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Bridging Economics and Physics in Energy System Analysis: Effects of Flexibility Representation on Model Outcomes

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Efficient decarbonization of fossil-based energy systems requires extensive electrification of end-users' heating and mobility sectors. Replacing gas-based heating with electric heat pumps and fuel-based private vehicles with battery electric vehicles increases the use of renewable electricity and can substantially improve overall energy efficiency. At the same time, distribution grids were largely designed for lower peak demand and will increasingly face local capacity constraints as electrification progresses. These constraints arise not only from higher baseline load, but also from price-driven operation: households and aggregators respond to market signals and shift demand in ways that can amplify simultaneity and peaks. Consequently, demand-side flexibility is becoming central to both market-oriented dispatch and grid-aware operation. To address these topics, energy system modelers must consider realistic yet feasible representations of sector coupling technologies. However, there is a wide range of ways to model demand-side flexibility, and the impact of these conceptual and physical differences on model outcomes remains insufficiently understood.

This study develops a meta-analytical modeling framework to assess and classify the physical fidelity of flexibility representations in market-oriented optimization models. First, we conduct a systematic literature review and derive a structured taxonomy for flexibility models of heat pumps and battery electric vehicles, distinguishing two key dimensions: (i) component modeling depth (e.g., constant versus operating-state-dependent efficiency, endogenous coefficient of performance behavior, explicit storage dynamics) and (ii) aggregation level (single-device versus fleet/virtual storage representations). Second, selected model classes are implemented in a case study to compute optimized dispatch schedules and to quantify the implications of modeling choices. To evaluate physical feasibility and realism, we couple the market optimization results with physics-based dynamic simulation, benchmarking optimized schedules against simulated component behavior. For the simulation, a dynamic model in Modelica using the TransiEnt Library is used. Because high-fidelity formulations can become numerically demanding at scale, we also analyze the effect of aggregation and introduce an aggregation and online disaggregation strategy that enables tractable optimization while preserving component-specific validation in the simulation domain.

Results show that greater component modeling depth generally yields more realistic optimization outcomes, but at higher computational cost. For heat pumps, modeling the coefficient of performance endogenously and representing storage dynamics more accurately improves the prediction of realized behavior and dampens price-arbitrage incentives, thereby reducing apparent flexibility compared to simplified constant coefficient of performance. For battery electric vehicles, accounting for partial-load charging, where charging efficiency typically decreases at low power, reduces the risk of energy underprovisioning and prevents systematic overestimation of flexibility and the value of market incentives. Across scenarios, aggregation level has only a minor influence on techno-economic outcomes when appropriate dispatch models are used that account for relevant system states (e.g., temperatures, states of charge, and electrical/thermal loads) and when disaggregation

reconstructs physically consistent device-level operation. Overall, the study indicates that errors from insufficient component-level physical detail can outweigh aggregation effects. Transparent reporting of modeling depth, aggregation assumptions, and validation practices is therefore essential to ensure robust and comparable insights for utilities and policymakers.

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