

# California semi truck electrification: Preliminary assessment of infrastructure needs and cost-benefit analysis

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## Executive summary

- Electrification presents a major opportunity to address greenhouse gas emissions and air pollution from heavy-duty trucking in California
- Here we provide a **preliminary estimate of infrastructure needs and economic impacts** of electrifying combination trucks in California
  - Electrifying CA trucking is estimated to require **~750 charging** stations at a **\$10.8B** upfront investment
  - Baseline costs of electrification (including charging infrastructure, grid upgrades, electricity, and truck electrification) is estimated to be **\$5.7B/yr**
  - Baseline savings on diesel, GHG emissions, and air pollution is estimated to be **\$7.8B/yr**
  - **Net savings from electrification of combination trucking in CA is estimated to be \$2.2B/yr**

# Opportunity for truck electrification

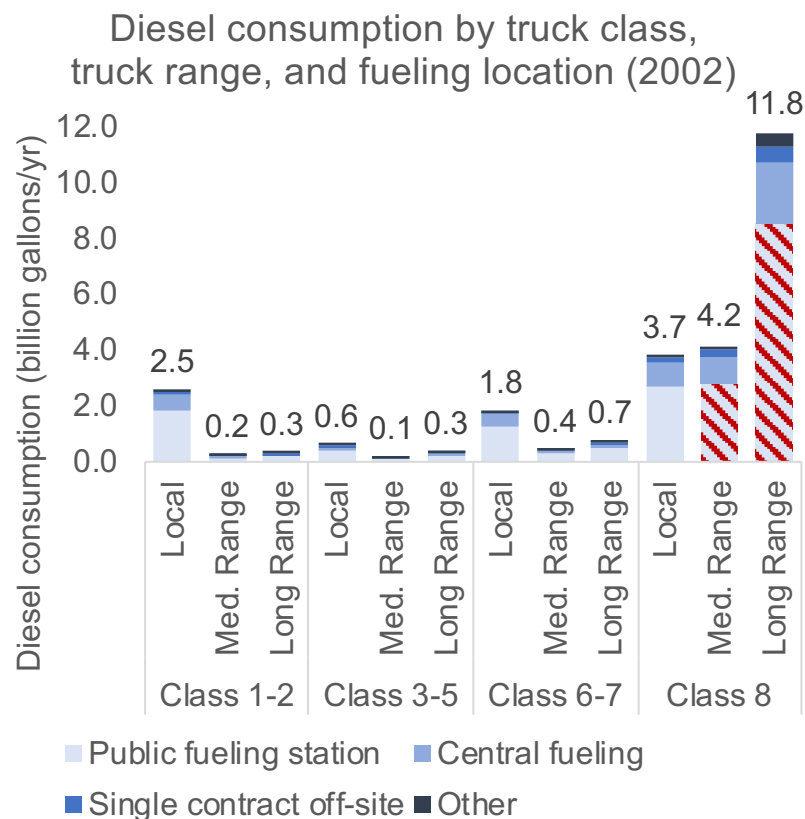
**Electrifying heavy-duty trucking has the potential to address air pollution and GHG emissions, and is becoming feasible as battery costs fall**

- Electrification of trucking in California presents a major opportunity to address air pollution and GHG emissions
  - Heavy-duty trucking accounted for **8% of CA's GHG emissions** in 2016
  - Heavy-duty trucking accounted for **27% of CA's NOx emissions** in 2015
  - Combination trucks (semi trucks) are responsible for an estimated **60%** of GHG and NOx emissions from heavy-duty trucking
- Truck electrification has been seen as challenging, but recent developments suggest that it is becoming more feasible:
  - **Battery costs are falling:** lithium-ion battery prices were \$175/kWh in 2017, an 80% drop from their cost in 2010; BNEF projects a cost of \$100/kWh by 2026
  - **Generation costs are falling:** The cost of electricity generation is dropping as wind and solar prices have become cheaper than coal and gas
- Truck OEMs are coming out with new electric models
  - At least **17 heavy-duty models** have been introduced since 2017

## Specifying “trucking”

In this analysis, we explicitly address combination trucks, though electrification of other classes of trucking merits exploration as well

- As battery costs fall, opportunities are opening up for electrification across many different types of vehicles
- In this analysis we quantify the electrification opportunity for **medium- to long-range combination trucks (i.e., tractor-trailers, “semis”) fueling at public stations**
  - This category alone accounts for **40%** of all diesel consumed by trucks
  - These trucks are Class 8 heavy-duty vehicles



# 1. Estimating Charging Infrastructure Needs

## Infrastructure needs: energy requirements

**Electrifying combination trucks in California would require 20 TWh/year, equivalent to 9% of California's electricity usage**

- Combination trucks currently account for an estimated **9,300 million vehicle-miles traveled (VMT)** per year in CA
  - 78% of miles are traveled on roads that see at least 3000 heavy-duty trucks/day
  - On-road freight transport is expected to rise in the future
- To electrify all combination truck VMT in California would require **20 TWh/year\***
  - This figure represents 9% of the energy usage of California in 2017 (206 TWh)
  - Fuel efficiency (either electricity or diesel) varies based on payload; VMT-based energy requirements should be taken as estimates based on averages



Representation of heavy-duty truck flows in CA in 2012

— >3000 trucks/day

## Infrastructure needs: charging stations (1/2)

To estimate truck charging infrastructure requirements, we modeled fast-charging stations able to simultaneously charge 10 trucks

- We model truck charging stations with the following characteristics:
  - **~20 MW** total capacity
  - **10-truck** simultaneous charging capacity, assuming 1-MWh battery/truck\* and 75% depth of recharge
  - **30-minute** charging time (DC fast charging)
  - **20%** utilization rate\*\*
  - **Transmission**-connected
- **Utilization rate:** represents hours trucks spend charging per day out of 24 hours
  - E.g., modeled charging station operating at a 20% utilization rate would deliver 72 MWh/day (i.e., would charge 96 trucks/day) out of a potential 360 MWh/day

## Infrastructure needs: charging stations (2/2)

An estimated ~750 charging stations would be needed to meet the energy needs of electrified trucking in California

- An estimated ~**750** charging stations would be needed to meet the energy needs of heavy-duty trucking in California
  - Assumes 20% station utilization rate
- While only a first-order estimate based on energy consumption, this estimate reflects certain important aspects of trucking in California
  - **Fueling behavior:** Models on-the-road fueling (rather than centralized fleet fueling), which account for **71%** of diesel sold to heavy-duty trucks
  - **Major highways:** Does not address station distribution in sparsely-traveled areas, but provides representative estimate given that **78%** of VMTs are traveled on major corridors
- Exact number of stations required for full electrification depends on truck flows and driver behavior, which merit further study

## 2. Estimating Costs and Benefits of Electrification

## Costs and benefits of electrification

The cost of charging infrastructure, electric trucks, and electricity are weighed against avoided diesel spend, GHG emissions, and air pollution

- We attempt to estimate the net benefit of truck electrification to the state of California
- We account for three major costs
  - Charging station and grid infrastructure cost
  - Electricity cost
  - Incremental cost of battery-electric trucks over diesel trucks
- We account for three major benefits
  - Avoided spending on diesel fuel
  - Avoided greenhouse gas emissions
  - Avoided air pollution damages

## Cost-benefit analysis: charging infrastructure (1/2)

The cost of charging station infrastructure to support electrified trucking in California is estimated to be **\$1.0B/yr**

- We estimate the cost of a ~20-MW charging station to be **\$15 million upfront and \$210,000/yr\***
  - This figure includes the cost of land, electric vehicle supply equipment, installation, and a transmission-level grid connection
- Total upfront cost of charging infrastructure needed in California to meet energy needs of combination trucks is estimated to be **\$10.8B**
  - Estimate reflects 20% utilization rate
- On an annualized basis, charging infrastructure cost is estimated to be **\$1.0B/yr\*\***

## Cost-benefit analysis: charging infrastructure (2/2)

Transmission grid upgrades to support new electric trucking load are estimated to cost **\$1.1B/yr**

- An important aspect of charging infrastructure is transmission grid upgrades that may be needed to support new trucking load
- An estimated **\$7.3B total**, or **\$1.1B/yr**, of transmission upgrades would be needed to support electrified trucking
  - Transmission cost taken as \$520,000/MW or \$76/kW-yr\*
  - Actual cost is highly dependent on station siting
- Together, station infrastructure and transmission infrastructure cost is estimated to be **\$2.1B/yr**

**Baseline charging infrastructure cost: \$2.1B/yr**

## Cost-benefit analysis: electricity cost

### Electricity cost for electric trucking is estimated to be \$2.2B/yr, but depends on tariff structure and time of charging

- Trucks may act as flexible loads that can charge when electricity prices are low and the grid is less constrained
- If charging occurs during the 8 lowest-cost hours of the day, average electricity price would be **\$110/MWh** as a customer of SCE, which would make electricity cost for electrified trucking **\$2.2B/yr**
  - Reflects 20% utilization rate
- Electricity cost can vary based on several factors
  - **Electricity provider:** purchasing electricity from IOU vs. directly from wholesale market
  - **Time of day:** electricity prices tend to be higher on-peak (e.g., 4-7 PM on weekdays) and lower off-peak (e.g., overnight or during high solar production)
  - **Demand charges:** per-kW demand charges are a common component of electricity tariffs that drive up electricity costs at low station utilization
- Electricity prices as a CAISO direct-access customer could be as low as **\$38/MWh** with modification of demand charges to be peak-coincident

**Baseline electricity cost: \$2.2B/yr**

## Cost-benefit analysis: incremental truck cost

### The incremental cost of electric trucks over diesel trucks is estimated to be **\$1.4B/yr**

- The battery in an electric truck is the major driver of the cost increase of electric over diesel trucks
  - \$100/kWh battery costs are expected by Tesla by 2020 and by BNEF by 2026
  - At this battery cost, a 1000-kWh truck battery will cost **\$100,000**
- However, electric trucks realize incremental savings over diesel in the diesel engine, transmission, and drivetrain which amount to **\$22,000**
- Electric trucks also realize lower lifetime maintenance costs than diesel trucks, which are not taken into account in this analysis
- Average battery depreciation cost is estimated to be **\$0.15/mi\***
  - Assumes 75% battery depth of discharge and 2000 cycle life
  - Battery treatment (depth of discharge, state of charge parameters, temperature) has major impact on lithium-ion cycle life and depreciation cost
- Electrifying all miles driven by combination trucks in California would equate to **\$1.4B/yr** in net incremental electrification cost

**Baseline incremental truck cost: \$1.4B/yr**

## Cost-benefit analysis: avoided diesel spend

Combination trucks spend an estimated \$5.0B/yr on diesel that could be avoided with electrification

- Assuming combination trucks achieve 5.87 mi/gal on average, an estimated **1.6B gallons** of diesel per year are consumed by combination trucks in California\*
- This equates to an estimated **\$5.0B/yr** spent on diesel at \$3.16/gallon

**Baseline diesel savings: \$5.0B/yr**

## Cost-benefit analysis: avoided GHG emissions

**Avoided GHG emissions from electrifying trucking are worth an estimated \$0.9B/yr**

- Combination trucks in CA emitted an estimated **20 million tonnes (MT)** of CO<sub>2</sub>e in 2016 (**5%** of total state emissions)
- GHG emissions reduction benefits depend on:
  - **Emissions intensity of electricity** (currently 0.24 tonne CO<sub>2</sub>e/MWh; expected to be 50% renewable by 2030 and carbon-free by 2045)
  - **Social cost of carbon** (at baseline taken as \$52/tonne\*; cost varies substantially by year and by assumed discount rate)
- Eliminating GHG emissions from combination trucks in California is valued at **\$1.0B/yr**
- Emissions from charging trucks with 50% renewable power are estimated to cost **\$170M/yr**, making net GHG benefits of electrification **\$0.9B/yr**
- Near-term benefits can be increased if charging is done at hours where low-carbon energy is marginal

**Baseline GHG savings: \$0.9B/yr**

# Cost-benefit analysis: avoided air pollution

Net air pollution savings from electrification are estimated to be **\$1.9B/yr**

- Diesel trucks emit a range of pollutants including NO<sub>x</sub>, PM2.5, ROG<sup>\*</sup>, ammonia, and SO<sub>2</sub>
  - Heavy-duty diesel vehicles in California substantially and disproportionately contribute to NO<sub>x</sub> pollution
  - CARB: “The estimated contribution of on-road heavy-duty diesel vehicles to the total NO<sub>x</sub> emission in California was ~32% in 2016, which is considerably higher than the US average (~16-18% in the past decade)”
- Eliminating emissions from heavy-duty diesel trucks in California in 2016 would have an estimated value of **\$2.0B/yr** (79% of which comes from eliminating NO<sub>x</sub>)
- After accounting for increased power sector emissions to fuel electric trucks, net air pollution savings from electrification are **\$1.9B/yr<sup>\*\*</sup>**

**Baseline air pollution savings: \$1.9B/yr**

## Cost-benefit analysis: baseline total savings

California stands to realize \$2.2B/yr in net benefits with fully electrified combination trucks

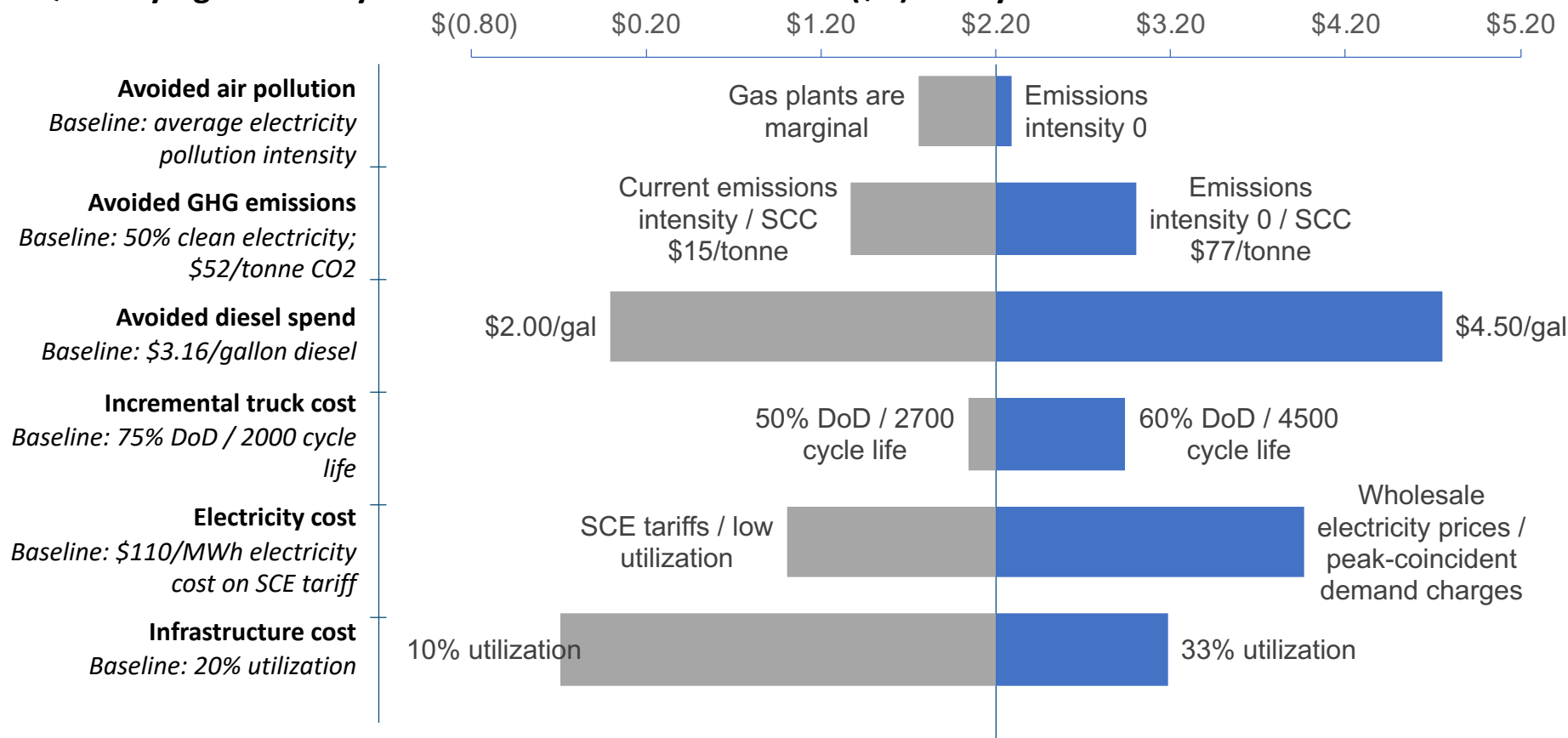
### Baseline cost-benefit analysis results

Category	\$B/yr	Baseline assumption
<b>Costs</b>		
Charging/grid infrastructure	\$2.1	20% utilization rate
Electricity	\$2.2	\$110/MWh electricity cost (incl. demand charges) as SCE customer
Incremental truck cost	\$1.4	
<i>Total costs</i>	<i>\$5.7</i>	
<b>Benefits</b>		
Avoided diesel spend	\$5.0	\$3.16/gallon diesel
Avoided GHG emissions	\$0.9	50% clean electricity; \$52/tonne carbon cost
Avoided air pollution	\$1.9	Gas plants are marginal during truck charging
<i>Total benefits</i>	<i>\$7.8</i>	
<b><i>Net benefit</i></b>	<b><i>\$2.2</i></b>	

# Cost-benefit analysis: sensitivities (1/2)

Net benefit of truck electrification is sensitive to key variables, potentially ranging from **-\$3.9B - \$7.9B/yr** according to the sensitivities considered

Quantifying sensitivity of net benefit of electrification (\$B) to key variables\*



Net benefit of electrification at baseline = \$2.2B/yr

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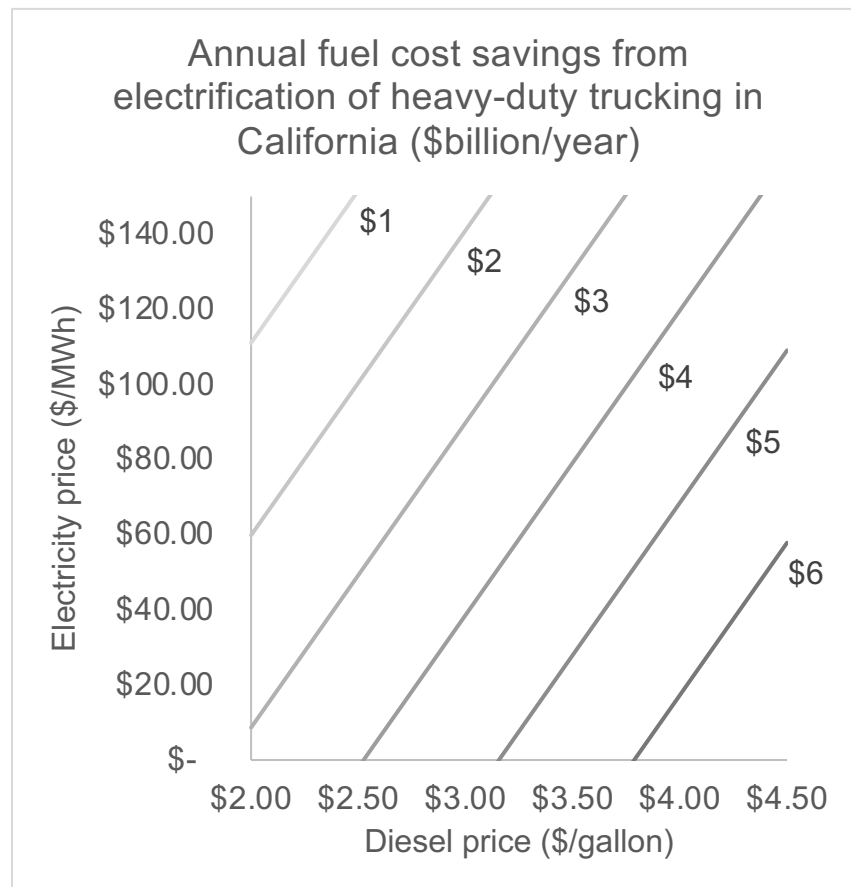
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\*The variable under consideration is manipulated while other variables remain at baseline values

## Cost-benefit analysis: sensitivities (2/2)

Even at low-end diesel prices and high-end electricity prices, fuel cost is roughly equivalent

- Diesel prices have ranged between \$2.00/gal and \$4.50/gal in California between 2009 and 2019
- Electricity prices are highly dependent on tariff structure and policy
  - Low-end prices of \$35/MWh could be achieved with wholesale price access, modification of demand charges to be peak-coincident, and off-peak charging
  - High-end prices of \$160/MWh will occur in SCE territory at low station utilization, even if trucks charge off-peak
- Even at a diesel price of \$2.00/gal and an electricity price of \$160/MWh, **electric and diesel fuel cost are roughly equivalent**



## Further considerations

### The evolution of key variables and implementation issues are both important to consider when evaluating costs and benefits of electrification

- This analysis does not account for evolution of key variables, but certain trends are relevant in considering the future value of electrification
  - **Total on-road freight VMT** are expected to increase ~75% from 2012-2045
  - **Charging infrastructure cost** is dependent on utilization rate and industry scale, both of which are likely to increase over time and drive down unit costs
  - **Electricity cost** under very high renewable scenarios is uncertain, but average wholesale electricity prices are expected to decline under 40-50% penetrations of wind and solar
  - **Diesel cost** is expected to rise modestly in real terms between 2018 and 2050
  - **Avoided GHG emissions** will be more valuable in the future; current estimates may change with greater understanding of climate impacts and discount rates
- Further research is needed to better understand charging infrastructure needs and costs and benefits of electrification
  - **Agent-based modeling** to site charging stations based on actual truck flows
  - **Power systems analysis** to understand grid upgrades required
  - **Electricity rate design** to optimize timing of charging

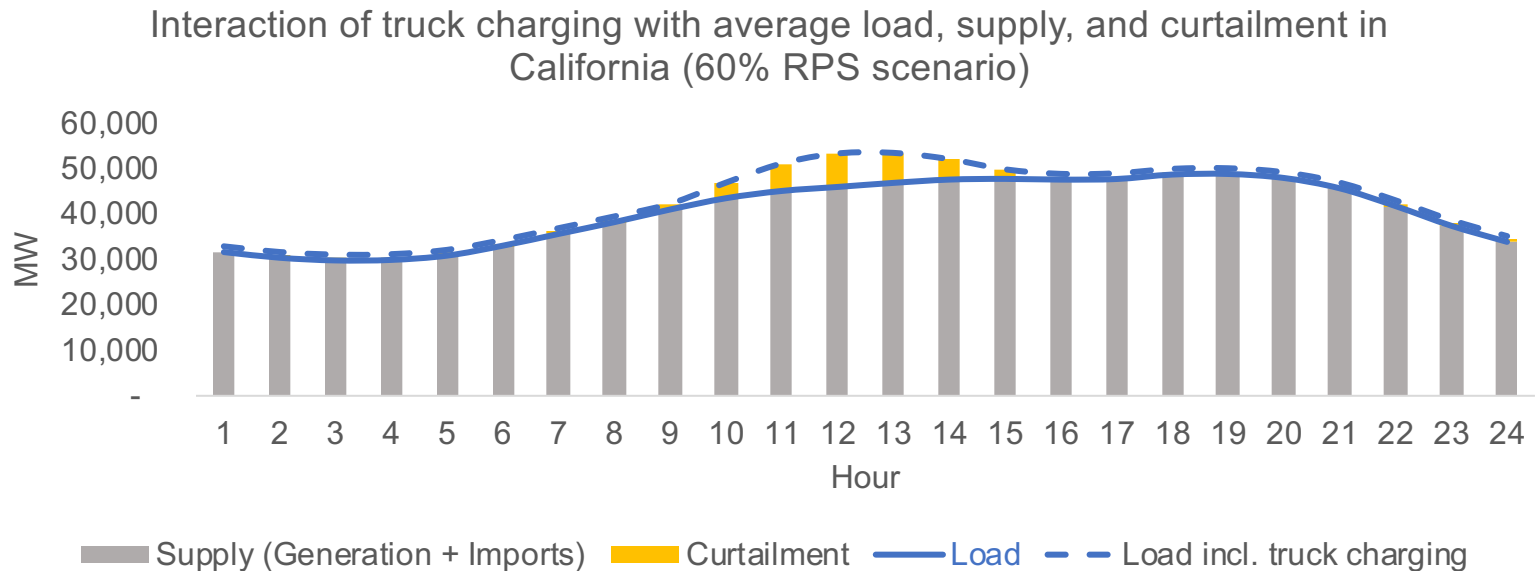
## Electricity cost deep dive: trucking and curtailment (1/3)

**We model two high renewable penetration scenarios to investigate the extent to which electric trucking could consume curtailed renewables**

- Trucks are theoretically able to respond to price signals and charge at hours of the day where electricity prices are low
- One such opportunity is to charge during times of excess renewable energy production
- We model two high renewable energy penetration scenarios to investigate the extent to which truck charging could absorb curtailed renewable energy
  - Scenario 1: California meets 60% RPS target
  - Scenario 2: California meets 100% RPS target with 100 GW of wind and solar and 150 GWh of battery storage

## Electricity cost deep dive: trucking and curtailment (2/3)

With a 60% RPS, if trucks charge during hours of excess solar production, curtailed renewables could meet up to 60% of trucking's energy needs

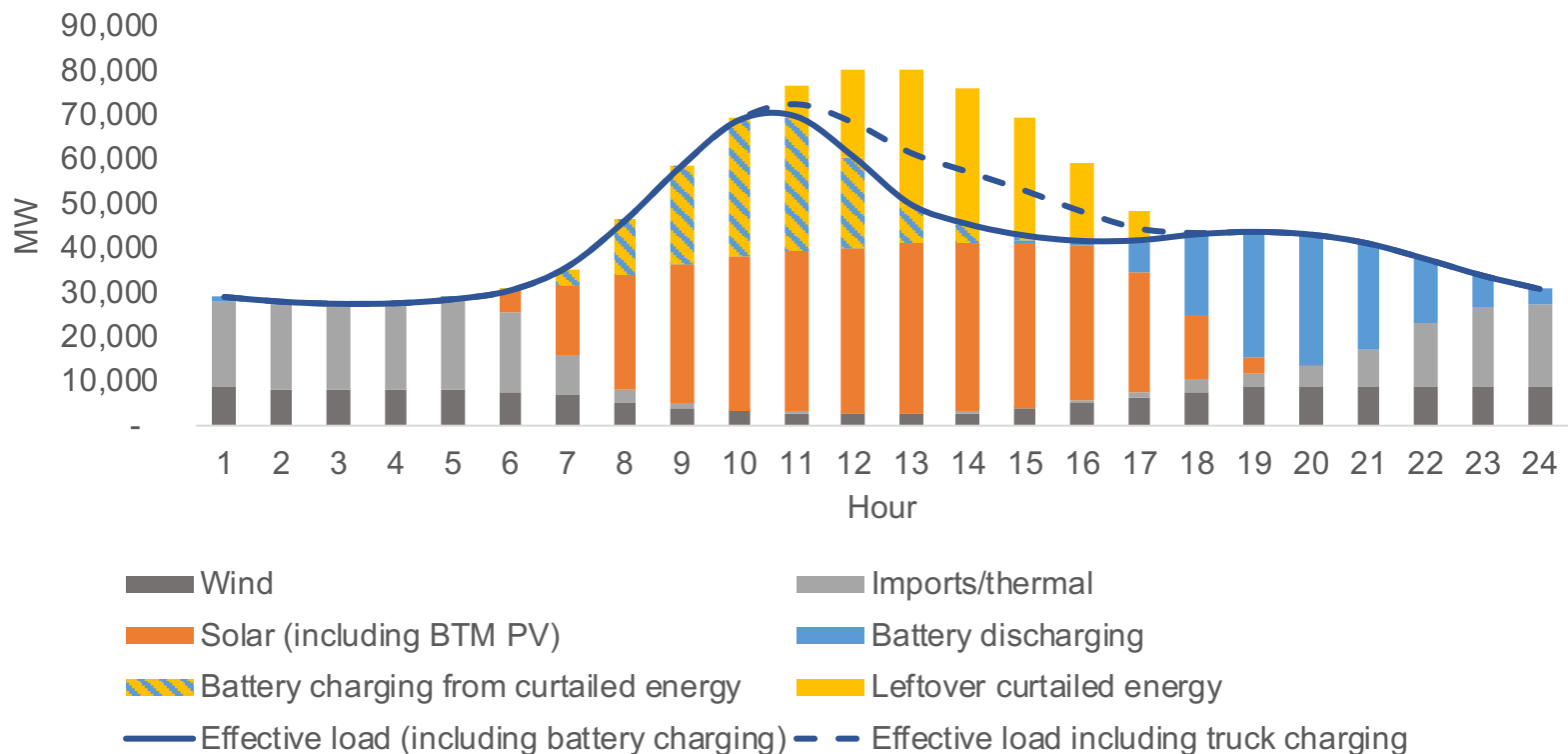


- With a 60% RPS\*, curtailed renewable energy could meet **60%** of trucking's energy needs on average if trucks can charge during excess production
- Curtailed energy available varies throughout the year, only able to meet **8%** of trucking needs in December but **92%-150%** from March-June

## Electricity cost deep dive: trucking and curtailment (3/3)

**With a 100% RPS, if trucks can charge during hours of excess solar production, truck charging could absorb over 1/3 of curtailed energy**

Interaction of truck charging with average renewable curtailment in California, 100% RPS scenario



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# Appendix A: Estimating the Cost of Electric Truck Fast-Charging Stations

# Truck charging cost components

Here we detail the costs of a 9.4-MW charging station with five 1.9-MW chargers

## ■ Key components of truck charging cost:

### — Station costs

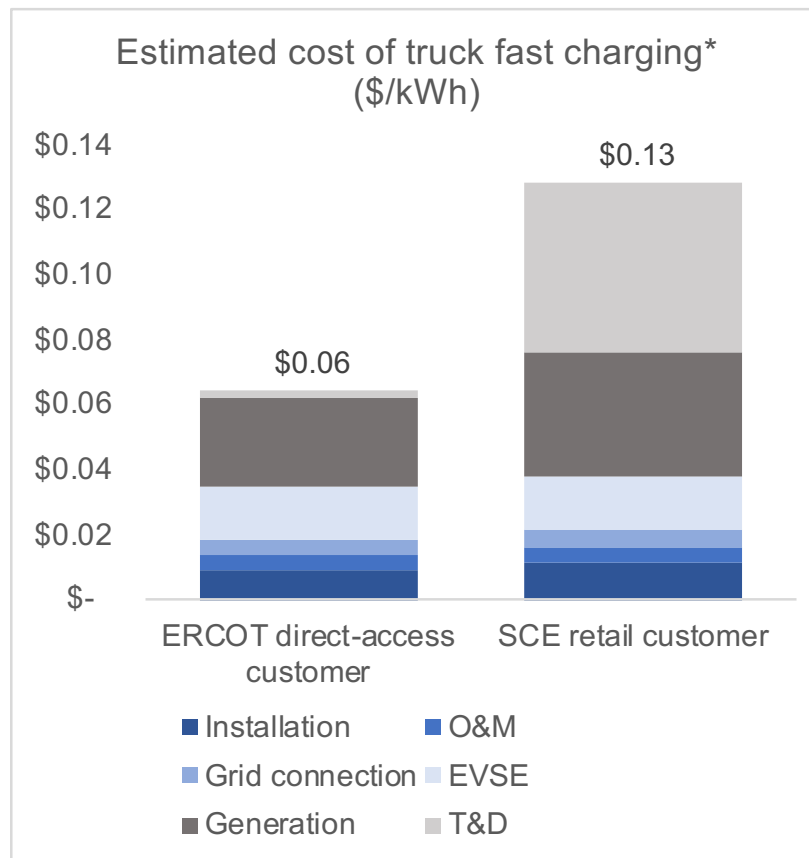
- EVSE (truck charger)
- Grid connection
- Installation
- Operations & maintenance

### — Electricity costs

- Energy
- Transmission & distribution

- Our modeling suggests that truck fast-charging can be achieved at a cost of **\$0.06-\$0.13/kWh**, depending on the state and electricity tariff structure

- **This presentation will detail the costs of electric truck charging stations rather than electricity tariffs**



## Cost estimation: EVSE (truck charger)

We estimated the cost of each 1.9-MW DC truck charger from two complementary perspectives

### Industry experience of DC station costs

*We blended industry estimates of large fast charger costs with scaled-up costs of car-scale fast chargers.*

- Estimated hardware cost of 1.9-MW charger, provided via industry conversation: **\$700,000**
- Average estimated hardware cost of 50-120 kW car chargers: \$511/kW → cost of 1.9-MW charger: **\$960,000**

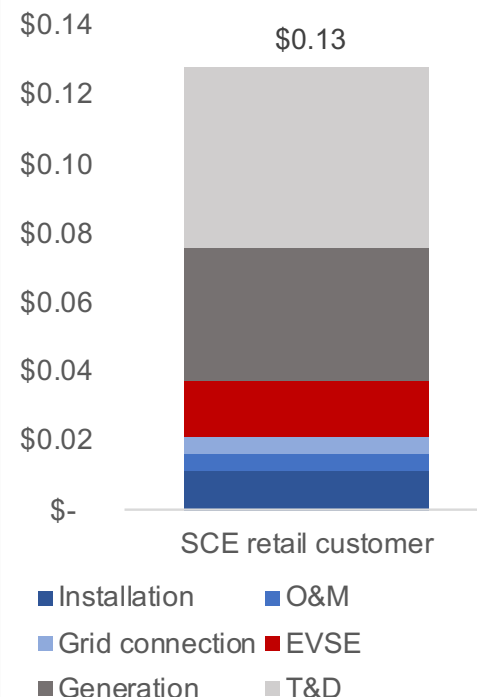
### Bottom-up estimate based on grid-scale S+S

*The core element of a truck fast charger is an AC/DC power converter. The cost of grid-scale solar-plus-storage projects includes the cost of a bidirectional inverter as well as relevant balance-of-system costs.*

- Inverter, structural BOS, and electrical BOS for grid-tied solar+storage project: \$265/kW → cost of 1.9-MW DC charger: **\$500,000**

**Estimated 1.9-MW\* truck charger cost: \$670,000**

Estimated cost of truck fast charging (\$/kWh)



## Cost estimation: Grid connection

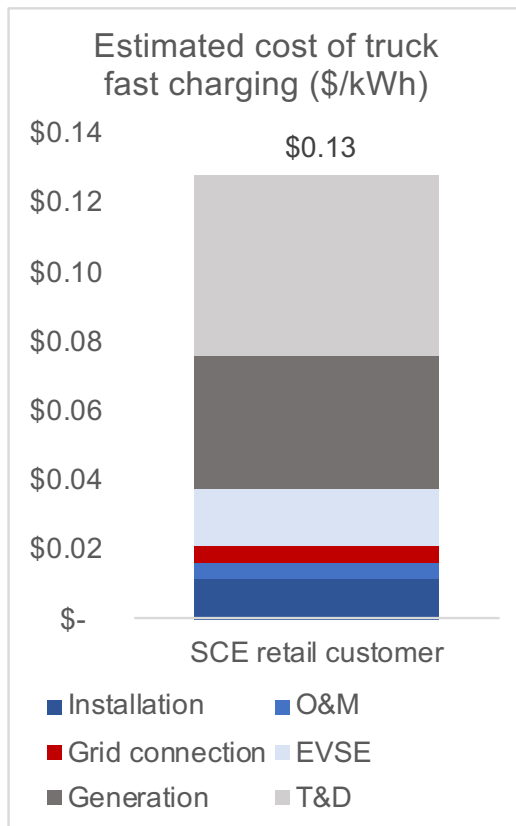
We used utility-scale solar PV grid connection costs as a proxy for charging station grid connection costs

### Utility-scale solar PV grid connection costs

*We used IRENA's 2016 estimate of US utility-scale solar PV grid connection costs. In our model, we assume the truck station is connected at the transmission level.*

- Grid connection cost: **\$144/kW**
- Grid connection lifetime: **30 years**

**Estimated 9.4-MW grid connection cost: \$1.3M**

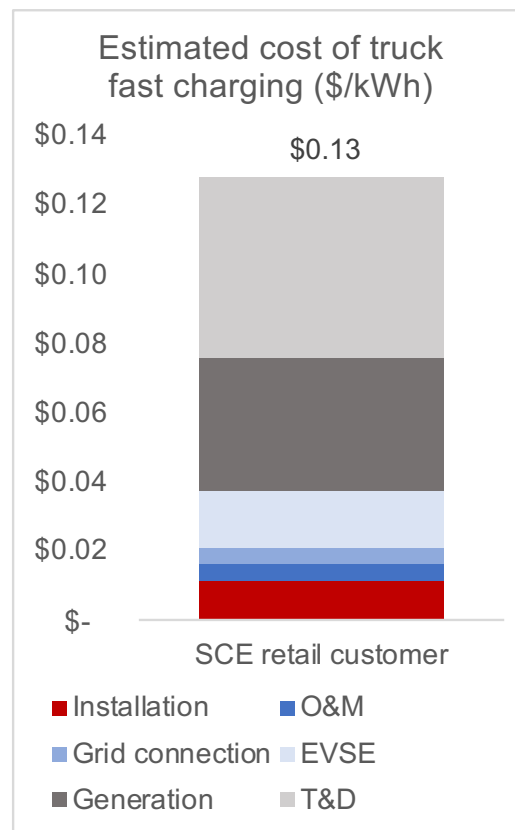


## Cost estimation: Installation

We combined land costs and grid-tied battery installation costs to estimate truck charging station installation costs

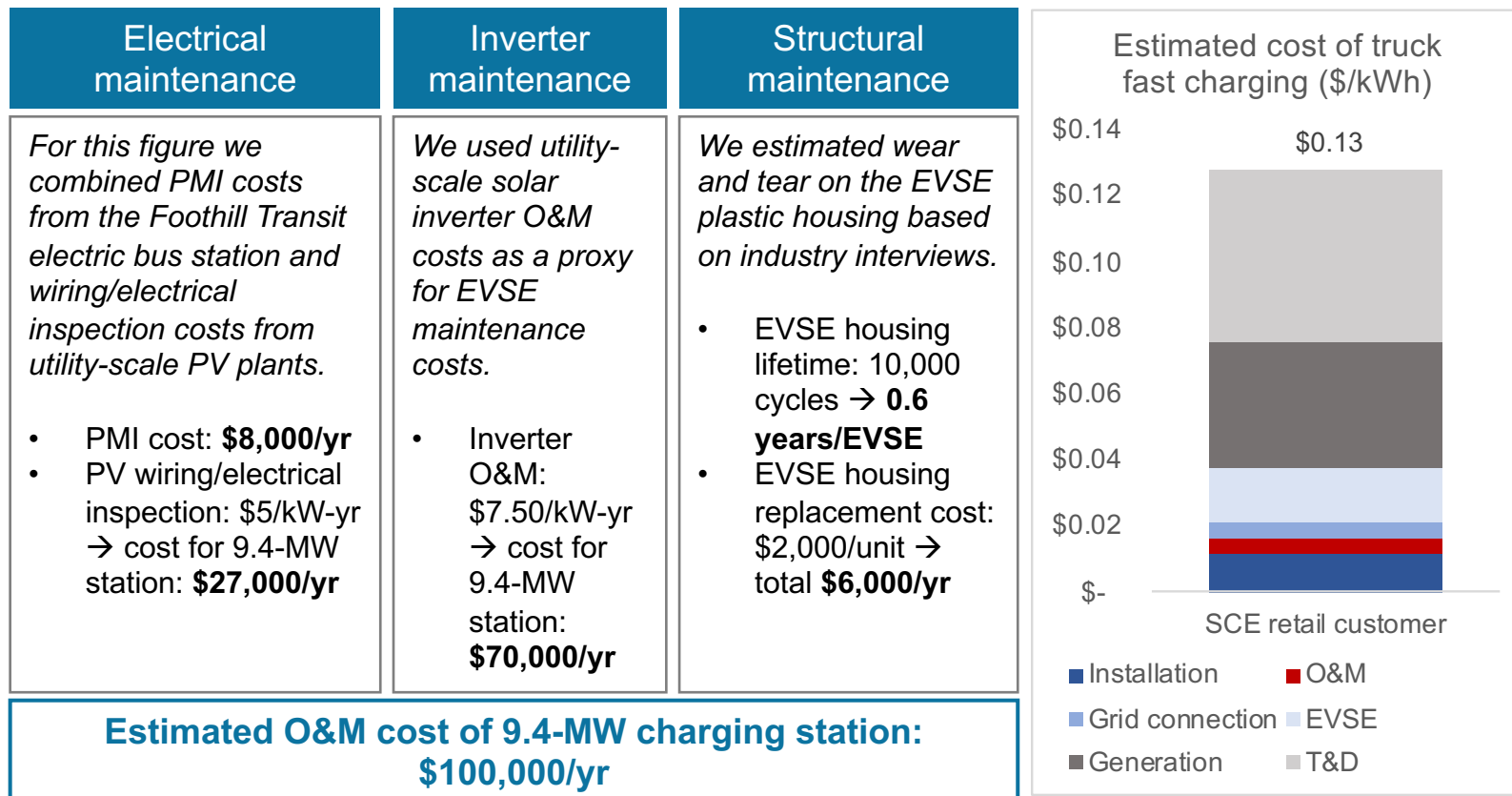
Land costs	Grid-tied battery installation
<p><i>We estimated the cost of land in both California and Texas by finding an average per-acre sale price of existing truck stops.* We scaled that figure based on the estimated area needed for the charging station.</i></p> <ul style="list-style-type: none"><li>• Total cost of land in Texas: <b>\$420,000</b></li><li>• Total cost of land in California: <b>\$1.1M</b></li></ul>	<p><i>We used installation costs associated with a grid-connected battery as a proxy for installation costs of a truck charging station.</i></p> <ul style="list-style-type: none"><li>• Installation labor and equipment: <b>\$88/kW</b></li><li>• EPC overhead: <b>\$49/kW</b></li><li>• Interconnection fee: <b>\$29/kW</b></li><li>• Total installation cost: <b>\$167/kW</b> → cost of 9.4-MW charging station: <b>\$1.5M</b></li></ul>

**Estimated installation cost of 9.4-MW charging station: \$2.0M - \$2.6M**



## Cost estimation: O&M

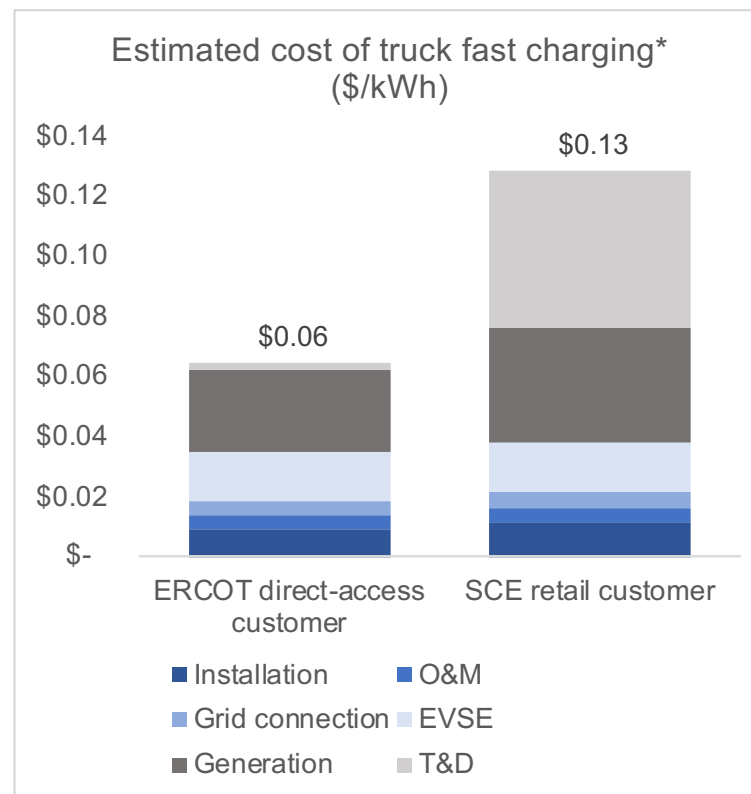
We estimated O&M costs by combining data from utility-scale PV systems, electric bus stations, and industry interviews



# Total cost of charging station

The total cost of a charging station is \$6.6-7.3M, plus \$100,000/yr; this is less than \$0.04/kWh

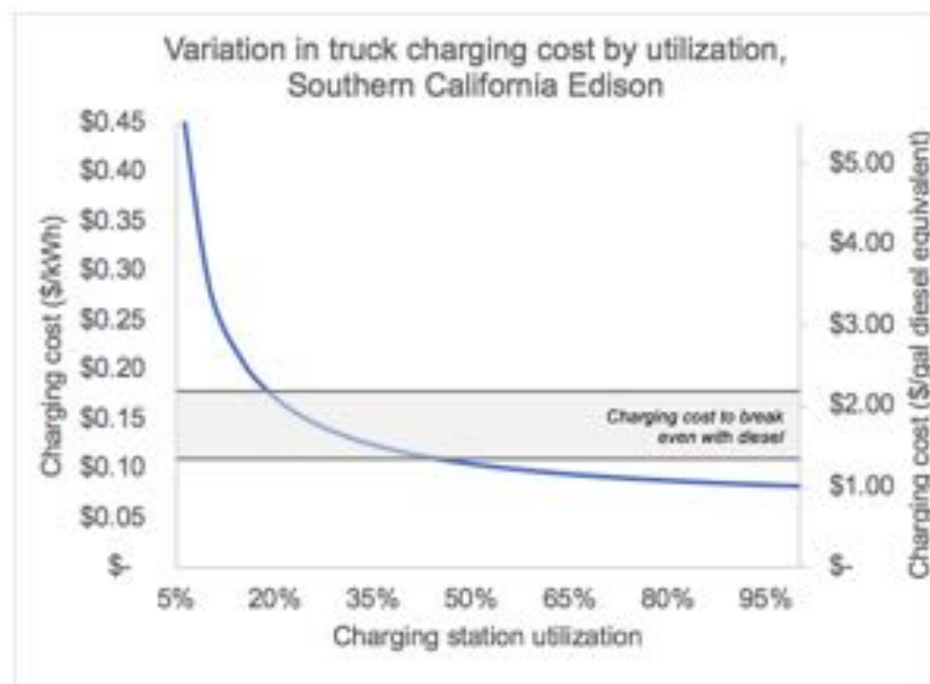
- The total cost of an electric truck fast charging station is estimated to be **\$6.6M (Texas) - \$7.3M (California)**, plus **\$100,000/yr in O&M**
- This cost is levelized over:
  - **The lifetime of the charging station** (assumed to be **15 years** except for the grid connection, which is assumed to be **30 years**)
  - **The number of kWh sold** (here assumed to be **22,000/yr** if the station achieves a 33% utilization rate—i.e., all chargers are in use 8 hrs/day at 80% of max capacity)
- Station cost accounts for less than **\$0.04/kWh** out of a total charging cost of **\$0.06-0.13/kWh** when levelized
- This cost is competitive with diesel trucking, which breaks even with electric trucking at **\$0.11-0.18/kWh** charging cost (see next slide)



# Impact of utilization on charging costs

## Station utilization rate has a major impact on the cost of truck charging

- **Station utilization rate** has a major impact on the cost of charging
  - Achieving high levels of utilization allows fixed station costs to be spread over a larger number of kWh
  - Lower per-kWh costs increase competitiveness with diesel trucking
- Achieving high enough utilization to break even with diesel at **\$0.11-0.18/kWh** is critical to the success of electric trucking
- Truck charging station costs account for less than **\$0.04/kWh** at 33% utilization, but rise to **\$0.12/kWh** at 10% utilization



# Conclusion

Truck fast charging station costs are estimated at less than \$0.04/kWh

- **Decarbonizing road freight is critical**, and electrifying large trucks is becoming a feasible solution
- **Understanding the cost of truck fast charging** is key to planning for road freight decarbonization
- **The cost of truck charging** is driven by the cost of the charging station and the cost of electricity, which vary based on location and electricity tariff structure
- **The cost of the charging station** consists of the cost of the EVSE, grid connection, installation, and O&M
- **Charging station cost** is estimated to be **\$6.6M-\$7.3M + \$100,000/yr**; on a levelized-cost basis, this is less than **\$0.04/kWh** (at 33% station utilization)
- **Station utilization rate** has a major impact on the levelized cost of truck charging and, thus, on its competitiveness with diesel