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Mobility-Aware Smart Charging of Electric Bus Fleets

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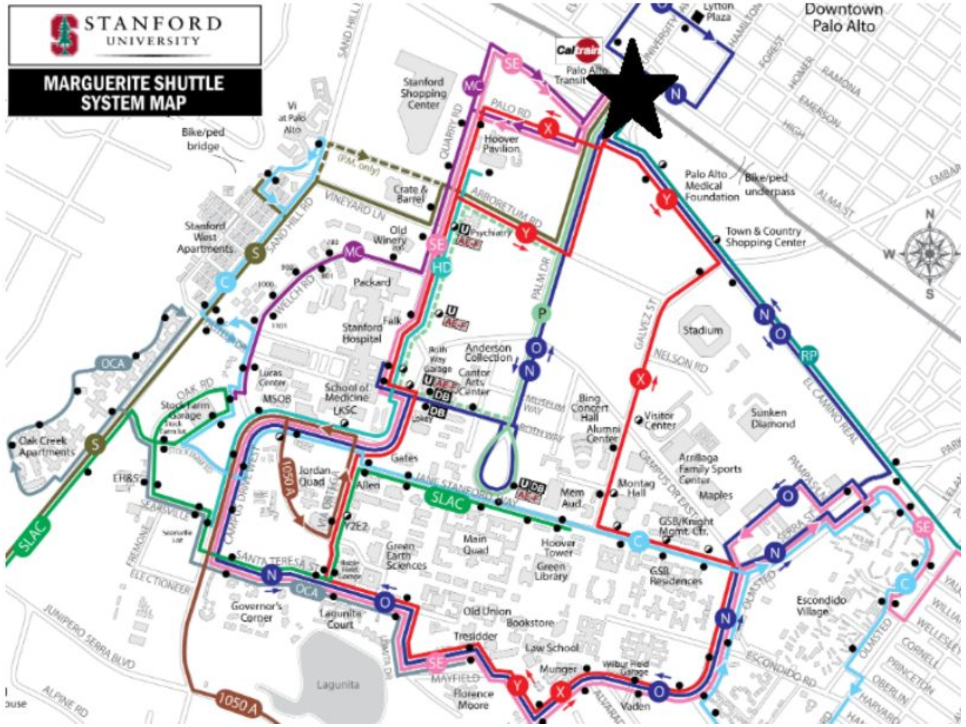
Background

- Stanford University's Marguerite Shuttle
  - Which electric bus should be assigned to each route at each time?
  - When should each bus be recharged?
  - Does the system need to utilize spare diesel buses?
  - What size of on-site solar generation system is needed to fully supply the fleet with renewable energy?



Additional Background

PG&E E-20 RATE STRUCTURE

Time Interval	Label	Price
12:00am-8:30am	Off-Peak	$0.08422/kWh
8:30am-12:00pm	Partial-Peak	$0.11356/kWh
12:00pm-6:00pm	Peak	$0.16127/kWh
6:00pm-9:30pm	Partial-Peak	$0.11356/kWh
9:30pm-12:00am	Off-Peak	$0.08422/kWh

A) Electricity Rate Structure

STANFORD MARGUERITE SHUTTLE ROUTE INFORMATION

Route Name	Daily Trips	Trip Miles
C Line	33	7.00
C Limited	11	4.60
MC Line (AM/PM)	46	3.00
MC Line (Mid Day)	11	5.10
P Line (AM/PM)	56	2.50
P Line (Mid Day)	11	4.00
Research Park (AM/PM)	24	10.40
X Express (AM)	12	1.20
X Line	44	4.60
X Limited (AM)	10	2.00
X Limited (PM)	10	1.50
Y Express (PM)	20	1.20
Y Line	44	4.60
Y Limited (AM)	10	2.40
Y Limited (PM)	10	2.00
Totals	**352 trips/day**	**1431.50 miles/day**

B) Daily Trip Information

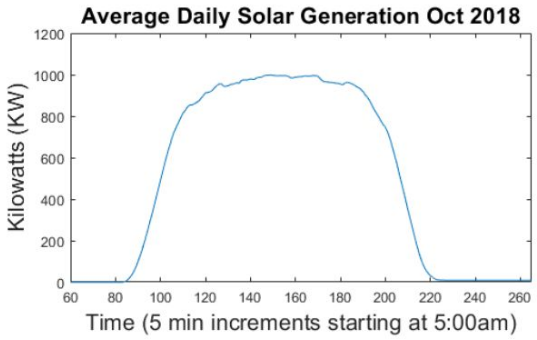


Fig. 2. Average daily solar generation for a 1 MW on-site installation. Data averaged from CAISO renewable database in October 2019.

C) Daily Solar Power Generation

Problem Formulation

- Formulated a Mixed-Integer-Linear-Program (MILP) to solve for the minimal cost operational strategy
- 38 electric buses, 23 double port chargers, 352 unique trips per day, 1431.50 miles per day
- PG&E E-20 rate structure

$$\text{Minimize} \quad \sum_{t\in\mathcal{T}} p(t)V(t) \tag{1a}$$

Subject to:

$$Z^k(t) + \sum_{i\in\mathcal{S}} X_i^k(t) \leq 1, \quad \forall k \in \mathcal{K}, t \in \mathcal{T} \tag{1b}$$

$$\sum_{k\in\mathcal{K}} X_i^k(t) = 1, \quad \forall i \in \mathcal{S}, t \in [a_i, b_i] \tag{1c}$$

$$X_i^k(t+1) = X_i^k(t), \quad \forall i \in \mathcal{S}, k \in \mathcal{K}, t \in [a_i, b_i - 1] \tag{1d}$$

$$\sum_{k\in\mathcal{K}} Y_n^k(t) \leq 1, \quad \forall n \in \mathcal{N}, t \in \mathcal{T} \tag{1e}$$

$$\sum_{n\in\mathcal{N}} Y_n^k(t) = Z^k(t), \quad \forall k \in \mathcal{K}, t \in \mathcal{T} \tag{1f}$$

$$E^k(t) = E^k(t-1) + \sum_{n\in\mathcal{N}} u_n Y_n^k(t) - \sum_{i\in\mathcal{S}} d_i X_i^k(t), \quad \forall k \in \mathcal{K}, t \in \mathcal{T} \tag{1g}$$

$$\sum_{n\in\mathcal{N}} \sum_{k\in\mathcal{K}} Y_n^k(t) u_n = V(t) + S(t), \quad \forall t \in \mathcal{T} \tag{1h}$$

$$E_{min}^k \leq E^k(t) \leq E_{max}^k, \quad \forall k \in \mathcal{K}, t \in \mathcal{T} \tag{1i}$$

$$X_i^k(t) \in \{0,1\}, \quad \forall i \in \mathcal{S}, k \in \mathcal{K}, t \in \mathcal{T} \tag{1j}$$

$$Y_n^k(t) \in \{0,1\}, \quad \forall n \in \mathcal{N}, k \in \mathcal{K}, t \in \mathcal{T} \tag{1k}$$

$$Z^k(t) \in \{0,1\}, \quad \forall k \in \mathcal{K}, t \in \mathcal{T} \tag{1l}$$

$$0 \leq S(t) \leq g(t), \quad \forall t \in \mathcal{T} \tag{1m}$$

$$E^k(0) = e_0^k, \quad \forall k \in \mathcal{K} \tag{1n}$$

$$E^k(T) = e_0^k, \quad \forall k \in \mathcal{K}. \tag{1o}$$

Problem Formulation - Details

$$\text{Minimize} \quad \sum_{t \in \mathcal{T}} p(t)V(t) \tag{1a}$$

Subject to:

$$Z^k(t) + \sum_{i \in \mathcal{S}} X_i^k(t) \leq 1, \quad \forall k \in \mathcal{K}, t \in \mathcal{T} \tag{1b}$$

$$\sum_{k \in \mathcal{K}} X_i^k(t) = 1, \quad \forall i \in \mathcal{S}, t \in [a_i, b_i] \tag{1c}$$

$$X_i^k(t+1) = X_i^k(t), \quad \forall i \in \mathcal{S}, k \in \mathcal{K}, t \in [a_i, b_i - 1] \tag{1d}$$

$$\sum_{k \in \mathcal{K}} Y_n^k(t) \leq 1, \quad \forall n \in \mathcal{N}, t \in \mathcal{T} \tag{1e}$$

$$\sum_{n \in \mathcal{N}} Y_n^k(t) = Z^k(t), \quad \forall k \in \mathcal{K}, t \in \mathcal{T} \tag{1f}$$

$$E^k(t) = E^k(t-1) + \sum_{n \in \mathcal{N}} u_n Y_n^k(t) - \sum_{i \in \mathcal{S}} d_i X_i^k(t), \quad \forall k \in \mathcal{K}, t \in \mathcal{T} \tag{1g}$$

$$\sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}} Y_n^k(t) u_n = V(t) + S(t), \quad \forall t \in \mathcal{T} \tag{1h}$$

$$E_{min}^k \leq E^k(t) \leq E_{max}^k, \quad \forall k \in \mathcal{K}, t \in \mathcal{T} \tag{1i}$$

$$X_i^k(t) \in \{0, 1\}, \quad \forall i \in \mathcal{S}, k \in \mathcal{K}, t \in \mathcal{T} \tag{1j}$$

$$Y_n^k(t) \in \{0, 1\}, \quad \forall n \in \mathcal{N}, k \in \mathcal{K}, t \in \mathcal{T} \tag{1k}$$

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$$0 \leq S(t) \leq g(t), \quad \forall t \in \mathcal{T} \tag{1m}$$

$$E^k(0) = e_0^k, \quad \forall k \in \mathcal{K} \tag{1n}$$

$$E^k(T) = e_0^k, \quad \forall k \in \mathcal{K}. \tag{1o}$$

Objective Function:

- 1a) Minimize daily electricity cost

Constraints:

- 1b) Each bus must be either charging, driving, or parked
- 1c) All trips must be served
- 1d) Each trip must be served by 1 unique bus
- 1e) Each bus can use only 1 charger
- 1f) If a bus is plugged in, it is charging
- 1g) Calculation of the battery level of each bus
- 1h) Power is from the local grid or from on-site solar
- 1i) Bus battery level stays within a desired range
- 1j) Binary constraint on trip decision variable
- 1k) Binary constraint on charger assignment variable
- 1l) Binary constraint on charging decision variable
- 1m) Solar power usage constraint
- 1n) Initial energy level of each bus
- 1o) Final energy level of each bus

Results

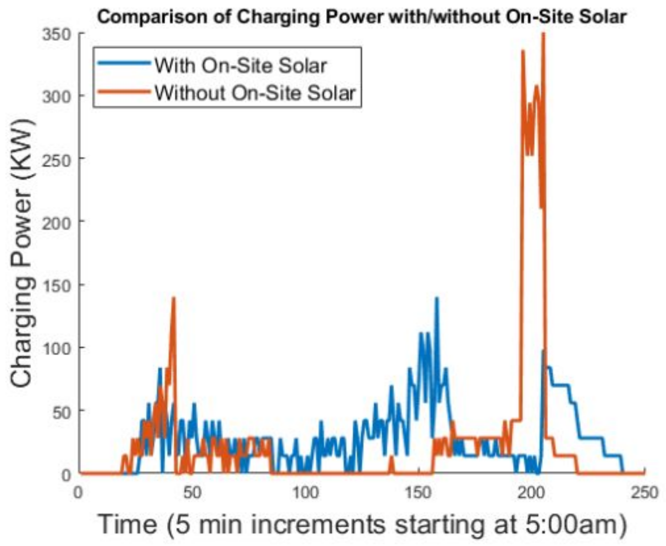

Fig. 4. Total charging power of the fleet throughout the day. Blue: Solution accounting for on-site solar generation. Red: Solution does not include on-site solar generation.

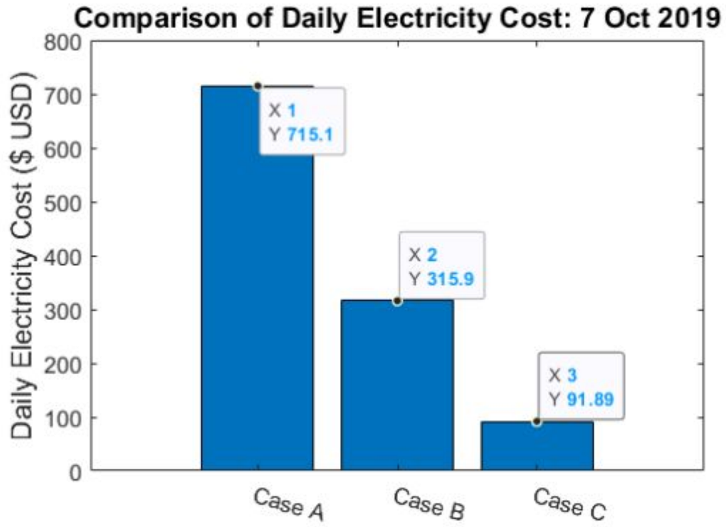

Fig. 5. Price Comparison for 3 difference regimes: Case 1: Status Quo, electric bus charging data obtained from real-implementation (Stanford Marguerite Shuttle) on 7-Oct-2019. Case 2: Mobility-Aware MILP solution for same routes and buses as Case A, *without* on-site solar generation. Case 3: Mobility-Aware MILP solution for same routes and buses as Case A, *with* on-site solar generation.

Red: Total charging load without on-site solar

Blue: Total charging load with on-site solar

Left column: $715 daily electricity cost from status quo, 7-Oct-2019

Middle column: $315 cost for the MILP charging schedule without free on-site solar

Right column: $91 cost for the MILP charging schedule with free on-site solar

Conclusion

- Formulated a M.I.L.P. to solve for the joint route assignments and charging schedules for a large-scale electric bus fleet
- Numerical results from a real electric bus fleet showed significant cost savings compared to the status quo
- Future work:
  - Moving-horizon solution to account for stochastic solar generation
  - Addition of traditional diesel routes to expand clean operation
  - Add an emissions penalty to the objective function
  - Field-test experiments with real buses during operational hours
- Must ensure results from simulations match results from field-test experiments on real buses
- Potential causes for discrepancies:
  - Daily schedule variance
  - Energy usage per trip can vary
    - Simulation requires accurate energy usage per trip
    - Traffic or additional unplanned mileage
  - Drivers' preferences on buses and desired minimum battery levels before departure
  - Variance in charging/discharging power
    - Results in inaccurate calculation of battery levels