Competition Between Regulation-Providing and Fixed-Power Charging Stations for Electric Vehicles

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Abstract—This paper models a non-cooperative game between two EV charging stations. One is a fixed-power charging station purchasing electricity from the grid at wholesale price and reselling it in their batteries until leaving the charging station. This particularity of EV charging demand can be leveraged, in particular for regulation purposes. In practice, when there is extra (resp. a lack of) energy production with respect to demand, the grid can send a “down” (resp., “up”) regulation signal so that the production side–reacts accordingly. In this paper, we consider the economic aspects of such an option, from the point of view of EV owners and charging stations.

We analyze the competition among those charging providers, and examine the performance at the equilibrium in terms of user welfare, station revenue and electricity prices. As expected, competing stations provide users with lower charging prices than when both charging solutions are offered by a monopolistic provider. Moreover, while competition benefits users, it also benefits the grid in that the amount of regulation services increases significantly with respect to the monopolistic case.

I. INTRODUCTION

Among the main difficulties of the penetration of Electric Vehicles (EVs) in the smart city is the associated energy equation: how can the power grid accommodate the corresponding demand? [1]. And together with the technical limitations, the question of economic incentives to elicit the most efficient use of resources needs also to be considered (see [2] and references therein). But EVs do not use the energy in real time, they just store it in their batteries until leaving the charging station. This particularity of EV charging demand can be leveraged, in particular for regulation purposes. In practice, when there is extra (resp. a lack of) energy production with respect to demand, the grid can send a “down” (resp., “up”) regulation signal so that the production side–reacts accordingly. In this paper, we consider the economic aspects of such an option, from the point of view of EV owners and charging stations.

Previous work focuses on fairness issues among users in terms of final state-of-charge [3]; on incentivizing EV owners to contribute to regulation [4], [5]; or on the resulting user welfare [6], [7]. The closest works to ours are [8], [9], where the focus is on the pricing strategies of the charging stations: in [8], Gao et al. consider a regulator designing contracts to incentivize EVs to participate so that the station profit is maximized. On the other hand, in [9] we considered a charging station offering two simple options, namely a fixed-power charging (no regulation) and a varying-power charging (following regulation signals). Another difference is that [8] allows vehicle-to-grid energy exchanges while in [9] the regulation services are just provided by varying the current charging power. But both of those works, as well as [10], assume a monopolistic revenue-maximizing charging station.

In this paper, we focus on the effect of competition, by considering two competing charging stations, one implementing only regulation-based charging and the other only fixed-power charging. When compared to monopolistic situations, we expect competition to benefit users, through lower recharging prices. But also, we investigate the viability of each competition: indeed, regulation is rewarded through financial incentives, and providing regulation during charging may not yield sufficient revenues if those incentives are not large enough. Hence some regions of reward values where EV-charging-based regulation can occur; this was investigated in the monopolistic case in [9], here we study the effect of competition on that aspect as well.

Our results indicate that, as expected, competition is beneficial to users, through lower recharging prices. Also, competition appears to be better from the grid perspective, since both the region of rewards for which regulation is viable and the amount of regulation offered are larger in the competition setting. The remainder of the paper is organized as follows. Section II presents our model; Section III analyzes the price competition and the resulting Nash equilibrium; In Section IV we compare the performance of the competition with the monopolistic case and Section V concludes the paper.

II. MODEL DESCRIPTION

According to a national household travel survey of the United States [11], [12], a passenger vehicle spends on average 75 minutes a day on journey, hence is parked most of the time. We assume this to remain true for EVs. So this is interesting, at least for some EV drivers, to accept longer charging durations for cheaper energy. This opens an opportunity for charging stations to increase revenue through the rewards offered to regulation-contributing entities, as well as for EV owners to save on their energy bill.

Conventional recharging services are provided by what we will call an S-charging station, purchasing electricity at the low wholesale unit price $t$/kWh and reselling it to EV owners at a higher price; whereas in a R-charging, charging power
is not guaranteed but subject to variations over time, as a response to regulation requests issued by grid operators. We model the interactions among both stations (or sets of stations, each set controlled by a separate entity) as a noncooperative game since they compete over prices to attract EV owners. User preferences between price and charging power variations are assumed heterogeneous, so each station seeks the best tradeoff between market shares and per-client profit in order to maximize its expected revenue.

A. Regulation mechanism

Frequency regulation, depending on the response time, is mainly divided into: primary, secondary, and tertiary control, with the response time increasing from seconds, to minutes and finally to half an hour respectively [13]. In our proposal, the R-charging station modulates the EV charging power to provide the secondary control: one regulation time slot lasts for \( \Delta \) hours, with \( \Delta \) typically between 0.1 (6 minutes) and 0.25 (15 minutes). Periodically, the grid operator, buyer of the regulation service, sends a regulation request to the R-charging station specifying its demand, which can be regulation-up, -down or -null. Receiving the signal, the R-charging station sets the EV recharging power to be 0 kW\(^1\), \( P_d \) kW, or \( P_n \) kW respectively: \( P_d \) is the maximum acceptable power level allowed by the EV supply equipment in the station, and \( P_n \) is the default recharging power (\( 0 \leq P_n \leq P_d \)) defined by the R-charging station itself, when no regulation is needed, namely regulation null. Note that this mechanism increases (decreases) the EV consumption responding to regulation-down (-up). This counter-intuitive naming stems from conventional regulation services, where providers are generation units whereas the task is given to consumers here. For later convenience we will use the notation \( x := \frac{P_d}{P_n} \), so that \( x \in [0,1] \).

At the S-charging station, EVs are always charged at full speed \( P_d \) kW. Figure 1 illustrates the charging power profiles for the two stations as well as the energy accumulated in an EV battery being charged for a given scenario of regulation requests. We denote by \( C_B \) the energy demand of an EV, and by \( \rho_u \) (\( \rho_d \)) the probability of occurrence of regulation-up (-down) at each time slot, those signals being assumed independent at each regulation period in this paper.

There may be concerns that varying the charging power for all EVs in R-charging station(s) simultaneously and drastically following this “ping-pong” policy can lead to an oversupply of regulation, i.e., the aggregated increase or decrease in power is larger than that actually needed by the grid operator. This is hardly possible since in the scale of a grid operator, the disposable regulation capacity scattered in EVs is non-dominant if not negligible given the current penetration levels. For example data from RTE (Réseau de transport d’électricité), the biggest independent system operator in France, show that the regulation-down demand in 30 minutes\(^2\) can easily go over

\[ E_\Delta = t \Delta (\rho_u r_u P_n - \rho_d (1-r_d) (P_d - P_n) - P_n) \]  

100 MWh, a quantity that could only be absorbed by at least ten thousand EVs doing level 2 recharging (19.2kW [14]) at the same time. Since the whole country has an EV population of 30 thousand, sharing 8600 public charging facilities, the regulation oversupply problem is not of concern so far. But it can rapidly become one if EV penetration increases; nevertheless we expect that in this case, the incentives to provide regulation will be adjusted (regulation being rewarded less) so that market mechanisms will reduce supply. In addition, demand for regulation is likely to increase in the next future, with the development of renewable energy production which cannot be controlled like fossil-based electricity plants can: the overall supply-demand balance will be more difficult to maintain, hence a probable larger need for ancillary services such as regulation.

B. Regulation incentives

In return for providing regulation, the R-charging station receives monetary incentives, with respect to the default wholesale price \( t \).

- In regulation-null periods, it charges each plugged EV with power \( P_n \) kW, and pays \( \Delta t P_n \) monetary units (no compensation) over such a duration-\( \Delta \);
- in regulation-up periods, the grid operator “re-buys” the energy saved at a unit price \( r_u t \), hence the station pays \( \Delta t (1-r_u) P_n \) monetary units over such a period (note that we can expect to have \( r_u \geq 1 \), although it is not always the case in practice);
- similarly, in a regulation-down, the R-charging station pays for the extra energy it consumes at a discount price \( t(1-r_d) \) monetary units per kWh, thus a total price paid \( \Delta (P_n t + (P_d - P_n) t (1-r_d)) \) monetary units per EV.

Together with the probabilities of regulation-up (\( \rho_u \)) and down (\( \rho_d \)), the expected net revenue (possibly negative) over one regulation slot is:

\[ E_\Delta = t \Delta (\rho_u r_u P_n - \rho_d (1-r_d) (P_d - P_n) - P_n) \]  

C. User preferences

We assume that each EV owner needs \( C_B \) kWh of energy, say, per day, the owner can choose to charge at the constant

\[ P_r \]
power $P_d$ in the $S$-charging station, or to charge at a variable power in the $R$-charging station. They can also choose neither solution (a no charging choice) if they consider both too expensive. Naturally, users are assumed to:

- prefer to recharge faster, i.e., at higher power rate;
- be reluctant to uncertainty in the recharging power caused by regulations. Additionally, batteries can be sensitive to power variations in the recharging process, another reason for EV owners to be reluctant to contributing to regulation.

Following these criteria, we define the user utility (willingness-to-pay minus price paid) for a recharging option as being of the form

$$V = \theta(\bar{P} - \gamma \delta(P)) - TC_B$$

where $\bar{P}$ is the expected charging power, and $\delta(P)$ its standard deviation. $\theta$ is user-specific: we assume it to be exponentially distributed, with mean $\bar{\theta}$, over the EV owner population. The parameter $\gamma$ is the reluctance toward power fluctuations, and is assumed the same for all users. Finally, $T$ represents the unit energy price set by the charging station chosen by the user. (We take $T = 0$ for users who choose no charging.)

Let us define $P_A$ as the value of $P - \gamma \delta(P)$ for the $R$-charging option, which can easily be expressed from $P_d$, $P_n$, $\rho_d$ and $\rho_u$. The parameter ($\gamma$) we choose always guarantees $P_A \geq 0$ which means that this proposal does not target users with a too high sensitivity to power fluctuation. The probability $\alpha_r$ (resp., $\alpha_s$) that a user chooses the $R$-charging (resp., $S$-charging) station can then be expressed as

$$\alpha_r = \begin{cases} 1 - \exp\left(-\frac{C\theta(T_r - T)}{\rho_d - P_A} \right) & \text{if } T_r < 0 \\ \exp\left(-\frac{C\theta(T_r - T)}{\rho_d - P_A} \right) - \exp\left(-\frac{C\theta(T_r - T)}{\rho_d - P_A} \right) & \text{if } 0 \leq T_r \leq \frac{P_A}{\rho_d} T \\ 0 & \text{otherwise} \end{cases}$$

$$\alpha_s = \begin{cases} \exp\left(-\frac{C\theta(T_r - T)}{\rho_d - P_A} \right) & \text{if } T_s \leq \frac{P_A}{\rho_d} T_r \\ \exp\left(-\frac{C\theta(T_r - T)}{\rho_d - P_A} \right) & \text{otherwise} \end{cases}$$

Note that we allow negative charging prices with the $R$-charging station: indeed, since that station can make money from the grid thanks to EV owners, the corresponding rewards could be so large that the station would be willing to attract a large number of EVs, even by paying them. This case is for completeness of the model, we think it is not very likely to occur but we cover it in this paper.

Following the classical backward induction method, we first assume $P_n$ (or equivalently $x$) fixed and analyze the game (defined below). The outcome is dependent on $x$ so the $R$-charging station can maximize its profit through altering its value. We examine the first part analytically while the second numerically due to complexity.

**Definition 1.** The pricing game between the $S$-charging station and the $R$-charging station as a collection: $(N, T, (R_i))$, where the player set $N$ consists of the two stations, the price profile $T$ is a vector $(T_s, T_r)$ on the semi-plane $\mathbb{R}_{\geq 0} \times \mathbb{R}$, and the payoff function $R_i : T \rightarrow \mathbb{R}$ gives each station’s expected revenue obtained from one EV.

| Table I: Model notations |
|---------------------------|
| $t$ | unit price of energy paid by stations (unit: €/kWh) |
| $r_u$ | remuneration ratio for regulation-up (no unit) |
| $r_d$ | discount ratio for regulation-down (no unit) |
| $\rho_u$ (resp. $\rho_d$) | probability of an "up" (resp. "down") regulation signal |
| $C_B$ | average energy recharged per EV per day |
| $\theta$ | user sensitivity to recharging power (including variability) |
| $\gamma$ | average value of $\theta$ among users |
| $P_n$ (resp. $P_d$) | default (resp. "regulation-down") recharging power |
| $x$ | unit energy price set by the charging station chosen by the user |
| $P_A(x)$, or $P_A$ | $P - \gamma \delta(P)$ |

**III. Analysis of the Game**

In this section, we analyze the non-cooperative strategic game defined in 1. We derive their respective best-response prices, to characterize the Nash equilibria.

**A. Best-response prices**

1) $S$-charging station revenue and best-response price $T_s^{br}$: For the $S$-charging station owner, its average income $R_s$ depends on the market share $\alpha_s$, and the unit price $T_s$ it offers:

$$R_s = C_B(T_s - t)\alpha_s = \begin{cases} C_B(T_s - t) \exp\left(-\frac{C\theta(T_s - T)}{\rho_d - P_A} \right) & T_s \leq \frac{P_A}{\rho_d} T_r \\ C_B(T_s - t) \exp\left(-\frac{C\theta(T_s - T)}{\rho_d - P_A} \right) & T_s > \frac{P_A}{\rho_d} T_r \end{cases}$$

Depending on its opponent’s strategy $T_r$, the price $T_s$ that maximizes $R_s$ provides the best-response price.

**Proposition 1.** The $S$-charging station has a unique best-response price as follows:

$$T_s^{br}(T_r) = \begin{cases} t + (P_d - P_A) \frac{\theta}{C_B} & \text{if } T_r < (t + (P_d - P_A) \frac{\theta}{C_B}) \frac{P_A}{P_d} \\ T_r \frac{P_d}{P_A} & \text{if } T_r > (t + P_d \frac{\theta}{C_B}) \frac{P_A}{P_d} \end{cases}$$

**Proof:** The proof is provided in the Appendix of the full paper version [15].

**II. Figure 2 illustrates the $S$-charging station revenue as a function of $T_r$, and the best-response $T_s^{br}(T_r)$.

2) $R$-charging station revenue and best-response price $T_r^{br}(T_s)$: Let us now consider the $R$-charging station owner, having to decide its price $T_r$.

To estimate how much net remuneration the $R$-charging station gets from recharging EVs through regulation, we multiply the regulation revenue per slot, i.e. $E_s$ in (1), by the average number of slots a regulating EV remains plugged-in before its battery is fully recharged, i.e. $C_B / (\Delta P)$. To facilitate the writing we further divide the product, which has a unit of €, by the EV energy demand ($C_B$ kWh), so that its final unit is €/kWh and has a form of $E_r := (\rho_u r_u x - \rho_d (1 - r_d)(1 - x)) \frac{P_d}{P}$. 

The average R-charging station revenue consists of remuneration from providing regulation and income from charging EVs:  

\[ R_r = C_B(T_r + E_r)[1 - \exp\left(-\frac{C_B(T_r + E_r)}{\theta P_A}\right)] \]

where

* \( C_B(T_r + E_r) = \frac{\theta(P_d - P_A)(1 - \exp(-C_B T_r / \theta P_A))}{C_B(P_d - P_A) - 1 + \exp(-C_B T_r / \theta P_A)} \)

\[ E_r,1(T_s) = \frac{\theta(P_d - P_A)(1 - \exp(-C_B T_s / \theta P_A))}{C_B(P_d - P_A) - 1 + \exp(-C_B T_s / \theta P_A)} \]

\[ E_r,2(T_s) = E_r,1(T_s) + \frac{P_d - P_A}{P_d - P_A} \exp\left(-\frac{C_B T_s}{\theta(P_d - P_A)}\right). \]

**Proposition 2.** The R-charging station has a unique best-response price as follows:

\[ T_s^{br}(T_r) = \begin{cases} 
T_s \frac{P_d}{P_d - P_A} & \text{if } T_s \leq -E_r, \frac{P_d}{P_d - P_A} \\
0 & \text{if } T_s \in \{T_s : E_r,1(T_s) \leq E_r \leq E_r,2(T_s)\} \\
\{T_s \in \mathbb{R} : \frac{\partial R_r}{\partial T_r} = 0\} & \text{otherwise} 
\end{cases} \]

**Proof:** The proof is provided in the Appendix of the full paper version [15].

Figure 3 shows the R-charging station revenue as well as the best-response price \( T_s^{br}(T_r) \), as a function of \( T_r \).

**B. Nash equilibrium**

**Proposition 3.** The pricing game defined in 1 has either a unique Nash equilibrium or a unique Pareto-dominant one when there exist infinite number of Nash equilibria. The equilibrium prices \( N^E \) in different circumstances are:

\[ T_r = -E_r, T_s = -\frac{P_d}{P_A} E_r \]

\[ \text{if } E_r \leq -\frac{P_A}{P_d} [t + (P_d - P_A) \frac{\theta}{C_B}] \]

\[ T_r = 0; T_s = t + (P_d - P_A) \frac{\theta}{C_B} \]

\[ \text{if } E_r = \frac{P_A}{P_d} [t + (P_d - P_A) \frac{\theta}{C_B}] \leq E_r < E_r,1(t + (P_d - P_A) \frac{\theta}{C_B}) \]

\[ T_r \in (-E_r, 0); T_s = t + (P_d - P_A) \frac{\theta}{C_B} \]

\[ \text{if } E_r < E_r,2(t + (P_d - P_A) \frac{\theta}{C_B}) < E_r \]

\[ \text{if } E_r,2(t + (P_d - P_A) \frac{\theta}{C_B}) < E_r \]

**Proof:** The proof is provided in the Appendix of the full paper version [15].

Note that \( N^E \) (8a) which occurs when \( E_r \leq -\frac{P_A}{P_d} [t + (P_d - P_A) \frac{\theta}{C_B}] \) is not profitable for the R-charging stations since zero revenue is obtained, and that the condition for a positive R-charging station revenue is \(-\frac{P_A}{P_d} [t + (P_d - P_A) \frac{\theta}{C_B}] \leq E_r \). We will refer to this condition in Section IV-B.

Figure 4 illustrates best-response prices and resulting Nash equilibria in four different circumstances. Figure on the left hand side shows that when regulation remuneration is not significant (eg. \( r_u = 1 \) and \( r_d = 0 \) in the figure), it is likely to encounter equilibrium \( N^E \) (8a) or \( N^E \) (8b), due to small regulation profit \( E_r \). On the right hand side, equilibrium \( N^E \) (8c) or \( N^E \) (8d) happens when regulation revenue is very attractive. Note that we choose very high regulation prices just to depict the case where free recharging or even negative price recharging is offered. To our knowledge, such high prices rarely exist on the market.

1) **Optimization of \( P_A \):** The pricing game defined in 1 is played given a fixed \( P_a \), set by the R-charging station, who
can afterwards modify its value to pursue a higher equilibrium revenue. Due to the complexity of the equilibrium price profile we resort to numerical search for the optimal \( P_u \).

IV. COMPARISON BETWEEN THE NASH EQUILIBRIUM AND THE MONOPOLISTIC CASE

In this section we compare the competition model with the monopolistic case where a single manager sets both the S-charging price as well as the R-charging price to maximize its overall revenue. We do not repeat the results in [9] for the monopolistic case due to space limit, but simply compare their performances under the same parameters.

A. User welfare

User welfare is the average user utility over the distribution of user preference parameter, i.e. \( \theta \). The following formula works for both the monopolistic case and the Nash equilibrium.

\[
U = \int_{T_s-T_c}^{T_d-T_c} \left( \frac{x}{r_u r_d} \right) \exp(-\frac{\theta}{\theta}) d\theta
\]

Whereas in competition, (8a) and (8b) give the condition of:

\[
\frac{t (\rho_u r_u x - \rho_d (1 - r_d)(1 - x) - x - P_u P_d^2)}{C_B} > 0
\]

Comparing these two we find that the competition enlarges the viable region of \( \{r_d, r_u\} \). The blue and red areas in Figure 6 are referring to the optimal default recharging power \( P_u \) in these regions, i.e. the optimal \( x \) after exhaustive search. In most combinations of \( \{r_d, r_u\} \), this optimal \( x \) is either 0 or 1, except for a few \( \{r_d, r_u\} \) observed in the gap between the blue region and the red, in the figures on the third column where average user preference on power is smaller: \( \bar{\theta} = 0.1 \) and user sensitivity to variation is greater: \( \gamma = 0.5 \). We also plot the actual \( \{r_d, r_u\} \) offered by a French operator RTE on these figures. The blue circles correspond to the 48 \( \{r_d, r_u\} \) pairs on the day of 20/07/2015 and the red rectangles are showing the daily averages during the week from 20/07/2015 to 26/07/2015.

V. CONCLUSION AND PERSPECTIVES

This paper considers a competition between two self-interested charging stations. At the Nash equilibrium of this non-cooperative game, both stations tend to offered lower prices to EV owners than a monopolistic controller would do, thus more clients are attracted and greater regulation services is provided to the grid operator. This work can be extended in several ways including: bring in more actors such as charging stations with private renewable energy sources; considering the actor of a “Grid” who can play with the wholesale electricity price imposed on both R-charging and S-charging station; or differentiate two charging stations by their locations, which effect users’ preferences among them.

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Fig. 5: Comparison between Monopoly (first row) and Nash equilibrium (second row), with $t = 0.03$, $\bar{\theta} = 0.3$, $C_B = 50$, $\rho_d = \rho_u = 0.48$, $\gamma = 0.05$, $r_d = 0.4$, $r_u = 1.6$ ($r_d$ and $r_u$ are the daily average of 20/07/2015).

Fig. 6: Comparison of variable regions on $r_d \times r_u$ plane and the $x$ chosen, $t = 0.03$, $C_B = 50$, $\rho_d = \rho_u = 0.48$