Doctoral Program in Energetics (37thcycle)

Advanced energy management strategies for Renewable Energy Communities

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ABSTRACT

The urgent transition to sustainable energy systems requires not only the integration of renewable energy sources (RES) but also advanced energy management strategies to address challenges related to variability, reliability, and grid interaction. Buildings, as major energy consumers, play a central role in this shift, particularly through electrification, energy flexibility, and their participation in Renewable Energy Communities (REC). This dissertation investigates the deployment of advanced control strategies, flexibility assets, and financial incentivization mechanisms to optimize energy use within large-scale RECs.

To support this, a novel Python-based simulation framework, RECsim, was developed to model complex REC scenarios with high temporal and spatial resolution. RECsim features scalable building clusters, detailed thermal and electrical modeling, and integration with reinforcement learning environments. It enables testing of control strategies such as Rule-Based Control (RBC) and Deep Reinforcement Learning (DRL) in a simulated REC of 50 households equipped with PV systems, Thermal Energy Storage (TES), Battery Energy Storage Systems (BESS), and heat pumps.

The results demonstrate that DRL significantly improves energy self-sufficiency, self-consumption, and cost-efficiency compared to RBC, particularly under flat tariff schemes. However, DRL impact on peak demand reduction is limited. TES deployment under DRL helps lower energy costs but may reduce community-wide renewable utilization when not optimally coordinated. Moreover, the study reveals that traditional flexibility tools like ToU tariffs and thermal storage may conflict with REC goals under decentralized control.

A second investigation evaluates financial incentive schemes as a means to align REC behavior with grid objectives. Through large-scale simulations under a Model Predictive Control (MPC) framework, the analysis quantifies the financial cost of incentivized flexibility and explores

optimal configurations in terms of prosumer participation, storage sizing, and PV generation. The findings indicate that moderate prosumer engagement (~%40) and generation-to-consumption ratios between 0.3–0.5 yield the highest benefit-to-cost outcomes

Importantly, the study highlights equity concerns around BESS adoption, as private storage can reduce shared energy availability and exacerbate energy inequality. Shared storage and demand-side management strategies are proposed as more equitable solutions, though they face financial and regulatory hurdles.

Overall, this work offers a comprehensive framework for optimizing REC performance through a combination of advanced control, flexibility repurposing, and pricing scheme, providing actionable insights for researchers, policymakers, and grid operators aiming to enhance sustainability, efficiency, and fairness in future energy communities.