

Coordination and payment mechanisms for electric vehicle aggregators

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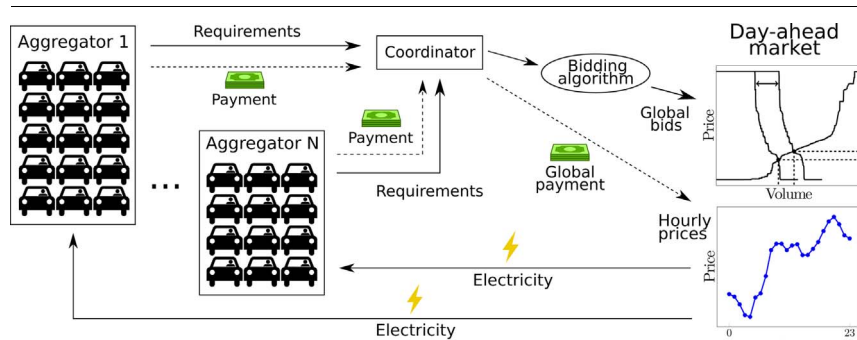
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HIGHLIGHTS

- Proposing a novel coordination mechanism for electric vehicle charging aggregators.
- Employing a novel price-maker bidding algorithm for day-ahead electricity markets.
- Presenting a realistic case study based in real market and driver data.
- Results indicate considerable benefits even for moderate EV aggregator numbers.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:

Electric vehicle charging
Electric vehicle aggregation
Inter-aggregator coordination
Mechanism design
Vickrey-Clarke-Groves
Day-ahead electricity market

ABSTRACT

Motivated by the high electric vehicle (EV) penetration percentages foreseen for the near future, this paper studies the participation of large fleets of EVs in electricity day-ahead markets. Specifically, we consider a scenario where a number of independent and self-interested EV aggregators participate in the day-ahead market to purchase energy to satisfy their clients' driving needs. In this scenario, independent bidding can drive prices up unnecessarily, resulting in increased electricity costs for all participants. Inter-aggregator cooperation can mitigate this by producing coordinated bids. However, this is challenging due to the self-interested nature of the aggregators, who may try to manipulate the system in order to obtain personal benefit. In order to overcome this issue, we employ techniques from mechanism design to develop a coordination mechanism which incentivises self-interested EV aggregators to report their energy requirements truthfully to a third-party coordinator. This coordinator is then able to employ a day-ahead bidding algorithm to optimise the global bids on their behalf, extending the benefits of smart bidding to groups of competing EV aggregators. Importantly, the proposed coordination mechanism is straightforward to implement and does not require any additional infrastructure. To ensure scalability and computational tractability, a novel price-maker day-ahead bidding algorithm is proposed, which is formulated in terms of simple energy requirement constraints. The coordination mechanism substantially reduces bidding costs, as shown in a case study which uses real market and driver data from the Iberian Peninsula.

1. Introduction

Climate change and environment conservation constitute two of the main challenges to address in the twenty-first century. In particular,

fossil fuels account for a great proportion of the global contaminant emissions. Nowadays, around 29% of the total energy consumption in the US is attributable to the transportation sector, and fossil fuels power around 95% of this amount [1]. Similarly, in the UK, transportation is

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the biggest energy consumer accounting for 40% of the total energy consumption [2], where 96% of this consumption depends on fossil fuels [3].

Transportation is then a key participant in the modernisation and improvement of the energy generation-demand duo. Specifically, the electrification of transportation has the potential to reduce the dependence on fossil fuels and allow the effective use of renewable electricity sources. However, it presents important challenges, such as accommodating the very large electricity requirements of a large electric vehicle (EV) fleet. If left unmanaged, uncoordinated operation can pose a novel and heavy strain on the existing electricity generation, transmission and pricing methods. As an example, currently, the UK has a fleet of nearly 100,000 EVs, combining purely electrical and hybrid vehicles [4]. Furthermore, the UK has a 10% target for electrification in the transportation sector by 2020 [5]. Similarly, at a global scale, there are targets to achieve 100 to 140 million of EVs by 2020 [6]. Hence, given the current and targeted EV penetration numbers, EV fleet management must be seen as a priority [7].

In order to address this issue, one of the proposed methods is to employ an EV aggregator. Originally introduced in [8], this entity acts as an intermediary between an EV fleet and the electricity grid and markets, and has control of the charging, and possibly discharging, of the fleet's batteries. By harvesting the combined capacity of a number of EVs, the EV aggregator can participate in wholesale electricity markets and provide ancillary services. However, given the increasing numbers of EVs, we envision a scenario where independent and self-interested EV aggregators compete in the same electricity market, trying to maximise their own profit [9]. Each of these aggregators can optimise its own operation, but lack of coordination can cause global inefficiencies.

In more detail, we consider EV aggregators purchasing energy in day-ahead markets, in order to meet their clients' electricity requirements. Without coordination, energy bidding could become concentrated in time, driving prices up and resulting in more expensive costs. This issue can be overcome by sharing information, *cooperating*, which can translate in cost decreases, a more stable grid and cleaner production methods, as demand peaks can be softened. However, manipulation can exist due to the self-interested nature of the aggregators, who could choose to cheat the system if greater personal benefit is perceived.

EV aggregator participation in day-ahead markets has been widely studied in the literature. Existing works consider either price-taker approaches [10–13], where prices are exogenous and unaffected by the EV aggregator activity, or price-maker approaches [14–17], where the aggregator's bids affect electricity prices. However, all these works consider a single EV aggregator which is able to optimise its own bidding, but do not consider the realistic scenario of several aggregators coexisting. To extend these works to a multi-aggregator setting, and to address the inter-aggregator cooperation challenge presented above, we propose a novel coordination mechanism which uses techniques from mechanism design to allow extending the benefits of optimised bidding to groups of self-interested EV aggregators. Mechanism design studies agent interaction protocols which take into account the fact that agents are rational and self-interested [18]. Our approach is based on the well-known Vickrey-Clarke-Groves (VCG) mechanism [18], and we consider three approaches for computing the payments using well-known redistribution mechanisms to ensure the payments made by the aggregators are fair. Two of these payment approaches are guaranteed to be truthful in our setting, meaning that participating EV aggregators are incentivised to cooperate by truthfully reporting their requirements to the third-party coordinator. By doing so, globally informed bidding decisions can be made, lowering total energy costs. This challenge has not been previously addressed for this setting.

In addition to the coordination mechanism, we introduce a novel price-maker bidding algorithm which is scalable and computationally tractable. This algorithm extends the price-taker algorithm from [13]

by accounting for price impact through using residual supply curves [19]. We consider two approaches. The first utilises raw historical supply and demand data, while the second formulation employs a quadratic convex approximation. These approaches are in contrast with the linear price impact utilised in [14–16]. Moreover, unlike [17], who also consider non-linear price impact, our approach has only 72 linear constraints. Hence, it is simpler to implement and scales to arbitrary numbers of EVs. Another advantage of our convex approximation approach is that it guarantees finding the global minimum of the approximated function. This is important for using the VCG-type mechanisms, which require an optimal solution to ensure the truthfulness property.¹

More precisely, the contributions of this paper are threefold.

1. The development of a novel price-maker day-ahead bidding algorithm for EV aggregators, formulated in terms of simple driver requirement constraints, which scales to very large fleets with very little computational burden.
2. The development of a novel EV aggregator coordination mechanism in which different self-interested EV aggregators can coordinate their bids in the day-ahead market to achieve reduced costs. This mechanism is generic and can be employed in combination with any underlying bidding algorithm. However, when employing our proposed bidding algorithm, the coordination mechanism scales linearly with number of aggregators and fleet size, allowing it to be applied to very large populations. Moreover, when combined with the convex approximation variant of the bidding algorithm, the mechanism incentivises truthful reporting.
3. Evaluation of the proposed bidding algorithm and coordination mechanism in a realistic scenario using real market and driver behaviour data from the Iberian Peninsula.

The rest of the paper is structured as follows. Section 2 introduces the novel price-maker day-ahead bidding algorithm. Section 3 details the proposed inter-aggregator coordination mechanisms, which utilise the bidding algorithm from Section 2. Then, Section 4 presents a realistic case study to evaluate the performance of the proposed algorithms. Finally, Section 5 presents the conclusions.

2. Participation of an EV aggregator in the day-ahead market

This section introduces the proposed day-ahead bidding framework. Firstly, the typical day-ahead market found in most countries is detailed, together with the mathematical formalism to quantify the impact of the aggregator's bids on electricity prices. Then, the proposed EV aggregator and novel bidding algorithm are described.

2.1. The day-ahead market

Typical day-ahead markets are daily forward markets featuring a uniform-priced double-sided auction. In more detail, they run every day of the year and each day is divided into 24 one-hour slots. A separate auction is run for each hourly slot. All bids and offers for each hourly slot of day $D + 1$ need to be submitted before market closure time, noon on day D . Uniform price refers to marginal pricing, by which all the accepted orders have the same price, which coincides with the price of the intersection between supply and demand.

The supply side, consisting of electricity producers, offers volumes of electricity at different prices. All supply side offers are aggregated by low-price priority, resulting in a generation stack curve, which relates

¹ More precisely, even though the function is not optimal from the coordinator perspective, because the allocation and payments are both based on this function, from the individual aggregator perspective the allocation is perceived to be optimal and their utility cannot be improved by misreporting.

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