Doctoral Dissertation
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Multi-Vector Energy Integrated Networks for Local Energy Systems

By

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Abstract

To limit the effects of climate change and move towards a post-carbon society, the ongoing energy transition must accelerate. The global and European objectives regarding enhancements in energy efficiency, greenhouse gas emissions reduction and increased adoption of renewable sources are ambitious and imminent. Therefore, it is necessary to speed up the process. Heating and cooling of buildings plays a key role in this transition. Interventions must take place on the demand side by reducing consumption, and on the supply side by modifying energy mix and production technologies, resulting in more efficient and less polluting configurations.

My Ph.D. research tackles this challenge, exploring the district heating field, recognized as a promising driver for decarbonizing the thermal sector. Given the different available technologies for present and future district heating, it can be considered as a multi-vector energy system (MVES) for local energy networks, thanks to the synergy of different energy carriers in satisfying thermal demand. As the European legislation will require an increasingly higher percentage of renewables to define the efficient district heating, having a flexible system has become a prerequisite for each network. The overall objective of the Thesis is therefore the assessment and quantification of the flexibility potential in multi-vector energy integrated networks.

A review conducted on the methods currently used in literature led to the identification of the gaps and the definition of a simulation-based methodology for the assessment of flexibility in MVES. In fact, one of the shortcomings of the methods analyzed was the lack of analysis of impacts of the networks on the calculation of flexibility. Thanks to the energy simulation it was possible to consider the system in its entirety, from production technologies to the network and users. This general theme was then divided into four more specific research questions which deal with the necessity of: (i) identifying the flexible sources for the district heating "of today" and "of the future", (ii) finding which instruments can facilitate the flexibility assessment in MVES, (iii) evaluating the effects of all the involved components (including the network) and finally (iv) analyzing how flexibility can be exploited in an all-electric district heating system with heat pumps. The research questions are described in detail in the dissertation, and led to the development of two main applications.

Specifically, the first Case Study was mostly devoted to the development of a dynamic simulation tool, capable of conducting quick but accurate simulations of a

third-generation district heating network. This application was chosen as representative of the district heating currently under operation, with a centralized layout and fossil fuels in the main power plant. Indeed, the power station was composed of a gas combined heat plant and a gas boiler able to provide heat to a high temperature network (almost 90°C). The results of the simulation phase allowed to understand the dynamic behaviour of such a complex energy system and then they were used as input for flexibility computation. In this first application, flexibility was evaluated from the supply side; technical and physical limitations were explored for conversion technologies but also for the thermal network, while users were considered as passive. Through Application #1 it was demonstrated how the dynamic simulation of the district heating network is a fundamental instrument not only for calculating flexibility, but also for verifying the functioning of the network through the hourly visualization of some reference quantities (e.g., temperature, pressure and flow rate along the pipes).

On the other hand, the second application was developed to analyze the issue from another perspective. Indeed, the simulation tool was customized to model a fifth-generation district heating network, with an all-electric layout, composed of a ground-water source heat pump in the main power station and water-to-water heat pumps at district level. In this case study, without neglecting the modeling effort, the objective was to investigate how to make the system flexible, since, without any backup unit, it was not possible to modify the generation profiles of the heat pump while guaranteeing the heat provision to users. Thus, in Application #2, it was studied how Demand-Side Management can be exploited on users' thermal loads. By varying the consumption according to external forcing (i.e., advantageous prices on intra-day market or presence of renewables) while maintaining acceptable comfort temperatures, it was possible to modify the electrical absorption of the heat pumps to follow the load, providing upward or downward flexibility to the electric grid. In this application, also financial implications were evaluated.

To conclude, the development of the MVES models on the dynamic simulation tool, coupled with the elaboration of results for flexibility computation, is a valuable instrument for the grid operator to understand the behaviour and operation of the system but also to calculate flexibility KPIs (both energy and financial ones) useful for improving the system management.

ASSESS AND COMPUTE FLEXIBILITY POTENTIAL IN MULTI-VECTOR ENERGY INTEGRATED NETWORKS

RQ1: Which flexible sources can be exploited in the network of 'TODAY' and 'TOMORROW'?

RQ2: Which instruments can facilitate the flexibility assessment in Multi-Vector Energy Systems?

	APPLICATION #1 TODAY	APPLICATION #2 TOMORROW
TECHNOLOGIES	3° GENERATION DH CHP + Gas Boiler	5° GENERATION DH Heat Pumps
RQs	RQ3: How can the evaluation of flexibility in a DH multi-vector system consider the influence of all the involved components (production, network and users)?	RQ4: How can flexibility be introduced into an all-electric DH system incorporating heat pumps?
INSTRUMENTS	Network dynamic simulation, flexibility KPIs	Network dynamic simulation, RB approach, building dynamic simulation, flexibility KPIs
STAKEHOLDERS	DH grid operator	DH grid operator, DH final users