Incentivizing Electric Vehicles to Provide Regulation While Recharging

SHUAI Wenjing Patrick Maillé Alexander Pelov

Telecom Bretagne

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System sketch

Three options for EV owners:

- *S-charging*: simple charging, battery is recharged at the maximum rate
- *R-charging*: recharge power subject to the regulation signal sent by TSO
- *no_charging*: do not recharge at all

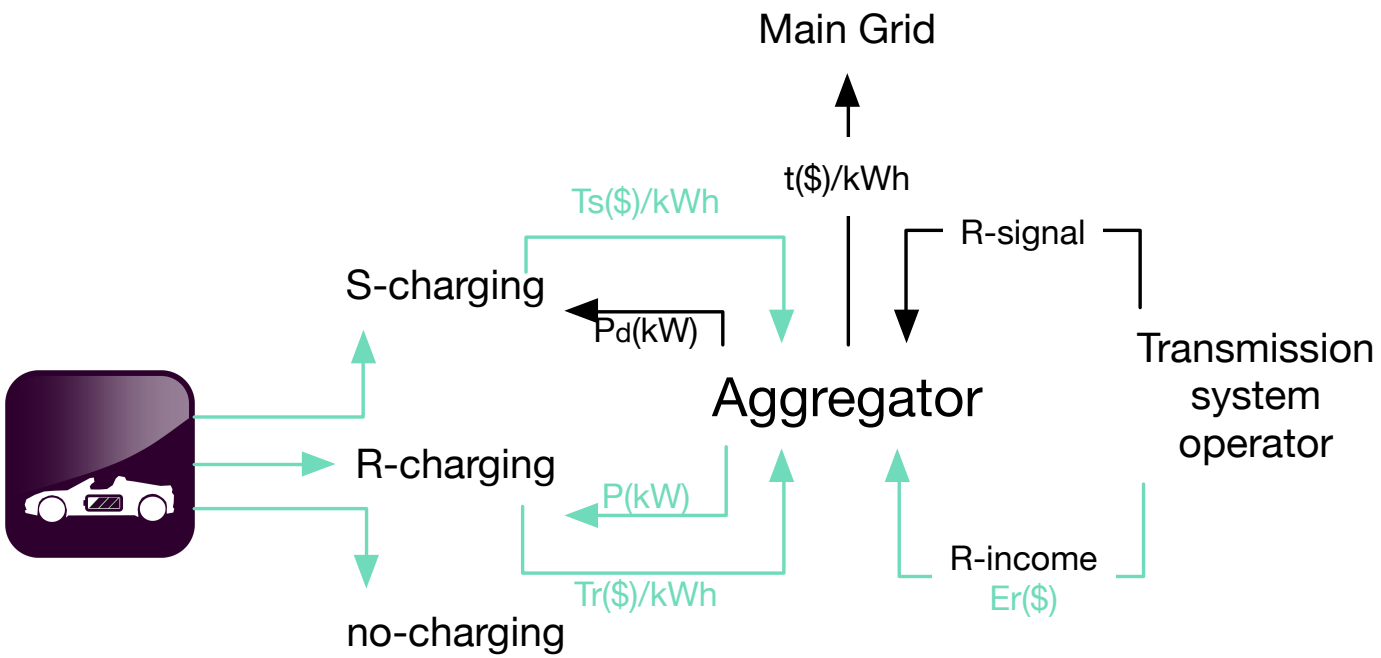
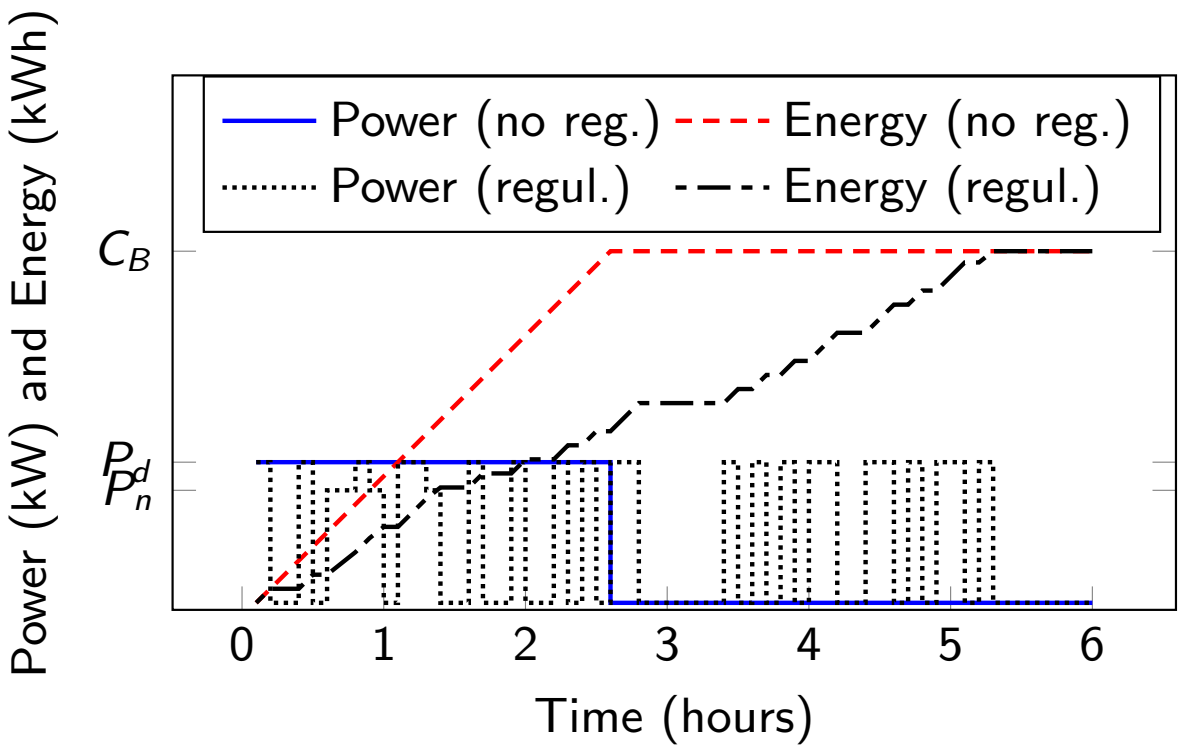


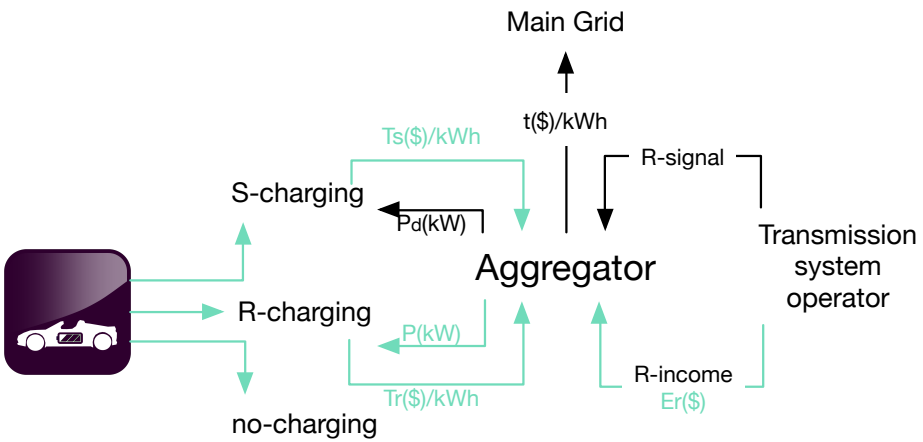
Figure: A sketch of the charging management scenario

Regulation mechanism—power modulation

A comparison between recharging at full power P_d and recharging while reacting to regulation requests, in terms of the recharging power and energy transferred to the EV battery. We denote by C_B the total energy requested by the EV, and by ρ_u (ρ_d) the probability of occurrence of regulation up (down), assumed independent at each regulation period in this paper.



Regulation mechanism—incentive composition



$$E_r = \Delta t(\rho_u r_u P_n - \rho_d(1 - r_d)(P_d - P_n) - P_n) \quad (1)$$

- t: unit price of energy at which the aggregator buys electricity;
- r_u: remuneration ratio for regulation up;
- r_d: discount ratio for regulation down;
- ρ_u (resp. ρ_d): probability of an "up" (resp. "down") signal, $\rho_n = 1 - \rho_d - \rho_u$ gives the probability that no regulation is needed at this slot;
- P_n (resp. P_d): default (resp. "down") charging power.

User preferences

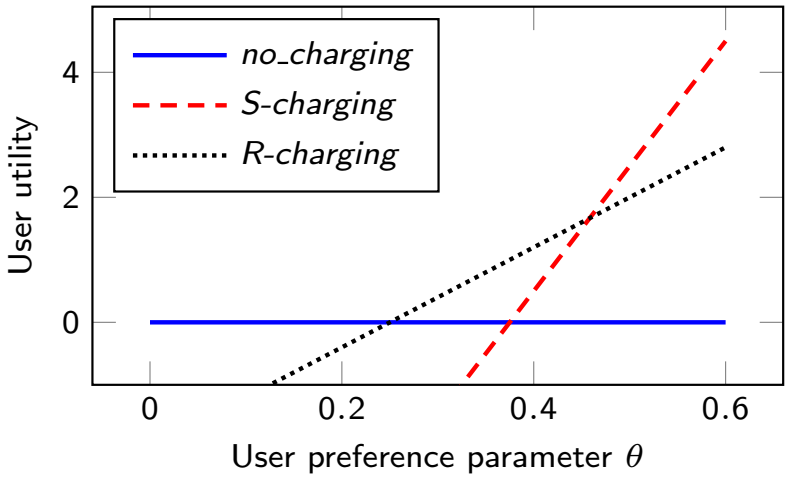


Figure: User utility for the three charging options ($C_B = 50$, $P_d = 20$, $P_A = 8$, $T_s = 0.15$, $T_r = 0.04$): the best choice depends on the user sensitivity θ

$$U = \theta(\bar{P} - \gamma\delta(P)) - TC_B \tag{2}$$

- "*S-charging*" over "*no_charging*" if $\theta > \frac{T_s}{P_d} C_B$
- "*R-charging*" over "*no_charging*" if $\theta > \frac{T_r}{P_A} C_B$
- "*S-charging*" over "*R-charging*" if $\theta > \frac{T_s - T_r}{P_d - P_A} C_B$.

Maximizing aggregator revenue—Problem&Solution

$x := \frac{P_n}{P_d}$ i.e. $x \in \{0, 1\}$

$$R(T_r, T_s, x) = \begin{cases} \alpha_r(T_r + \frac{E_r}{\bar{P}\Delta})C_B + \alpha_s(T_s - t)C_B & \text{if } \frac{T_r}{P_A} < \frac{T_s}{P_d} \\ \alpha_{s0}(T_s - t)C_B & \text{otherwise,} \end{cases} \tag{3}$$

$$\alpha_r = \exp(-\frac{T_r}{P_A\bar{\theta}}C_B) - \exp(-\frac{T_s - T_r}{(P_d - P_A)\bar{\theta}}C_B) \tag{4}$$

$$\alpha_s = \exp(-\frac{T_s - T_r}{(P_d - P_A)\bar{\theta}}C_B) \tag{5}$$

$$\alpha_{s0} = \exp(-\frac{T_s}{P_d\bar{\theta}}C_B) \tag{6}$$

Gives:

$$T_c^* = t + \frac{P_d\bar{\theta}}{C_B} \tag{7}$$

$$T_r^* = \frac{P_A\bar{\theta}}{C_B} - \frac{E_r}{\bar{P}\Delta} \tag{8}$$

$$\tag{9}$$

Revenue maximizing prices T_r and T_c

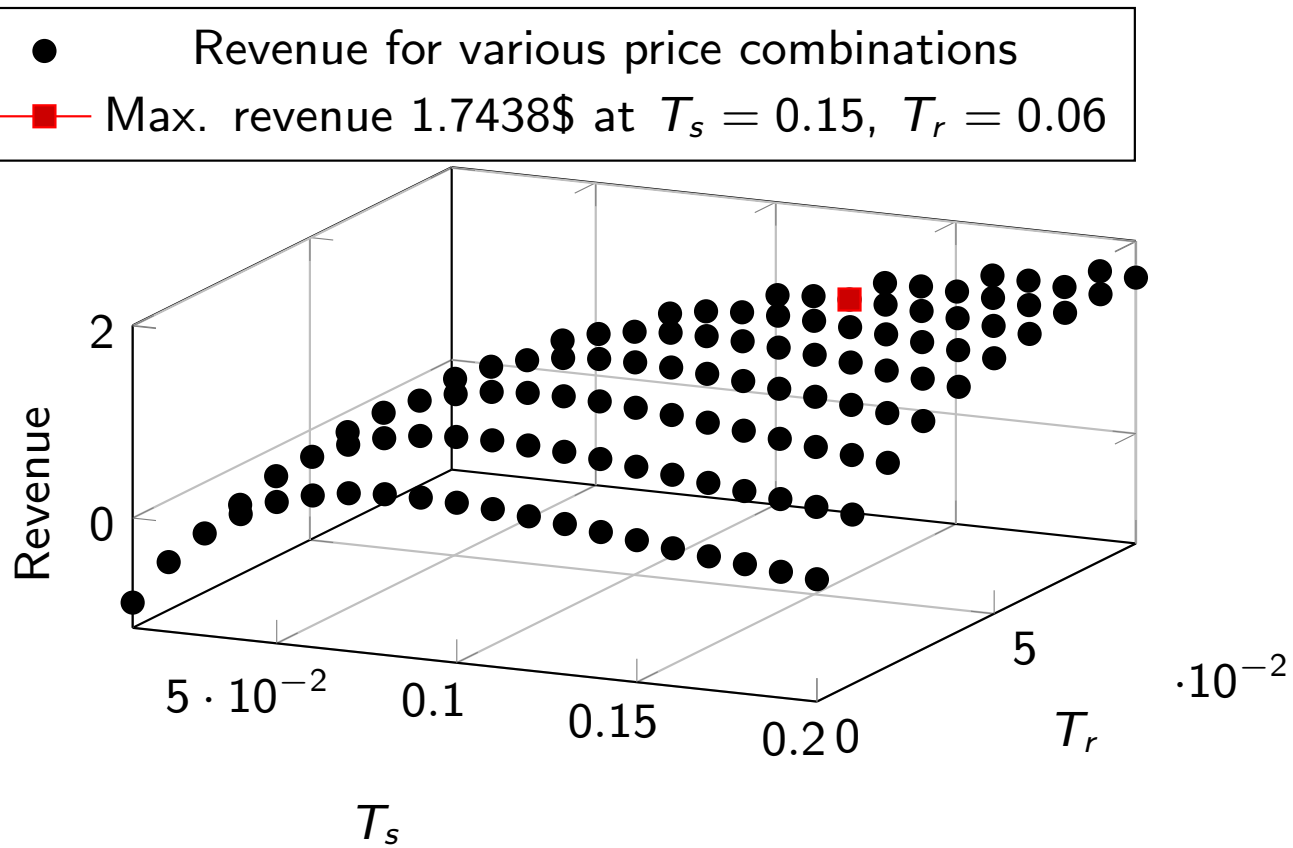


Figure: Revenue as a function of T_s and T_r, $P_n/P_d = 0.8$, $\bar{\theta} = 0.3$, $\gamma = 0.05$, $C_B = 50$, $\rho_u = \rho_d = 0.48$, $\Delta = 0.1$, $t = 0.03$, $r_u = 2.0$, $r_d = 0.6$

Aggregator benefit

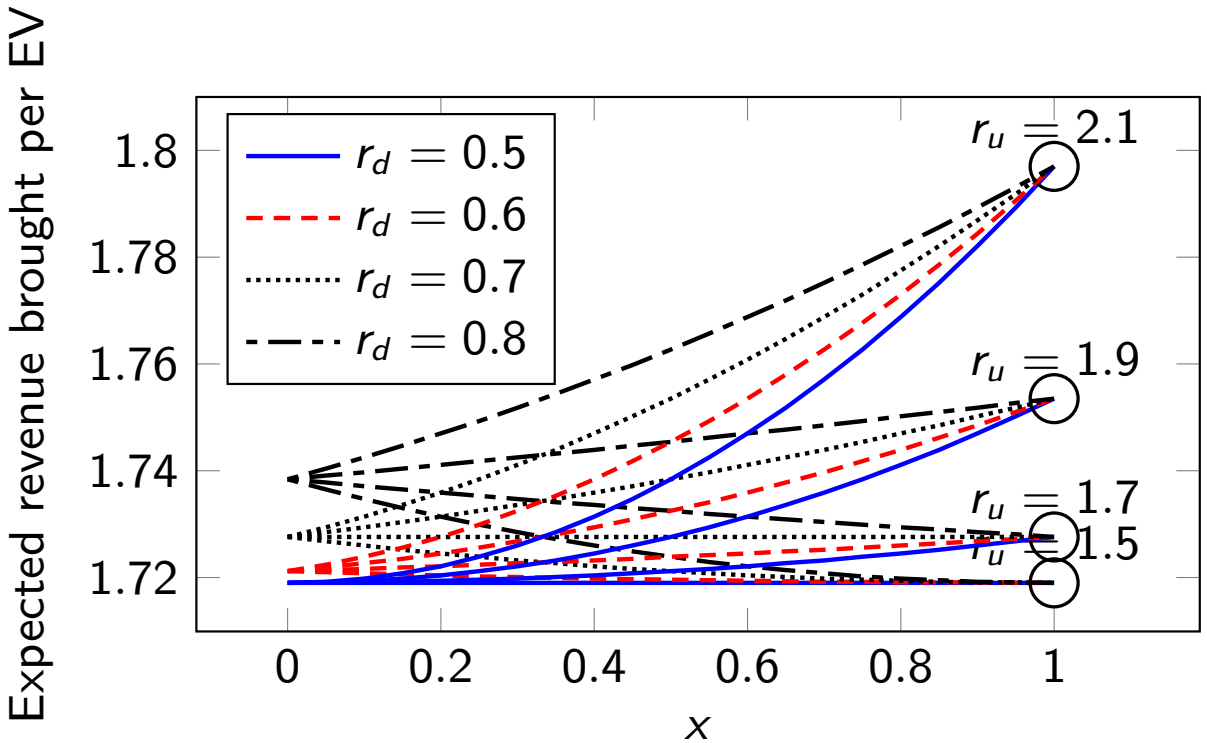


Figure: Aggregator Revenue with multiple combinations of r_d and r_u

$$r_u^{\min} = 2 - \rho_u + \gamma \rho_u^{-0.5}(1-\rho_u)^{1.5} \tag{13}$$
$$r_d^{\min} = 1 - \rho_d + \gamma\sqrt{\rho_d - \rho_d^2}.$$

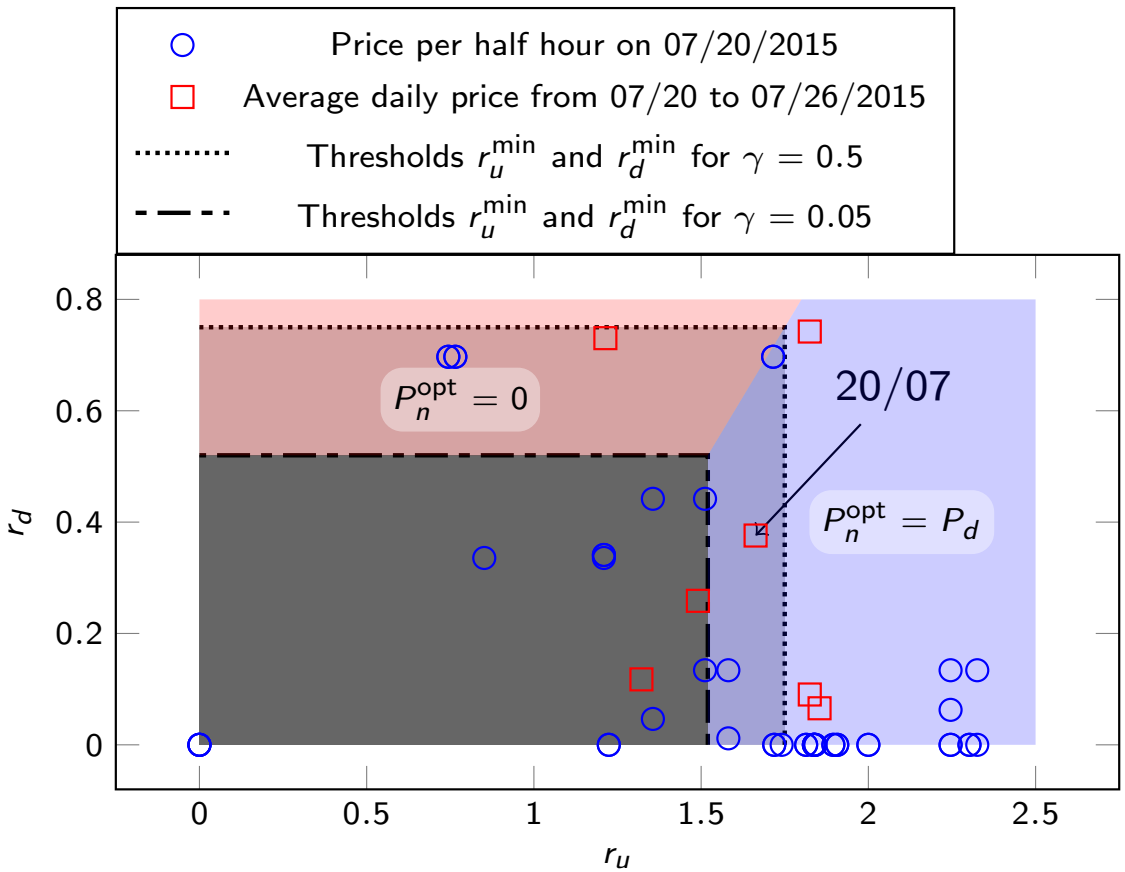


Figure: Observed regulation prices, and thresholds for *R-charging* to be beneficial for the aggregator