Doctoral Dissertation

Doctoral Program in Electrical, Electronics and Communications Engineering

(37$^{\text{th}}$cycle)

Methodologies for Modeling, Assessment, and Optimization of Integrated Community Energy Systems

By

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2025

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2025

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

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The transition to sustainable energy systems is driven by decarbonization and decentralization of energy production, necessitating community-level integration of renewables for optimal use. Integrated Community Energy Systems (ICES) and Renewable Energy Communities (RECs) have emerged as key paradigms in this context. ICES offer a framework for managing multi-energy systems across communities, while RECs provide a practical means to implement these models within existing regulatory and market landscapes.

This thesis advances ICES and REC modeling, optimization, and assessment by developing methodologies to address key challenges in their design and operation. A multi-node, multi-energy model is formalized to capture the complexities of community energy systems, incorporating sector coupling and storage. Key Performance Indicators (KPIs) are introduced to evaluate ICES from energy, environmental, and economic perspectives. Three key areas are explored: optimal energy management, energy consumption prediction, and many-objective design.

First, a Mixed-Integer Linear Programming (MILP) framework is developed to optimize operational energy flows in complex ICES, enabling assessment of energy, environmental, and economic performance. Results show the benefits of coordinated optimization strategies and detailed multi-node modeling for accurate economic evaluations. However, scalability analysis highlights that trade-offs between model accuracy and computational complexity are required, suggesting that data-driven approximations could enhance scalability.

Second, a data-driven methodology is proposed to predict hourly electricity consumption profiles from minimal data, such as time-of-use bills. This is often necessary due to the lack of measurements, while other data (e.g., renewable generation or prices) can be derived from historical records or consolidated methods. A regression approach is shown to outperform traditional benchmarks, particularly for non-residential end users. This method is validated for ICES optimization, offering solutions in data-limited scenarios. Future work could refine this approach by incorporating category-specific models and accounting for seasonal variability.

Finally, the thesis explores many-objective design optimization of ICES, focusing on scalarization approaches to identify compromises between conflicting objectives. Game-theory concepts are used to treat objectives as players in a cooperative game, identifying equilibria. A preliminary study samples the design space, highlighting the increasing complexity of Pareto-dominance relationships as objectives increase. Scalarization metrics offer insights into many-objective optimization strategies, though further research is needed to validate these findings in real-world scenarios.

Overall, key contributions and innovations to the current state-of-the-art include:

- Formalization of a multi-node modeling and optimization framework for assessing physical and virtual energy flows within ICES.
- Integration of sector coupling, storage, and multi-energy modeling in ICES for integrated assessment.
- Comparison of individual node and overall ICES perspectives through optimization and KPI assessment.
- Testing the scalability of MILP-based optimization in relation to an increasing ICES size.
- Data-driven approach for predicting hourly load profiles to improve ICES assessment in data-limited contexts.
- Preliminary exploration of game theory-inspired strategies for multi and many-objective optimization in ICES design.

These contributions advance the understanding and capabilities of ICES and RECs, laying a foundation for their broader adoption and the transition to sustainable energy systems. While offering impactful methodologies and insights, this work highlights the need for further research in areas not covered, including sensitivity analysis and optimization under uncertainty, real-time resource management, and scalable data-driven methods.