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Beyond Standard Load Profiles: Capturing Heterogeneity and Stochasticity in Residential Energy Demand

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Motivation
Residential energy usage accounts for 27% of the Swiss final energy demand and 15% of CO2 emissions. With the electrification of the heat and transport sectors, the characteristics of residential energy demand are changing. Understanding these changes is essential in light of the energy transition and the resulting decrease in supply-side flexibility from intermittent energy supply. Demand-side management is one option to introduce the required flexibility but relies on high-resolution residential load profiles to correctly assess flexibility needs and potentials.

Traditional standard load profiles fail to capture occupant behaviour, a critical driver for energy demand variability. Stochastic load profile models address this limitation but often focus on either heat or electricity demand. Another essential characteristic of demand is the heterogeneity of demand among different consumers. However, most models do not sufficiently differentiate between occupant types. To address these gaps, this study develops a novel stochastic load profile model that integrates heterogeneous occupant groups, activity-driven energy demand, and multiple end-use sectors, including appliances, heating, and electric vehicles (EV). This approach provides a more accurate and flexible representation of residential energy demand.

Methods
Using Swiss time use survey data, unique load profiles that introduce heterogeneity and stochasticity are created in a three-step process. First, to introduce heterogeneity, survey participants are grouped into eight occupant types by age (working, underage, retired), employment status (full-time, part-time, unemployed), and family status (children or no children). The survey data also enables the distinction between eight household activities, each one linked to distinct household and vehicle technologies with a unique use probability. Then, the occupancy behaviour of each group is modelled using a first-order inhomogeneous Markov Chain to generate stochastic probability distributions per activity and timestep. Finally, the resulting activity schedules for each occupant group are used to determine the technology use pattern, which in turn informs the load profiles. For this final prediction of the energy demands, the activity-technology mapping is complemented with technology-specific energy consumption values and use probabilities. The lighting model accounts for ambient irradiance, while the electric vehicle model incorporates commuting distance, vehicle efficiency, and charging speeds. The validation indicates that the modelled annual residential energy consumption and peak demand estimates match well with existing studies.

Results
Our results reveal distinct energy demand patterns across occupant groups. Figure 1 illustrates this for two household types: a 2-person household of retirees and a 2-person household with full-time employees. The retired household exhibits greater variability in demand, reflected in the wider uncertainty bands. In contrast, the full-time household has a much narrower range. The introduction of EV charging demands substantially increases peak loads across all occupant groups.

When aggregating the individual load profiles, they approximate the standard load profile as hundreds of households are combined. This suggests that these load profiles can be used to tailor load profiles to specific contexts, such as municipal energy systems, reflecting their unique demographic composition in distinct load profiles.

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