

The Mathematics of Energy Systems

Isaac Newton Institute, Cambridge

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Final report

The Mathematics of Energy Systems brought together internationally leading mathematicians, power systems engineers and economists over a period of four months to address a theme of global interest and significance. Both academia and industry were strongly represented in its senior international scientific advisory committee, in order to create a programme with the broadest possible relevance.

Particular focus was placed on the contribution of the mathematics of uncertainty to energy systems research, including predictive modelling and ensemble forecasting; stochastic optimal control, scheduling and maintenance; rare event analysis; and market pricing under uncertainty. These methods were applied to problems of planning, operation and trading in both present and anticipated future zero-carbon energy systems.

The scientific programme, which was designed to promote cross-disciplinary collaboration, took the form of three international workshops and nine research tracks. The three workshops addressed problems respectively at short, medium and long timescales. Beyond scientific excellence, a particular highlight of the workshops was their industrial participation. Senior industry figures from the US, Europe and the UK presented and participated in discussions, providing an invaluable perspective on the research agenda.

Preparatory “industrial impact” workshops [1] were organised in the two years prior to the INI programme to deepen links with industry and identify key problems for consideration in Cambridge. The first of these workshops, held at Wokingham in January 2017 and sponsored by National Grid and the EPSRC, focused on the design and operation of future energy markets. The second, funded and hosted by the International Centre for Mathematical Sciences in Edinburgh in January 2018, considered the mathematical challenges in the management of future energy networks, particularly those at the distribution level.

Flexible operation and advanced control for energy systems (MESW01) addressed the need for in-depth revision of the way power systems are operated as decarbonisation advances. The needs discussed included faster frequency control, more efficient power balancing mechanisms, and more effective ways of controlling flows within the interconnected transmission system. Recent methodological advances and open questions were presented in data analytics, stochastic and distributed control, dynamic contracts, inference, learning and approximate optimal control.

Electricity systems of the future: incentives, regulation and analysis for efficient investment

(MESW02) focused on economic mechanisms to incentivize investment in technologies and systems, particularly renewable energy. A particular feature was that each talk was allocated a discussant who helped to “break the ice” at question time. The workshop gave participants from different backgrounds - economists, mathematicians and engineers - an appreciation of what their particular models were overlooking and also included industry presentations on transmission and generation planning in the UK, delivering a useful reality check. The workshop has been reported in an article [2] in the September issue of SIAM News, and an appearance on YouTube [3].

While the first two workshops focused on operational and economic issues, respectively, the **Closing workshop: Looking forward to 2050** (MESW03) stimulated debate between experts from these two fields on which research problems will be most important in the years to come. Researchers from adjacent fields, such as atmospheric science and public policy, also presented. The workshop was combined with the INI Open for Business Day on “Managing Next Generation Energy Systems” in which several research track leaders (see below) presented the outcomes of their tracks to a broad audience. The workshop was notable for its gender balance, with 10 female and 11 male speakers.

The **research tracks** focused on specific themes across the main programme’s scope. Each was a week or fortnight-long period of cross-disciplinary exchange led by experts in the field, during which current research blockages were identified and potential routes forward proposed. Each track had goals appropriate to its theme. In some cases, collaborative projects were begun in which methodology from one domain was brought into another for the first time, in order to overcome current limitations in the state of the art. Other tracks resulted in the writing of opinion pieces assessing current research blockages and proposing routes forward over the coming years. In addition to their timeliness, all these projects will contribute to overcoming disciplinary ‘language barriers’ and fostering future interdisciplinary exchange.

The motivation for the first two research tracks, **Look-ahead operational planning under uncertainty** [4] and **Budgeting and scheduling of maintenance and replacement of power system components**, was the problem faced by transmission (and, in the future, distribution) system operators: namely, to ensure sufficiently reliable electricity supply at minimal cost. The research problem was to develop better reliability management methods by leveraging data, models and algorithms, over timescales ranging from a few minutes to several years. In the first track, the time horizon considered was a few hours to a few days and both continuous and discrete time optimal control formulations were considered. The outputs included an ongoing project titled ‘rangl’ to create an open computational platform on which benchmark problems in this area can be posted and solved. Its motivation is to enhance the relevance and reproducibility of empirical validations, facilitate the sharing of results among researchers, and to accelerate the transfer of results towards industry. In the second track, the challenge was the modelling of failure rates of power system components over a time horizon ranging from months to years. Its outputs took the form of two working papers. In the first, “Bayesian estimates of transmission line outage rates considering dependencies” [5], power system engineers and statisticians collaborated to infer the outage rates of high-voltage electrical lines from historical data provided by industry. In the second, “Maintenance for populations” [6], techniques of operational research are applied to determine

whether a given fixed total maintenance budget is sufficient to hold a system consisting of multiple subpopulations of ageing components in a satisfactory state.

The research track on **Data and analytics for short-term operations** [7] comprised a mixture of seminars and working group discussions. Topics covered included challenges and current needs from an applied perspective, modern statistical and machine learning approaches for forecasting applications, high dimensional modelling and forecasting, and probabilistic forecasting. An opinion piece was initiated at the interface between energy and modern analytics, identifying needs and challenges and a list of relevant datasets which can be used as benchmarks. A number of toy problems which could be used to link the quality and value of predictive modelling in relevant decision processes were also developed.

Moving energy through time: storage and demand side response [8] was organised to devise models and methodology to enable effective demand response from large and small scale consumers. The track brought together relevant researchers from the UK, Australia and New Zealand using techniques from multi-period optimisation, Lagrangian optimization and optimal control. Two new collaborations were begun: one concerning simultaneous participation in multiple products or markets, and another endeavouring to find when the profit maximising and welfare optimising paradigms coincide.

Equilibria and computation in markets with risk [9] was a loosely organized collection of presentations and discussions with the aim of fostering research collaborations between participants on issues related to risk and markets. A number of new collaborations came out of this work in the areas of generation expansion, transmission capacity expansion, bilevel investment problems and lower level market equilibrium using extended mathematical programming, model decomposition, the representative day method and clustering techniques.

Pricing and optimization of intraday/day-ahead electricity and futures contracts [10] began with a two-day mini-workshop on “Intraday electricity markets”. The research track brought together researchers from three areas: mathematical finance and statistics, economics and finance and operations research, applying both purely theoretical and empirical approaches. Three directions were pursued in detail: Identification of patterns in intraday prices and the move towards trading strategies and automatic trading; Advances in random field modelling reflected in energy data, including consideration of stochastic volatility and empirical approaches; and Risk assessment in energy markets. Arrangements were also put in place to continue these discussions following the MES programme.

Productive research tracks were also held in the areas of **Planning Low-Carbon Electricity Systems under Uncertainty Considering Operational Flexibility and Smart Grid Technologies; Future Electricity Markets; and Mechanism Design for the Economics of Future Energy Systems.**

The programme supported two satellite workshops, each presenting internationally leading mathematical research in a subdiscipline with emerging applications to energy systems. Scientific dissemination was promoted through mutual exchange visits between the satellites and the main programme in Cambridge. **Stochastic control and games under ambiguity** [11] at the University of

Leeds took the form of a two-week workshop including a two-day conference on stochastic control methods for problems involving strategic interaction and uncertainty. Workshop session themes included robust optimal stopping, principal-agent problems, controller-stopper games, mean-field games and irreversible investment with multiple technologies. Outputs included new collaborations in the areas of mean-field games of irreversible investment, investment with multiple technologies, and zero-sum stopping games. **Mean-field games, energy systems, and other applications** [12] at the International Centre for Mathematical Sciences included a one-day mini-course and four-day workshop. The workshop brought together researchers in some of the most active and promising areas of research in mean-field games and mean-field control, simulation, regularity and applications in the scope of energy systems. The mini-courses (34 attendees, including 16 PhDs plus postdocs and early career researchers) were delivered by an internationally leading expert in the field (Daniel Lacker, Columbia) who was recently awarded the highly prestigious SIAM Activity Group on Financial Mathematics and Engineering Early Career Prize.

Following the programme an open call for papers was made to all participants for contributions to a theme issue of Philosophical Transactions of the Royal Society A on the Mathematics of Energy Systems. This volume will present opinion pieces on future energy markets, predictive modelling for electricity systems, and short term security management; together with original, highly interdisciplinary research which was begun or significantly advanced at the programme in the areas of planning under uncertainty, data and analytics for short-term operations, and electricity trading.

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References

(Items [1, 3, 4, 6-12] are available from the programme organisers on request)

- [1] Stan Zachary, Report on industrial impact workshops.
- [2] <https://sinews.siam.org/Details-Page/electricity-markets-and-renewable-energy>
- [3] <https://www.youtube.com/watch?v=vHOQiBRHOa4&feature=youtu.be>
- [4] Janusz Bialek, Tiziano De Angelis, Chris Dent, Elena Issoglio, Stella Kapodistria, Efthymios Karangelos, Jan Maciejowski, Randall Martyr, John Moriarty, Tommaso Nesti Eleni Stai, Simon Tindemans, Louis Wehenkel and Alessandro Zocca. *INI - MES Programme - Research Track 1: Look-ahead operational planning under uncertainty*. Working paper.
- [5] Kai Zhou, James R. Cruise, Chris Dent, Ian Dobson, Louis Wehenkel, Zhaoyu Wang, Amy Wilson. *Bayesian estimates of transmission line outage rates that consider line dependencies*. Working paper.
- [6] Edward Anderson. *Maintenance for populations*. Working paper.
- [7] Report on the research track "Data and analytics for short-term operations"
- [8] Stan Zachary, Report on the research track "Moving energy through time: storage and demand side response"
- [9] Michael Ferris, Report on the research track "Equilibria and computation in markets with risk"
- [10] Florentina Paraschiv, Report on the research track "Pricing and optimization of intraday/day-ahead electricity and futures contracts"
- [11] Tiziano De Angelis and Jan Palczewski, Report on the satellite workshop "Stochastic control and games under ambiguity"
- [12] Goncalo dos Reis, Report on the satellite workshop "Mean-field games, energy systems, and other applications"