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A collaborative energy sharing optimization model among electric vehicle charging stations, commercial buildings, and power grid

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HIGHLIGHTS

- A collaborative decision model to study energy sharing among buildings and charging stations.
- A customized solution approach to solve the optimization model in a realistic-size problems.
- Managerial insights drawn for decision makers to design an efficient collaborative scheme.

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ABSTRACT

This paper studied a collaborative decision model to optimize electricity flow among commercial buildings, electric vehicle (EV) charging stations, and the grid under power demand uncertainty. We propose a two-stage stochastic programming model that realistically captures different operational constraints between multiple commercial buildings and EV charging stations. We developed a customized solution approach based on Sample Average Approximation method that can solve the proposed model efficiently and accurately. Finally, a real-life case study is constructed that draws managerial insights into how different key input parameters (e.g., grid power unavailability, power collaboration restriction) affect the overall energy network design and cost.

1. Introduction

Commercial buildings and surface transportation sectors utilize a significant portion of energy causing a number of global challenges such as climate change and resource scarcity. According to the U.S. Energy Information Administration [1], buildings and surface transportation sectors consume approximately 43.35% and 28.79% of total energy generated in the United States, respectively. Regarding indirect emissions, both sectors cause approximately 78.9% of greenhouse gas (GHG) emissions, of which the building and transportation sectors are responsible for 44.6% and 34.3%, respectively [2]. Recently, the growing concerns of energy efficiency, dependence on fossil fuels, and environmental impacts have attracted increasing attention on smart buildings and electric vehicles (EVs) in relation to commercial building and road transportation sectors, respectively.

A *smart building* is a structure utilizing automated processes to control the building's operations including heating, ventilation, air conditioning, lighting, security, and other systems. According to [3], an undeniable fact about smart building management is the need to accurately coordinate its electrical and thermal loads. To achieve greater economic performance and environmental sustainability, an efficient energy management system is needed, which can optimally coordinate the generation, consumption, and storage of energy across the available resources [4,5]. On the other hand, *electric vehicle* sales in the U.S. increased by 22% from 2015 to 2016 and it is anticipated that there will be approximately 2.7 million EVs on the U.S. road by 2020 [6]. Furthermore, it is expected that the EV market share will hit 10% by 2025 [6]. Higher EV market penetration brings both challenges and opportunities in the area of power grid management. Unmanaged charging of EVs might trigger an extreme swell in electricity demand at peak hours and, consequently, negatively affect the stability and security of the power grid. This being the case, there is an urgent need to manage EV charging activity efficiently to promote widespread adoption of EVs. Towards this goal, this study investigates optimal operational strategies in relation to smart commercial buildings and electric vehicle charging stations to optimize individual and integrated operations under systems uncertainty.

The power grid is currently experiencing a variety of challenges

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from the viewpoint of sustainable development of advanced technologies. The future power grid, known as the *smart grid*, together with smart commercial buildings defines the next-generation of electrical power generation and consumption systems. The smart grid can be characterized by increased utilization of real time communications, information technology, and control and management in the production, distribution, and consumption of electrical energy. The aim of employing an upgraded smart grid together with smart commercial buildings is to allow two-way electricity and information flow between them so that they are capable of monitoring and responding to demand changes.

One possible way to alleviate excessive loads on the power grid is to design EV charging stations that integrate renewable energy resources (RES) with vehicle-to-grid (V2G) resources, while planning optimal charging schedules for EVs. A stream of studies have addressed the integration of the RES with V2G. Liu et al. [7] and Marmaras et al. [8] study the effects of EV smart charging patterns on power system scheduling, while considering coordination of wind energy, thermal units, and V2G. Likewise, He et al. [9] present a global and local scheduling model that is capable of making charging and discharging decisions for EVs with the goal of minimizing the overall system cost. Another study, proposed by Ortega et al. [10], integrates V2G with power systems in order to achieve better efficiency and security while operating under an existing power infrastructure. Along the same line, Haddadian et al. [11,12] study the effects of considering V2G and RES as viable resources for the smart grid. Similarly, Fathabadi [13] studies the different effects of incorporating V2G and RES in a power network. The goal is to identify the best coordination that is effective in sustaining the system while reducing cost and loss of power production. Thomas et al. [14] investigate the bi-directional capabilities of EV energy trading with respect to renewable power uncertainty. In another study, DeForest et al. [15] show a day-ahead optimization of an EV fleet providing ancillary services at the Los Angeles Air Force Base vehicle-to-grid demonstration, including a number of practical considerations and scenario analysis. Jin et al. [16] and Hong et al. [17] propose a stochastic optimization model to minimize the average cost of utilizing RES under system uncertainty. Rahmani-Andebili and Fotuhi-Firuzabad [18] propose a stochastic predictive control model for management charging of plug-in EVs and distribution system reconfigurations considering driving patterns of the plug-in EV owners. Another study, conducted by Zhang et al. [19], introduces a scheduling model to minimize the mean waiting time for charging electric vehicles at EV charging stations equipped with multiple plug outlets and the availability of RES. The authors consider arrival time of EVs, fluctuation in grid power prices, and the RES generation level using a markov decision process (MDP). The existing studies provided along this line attempt to manage operational decisions for a single charging station while no consideration is given to optimize integration decisions on cluster-based EV charging stations.

Several studies attempt to optimize battery management related decisions at battery swapping stations where an EV can quickly exchange its depleted battery with a fully-charged battery. Pan et al. [20] present a two-stage stochastic programming model to determine the optimal location of battery swapping stations and then make appropriate operational decisions (e.g., the number of charged and discharged batteries) based upon realized battery demands, EV loads, and production of RES energies. It can be note that decisions involving discharging batteries to the power grid during peak hours is an important feature of the proposed model. Similarly, Worley and Klabjan [21] present a dynamic programming model to determine the number of batteries purchased and their charging times based on dynamic changes in the power grid pricing rate. Along the same line, Mak et al. [22] propose various models that aid the planning process for establishing battery swapping infrastructure based on a robust optimization framework under demand uncertainty. The authors determine the potential impact of battery standardization and other related technology advancements on the optimal infrastructure establishment strategy. Nurre et al. [23] develop an integer programming model to determine the optimal operational decisions (e.g., the number of charged, discharged, and exchanged batteries) of a battery swapping station over a pre-specified planning horizon. Liu et al. [24,25] propose an optimization model to determine energy exchange strategies of a battery swapping station considering solar energy availability and demand management decisions (e.g., optimal pricing, charging and discharging batteries). Recently, Widrick et al. [26] demonstrate optimal policies for battery swapping station management, integrated with V2G capability, to control charging and discharging operations under non-stationary stochastic demand. Note that most of the existing studies provided along this line attempt to optimize battery management decisions (e.g., hourly charging, discharging, storing, and exchanging) within a single facility while no consideration is given to the integration between battery swapping and EV charging across multiple charging stations.

In addition to power grid load reduction and EV charging station management, another possible way to reduce the energy consumption from the two main sectors (i.e., commercial buildings and surface transportation) is via vehicle-to-building (V2B) connection capability. In the V2B integration mode, a smart commercial building can cooperate with an EV charging station(s) to achieve higher energy efficiency and lower network costs. This being the case, two-way electricity flow among related buildings and charging stations can help manage demand fluctuations. Flores et al. [27] show that significant cost savings cost be achieved if a charging station can be integrated with a commercial or industrial building using a coordinated operation strategy. Karan et al. [28] investigate possible GHG emission reduction and mitigation strategies based on the current trend of energy usage in transportation and building sectors. In another study, Clarke et al. [29] and Stadler et al. [30] demonstrate how the design of distributed energy systems can be improved by increasing participation of EVs battery storage, which enhances system flexibility and facilitates integration of further distributed energy resources such as solar and wind energy. Pang et al. [31] and Su et al. [32] demonstrate that V2B connections provide some benefits including backup power, high power quality for buildings, and peak shaving in the power grid. Additionally, the authors state that V2B integration can significantly improve demand side management and power outage. Gough et al. [33] find that participating in both the peak power and the ancillary services market may prove the most profitable for V2B connections. Sehar et al. [34] and Liu et al. [35] propose a heuristic operation strategy for a commercial building microgrid, equipped with EVs and a photovoltaic (PV) system, to improve self-consumption capability of PV energy. Erdinc [36] considers both pricing scheme and peak power limiting on demand response, which can further improve the economic advantage of the home energy management structure by increasing flexibility. Studies by [37–39] investigate the impact of integrating the EVs into an office building microgrid, which is supported by PV and combined heat and power (CHP) units. Authors found that the EVs with optimal coordinated charging strategies can help in reducing the fluctuation grid energy during the peak hours. Recently, Robledo et al. [40] study the performance of an integrated hydrogen fuel cell EV with V2G technology, PV power, and a residential building. The results show that integrated model can reduce imported electricity from the power grid by approximately 71%.

To the best of the author's knowledge, none of the prior studies have investigated the effects that integrated cluster-based smart commercial buildings and EV charging stations will have on operational decisions under uncertainty. To fill this gap in the literature, this study proposes a novel collaborative energy sharing decision model to study energy sharing among a cluster of commercial buildings and EV charging stations in concert with the power grid. In summary, the main contributions of this paper to the existing literature are summarized as follows: