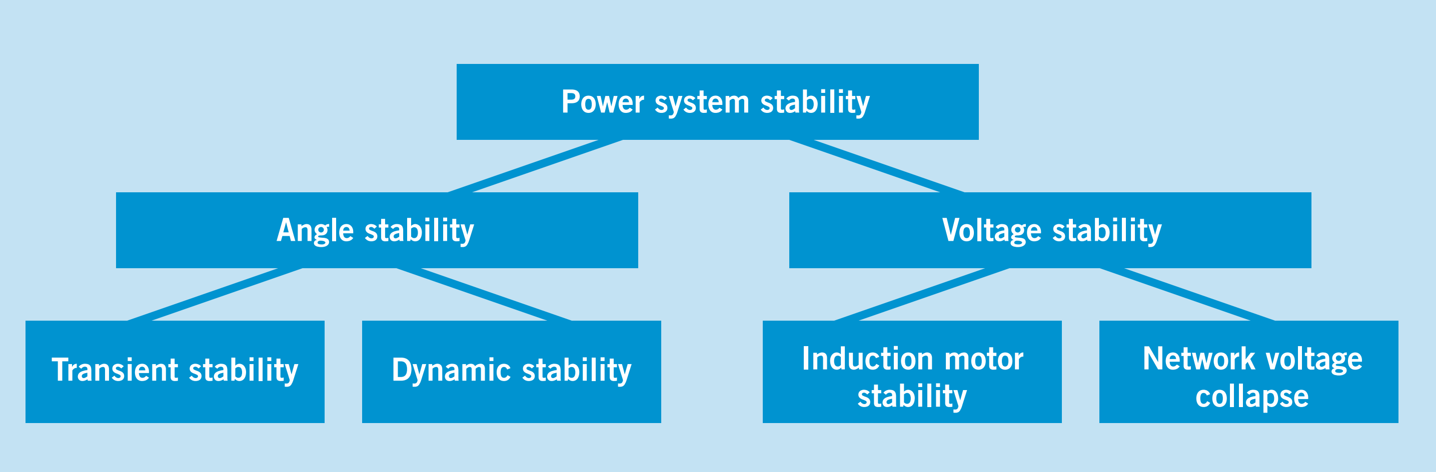

Figure 2: Conventional view of the power system stability problem.

The main areas of change to the GB power system are described in [12] as:

- Reduced system inertia. The increasing connection of converter connected generation plant (e.g. photovoltaic generation) will lead to reduced system inertia. Transient stability will be reduced and require faster clearing times of protection.
- Distributed generation (i.e. rotating generators connected to the distribution system). Much distributed generation is unlikely to be stable after network faults due to its low inertia and the long protection clearing times of distribution networks.
- Series compensation. The use of series capacitors on the transmission network increases the risk of sub-synchronous resonance.
- Interactions of AC/DC systems. Increasing numbers of DC links are being connected to GB. These international interconnectors (LCC or VSC) have important consequences for the stability of the GB AC power system.
- Increase in maximum single loss of power infeed. The increase of the maximum allowable loss of power in-feed from 1320 MW to 1800 MW will require significant additional of part loaded generators to be operated in order to maintain stability unless innovative solutions using DSR are used.

Recent technical developments offer ways to manage potential instability:

- Phasor Measurement Units allow greater visibility of the power system and particularly give early warning of small signal instability.
- ICT techniques to acquire and manage very large data sets are being used in other industries and offer the possibility of recording and subsequently analysing system events.
- Converter connected generators and interconnectors offer the possibility of using active control to increase stability.

The recommendations made in [12] are:

Although there is considerable academic research being undertaken on the stability of the “smart grid” much of it is not directly relevant to GB as much of the necessary machine data is confidential to the generating companies. A “quick win” would be to complete an agreed open access simplified GB dynamic model and ask UK researchers to test their ideas on that rather than IEEE models as is done at present. A regular annual day colloquium could be held of studies undertaken on the GB model.

Paper Thirteen: Modelling Requirements to Assess The Resilience of The Electricity System as it is Adapted to Deliver Low Carbon Transition: Dynamic Analysis of Systems with New Equipment, Devices, Control Approaches and Operating Modes

[13] provides an overview of recent initiatives to address the transient stability issues in power systems (both internationally and with a specific focus on GB):

- Transient stability assessments and control islanding schemes
- Data driven methods for electromechanical oscillations and voltage stability
- Estimation using real-time dynamic data
- Modelling of distributed generation for stability study
- WAMS and PMU monitoring data
- Modelling and simulation for system dynamics
- GB power systems/Analytical tools
- GB National Grid reports tackling future energy scenarios, wind energy development and the long-term development of the power system

[13] points out that in spite of this noticeable activity in modelling future network scenarios the software tools used are to a large extent conventional (PSCC, DIgSILENT/PowerFactory, EMTDC, IPASA, etc.) and the models used largely limited by capabilities of the software environments. The studies carried out are almost exclusively deterministic with very little attention paid to modelling uncertainties and the test systems used are generic test networks or simplified real network models.

[13] highlights the following modelling challenges that need to be addressed:

a. Modelling for steady state and dynamic (small disturbance and transient) studies for large interconnected networks with mixed generation, FACTS and short/long distance bulk power transfers using HVDC cables and series compensated AC lines operating in parallel.

b. Clusters of renewable energy systems and energy storage technologies either of the same or different type and considering the associated uncertainties. The uncertainties considered should include both temporal and spatial uncertainties. The latter are particularly important as hundreds if not thousands or hundreds of thousands of different devices may need to be represented.

c. Modelling of whole LV and MV distribution network cells with thousands of stochastic and intermittent RES which may exhibit temporal and spatial uncertainty.

d. Modelling of demand, including new types of energy efficient and Power Electronics controlled loads, customer participation and behavioural patterns, EV, etc. Demand modelling as generic term used here includes forecasting of demand response to network disturbances (not only forecasting of P and Q consumption), i.e., dynamic response of demand to both voltage and frequency disturbances.

e. Efficient use and reliance on global monitoring data (Wide Area Monitoring Systems - WAMS) for state estimation, dynamic equivalents and control (including, but not limited to, real time control).

f. Design of supplementary area controllers based on WAMS to control and stabilise large system (including but not limited to real-time) or parts (which may vary) of it with uncertain power transfers and load models and stochastically varying and intermittent generation and demand.

g. Design of hierarchical, adaptive control systems/structure for power networks with fully integrated sensing and ICT technologies. The consensus control, for example, may be an option considering potentially thousands of individual devices (including different generation, storage and load technologies) in the network and a number of existing or new local/area controllers.

h. Modelling/analysis of efficient and effective integration of different energy carriers into self-sufficient energy module/cell.

The recommendations presented for developing and deploying new modelling capabilities to address transient and stability issues to facilitate the smooth transition to efficient and secure operation of future power systems are:

- Modelling of new types of power electronics interfaced generation, demand, storage, transmission and communication technologies (renewables interfaces, HVDC, FACTS devices, power electronics interfaced loads, energy storage)
    - large interconnected networks with mixed generation, FACTS and short/long distance bulk power transfers using HVDC lines of different technologies
    - clusters of renewable energy systems (generation and storage) of the same or different type
    - static and dynamic aggregate models for different types of studies with clear specification of modelling requirements and bounded parameter values
    - LV and MV distribution network cells with thousands of renewable energy systems
    - Demand, including new types of energy efficient and PE controlled loads, customer participation and behavioural patterns, EV, etc.
- Increased reliance on global (WAMS) signals but also on global increase in network monitoring at all voltage levels, calling for:
    - advanced steady state and dynamic state estimation (observability of the network), dynamic equivalents at different time scales and application for control and stability considering associated spatial and temporal uncertainties
    - efficient data management (signal capture, processing, aggregation, transmission) and analysis (clustering and classification techniques for knowledge extraction)
    - ICT network reliability and interaction with power network
    - Increased penetration of power electronics

- Increased uncertainties in controlled plant (system) both in terms of model uncertainties and operational uncertainties, calling for:
    - robust, (self) adaptive control strategies and probabilistic plant modelling
    - probabilistic, risk based assessment of system operation both steady state and dynamic
    - assessment of system control/stability/power quality contribution by new types of generation/load/storage
    - design of supplementary controllers based on WAMS to control and stabilise large system (including but not limited to real-time) or parts of it (which may vary) with uncertain power transfers and load models and stochastically varying and intermittent generation, demand and storage – stochastic/probabilistic control
    - design of new control systems/structure (hierarchical, adaptive, close to real time) for power networks with fully integrated sensing, ICT technologies and protection systems – risk limiting control

The extent and the timeline of the activities addressing modelling requirements specified above will depend on the type of studies required (planning, operation, control, etc.) The key requirement is that in all cases as realistic as possible scenarios are used and that clear recommendations are given for different types of studies and different phenomena (faults, planning, angular and frequency stability, etc.) considered so that they can be transferred to industrial practice as soon as possible.

Paper Fourteen: Modelling Requirements for Least-Cost and Market-Driven Whole-System Analysis

[14] summarises the need for whole system analysis as follows:

Development of holistic modelling approaches of the whole electricity system chain (generation, transmission, distribution) across both operation and planning time horizons will be essential, as the historical, individual sector centric approaches are no longer sufficient to facilitate cost-effective operation and development of the system. The whole-electricity system modelling should consider all sectors concurrently as new technologies, such as demand side response or distributed storage will simultaneously impact distribution, transmission and generation sectors. In this context consideration of national level objectives will need to be included in modelling of operation and design of local distribution networks, which is in stark contrast with the established models currently used. Furthermore, given that substantial asset replacement will take place in the next 20 years, it will be important to replace the incremental, like-with-like network replacement approach, with a whole-system, strategic development paradigm, accounting for the impact of alternative emerging smart grid technologies.

Furthermore, a new generation of models is needed to understand responses of market participants to alternative future market designs and regulatory and commercial incentives, across all time scales from real time operation to long term investment. Significant changes in the commercial framework will be needed to support efficient operation and investment in the context of whole-electricity system paradigm. Given the growing requirement for flexibility, there is a need for new market modelling techniques to be developed, to optimally allocate available supply and demand side resources including network capacity, to ancillary services and energy markets, considering participation of both traditional and new players. The roll-out of smart metering is expected to enable millions of small-scale participants to participate in electricity markets and provide system management services. The traditional centralised operation paradigm will no longer be applicable and distributed coordination models will be therefore required to facilitate the interaction between all supply and demand side market participants, while considering simultaneously distribution and transmission network infrastructure constraints.

Finally, an integrated approach to electricity system modelling within the entire whole-energy system context is becoming essential given significant interactions between different sectors in achieving the national carbon reduction targets. A number of comprehensive multi-energy models (e.g. TIMES/MARKAL, MESSAGE and ESME) have been enhanced recently, although time and space resolution of these models may not be adequate for future low-carbon energy systems, in the context of capturing the phenomena in real-time operation and across different locations in energy networks. Key challenges in this respect are associated with the complexity of representing the multi-energy system with sufficient granularity, in order to capture the key phenomena and interactions across different time scales and energy infrastructure operation and design.

[14] highlights the requirement for modelling of future market and commercial arrangements to address the issues of integrated energy and ancillary services markets, realising the whole-system value of new technologies, gaining consistency between social welfare maximisation and market participant objectives and modelling of distributed market places that are expected to emerge. The need and available multi-energy system modelling platforms (e.g. MARKAL-TIMES, ESME, CGEN, MESSAGE) are put forward to tackle the growing interactions between the electricity, heat, transport, gas, hydrogen and water sectors, driven by low carbon agenda.

The conclusions presented in [14] are:

Meeting the economy-wide decarbonisation targets cost-efficiently requires a paradigm change in electricity system modelling, so that the analytical tools adopt a fully integrated approach in order to capture growing interactions across different industry sectors. Although several modelling platforms have emerged in the recent years that focus on integrated energy system analysis considering the impact of new technologies, a number of potential areas for future developments have been identified incorporating aspects such as uncertainty, location, chronology and distributed operation in least-cost whole-system models, more effort is required to develop models capable of investigating whether the market signals in a low-carbon economy will provide adequate incentives to deliver the necessary investments in DSR and energy storage technologies i.e. to support the cost-efficient transition to a low-carbon energy system.

Furthermore, novel modelling approaches are needed to establish whether the market arrangements and the related regulatory and commercial framework can provide sufficient incentives to the market participants in order to deliver the social welfare-maximising system operation and development in the low-carbon future. In this context, modelling of responses of network companies to different regulatory frameworks and incentive regimes is particularly underdeveloped. Changes in commercial and regulatory arrangements will be needed to adequately reward the value of new flexible technologies, which requires new whole-system models to be developed that are able to consider participation of both traditional and emerging new market participants, while optimally allocating network capacity between energy and ancillary services provision. Given the roll-out of smart meters, new models for simulating operation of fully decentralised energy and ancillary markets are needed to understand the ability of price based control to deliver energy efficiency and provide system management services. New modelling should deal with communication and computational scalability needed to achieve distributed coordination between market participants.

Traditional multi-energy models (TIMES/MARKAL, MESSAGE and ESME) do not use sufficiently refined spatial and temporal resolution required for future low-carbon energy systems. Further development in this area is therefore needed to extend chronological multi-energy models to include other vectors such as heat, hydrogen, mobility etc. Key challenges that need overcoming arise from the significant complexity of representing the multi-energy systems and interactions between different energy vectors.

Paper Fifteen: Power System Modelling Data: Requirements, Sources and Challenges

[15] addresses the issues of data for modelling and analysis of power systems. Table 6 presents the projects being led by National Grid exploring new sources of data and the accompanying focus on power system modelling for planning or operations purposes. There are already potentially valuable avenues of exploration to enhance the visibility and understanding of the power system by accessing data on demand and generation with implications for various power system stability issues and enhanced visibility.

Category	Title	Years	Modelling Data Sources
Modelling of Demand	Development of Dynamic Demand Models in DIgSILENT Power Factory	2014-2016	Dynamic demand models are being developed in DIgSILENT to represent the industrial load service. The project includes the investigation of feasibility, reliability and predictability
Modelling of Demand	Electricity Demand Archetype Model 2 (EDAM2)	2013-2014	Inclusion of industrial and commercial demand to extend EDAM1 model
Stability/ Modelling of Phasor Measurement Units	Developments in Protection and Control	2008-2011	Includes laboratory scenario testing against a system model and pilot deployment on the transmission systems in the UK and Ireland to track network stability issues
Stability / Modelling of Sub-synchronous Interactions	Investigation of Sub-Synchronous Between Wind Turbine Generators and Series Capacitors	2014-2016	Modelling of dynamic interactions between series capacitors and large wind farm generators, and identify controls to mitigate impact of interactions
Stability/ Modelling real time data sources	EPRI Research Collaboration on Grid Operations and Control	2013-2015	Development of tools to enable system operators to use real time data to assess the system, manage the grid and restore the system in the event of an outage
Stability / Visibility	Scalable Computational Tools and Infrastructure for Interoperable and Secure Control of Power System	2012-2016	Development and deployment of standards such as the Common Information Model to enable power system data exchange between network operators
Visibility of renewable generation	Modelling of Embedded Generation with Distribution Networks and Assessing the Impact	2012-2014	Investigating candidate techniques to determine nature and magnitude of impact of distributed generation on transmission demand
Visibility of renewable generation	Visualization of Renewable Energy Models	2013-2017	Development of prototypes for visualising wind and solar generation on the transmission networks

Table 6: National Grid projects with power systems data opportunities.

The DNOs have also explored several new data sources in innovation projects through LCNF projects and Table 7 presents the topics and data sources explored to date.

DNO	Title	Years	Data Source	Description
ENW	Capacity to Customers (C2C)	2012-2014	Demand Models	Trialling new operational techniques to release latent capacity within the HV network by combining network automation with "interruptible" contracts with large customers
ENW	Customer Load Active System Services (CLASS)	2012-2015	Collection of Power Quality and Voltage Data	Exploring the relationship between voltage and demand – provide DNOs with knowledge to use voltage control to manage network constraints
ENW	Smart Street	2014-2017	LCT Generation and Demand Models	Trialling interconnection and voltage management on LV networks. Utilising real time optimisation software and integrating capacitors, on load tap changers and automation to manage voltage
Northern Powergrid (NPG)	Customer-Led Network Revolution	2011-2014	Analysis of Smart Meter Data, LCT Generation and Demand Profiles	Trialling of smart meters and customer interactions with new network technologies. Development of NPADDS decision support tool
SP Energy Networks (SPEN)	Flexible Networks for a Low Carbon Future	2012-2014	Voltage Regulator Model	Looking to obtain extra capacity from HV network in three separate locations through the use of voltage regulators
SSE	New Thames Valley Vision	2012-2017	Demand Models, ADR models, Energy Storage Models	Developing a tool to help forecast where low carbon technologies might connect to the network. Trials network monitoring, energy storage and novel commercial arrangements with large customers. Modelling facilitated using Common Interface Model (CIM)
SSE	My Electric Avenue (Innovation Squared)	2013-2015	EV Charging Models	Facilitating connection of EV (electric vehicle) chargers to LV network with the aim to give a low cost, easy to implement alternative to network reinforcement

DNO	Title	Years	Data Source	Description
SSE	Solent Achieving Value from Efficiency (SAVE)	2014-2018	Customer Receptiveness Models	Trialling and establishing energy efficient measures to manage peak demand as an alternative to network reinforcement. Development of tools to assess a particular network's suitability for demand reduction through energy efficiency measures
UKPN	Flexible Plug and Play	2012-2014	Quad Booster Model	Trialling ways to improve control of EHV (extra high voltage) network to connect increased wind generation
UKPN	Low Carbon London [26]	2011-2014	Derivation of Load Profiles	Exploring technical and commercial innovations to integrate low carbon technologies. One objective is "increase modelling robustness" with an emphasis on using modelling to derive load profiles
Western Power Distribution (WPD)	FALCON	2011-2015	Intervention Technique Models (e.g. demand side management, Storage)	Deploying smart interventions on the HV network and novel commercial arrangements with customers. Data used to develop investment tool (Scenario Investment Model – SIM) to model where techniques can be deployed efficiently across HV network
WPD	FlexDGrid	2012-2017	Fault Level Mitigation Technology Models	Developing new fault level assessment processes, real-time monitoring of fault levels and deployment of alternative mitigation solutions to reduce cost and time to connect DG
WPD	LV Templates for a Low Carbon Future	2010-2013	Templates of Domestic Generation/ Demand Models	Assessing impact of low carbon, demand-side technologies connected to the LV network
WPD	Low Carbon Hub	2011-2015	Dynamic Rating Plug-In, DStatcom Model	FInvestigating how network technologies can increase the capacity of wind generation that can be connected to a rural distribution network

Table 7: Distribution (Tier 2 LCNF) Projects with new data opportunities.

The paper derives recommendations from reviews of these projects and the opportunities that they are exploring:

- Improvements for Transmission System Operation based on new data sources:
    - More accurate demand profiles which reflect the changing patterns of domestic and commercial consumption and production of electricity are necessary for the SO to carry out effective system balancing. Liaison with the DNOs and access to results of their work on demand modelling would be a useful resource in this process.
    - Another key recommendation in order that effective system balancing can take place is an improvement in the visibility of DG by the transmission operators, providing more information for forecasting. Better telemetry and monitoring of DG sites, and access to this data by the SO, would also go a long way to achieving this on operational timescales.
- Cross-System Modelling in an Operational Context
    - There is now a case for better representation of the distribution system in transmission modelling (and vice versa) for operational purposes. Consideration should be given to the real-time data exchange of topology arrangement and network operating conditions, as well as the additional DG telemetry described above.
- Harmonisation and Sharing of Model Developments
    - There are a large number of projects ongoing in developing data sources for distribution network modelling activities. These models are being conceived, designed and built in a variety of different modelling software packages. It is important not only that these models continue to be developed, but also that the DNOs are able to share and disseminate these models across a variety of DNOs (and the SO) and software platforms. It is therefore suggested that there should be a harmonised approach for the development and deployment of these software models.
- Data and Modelling of LV Networks
    - It will be important to improve databases and methods of data capture. Also, understanding the sensitivity of the analysis to missing data could help to prioritise areas of data improvement. An increase in key area monitoring to improve accuracy and reduce modelling uncertainties is one recommendation to overcome the challenges faced with LV modelling.

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[5] Methods and Tools for planning the Future Power System: Issues and Priorities. Keith Bell, ScottishPower Professor of Smart Grids, University of Strathclyde **keith.bell@strath.ac.uk**

[6] Emerging Modelling Capabilities for System Operations. Goran Strbac, Ioannis Konstantelos, Rodrigo Moreno, Imperial College London **g.strbac@imperial.ac.uk, ioannis.konstantelos03@imperial.ac.uk**

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[15] Power System Modelling Data: Requirements, Sources and Challenges. Stephanie Hay, Anna Ferguson, TNEI Services **Stephanie.hay@tnei.co.uk**

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