International Centre for Mathematical Sciences
Management of Energy Networks
Post-workshop report

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1 Introduction

The purpose of this very successful meeting, which was well attended by researchers from both universities and the energy industry, was to identify mathematical challenges in the management of energy systems, particularly at the level of the network infrastructure and its management. Details of the meeting and copies of the presentations are available at http://www.icms.org.uk/energynetworks.php. The outcomes of the meeting are summarised in the discussion below.

2 New challenges in the management of distribution networks

Current distribution networks are significantly over-engineered in the sense that they are designed to be able to cope with a wide range of possible loads without the need to actively manage the latter. This leads to higher costs. However, much of this network infrastructure is ageing, and is further unable to cope with the renewable and dispersed generation of the future. Set against this is the possibility of much greater flexibility in the management of future energy requirements; this is largely made possible by the availability of technology for much better control. Hence there is a move towards a more active and more probabilistic approach to distribution management—something which is already at a more advanced stage in the management of transmission networks. This may also incorporate the economic costs of such, very occasional, service failures as may occur.

Such an approach requires a much better knowledge of the stochastic environment (spatial and temporal distributions of generation, demand and network state) than is currently typically available. This in its turn requires the routine availability of much more and better quality data, together with the statistical and forecasting techniques required to make proper use of it. Novel algorithms for the management and control of networks are also required.

The management of such networks necessarily takes place on a range of time scales. These range from milliseconds to seconds in the case of control, to minutes, hours or days in the case of operational decisions, to months, years or longer in the case of planning decisions.

Formally the mathematical problems may be formulated as (multi-stage) stochastic dynamic programming. However, exact approaches to the latter are often computationally intractable and workable approximations are required.

We give below some particular challenges faced in the management of future networks.

- *Decarbonisation of heating and transport.* The decarbonisation of heating and transport is likely to be achieved largely by a switch to the use of electric power, itself to be produced from non-fossil fuel sources. This will place much increased demands on existing networks, and may also reduce the predictability of those demands, as the use of power for heating, for example, may be highly weather dependent. The variability of the demand profile over a day may also increase. All of this will increase the difficulty of active network management, particularly if the capacity of existing networks is not increased in proportion.

- *Increased distributed and embedded generation (wind and solar PV).* The much increased presence in future networks of distributed and embedded generation (most of which is provided by highly variable renewable resources) raises issues of diversity, variability, volatility, and seasonality. These problems are further compounded by the typical lack of inertia associated with renewable generation in particular. As in the case of the likely more variable future demand patterns considered above, there are technological solutions to these problems which will ensure that supply and demand can continue to be balanced, and that networks can continue to deliver energy whenever and wherever it is required. However, many different parties—generators, suppliers, consumers and network operators—are involved, each naturally seeking to optimise with respect to their own interests. Hence there is a strong need for the design of market mechanisms which deliver solutions which are more generally optimal (with respect to some appropriate measure of the overall benefit of the way in which the system is operated). In particular while the presence of increased distributed generation will (like the presence of increased future demand) require considerable network reinforcement, market solutions driving towards societal optimality should assist in keeping he need for such reinforcement to a minimum.

- *Storage, demand management and electric vehicle (EV) charging.* Traditionally supply and demand have been balanced by the management of the former (i.e. of generation) on a minute-by-minute, and indeed second-by-second, basis. Storage, demand management (which may be regarded as “virtual” storage) and EV charging all offer new ways to assist in achieving this balance, essentially by shifting energy through time so as to better balance the supply and demand profiles. The former two capabilities can further assist is smoothing locational imbalances, thereby reducing or postponing the need for further network reinforcement. However, the need to charge EVs also requires a much greater overall supply of energy, necessitating some considerable network reinforcement, unless the need can be mitigated by careful management of the way in such recharging occurs.

  Major challenges for storage and demand management are therefore those of how optimally to use these capabilities to achieve the required spacial and temporal smoothing, so minimising both generation and network reinforcement requirements. In the case of storage, a further challenge is that of how to position and dimension it, which is one of long-term planning—see Section 4.

The major challenge for EV charging is that of how to schedule it so as to achieve similar aims to those above. This requires smart management algorithms. There are also issues of fairness, waiting times, and system stability.

- *Frequency control in networks with low inertia.* Existing frequency control mechanisms rely heavily on the presence of inertia in conventional generation. The lack of such inertia in renewable generation raises risks of network instability. One solution to this problem is the increased use of ancillary services whose sole purpose is to provide this inertia, but there are also many other opportunities for adding further inertia to networks, and, perhaps, for better control of networks with lower inertia. Again many competing players are involved and market solutions are required.

- *Computational challenges.* The active management of future distribution networks presents significant computational challenges. Notably the highly distributed nature of the networks themselves means that it may neither be desirable, nor even feasible, to collect and process centrally in real time all the data required for such management. Hence, as in the case of telecommunications networks, it may be natural to implement distributed algorithms for localised decision making based on locally available information. Such decisions could include those necessary for load balancing—via the management of distributed generation, storage or local demand—and those necessary for the control of the network state itself.

  Further major computational challenges relate to the management of *uncertainty*, both in the problems described above and in, for example, the solution of OPF problems.

  There is a need also to consider the role of the increased telecom and computational infrastructure associated with future networks.

3 Forecasting and data issues

This section is principally concerned with network data, state estimation and short-term forecasting. The following issues are of particular importance (data issues specifically associated with capital planning are described in Section 4).

- *Assessing the current state of the system.* At transmission level, visibility of the network through monitoring, and thus availability of data for state estimation is generally reasonably good, as there are a limited number of large assets. However with the large number of smaller assets, available data from distribution networks is typically sparser. These data issues will become more critical with the move to greater active participation of small demands, and further increases in small scale distributed generation—this applies both to distribution network management and to whole-system level balancing (where the SO may have limited observations of local distribution-connected resources).

- *Modelling of system resources and demand.* It is necessary to develop models of the (joint) spatial and temporal behaviour of both supply and demand, as well as of new devices connected to the system (e.g. dynamic models of power electronic devices). These are required for both system operation and planning. A particular area where little data exists is the fine time resolution output of renewables (on sub-30 minute timescales), which is needed for multiple applications in system operation including operating reserve setting and dynamic stability.

- *Short term forecasting.* Much better forecasting models (for renewable and conventional generation, for demand, for network state) are required. Forecasting models need to be probabilistic (i.e. their outputs are stochastic processes, including temporal structure of forecast uncertainty), and they need to incorporate data uncertainty.

As mentioned above, the monitoring of distribution networks is generally less detailed than that of transmission networks. While there are projects underway to improve the availability of distribution network data, there is an extent to which this reduced level of monitoring will inevitably remain the case, due to the economic and practical constraints on monitoring a very large number of small assets. This is a general issue, relevant to a number of operational processes including state estimation and renewables forecasting. There are a number of areas where mathematical sciences may be able to help manage this challenge, including experimental design for cost-effective data collection projects, the management of uncertainty in state estimation, and forecasting based on limited or imperfect data.

Furthermore, there are complications arising from limited sharing of data between different network operators. Where sharing all data is impractical (whether due to confidentiality or sheer volume), there may be value in work on what data or summary statistics need to be shared in order for different operators to have the necessary information on each other's networks.

A further issue is that network switching states are typically not modelled by researchers (for instance it is often assumed in academic work that all circuit breakers at substations are closed). Thus care should be taken in interpreting academic modelling results where this is relevant, and researchers should be aware of the consequent practical issues in implementing new optimisation and control techniques.

4 Capital planning under uncertainty

Energy network assets have long lifetimes - their book lives are typically 40 years, and in practice the useful lives of many assets are considerably longer. To this must be added planning and construction times, as there may be several years between an investment decision and commissioning. Moreover energy networks are very capital intensive. Improved methods are thus required for taking investment decisions under uncertainty over the future planning background. Specific questions include:

- How to quantify uncertainty in the future background against which the system is planned, for instance in demand patterns driven by a combination of human behaviour and technology development, or in the level of deployment of renewable generation.
- How to perform decision analysis under uncertainty, where even the analysis of a single future scenario is computationally intensive, and where it is thus not possible to densely explore a range of scenarios?
- How to map national level future scenarios to local area decision making, and specifically how to interpret and use National Grids Future Energy Scenarios for local planning?

- How to avoid the risk of stranded assets (or how to ensure an appropriate level of stranded assets if that is deemed a more reasonable level of risk aversion)? What decision criteria should be used in formal decision analysis, in order to reflect the thinking of decision makers? Part of the context here is that there is often a degree of discomfort with the assignment of probabilities to possible futures in the case where these probabilities are obtained through expert elicitation.
- How to ensure sufficient flexibility in decision support for planning, so that 'wait and see' policies are properly considered?
- How to plan under limited information on present and future end use demand, and on the future nature of supply and demand side technologies?

5 Future roles and interaction of TSO and DSO.

Currently the TSO is responsible for the most of the active management of the entire electricity system, i.e. for the balancing of supply and demand both in time and across geographical locations. However some functions, e.g. network capacity and voltage management, require also the participation of the DSOs. The entire system needs to be managed in such a way that the transmission network is able to cope; the distribution network is currently over-engineered so that (other than in the case of major malfunction) it may be expected to always cope. Thus the role of the DNO has heretofore largely been one of planning and maintaining the distribution network.

As discussed above, there are now many new physical functions which require active management at the distribution level. These require detailed knowledge of the distribution networks, and the complexity of the entire system is such that it cannot be entirely managed centrally. Nevertheless overall management of the system continues to require central coordination as at present. Some of the issues which therefore arise are the following.

- Clearer identification of the particular new physical functions (distributed generation, demand management capabilities, storage capabilities, ancillary services) that need to be actively managed at the DNO/DSO level.
- The division of responsibilities between DSO and TSO.
- The management of the TSO/DSO interface work, e.g. the resolution of conflicting objectives (economics, service, system stability). There are similar issues at the HV/MV/LV interface.
- Whether a new body is required to be responsible for the overall operation of the system.
- The role of regulation in the management of future systems.
- The role of markets in the management of future systems. In particular, is it possible to structure these is such a way that individual players are incentivised to contribute to a societally optimal management policy?
- The identification of the mathematics required for all of the above. The mathematical expertise required for the management of the physical system (probabilistic modelling, statistics, optimisation) is reasonably well understood, even if the detailed mathematical models and techniques need to be developed and analysed. However, the mathematical disciplines required for the management of a system in which there are many difference players with competing interests is much less well understood: presumably economic theory, auction theory and game theory are all required, but the correct application of these theories is far less certain than in the case of the

optimal management of the physical system.

6 Market design and operation

As already observed many different players participate in energy markets. These include generators of both conventional and renewable energy, suppliers, consumers and network operators, as well as providers of storage, demand management and ancillary services. Future networks will contain very many more players, often—as in the case of distributed generation—with their inputs widely spread throughout the networks themselves. There is therefore a need to provide appropriate market mechanisms for all these participants, and—as already indicated in particular cases above—to design market structures and algorithms which correctly align the interests of individual players with those of society. The required mathematical techniques, as also indicated above, are those of economic theory, auction theory, and game theory.

There are especial challenges in providing routes to market for new players such as providers of distributed energy resources and ancillary services. The intermittent nature of renewable generation provides considerable further complications in designing appropriate market structures. New players might participate directly in the wider energy markets, or they might contract with DSOs, with the TSO, or participate in markets specially developed to maximise their societal contribution. There are advantages and disadvantages associated with all these possibilities, and again detailed analysis of possible market mechanisms is required. Different models may be appropriate in different countries.

Finally, the introduction of new technologies such as smart metering means that consumers will also be able to participate more actively in future markets.

7 The role of mathematics

We have already discussed extensively the need for mathematical and statistical modelling and analysis in the design and management of future networks. The required subdisciplines are primarily those of probability theory, statistics, optimisation, economic analysis, auction theory and game theory. However, there is a further need to identify how mathematics may best provide its input. A particular issue is that of understanding the gap between mathematical models and practical applications: it is important that the effect of any discrepancy between model and reality is well understood, and that the mathematical models used are such that their conclusions are *robust*.

A further issue is that of the need to continue to build a common language shared between mathematicians and practitioners so as to permit a common understanding of the applicability of mathematical models and outputs.