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Integrating energy hubs into smart cities using a decentralized optimization framework: Advancing the transition to low-carbon urban energy systems

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Abstract-

The integration of energy hubs into interconnected energy and carbon management systems is a pivotal step toward achieving decarbonized, sustainable, and intelligent urban energy infrastructures. This paper proposes a bi-level distributed optimization framework that enables the coordinated operation of multi-energy hubs while ensuring system-wide efficiency. At the lower level, the model captures the techno-economic behaviors of industrial agents, including flexible production lines, multi-energy storage units, and vehicle-to-grid (V2G)-enabled parking facilities, under uncertainty. A Conditional Value at Risk (CVaR)-based strategy is employed to mitigate operational and environmental risks. The upper level, supervised by a smart grid operator, ensures network-constrained dispatch and balanced energy-carbon flows using a DistFlow-based representation of the distribution network. Coordination between the two levels is achieved through an adaptive Alternating Direction Method of Multipliers (ADMM) that dynamically adjusts penalty parameters to accelerate convergence while minimizing communication needs, an essential feature for privacy-preserving smart city architectures. Simulation results on a modified 118-bus distribution system with 34 industrial energy hubs indicate reductions of up to 21.78% in total operating costs and 18.72% in carbon emissions, while substantially enhancing robustness against system uncertainty. Furthermore, the additional implementation on a 594-bus distribution system with 285 industrial energy hubs confirms the scalability of the proposed adaptive ADMM algorithm to large-scale multi-hub networks. Overall, the proposed architecture offers a scalable and intelligent solution for the coordinated operation of multi-energy systems in sustainable smart city environments.

Index Terms- Urban energy systems; Low-carbon transition; Smart grids; Energy hubs; Renewable energy resources; Distributed Optimization

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