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SCS-393; No. of Pages 11

ARTICLE IN PRESS

Sustainable Cities and Society xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Optimization model and economic assessment of collaborative charging using Vehicle-to-Building

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ARTICLE INFO

Article history:
Received 20 July 2015
Received in revised form 19 February 2016
Accepted 19 March 2016
Available online xxx

Keywords:
Cooperative charging
Smart charging
Vehicles-to-Building
Vehicles-to-Grid
Electric vehicles
Linear programming

ABSTRACT

Electric vehicles and plug-in hybrids are gaining popularity on the personal transportation market. These vehicles store energy that is unused when parked. This distributed energy source can therefore be used to provide ancillary services such as grid regulation or spinning reserves, but also for demand-side management. In this paper, we are proposing the concept of *collaborative charging* in the context of Vehicle-to-Building, where the vehicle and building operators engage themselves into a synergistic relation, with vehicles freely charged in exchange for shaving power peaks of buildings. For that purpose, simulations of vehicle fleets are conducted, with the charging schedule optimized by a linear programming model that is applied to manage the electric demand of a suburban university campus. These simulations, made in the context of a regulated electric market, demonstrate that collaborative charging can be financially viable for both the institution hosting the system and the participants.

1. Introduction

The deployment of electric vehicles (EVs) is a major trend in today's personal transportation market. Hybrid vehicles have become a sizable portion of the number of cars driven and their evolution involves the possibility to recharge them with enhanced battery capacity. Likewise, pure EVs are gaining market shares and this trend is rising.

But is the power grid able to sustain a massive adoption of EVs? In 2007, it has been estimated that the conversion into EVs of up to 84% of the vehicles in the U.S. can be supported by the existing power grid, assuming that these vehicles will be charged through some valley-filling charging methods (i.e., charging off-peak in order to maintain a flat power demand over the whole day) (Kintner-Meyer, Schneider, & Pratt, 2007). But valley-filling charging is not obviously achieved in practice, such that a significant shift toward EVs combined with a disorganized charging would constitute a stress for the grid, creating overload issues at peak times (Clement-Nyns, Haesen, & Driesen, 2010).

Organizing charging of EVs is thus required, in order to spread the load over the day while ensuring that cars are properly charged for the needs of their owners. Moreover, the electronic and charging systems of EVs can be designed to interact with the grid in a bidirectional manner (a.k.a. Vehicle-to-Grid or V2G) to alleviate the expected negative effects of their presence and even provide an enhancement to the grid (Kempton, Tomić, Letendre, Brooks, & Lipman, 2001). It is therefore not surprising that industry leaders are investigating the potential, the challenges, and the possible outcomes of the deployment of a smarter grid where EVs would not just be an additional load (Schewel, Brylawski, Chan-Lizardo, & Lovins, 2008).

In this study, a bidirectional relationship is simulated at a smaller scale, at a building or campus level with a power-constrained grid, where a substantial fraction of the electricity bill will be determined by the cost of the peak power consumption of the building or campus grid ($/kW), in addition to energy cost ($/kWh). The Vehicle-to-Building (V2B) concept was introduced in 2008 (Schewel et al., 2008) as a subclass of the V2G idea, where EVs would exchange electrical energy with a building and provide demand-side management features to optimize the building energy consumption (Benetti, Caprino, Della Vedova, & Facchinetti, 2016; Gelazanskas & Gamage, 2014). V2B has the same implications as V2G in terms of hardware needed and synchronization between the agents involved, but at the community level. Moreover, V2B should be easier to deploy due to its smaller scale and thus be achievable before V2G.

Vehicles in working place parking lots are traditionally in a standby mode from arrival in the morning to departure in the

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http://dx.doi.org/10.1016/j.scs.2016.03.012
2210-6707/

Please cite this article in press as: Tanguy, K., et al. Optimization model and economic assessment of collaborative charging using Vehicle-to-Building. *Sustainable Cities and Society* (2016), http://dx.doi.org/10.1016/j.scs.2016.03.012

afternoon or evening. For rechargeable plug-in hybrids or EVs, that could mean a formidable amount of energy sleeping right next to an avid energy consumer such as a building, a university campus, a hospital, etc. With a smartless infrastructure for recharging these vehicles, the worst case scenario is a mass demand in the morning when vehicles arrive within a short period of time, creating or accentuating a peak in the power demand. Smart charging stations that avoid charging when the grid is overloaded already exist and can distribute the load over a long period, so that the grid does not suffer from excessive punctual demand. However, it would be even better to charge the vehicles when the power demand is low and use their energy capacity to prevent peak energy demands. A building or a campus using such a strategy will allow the power component of its electricity bill to be reduced by capping the peak power demanded on its connection to the utility company. Eventually, V2B may even enable the building or campus to reduce their power requirements.

In the scope of this study, we intend to create a win-win situation that we refer to as *collaborative charging*, where the vehicle owner will have his vehicle recharged for free in exchange for providing the parking lot owner (e.g., building, university, hospital) with the control of the energy contained in his vehicle battery. Doing so, the institution will benefit from an energy reserve it can use to lower its power peaks and thus its electricity bill.

In this paper, linear programming optimization is applied to a system model to produce an optimal decision sequence, a schedule of whether vehicles should charge, discharge, or standby for each of the time steps during which they are plugged into a smart, bidirectional charging station in the parking lot. Using the power consumption profile of a university campus for the year 2011 as the input for our model, the output of linear programming will generate a power profile optimized with a reduced electricity costs. In essence, the V2B feature of the plugged-in vehicles will enable the reduction of the excess power peaks. The results of this optimization will be compared to the actual cost of energy for a given campus and demonstrate the financial viability of V2B.

In addition to the proposal of the collaborative charging concept, two main contributions stem from this paper. First, we are proposing a realistic model for simulating collaborative charging, a model which can be optimized through a convex optimization method. This model is a baseline for evaluating collaborative charging approaches, allowing the evaluation of the extend to which the results of scheduling methods are working online in comparison to those obtained with our model, which is providing the optimal results but is assuming prior knowledge of the energy demand and when the vehicles are arriving and departing. The second contribution is to demonstrate that collaborative charging can be economically viable in the context of a strictly regulated market (such as Québec), achieving a win-win situation when shaving demand peaks of large electricity consumers while charging the cars for free.

The paper is organized as follows. The state of the art of V2B is detailed in Section 2. The system model along with explanations of the context where we are simulating collaborative charging are presented in Section 3. Section 4 presents the linear programming formulation for the optimization of the model. The methodology used in conducting the simulations is presented in Section 5, followed by simulation results and analysis in Section 6. Finally, we conclude our paper in Section 7.

2. State of the art

The concept of V2G has been exposed in preliminary works (Kempton et al., 2001) where it has been demonstrated as being technically feasible (Gage, 2003). Detailing the different possible usages of V2G (Tomić & Kempton, 2007) and financially assessing its capacity (Kempton & Tomić, 2004) was an important step in this research area. V2G concepts assume that electric powered vehicles will penetrate the personal transportation market en-masse and that this arrival could be a burden to the power grid (Ashtari, Bibeau, Shahidinejad, & Molinski, 2012). For instance, Shahidinejad, Filizadeh, and Bibeau (2012) used real-world vehicle usage data to predict the increased load on the grid associated with these vehicles using either a stochastic model or fuzzy-logic to decide whether or not the car should be plugged into a charging station between trips. The majority of studies agree on the necessity of aggregators to organize the future smart grid into multiple large entities, each one controlling a fleet of vehicles which independently do not represent a consequent power source (San Román, Momber, Abbad, & Miralles, 2011).

An important aspect of the aggregator is the actual decision making process in scheduling vehicle activity depending on the goal pursued. Sandels, Franke, Ingvar, Nordstrom, and Hamren (2010) proposed an aggregator model using Monte Carlo simulations applied to the German control market. Sekyung, Soohee, and Sezaki (2010) detailed the aggregator duties and used dynamic programming to maximize vehicle state of charge and participant revenues from frequency regulation. Binary particle swarm optimization has been used to maximize the vehicles owners' profits by selling excessive energy to the grid in a parking lot (Hutson, Venayagamoorthy, & Corzine, 2008), with expansion of this work to real time considerations (Venayagamoorthy, Mitra, Corzine, & Huston, 2009). Shi and Wong (2011) used the Q-Learning algorithm to control the real-time decision process on whether a vehicle should charge, discharge or provide frequency regulation under electricity price uncertainty. Managing a large number of vehicles (3000) was evaluated in Su and Chow (2012), using an estimation of distribution algorithm to optimize the charging schedule and maximize the average state of charge of the vehicles involved.

A linear programming model, also adapted to large vehicle fleets (10,000), was investigated in Sortomme and El-Sharkawi (2012), to take into account both bidding of energy and ancillary services. A stochastic dynamic programming model has also been proposed for the optimization of charging and frequency regulation capacity bids of EVs (Donadee & Ilić, 2014). Operation planning of a small electric energy system including renewable energy sources is described in Battistelli, Baringo, and Conejo (2012), using a linear programming model with few data at a time and taking into account uncertainties associated with charging/discharging patterns of EVs. Focusing on deployability, the comparison between a mixed integer linear programming model and its simulated annealing counterpart presented in Sousa, Morais, Vale, Faria, and Soares (2012) is positive for the latter both in terms of results and execution time.

García-Villalobos, Zamora, San Martí, Asensio, and Aperribay (2014) presents a survey of smart charging of EVs, identifying four main approaches: uncontrolled charging, off-peak charging, smart charging (valley filling), and smart charging (peak shaving). The last case corresponds to what we are looking for in the current work, by using the vehicles to manage the demand by charging the vehicles when the power demand is below the subscribed level (up regulation) and using energy available in the vehicles to shave peak demand (down regulation). This type of management of the power demand of a building is a form of demand-side management (Palensky & Dietrich, 2011) from the grid perspective.

In line with that, several studies have been conducted at the scale of buildings or microgrids. For instance, Pang, Dutta, and Kezunovic (2012) used EVs and plug-in hybrids in a V2B context for two distinct cases: demand-side management where only charging is considered, shifting charging from peak to mid-peak time, and outage management where the vehicles power the building. Momber et al. (2010) explored how EVs can integrate with a