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Peak shaving and valley filling of power consumption profile in non-residential buildings using an electric vehicle parking lot

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ABSTRACT

The renewed interest in the deployment of electric vehicles promises enhanced environmental and social compatibility, higher energy efficiency, as well as effective power grid support through the vehicle-to-grid energy exchange mode. Focusing on a smaller scale, such as buildings with large parking lots for electric vehicles, the aim of the so-called vehicle-to-building concept is to regulate the power consumption of a building by either throttling the charging rate of electric vehicles or by delivering electricity (discharging) into the building when needed. In this paper, a mathematical model is implemented in MATLAB to peak-shave and valley-fill the power consumption profile of a university building by scheduling the charging/discharging process in an electric vehicle parking lot, using real-world data of power consumption and parking lot occupancy. The simulation of three scenarios with different number of parking spots reveal the feasibility of the proposed approach to effectively flatten the power consumption profile during daytime, which is particularly important for electricity customers that the energy cost depends on the contracted power capacity. In detail, the results indicate that the peak power consumption is reduced by approximately 3% and 20% for the scenarios with the minimum and maximum number of electric vehicle parking spots respectively.

1. Introduction

1.1. Background

Recent years have witnessed a renewed interest in electric vehicles (EVs), mainly due to their distinctive advantages over conventional vehicles with internal combustion engines, including the effective reduction of carbon emissions and dependence on fossil fuels, lower noise levels, higher efficiency of vehicle operation, and lower operating costs. It is indicative that the experiences from early EV adopters in Sweden are analyzed in Ref. [1] in order to characterize the profile of EV drivers, motivation for EV use, and preferences of charging locations, as well as to assess the impact of large-scale EV penetration on existing power distribution systems. In terms of CO_2 emissions, a relevant study for the case of Ireland reports that the transition to EVs can yield substantial reductions for urban-type drive cycles; however the potential benefit in intercity travels is much smaller [2]. Given that a key feature of EVs is the emission of significantly lower propulsion noise compared to combustion engine propulsion systems, the tire-road noise of potential and dedicated tires for electric cars is assessed in Ref. [3] using pass-by measurements. In support of route planning and dynamic route guidance applications for EVs, a state of charge (SOC) estimation method based on dynamometer test data is proposed in Ref. [4]. Moreover, an EV data collection system is developed in Ref. [5] to collect in-use EV data in order to analyze the EV performance and driver behaviors. According to recent figures of global sales, electric cars reached the share of 0.1% of total passenger cars in 2015 [6], compared to the level of 0.08% in 2014 [7]. In this context, the release of new EV models by the automotive industry and the growing interest of consumers, combined with the government support both on the demand and supply side, are among the key drivers for the market uptake of EVs [8]. In this direction, the transition to electro-mobility received further support by defining a target of more than 100 million electric cars and 400 million electric two- and three-wheelers to be driven globally by 2030 in the "Paris Declaration on Electro-Mobility and Climate Change & Call to Action" [9].

Passenger cars are still the dominant mode of transportation on

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Nomenclature

C	Average of peak and minimum power consumption of building
E_{T+1}	Energy needed for next trip
E_m^{cap}	Battery capacity of EV m
E_m^{fin}	Final battery energy of EV m
E_m^{ini}	Initial battery energy of EV m
F	EV presence matrix
M	Set of EVs
N	Set of time intervals
P_{ui}	Power consumption of building in interval i
$Q^{(i)}$	Set of intervals prior to interval i
T_m	Charging/discharging period of EV m
m	Electric vehicle (EV)
p_{max}	Maximum charging or discharging power
t_m^{arr}	Arrival time of EV m
t_m^{dep}	Departure time of EV m
x_{mi}	Charging/discharging power of EV m in interval i
y_i	Total load for charging/discharging the available EVs in interval i
i	Time interval
τ	Length of each interval i

land in EU-28, representing 80.1% of all passenger kilometers traveled in 2014 [10]. Therefore, it is commonly accepted that the particularly high use of private vehicles to cover the increasing human mobility needs is a primary cause of major environmental and social problems worldwide, having adverse effects on the quality of life [11]. Indicatively, it is responsible for high levels of air and noise pollution, as well as parking and traffic congestion problems, mainly in urban areas [12]. Given that traffic congestion typically occurs in its worst form at peak hours when people commute to work [13], a main contributor to this situation is the low vehicle occupancy, which leads to a higher number of vehicles on the road than really needed. In practice, the target of higher vehicle occupancy in public transportation as well as in alternative modes of transportation such as carpooling, serves not only as a means of covering the increasing requirements for human mobility, but also as a low-cost measure to alleviate the effects of traffic congestion, energy consumption and environmental degradation, among others. As an example, a web application to support the use of carpooling in home-university trips for students and employees is presented in Ref. [14]. In addition, recommendations for the integration of carsharing into an environmentally sustainable transport system are given in Ref. [15]. In this regard, multiple benefits may be attained by combining the carpooling concept with the use of EVs, taking into account the potential interest of the populations under study. Specifically, the survey in Ref. [16] reveals the positive attitude towards the transition to electromobility and use of carsharing/carpooling services with EVs in an academic community in Bilbao, Spain. In the same direction, the survey in Ref. [17] reveals the user preferences for the adoption of a university-based carpooling system with EVs in the city of Mons, Belgium, providing also some useful insight for the implementation of such a system.

A secondary, yet very important application of EVs, and in particular of plug-in electric vehicles (PEVs), is the provision of ancillary services to the grid while parked through the vehicle-to-grid (V2G) energy exchange mode [18]. Using V2G technologies, PEVs can play the role of distributed energy storage for the grid and intelligently interact with electric utilities [19]. The underlying idea in V2G is to regulate the charging process of PEVs so that they charge during off-peak demand periods, and discharge during times of high demand in order to feed power back to the grid. The authors in Ref. [20] study the effect of such a large-scale implementation on the power systems of five Northern European countries. The results show that, when charged/discharged intelligently, EVs can facilitate significantly increased wind power investments already at low vehicle fleet shares. When implementing this concept in a smaller scale, for instance, in smart buildings or houses as shown in Fig. 1, the objective of the so-called vehicle-to-building (V2B) is to regulate the power consumption of the building by either throttling the charging rate of EVs or by delivering electricity into the building when needed. In this context, the authors in Ref. [21] examine the stochasticity of EV presence and the uncertainty of solar photovoltaic (PV) production for the optimal energy management in a grid-connected smart office building. In the same direction, the work in Ref. [22] considers the integration of plug-in hybrid electric vehicles (PHEVs) into energy and comfort management for a smart building environment.

1.2. Related work

An increasing number of studies have considered EVs integration in small or large scale applications. The work in Ref. [23] explores daily optimized charging EV strategies over each electricity reliability region of the United States attempting to minimize CO_2 emissions by strategically charging the EVs during different times. This study reports that optimized charging can reduce CO_2 emissions over pre-timed charging by up to 31% for standard use and 59% for V2G use. Risk management regarding the participation planning of EVs in smart grids for demand response applications is addressed in Ref. [24]. The authors in Ref. [25] propose a decentralized valley-filling charging strategy, in which a day-ahead pricing scheme is designed by solving a minimum-cost optimization problem. The pricing scheme can be broadcasted to EV owners, and the individual charging behaviors can be indirectly coordinated. Their simulation results show a satisfactory valley-filling charging effect of 28% less generation cost than the uncoordinated charging strategy.

A digital testbed to assess a range of charging scenarios, control strategies and communication technologies for an EV parking lot in the context of Smart Grid is described in Ref. [26]. The authors in Ref. [27] employ numeric experiments to validate the performance of the proposed Simulation-Based Policy Improvement (SBPI) method to solve the problem of scheduling the charging load of EVs for package delivery with building-mounted wind power systems, taking into account multiple parking locations and multiple parking events for the EVs. The work in Ref. [28] proposes a two-stage approximate dynamic programming framework for the optimal charging strategy in a commercial building parking lot and simulates a number of scenarios where the vehicle arrival behavior is modeled as a Poisson process. A mixed-integer linear program to solve the distributed-energy resources adoption problem with the objective to minimize the annual building energy costs or CO_2

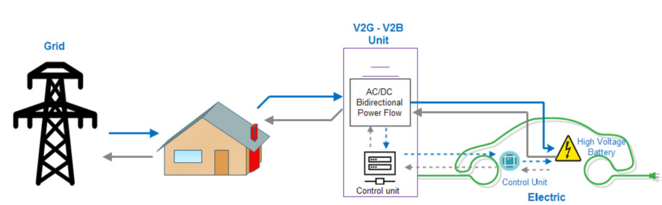

Fig. 1. Vehicle-to-building (V2B) concept.