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Editorial

Advanced Techniques for the Modeling and Simulation of Energy Networks

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1. Research Substrate

The need for a "smarter" energy grid infrastructure, with the large-scale integration of renewables and a better demand–response mechanism, is leading to an ever-increasing complexity of next-generation energy networks [1,2]. These networks are characterized by the increasing role of the interconnection between different domains, as well as by several peculiar features, such as large numbers of nodes, the interconnection of heterogeneous objects (e.g., distributed renewable sources), and stochastic behavior due to fluctuations in customer demand and other external conditions affecting power generation and consumption. All of the above features make the design, optimization, and monitoring of energy networks extremely challenging, thus motivating the demand for advanced modeling and simulation approaches able to accurately and inexpensively predict a network's behavior to achieve functional applications and reliability assessments [3,4].

2. The Special Issue

This Special Issue is composed of five papers and it is designed to bring together expertise from multiple domains. Specifically, it focuses on on-going research towards the development of advanced modeling and simulation tools for complex energy infrastructures. It provides a well-balanced mix of robust methodological pieces of work applied to some key application examples, including the integration of distributed renewable photovoltaic generators in electrical networks, the statistical assessment of blending hydrogen into gas networks, the real-time modeling of power systems, high-impedance fault detection and the analysis and planning of countrywide multi-energy scenarios.

The developed methods range from probabilistic load flow analysis to statistical approaches and topological (i.e., high-level, graph-based) modeling and the application of energy policy optimization tools and (data-driven) machine learning methods. Contributors have shared valuable insights into the recent developments of their research in this field, while also stressing existing challenges and trends, offering a sharp picture of the typical applications in which the proposed solutions fit.

Topics of interest for publication included, but were not limited to, advanced simulation and modeling methods for complex energy problems, soft computing and artificial intelligence in energy systems, machine learning, multi-energy systems, co-simulation, distributed energy resources, and energy demand prediction.

3. Contributions and Trend

Table 1 provides a compact summary of the contributions included in this Special Issue, highlighting both their main methodological content and target applications.

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Table 1. Summary of the different contributions published in the Special Issue in terms of both methodology and application.

Paper	Methodology	Application
[5]	Probabilistic load flow analysis; Gaussian Copula	Node voltage uncertainty and network health (13 node IEEE test feeder and European low voltage test network), with uncertain photovoltaic generators and statistical user loads
[6]	Synthetic network/graph generation; Gaussian Mixture Model (GMM); steady-state analysis; Monte Carlo	Statistical assessment of the effect of deploying hydrogen in existing gas networks, with increasing penetration levels and different locations of grid injection
[7]	Real-time system identification; generalized time-domain vector fitting	Generator and wide area modeling in the IEEE 39-bus test system
[8]	Machine learning; unsupervised learning via convolutional auto-encoders	IEEE 13-node test feeder taking into account various high impedance fault detection
[9]	MARKAL (MARK et al. location model) energy policy optimization tool	Long-term transition toward low-emission power grid and district heating systems in Poland

The first paper, “Gaussian copula methodology to model photovoltaic generation uncertainty correlation in power distribution networks” [5], presents a data-driven approach to the statistical modeling of photovoltaic (PV) generation uncertainties, with specific attention being paid to the correlation among PV generators. The results collected in this paper highlight that the inclusion of the mentioned dependence in a typical power flow analysis produces a better estimate of important parameters such as the variability range of node voltages and the voltage unbalance factor. The proposed methodology is general and can be readily extended to correlated wind generators and loads in probabilistic load flow studies.

The second paper, “A statistical assessment of blending hydrogen into gas networks” [6], provides a tool for the statistical assessment of deploying hydrogen in existing gas networks. The results are derived via steady-state fluid dynamic simulations based on a large number (i.e., thousands) of synthetically generated gas networks which are representative of existing structures (e.g., at the city level). A robust topological tool for gas network generation and technical sizing is fully described. Results provide guidelines for the most advantageous hydrogen injection points that can help operators in the planning of power-to-gas infrastructure. In addition, the study provides insights into injecting hydrogen in pure or blended form.

The third paper, “Handling initial conditions in vector fitting for real time modeling of power system dynamics” [7], proposes a new procedure which performs real-time predictive modeling of linearized dynamics in the presence of ambient perturbation. The proposed method has proven benefits with respect to traditional state-of-the-art alternative solutions, offering power system operators with a valuable tool for building real-time models of power system components whose physical prior models are unknown or possibly inaccurate.

The fourth paper, “Deep learning for high-impedance fault detection: convolutional autoencoders” [8], stresses the strengths of machine learning techniques in practical applications, such as the detection of High-Impedance Faults (HIF). The proposed approach has been proven to rely on a well-established procedure, yielding a procedure robust to noise and allowing the detection of both HIF and non-HIF scenarios.

The last paper in this collection, “Modelling long-term transition from coal-reliant to low-emission power grid and district heating systems in Poland” [9], presents a higher-level planning strategy for setting the directions for the development of generation energy infrastructures, supporting investment decisions in electricity and heat-generation technologies. The study is based on an analysis carried out for Poland and on the definition of the long-term optimal path for the development of the country’s energy sector following two different possible scenarios toward a certain degree of climate neutrality. The role of technical development involving nuclear energy, wind power, cleaner gas-fired power plants, solar and geothermal energy is thoroughly discussed.

All of the above papers actively contribute to the challenges and trends in this field. The cross-fertilization among different research areas will play a dominant role in addressing these challenges in the future, together with the availability of tools and methods belonging to complex networks and systems.

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