Bidirectional Electric Vehicle Charging to Reduce Grid Impact of Deep EV Penetration

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Motivation

As Electric Vehicle EV penetration deepens in California, the "Duck Curve" effect and need for generation ramping in the evening hours is set to increase dramatically. Currently, we see a need to ramp generation by 13,000 MW in roughly 5 hours to meet evening demand.

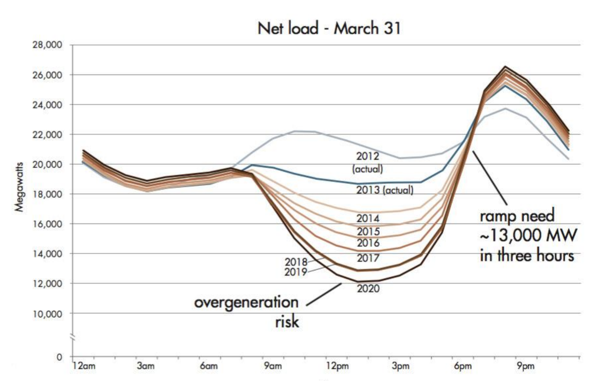

Figure 1: Duck curve in California.

As demonstrated in Siobhan Powell's papers on EV driver charging behavior in CA, traditional charging during the day can increase the health of the grid. If many drivers were to participate in vehicle-to-grid charging, could the current grid be adequate for an electrified future and the need for new generation/transmission systems be avoided?

Model

Our model is a 3 bus system with PV generation and variable loads at each node. All of the nodes also contain dispatchable gas generation that can be ramped quickly from hour-to-hour in order to meet the total demand of the system.

The optimization problem is formulated to minimize the total generation cost while giving optimal values such as when to charge/discharge EVs focusing on peak hours from 4pm-9pm in California.

Objective Function

The objective function is defined as follows:

$$\text{obj} = \sum_{b\in B}\sum_{t\in T} \text{gen\_cost}_b \cdot (\text{gen\_bus}_{b,t})^2 + \text{peak\_price} \cdot \sum_{t\in T} \max(0, P_{t,1} - P_{t,2}) + \text{offpeak\_price} \cdot \sum_{t\in T} \max(0, P_{t,1} - P_{t,2})$$

Constraints

The constraints of the problem are defined as follows:

- Power flow constraints:
  - $\theta_{0,t} = 0$, for all $t \in T$
  - $P = Y_{\text{bus}} \cdot \theta$
  - $P_{t,b} = \text{demand}_b - \text{PV}_b - \text{gen\_bus}_{b,t}$, for all $b \in B, t \in T$
- Generator capacity constraints:
  - $\text{gen\_bus}_{b,t} \leq \text{gen\_max}_b$, for all $b \in B, t \in T$
- EV charging and discharging constraints:
  - $\text{EV\_charge}_{e,t} \geq 0$, if $\text{initial\_SOC}_e < \text{charge\_limit}$, for all $e \in E, t \in T$
  - $\text{EV\_charge}_{e,t} \leq 0$, if $\text{peak\_start\_time} \leq t \leq \text{peak\_end\_time}$ and $\text{initial\_SOC}_e > \text{discharge\_limit}$, for all $e \in E, t \in T$
- Energy neutrality constraint:
  - $\sum_{e\in E} \text{EV\_charge}_{e,t} = P_{t,1} - P_{t,2}$, for all $t \in T$

Results

Case 1: Our model runs as expected, with our most expensive generator behaving like a peaking generator and ramping its production in the evening to match demand. The total fossil fuel ramping was 7,833 kW in this case.

Parameters

The parameters used in the problem are defined as follows:

- PV production profiles: PV_b, for all $b \in B$
- Demand profiles: demand_b, for all $b \in B$
- Admittance matrix: $Y_{\text{bus}_{b_1,b_2}}$, for all $b_1, b_2 \in B$
- Admittance imaginary matrix: $B_{\text{bus}_{b_1,b_2}}$, for all $b_1, b_2 \in B$
- Generation costs: gen_cost_b, for all $b \in B$
- Maximum generation limits: gen_max_b, for all $b \in B$
- Number of electric vehicles: num_EVs
- Charging limit for EVs: charge_limit
- Discharging limit for EVs: discharge_limit
- Start time of peak hours: peak_start_time
- End time of peak hours: peak_end_time
- Peak price: peak_price
- Off-peak price: offpeak_price

Variables

The variables used in the problem are defined as follows:

- Power injection at each bus: $P_{t,b}$, for all $t \in T, b \in B$
- Voltage angles at each bus: $\theta_{b,t}$, for all $b \in B, t \in T$
- Generator power output for each bus: $\text{gen\_bus}_{b,t}$, for all $b \in B, t \in T$
- EV charging/discharging power: $\text{EV\_charge}_{e,t}$, for all $e \in E, t \in T$

Sets

The sets used in the problem are defined as follows:

- Set of time periods: T
- Set of buses: B
- Set of electric vehicles: E

Figure 4 shows when new introduced EVs are able to discharge during the day based on the optimal values from the optimization. In addition, the model also recognizes that the best times to charge EVs is during the middle of the day by taking full advantage of cheaper prices and renewables as shown in Figure 5.

(**Note**:Figure 4 and 5, models can further be improved.)

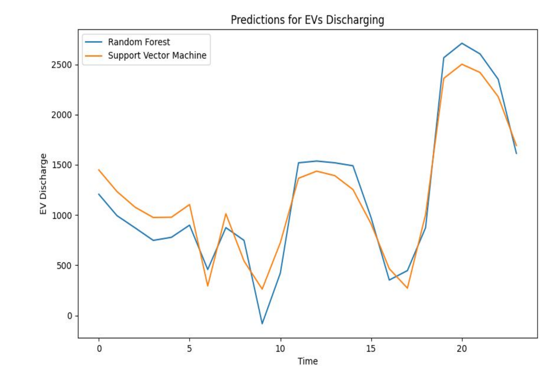

Figure 4: Models demonstrating the times to discharge EVs.

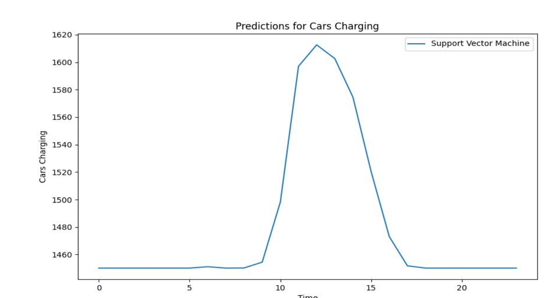

Figure 5: Charging times for EVs.

In Figure 2, we can see the times to discharge EVs if their state of charge (SOC) is above .7 and stop discharging if it reaches SOC of 0.5.

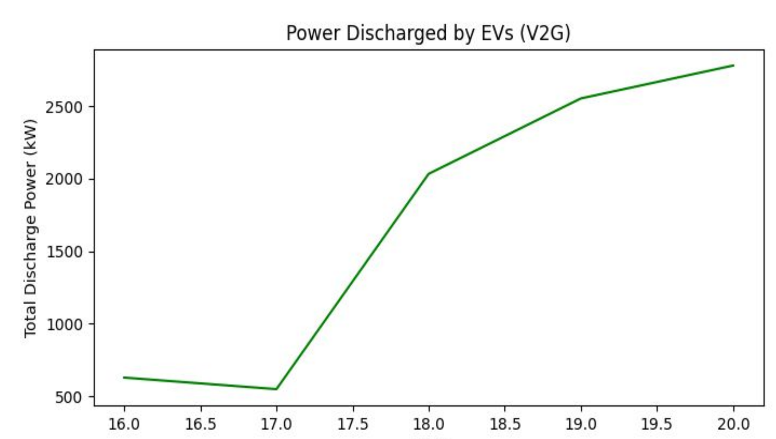

Figure 2: EVs discharging from optimization results.

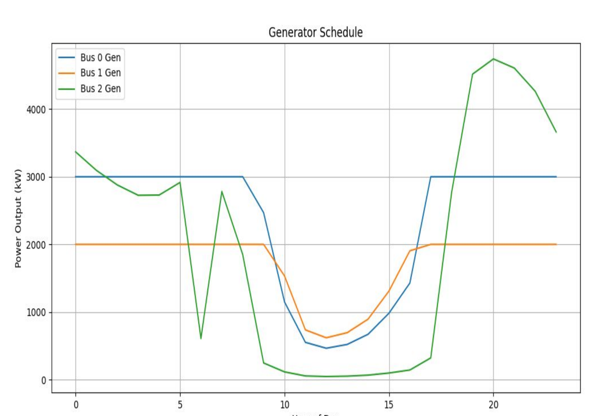

Figure 3: Generation by each bus.

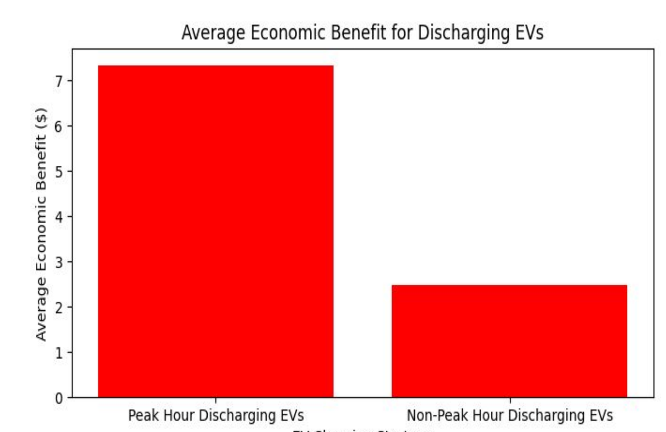

Figure 6: Average economic benefits of discharging for EVs during a day.

Conclusions

Our model found it most cost efficient to have large groups of cars charging/discharging at the same time. Due to the cost structure of charging your car at peak/non-peak hours, the financial incentives encourage drivers to discharge their vehicles during peak hours with a higher average economic benefit as seen in Figure 6.

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Methodology

We obtained sample PV generation data from 3 different cities in CA using PVWatts to generate hourly datasets of production. We then used the CAISO Demand Outlook database to take total demand from May, which we then scaled and modified so that the loads at different buses looked slightly different from each other.

We also used data from Pecan Street and from the Powell's papers on EV charging behaviors to provide ourselves with an understanding of how driver's tend to behave around charging their cars.

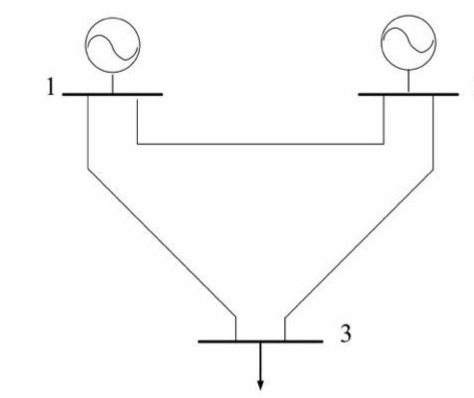

Figure 6: Bus system

Finally, we run our CVX model to optimize the generator outputs and minimize the cost of EV charging/discharging. This leaves us with a large set of V2G charging behaviors for our 3 bus system that we can then use to train an SVR model and a random forest model to predict the optimal V2G behavior for a single car in our model.

Modeled Scenarios

Case 1: Here we model our 3 bus system with generators at each bus and no storage in the system. This scenario tests our model and gives us a control to compare our EV charging models against.

Case 2: We look at the case where vehicles can be both charged and discharged to and from the grid. We add in charging/discharging and battery SOC evolution constraints into the model in order to capture driver behavior that we found in Powell's papers and on Pecan Street.

This case makes the most assumptions as driver behavior cannot accurately be predicted. To combat this, we added constraints to eliminate V2G discharging if an EV was below a certain SOC. This one constraint allows us to eliminate a bulk of impractical charging behavior in our model while still finding a solution that helps the 3-bus system in our model.