Collaborative Vehicle-to-grid Operations in Frequency Regulation Markets

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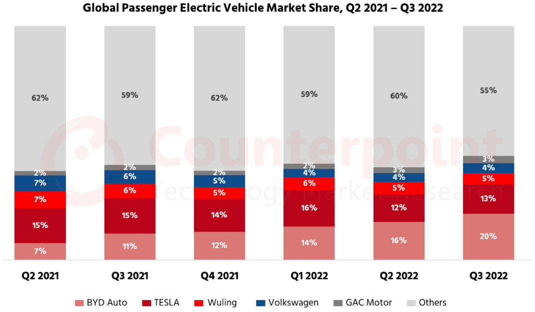
- Global passenger electric vehicle (EV) sales grew 71% YoY(year over year) in Q3 2022
- Three of the top five best-selling EV brands are from China.



https://www.counterpointresearch.com/global-electric-vehicle-market-share/

EV trends

7kW家充桩 2.0

体积小功能强，首桩权益随车附赠

宽高深218x345x153mm，无论挂壁，还是立柱安装都更加灵活。采用分体式设计，在收线时能更方便缠绕在插枪件上，减少发生缠线问题。

20kW家用快充桩

三倍充电速度，在家就能极速快充

宽高深395x760x205mm，IP65的防护等级，远超IP54行业标准，暴雨和沙暴天气仍可安心使用，连粉尘都难以进入桩体。开启后声音可小于50分贝，“静”享快速充电。

电量从10%充电至100%*所需时间

长续航电池包（100kWh） 标准续航电池包（75kWh）

20kW家用快充桩

5 小时

7kW家充桩 2.0

14 小时

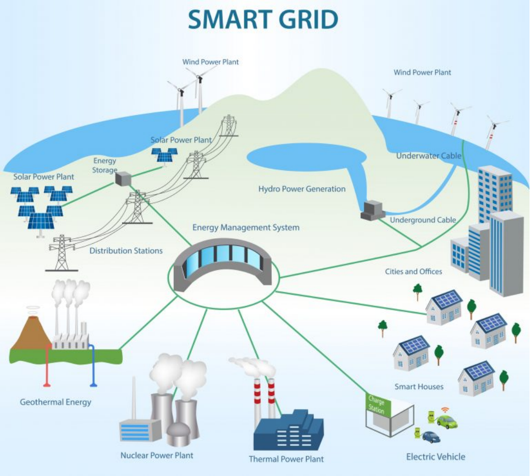
Electric Vehicle Market

Grid side:

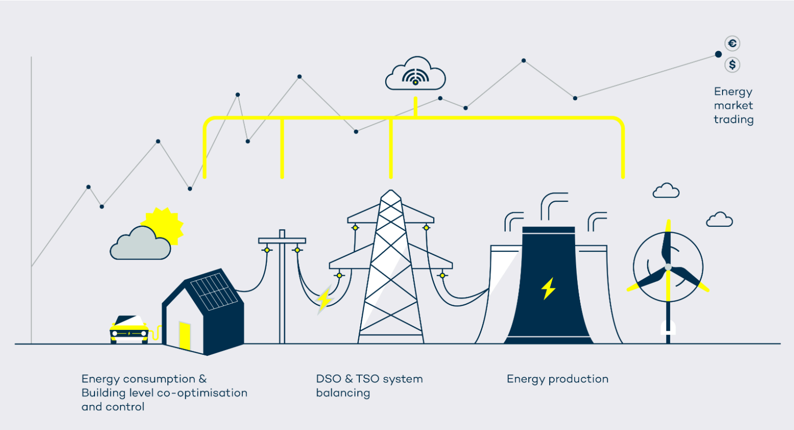
- inbalance electricity usage
- instability because of new energy

EV side:

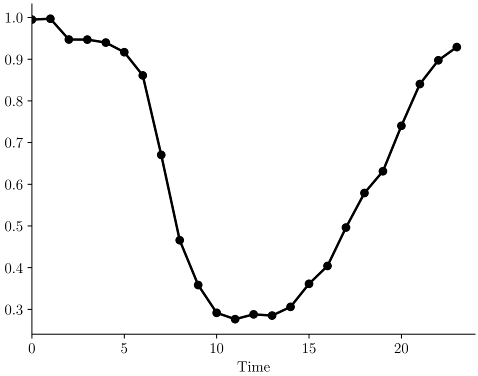
- Battery size
- Range
- Charging rate
- Sizable battries
- Idle 90% of time

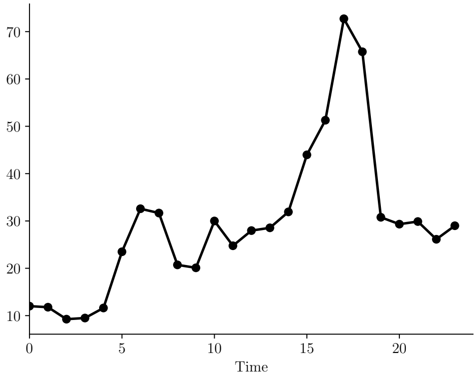


Vehicle to grid (V2G): technology that enables energy to be pushed back to the power grid from the battery of an electric car.



Look at the data





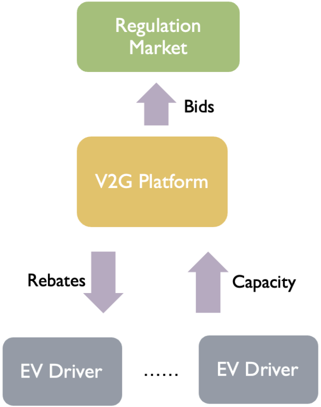
Proportion of cars parked at home (CHTS)

Market clearing prices for capacity (PJM)

Research Question:

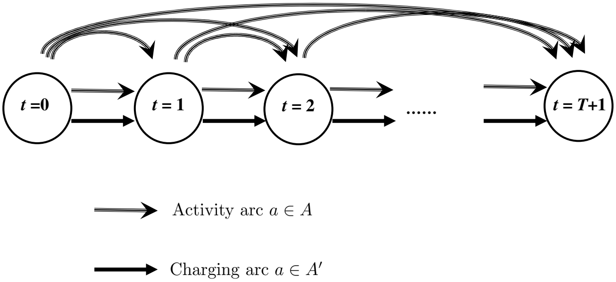
For a V2G platform:

- How to bid in the day-ahead regulation market?
- How to incentivize (by rebates) the EV drivers?



V2G platform

Driver side



$$\Pi(v) = \max_{\boldsymbol{x} \in \boldsymbol{\Lambda}} \sum_{a \in A \cup A'} v_a x_a, \quad \text{where } \boldsymbol{\Lambda} \equiv \left\{ \boldsymbol{x} \in \{0,1\}^{|A \cup A'|} : \sum_{a \in A \cup A'} b_{na} x_a = f_n, \quad \text{for } n \in N \right\}.$$

Persistency model

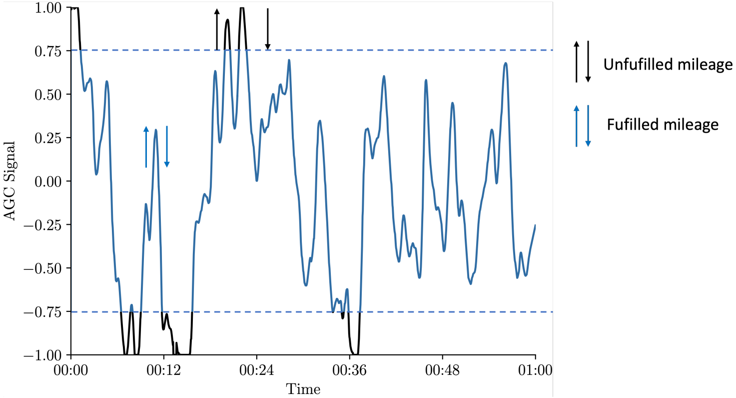
Suppose $\tilde{v}_a$ has mean μ_a and standard deviation σ_a.

$$\sup_{\tilde{v}_a} E(\Pi(\tilde{v})) = \max_{y \in \text{conv}(\Lambda)} \sum_{a \in A} (\mu_a y_a + \sigma_a \sqrt{y_a(1 - y_a)})$$

- (Linear) reward longest-path problem $\rightarrow$ (Concave) reward network flow problem on same graph
- SOCP fomulation

Natarajan K, Song M, Teo CP (2009) Persistency model and its applications in choice modeling. *Management Science* 55(3):453-469.

Mileage-based performance



Requirement: performance index $=$ fulfilled mileage/total mileage $\geq 1 - \eta$

- Challenge: the AGC signal is stochastic

$$P\left(\underbrace{\psi\tilde{K}_t}_{\text{Total capacity from EV on charge}} - \underbrace{\tilde{r}_t C_t}_{\text{AGC requirements}} \geq 0\right) \geq 1-\eta.$$

which is equivalent to the VaR expression

$$\hat{\phi}_{1-\eta}(\tilde{r}_t C_t - \psi\tilde{K}_t) \leq 0$$

We can use CVaR as a surrogate

$$\phi_{1-\eta}(\tilde{r}_t C_t - \psi\tilde{K}_t) \leq 0$$

Proposition.

Let $\bar{r}_t$, σ_t^f and σ_t^b be the mean, forward deviation and backward deviation of $\tilde{r}_t$, respectively. Then either of the following is a sufficient condition that guarantees the CVaR constraint holds:

$$\bar{r}_t C_t - \psi M y_t + \sqrt{-2\ln\eta}\sqrt{\psi^2 M y_t(1-y_t) + (\sigma_t^f C_t)^2} \leq 0 \tag{1}$$

$$\bar{r}_t C_t - \psi M y_t + \frac{1-\eta}{\eta}\sqrt{-2\ln(1-\eta)}\sqrt{\psi^2 M y_t(1-y_t) + (\sigma_t^b C_t)^2} \leq 0. \tag{2}$$

Chen, X., Sim, M., & Sun, P. (2007). A Robust Optimization Perspective on Stochastic Programming. *Operations Research*, 55, 1058-1071.

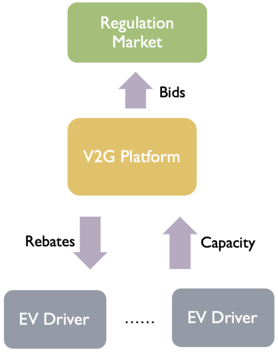
Platform (leader)

$$\max_{\mathbf{C},\mathbf{s}} \sum_{t=1}^{T} (\bar{p}_t C_t - s_t y_t M)$$

$$\text{s.t.} \ \ P\left(\psi \tilde{K}_t - \tilde{r}_t C_t \geq 0\right) \geq 1 - \eta, \ \text{for } t = 1, \cdots, T$$

Drivers (follower)

$$\max \sum_{a \in A} \left(\mu_a y_a + \sigma_a \sqrt{y_a(1 - y_a)}\right) + \sum_{t=1}^{T} \left((\mu_t + s_t) y_t + \sigma_t \sqrt{y_t(1 - y_t)}\right)$$



V2G platform

Denote by $\underline{y}_t$ the optimal flow for charging arc $t \in A'$ in the pricing optimization model with extra constraints $s_{t'} = 0$, for $t' \in A' \backslash \{t\}$. Similarly, denote by $\bar{y}_t$ the optimal flow for charging arc $t \in A'$ in the pricing optimization model with the extra constraints $s_{t'} = \bar{s}$, for $t' \in A' \backslash \{t\}$. Then, the following holds:

Proposition.

The optimal flow for arc $t \in A'$ satisfies $\underline{y}_t \leq y_t \leq \bar{y}_t$.

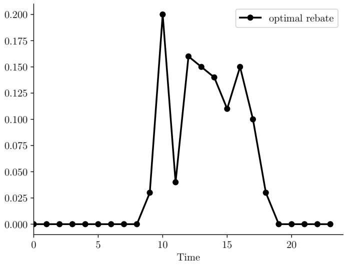
We can add these valid inequalites during the branch-and-bound process to reduce the search space.

Granot F, Veinott AF (1985) Substitutes, complements and ripples in network flows. *Mathematics of Opereations Research* 10:471-497

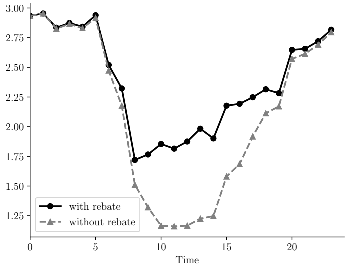
Computational Performance

Composition		without valid inequalities			with valid inequalities		
Cluster 1	**Cluster 2**	**Time(s)**	**Gap**	**% Solved**	**Time(s)**	**Gap**	**% Solved**
0.4	0.6	174.02	-	100%	42.46	-	100%
0.45	0.55	202.68	-	100%	58.31	-	100%
0.5	0.5	298.45	2.38%	94%	54.78	-	100%
0.55	0.45	490.88	2.23%	86%	102.80	-	100%
0.6	0.4	676.23	2.41%	62%	171.98	2.13%	98%
0.65	0.35	758.29	2.46%	40%	330.58	2.20%	86%
0.7	0.3	994.54	2.60%	18%	473.09	2.29%	64%

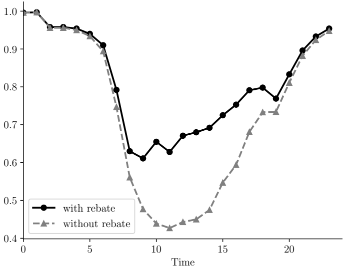
Overall, the fleet of 200 EVs generates a monthly profit of $220.60 (per EV) for the platform, and $20.52 in rebates on average for each driver. Compared with the case of not offering rebates, offering such incentives helps improve the platform's profit by 4.37%.



optimal rebates



optimal bids

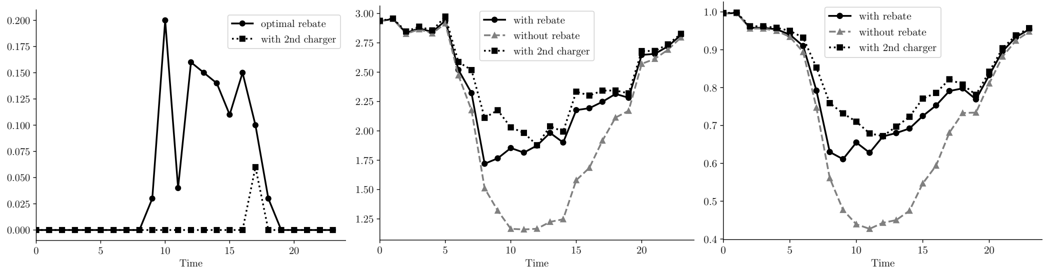


optimal persistency values

Observations:

- Both increasing the participating EV fleet size and offering plug-in rebates help improve the platform's profits due to a pooling effect. Furthermore, the two work as strategic substitutes in improving profits.
- Upgrading the chargers' powering rating is a strategic complement with offering rebates, and can benefit EV drivers even more than the platform.
- When EV drivers have lower valuations for using their EVs, they become more sensitive to rebates. Consequently, the platform offers higher rebates and obtains higher profits.

Workplace charging



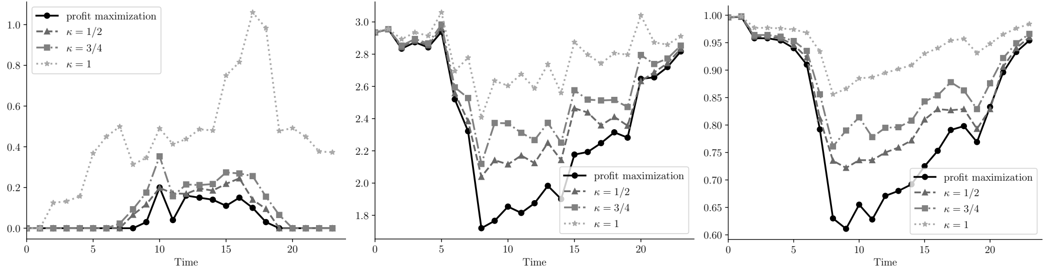
Two alternative strategies to promote V2G participation, installing workplace chargers and providing plug-in rebates, work as strategic substitutes in improving the platform's profits.

Alternative objective

We consider the case where the platform is jointly owned by the drivers.

$$
\begin{aligned}
\max_{\mathbf{C},\mathbf{s},\rho} \quad & \sum_{a\in A}\left(\mu_a y_a + \sigma_a\sqrt{y_a(1-y_a)}\right) + \sum_{t=1}^{T}\left((\mu_t + s_t)y_t + \sigma_t\sqrt{y_t(1-y_t)}\right) \\
& + \frac{1}{\kappa M}\sum_{t=1}^{T}(\bar{p}_t C_t - s_t y_t M) \\
\text{s.t.} \quad & \sum_{t=1}^{T}(\bar{p}_t C_t - s_t y_t M) \geq 0, \\
& \text{Other Constraints.}
\end{aligned}
$$

Alternative objective



As more EV drivers become stakeholders in the community V2G platform, the optimal rebate schedule more closely resembles the pattern of regulation prices.

- Bilevel problem for platform-driver game
  - Bilevel convex optimization
  - Persistency model for drivers' behavior (temporal substitution)
  - Dist-Robust Optimization for chance constraint
  - Inverse optimization for parameter calibration
- Observations
  - **Mismatch** between the availability of regulation power (parked EVs) and the regulation revenue. $\rightarrow$ offering rebates.
  - The infrastructure enhancements of increasing the power rating of chargers and providing workplace chargers work as a *strategic complement* and a *strategic substitute* with the pricing strategy of offering rebates.
  - In an alternative, community-based business model, the optimal rebates will be higher.