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Evaluation of the impact of robustness regarding demand side uncertainty on the estimation of load flexibility bands for home energy systems

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Motivation

The ongoing electrification of sector-coupling applications within distribution grids is particularly pronounced at the household level, where distributed energy resources (DERs) such as electric heat pumps, battery electric vehicles, and battery storage systems are increasingly utilized. These DERs provide operational flexibility, i.e. the ability to adjust electricity consumption within given limits. While volatile demand profiles can strain the distribution network, the controllable nature of DERs also enables their use for congestion management and grid stabilization. To effectively exploit these potentials, a quantification of available flexibility is essential. Existing approaches often focus on flexibility evaluation at single points in time or require continuous updating after each flexibility use, consequently limiting planning reliability and increasing communication overhead. This study addresses these limitations by proposing a flexibility band concept that is predetermined for an entire planning horizon and can be used by higher-level actors to request flexibility services from prosumers. A fundamental idea behind this approach is to guarantee flexibility availability within the defined band, which is made difficult by uncertainties on the demand side. Robust schedules may impose tighter than necessary bounds to deal with uncertainty, leading to possibly conservative estimates of the available flexibility. The aim is to find a trade-off between ensuring user comfort and meaningful flexibility estimates.

Methods

The proposed framework begins by establishing a baseline power demand trajectory for the planning horizon (e.g., one day), derived from a home energy management system (HEMS) that cost-optimally schedules the operation of household DERs under dynamic electricity prices. Key metrics from the IEA Energy in Buildings and Communities Programme (IEA EBC Annex 67) are employed and extended to characterize system response when deviations from the baseline occur. These include maximum load response, response duration, and recovery time to baseline (see figure 1). For each time step within the planning horizon, maximum positive and negative deviations from the baseline power demand are computed (Δ in fig.) such that the load trajectory is able to return to the baseline within a defined period of time (α), forming a flexibility band around the baseline demand. If a flexibility call takes place, the band will only be meaningful again after the recovery time. This way, the band can be calculated in advance and does not require updating during operation, thus reducing computational and communication requirements. The calculation of maximum deviations considers all constraints of the initial baseline optimization. Assuming tight, robust bounds for some state variables are imposed to handle load uncertainties, these bounds are also imposed in the flexibility estimation. By allowing brief periods of violation of these bounds (γ), while still adhering to the technical constraints of the components, the impact of the robustness on the flexibility band can be evaluated. To assess these concepts, a MILP-based model is set up to estimate the flexibility in power-to-heat systems of prosumers from the SimBench database. Physical system states such as storage temperature and the heat pump's coefficient-of-performance (COP) are explicitly modeled to capture dynamic behavior in rebound effects.

Results

As the baseline scheduling tends to operate close to thermal comfort limits with minimal energy buffers, the potential for load reductions is limited. For the calculation of the maximum response, the flexibility usage is also not anticipated, so the response cannot be prepared in prior time steps. Preliminary results show that

always adhering to the tighter bounds leads to no flexibility potential at many time steps. When relaxing robust thermal bounds, there is potential for load reduction in every time step. The additional flexibility is considerable: Ignoring a buffer level of 10% of the temperature range in the heat storage for a single time step of 15 minutes leads to a threefold increase in reducible power on average. Allowing the temperature to be below this level for longer, however, increases the flexibility only slightly, reducing the incentive to allow longer non-robust periods of time.

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