Coordination of Electric Vehicle Aggregator Participation in the Day-Ahead Market

Doctoral Consortium

Alvaro Perez-Diaz
University of Southampton, UK
a.perez-diaz@soton.ac.uk

ABSTRACT

Motivated by the high electric vehicle (EV) penetration percentages foreseen for the near future, we study the integration of large fleets of electric vehicles into the existing electricity market structure, with special emphasis on day-ahead markets. Specifically, the large energy requirements characteristic of the widespread use of EVs require careful managing in order to limit environmental and infrastructural impacts. A key characteristic of EVs is their intrinsic flexibility, given that most vehicles are idle most of the day. This translates into coordination opportunities which allow for the temporal spreading of the energy consumption of an EV fleet, avoiding unnecessary demand peaks which translate into increased electricity prices and stress in the grid. Given the self-interested nature of market participants, this coordination is challenging and needs to be carefully addressed.

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1 INTRODUCTION

Day-ahead electricity markets are the main source of wholesale electricity in decentralised countries. Typical day-ahead markets are daily forward markets featuring a uniform-priced double-sided auction [4]. In more detail, they run every day of the year and each day is divided into 24 one-hour slots, where a separate auction is run for each hourly slot. A key characteristic of this type of market is the price impact of both buy and sell orders. In more detail, buy (sell) orders push prices up (down), the so-called *price impact*. This is essential for large market participants, such as large fleets of EVs, and needs to be carefully considered

In more detail, we focus on the issue of aggregator competition in day-ahead markets. Specifically, we consider a scenario where an arbitrary number of EV aggregators participate in the day-ahead market with the intention of purchasing the energy needed to meet their clients' needs. Each aggregator is considered to be independent and self-interested, as reduced electricity costs translates into increased profit and/or lower charging tariffs for their clients. Specifically, the price impact of the bidding orders of each market participant pushes prices up, causing high electricity prices whenever there is a demand peak. Given the inherent flexibility of EV charging, we study the possibility of inter-aggregator coordination in order to produce joint bidding, in order to minimise price and grid impact. However, this cooperation is challenging given the self-interested nature of the aggregators.

In order to address this challenge, we approach the problem from two different perspectives [4, 5]. Firstly, from a centralised mechanism design perspective, and secondly using results from cooperative game theory where participants are allowed to form arbitrary coalitions. Both approaches are described in more detail in the following sections.

2 MECHANISM DESIGN APPROACH

Mechanism design allows us to determine the rules of a coordination mechanism which incentivises cooperation among self-interested aggregators. The three contributions of this study are detailed below [4].

Firstly, a novel price-maker day-ahead bidding algorithm is proposed, which optimises the bidding schedule of an electric vehicle aggregator. This algorithm is extends the work in [2] by considering the price impact of the aggregator's bids, an essential feature for large market participants, and is formulated in terms of a convex minimisation problem with simple constraints. The resulting algorithm is computationally very cheap and scales well to very large problem sizes.

Secondly, we propose a novel coordination mechanism for competing self-interested EV aggregators. This mechanism extends the benefits of coordinated charging to multi-aggregator scenarios, where normally individual and uncoordinated bidding would take place. In this mechanism, the aggregators report their requirements to a third-party coordinator, who bids on their behalf employing the proposed bidding algorithm. The proposed system is depicted in Fig. 1. Results from mechanism design are employed to handle aggregator payments. Specifically, we consider VCG-based payment systems in order to incentivise cooperation and minimise strategic manipulation by the participating aggregators.

Thirdly, a case study utilising real market and driver data from the Iberian Peninsula is studied. The results for the novel bidding algorithm indicate significantly increased performance when comparing to existing bidding algorithms, achieving payment reductions which grow linearly with the fleet size. Similarly, the proposed coordination mechanism achieves significantly better performance when compared to uncoordinated bidding, where the performance improvement

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grows linearly with fleet size and number of participating aggregators.

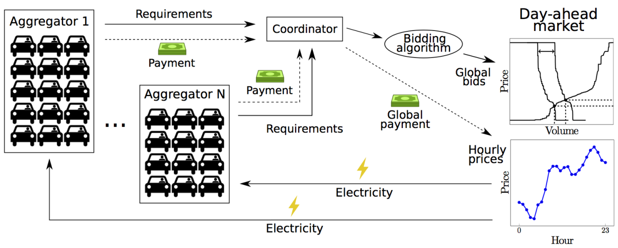

Figure 1: Graphical depiction of the proposed coordination mechanism [4]. An arbitrary group of N EV aggregators perform coordinated bidding through the coordinator. The coordinator employs the proposed bidding algorithm to bid on their behalf, and distributes payments and energy to each aggregator.

3 COALITIONAL APPROACH

In this part of the work we explore the coalitional properties of the multi-aggregator coordination mechanism proposed in the previous section. In more detail, the figure of the coordinator is not necessarily unique any trusted entity can assume such role, allowing the formation of arbitrary coalitions of aggregators. By looking at this scenario under the perspective of cooperative game theory, we are able to study the stability and coalitional incentives of the previously proposed coordination mechanism. The three contributions of this study are detailed below [5].

Firstly, we model the multi-aggregator scenario as a coalitional game. Given the presence of price impact, the resulting game is a coalitional game with externalities, in which any participant affects the value of any given coalition through their bids. In order to address this issue, three different variations of the game are considered: a generalised partition function form game, and finally *outsider-coalition* and γ-conjecture formulations.

Secondly, we show that the γ-conjecture formulation has desirable theoretical properties. Namely, the resulting game is superadditive and balanced, hence it has a non-empty core and the grand coalition has an incentive to form. Due to the game not being convex, the Shapley value is not guaranteed to be in the core. As a result we propose an alternative payment mechanism which does lie in the core, the least-core. These results indicate that the scenario where all participating aggregators cooperate through a unique coordinator achieves minimises energy expenditure. Also, by distributing the energy costs among the aggregators using the least-core distribution, no participating aggregator has an incentive to deviate from the coalition.

Thirdly, a case study is presented, employing real market and driver data from the Iberian Peninsula. The two considered payment mechanisms, namely the Shapley value and the Last-core are compared, and found to be very close for a plethora of scenarios, suggesting that both payment mechanisms are fair and stable.

4 FUTURE WORK

Our work so far has focused on optimising EV aggregator bidding in day-ahead electricity markets and exploring its coordination capabilities. Results from the fields of mechanism design and cooperative game theory allow us to formalise a cooperative framework which incentivises all participating EV aggregators to share their requirements truthfully and perform joint bidding through a coordinator, which provides greatly reduced electricity costs.

However, the issue of multi-EV aggregator coordination can be extended further than only energy purchasing from day-ahead markets, opening several directions for future work. One of the exciting possibilities arising from the use of EV is the fact that they can be used as distributed energy storage. The energy stored inside a vehicle's battery can be used to power external devices, or injected back to the electricity grid in times of scarcity, the so-called *vehicle-to-grid* or *V2G* [3]. V2G has been extensively studied in the literature in the last years, but the participation of large fleets, where price impact needs to be considered, has not been addressed so far. Similarly to the day-ahead bidding case, coordination opportunities could provide great benefits.

In a similar vein, the participation of large fleets of EVs in short-term energy markets, such as intra-day and reserve [1], and the coordination possibilities arising from this setting, have not been studied in the literature.

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