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Scuola di Dottorato - Doctoral School
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Doctoral Dissertation

Doctoral Program in Energy Engineering (37th cycle)

Advanced management for resilient and sustainable Multi-Energy Systems

By

Giulia Manco'

Supervisor(s):

Prof. Vittorio Verda, Supervisor

Prof. Elisa Guelpa, Supervisor

Doctoral Examination Committee:

Prof. Costanza Saletti, Referee, University of Parma

Prof. Claudio Del Pero, Referee, Politecnico di Milano

Prof. Paola Caputo, Committee Member, Politecnico di Milano

Prof. Luis Serra, Committee Member, University of Zaragoza

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Giulia Manco'
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Abstract

Achieving the European Union’s decarbonisation targets requires a fundamental shift towards energy systems capable of integrating decentralised renewable sources at a small-scale level within larger-scale energy networks. Designing flexible and resilient multi-energy systems to enable deep decarbonisation while ensuring a reliable and efficient energy supply has thus become a critical priority. This thesis explores modelling and optimisation strategies to support this transition, with a particular focus on *thermal prosumers*—buildings that can both consume and inject thermal energy into district heating networks.

The work is structured around two closely connected pillars: (1) the application of the multi-energy system concept to buildings, and (2) the exploration of the potential of thermal prosuming in district heating networks. These two directions are complementary, as the accurate modelling and optimisation of energy systems at the building level provides the foundation for assessing and enhancing their contribution as thermal prosumers.

Starting from a critical literature review, this thesis proposes a structured methodology to classify energy system optimisation problems based on their discriminating features — such as the choice of objective function, the presence of uncertainty, the degree of nonlinearity, etc. — and maps them to suitable mathematical formulations (Linear Programming, Mixed-Integer Linear Programming, Nonlinear Programming, Mixed-Integer Nonlinear Programming). This theoretical framework is applied to case studies involving residential and non-residential buildings within the context of the *RE-cognition* European project. Specific optimisation tools are developed to support system sizing and operational strategy definition, integrating low-TRL technologies (such as micro combined heat and power units, latent heat thermal storage, small-scale wind turbines and lightweight photovoltaic panels) along with more established technologies such as solar thermal systems and heat pumps. In

addition, uncertainty in investment costs and energy prices is addressed through stochastic programming.

These initial analyses focus on the optimisation of distributed energy resource sizing, aiming to satisfy a building internal energy demand through the integration of renewable and high-efficiency technologies. The subsequent focus shifts towards the role of buildings as thermal prosumers, actively interacting with district heating networks by supplying renewable energy. To enable reliable system representation, detailed models are developed for key thermal energy components. These models aim to balance physical accuracy with computational tractability and are designed for seamless integration into larger simulation and optimisation frameworks. Building on a detailed study of bidirectional substation layouts, a preliminary temperature-constrained optimisation framework is introduced to support technology sizing and operating strategies consistent with network conditions and user requirements. Subsequently, several configurations combining solar thermal systems and water-to-water heat pumps are systematically analysed and compared. A comparative assessment highlights the strengths and limitations of each solution. Finally, clustering techniques are applied to identify representative operating patterns and support the selection of promising prosumer profiles.

The thesis contributes:

- A methodological guide for selecting appropriate mathematical formulations based on problem nature;
- Simulation and optimisation tools for buildings and emerging technologies under uncertainty;
- Validated detailed models for thermal components;
- Detailed analysis and design optimisation methodologies for thermal prosumers;
- Data-driven analysis to support the integration of prosumers into existing networks.

These contributions aim to close the gap between academic research and practical implementation, supporting the EU decarbonisation goals through flexible, decentralised, and smart energy system design.