Power System Regulation, Planning and Control with the Support of An Energy Market Simulator

T. Siewierski*, S. Galloway, G. Burt, J. McDonald
Institute for Energy and Environment,
University of Strathclyde, Glasgow,UK.
Email: t.siewierski@eee.strath.ac.uk; Tel: +44 (0)141-548-4839;

Y. Kabouris
Hellenic Transmission System Operator (HTSO), Greece

ABSTRACT: Energy market simulation has a role to play in regulation, planning and control of liberalised electricity markets. The development and evolution of such markets internationally has focused the needs of different stakeholders within these markets over a variety of time scales. This paper describes the main objectives and principal assumptions for development and implementation of energy market simulators. The authors describe the background requirements and needs from the perspective of different user groups for this kind of tool. Examples of possible applications are presented for the use of a market simulator and data requirements and indications for a practical realisation of models have also been included.

Keywords: energy market, power system modelling and simulation.

I. INTRODUCTION

Since the early 1990's when the UK was the first country to open its energy market there has been, year by year, more countries following this example [1],[2]. Gradually throughout the last decade significant liberalisation of the rules associated with energy production, trade and supply has been introduced. This has resulted in many different models for the electricity market place being proposed and implemented with varying degrees of success. For some countries this process has not yet been undertaken, and driven by EC Directive 96/92 countries, such as Greece, are now looking for suitable market solutions which accommodate particular conditions. These conditions relate to generation, transmission, security of fuel supply and ownership pattern.

With respect to energy market design most countries appoint an Independent System Operator (ISO) who is typically responsible for the safe and efficient operation of the power system. In addition a Market Regulator (MR) is established who typically represents the government on issues concerning electricity. For example the MR typically formulates the market rules which, in the liberalised environment, are usually based on the principles of competition. Lastly one or more Market Operators (MO) are created who are typically responsible for facilitating and operating the bulk trading of power to the satisfaction of the ISO and ultimately the MR.

In Greece, as the first step on the way to liberalizing energy market, Energy Regulatory Authority (RAE) was established in July 2000. In 2001, Hellenic Transmission System Operator (HTSO) was formed from the previous monopoly structure of the Greek power system as the results of legal and ownership unbundling.

As a result of market liberalisation and the demonopolisation process for generation and supply industries, an increased number of participants are appearing. Energy traders, which do not own any generation transmission or generation assets, are new entities to many energy markets and complete the new structure of the energy sector.

Fig.1 depicts the main players and official bodies dominating the operation of a contemporary power system, together with the principal relationship of physical energy flow, information exchange and settlement (cash-flow).

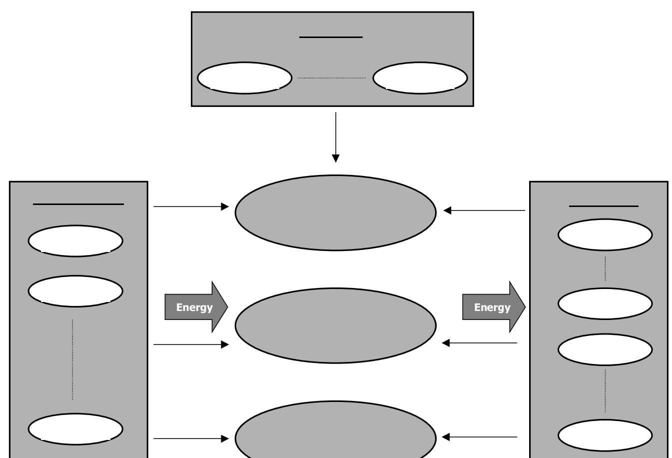

Fig.1 Market Entities with Power, Data and Cash flows

The operation and behaviour of market entities influences market performance and operation. For example, under the UK electricity POOL, dominant generators were observed to be in a position to manipulate market prices [3]. This observation influenced future policy, which resulted in a move towards the current more competitive and transparent trading environment for the UK.

The use of market simulation for a variety of different energy market stakeholders is seen as a useful step forward in the assessment of existing and new energy market implementation. Market simulation is primarily a time domain interdisciplinary problem consisting of a large number of parameters and constraints, which evolve over time, whose purpose is to obtain an informed picture of the future market state and consequently state of the network.

In Section II the importance of temporal aspects of market simulation will be highlighted with three distinct modelling time-scales identified. In Section III the market simulator requirements and methods suitable for modelling will be discussed and identified. In Section IV different energy market segments are discussed. In Section V different modes of use for market simulation by different stakeholders is presented and finally in Section VI some conclusions are drawn.

II. MARKET CHARACTERISTICS

The temporal aspect is one of the most important issues in the determination of the future state of the market. An interval of study could vary between a couple of hours and couple of years depending on the problem under investigation. Like in the case of power system modelling where for the purpose of efficiency and precision we develop sub-transient, transient and steady state models, also energy market requires different modelling of market objects and different methodology used for the calculation of a future state of the market.

The time scale for different market modelling horizons is illustrated in the Fig.2.

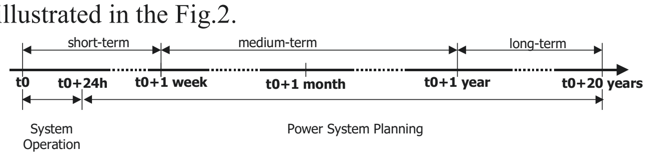

Fig.2 Market simulation time scales

A. **Short-term** market modelling covers the period of hours and days ahead. The time scale is determined mainly by the mode of operation of specific market functions (e.g. gate-closure time, day-ahead delivery, intra-day sessions) and the market segment sequence. This time scale includes influences from all elements of internal market structures and has a strong link with the technical aspects of network operation (e.g. initial state and operational parameters of generating units, network load flow feasibility and standard system reliability or security requirements). A higher degree of certainty exists in short-term studies, and consequently only a limited number of possible scenarios need to be considered in the simulation.

B. **Medium-term** market modelling is considered for the simulation of the market on a time scale of more than one week and less than one-year. An approximate thermo-electrical model of unit operation and the network operation is often adapted for this kind of study. Maintenance scheduling and reliability study aspects are included in the planning for this period. Seasonal influences (derived from historic data) are considered in the demand forecast and participants' behaviour plays an important part in the direction of the market. New market entrances/exits can be influential, and over this modelling horizon they are well defined and do not require any statistical approximation Changes in ownership are of rather limited applicability but should be considered if anticipated over the modelling horizon.

C. **Long-term** modelling usually covers periods of between one year and up to 20 years ahead [4]. Network modelling on this time-scale is limited only to a high-level consideration of the most common constraints (e.g. branch thermal limits and must-runs) and also generating units' parameters such as only stable export limits. New market entrances/exits need separate modelling and the impact of changes in the applied generation technology on the market needs to be accounted for. Changes in market design and the rules of operation, which can be anticipated, can also be considered within the strategic study of energy market and power system development. Ownership patterns and environmental regulations especially for advanced mature markets become one of most important factors impacting market solution [5].

For each of short, medium and long-term modelling time-scales different participation strategies can be adopted by market participants and should therefore be modelled. Neighbouring markets, fuel and financial market models have a varying role to play, which differs depending not only on the implemented market solution but also on the time scale modelled.

III. MARKET SIMULATIONS AND METHODS

A. Requirements

Market simulation endeavours to provide three principal data about system and market states, which are as follows:

- future market prices,
- a price sensitivity function, and
- a generation schedule.

Utilising the principal market data with other information used in power system planning, generation availability, possible network constraints and exploitation of market power a full market analysis can be conducted. Flexible tools have to be designed to account for different market architectures and market rules, system planning, operational requirements and ownership patterns. Furthermore, satisfactory modelling of market participants and other markets, which influence market solutions needs to be applied. Suitable models for participants must include technical, economic and behavioural aspects. Based on these assumptions, the market simulator has to provide reliable information about future market states, where the precision is a function of the time of forecast and scope of available data.

B. Methods and Capabilities

Depending on the objective of simulation and the time scale, different methodologies for energy market simulation can be employed to determine future market states. A short description of the most common methods employed is given below:

1) **Stochastic methods** are based mainly on the analysis of a historic price data looking for the correlation between different factors such as energy price and volatility [6], [7]. These methods represent a static approach, which can often require significant amounts of data to be analysed. This type of method does not provide deep understanding of the market dynamic. It is appropriate rather for long-term studies where local (actual) factors do not play an important role. Similar implementation is possible with the use of neural networks [8], but unless significant volumes of representative data is available as part of the learning set, results can be erroneous.
2) **Game theory methods** such as Cournot or Bertrand competition modelling have been employed to determine the optimal position of the market through the identification of a suitable equilibrium point [9],[10]. For markets these methods enable assessment of strategic bidding for participants using their position in the market to raise their output above the level of investment and production costs. Similar to previous methods it does not require historic market data to set market prices, but still remains a static method.
3) **Cost base methods** use fixed and variable costs of generation, as well as historic availability and capacity factors for all generators to build a supply curve [11]. The demand side model is often defined as a non-flexible demand. Matching of supply and demand curves determines market price and volumes. All units bidding under this price are assumed to be dispatched, all others are not accepted for the delivery period. Two main disadvantages of this method are the lack of consideration of the influence of network constraints, and the absence of consideration for potential strategic bidding from market participants.
4) **Price function modelling methods** can be used to build a mathematical model of energy prices, which depend on selected independent variables from the market, and from the power system [12]. Again historic data either from the market or the power system is used to set up and calibrate the model. A sufficiently large volume of data is required for model efficiency. This method requires deep understanding of market operation and the relationship between market entities.
5) **Heuristic methods** make use of expert knowledge that is often acquired after years of market analysis and operation. These heuristics may relate to intuitive knowledge of the participants within a market or to the behaviour of energy markets in general. Heuristics can usefully supplement other techniques to improve forecast accuracy [13].
6) **Time domain simulation methods** are based on repeated simulation of market cycles where all objects (e.g. market entities, network and associated markets) are modelled not only as function of the system and market parameters, but also as time domain functions, thereby accounting for evolution in the behaviour. This method is flexible with respect to modelling, but may result in a high computational burden. Using these methods behavioural aspects related to market operation (e.g. strategic bidding), technical aspects (e.g. network and unit constraints, system requirements) are embedded in the marker simulator. Example outages and scheduled maintenance studies can also be included.

Among the modelling methods described above methods 1 and 2 are best suited to long-term studies. Methods 3, 4 and 5 can be used in a wide range of energy market analyses over a short to medium horizon. Method 6 is often applied for short-term study due to the computation burden, which often results from longer-term simulation.
Methods 1 and 4 require relatively large quantities of historic market data to provide reliable answers. In the case of neural networks or expert system applications it is often quite difficult to define bounds for the error. Methods 4, 5 and 6 require direct modelling of all important market entities; this is not the case in the other methods. This can result in unacceptable computational costs during simulation especially with the repeated simulation required by method 6.
Price sensitivity information can at times be important. Direct methods such as method 4 can provide such sensitivity data directly, while method 6 would require repeated application. In comparison, method 6 provides the advantage of being able to incorporate important technical issues such as maintenance scheduling and system emergencies.

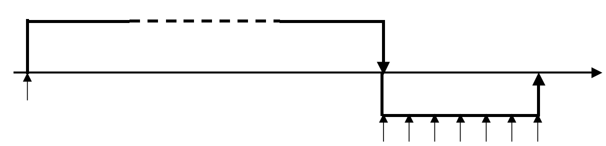

Fig.3 Market simulation in long/medium and short-term study.

It is evident that no one group of methods provides the capabilities required of a generic market simulation intended for short and long-term modelling. A combination of methods provides a viable solution and this has been adapted by the authors in their work.
Previous work has adapted an interactive parameter adjustment to encapsulate long-term market activity [10].
Interactive parameter adjustment completed with the use of long-term and short-term models, as illustrated in Fig.3, provides required generic market simulation capability.

IV. MARKET SIMULATOR COMPONENTS

As discussed in Section III.B the construction of a market simulator depends on the simulation length and the methods to be applied. Clearly, the market simulator construction is also determined by the architecture and market rules as implemented in the particular market.

In time domain simulation all the market segments can be modelled as configurable models [14]. Any market architecture can be reflected with this approach. An example of this general structure is illustrated in Fig.4.

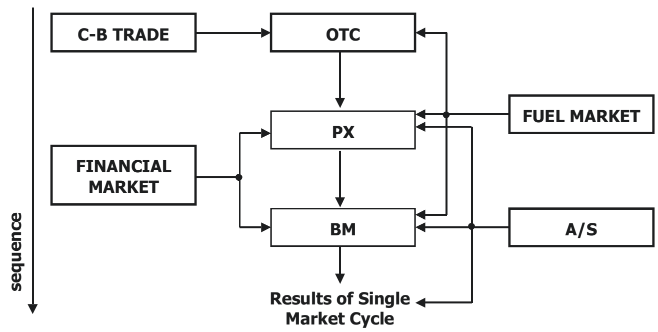

Fig.4 General Market Architecture

In liberalised electricity markets the general energy market segments shown in Fig.4 are identified and characterised as follows:

- Bilateral or Over-the-Counter (OTC) market involves energy being traded via bilateral contracts where all transaction details can be agreed individually for each contract or use a standardised contract.
- Power Exchange (PX) is a mechanism for the centralised trading of energy. Hence for each delivery period there is only one price determined by the ISO, using a matching procedure of supply and demand curves. There can be many power exchanges in the same market and a different number of sessions in each of them.
- Balancing Market (BM) is the first of the technical markets controlled by the ISO. The principal goal of this market segment is to balance demand and supply in the system, using offers and bids from generators and, for some markets, also from demand side.
- Ancillary Services Market (A/S) is a successive technical market controlled by the ISO. Frequency and voltage regulation, and hot and cold spinning reserve can typically be bought under contracts or auctions.
- Cross-border market (C-B) deals with energy imported to or exported from the network over interconnectors.
- Financial market is a hedging market where participants can hedge their exposed position against price risk.
- Fuel market includes coal, gas and crude oil commodity and financial markets.

For medium and long-term market simulation, either all market segments are modelled separately using independent models or a single model is used for the whole market with representative single prices. Depending on a market architecture all (advanced markets, like PJM), selected (UK NETA) or single (UK POOL) segments are included in the simulation engine, what makes the part of simulator configuration process.

V. MODES OF USE FOR MARKET SIMULATOR

In the design and implementation of an energy market simulator one of the critical questions relates to understanding the future use of this tool. The market functions and requirements of future users primarily determine these issues. The following groupings of stakeholders, with respect to liberalised energy markets, are considered the most significant:

- MR or any other legal body supervising or related in some way to an energy market,
- ISO responsible for the control and usually also for the maintenance of a transmission network, and
- Market participants selling and buying real power in bilateral contracts, power exchanges and balancing markets; and also reactive power and reserve capacity in ancillary services market.

A. Market Regulator

The MR is a legal body responsible for enabling the fair competition in electricity market. To achieve its goals the MR uses static methods to investigate market power and calculates concentration indices [9]. Unfortunately this kind of measurement of market power ignores important aspects associated with technical constraints and market issues such as demand elasticity.

The application of game theory based methods with respect to the MR are successful when a relatively long-term equilibrium point is sought [10]. These techniques do not necessarily work in the case of short-term strategy applied by market players.

An example of a situation, that showed the effect of poor short-term forecasting is the strategic bidding of some market players observed in the Californian market between 1999 and 2001 [15]. Companies created and used network congestion to benefit from network charges, use cross-border circular flow to avoid price cap set up for energy generated inside the system or deceive ISO supplying ancillary services generated outside the system. These events were compounded by an insufficient overview of system operation by the regulator for short time periods.

Through the use of an appropriately designed short-term market simulation with an embedded model of network constraints, identification of the types of market abuse described above could be realised. A market simulator could also be of use to the MR at the design stage of an energy market. For example, the architecture and rules of the energy market in Greece are still under discussion [16]. Authorities need to decide about future ownership patterns in the generation and supply by analysing, not only market concentration, but also technology mix, transmission constraints and incentives to locate new generation in preferred regions. Market simulation of a variety of scenarios over different time scales would be of real benefit to the decision making process.

B. Independent System Operator

After liberalisation of the energy market, normally the ISO's influence on the generation schedule is much more limited than in the past, when direct control as the owner of most of the generating units was the norm. Typically, after liberalisation it looses dominant position in the sector, which was previously running as a monopoly, and takes sole responsibility for system security and for energy transmission over the transmission grid.

For the ISO in the liberalised market many planning actions are now managed using forecasting tools. These tools support operational planning and policy decisions associated with the market and ideally, market behaviour can be accounted for. For example, long and short-term system analysis (e.g. connection of new generation, network reinforcement, maintenance scheduling, year, month and day ahead operational system forecasts) is accommodated. An example of how an energy market simulator can be embedded into IT tools that are used for supporting the ISO is illustrated in Fig.5.

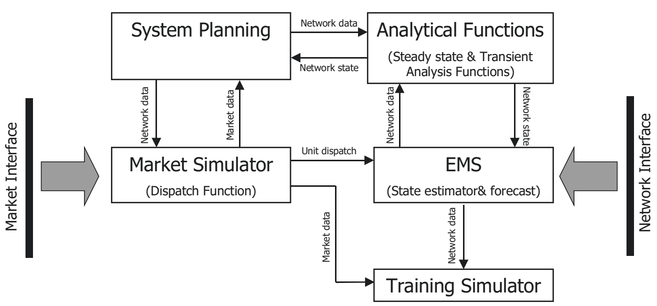

Fig.5 ISO IT System Support Tools

The system-planning module extends to long and short-term plans, prepared and published by the ISO. In long or medium-term studies, the market simulator module takes information from system planning about the future network topology, expected demand and system operational requirements. The market simulator module gives system planners information about available generation, market price, and possible generation dispatch. With this information supplied to an analytical function module the operator can perform steady state analysis (e.g. load flow, fault level) and dynamic stability studies (e.g. voltage and transient stability) in order to correct system plans to meet security requirements in the light of the market information. The completed plan can then be used in an operator training simulator, as shown in Fig.3. This can be used to give system dispatchers the opportunity to exercise planned and emergency control actions. Both commodity markets and ancillary services markets can also be planned in this way.

In the short-term planning mode with the market simulator directly connected to electronic trading systems, information can be gained about transactions from market participants, including both individuals' and institutional information e.g. power exchanges. In Fig.3, the Energy Management System (EMS) shown provides information about the "real" state of the network, as well as a short-term demand forecast. The market simulator module calculates a real unit commitment, which is the final market resolution for energy trades and system balancing. In on-line system control the market simulator could provide information about technical markets (e.g. ancillary services) and, together with the analytical function, module help dispatchers select optimal control actions.

C. Market participants

Market participants can be classified in three groups akin to the groupings shown in Fig.1, which are:

- generators which may consist of anything from single generating units up to groups of power plants under the same ownership),
- loads including suppliers and individual customers who qualify for Third Party Access,
- trading companies, which in contrast to the first two groups usually do not have any network, generation or load assets and profit as brokers from trades in different segments of energy markets.

Due to the real time balancing of supply and demand all market players are exposed to high levels of risk regarding prices and volumes. This exposure is present in all market segments either through short-term bidding when market participants have to submit their bids and offers during intra-day or day-ahead trading and also in contracts markets.

Market participants expect information about future prices with some level of confidence to determine the market position of available generating assets and subsequently plan their operation. For example to divide sales or purchases of energy among different market segments, and to apply financial tools to hedge against anticipated price spikes and drops.

A good example of the complexity of bidding strategies, which depends on the price forecast, is the case of hydroelectric pumped storage plants. These plants try to conserve the use of stored water and re-fill a reservoir as economically as possible using forecasted market prices. Bidding under uncertainty about future prices of this type is a trade-off between price, revenue and dispatch frequency or in other words between immediate and future operation. Self-dispatch of generation assets directly depends on market buy and sell prices so a forecast capability is a very important supporting tool for any optimisation procedure for pumped storage.

Results of market simulation analysis can also be very useful for traders who have to determine market submissions over a very short time scale. Typically, these bids and offers will be constructed from a large amount of data from different market segments accounting for:

- historical data,
- actual system state,
- generation assets available in the market,
- demand elasticity,
- company hedging position and risk strategy, and
- possible competitors and their market position.

This complex analysis is difficult even for experienced market players and therefore supporting tools, such as market simulation over a suitable time-scale, which suggest an “optimal” bidding strategy are of great benefit. Unfortunately for cases of this type the limiting factor is often availability of market data, information about competitors, about the network and the system making the results of market simulation more difficult as compared to the two previous discussed cases, but all include participant modelling.

VI. CONCLUSIONS

In this paper an overview of different aspects of energy market simulation, including temporal aspects, simulation methods and tool construction have been presented. Three important applications were also presented and their general requirements have been discussed.

An approach based on short and long-term models has been indicated. Because of the wide range of energy market architectures a modular construction has been applied. Particular modules representing market segments reflect market rules and time aspects as implemented in the market under study.

No single method provides the solution to the problem of simulating future market behaviour. The implemented system provides some generic capability that will allow application to different markets with some degree of reconfiguration.

Simulation tools for energy markets are highly desirable for both legal entities and market participants. They can be used to either study off-line market behaviour or to support system control in an on-line mode. Future work is being directed towards testing the modular market simulator within different modes of operation.

VII. REFERENCES

[1] “Electricity Market Trading”, P. Stephenson and M. Paun, Power Engineering Journal, December 2001, pp. 277-288.

[2] “An overview of the new electricity trading arrangements”, OFGEM document, May 2000. Available at: http://www.ofgem.gov.uk.

[3] “Competition, Contracts and Entry in the Electricity Spot Market”, D. Newbery, RAND Journal of Economics, 29(4), 1997, pp. 726-49.

[4] “Simulation Model Explores Alternative Wholesale Power Market Structures”, S. Lee, IEEE Comp Apps in Power, April 2002, pp. 28-35.

[5] "Performance and Innovation Unit Report", The Energy Review, February 2002. Available at: http://www.piu.gov.uk/2002/energy/report/TheEnergyReview.PDF.

[6] "The Stochastic Behavior of Commodity Prices: Implications for Valuation and Hedging", E. Schwartz, The Journal of Finance, Vol. 7, No. 3, July 1997, pp. 923-973.

[7] "Stochastic Models of Energy Commodity Prices and Their Applications: Mean-reversion with Jumps and Spikes", Shijie Deng, working paper, University of California, Energy Institute, February 2000. Available at: http://www.ucei.berkeley.edu/ucei/PDF/pwp073.pdf.

[8] "Neural Network Time Series Forecasting of Financial Markets", E.M. Azoff, John Wiley & Sons, 1994, pp. 67-142.

[9] "Determining Equilibrium of Competitive Power Markets", Duy Huu Manh Nguyen, Kit Po Wong, IEEE Proc. Int. Conf on Electric Utility Deregulation and Restructuring and Power Technologies 2000, London April 2000, pp. 119-124.

[10] "Dynamic Games-based Modeling of Electricity. Markets,", P. Visudhiphan and MD Ilic, Proceedings of the IEEE PES Winter Meeting, New York, NY, January 1999, pp. 274-281.

[11] "Dependence of Generation Market Power on the Demand/Supply Ratio: Analysis and Modeling", P. Visudhiphan, M. D. Ilić, Proceedings of the IEEE Power Engineering Society Winter Meeting, Singapore, January 2000.

[12] "A Joint State-Space Model for Electricity Spot and Futures Prices", K.F. Kaaresen, E. Husby, Report of Norsk Regnesentral, December 2000.

[13] "Genetic algorithms for scheduling generation and maintenance in power system", Aldridge, C.J., Dahal, K.P. and McDonald, J.R., in Y. H. Song (ed.), "Modern Heuristic Techniques in Power Systems", Kluwer Academic publishers 1999, pp. 63-89.

[14] "Effective Electricity Market Simulators”, A. Debs, C. Hansen, and Y. Wu, IEEE Comp Apps in Power, January 2001, pp. 29-34.

[15] "Fact-Finding Investigation of Potential Manipulation of Electric and Natural Gas Prices", Federal Energy Regulatory Commission, Office of Markets, Tariffs and Rates (FERC), USA, May 2002.

[16] "Second Benchmarking Report on the Implementation of the Electricity and Gas Directives", Report of the Regulatory Authority for Energy of Greece (RAE), June 2002.

VIII. BIOGRAPHIES

Dr Tomasz Siewierski received his M.Sc. in 1988 from the Technical University of Lodz in Electrical Engineering and his Ph.D. in 1996 from University of Pavia, Italy for his research dealing with the application of Direct Methods in the analysis of Power System Stability. Since 1999 he has focused on the theory and practice of open energy market operation and in 2001 he was appointed as a Research Fellow in the Institute for Energy and Environment at the University of Strathclyde, working in the area of energy market modelling and simulation.

Dr Stuart Galloway received his BSc(hons) degree in Mathematical Sciences from the University of Paisley, an MSc in the Mathematics of Non-Linear Modelling jointly from Heriott-Watt and Edinburgh Universities and a PhD from the University of Edinburgh. He is currently a Senior Research Fellow in the Institute for Energy and Environment at the University of Strathclyde. His research interests include electricity market modeling and design, economic modeling and optimisation.

Dr Graeme Burt received a BEng in Electrical and Electronic Engineering in 1988 and a PhD in 1992, both from the University of Strathclyde. He is currently a Senior Lecturer in the Institute for Energy and Environment ata the University of Strathclyde. His is also associate Director of the Rolls-Royce University Technology Centre in Power Engineering at the University of Strathclyde. His research interests lie in the areas of intelligent system applications in power engineering, optimisation and scheduling, power system modeling and simulation, and embedded generation.

Professor Jim McDonald holds the Rolls-Royce Chair in Power Engineering at the University of Strathclyde Professor James R. McDonald received his BSc and PhD degrees from Strathclyde University. He was appointed as the Manager of the Centre for Electrical Power Engineering at Strathclyde University in July 1990 and took up the position of the Rolls-Royce Chair in Power Engineering in February 1994. His research activities lie in the areas of: Power System Protection and Measurement; Expert System Applications in Power Engineering; Energy Management. He has published over 250 technical papers has published three books.