Optimizing Interconnection Costs for California's Future Grid

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I. Introduction

California faces a surge in electricity demand driven by two major trends: widespread electrification and the proliferation of data centers. The California Energy Commission forecasts that electricity demand within CAISO's service territory—which covers most of the state—will rise by 40.8

Projects are being proposed at record rates to meet this load increase, yet many face long delays in getting approval due to an overwhelmed interconnection queue. More capacity (nearly 2600 gigawatts (GW) sits in the interconnection queue than in grid operating capacity (1,189 GW) [1] [2].

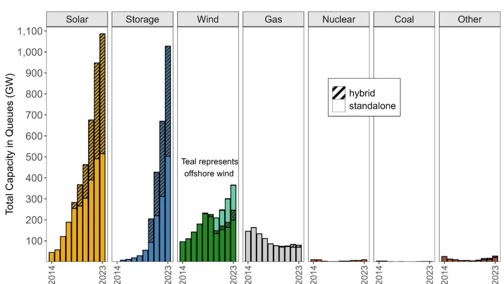

Fig. 1: Capacity in interconnection queues at the end of 2023. The capacity in the queue has rapidly grown since 2014. [1]

This project develops a copper plate interconnection model to accelerate interconnection queue decision-making. We evaluated the cost and feasibility of adding new solar, wind, gas, and batteries to the grid to match the CPUC's 10-year load increase projections. Our model accounts for bus-level capacity availability, transmission upgrade costs, system-wide generation constraints, and includes a least-cost-path analysis for constructing transmission lines from each project to the closest substation. By optimizing project selection under realistic transmission constraints, the model provides a transparent and data-driven framework to support efficient and equitable grid expansion.

II. Methods

We created a mixed-integer linear program that minimizes project interconnection cost while expanding capacity on lines or substations and, dispatching resources to meet load requirements. We formulated the model from the grid operator and CPUC perspective, so costs include grid upgrades and emissions costs, but do not include costs to dispatch a particular source or build a project. It answers the question "What is the least-cost way to accommodate new generation from a system-wide perspective?"

This is a copper plate model, which means we do not model transmission between projects and load. However, we account for the cost of upgrading the capacity at a substation and the line cost to that substation for each project.

The model dispatches the projects built to meet the projected load increase by 2035 (the difference between the projected 2035 load and the 2026 load). The 2035 load profile is constructed by applying 2035 demand levels to historical weather patterns from 2000-2022, then using k-means time series clustering to identify a representative centroid year from these 23 years.

What follows is the mathematical formulation for our model.

Decision Variable	Description
$x_i^{\mathrm{sol}} \in \{0,1\}$	Binary build decision for solar project i (1 = build, 0 = do not build).
$x_i^{\mathrm{win}} \in \{0,1\}$	Binary build decision for wind project i.
$x_i^{\mathrm{gas}} \in \{0,1\}$	Binary build decision for gas-fired generator i.
$x_i^{\mathrm{bat}} \in \{0,1\}$	Binary build decision for battery system i.
$S_b^{\mathrm{add}} \geq 0$	Total new capacity (MW) added at bus b from all projects located there.
$S_b^{\mathrm{inc}} \geq 0$	Additional headroom (MW) created at bus b by local station upgrades.
$y_c \in \{0,1\}$	Binary indicator that network upgrade/constraint relief option c is taken.
$P_t^{\mathrm{in}} \geq 0$	Battery charging power (MW) at time step t.
$P_t^{\mathrm{out}} \geq 0$	Battery discharging power (MW) at time step t.
$E_t \geq 0$	Energy stored in the battery fleet (MWh) at time step t.
$P_t^{\mathrm{sol}} \geq 0$	Dispatched solar generation (MW) at time step t.
$P_t^{\mathrm{win}} \geq 0$	Dispatched wind generation (MW) at time step t.
$P_t^{\mathrm{gas}} \geq 0$	Dispatched gas generation (MW) at time step t.
$C_t \geq 0$	Renewable curtailment (MW) at time step t (unused available output).
$s_t \geq 0$	Slack variable capturing "depth-of-cycle" excursions that exceed the allowed swing, used to approximate battery wear at time step t (defined for $t \geq 2$).

Sets, found after compiling and cleaning data, include:

$$\begin{aligned}
\mathcal{S} &: \text{solar projects } i && (|\mathcal{S}| = N_{\text{solar}})\\
\mathcal{W} &: \text{wind projects } i && (|\mathcal{W}| = N_{\text{wind}})\\
\mathcal{G} &: \text{gas projects } i && (|\mathcal{G}| = N_{\text{gas}})\\
\mathcal{B} &: \text{battery projects } i && (|\mathcal{B}| = N_{\text{batt}})\\
\mathcal{T} &: \text{time steps } t && (|\mathcal{T}| = 8760)\\
\mathcal{N} &: \text{network buses } b && (|\mathcal{N}| = N_{\text{bus}})\\
\mathcal{C} &: \text{upgrade constraints } c && (|\mathcal{C}| = N_{\text{const}})\\
\mathcal{C} &: \text{upgrade constraints } c && (|\mathcal{C}| = N_{\text{const}})
\end{aligned}$$

Constants used include:

Constant	Description	Source
$\bar{P}_i^{\text{bat}}$	Battery power capacity (MW) of project i	[3]
$\bar{E}_i^{\text{bat}}$	Battery energy capacity (MWh) of project i	[3]
$\bar{P}_i^{\text{sol}}$	Solar project i nameplate capacity (MW)	[4]
$\bar{P}_i^{\text{win}}$	Wind project i nameplate capacity (MW)	[4]
$\bar{P}_i^{\text{gas}}$	Gas project i nameplate capacity (MW)	[4]
CF_t^{sol}	Solar capacity factor at time t	[5]
CF_t^{win}	Wind capacity factor at time t	[5]
A_b	Pre-existing available headroom (MW) at bus b	[6]
Γ_c	Additional headroom (MW) unlocked by constraint c	[7]
L_t	Load demand (MW) at time t	[5]
η^{ch}	Battery charging efficiency: 0.93 %	[8]
η^{dis}	Battery discharging efficiency: 0.93 %	[8]
SOC^{init}	Initial state-of-charge (SOC) as fraction of max capacity: 0.5	
SOC^{fin}	Final state-of-charge (SOC) as fraction of max capacity: 0.5	
e^{gas}	Emissions factor of gas: 0.20196 tCO_2/MWh	[9]
c_i^{sol}	Transmission cost path from project to bus for solar project i	[10]
c_i^{win}	Transmission cost path from project to bus for solar project i	[10]
c_i^{gas}	Transmission cost path from project to bus for solar project i	[10]
c_i^{bat}	Transmission cost path from project to bus for solar project i	[10]
c^{curt}	Cost of curtailed renewable energy estimated from PTC: 20 per MWh	[11]
c^{CO_2}	Current California cap and trade carbon price: 55 \$/tCO_2	[12]
c^{wear}	Battery wear cost to prevent unrealistic model results: 20 \$ per MWh	
k_c^{up}	Cost of network upgrade for constraint c	[7]

TABLE I: Table of constants and their descriptions.

Equations (1) and (2) show how the maximum power charged and discharged, as well as the energy storage for the battery resource, are found.

$$P^{\text{bat,max}} = \sum_{i \in \mathcal{B}} x_i^{\text{bat}} \ \bar{P}_i^{\text{bat}} \tag{1}$$

$$E^{\text{bat,max}} = \sum_{i \in \mathcal{B}} x_i^{\text{bat}} \ \bar{E}_i^{\text{bat}} \tag{2}$$

Each line constraint connects to multiple buses. To build a project, there must be enough capacity at the substation and on the associated transmission line to accommodate the new project. If there is not enough capacity, the model can choose to increase the line and substation capacity to accommodate the new project. Each line constraint is associated with multiple substations, so when a line constraint is increased, the substations must also be increased by an amount such that the aggregate substation increase is equal to the line constraint increase.

Equation (3) shows how the additional capacity needed on the bus is found. Equation (4) is a model constraint on how much capacity can be added to each bus. Equation (5) is a model constraint that sets the sum of the increased capacity addition at each bus that connects to the line constraint to the increased line capacity addition if the model chooses to upgrade that line.

$$\begin{aligned}
S_b^{\text{add}} = &\sum_{\substack{i \in \mathcal{S} \\ \text{bus}(i)=b}} x_i^{\text{sol}} \bar{P}_i^{\text{sol}} + \sum_{\substack{i \in \mathcal{W} \\ \text{bus}(i)=b}} x_i^{\text{win}} \bar{P}_i^{\text{win}} \\
&+ \sum_{\substack{i \in \mathcal{G} \\ \text{bus}(i)=b}} x_i^{\text{gas}} \bar{P}_i^{\text{gas}} + \sum_{\substack{i \in \mathcal{B} \\ \text{bus}(i)=b}} x_i^{\text{bat}} \bar{P}_i^{\text{bat}}, \\
&\forall b \in \mathcal{N}
\end{aligned} \tag{3}$$

$$S_b^{\text{add}} \leq A_b + S_b^{\text{inc}}, \qquad \forall b \in \mathcal{N} \tag{4}$$

$$y_c \, \Gamma_c = \sum_{b \in \mathcal{N}_c} S_b^{\text{inc}}, \qquad \forall c \in \mathcal{C} \tag{5}$$

Equations (6)–(8) are model expressions that calculate, for each hour t, the maximum power that can be delivered by the solar, wind, and gas plants if they were fully dispatched. They multiply the binary build decision for every candidate project by its nameplate capacity and (for the variable renewables) the exogenous hourly capacity-factor profile. The resulting quantities $P_t^{\text{sol,avail}}$, $P_t^{\text{win,avail}}$, and $P_t^{\text{gas,avail}}$, represent the upper bound on how much of each resource is able to dispatch in hour t.

$$P_t^{\mathrm{sol,avail}} = \sum_{i\in\mathcal{S}} x_i^{\mathrm{sol}} \bar{P}_i^{\mathrm{sol}}\, \mathrm{CF}_t^{\mathrm{sol}}, \qquad \forall t \in \mathcal{T} \tag{6}$$

$$P_t^{\mathrm{win,avail}} = \sum_{i\in\mathcal{W}} x_i^{\mathrm{win}} \bar{P}_i^{\mathrm{win}}\, \mathrm{CF}_t^{\mathrm{win}}, \qquad \forall t \in \mathcal{T} \tag{7}$$

$$P_t^{\mathrm{gas,avail}} = \sum_{i\in\mathcal{G}} x_i^{\mathrm{gas}} \bar{P}_i^{\mathrm{gas}}, \qquad \forall t \in \mathcal{T} \tag{8}$$

Inequalities (9) and (10) are model constraints. The first block in (9) caps actual solar, wind, and gas dispatch at the availability levels just defined, while permitting curtailment. The second block in (10) restricts battery charging and discharging power to the fleet-wide rating $P^{\mathrm{bat,max}}$ and prevents the battery from releasing more energy than is currently stored.

$$\begin{aligned} &0 \le P_t^{\mathrm{sol}} \le P_t^{\mathrm{sol,avail}}, \forall t \in \mathcal{T} \\ &0 \le P_t^{\mathrm{win}} \le P_t^{\mathrm{win,avail}}, \forall t \in \mathcal{T} \\ &0 \le P_t^{\mathrm{gas}} \le P_t^{\mathrm{gas,avail}}, \forall t \in \mathcal{T} \end{aligned} \tag{9}$$

$$\begin{aligned} &0 \le P_t^{\mathrm{in}} \le P^{\mathrm{bat,max}}, \forall t \in \mathcal{T} \\ &0 \le P_t^{\mathrm{out}} \le P^{\mathrm{bat,max}}, \forall t \in \mathcal{T} \\ &P_t^{\mathrm{out}} \le E_t, \forall t \in \mathcal{T} \end{aligned} \tag{10}$$

Equations (11)–(14) form the battery state-of-charge (SOC) tracking constraints. (11) fixes the initial SOC to a fraction of the total energy capacity, (12) propagates the SOC hour-to-hour, accounting for round-trip efficiencies, (13) forces the battery to finish the year at its starting SOC, and (14) keeps the SOC within physical limits.

$$E_1 = E^{\mathrm{bat,max}}\, \mathrm{SOC}^{\mathrm{init}}, \tag{11}$$

$$E_t = E_{t-1} + \eta^{\mathrm{ch}} P_t^{\mathrm{in}} - \frac{1}{\eta^{\mathrm{dis}}} P_t^{\mathrm{out}}, \forall t = 2, \ldots, |\mathcal{T}| \tag{12}$$

$$E_{|\mathcal{T}|} = E^{\mathrm{bat,max}}\, \mathrm{SOC}^{\mathrm{fin}}, \tag{13}$$

$$0 \le E_t \le E^{\mathrm{bat,max}}, \qquad \forall t \in \mathcal{T} \tag{14}$$

The first line of (15) is an expression that defines the difference between the battery SOC in two time periods. The second line of (15) sets a depth trigger D. The two inequalities that follow are constraints introducing slack s_t. The inequalities that follow are model constraints introducing slack s_t. Whenever the hour-to-hour swing Δ_t exceeds the $\pm D$ threshold, s_t captures the excess. This penalized term in the objective discourages unrealistically fast battery cycling in which the battery charges and discharges completely in just a few hours, to prolong battery lifespans.

$$\begin{aligned} \Delta_t &\equiv E_t - E_{t-1}, \\ D &= 0.1\, E^{\mathrm{bat,max}}, \\ s_t &\ge \Delta_t - D, \\ s_t &\ge -\Delta_t - D, \\ \forall t &= 2, \ldots, |\mathcal{T}| \end{aligned} \tag{15}$$

Equation (16) is the energy-balance constraint. In every hour, dispatched generation plus net discharging, minus efficiency-adjusted charging, must equal the projected load increase L_t.

$$\begin{aligned} L_t = P_t^{\mathrm{sol}} &+ P_t^{\mathrm{win}} + P_t^{\mathrm{gas}} \\ &- \frac{1}{\eta^{\mathrm{ch}}} P_t^{\mathrm{in}} + \eta^{\mathrm{dis}} P_t^{\mathrm{out}}, \\ &\forall t \in \mathcal{T} \end{aligned} \tag{16}$$

Inequality (17) is a model constraint that limits battery charging to the instantaneous excess of generation over load, accounting for simultaneous battery discharge. This prevents infeasible behavior where the model charges the battery while relying on the same electricity to meet load.

$$P_t^{\mathrm{in}} \le P_t^{\mathrm{sol}} + P_t^{\mathrm{win}} + P_t^{\mathrm{gas}} - L_t + \eta^{\mathrm{dis}} P_t^{\mathrm{out}}, \forall t \in \mathcal{T} \tag{17}$$

The first line of (18) defines curtailment C_t as a model expression: the unused renewable energy after meeting load and charging. The second line is a constraint enforcing that curtailment must be non-negative ($C_t \ge 0$).

$$\begin{aligned} C_t = P_t^{\mathrm{sol,avail}} + P_t^{\mathrm{win,avail}} - P_t^{\mathrm{sol}} - P_t^{\mathrm{win}} - \frac{1}{\eta^{\mathrm{ch}}} P_t^{\mathrm{in}}, \\ C_t \ge 0, \\ \forall t \in \mathcal{T} \end{aligned} \tag{18}$$

Equation (19) is a model expression that calculates total CO_2 emissions by multiplying hourly gas dispatch by a fixed emissions factor.

$$E^{\mathrm{CO_2}} = \sum_{t\in\mathcal{T}} e^{\mathrm{gas}}\, P_t^{\mathrm{gas}} \tag{19}$$

The objective function in (20) minimizes total system costs:

- The first four summations represent the cost of interconnecting new electricity projects to the grid.
- $c^{\mathrm{curt}} \sum_t C_t$ penalizes renewable energy curtailment, representing the loss of tax credits or generation incentives.

- $c^{\mathrm{CO_2}} E^{\mathrm{CO_2}}$ applies a cost to CO_2 emissions at the current California cap-and-trade carbon price.
- $\sum_c y_c k_c^{\mathrm{up}}$ represents the infrastructure cost of upgrading lines and substations.
- $10^{12} P_1^{\mathrm{out}}$ is a numerical deterrent to prevent the battery from fully discharging in the first hour of the representative year, which would otherwise appear optimal in a static annual model but is physically unrealistic.
- $c^{\mathrm{wear}} \sum_{t\geq 2} s_t$ penalizes excessive battery depth-of-cycle excursions, using the slack variables s_t introduced in (15), to discourage behavior that would result in battery degradation.

$$\begin{aligned} \min \sum_{i\in\mathcal{S}} c_i^{\mathrm{sol}} x_i^{\mathrm{sol}} + \sum_{i\in\mathcal{W}} c_i^{\mathrm{win}} x_i^{\mathrm{win}} + \sum_{i\in\mathcal{G}} c_i^{\mathrm{gas}} x_i^{\mathrm{gas}} \\ + \sum_{i\in\mathcal{B}} c_i^{\mathrm{bat}} x_i^{\mathrm{bat}} + c^{\mathrm{curt}} \sum_{t\in\mathcal{T}} C_t + c^{\mathrm{CO_2}} E^{\mathrm{CO_2}} \\ + \sum_{c\in\mathcal{C}} y_c\, k_c^{\mathrm{up}} + 10^{12} P_1^{\mathrm{out}} + c^{\mathrm{wear}} \sum_{t=2}^{|\mathcal{T}|} s_t \end{aligned} \tag{20}$$

III. Data

Data	Source
Solar Projects Proposed or Built (Since 2020)	EIA, 2025 [4]
Wind Projects Proposed or Built (Since 2020)	EIA, 2025
Gas Projects Built (Since 2016)	EIA, 2025 [4]
Planned Storage Projects	Internal CEC Dataset [3]
Bus Capacity Availability	CAISO Points of Interconnection Website [6]
Transmission Cost Raster	Emily Leslie [10]
Substation Locations	Southern California Association of Governments [13]
Bus Upgrade Amounts and Costs	2024 CPUC TPP Data Dashboard [7]
Solar & Wind Capacity Factors	CPUC System Reliability Modeling Datasets [5]
Demand Profile Changes	CPUC System Reliability Modeling Datasets [5]

TABLE II: Data Sources and their Respective Providers

Before we ran our model, we combined data points from different locations. CAISO's point of interconnection website had bus names, but no location information to match energy projects to their interconnected substation.

We copied bus names and capacities from the CAISO website. The website displays information in a table that can be copied into a CSV. We then extracted coordinates from a shapefile with substations and their names and ran a string matching algorithm to match the names in the shapefile to the CAISO data. About 20% of CAISO substations did not receive a match due to name formatting differences and substations of the same name in different utilities and territories. The missing information was manually cleaned. Then, these substations and names were matched using the Python library 'Rapid Fuzz' to the names and limiting constraints in the CPUC TPP Data Dashboard 'Sub_Constraint_Matrix' sheet. This data was then matched to the Binding Constraint Name in the 'TXCriteria_by_Sub_2034' sheet. We then re-ran our Rapid Fuzz string matching algorithm to add the cost and capacity amounts of upgrades to the bus data.

Using the transmission cost raster, we conducted a least-cost-path analysis in ArcGIS to estimate interconnection costs from proposed energy projects to buses. Our analysis included natural gas projects built since 2016 (as no new gas projects are planned in CAISO), planned and recently built solar and wind projects (excluding Wyoming Wind), and planned battery storage projects based on an internal CEC dataset.

To determine capacity factors for our representative year, we performed k-means clustering on CPUC's backcasted single-axis tracking solar and wind generation profiles from 2000–2022. We identified a centroid year based on normalized profiles, calculated as generation divided by total renewable capacity for each year.

Our estimated load growth was calculated using a similar approach. We subtracted forecasted 2026 and 2035 loads using CPUC's weather assumptions from 2000 to 2022, then identified the centroid year through clustering.

IV. Results

Our model selects 11 GW of solar, 4 GW of batteries, 1.3 GW of gas, and 0.8 GW of wind for construction (specific projects are listed in the appendix). The dominance of solar and battery capacity reflects the composition of CAISO's interconnection queue. The model builds nearly all available gas and wind projects—11 of 12 gas projects and 18 of 20 wind projects—but is more selective with solar and batteries, choosing 102 of 245 solar projects and 31 of 103 battery projects.

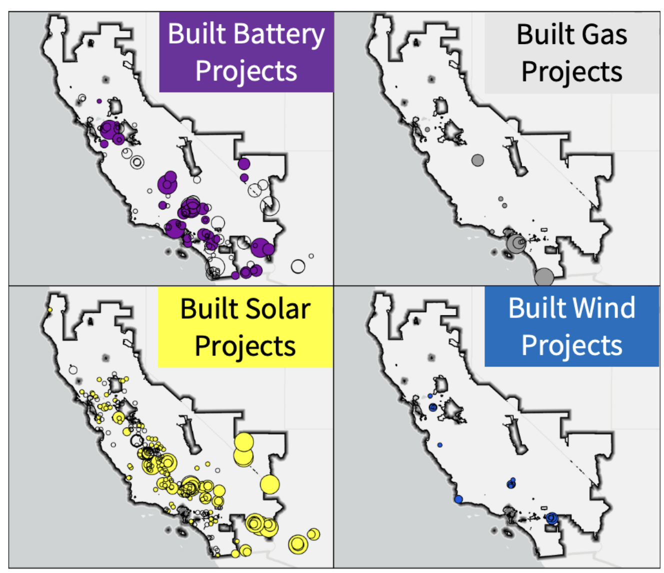

Fig. 2: Geographical Location of projects. Filled in circles are build projects; size of circle indicates project size.

In order to build these projects, the model chooses to upgrade 53 substations and 18 transmission lines. This costs $11.4

billion. The cost for transmission lines from the projects to the substation is $2.3 billion.

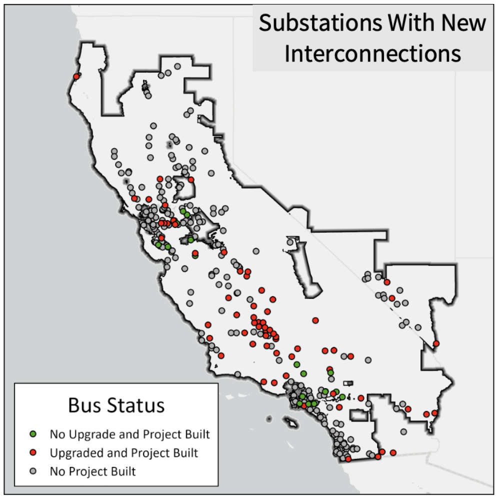

Fig. 3: Substations

Due to emissions and curtailment costs, the model follows a dispatch order of renewables first (solar and wind), then batteries, and finally gas. Battery dispatch exhibits smooth behavior most of the time due to degradation costs, while gas plants frequently ramp between 0% and 100% output within an hour. When solar generation approaches its capacity limit, the model curtails wind rather than solar.

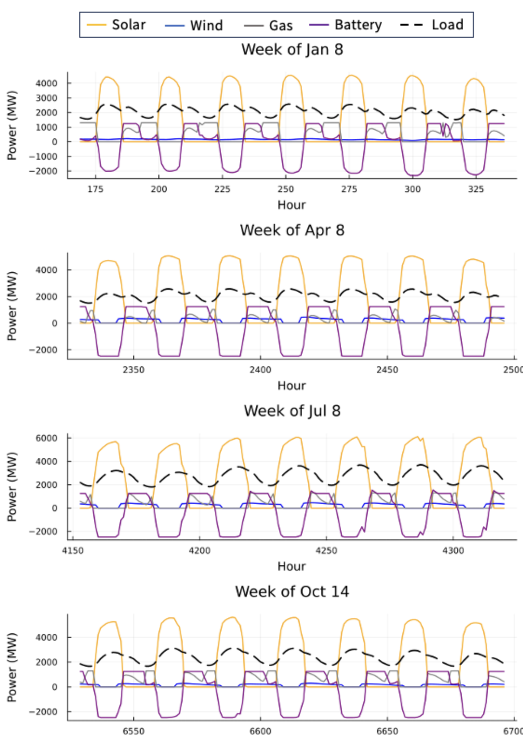

Fig. 4: Built Generation Dispatch to meet New Load

More detailed results from our model can be found in the appendix.

V. Sensitivity

Overall, different assumptions for emissions cost, wear cost, and curtailment costs significantly affected project dispatch.

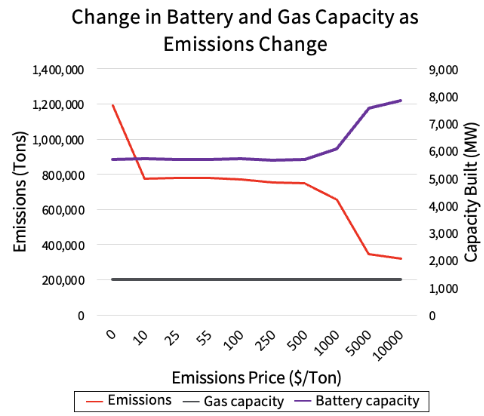

Fig. 5: Sensitivity Analysis on Emissions Cost

The figure above shows how gas capacity is constant even as emission prices increase. This illustrates the need for gas capacity on the grid to meet the load. However, as emission costs rise, it is cheaper to upgrade transmission and build more battery capacity so that batteries get dispatched instead of gas.

Furthermore, upgrade costs range from $11.4 billion to $18.8 billion, depending on emission cost and curtailment cost assumptions.

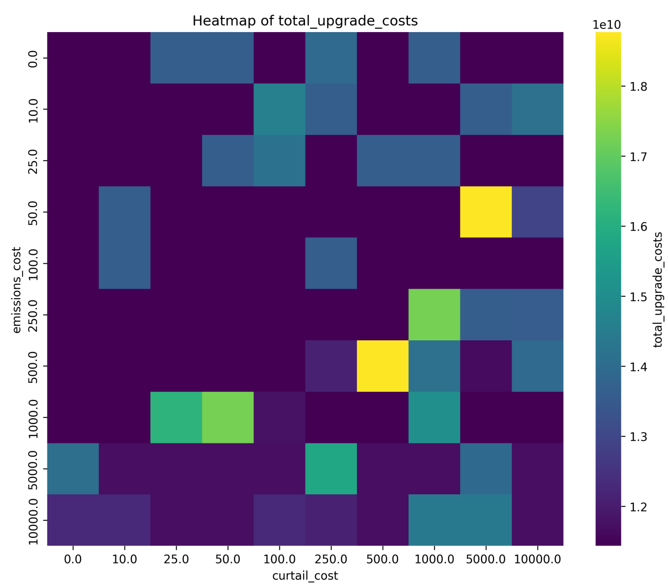

Fig. 6: Sensitivity Analysis on Upgrade Costs

As illustrated by the graph, lower curtailment and emissions costs tend to result in lower upgrade costs but lead to higher emissions. Other values from our sensitivity analysis can be found in the appendix.

VI. Discussion

The results of this model provide a potential pathway for California to meet growing electricity demand. It is a simplistic, but quick, alternative approach to determine what projects should be built given a load increase. Utilizing this model would be able to decrease project approval time and grid costs, keeping costs low while helping California meet its growing electricity needs.

In the sensitivity analysis, we see the importance of gas capacity. Even with a high emissions cost, the model still builds dispatchable natural gas. California needs clean, firm electricity resources to meet load increases. It would be expensive to power the grid with just wind, solar, and storage.

When collecting data, we made several assumptions that future models can improve upon. First, we assumed that solar and storage co-located projects were not co-located. The model could build either storage or solar, and the projects would have two different interconnection costs. Similarly, projects located near each other cannot share lines to reduce interconnection costs. Once these projects were interconnected, we assumed they were injecting at the closest substation and the highest voltage possible. Certain line increase constraints were only applied to lower or higher voltage interconnections. If different line limits were mentioned on the CAISO points of interconnection website, we chose the voltage with the lowest remaining capacity.

When selecting our projects, we also made several key assumptions. We did not have enough energy projects to solve for our 10-year load increase time-horizon, as projects in the interconnection queue may only take a few years to build. So, we also considered projects that were recently constructed or under construction. We also removed the Chokecherry and Sierra Madre Wind Project, a 3 GW wind project in Wyoming that will interconnect into CAISO at the end of 2026. Wyoming wind has a different generation profile than California wind, and there was not enough capacity to interconnect this wind project into our model. This is likely because the capacity associated with this project has already been removed from the CAISO points of interconnection website.

Finally, our model makes several simplifying assumptions about power flow and transmission constraints. We ignore reactive power compensation and detailed power flow mechanics, assuming that generation injected at any substation can serve load increases anywhere in the system. We also consider only the single most binding transmission constraint at each bus, assuming that relieving this constraint would increase the bus capacity by the full calculated amount. In reality, once the primary constraint is relaxed, secondary constraints may limit the actual capacity increase. We lacked data on these secondary binding constraints, which may cause our model to overestimate the benefits of transmission upgrades.

Future iterations of this model expand the project scope in several ways. First, we could incorporate full construction costs rather than just interconnection costs, enabling true system-wide cost minimization and better assessment of electricity price impacts. Second, given the variability in load growth forecasts, we could conduct sensitivity analyses across different demand projections. Finally, the model could adopt a priority-based approach to interconnection queue management, ranking projects by their system value to help policymakers prioritize approvals and streamline the interconnection process.

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APPENDIX

A. Model Output

Objective value (total cost): $2.50e14
Max modeled load (MW): 3963
Total Emissions (tons CO_2): 770298.75
Total Curtailment (MWh): 1.01e6
Total Upgrade Costs ($): 1.14e10
Total Emissions Cost ($): 4.24e7
Total Curtailment Cost ($): 2.03e7
Total Load (MWh): 2.04e7
Total (minus storage in) Generation (MWh): 2.04e7

Total Solar Project Path Cost: $1.77e10
Total Wind Project Path Cost: $2.66e9
Total Gas Project Path Cost: $1.02e8
Total Battery Project Path Cost: $2.06e8

Total Solar Capacity Added (MW): 11606.6
Total Wind Capacity Added (MW): 842.8
Total Battery Power Added (MW): 4426.0
Total Battery Storage Added (MWh): 14652.0
Total Gas Capacity Added (MW): 1299.31

Total Solar Generation (MWh): 1.89e7
Total Wind Generation (MWh): 1.58e6
Total Gas Generation (MWh): 3.81e6
Total Battery Charge (MWh): 1.38e7
Total Battery Discharge (MWh): 1.18e7

Selected Solar Projects:
- Northern Orchard Solar PV, LLC at bus 87 — Capacity: 150.0 MW
- BCE Seal Beach at bus 286 — Capacity: 12.0 MW
- Rosamond South 1 at bus 283 — Capacity: 140.0 MW
- Bellefield Solar and Energy Storage Farm at bus 210 — Capacity: 500.0 MW
- Pastoria Solar at bus 143 — Capacity: 105.2 MW
- Aratina Solar Center 1B at bus 86 — Capacity: 200.0 MW
- Solar Star 3 at bus 283 — Capacity: 24.0 MW
- Angela Solar Project at bus 1 — Capacity: 40.0 MW
- Windhub Solar B, LLC at bus 210 — Capacity: 20.0 MW
- Desert Breeze Solar, LLC at bus 167 — Capacity: 125.0 MW
- Lockhart Solar PV IV, LLC at bus 167 — Capacity: 80.0 MW
- Bellefield 2 Solar Energy Storage Farm at bus 210 — Capacity: 500.0 MW
- Aramis I Solar Project at bus 21 — Capacity: 100.0 MW
- Easley Solar at bus 157 — Capacity: 290.0 MW
- JVR Energy Park LLC at bus 48 — Capacity: 90.0 MW
- Portal Ridge Solar A, LLC at bus 285 — Capacity: 19.0 MW
- Purple Sage Energy Center at bus 196 — Capacity: 400.0 MW
- Chalan at bus 3 — Capacity: 64.9 MW
- Sand Luis West at bus 60 — Capacity: 125.0 MW
- Pelicans Jaw Hybrid Solar at bus 3 — Capacity: 440.0 MW
- Bellefield 3 Solar and Battery Storage at bus 210 — Capacity: 150.0 MW
- Dynamo Solar LLC at bus 197 — Capacity: 24.5 MW
- Zeta Solar Storage at bus 279 — Capacity: 75.0 MW
- Elisabeth Solar at bus 251 — Capacity: 350.0 MW
- Syracuse and Tours Renewable Energy at bus 210 — Capacity: 40.0 MW
- Rough Hat at bus 196 — Capacity: 400.0 MW
- Kingsley Solar Farm at bus 75 — Capacity: 225.0 MW
- Lycan Solar Project at bus 157 — Capacity: 400.0 MW
- Bonanza Solar and Storage Project at bus 205 — Capacity: 300.0 MW
- Gibson Solar Project - Hybrid at bus 102 — Capacity: 13.0 MW
- Sienna Solar Farm at bus 272 — Capacity: 200.0 MW
- Rexford 2 Solar Farm at bus 203 — Capacity: 200.0 MW
- Sienna 2 Solar and Storage Project at bus 272 — Capacity: 55.0 MW
- Lockhart Solar PV, LLC at bus 167 — Capacity: 100.4 MW
- Desert Quartzite at bus 29 — Capacity: 300.0 MW
- White Wing Solar at bus 251 — Capacity: 175.0 MW
- RE Gaskell West 2 LLC at bus 283 — Capacity: 45.0 MW
- RE Gaskell West 4 LLC at bus 283 — Capacity: 20.0 MW
- Antelope Expansion 1B at bus 285 — Capacity: 17.0 MW
- Antelope Expansion 3A at bus 285 — Capacity: 15.0 MW
- Antelope Expansion 3B at bus 285 — Capacity: 5.0 MW
- Drew Solar LLC at bus 75 — Capacity: 100.0 MW
- Athos Solar Project at bus 157 — Capacity: 250.0 MW
- Sun Streams 2 at bus 251 — Capacity: 150.0 MW
- Camino Solar Hybrid at bus 283 — Capacity: 44.0 MW
- Central 40 at bus 280 — Capacity: 40.0 MW
- San Diego - EMDF at San Diego at bus 134 — Capacity: 2.9 MW
- Maverick Solar 6, LLC at bus 157 — Capacity: 100.0 MW
- Fifth Standard Solar PV, LLC (Hybrid) at bus 60 — Capacity: 150.0 MW
- EMWD - Perris Valley RWRF at bus 261 — Capacity: 3.4 MW
- Byron Highway Solar at bus 82 — Capacity: 5.0 MW
- Arlington Energy Center II at bus 29 — Capacity: 100.0 MW
- Resurgence Solar at bus 86 — Capacity: 90.0 MW
- Hudson - High Desert Hybrid at bus 263 — Capacity: 100.0 MW
- Rabbitbrush Solar, LLC at bus 283 — Capacity: 100.0 MW
- Rexford Solar Farm at bus 203 — Capacity: 300.0 MW
- Daggett 2 at bus 32 — Capacity: 182.0 MW
- Chaparral Springs at bus 283 — Capacity: 102.0 MW
- Edwards Sanborn E3 at bus 210 — Capacity: 27.1 MW

- Edwards Sanborn E1A at bus 210 — Capacity: 149.3 MW
- Edwards Sanborn E2 at bus 210 — Capacity: 137.8 MW
- Luciana at bus 203 — Capacity: 55.8 MW
- Edwards Sanborn S3 at bus 210 — Capacity: 37.7 MW
- Edwards Sanborn S1 at bus 210 — Capacity: 44.6 MW
- BigBeau Solar, LLC at bus 283 — Capacity: 70.0 MW
- Blythe Mesa Solar II at bus 251 — Capacity: 223.6 MW
- IGS KSBD at bus 252 — Capacity: 4.3 MW
- University of the Pacific at bus 284 — Capacity: 4.5 MW
- Wonderful Lost Hills at bus 3 — Capacity: 17.1 MW
- Amazon Bakersfield 1 Solar Project at bus 83 — Capacity: 4.3 MW
- West Valley Mission CCD Solar Project at bus 249 — Capacity: 2.7 MW
- Orange Coast College PH2 Solar Project at bus 304 — Capacity: 3.1 MW
- Sandrini Solar 200 at bus 87 — Capacity: 200.0 MW
- Sandrini Solar 100 at bus 87 — Capacity: 100.0 MW
- Edwards Sanborn E1B at bus 210 — Capacity: 154.4 MW
- Edwards Sanborn E4 at bus 210 — Capacity: 148.9 MW
- Edwards Sanborn E5 at bus 210 — Capacity: 68.0 MW
- Edwards Sanborn S4 at bus 210 — Capacity: 41.2 MW
- Oberon Solar Project at bus 157 — Capacity: 250.0 MW
- Victory Pass at bus 157 — Capacity: 200.0 MW
- Ocotillo Wells at bus 130 — Capacity: 50.0 MW
- Proxima at bus 277 — Capacity: 190.0 MW
- CA Jurupa Valley 3251 De Forest Circle at bus 314 — Capacity: 4.5 MW
- BCE Los Alamitos 2 at bus 286 — Capacity: 10.0 MW
- BCE Los Alamitos 1 at bus 286 — Capacity: 10.0 MW
- Baldy Mesa Solar Storage at bus 263 — Capacity: 150.0 MW
- McFarland A Solar and Storage at bus 251 — Capacity: 200.0 MW
- McFarland B Solar and Storage at bus 251 — Capacity: 300.0 MW
- Visalia CSG LLC at bus 156 — Capacity: 3.0 MW
- Tulare CSG LLC at bus 1 — Capacity: 3.0 MW
- Lockhart Solar PV II at bus 167 — Capacity: 84.4 MW
- Fresno Community Solar at bus 206 — Capacity: 10.0 MW
- Estrella Solar Storage at bus 283 — Capacity: 56.0 MW
- Raceway Solar Storage at bus 283 — Capacity: 125.0 MW
- Baldy Mesa 2 Silver Peak Hybrid at bus 263 — Capacity: 50.0 MW
- IPC 25 Solar at bus 239 — Capacity: 2.4 MW
- Paulsell at bus 277 — Capacity: 20.0 MW
- Amazon SAN3 Solar Project at bus 134 — Capacity: 4.6 MW
- Highway 43 1887-WD at bus 176 — Capacity: 2.3 MW
- Terry 1818-WD at bus 22 — Capacity: 4.6 MW
- North Kern 3 at bus 56 — Capacity: 5.0 MW
- Avalon Dairy at bus 181 — Capacity: 3.1 MW
- Lockheed Martin Palmdale Solar PV at bus 308 — Capacity: 20.0 MW

Selected Wind Projects:
- Tehachapi Wind Resource II at bus 210 — Capacity: 15.5 MW
- Rooney Ranch at bus 273 — Capacity: 21.0 MW
- Sand Hill A at bus 273 — Capacity: 13.5 MW
- Sand Hill B at bus 82 — Capacity: 17.0 MW
- Sand Hill C at bus 82 — Capacity: 80.0 MW
- Solano Wind at bus 215 — Capacity: 108.0 MW
- Painted Hills Wind Park at bus 266 — Capacity: 46.8 MW
- Sky River Wind Energy Center at bus 210 — Capacity: 60.2 MW
- 85 A at bus 210 — Capacity: 21.3 MW
- 85 B at bus 210 — Capacity: 25.2 MW
- Mountain View I II at bus 266 — Capacity: 70.9 MW
- Strauss Wind Farm at bus 179 — Capacity: 95.3 MW
- Point Wind at bus 210 — Capacity: 64.5 MW
- Oasis Alta at bus 210 — Capacity: 14.4 MW
- Coachella Hills Wind at bus 266 — Capacity: 61.2 MW
- Summit Winds at bus 21 — Capacity: 47.5 MW
- AM Wind Repower LLC at bus 266 — Capacity: 27.0 MW
- Mesa Wind Repower at bus 266 — Capacity: 30.0 MW
- CalPorlland Company Mojave Wind at bus 210 — Capacity: 23.5 MW

Selected Gas Projects:
- Santa Rita Jail Fuel Cell (Now F0002) at bus 126 — Capacity: 1.4 MW
- CEFF II Tehachapi Property, LLC (formerly SunSelect 1) at bus 67 — Capacity: 6.86 MW
- Kaiser Permanente at bus 312 — Capacity: 2.2 MW
- AT and T Services Inc at bus 301 — Capacity: 1.25 MW
- Procter and Gamble Oxnard I (duplicate of G0468) at bus 170 — Capacity: 19.9 MW
- Santa Rita Jail Fuel Cell at bus 126 — Capacity: 1.4 MW
- Acid (CAISO) at bus 206 — Capacity: 110.6 MW
- Berry Cogen Pan Fee at bus 90 — Capacity: 5.7 MW
- Pio Pico Energy Center at bus 134 — Capacity: 336.0 MW
- Alamitos Energy Center at bus 286 — Capacity: 693.0 MW
- Stanton Energy Reliability Center at bus 309 — Capacity: 121.0 MW

Selected Battery Projects:
- Aramis I Solar Project at bus 21 — Capacity: 100.0 MW
- Buena Vista Energy LLC at bus 82 — Capacity: 100.0 MW
- Kingsley Solar Farm at bus 75 — Capacity: 74.0 MW
- Big Rock Solar Farm at bus 75 — Capacity: 200.0 MW
- Bellefield 3 Solar and Battery Storage at bus 210 — Capacity: 150.0 MW
- Sagebrush Solar 2 ESS 40 at bus 210 — Capacity: 40.0 MW
- Golden Field Solar III, LLC at bus 283 — Capacity: 147.0 MW
- AVEP BESS at bus 283 — Capacity: 126.0 MW
- Rosamond South 1 at bus 283 — Capacity: 117.0 MW
- Northern Orchard Solar PV, LLC at bus 87 — Capacity: 92.0 MW
- Raceway Solar Storage at bus 283 — Capacity: 80.0 MW

- Cathode (Hinson) BESS at bus 292 — Capacity: 100.0 MW
- Cald BESS at bus 307 — Capacity: 100.0 MW
- Humidor Storage I at bus 119 — Capacity: 300.0 MW
- Beaumont BESS at bus 256 — Capacity: 100.0 MW
- Desert Quartzite at bus 29 — Capacity: 150.0 MW
- Victory Pass at bus 157 — Capacity: 50.0 MW
- Menifee Power Bank at bus 261 — Capacity: 230.0 MW
- Trestles Grid LLC at bus 261 — Capacity: 150.0 MW
- Lycan Solar Project at bus 157 — Capacity: 400.0 MW
- Aratina Solar Center 1 Hybrid at bus 86 — Capacity: 125.0 MW
- Condor Energy Storage LLC at bus 258 — Capacity: 200.0 MW
- Separator (Etiwanda) BESS at bus 311 — Capacity: 112.5 MW
- Cascade Energy Storage, LLC at bus 233 — Capacity: 25.0 MW
- Kola Energy Center at bus 273 — Capacity: 400.0 MW
- Hummingbird Energy Storage LLC at bus 248 — Capacity: 75.0 MW
- Proxima at bus 277 — Capacity: 162.0 MW
- Paulsell at bus 277 — Capacity: 15.0 MW
- Anode 1 (Springville) BESS at bus 184 — Capacity: 112.5 MW
- Rexford Solar Farm at bus 203 — Capacity: 300.0 MW
- Bottleneck Energy Storage at bus 203 — Capacity: 80.0 MW
- Gibson Solar Project - Hybrid at bus 102 — Capacity: 13.0 MW

Selected Constraints Increased:
- Constraint: Midway-Q2005 230kV Line — Cost: $9.4e8 — Increase Amount: 16891
- Constraint: Birds Landing-Contra Costa 230kV Line — Cost: $7.0e8 — Increase Amount: 1766
- Constraint: Antelope-Neenach Constraint — Cost: $1.0e8 — Increase Amount: 2000
- Constraint: VEA 138kV area constraint — Cost: $3.791300305e8 — Increase Amount: 1367
- Constraint: Windmaster-Delta pumps 230 kV line — Cost: $4.17332e8 — Increase Amount: 6034
- Constraint: Midway 230/115kV TB 3 — Cost: $1.5e8 — Increase Amount: 784
- Constraint: Semitropic-Midway 115kV Line — Cost: $7.6e8 — Increase Amount: 637
- Constraint: GLW 230kV area constraint — Cost: $3.563877756e8 — Increase Amount: 1285
- Constraint: Devers-Red Bluff Constraint — Cost: $1.386722862e9 — Increase Amount: 5000
- Constraint: Kramer to Victor Area Constraint — Cost: $3.344775543e8 — Increase Amount: 1206
- Constraint: Lakeville-Ignacio 230 kV line — Cost: $0.01 — Increase Amount: 861
- Constraint: East of Miguel constraint — Cost: $7.82943728e8 — Increase Amount: 2823
- Constraint: South of Magunden Constraint — Cost: $4.358e9 — Increase Amount: 2000
- Constraint: Silvergate - Bay Blvd 230 kV constraint — Cost: $2.9971e7 — Increase Amount: 4754
- Constraint: Windhub Constraint — Cost: $6.12e8 — Increase Amount: 2500
- Constraint: Etiwanda-Rancho Vista Constraint — Cost: $8.9e7 — Increase Amount: 3350
- Constraint: Newark-Newark Distribution 115 kV line — Cost: $0.01 — Increase Amount: 831
- Constraint: Antelope-Vincent Constraint — Cost: $1.32e7 — Increase Amount: 1500
- Constraint: Hinson - Del Amo Constraint — Cost: $2.8e7 — Increase Amount: 800

Buses Increased:
- Bus 1 — Name: ALPAUGH — Increased by: 43.0
- Bus 3 — Name: ARCO (PGE) — Increased by: 522.0
- Bus 6 — Name: BAHIA — Increased by: 1632.0
- Bus 8 — Name: BAKERSFIELD — Increased by: 15377.3
- Bus 13 — Name: BRENT — Increased by: 5581.7
- Bus 15 — Name: CABRILLO (PGE) — Increased by: 688.7
- Bus 21 — Name: CAYETANO — Increased by: 247.5
- Bus 22 — Name: CHARCA — Increased by: 4.6
- Bus 23 — Name: CHARLESTON PARK — Increased by: 485.0
- Bus 29 — Name: COLORADO RIVER — Increased by: 550.0
- Bus 32 — Name: COOL WATER — Increased by: 182.0
- Bus 48 — Name: EAST COUNTY — Increased by: 90.0
- Bus 56 — Name: FAMOSO — Increased by: 5.0
- Bus 60 — Name: GATES — Increased by: 275.0
- Bus 67 — Name: GRIMMWAY-MALAGA — Increased by: 6.86
- Bus 75 — Name: IMPERIAL VALLEY — Increased by: 599.0
- Bus 82 — Name: KELSO — Increased by: 202.0
- Bus 83 — Name: KERN OIL — Increased by: 4.3
- Bus 86 — Name: KRAMER — Increased by: 415.0
- Bus 87 — Name: LAKEVIEW — Increased by: 542.0
- Bus 88 — Name: LAKEVILLE — Increased by: 836.5
- Bus 90 — Name: LAMONT — Increased by: 5.7
- Bus 102 — Name: MADISON (PGE) — Increased by: 26.0
- Bus 119 — Name: MOORPARK — Increased by: 300.0
- Bus 126 — Name: NORTH DUBLIN — Increased by: 2.8
- Bus 130 — Name: OCOTILLO — Increased by: 50.0
- Bus 134 — Name: OTAY MESA — Increased by: 4754.0
- Bus 143 — Name: PASTORIA — Increased by: 2000.0
- Bus 156 — Name: RECTOR — Increased by: 3.0
- Bus 157 — Name: RED BLUFF — Increased by: 1940.0
- Bus 167 — Name: SANDLOT — Increased by: 389.8
- Bus 170 — Name: SANTA CLARA — Increased by: 19.9
- Bus 176 — Name: SHAFTER — Increased by: 2.3
- Bus 179 — Name: SISQUOC — Increased by: 95.3
- Bus 181 — Name: SMYRNA — Increased by: 3.1
- Bus 184 — Name: SPRINGVILLE — Increased by: 112.5

- Bus 196 — Name: CRAZY EYES — Increased by: 800.0
- Bus 197 — Name: TULUCAY — Increased by: 24.5
- Bus 203 — Name: VESTAL — Increased by: 935.8
- Bus 205 — Name: VISTA (VEA) — Increased by: 1367.0
- Bus 206 — Name: WEST FRESNO — Increased by: 120.6
- Bus 207 — Name: WEST PARK — Increased by: 616.24
- Bus 210 — Name: WINDHUB — Increased by: 2500.0
- Bus 214 — Name: BIG CREEK 1 — Increased by: 628.8
- Bus 215 — Name: BIRDS LANDING — Increased by: 108.0
- Bus 219 — Name: ELDORADO — Increased by: 2510.0
- Bus 251 — Name: BLYTHE — Increased by: 2084.0
- Bus 258 — Name: VISTA (SCE) — Increased by: 85.34000000000002
- Bus 261 — Name: VALLEY (SCE) — Increased by: 199.56000000000003
- Bus 263 — Name: ROADWAY — Increased by: 219.2
- Bus 266 — Name: DEVERS — Increased by: 3065.1
- Bus 273 — Name: TESLA — Increased by: 831.0
- Bus 283 — Name: WHIRLWIND — Increased by: 1500.0
- Bus 286 — Name: ALAMITOS — Increased by: 800.0

B. Further Sensitivity Analysis

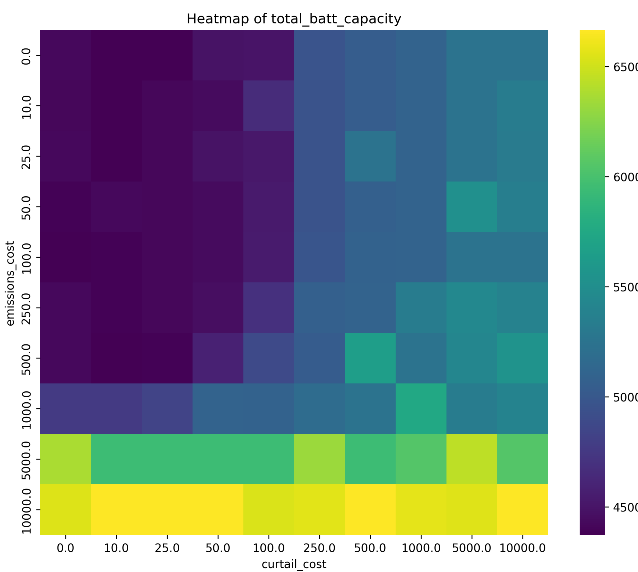

Fig. 7: Heatmap for Battery Capacity

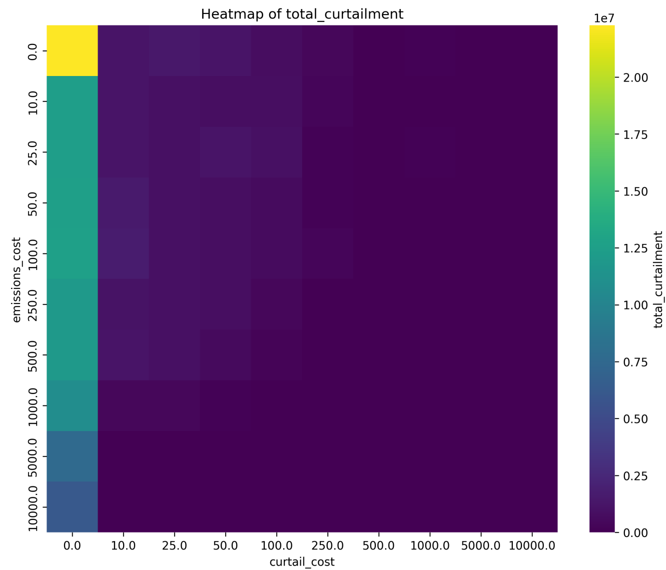

Fig. 8: Heat map for Curtailment

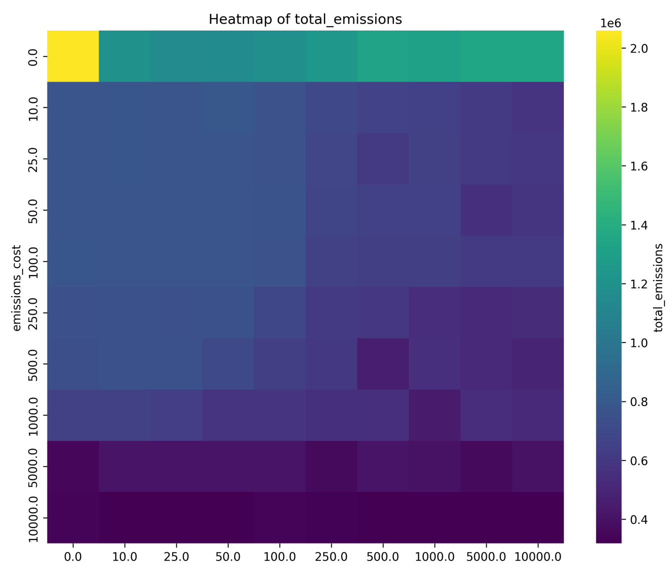

Fig. 9: Heat map for Emissions

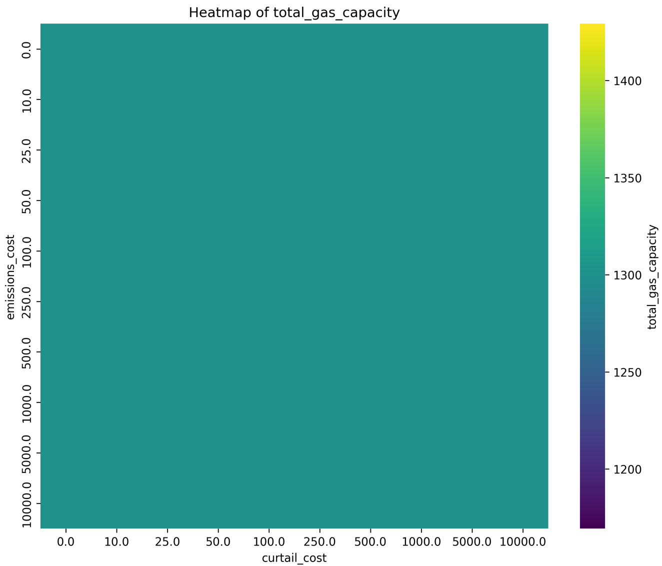

Fig. 10: Heat Map for Gas Capacity

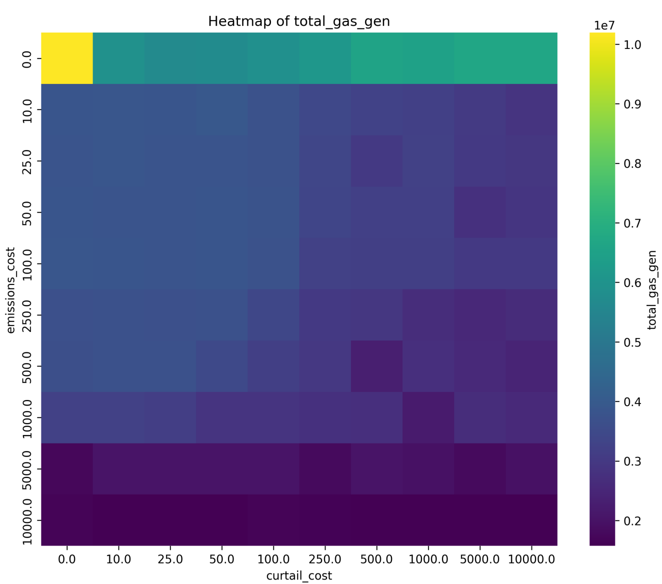

Fig. 11: Heat Map for Gas Capacity

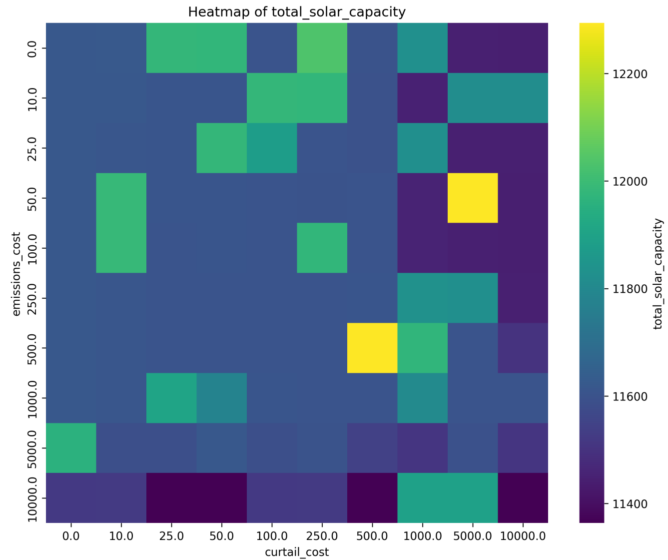

Fig. 12: Heat Map for Solar Capacity

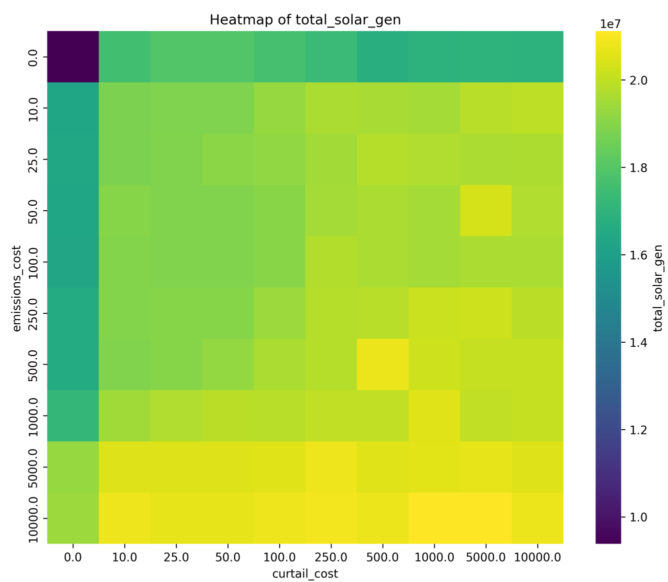

Fig. 13: Heat Map for Solar Generation

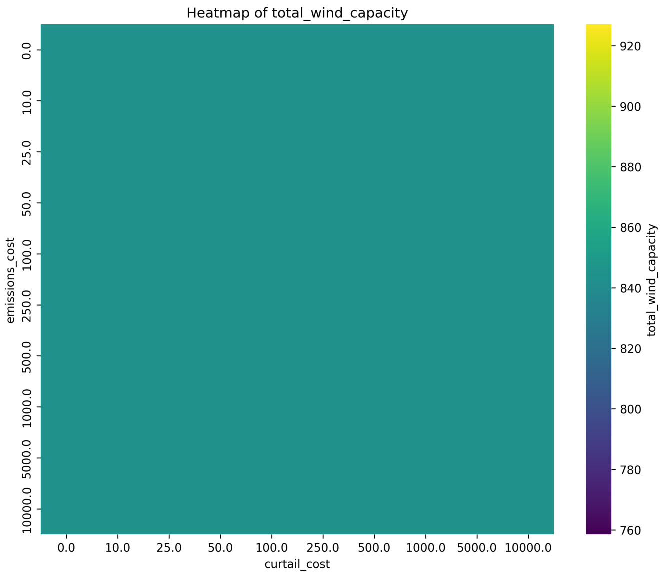

Fig. 14: Heat Map for Wind Capacity

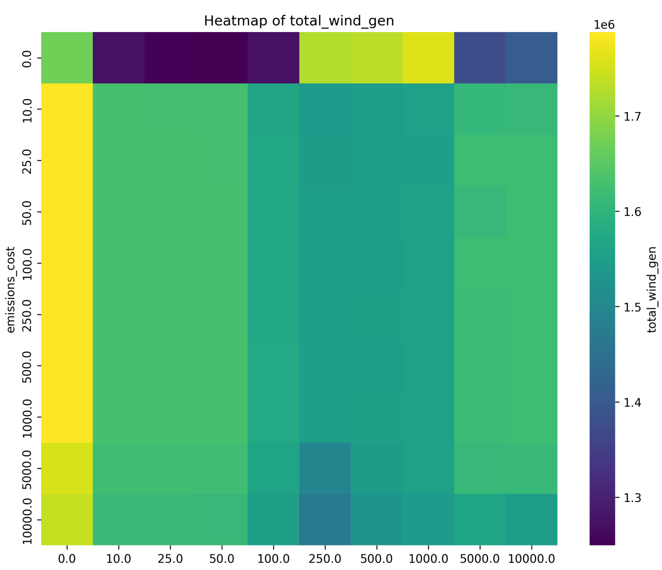

Fig. 15: Heat Map for Wind Generation