Day Ahead Electric Vehicle (EV) Scheduling:
Reference for Charging Station (CS)

First of all, in order to provide the incentive for EV to discharge, we need to quantify the "flexibility" of the EV.

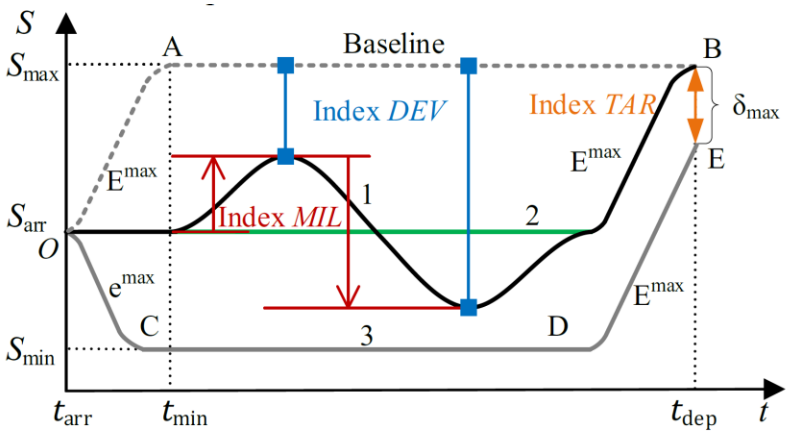

Figure 1: Examples of an EV's possible SoC curves during its charging time period [1].

For most of EVs when they arrived, they tend to want to charge to EV's to 100% charge, as fast as possible. We call this pattern the EV's "Baseline" and can be described by :

$$B^{SOC}(t) = \begin{cases} S_{arr} & ,t = t_{arr} \\ B^{SOC}(t)(t-1) + \frac{\rho^{ch} E^{max}}{Q} & ,t_{arr} < t \leq t_{dep} \\ S_{max} & ,t = t_{dep} \end{cases} \quad (1)$$

In our project, the flexibility is basically calculated through how much the EVs are willing to deviate from the baseline. We introduce two major indicators, first is *DEV*. When the EV provides flexibility to the grid, its charging power will be regulated to respond to the grid's needs. This will cause its SoC curve to deviate from the base line [1], which is defined as *DEV* and is calculated by :

$$DEV = Q \cdot \sum_{t \in [t_{arr}, t_{dep}]} [B^{SOC}(t) - S(t)] \quad (2)$$

Another one is *TAR*, where it indicates how much energy the EV is willing to give up when leaving the charging station. If the EV do not participate in contributing flexibility, *TAR* will always be zero. *TAR* can be calculated by :

$$TAR = Q \cdot [S^{obj} - S(t_{dep})] \quad (3)$$

After we quantify the flexibility indices, we further relate it to the price. We use a supply curve concept to turn flexibility into economic incentive via:

$$ind = k\lambda \quad (4)$$

where k is self-defined as parameter which indicates how proactively EV's owner want to participate the market and λ is the price CS will need to pay EV for contribute the incentive. ind is a compound index to flexibility, which can be described as :

$$a \cdot DEV + b \cdot TAR = ind \quad (5)$$

where a and b indicate the EV's owner decision, on which form of flexibility they want to provide.

We can now quantify the economic benefit for EV to discharge, IBM CPLEX is utilised to decide how much profit the CS and smart home prosumers can gain without participate in P2P trading (base case). This will compare with the benefit they get when participate P2P, in the later stage.

For the n Charging Station's Base Case：

$$\max\ (U_n^{CS}) = c^{sell}P_n^{sg} - c^{buy}P_n^{bg} \quad \text{Interaction with grid}$$

$$+\underbrace{\pi_n \sum_m \left[S_{n,m}(t_{n,m}^{dep}) - S_{n,m}^{arr}\right]}_{\text{Profit from charging EVs}} - \underbrace{\sum_m \left[\lambda_{n,m} ind_{n,m}\right]}_{\text{Reward paid to EVs}} \tag{6}$$

$$s.t.$$

$$< flexibility\ quatification\ constaints >$$

$$\left.\begin{aligned} 0 \le q_{n,m}^d(t) \le q_{n,m}^{d,max}, t \in \left[t_{n,m}^{arr}, t_{n,m}^{dep}\right] \\ 0 \le q_{n,m}^c(t) \le q_{n,m}^{c,max}, t \in \left[t_{n,m}^{arr}, t_{n,m}^{dep}\right] \end{aligned}\right\} \text{EV's charge discharge limit}$$

$$\left. q_{n,m}^c, q_{n,m}^d = 0, t \notin [t_{n,m}^{arr}, t_{n,m}^{dep}] \right\} \text{No charge discharge outside charging station}$$

Relation between charge/discharge

and EV's SOC

$$\left. S_{n,m}(t) = S_{n,m}^{arr}, t = t_{n,m}^{arr} \right\} \text{Initialize EV's SoC when arrive charging staion}$$

$$S_{n,m}(t) = S_{n,m}(t-1) + \frac{\rho_{n,m}^{ch} q_{n,m}^c(t)}{Q_{n,m}} - \frac{\rho_{n,m}^{disch} q_{n,m}^d(t)}{Q_{n,m}}, t \in (t_{n,m}^{arr}, t_{n,m}^{dep}]$$

$$\left. S_{n,m}^{min} \le S_{n,m}(t) \le S_{n,m}^{max}, t \in [t_{n,m}^{arr}, t_{n,m}^{dep}] \right\} \text{SoC limit}$$

$$\left. 1 - TAR_{n,m}(t) \le S_{n,m}(t) \le 1, t = t_{n,m}^{dep} \right\} \text{TAR flexibility}$$

$$\left. -P_n^{sg} + P_n^{bg} = -\sum_m q_{n,m}^d(t) + \sum_m q_{n,m}^c(t) - Solar_n \right\} \text{Power Balance}$$

for the k Smart Home's Base Case：

$$\max\ (U_k^{SH}) = c^{sell}P_k^{sg} - c^{buy}P_k^{bg} \quad \text{Interaction with grid} \tag{7}$$

$$s.t.$$

$$\left. -P_k^{sg} + P_k^{bg} = Load_k - Solar_k \right\} \text{Power Balance}$$

By solving the problem above for all prosumers, it will provide us with the cost of prosumers without trading in P2P market. Next, with the introduction of P2P trading for profit maximization, the Prosumer's objective U will become:

$$U_i^{P2P} = U_i + \sum\nolimits_{i' \in \mathcal{I} \setminus i} Z_{i,i'} - \theta_{i,i'} |P_{i,i'}^{ex}| \tag{8}$$

where the cost of prosumer i's with P2P (U_i^{P2P}) will include three terms: the base case cost from U^{SH} or U^{CS}, P2P payment received by prosumer i ($Z_{i,i'}$) and the wheeling cost paid by prosumer i to the power grid based on a rate of $\theta_{i,i'}$.

The power balance constraints for each type of prosumer will thus become :

Charging Station :

$$-P_n^{sg} + P_n^{bg} = -\sum_m q_{n,m}^d(t) + \sum_m q_{n,m}^c(t) - Solar_n + \sum_{i' \in \mathcal{I} \setminus i} P_{i,i'}^{ex} \tag{9}$$

Smart Home:

$$-P_k^{sg} + P_k^{bg} = Load_k - Solar_k + \sum_{i' \in \mathcal{I} \setminus i} P_{i,i'}^{ex} \tag{10}$$

The P2P payment variable $Z_{i,i'}$ and power exchange variable $P_{i,i'}^{ex}$ must be exactly opposite polarity, when observed from then other side of the prosumer. Thus, the constraints below must be enforced.

$$P_{i,i'}^{ex} = -P_{i,i'}^{ex} \tag{11}$$

$$Z_{i,i'} = -Z_{i,i'} \tag{12}$$

Now consider this community constitute a cooperative coalition, which can guarantee a fair allocation of the additional profits brought by the P2P trading and can maximize the total profit of utilizing EV. The prosumer coalition can be represented by a standard Nash bargaining model. In this project, we aim to get the day-ahead EV's scheduling as reference solution for real-time market. The real-time market clearing, or customer matching will be implemented via a simple and straightforward linear programming optimization model, which is out of the discussion in this documentation.

Lastly, Nash bargaining's profit maximizing problem is formulated as :

$$\max \left(\sum_n U_n^{CS,P2P} + \sum_k U_k^{SH,P2P}\right) \tag{13}$$

$s.t.$

$$U_n^{CS,P2P} = U_n^{CS} - \theta_{n,i'} \left|P_{n,i'}^{ex}\right|, \forall i', \forall n \in \mathcal{N}$$

$$U_k^{SH,P2P} = U_k^{SH} - \theta_{k,i'} \left|P_{k,i'}^{ex}\right|, \forall i', \forall k \in \mathcal{K}$$

$$< flexibility\ quatification\ constaints >$$

$$0 \le q_{n,m}^d(t) \le q_{n,m}^{d,max}, t \in \left[t_{n,m}^{arr}, t_{n,m}^{dep}\right], \forall n$$

$$0 \le q_{n,m}^c(t) \le q_{n,m}^{c,max}, t \in [t_{n,m}^{arr}, t_{n,m}^{dep}], \forall n$$

$$q_{n,m}^c, q_{n,m}^d = 0, t \notin [t_{n,m}^{arr}, t_{n,m}^{dep}], \forall n$$

$$S_{n,m}(t) = S_{n,m}^{arr}, t = t_{n,m}^{arr}, \forall n$$

$$S_{n,m}(t) = S_{n,m}(t-1) + \frac{\rho_{n,m}^{ch} q_{n,m}^{c}(t)}{Q_{n,m}} - \frac{\rho_{n,m}^{disch} q_{n,m}^{d}(t)}{Q_{n,m}}, t \in (t_{n,m}^{arr}, t_{n,m}^{dep}], \forall n$$
$$S_{n,m}^{min} \leq S_{n,m}(t) \leq S_{n,m}^{max}, t \in [t_{n,m}^{arr}, t_{n,m}^{dep}], \forall n$$
$$1 - TAR_{n,m}(t) \leq S_{n,m}(t) \leq 1, t = t_{n,m}^{dep}, \forall n$$
$$-P_n^{sg} + P_n^{bg} = -\sum_m q_{n,m}^{d}(t) + \sum_m q_{n,m}^{c}(t) - Solar_n + \sum_{i' \in \mathcal{I} \setminus i} P_{i,i'}^{ex}, \forall n$$
$$-P_k^{sg} + P_k^{bg} = Load_k - Solar_k, \forall k$$
$$P_{i,i'}^{ex} = -P_{i,i'}^{ex}, \forall k$$

By solving the above problem, we can plot the corresponding EV's SoC scheduling results and the overall trend for a particular CS. For instance, Figure 2 below shows the scheduling reference of CS1. In the figure, the CS1 system operator can have an idea or guidance on how to dispatch the EV during the real time market. The day ahead scheduling suggests that if CS1 discharge around 11:00~12:30 and 20:00~20:30, it will gain the maximum profit. In Figure 3, it is observed that other than the proposed two discharging periods, the EV will tend to charge from the CS. In summary, the day-ahead scheduling result provides us the guidance, for participating the real time market. More results can be discovered from our case study in the presentation slide, where the CS and smart home prosumers are indeed getting saving and profit!

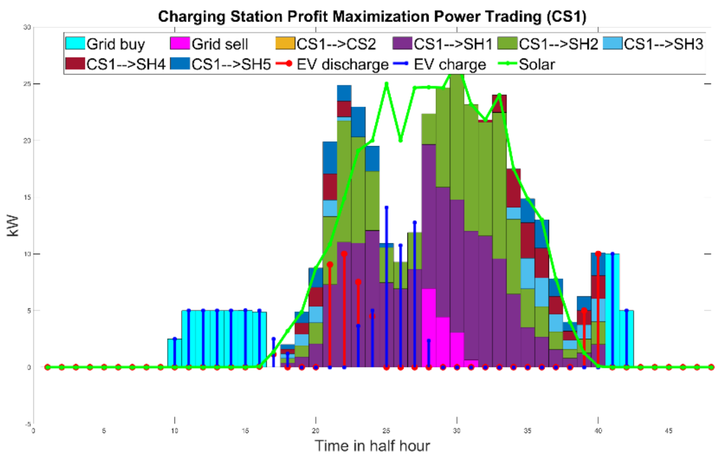

Figure 2: Nash scheduling for Charging Station 1

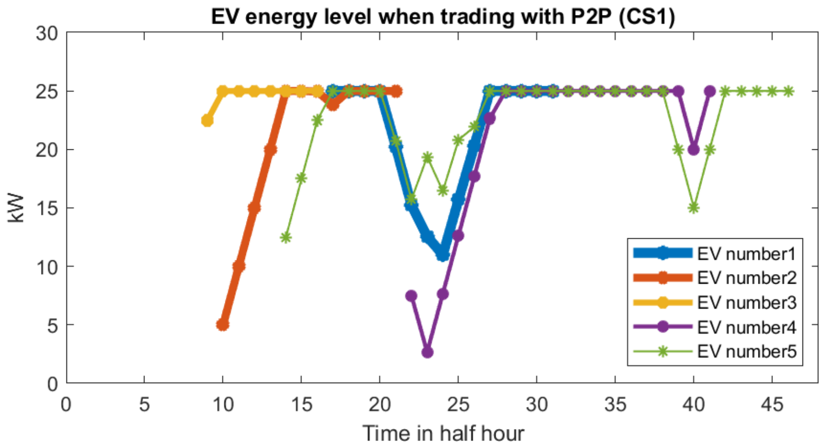

Figure 3: Scheduling for individual EV

Reference

[1] J. Zhang, L. Che, X. Wan, and M. Shahidehpour, "Distributed hierarchical coordination of networked charging stations based on peer-to-peer trading and EV charging flexibility quantification," *IEEE Transactions on Power Systems,* 2021.