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Designing integrated and resilient multi-energy systems via multi-objective optimization and scenario analysis

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Multi-energy systems (MESs), which integrate various technologies and energy vectors in a single unified framework, have proven to be effective and flexible tools for addressing the challenges faced by energy systems in a changing world. These include the need for decarbonization, increasing penetration of renewable energy sources, a push for decentralization and independence in energy markets, and rapidly shifting socio-economic and climatic conditions.

However, traditional modeling tools for MESs planning and management have several shortcomings. Existing multi-energy planning and modeling frameworks often prioritize minimizing a single monetary objective. Even when multiple objectives are considered, they are often monetized, reducing the problem to a single-objective approach and limiting the exploration of possible solutions. Additionally, MES planning struggles to account for uncertainties arising from climate and socio-economic variables, especially with the rise of non-programmable energy sources and frequent disruptions in global supply chains and energy stability.

The work hereby presented aims to overcome these limitations by developing modeling frameworks that allow for exploring various configurations of multi-energy systems based on non-comparable objectives. The goal is to extract trade-off solutions through optimization algorithms under different future scenarios. The framework integrates the single-objective configuration model CALLIOPE with multi-objective evolutionary algorithms to explore the decision space thoroughly. Multiple algorithms are tested, and the best-performing algorithm is used to extract optimal configurations under alternating scenarios of renewable energy generation potential and energy prices.

The new framework is tested on a synthetic case study based on the Sulcis Iglesiente (SI) Province in Sardinia, Italy, a region facing socio-economic challenges exacerbated by the planned phase-out of a local coal power plant. The analysis considers opportunities for investing in renewable resources, expanding the local renewable power pool, installing energy storage batteries, and transitioning from gas and oil boilers to heat pumps and biomass generators. Objectives such as air quality, energy independence, economic considerations, and emission targets are taken into account.

Results demonstrate that the new methodology allows for the extraction of multiple optimal configurations of the multi-energy system, incorporating different technology combinations based on the relative importance of objectives. Among the tested algorithms, EpsMOEA and OMOPSO perform the best, thoroughly exploring the decision space and returning unique optimal configurations. Scenario analysis reveals that the attractiveness of certain technologies, especially for heat generation, is highly sensitive to different objectives and scenarios. In contrast, others, such as onshore wind plants, remain favorable regardless of circumstances.

The methodologies presented in this work signify a significant step forward in finding optimal planning and management solutions for multi-energy systems. They successfully capture the intrinsic complexity of the problems considered, supporting the search for integrated, efficient, participatory, and sustainable solutions.