

Thermodynamic Mapping of Italy's Green Energy Transition: An Exergy-Based Leontief Input-Output Analysis of Sectoral Emissions and Entropy Flows

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The transition to low-carbon energy systems requires analytical tools that integrate economic interdependencies with the laws of thermodynamics. This study develops a thermodynamically extended Leontief Input-Output (I-O) model, incorporating Environmentally Extended Input-Output Tables (EE-IOTs), to quantify exergy flows, emissions intensities, and entropy generation across Italy's key economic sectors during its green energy transition.

By treating the national economy as an open thermodynamic system, we trace how energy carriers of differing exergy quality are allocated, transformed, and degraded across intersectoral production networks. Emphasis is placed on electricity, manufacturing, and construction—sectors critical to both economic output and energy throughput. Sector-specific exergy destruction and entropy generation rates are derived from transformation efficiencies, energy balances, and emissions data.

Results show that renewable electricity—particularly solar and wind—achieves the highest exergy efficiency and the lowest entropy generation per unit of output, generating positive systemic spillovers. In contrast, fossil-dependent manufacturing sectors emerge as thermodynamically irreversible nodes, with substantial exergy losses. The construction sector, while moderate in exergy terms, plays a pivotal enabling role in infrastructure deployment.

Scenario analysis indicates that aligning renewable energy investment with sectors characterized by low entropy-to-output ratios yields maximum decarbonization efficiency. By embedding thermodynamic constraints into macroeconomic modeling, this work presents a novel exergy-based framework for assessing the sustainability of national energy transitions. It advances the integration of physical energy metrics into economic policy design, enabling more physically consistent and systems-informed decarbonization strategies.

Keywords: Exergy analysis, Entropy generation, Thermodynamic economics, Leontief Input-Output model

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