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

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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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EXECUTIVE SUMMARY

Probabilistic methods have attracted renewed attention in power systems engineering in recent years. Most prominently, they provide the natural framework in which to analyse the variable output from renewable sources and their integration into the system. Also, because probabilistic methods can often reflect underlying uncertainties better than deterministic approaches which have been used in the past, they can also support more efficient planning and operation of systems.

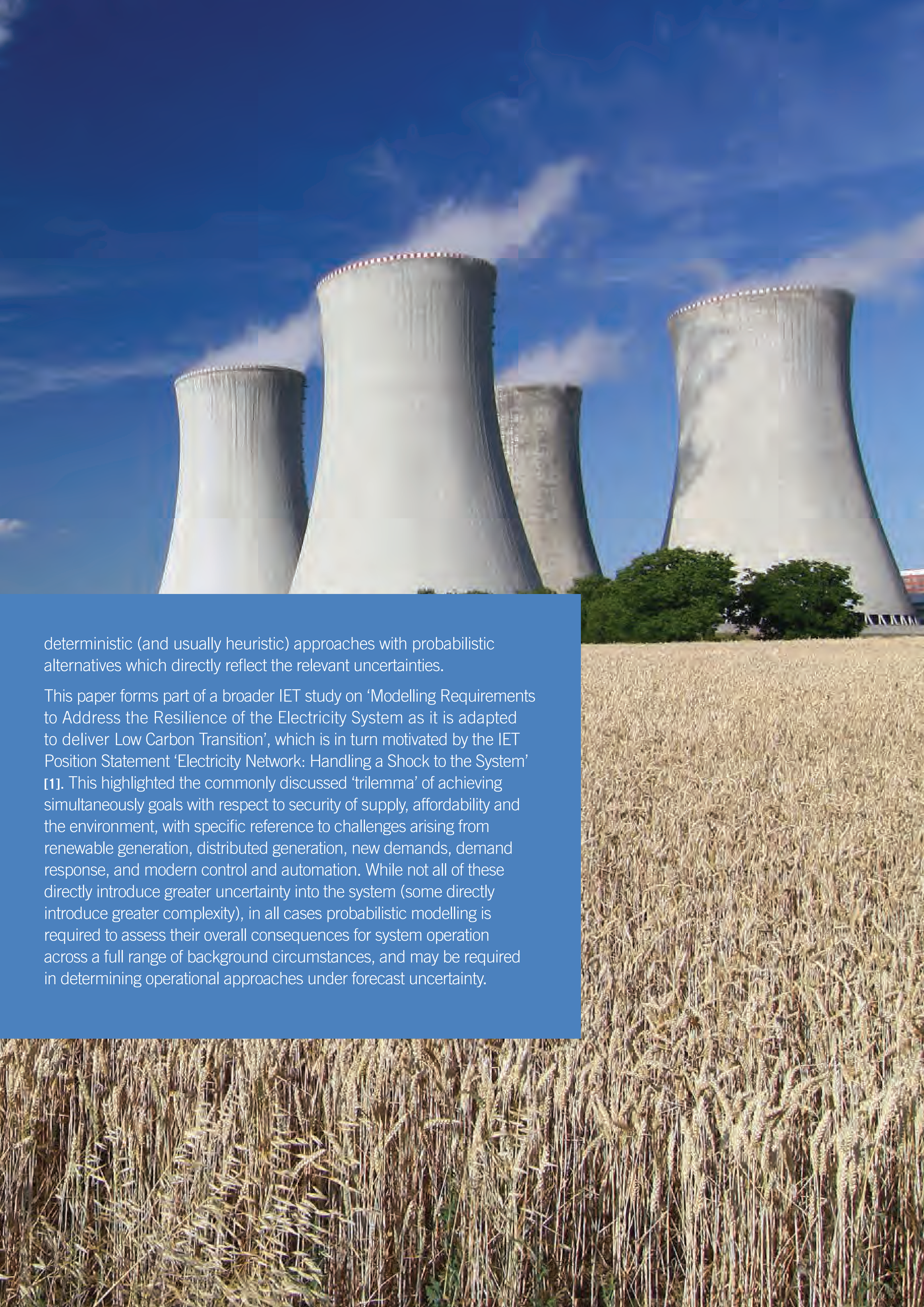
This paper reviews UK research capabilities in the area of probabilistic modelling applied to power systems, based on a broad survey of recent research outputs. The field is divided into four broad categories of planning timescale generation adequacy assessment, network planning, forecasting and short term operation, and network reliability analysis. The survey is based on the author's own knowledge and experience, combined with advice from a number of relevant researchers as to which of their own and others' research outputs best represent current capabilities. While there is discussion of the context of current industry practices, the emphasis throughout is on original research originating in the UK.

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.

1. BACKGROUND

Greater uncertainty in resource availability on both planning and operating timescales, arising from variable output renewable generation, is a key motivation for increased use of probabilistic methods in power system analysis; probability is the natural language in which to quantify and manage such uncertainties. It is of course the case that in general the advent of variable generation only increases uncertainty rather than introducing uncertainty in the first place. Hence a further motivation for the introduction of probabilistic methods is the desire to plan and operate systems more securely and efficiently, by replacing deterministic (and usually heuristic) approaches with probabilistic methods is the desire to plan and operate systems more securely and efficiently, by replacing



deterministic (and usually heuristic) approaches with probabilistic alternatives which directly reflect the relevant uncertainties.

This paper forms part of a broader IET study on ‘Modelling Requirements to Address the Resilience of the Electricity System as it is adapted to deliver Low Carbon Transition’, which is in turn motivated by the IET Position Statement ‘Electricity Network: Handling a Shock to the System’ **[1]**. This highlighted the commonly discussed ‘trilemma’ of achieving simultaneously goals with respect to security of supply, affordability and the environment, with specific reference to challenges arising from renewable generation, distributed generation, new demands, demand response, and modern control and automation. While not all of these directly introduce greater uncertainty into the system (some directly introduce greater complexity), in all cases probabilistic modelling is required to assess their overall consequences for system operation across a full range of background circumstances, and may be required in determining operational approaches under forecast uncertainty.

Fully probabilistic approaches are not widespread in industrial practice, partly due to the limited number of people with the full set of relevant skills (which do not fall within a traditional power engineering education syllabus). There are some areas such as transmission planning and generation capacity adequacy assessment where a fully probabilistic approach is already in use, the application in network planning being particularly distinctive internationally as discussed later. There are then areas such as short term forecasting by the system operator and distribution network capacity standards where a fully probabilistic approach has not yet been implemented, but where some form of probabilistic risk based assessment has been used in order to develop current operational practices. Use of probabilistic methods is much more widespread in academia across all areas of power system analysis, as will be reviewed in subsequent sections.

Some commercial power system modelling platforms are available which include probabilistic components, e.g. specialist packages such as GE MARS (Multi Area Reliability System), and more general system analysis packages such as Plexos, Powerfactory, etc. In current practice in both industry and academia, there are custom written packages held within one organisation (e.g. the Capacity Assessment Study and National Grid's network planning modelling), or specialist custom codes which are more widely available (e.g. tools associated with the P2 distribution planning standard). This may be because more widespread commercial packages do not have the capabilities required, or sometimes because one has complete knowledge of the model structure and data processes when custom-writing code. For bespoke codes, platforms may be high level languages such as Matlab, VBA for easy of linking to Microsoft applications for input and output, or traditional programming languages such as C.

It is necessary in all cases to have access to appropriate data for statistical estimation, or alternatively the necessary expert judgment if a subjective probability approach is to be taken to quantifying planning timescale uncertainties. While individual organisations hold their own operational data (e.g. on generation or circuit availability), and some relevant data is freely available for download (e.g transmission-metered demand [2] and transmission circuit parameters [3]), the UK has no equivalent of the North American Generation Availability Data System [4].

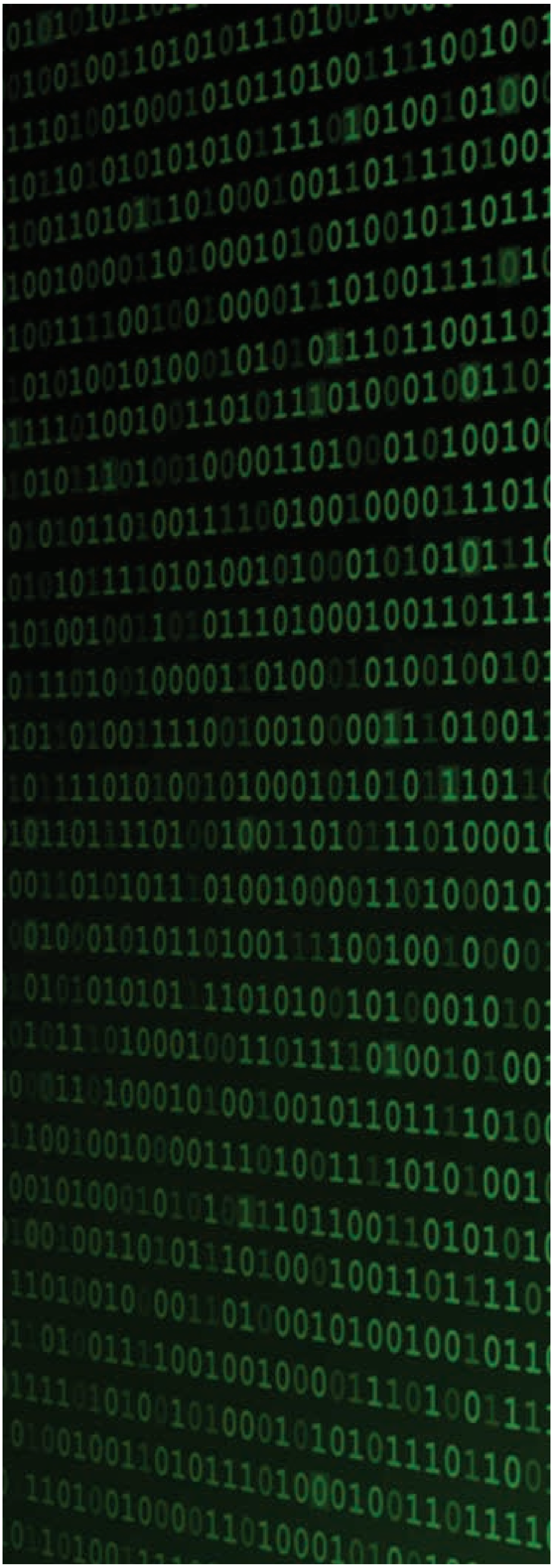
A particular difficulty for meaningful applied renewables integration studies is very limited availability of high quality renewable resource data (where there is no widely available GB equivalent of the whole system-level data exercises carried out by the US National Renewable Energy Laboratory [5]) though there have been individual research activities such as those at Edinburgh University [6] (which has developed an equivalent dataset to the US ones using physical downscaling of historic meteorological reanalysis[1] datasets to higher spatial resolution), and datasets underlying analyses of historic wind resource in the meteorological research community such as [7] (Met Office), [8] (University of East Anglia) and [9] (University of Reading), and commercial products (particularly aimed at wind resource assessment for developers) are available e.g. [10, 11]. Data sources vary between reanalysis (with or without downscaling) and metering at specific sites; there seems not to be a general consensus as to the preferred approach, and indeed this may well depend on both the specific application and on project budgets. The Edinburgh group has been active in development of resource data for other renewable sources such as wave power [12]; this paper further uses extreme value statistical approaches to estimate mean return times of extreme events.

On the other hand, the UK has been distinctively open in publishing full technical detail of studies underlying standards and major reports (e.g. the GB Security and Quality of Supply Standard reviews available at [13] and the reports on DG contribution to network security which underpin the present P2/6 distribution planning standard [14]).

2. METHODOLOGY

This content of this survey paper is based on the author's own knowledge and experience, supplemented by a literature review and the advice of a number of relevant researchers and industrial modellers on the institutions where key GB modelling capabilities lie. In general, work has only been included where there is a citeable record of it in the open literature (journal or conference papers), but some emerging activities have been referenced through other means (e.g. web seminars) where the researchers have energy interests and strong track records in other areas of application. Where all researchers in an activity are no longer active in UK energy research, the activity has been excluded from this study as not being an ongoing UK capability. To ensure a current snapshot

[1]Reanalyses are reconstructions of global atmospheric conditions using physical atmospheric modelling based on available historic data. Typically such a dataset would have a spatial resolution of 50–100 km over GB.



of activity in an international arena, all UK activity represented at the International Conference on Probabilistic Methods Applied to Power Systems in Durham in July 2014 is cited.

3. CAPABILITIES IN SPECIFIC MODELLING AREAS

3.1 Generation adequacy assessment

Generation adequacy assessments study the risk of available supply falling below demand. Assuming that fuel supplies remain secure, the GB system is capacity-limited, i.e. adequacy at present is about the MW supply-demand balance at each point in time, rather than the availability of sufficient energy over time. Adequacy conventionally does not include issues of short term operation (i.e. considerations such as whether even if the absolute supply-demand balance at each point in time is healthy, the supply is sufficiently flexible to match the demand continually).

Adequacy studies may be carried out looking a number of years ahead (e.g. the statutory Electricity Capacity Assessment Study which has been published by Ofgem for the last three years [15]), or looking at risks in the next winter (e.g. National Grid's annual Winter Outlook [16]). Adequacy assessments looking substantially more than about five years ahead (i.e. on a timescale when new plant can be built which is not yet in any planning stage) are generally highly speculative due to the very considerable uncertainties in all model inputs, though economic modelling is sometimes used to project generation investment and hence adequacy risk levels on longer timescales (a key example of this class of model is the Dynamic Dispatch Model commissioned by DECC as part of the recent Electricity Market Reform process [17]).

As evidenced by the impact of the Capacity Assessment Study in the media and in policy circles, adequacy risk (often referred to as risk of 'the lights going out') is regarded as being of paramount importance (c.f. discussion in the IET report [1]); beyond direct costs of any involuntary disconnections, if an adequacy crisis occurs in a system it has a major psychological effect on the economy and all aspects of society.

The GB Capacity Assessment Study used a fairly standard model structure (described in the three annual reports), with the major innovations coming in assessment of sampling uncertainty arising from finite size datasets, and broader thought about the relationship between model results and the real world issues which are under study. Research on probability theory and statistical modelling associated with the Capacity Assessment project has been published by the academic consultants from Heriot-Watt and Durham Universities who assisted with design of technical modelling for the project [18, 19, 20]. One point of particular interest has been the communication of impact of adequacy risk. It has been found that frequency and duration (F + D) outputs (e.g. on average how many years an event of given severity will occur) are more intuitive to non-modellers than the standard expected value indices such as Loss of Load Expectation (LOLE); while methods for adding direct calculation of these to the modelling are well established in the literature, the relevant statistical modelling (i.e. assessment of uncertainty in model outputs arising from input data and modelling assumptions) is not well established in GB or elsewhere, and further research would be needed to underpin a robust applied study.

A further key topic of debate is methodology for considering the contribution of interconnection to other systems. In the capacity assessment study this is treated through analysis of different scenarios for interconnector flows. As the level of interconnection increases, a fully probabilistic treatment explicitly considering capabilities in the other system will increasingly become more preferable. Work is underway at Imperial College on an approach to optimising investment and operational/reliability costs in the interconnected European system [21], and there is currently a European project to coordinate adequacy assessment methodologies between operator areas [22]. While there are commercial packages available for this kind of study, once more the international literature on relevant statistical modelling is very sparse.

Several other aspects of generation planning have been investigated by multiple groups at Imperial, including generators' commercial risks under different low carbon incentives [23], investigation of optimal portfolios of wind farms in GB [24], procurement of supply contracts by multistage mean-variance portfolio analysis in [25], and a stochastic optimisation approach to generation expansion planning [26].

3.2 Network planning

Transmission network planning will be covered fairly briefly here, as it is the subject of a separate paper in this study. GB is quite distinctive in using a full probabilistic approach in practical transmission planning on economic grounds (as described in various Security and Quality of Supply Standard review documents available at [13]; 'economic justification' as described in Appendix G of the SQSS itself would be based on a probabilistic approach, and probabilistic analysis also underlies the 'economy planned transfer' criterion in the present standard.

Early phases of the SQSS review for onshore intermittent generation drew on work at Strathclyde and Bath Universities and Imperial College London, as described in the 'GSR001' review reports at [13]. Transmission planning remains an ongoing area of interest at Strathclyde (e.g. Keith Bell's paper in the present IET study), and at Imperial (e.g. [27, 28]; further related work, is ongoing at Imperial encompassing multi-system issues with application to the European grid [21]).

Distribution planning standards in GB also to an extent have probabilistic underpinnings. The standard for higher voltage levels [29] contains explicitly a deterministic N-x criterion, with distributed generation assigned an equivalent circuit capacity based on a probabilistic calculation (described in detail in [14]). There are however doubts [30] as to whether such a deterministic equivalent standard can fully represent the complex circumstances which we see in current and future networks (distributed generation, active demand, multiple possible supply routes, etc). There is currently a comprehensive review of the P2 standard underway; research on DG's contribution which may feed in to this review includes [31] at Imperial and [32, 33] at Bath.

The ACE49 low voltage planning standard for low voltage networks involves limited probabilistic consideration of requirements to meet voltage and thermal limits with an appropriate degree of confidence [34]. Unfortunately the standard (dating from 1981) does not include full detail of the underlying analysis and intended interpretation of the mathematical structures specified. Work is underway in the Customer Led Network Revolution project specifically to update input data for application of ACE49 [35], and there is work ongoing in other Low Carbon Network Fund projects, e.g. [36, 37] (Bath/Western Power) and [38] (Manchester/ Electricity North West), on alternative approaches to LV network planning.

One broad concern with these standards is that the general structures underlying them are now several decades old (while P2/6 dates from 2006, it is a fairly limited update of the predecessor P2/5). These structures were developed in circumstances both of a very different industry, and of much lesser availability of data and computing power. There are undoubted benefits in terms of ease of application of these current standards, however this must be balanced against whether they reflect the nature of planning problems to which they will be applied in the future. If long-standing standards frameworks are to continue to be used, then this should be based on positive confirmation that they are well founded with respect to current circumstances. In this, a particular challenge will be to identify deterministic equivalents in a more complex system with multiple classes of demand and supply-side resources.

3.3 Short term forecasting and system operation

Issues of greater uncertainty arising from variable output renewables are seen also on an operational timescale. Key to use of forecasts in system operation is a realistic assessment of the forecast error distribution. National Grid has an active research and development programme in this area, and has for several years been contracting probabilistic forecasts as part of its wind forecasting [39]. National Grid is also carrying out research in collaboration with Reading University on statistics of extreme events in wind generation [9]; another statistical modelling output from the same Reading group is on validation of wind speed forecasts on a lead time of low numbers of weeks [40, 41]. There is further substantial R and D in meteorological service providers such as the Met Office [42].

In academia, there are ongoing activities in the power systems community such as [43] at Loughborough and [44, 45, 46] at Strathclyde; a further project at the latter institution studies prediction of high wind speed cutout events [47], a topic of major interest to operators of systems with high wind penetrations. There is a long standing activity in the Mathematical Institute and Business School at Oxford on both wind and load forecasting [48, 49, 50, 51]. There are also more recent activities on wind power forecasting in the statistics community including the EPSRC Locally Stationary Energy Time Series project at Lancaster and Bristol [52, 53], and at Heriot-Watt University as part of the Mathematical Foundations of Energy Networks EPSRC project [54]. Further recent work at Strathclyde has looked at wave energy forecasting [55].

There is a further very significant activity in the group of Peter Grindrod at Oxford (formerly Reading), and the associated company Counting Lab, on demand modelling and forecasting plus control applications; examples of their work include [56] on forecast quality metrics, storage scheduling at low voltage level [57, 58], and forecasting household demand profiles [59].

Colin Singleton and Nathaniel Charlton from Counting Lab were also the winners of the 2012 IEEE Global Energy Forecasting competition hierarchical load forecasting track **[60]**, with James Robert Lloyd from Cambridge in second place **[61]**. Further work from the power systems community on load modelling includes **[62]** at Strathclyde on load point modelling, and **[63]** at Manchester on the accuracy of a neural network approach to forecasting load composition.

A further aspect of forecasting is price forecasting, on which the most prominent activity is at London Business School,where Derek Bunn has been active in the area for many years. Recent papers include **[64, 65]**. This activity has also resulted in several monographs such as **[66]**. The LBS activity extends to a number of other areas such as interconnector transmission rights valuation **[67]**. There is also work at Imperial linking price forecasting to options valuation **[68]**.

In terms of stochastic optimisation methods for system operation, the most prominent line of work internationally has been in stochastic unit commitment, i.e. the question of which conventional units to commit, with explicit consideration in the optimisation problem of forecast uncertainty (as opposed to considering this only through an exogenous reserve requirement). **[69]** at Imperial makes a distinctive contribution to this through the inclusion of extreme events in the stochastic optimisation scenario tree, and the same authors have also worked on time series analysis for inclusion of wind in system operation simulations **[70]**. **[71]** at Edinburgh proposes a decomposition method for solving these highly structured integer optimisation problems efficiently, an important topic which has been studied much less than stochastic unit commitment problem formulation.

However the potential role of stochastic unit commitment in practical system operation remains unclear; most research papers have been limited to year-round production cost studies rather than making proposals for how the stochastic optimisation approaches presented may be integrated into day-to-day system operation, and few such papers have engaged in detail with the necessary statistical modelling for construction of scenario trees.

There has been work on other aspects of stochastic control at a number of universities. Work on district energy systems **[72]** including risk-sensitive dispatch **[73]** is ongoing at Manchester.

[74] describes collaborative work between Cambridge, Heriot-Watt and Warwick on optimal control of energy storage with application to whole system level, including a stochastic model considering uncertain future prices. [75] describes work at Imperial on stochastic control of responsive refrigeration units.

3.4 Network reliability analysis

When assessing risks of component failure and customer disconnections, as in previous application areas the motivation for use of probabilistic modelling remains that it reflects the nature of the problem, i.e. probability provides a framework in which to analyse uncertain events.

Apart from work described earlier relating to the network planning standards and the statutory adequacy study, the level of research on network adequacy is limited. Work at Strathclyde [76] and Durham [77] examines reliability consequences of alternative topologies for offshore grid connections, [78] integrates reliability considerations into an ongoing line of work in distribution network pricing at Bath, and [79] at Manchester assesses reliability consequences of different network operational topologies in a system with substantial demand response. Again at Strathclyde, [80] analyses fault data arising from the GB transmission network as part of a project on 'Climate Change Impact on Operation of Meshed Power Networks', and [81] (Met Office) investigates how rates of network fault events may change in a changing climate. There is further an ongoing collaboration between Newcastle University and Northern Powergrid on measuring and mitigating risk at distribution level [82]. A paper from Edinburgh [83] has considered a sequential model for supply interruptions, with unusually detailed consideration of repair processes and the consequences of this for supply quality metrics.

One important application of probabilistic methods is in the development of 'real time thermal ratings' (RTTR), i.e. applying ratings to circuits according to current weather conditions rather than using generic seasonal ratings. There is an ongoing line of work on this at Newcastle in collaboration with several network operators, e.g. [84] which looks at how anticipated use of RTTR in operation can bring benefits in terms of reduced capital investment on planning timescales; one particular insight of this line of work is how while RTTR increases line ratings most of the time, on some occasions the RTTR may actually be less than current generic seasonal ratings, providing a good example of where a probabilistic approach can decrease the risks faced by reflecting better the true situation.

Work on RTTR is also ongoing at Edinburgh [85], Manchester [86] and Southampton [87]– these concentrate on RTTR for cables, in contrast to the majority of the work in the literature which is applied to overhead lines.

Most UK work in the literature on probabilistic reliability assessment has been on adequacy, considering overall supply-demand balance and finite network capacity. A long-standing line of work under Jovica Milanovic at Manchester has considered broader applications, e.g. power quality [88, 89] and small disturbance security [90]. An active area of work in the international community is probabilistic assessment of the risks of cascading blackouts, e.g. the IEEE Task Force paper [91] co-authored by Keith Bell of Strathclyde. While there was an early project at Manchester on this subject [92], there seems to be no recent research in the area from the UK. It should be noted that cascade events are not as naturally susceptible to probabilistic analysis as system adequacy, as each individual event tends to originate in a very particular combination of background circumstances, combined with the system not responding as it should.

There is also active work in physical asset management. In collaboration with National Grid, Manchester has worked on statistical projection of transformer lifetimes based on condition data [93, 94], on consequent replacement strategies considering the balance between capital and unreliability costs [95], and on reliability of protection schemes [96]. A further significant line of work, again in collaboration with National Grid (including a sponsored Lectureship) is at Strathclyde on agent-based approaches for integrating condition monitoring with diagnostics and prognostics, including advanced statistical modelling approaches to manage lack of high frequency data [97], on selftuning alarm systems [98], and on anomaly detection in transformer monitoring data [99]. Also at Strathclyde is a project on strategic maintenance planning for offshore wind farms [100], the context being very limited operational experience of a new technology. There is related work at Cranfield on optimal maintenance policies for remote offshore wind farms [101], and researchers at Imperial [102] have used a statistical approach to study the deterioration in performance over time of existing UK wind farms. The latter work follows an earlier paper from Edinburgh [103] which gave a much more pessimistic assessment of the same issue, and which attracted much attention in the community.

A broad range of issues associated with reliability and maintenance of offshore wind turbines is summarised in the book [104] by Peter Tavner of Durham University, following earlier work on failure modes and effects analysis [105] among other technical studies.

4. CONCLUSIONS

This paper has reviewed current research capabilities in the UK on probabilistic and statistical modelling applied to power systems, both that directly related to current industry reviews and also the wider research literature. While there is considerable research activity in the area, there are relatively few lines of research which have been consistently developed over multiple individual projects. While this is a broad area, it is possible to offer some general conclusions:

- ***Existing centres of strength should be encouraged.*** This is an important area of research, as it is generally accepted in the international power systems community that when planning or operating against an uncertain background a probabilistic approach is to be preferred to a deterministic one, due to the former's ability to reflect directly the circumstances experienced. It is important that the UK has research centres of excellence in this area (which may lie within the traditional power community, or in other communities which supply necessary methodological skills such as in mathematical sciences or meteorology), and that they are well integrated with the needs of industry.
- ***Challenges in practical implementation.*** Even where probabilistic methods make major advances in improving planning or operation of real power systems, practical implementation may still be a major challenge as the relevant skills are not as widespread in the industry as more traditional power system analysis techniques. If the industry deems that probabilistic methods are the way forward in a particular area then a significant training or hiring programme may be needed; if the users of a method in the field do not have a sufficient understanding of the principles underlying the method, then misapplication of the method could bring bad consequences.
- ***Collaboration between research communities.*** There are areas of power systems analysis where skills are required which do not form part of a traditional power systems engineering education. This paper has already discussed significant contributions made by mathematical scientists and meteorologists, and methods from social sciences are also very important in e.g. analysing future demand patterns (economists have been deeply involved in power systems issues for many years, but large scale involvement from other social sciences is more recent.) There is a tendency at present for research on similar topics in the different communities to proceed in parallel, without the degree of collaboration which would give the best research outputs and support of societal goals. In particular, both the RCUK/EPSRC power systems activity, and industrial schemes such as TSB, Catapults and the Energy Technologies Institute, might consider how they can encourage more projects involving innovative collaborations between researchers from different relevant disciplines.
- ***Data requirements.*** Availability of high quality data for statistical modelling is key to any robust probabilistic study (or indeed studies using other classes of technical approach). While in some areas such as the technical parameters of the transmission system (as published in National Grid's Ten Year Statement) data availability in GB is particularly good compared to other power systems, there are other areas in which good data are not so widely available. In some cases (e.g. generation technical availability) commercial and contractual issues may make wide dissemination of historical data difficult, but one example of where a national project could add great value across many groups' work is in historic renewable resource data. Here limited access to high quality validated datasets has been a problem for many research and applied studies; while many interested parties may not have the skills or resource to produce this themselves, such a data project only needs to be carried out once, allowing all renewable integration studies by all organisations to be done better.

5. ACKNOWLEDGEMENT

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