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Computational methods applied to multi-energy networks

A B S T R A C T

Multi-energy networks facilitate the interactions of multiple energy carriers such as electricity, heat, cooling, and natural gas for manifold benefits in the construction and operation of energy systems. They also provide a unified platform to integrate and utilize various advanced energy technologies such as renewables, cogeneration, power-to-X, electric vehicles, and energy storage. The problem scale of multi-energy networks is increasing rapidly with the accelerated expansion and integration of regional and urban energy systems. For these reasons, the analysis and optimization of multi-energy networks are faced with significant challenges. New methods are urgently required to address the basic computational challenges in multi-energy networks such as the multi-temporal-spatial scales, nonlinearity, uncertainty, combinatorial property of mixed continuous and discrete variables, and the solving of large-scale systems in a multi-stakeholder context. This special issue mainly covers papers on the computational theories and methods that can be applied in multi-energy networks. The aim is to present a state-of-the-art collection of innovative models, algorithms, approaches, and tools for the control, operation, design, simulation, and analysis of multi-energy networks. The special issue provides an opportunity for researchers and practicing engineers to share their latest discoveries and best practices in these areas.

1. Introduction

Sector coupling is today considered as one of the key enablers for achieving climate neutrality before the end of the century. It involves the integration of energy end-use and supply sectors with one another, and as a consequence can improve the efficiency and flexibility of the energy system as well as its reliability and adequacy [1]. In detail, sector coupling with power-to-X (PtX) provides options to "absorb" excess electricity supply from RES, to store energy, and to convert it into any other form of energy in times of high demand and prices. However, considering the challenges related to the implementation of sector coupling at the regional level, a bottom-up approach is often preferable. This approach would focus on local multi-energy networks by offering several advantages. These systems can be more easily tailored to the specific needs, resources, and constraints of their communities, allowing for greater flexibility and adaptability in implementing sector coupling and PtX technologies at the local level. By involving local stakeholders in the planning and decision-making process, multi-energy networks may foster community engagement and ownership. This can lead to greater acceptance of renewable energy projects, PtX facilities, and sector-coupled systems. The paradigm of local multi-energy networks is also fully in line with the ongoing paradigm shift of the energy system from centralized energy generation (largely dependent on fossil-fueled power plants) to decentralized generation. The latter relies on small-scale RES and combined heat and power units not connected to the high-voltage or gas grid, namely usually small-scale plants that supply electricity and heat to a building, industrial site, or community, potentially selling back surplus electricity.

To achieve the benefits related to multi-energy networks and make them sustainable not only from the energy and environmental perspective but also from the economic one thus having a concrete option to centralized energy systems, coordinated planning and operation on multiple time horizons are crucial. In general, the system planning approach for the multi-energy networks has the goal to identify the optimal configuration of the network, by replying to questions such as *how to develop the system in terms of types and sizes of technologies*.

On the other hand, the operation planning approach allows achieving the optimal scheduling of the network with the support of forecasting tools for RES generation, energy prices for electricity and gas, and users' multienergy demand taking into account many uncertanities.

In the framework of optimization purposes, the models to be developed can traditionally be approached by exploiting mathematical programming methods, such as mixed integer linear programming (MILP) and dynamic programming (DP) methods, which are able to obtain an optimal solution or a near-optimal solution with quantifiable quality against a long computational time (due to the many discrete decision variables involved). Conversely, metaheuristic optimization methods allow obtaining a solution fast even if the problem is complex, while the solution quality is usually difficult to quantify. Moreover, multi-objective optimization models can consider both short- and long-run priorities in the optimal design and operation of multi-energy networks.

2. The topics of interest to this issue include

This special issue covers papers on the computational theories and methods that can be applied in multi-energy networks. The aim is to present a state-of-the-art collection of innovative models, algorithms, approaches, and tools for the control, operation, design, simulation, and analysis of multi-energy networks. The topics of interest to this issue included: 1) Integrated modeling methods of multi-energy networks; 2) Data-driven control of energy devices and storages; 3) AI-based system

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operation and optimization; 4) Advanced optimization methods for operation and planning; 5) Multi-objective optimization models and methods; 6) Advanced state estimation methods of multiple energy flows; 7) Synergies in the integration of energy networks (electricity, gas, heat, etc.); 8) Multi-scale forecasting methods for multi-energy networks; 9) Multi-energy data filtering, processing, compression technologies; 10) Applications of cloud computing and edge computing; 11) Co-simulation methods for multiple energy carriers; (12) Advanced simulation and analysis methods for large-scale systems; 13) Real-time simulation based on advanced hardware; 14) Novel evaluation and assessment methods for multi-energy networks; 15) Application of novel computational methods and experience in pilot projects; and 16) Local energy systems, energy districts and energy communities.

3. Paper published in this special issue

3.1. Survey and classification of tools for modeling and simulating hybrid energy networks

Methods and tools for conceptualization, system planning and operation support exist for all involved domains, but their adaptation or extension beyond the domain they were originally intended for is still a matter of research and development. Therefore, the work [2] presented innovative tools for modeling and simulating hybrid energy networks. A categorization of these tools was performed based on a clustering of their most relevant features. The work allows to provide a guideline for early adopters to understand which tools and methods best fit the requirements of their specific applications.

3.2. Energy management systems for microgrids

A multi-objective Energy Management System for polygeneration microgrids was proposed [3], through a detailed representation of generation units and flexible loads, as well as electric/thermal networks and storage systems that can be present in microgrids and sustainable districts. A novel optimization model was developed by considering as objective functions the minimization of costs, the maximization of the overall exergy efficiency of the system, and the minimization of stress indexes. To solve efficiently the optimization problem, a novel algorithm based on an accelerated version of the Bregman Alternating Direction Method of Multipliers (with Heavy Ball dual acceleration term) was established, and the model was applied to a real case study represented by the Savona Campus of the University of Genova in Italy.

3.3. Machine learning models for RES forecasting

The work [4] investigated the suitability of stacked machine learning-based models to predict wind and solar power available in the same site using a physics informed approach. The method recombines basic meteorological metrics widely available to compute new physics informed ones facilitating the learning procedure, while others are weak machine learning-models themselves. Further, to facilitate the integration of the point forecasters in the stochastic optimization field, a simple unsupervised estimation of the error distribution was proposed to characterize homogeneously scenarios for different resolutions and horizons.

3.4. Sizing and efficiency evaluation of hybrid photovoltaic thermal systems

The work [5] analyses the performance of photovoltaic thermal (PVT) panels in tropical climate regions. In PVT systems, a heat exchanger is coupled to conventional photovoltaic (PV) panels, making possible to improve the efficiency of the PV panels and to provide heat: The decrease in the PV cell temperature increases the electrical power produced, whereas the heat absorbed can be used in low temperature applications, such as water heating or air conditioning. In this work, the main factors that affect PVT systems performance were analyzed to support the choice of the most suitable set of parameters for a tropical climate operation based on technical and economic aspects.

3.5. Electric mobility in energy communities

For this topic, two works were published. The first work [6] proposed an optimization approach to evaluate the impact of electric mobility on the optimal design of renewable energy collective self-consumers. The integration of RES and storage systems with charging infrastructures for electric vehicles was analyzed by establishing a stochastic optimization model, developed in Matlab/Yalmip, to evaluate different scenarios with different electric mobility penetration levels. The second work [7] investigated the integration of active measures involving local energy communities and fast-charging stations for electric vehicles in a general framework for planning of active distribution grids. Active measures were also considered as temporary measures to defer grid investments and reduce the present value of the socio-economic costs of the grid development plan.

3.6. Optimal planning for integrated energy systems

The work [8] proposed a graph theory-based optimizing approach for identifying the energy supply network configuration for an integrated energy system with multiple energy carriers. The proposed method shows more feasibility, effectiveness, and superiority compared to the traditional graph theory. In the developed solving approach, the topology and capacities of pipelines of energy supply network can be optimized simultaneously.

3.7. Power flow methods for radial distribution systems

The work [9] proposed an interval power flow method based on a hybrid second-order cone and linear programming for radial distribution systems. Moreover, considering that the second-order cone programming formulation can only achieve half of the whole interval power flow process, a revised linear DistFlow formulation is adopted, and the interval power flow method based on a hybrid second-order cone and linear programming was devised. The proposed method was compared with the standard power flow equation-based interval power flow method and the Monte Carlo method.

3.8. Co-optimization of multi-stakeholders in multi-heterogeneous energy system

Multi-heterogeneous energy systems aim to exploit the advantages of coupling between electricity, heat, and gas. However, the common approach utilized to obtain the overall optimum cannot consider the existence and interests of all stakeholders in energy sectors such as electricity, heat, gas, and energy hubs. This work [10] developed collaborative optimization and solution methods after clarifying the interaction mechanism of multi-stakeholders.

4. Conclusions

Creation, development, and operation of multi-energy networks is motivated by possible benefits such as producing where energy is consumed, increasing energy efficiency and flexibility, end-user engagement, reducing system vulnerabilities, and addressing energy poverty. Planning and operation of multi-energy networks is very complex due to many technical and stakeholder interdependencies in addition to the need for considering several time horizons. New computational methods are needed to address the basic challenges in multi-energy networks such as the multi-temporal-spatial scales, nonlinearity, uncertainty, combinatorial property of mixed continuous and discrete variables, and the solving of large-scale systems in a multi-actor context.

Key insights from the featured works demonstrate the potential of multi-energy networks to enhance energy efficiency, optimize energy utilization, and serve as integral components of renewable energy-driven systems. Research contributions have addressed critical challenges such as optimal planning and operation, resource optimization, and scalability, offering solutions that balance operational efficiency with economic and environmental benefits as well as methods for addressing multi-actor complexity.

Finally, this editorial serves as a call to action for continued innovation and collaboration in exploring the vast opportunities offered by advanced computational methods for multi-energy networks.

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