Doctoral Dissertation
Doctoral Program in Energy Engineering (37th Cycle)

An energy planning perspective about the multi-sectorial synergies and implications of the energy transition

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Abstract

This thesis explores the pathways to a decarbonized energy system, focusing on the critical role of multi-sectorial energy system optimization models. By integrating interactions across sectors and optimizing complex energy configurations, it identifies cost-effective decarbonization pathways tailored to the Italian energy system.

The study underscores the interconnectedness of different sectors and the necessity of a comprehensive, integrated approach to decarbonization. Key findings highlight the potential of low-carbon technologies and energy carriers, such as blended low-carbon fuels, in reducing CO_2 emissions while utilizing existing infrastructure. These commodities are particularly effective in decarbonizing hard-to-abate sectors like transport and industry. The system-wide perspective adopted ensures that emissions accounting encompasses both supply and demand sectors, optimizing the utilization of carbon capture and storage technologies.

The analysis of marginal abatement costs reveals sector-specific challenges, emphasizing the need for targeted policies. While the power sector benefits from low-cost renewable technologies, the industrial sector faces higher abatement costs. Aligning sector-specific policies with broader strategies that leverage inter-sectoral synergies, such as electrification enabled by renewable electricity, is crucial for efficient decarbonization. Economic factors, including hurdle rates, significantly influence investment decisions, particularly in the transport sector. Integrating financial considerations into multi-sectorial models enhances the understanding of economic dynamics and identifies effective levers for driving decarbonization investments.

The thesis also addresses the challenges posed by critical raw materials availability. The rising demand for materials like lithium, essential for electric vehicles and storage systems, necessitates coordinated strategies to manage supply risks. Ensuring the availability of these materials and securing resilient supply chains is vital to prevent disruptions that could hinder the energy transition.

Several limitations are acknowledged, primarily stemming from model assumptions, data availability, and uncertainties in future energy system dynamics. Key constraints include the maturity and techno-economic characteristics of emerging technologies, assumptions about renewable energy resources and CO_2

storage potential, and the absence of transmission line representations. Simplifications in policy modeling, such as uniform carbon taxes and hurdle rates reductions, may not fully capture real-world complexities. Additionally, the model focus on emissions factors for classifying technologies may overlook broader sustainability dimensions relevant to green finance and investment decisions.

Future research directions include incorporating the AFOLU sector and revisiting emission factors for blended biofuels to provide deeper insights into the biofuel value chain. Sensitivity analyses on techno-economic parameters and sector-specific carbon pricing mechanisms will enhance the robustness of model outputs. Extending the geographical scope beyond Italy will improve the generalizability and resilience of the findings. In addition, testing the proposed methodologies on multiregional energy system models that explicitly capture transmission lines and grid infrastructure will provide more realistic assessments of renewable energy integration. Exploring materials recycling and technology reuse options within the modeling framework will support the development of resilient energy systems, reducing dependence on new material supplies.

In conclusion, this thesis demonstrates the importance of a multi-sectorial, integrated approach to energy system modeling. By considering interconnections between sectors, technologies, economic dynamics, and material supply chains, the study offers a comprehensive framework for evaluating decarbonization pathways. The findings provide valuable guidance for policymakers, investors, and industry leaders in navigating the complexities of the energy transition and achieving a sustainable, decarbonized energy system.