

INTERPRETABLE PREDICTIVE RULE-BASED ENERGY MANAGEMENT FOR RESIDENTIAL BALCONY PV SYSTEMS WITH HETEROGENEOUS STORAGE

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Abstract

Due to the worldwide increase in energy demand and the growing integration of renewable energy sources, residential energy systems increasingly incorporate distributed photovoltaic (PV) generation, battery storage, thermal storage, and dynamic electricity tariffs. In particular, the rapid deployment of small plug-in PV installations rated below 2 kW and directly connected to household circuits, commonly referred to as balcony PV systems, introduces new operational challenges. These systems often include batteries connected to the direct-current (DC) side of the PV generator to increase local energy utilization, but their limited capacity frequently results in unused surplus generation. Additional energy storage or thermal sinks can therefore increase local self-consumption, as feed-in remuneration for small residential systems is typically substantially lower than retail electricity prices. Coordinating such heterogeneous storage components under limited inverter power, asymmetric energy flows, time-varying tariffs, and the inherent temporal variability of both electricity demand and renewable generation further increases the complexity of residential energy management.

Model predictive control (MPC) is widely studied for managing distributed energy resources using forecasts of PV generation, demand, and electricity prices. However, MPC requires repeated numerical optimization and reliable solver convergence over extended prediction horizons, which can limit its practical deployment on low-cost embedded controllers typically used in residential installations, particularly in cost-sensitive systems such as balcony PV setups. In contrast, simple rule-based controllers remain common in practice due to their robustness and minimal computational requirements, but they generally operate reactively and cannot effectively exploit predictive information.

This work proposes an interpretable predictive rule-based energy management framework inspired by MPC concepts for residential balcony PV systems with heterogeneous storage components. The considered system architecture includes a PV generator connected to a DC-coupled balcony storage battery, an additional

alternating-current (AC)-coupled household battery, and a thermal hot-water storage acting as a flexible energy sink. The system operates under variable electricity tariffs and must balance self-consumption, electricity costs, and thermal comfort constraints.

Instead of solving an optimization problem at each control step, the proposed approach integrates short-term forecasts of PV generation, household load, hot-water demand, and electricity prices into a hierarchical rule-based controller. Forecast information is first condensed into a set of predictive indicators, including expected PV surplus, anticipated energy deficits, and forecasted peak demand periods. These indicators dynamically adapt controller parameters and activate strategy policies such as reserving battery capacity before expected PV peaks, preserving energy for evening demand periods, selectively charging from the grid during low-price intervals, and exploiting thermal storage capacity during periods of high solar production.

The proposed framework is evaluated using real-world residential datasets from Germany and Canada, capturing diverse climate conditions, consumption patterns, and PV production profiles. The predictive rule-based controller is compared with both a purely reactive rule-based baseline and a conventional MPC formulation. Results indicate that the proposed method captures a substantial portion of the performance benefits typically associated with MPC while maintaining the interpretability, robustness, and low computational overhead of heuristic control. The approach represents a promising intermediate strategy between reactive rule-based control and MPC for edge-deployed residential energy management systems.