Doctoral Dissertation
Doctoral Program in Energy Engineering (38th Cycle)

Sustainable approaches for the Land-Energy nexus through Energy System Optimization Models

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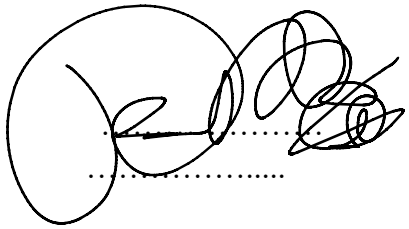

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Summary

Integrating sustainable development and climate change mitigation, into decision-making processes is one of the most pressing challenges for current policy frameworks. The energy sector has relied on modelling tools to understand system complexity and to design cost-efficient and environmentally effective policies. As a result, economic (least-cost optimization) and environmental (emission reduction) dimensions have long been at the core of energy system planning. However, these two dimensions alone are not sufficient. The growing of the sustainability agenda requires modelling approaches that incorporate additional dimensions—social, security-related, and cross-sectoral. Despite this need, Energy system optimization models (ESOMs), which for decades served as robust planning tools, remain limited in their ability to account for sustainability indicators and the so-called "nexus" of interlinked systems: climate, water, land use, and energy. In particular, the land-use sector is often mis-represented in current models, leading to biased conclusion about its role. This nexus is increasingly relevant considering new challenges such as the large-scale deployment of renewables and the impacts of climate change directly interact with agriculture, forestry and other land uses (AFOLU).

The scientific literature has highlighted two main research gaps. A first one is related to the necessity of developing sustainability metrics able to link energy system results with globally recognized sustainability objectives. Such metrics should extend beyond environmental impacts to also capture social and energy security aspects and should move beyond the subjectivity of current weighting schemes by introducing a methodology capable of identifying persistent critical indicators across different weight configurations. The second is related to the need for deeper integration of nexus elements, with particular emphasis on those aspects that represent critical bottlenecks depending on the regional context. In Mediterranean and European settings, the availability of land for energy purposes and the decline in agricultural yields due to climate change are particularly relevant. These constraints must be explicitly considered, especially since the land-use sector is often expected to provide significant ecosystem services for climate mitigation.

The objective of this thesis is therefore dual. The first objective is to provide a sustainability metric capable of overcoming the limitations of current approaches. The complementary objective is to enhance the representation of AFOLU sector within energy system. The thesis develops and applies a novel sustainability metric to the Italian power sector, demonstrating that land use and energy system reliability emerge as critical dimensions. Building on this insight, the thesis expands the modelling of the AFOLU sector within energy system frameworks. To test the robustness and reproducibility of the proposed methodology, two implementations were developed: one in the TIMES model for Sweden and one in the TEMOA model for Italy. In Sweden, the integration of AFOLU revealed that negative emissions from forests can, in some scenarios, reduce the mitigation effort required from other sectors. In Italy, by contrast, the analysis showed that while land use is highly emphasized in national plans, the sector is often unable to generate the assumed negative emissions—sometimes not even offsetting its own positive emissions. This highlights the risk of

overestimating AFOLU contribution in energy planning and the need for more balanced and realistic assumptions.

Graphical summary