Energy Transition & Multi-Energy Systems

A Holistic, Multi-Objective Optimization Perspective

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ABSTRACT: The decarbonisation of energy systems consistent with the 2050 net-zero trajectories cannot be reduced to a component-level substitution exercise; it must instead be formulated as a holistic, multi-scale optimisation problem in which conversion, storage, transport and end-use are co-designed under coupled techno-economic and environmental constraints. To this end, the authors propose a unified analytical framework for the optimisation of Smart Multi-Energy Systems (S-MES), articulated upon reduced-order component modelling, a three-pillar techno-economic-environmental assessment, and a two-layer master-planning / optimal-dispatch formulation. The methodological consistency of the approach is substantiated through two industrial-scale demonstrators drawn from hard-to-abate sectors.

1 Energy Transition as a Systemic Problem and the Multi-Vector Architecture

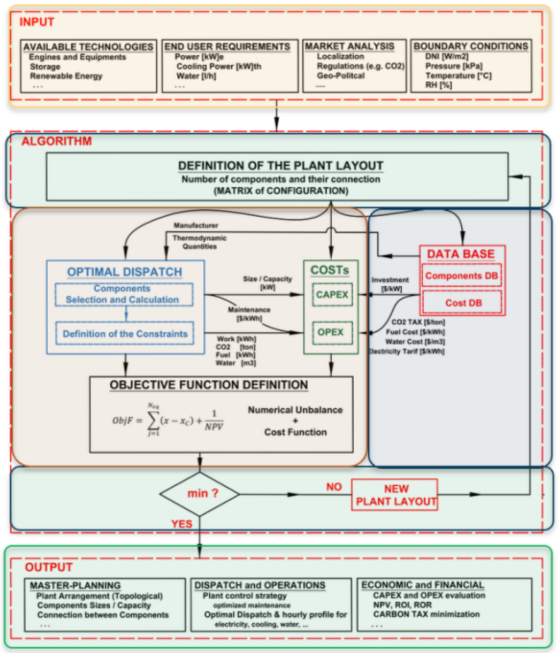
The costs and benefits associated with the transition are redistributed along the entire value chain, with the consequence that the relevant unit of analysis shifts from the individual converter to the integrated system. Accordingly, the authors adopt a four-block canonical representation of the **Smart Multi-Energy System** (S-MES) — comprising the supply chain, the conversion and storage assets, the multi-vector energy buses, and the demand chain. The systemic benefit does not stem from the peak efficiency of any individual asset, but rather from the engineered complementarity between loads and between energy carriers, exploited across the daily, seasonal and intermittency time-scales.

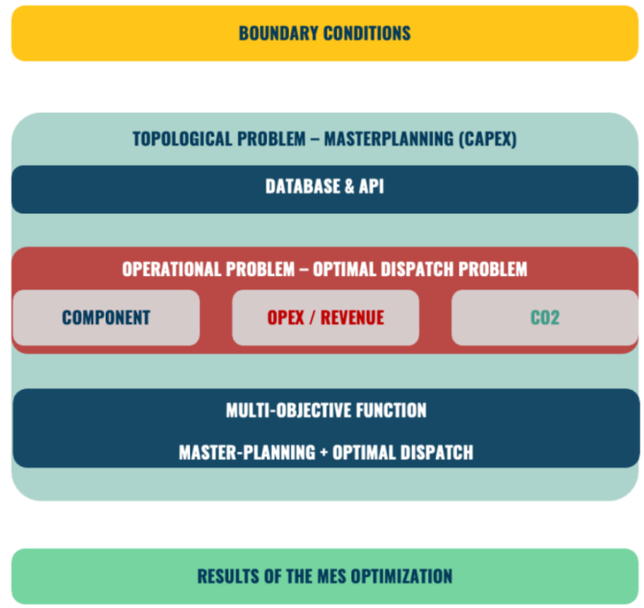
2 Modelling Approach: from Real Component to Reduced-Order Representation

Three modelling paradigms are distinguished — **white-box, gray-box, black-box** — and, in the context of MES master-planning and optimal dispatch, the 0-D grey-box, steady-state formulation is demonstrated to constitute the most adequate compromise in respect of interpretability, data availability and computational tractability. Each component is described through lumped performance parameters — efficiencies, coefficients of performance, off-design maps — coupled to the conservation equations of mass and energy, thereby producing a modular structure readily extendable to additional energy carriers (H_2, NH_3). It is worthy of note that model order reduction does not entail a loss of accuracy, but rather a controlled loss of information, whereby the aggregate quantities relevant to the decision layer are preserved while the local detail immaterial at that scale is deliberately suppressed.

3 The Three Pillars of MES Optimisation: Technical, Economic, Environmental

The optimisation problem is articulated upon three mutually reinforcing pillars. The **technical pillar** ensures that each asset operates within its admissible envelope under time-varying boundary conditions; the **economic pillar** quantifies CAPEX, OPEX — encompassing fixed and variable O&M, fuel and CO_2 expenditures — and the relevant revenue streams (energy sales, ancillary services, capacity payments, incentives, carbon credits); the **environmental pillar** accounts for Scope 1 and Scope 2 emissions and embeds carbon pricing as an endogenous decision variable. Accordingly, decarbonisation is not externalised as a constraint, but enters the multi-objective formulation as a monetised driver of both design and dispatch decisions.





4 KPIs, Multi-Objective Function and the ©E-OPT Optimisation Framework

Project viability is appraised through a coherent set of financial indicators — **NPV, IRR, PBP, ROI, LCOE/LCOX** — aggregated into a weighted multi-objective function reflective of the decision-maker's preferences. To this end, the ***©E-OPT*** platform implements the optimisation as a two-layer architecture: *master-planning* (topology, nominal sizes, redundancy) and *optimal dispatch* (power-flow balances, operating envelopes, time-dependent costs and emissions). The choice of solver — linear/MILP, NLP or metaheuristic — is dictated by the cardinality of the decision space; the output consists not of a single optimum, but of a scenario matrix that renders alternative technological pathways commensurable under conditions of market and regulatory uncertainty.

5 Industrial Case Studies

The framework is exercised on two industrial-scale demonstrators representative of hard-to-abate sectors: **(i)** a 200 MW combined-cycle gas turbine fired with 100% green ammonia, conceived for a hyperscale data centre in Asia, for which the analysis quantifies the premium cost of the decarbonised energy carrier and identifies the regulatory levers required to close the resulting bankability gap; and **(ii)** a 1 MW H_2-ready combined heat and power unit deployed at an electric-vehicle charging hub, exemplifying the integration of low-carbon polygeneration within electrified mobility infrastructure.

KEYWORDS *smart multi-energy systems · grey-box modelling · model order reduction · polygeneration · off-design maps · CAPEX · OPEX · LCOX · Scope 1–2 emissions · carbon pricing · multi-objective optimisation · master-planning · optimal dispatch · MILP · ©E-OPT · green ammonia · H_2-ready CHP · hard-to-abate sectors*

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