How Emissions-Optimized EV Charging Enables Cleaner Electric Vehicles

Smart timing of EV charging based on marginal emissions rates can reduce associated grid emissions by up to 18% annually and more than 90% on individual days

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ABOUT WATTTIME

WattTime is a 501(c)3 nonprofit with a software tech startup DNA, dedicated to giving everyone everywhere the power to choose clean energy. We invented Automated Emissions Reduction (AER), which allows IoT devices—smart thermostats, battery energy storage, electric vehicles, and more—as well as the utilities and people that use them, to effortlessly reduce emissions from energy, when and where they happen. AER works by deploying cutting-edge insights and algorithms, coupled with machine learning, to shift the timing of flexible electricity use to sync with times of cleaner energy and avoid times of dirtier energy. We conduct ongoing research collaborations into the algorithms and analyses that make AER possible, advocate for the spread of AER, and assist organizations in adopting the technology by selling solutions that make it easy for anyone to achieve emissions reductions without compromising cost and user experience. WattTime was founded by PhD students at the University of California, Berkeley, and in 2017 became a subsidiary of Rocky Mountain Institute.

For more information, visit **https://WattTime.org**.

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Executive Summary

The number of electric vehicles (EVs) on U.S. roadways is poised to explode from 1 million in 2018 to nearly 19 million in 2030. In tandem, electric vehicle charging points are also expected to balloon, including nearly 10 million level 2 charging stations distributed across homes, offices, and public locations. Level 2 chargers are especially ripe for optimization—price, emissions, or other—since an EV's charge duration is typically shorter than the overall charge window.

Meanwhile, the nation's electricity grids are evolving. As more renewable energy gets added to traditionally fossil-fueled power grids, real-time emissions rates are increasingly exhibiting large swings from clean to dirty and vice versa from one moment to the next. The growing variation in emissions rates at different times presents an opportunity to make clean EVs even cleaner, by optimizing charging to sync with clean energy and avoid dirty energy.

Effectively implementing this solution requires several prerequisites, from accurate data on which times are cleaner, to software that can seamlessly control the EVs to prioritize charging at these times. WattTime refers to a successfully implemented complete package of all the necessary components of emissions-optimized electricity use (including as used for EV charging in this report's analysis) as Automated Emissions Reduction (AER).

Moreover, we are beginning to see a growing number of periods of surplus renewable energy going to waste. Charging an EV at these exact moments causes literally no incremental pollution at all, because it simply absorbs surplus renewable energy that otherwise would have gone to waste. This opens up the alluring possibility of EVs that could charge on 100% renewable energy, at least at times, even on grids that still have some fossil-fueled generation as part of their mix.

This report's analysis thus answers two key questions: a) How much cleaner can EVs be with correctly implemented emissions-optimized charging? And b) What would be the collective environmental impact of emissions-optimized charging given 2030 EV adoption forecasts and widespread adoption?

We analyzed the additional, incremental emissions reductions that could be achieved with emissions-optimized charging vs. baseline EV charging. We considered average and high mileage scenarios for two of the most common EV charging profiles (i.e., daytime workplace charging, overnight at-home charging). We examined four representative grids that cover a spectrum of fossil fuel and renewable energy generation mixes:

- California Independent System Operator (CAISO) northern California subregion,
- New York Independent System Operator (NYISO) NYC subregion,
- Southwest Power Pool (SPP), and
- Western Area Power Administration Rocky Mountain Region (WACM).

OUR RESULTS FOUND THAT:

Smarter charging reduces ANNUAL emissions up to an additional 18%. While all EVs—even those charged on dirty grids—are cleaner than the average internal combustion engine auto, emissions-optimized charging makes them even cleaner still (by up to 18% vs. baseline charging). Emissions-optimized smart charging reduces EVs' per-mile emissions intensity, equivalent to giving them up to a 10 MPGe "boost."

Smarter charging reduces DAILY emissions up to an additional 90%. Because some days experience more emissions variability than others, emissions-optimized EV charging can achieve significant additional emissions reductions vs. baseline on select days. In addition to helping maximize overall total annual emissions reductions, such daily opportunities can help address regional air quality concerns on alert days and aid renewable energy grid integration during times of excessive curtailment and surplus renewable generation.

Emissions reductions are possible everywhere. We found emissions-reduction opportunities in a variety of U.S. geographies, although the biggest opportunities are in "blended" grids (i.e., fossil and renewable generation) that exhibit large emissions-rate swings. Charging protocols well-matched to the local generation mix (e.g., overnight charging in wind-rich SPP, daytime charging in sun-rich CAISO) maximize emissions reductions.

Adopted at scale, emissions-optimized EV charging could yield very large aggregate, absolute emissions reductions. For example, deployed across California's target of 5 million zero-emissions vehicles (ZEV) by 2030, emissions-optimized EV charging could achieve the emissions-reduction equivalent of taking more than 180,000 gasoline-burning international combustion engine (ICE) cars off the road. These emissions savings are incremental above and beyond emissions savings of baseline EV charging vs. tailpipe emissions from internal combustion engine (ICE) autos. Similarly, with New York's target of 2 million EVs by 2030, smarter charging could yield incremental additional savings equivalent to taking nearly 48,000 ICE cars off the state's roadways.

Thoughtful rate design is critical to align EV charging incentives—and should complement emissions-optimized EV charging. As EV-specific and overall time-of-use (TOU) rates and demand charges become more prevalent nationwide, thoughtful rate design will be helpful to ensure that price signals align with emissions intensity. However, even when prices and emissions rates do align, the vast majority of all rate structures still lack the granularity necessary to take advantage of short-term swings in emissions, which can often account for the lion's share of possible emissions savings. Thus, automated software like emissions-optimized EV charging that also intelligently avoids high-cost rates (such as AER does) are ideal for tapping into this opportunity.

CONCLUSION

Three trends are rapidly converging:

1. Accelerating electric vehicle adoption in the United States,
2. The growth of smart, level 2 EV charging, and
3. Increasingly variable grid emissions rates thanks to renewable energy additions to traditionally fossil-fueled grids.

The timing is right to integrate time-based marginal emissions signals into EV charging protocols. Doing so can help make clean EVs even cleaner, help states and utilities achieve policy goals (e.g., battery energy storage, climate, emissions), respond to consumer motivations and demand for green lifestyle options, and aid further renewable energy grid integration.

FIGURE ES1

Emissions-optimized EV Charging Waterfall

Average Mileage Scenario - SPP Night

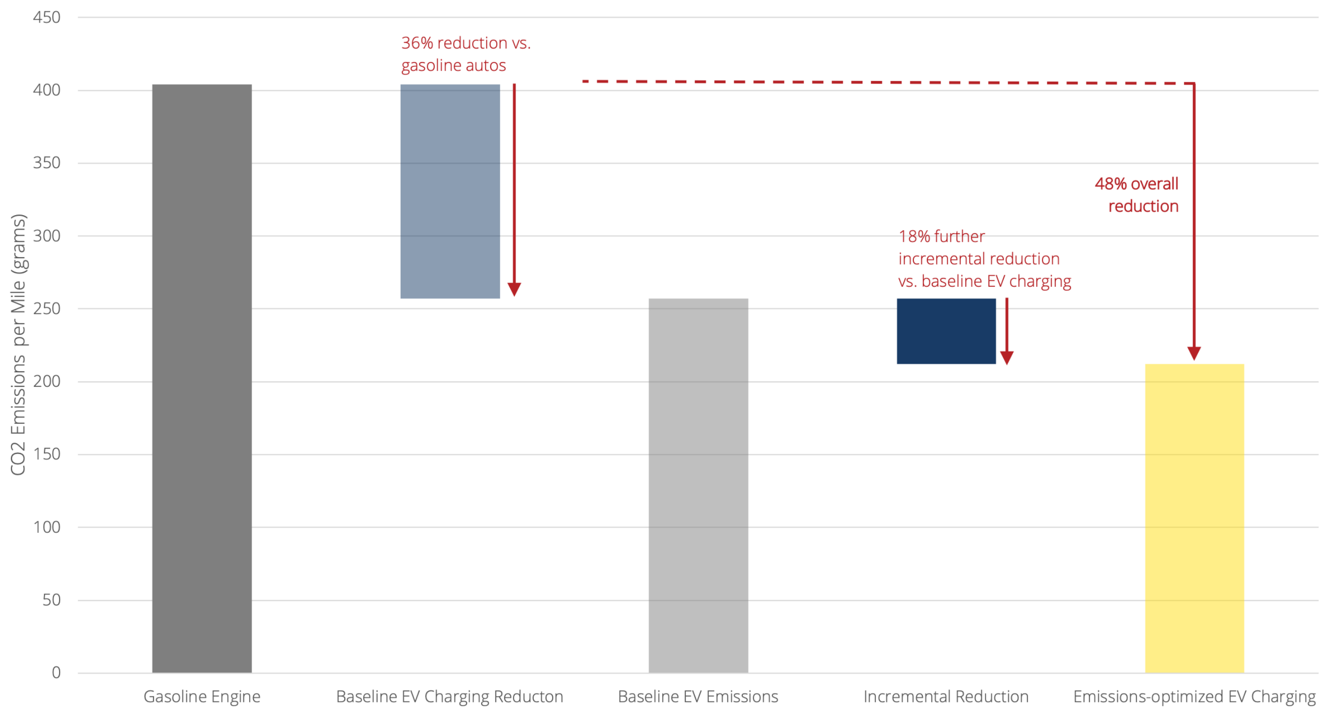


FIGURE ES2

Incremental Additional Emissions Reduction

Average Mileage Scenario - Emissions-optimized vs. Baseline EV Charging

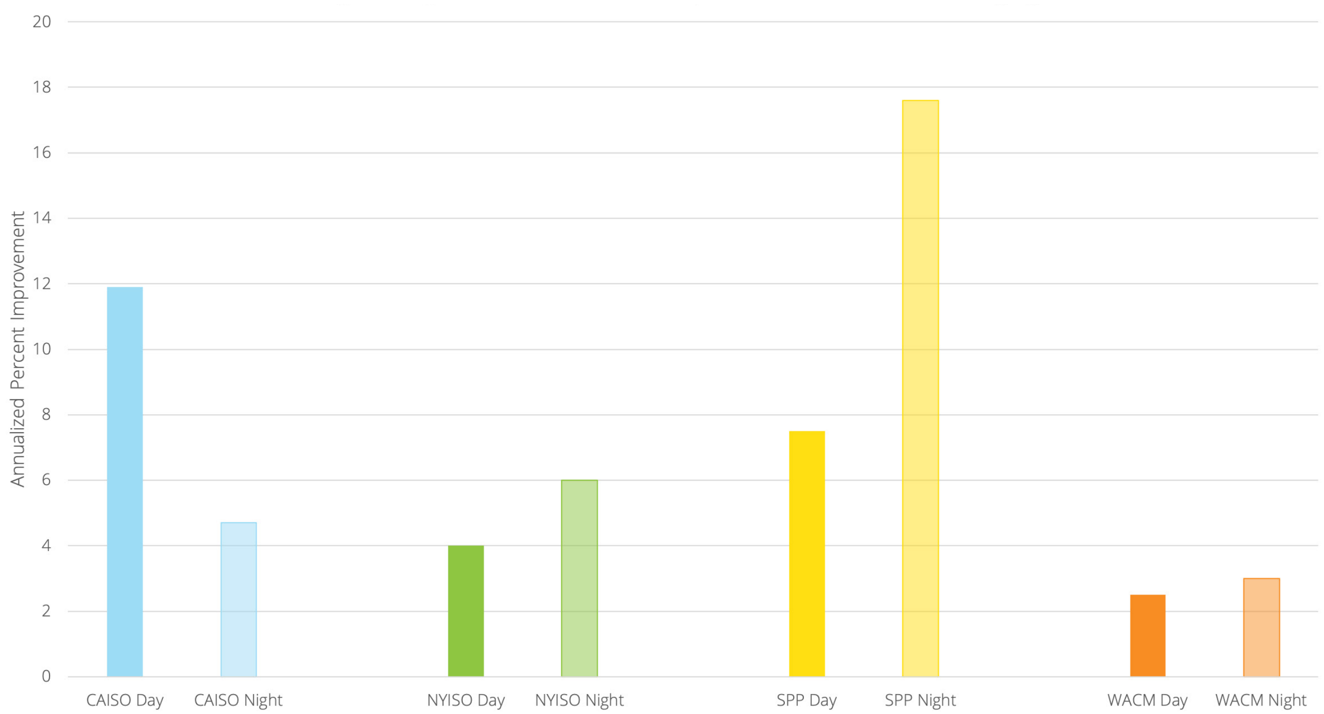
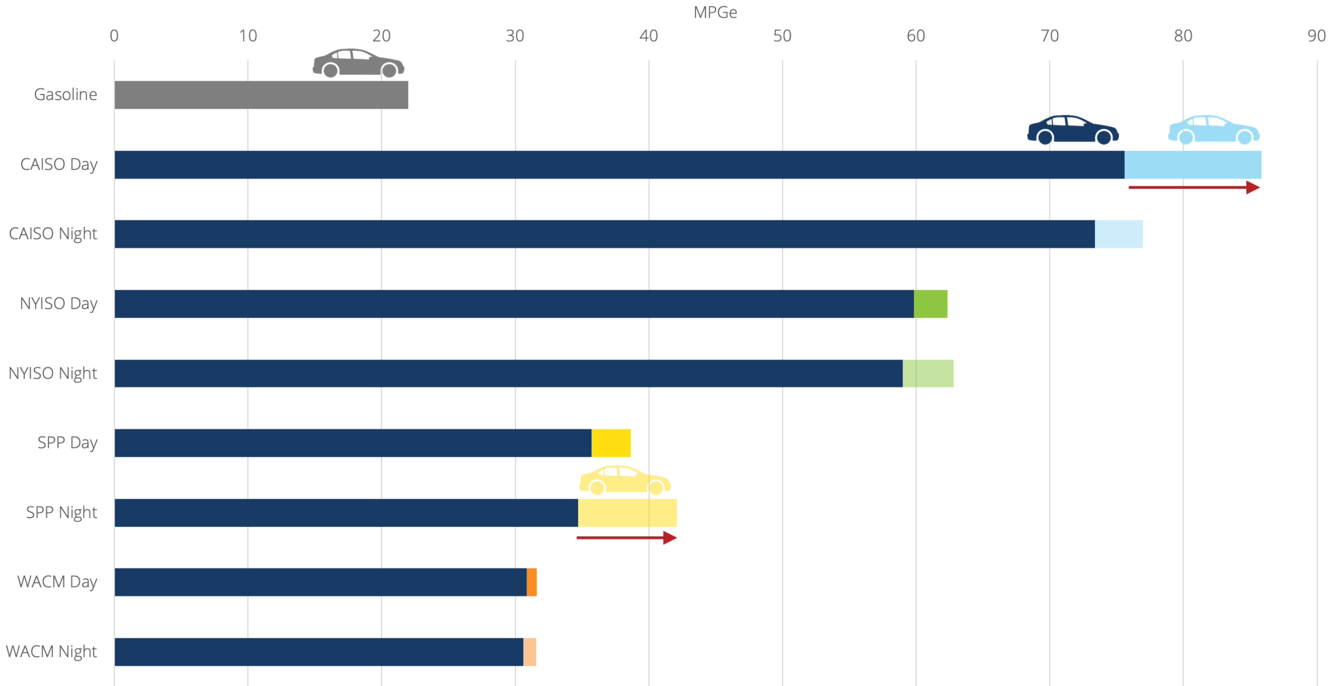


FIGURE ES3

Emissions-optimized MPGe 'Boost' to Baseline EV Charging

Average Mileage Scenario



Introduction

By the end of 2018, more than 1 million electric vehicles (EVs) were driving the roads and highways of the United States. Even by early 2017, U.S. drivers had already tallied more than 10 billion all-electric miles since 2010, thanks in large part to what were then known as the Big Three: Chevy Volt, Nissan LEAF, and Tesla Model S.[1] And by May 2019, the U.S. had nearly 63,000 level 2 and 3 public charging outlets, excluding residential installations.[2]

These numbers are poised to explode. Even since the Big Three helped the U.S. market surpass the 10-billion-mile mark in 2017, the recent addition of the popular Chevy Bolt, 2nd generation Nissan LEAF, and Tesla Model 3—not to mention many other planned EV rollouts from major automakers—is driving an overall acceleration of the market.

The Edison Electric Institute (EEI) and Institute for Electric Innovation (IEI) forecast 18.7 million EVs on U.S. roads by 2030.[3] In tandem, they project a need for 9.6 million additional charge ports over that time, primarily level 2 chargers spread across public, workplace, and at-home locations. Such a massive proliferation of level 2 EV charging infrastructure offers an incredible opportunity to integrate emissions-optimized EV charging at a massive scale, further decarbonizing already clean EVs.

Previous analyses have used ANNUALIZED AVERAGE emissions factors to determine total impact of EV charging.

According to numbers released in March 2019, the U.S. auto fleet reached a record average fuel economy of 24.9 miles per gallon (MPG) in 2017.[4] Time and again, experts have shown that even on the dirtiest power grids, EVs are still (much) cleaner than their internal combustion engine counterparts. For example, in the 2017 update to its *State of Charge* report, the Union of Concerned Scientists estimated that nationwide EVs had the grid-emissions equivalent of a 73 MPG gasoline-fueled auto.[5]

Analyses such as these typically use localized (e.g., state-level) average grid emissions factors to calculate EV-related emissions.[6] Average emissions factors essentially take total annual grid emissions vs. total annual kilowatt-hours of electricity generated to come up with a “tons of CO_2 per megawatt-hour” (tCO_2/MWh) number. Regions with more renewable energy and less fossil-fueled generation will have lower average emissions rates, and vice versa.

Using TIME-VARYING MARGINAL emissions factors is now possible and is a more-accurate approach that can better quantify the true emissions impact of EV charging while unlocking even deeper emissions reductions.

While a blended, annualized average can be useful and convenient, it omits and thus fails to harness important variability in emissions rates over time. Emissions variability should be viewed through three lenses:

1. **Location:** The local grid mix varies from one place to the next (e.g., California vs. New York).
2. **Time:** The emissions rate in a given place varies in real time as generators' contributions to the overall mix fluctuate (e.g., more solar and less natural gas during midday in California).
3. **Marginal response:** Every time an EV starts or stops a charging session, a power plant ramps up or down to handle the change in electricity demand. The emissions intensity of that change in generation—the *marginal* emissions rate—can vary greatly, depending on whether the currently ramping plant is an inefficient fossil-fueled peaker unit, a more-efficient but still relatively dirty baseload unit, or even a renewable energy unit such as surplus wind or solar that will otherwise waste zero-emissions energy if it is not used. Thus, for maximum emissions savings, EV charging must be synced to the marginal emissions rate. When optimizing many EVs, it is important to use the *marginal* emissions rates from all currently marginal units.

Annualized average emissions factors only capture the first variable. By contrast, time-varying marginal emissions factors capture all three, yielding both a more-accurate picture of EV charging-associated grid emissions *and* unlocking opportunities for even deeper emissions reductions. (That's why the Union of Concerned Scientists has called this a "game changer" for EV charging.)

Let's take a closer look at the interplay of these variables:

In practice, within any given region, emissions rates vary continuously over the hours of the day and night, as different generators—ranging from solar and wind to coal and natural gas—become the marginal generator. How the power grid and marginal generators respond to meet changes in demand is especially important. Thus, a location- and time-specific *marginal* emissions rate is critical for accurately assessing an EV's associated grid emissions . . . and leveraging the variability of that emissions rate to make EVs even cleaner.

How? Consider a hypothetical in which a driver purchases a new EV in a solar-energy-rich region of the country. Using average emissions factors—and generally noting that renewables contribute a significant portion of electricity to the overall generation mix—one might assume that such an EV would have "clean" charging, right? Not necessarily.

Consider this scenario: On Friday, May 3, 2019 at 1:30 PM, the CAISO was delivering 23,690 MW of power at a real-time emissions rate of 3,042 mTCO_2/hour. Nearly 50% of the total supply (12,086 MW) was from renewable sources. Using an approach of average emissions, one would say that the current emissions rate was 283 lbs CO_2/MWh.[8]

However, the marginal emissions rate for the same time was *much* higher, at 927 lbs CO_2/MWh. Despite the high penetration of midday solar, if an EV plugged in to charge at this time, the marginal emissions rate indicates that it is likely an inefficient gas generator would have responded by ramping up to meet the increased load, creating an emissions impact nearly three times the size of that calculated using average emissions.

By charging at this time, the EV could theoretically cause an *increase* in grid emissions. Reciprocally, if that EV plugged in to charge at a time when surplus solar energy was being curtailed, the EV battery could help the grid absorb zero-emissions surplus renewable energy and have no emissions associated with its charging (rather than an average emissions rate).

In this way, time-specific marginal emissions rates offer both a more-accurate assessment of EVs' true grid emissions impact *and* open the door to smarter charging that can make EVs even cleaner than they already are.

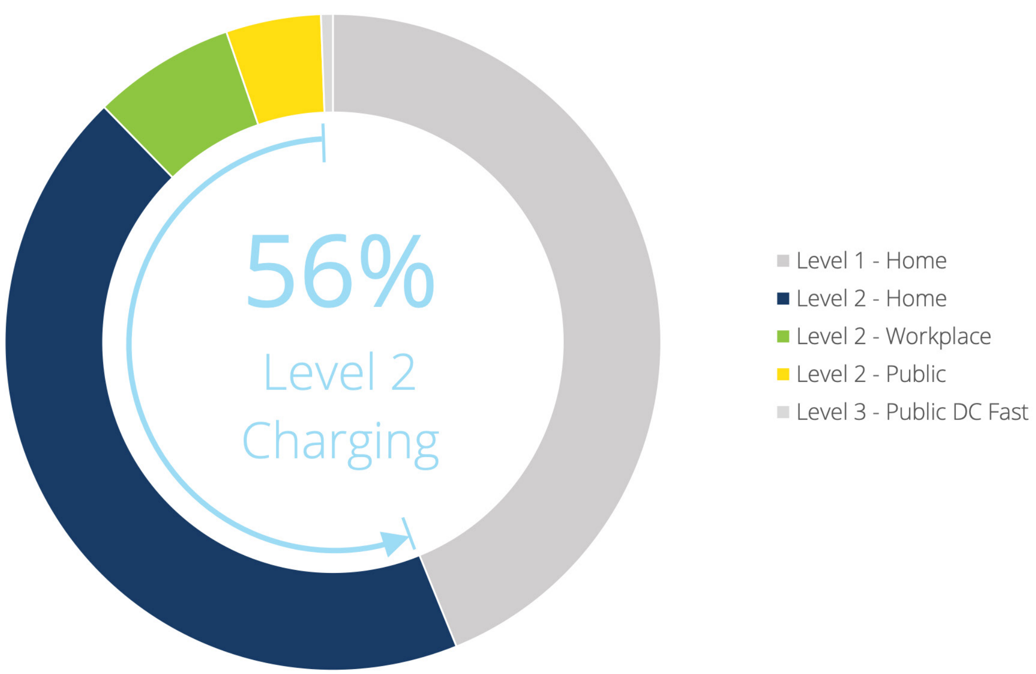
Emissions-optimized EV charging can work with any charging station configuration to reduce the impact of charging, but is especially suited to level 2 charging scenarios.

There are three major types of electric vehicle charging:

- **Level 1:** Also known as trickle charging, level 1 charging uses a standard 120-volt AC wall outlet to slowly recharge an EV battery (~4 miles per hour). Even for shorter-range EVs, the slow charge rate means that the full time window is required to replenish the battery, allowing little opportunity to modulate since they are "always on" until the driver next needs the vehicle.
- **Level 2:** Level 2 charging uses a 240-volt AC circuit to deliver a 6.6 kW charge that adds 10–20+ miles of range per hour. These are the most-popular and -numerous form of public EV charging, and are becoming increasingly popular for at-home charging as long-range EVs gain greater market share and require faster charging rates to replenish the battery overnight.
- **Level 3:** Delivering 150 kW or more of power, level 3 DC fast chargers push energy into the battery as quickly as possible to add range. They are popular along highway corridors where EV drivers need to replenish their battery as quick as possible before resuming their journey. However, because they call for as much energy as possible quickly, they offer little opportunity to modulate electricity demand within their tight charging time window.

Level 2 EV charging in particular represents a golden opportunity to reduce the emissions of charging. By 2030, more than 17 million electric vehicle charging stations will be needed to meet forecasted EV adoption. Nearly 56% (9.5 million) will be Level 2 charge points—home, workplace, and public—that open up opportunities for emissions reductions through flex charging (see Figure 1).

FIGURE 1
Forecasted U.S. Electric Vehicle Charging Infrastructure Needs by 2030



On the demand side: Level 2 chargers are forecasted to be the most-populous EV charging infrastructure in coming years. And in most overnight residential or daytime workplace scenarios, vehicles are plugged in for long periods of time (you can think of this as a "Charge Window"), and only need a fraction of that time for actual charging (a "Charge Duration"). A longer charge window combined with shorter charge duration leaves a lot of room for optimization; there's plenty of "wiggle room" to optimize the timing of battery demand while still filling the battery before the EV driver next needs the vehicle.

On the supply side: Meanwhile, as the clean energy revolution continues and historically fossil-fueled power grids add more and more renewable energy to their mix, emissions rates are becoming highly variable and continuously changing. The natural variability in their respective contributions to grid supply unlock compelling possibilities.

The intersection of demand-side flexible EV charging and grids with variable supply-side emissions rates can make clean EVs even cleaner, while providing valuable services to changing grids. Smart charging is proving to be a major asset to grid balancing, with companies like Enel X's eMotorWerks providing up to 30 MW of demand response capacity in the CAISO market.[9] By including emissions in the optimization equation, we show that EV-related grid emissions can be reduced up to 90%.

This analysis thus answers two key questions: a) How much cleaner can EVs be with emissions-optimized charging? And b) What would be the collective environmental impact of emissions-optimized charging given 2030 EV adoption forecasts and widespread adoption?

ABOUT AUTOMATED EMISSIONS REDUCTION (AER)

Emissions-optimized EV charging and other use cases require having data on power grid conditions at different times and places. Five years ago, such data by and large did not exist. That's why environmental researchers at UC Berkeley founded WattTime, an environmental nonprofit, to develop the first technology to make AER possible, provide the first working implementations, and raise awareness of the power of such data to jump-start a new form of environmental activism.

Today, WattTime's technology—including our version of AER—provides a data-driven empirical emissions model for every electricity balancing region in the U.S. (and many abroad). Leveraging past, present, and predictive grid data—combined with sophisticated algorithms and machine learning—we provide a much-needed emissions signal to devices that can optimize their electricity use. The core model is based on methods used in published literature,[10] with many proprietary improvements.

AER software knows how clean or dirty electricity is *right now*… and sends a corresponding signal via the cloud to any enrolled smart devices—including EVs. The software lets these devices know when using electricity would—and just as importantly, would *not*—reduce emissions, automatically.

This report focuses on AER emissions-reduction benefits for EV charging. However, AER can be used on *any* smart device that controls a flexible load (e.g., behind-the-meter batteries, smart thermostats, grid-interactive electric water heaters).

Such flexible loads can be significant, and are surprisingly ubiquitous. For example, many people think refrigerators are always consuming power. But in fact, refrigerator compressors only have to consume power in small bursts of cooling that happen every 30 minutes or so. AER can help find the cleanest 5-minute period within that 30-minute window, and reduce emissions without affecting the end use case.

For more information on WattTime's version of AER, please visit: **https://www.watttime.org/aer/**

Scenarios, Assumptions, and Methodology

This analysis considers two common electric vehicle charging scenarios across four different U.S. regional grids (i.e., balancing authorities) that both a) represent the spectrum of grid mixes found across the country and b) serve as useful proxies for electric grids at different stages of the clean energy transition.

EV CHARGING PROFILES

We examined two common EV charging scenarios:

- **Daytime workplace charging:** We assume an 8-hour charging window (9:00 am to 5:00 pm) for employees who drive their EV to work and charge during the workday with employer-provided level 2 charging.
- **Overnight at-home charging:** We assume a 12-hour charging window (7:00 pm to 7:00 am) for EV drivers who charge their vehicle overnight upon returning home from their daily activities.

For both scenarios, we compared two charging protocols:

- **Baseline charging protocol:** For this "dumb" charging protocol, we assume the EV starts charging when it is plugged in at the beginning of the charge window and continues charging uninterrupted until the EV battery is fully recharged.
- **Emissions-optimized charging protocol:** For this "smart" charging protocol, we assume that charging is optimized based on an emissions signal such as WattTime's, assuming perfect information. This optimization works by syncing the EV's charging with times of cleaner energy and pausing charging during moments of dirtier energy (while still concluding the charge window with a full EV battery).

Additional EV charging specifications included:

- **Daily miles:** We examine both an average driver profile (30 miles per day) and a high-mileage driver profile (60 miles per day).
- **Electric powertrain efficiency:** We assume a vehicle efficiency of 0.30 kilowatt-hours per mile (kWh/mi). (This is the average of three popular EVs that represent the range of electric powertrain efficiency common on the market today: Chevy Bolt = 0.28, Nissan Leaf = 0.30, Tesla Model S = 0.33.)
- **Battery recharge needs:** Based on the assumed electric powertrain efficiency, we assume 9 kWh and 18 kWh, respectively, for the EV battery to fully recharge within the charge window for the average and high-mileage scenarios.
- **Charging speed:** For both workplace and at-home charging, we assume a 6.6 kW AC level 2 charger (EVSE).
- **Utility rate structure:** For this analysis, we optimize EV charging purely to maximize associated emissions reductions, blind to the additional influence of utility rate structures. However, with time-of-use (TOU) rates, residential demand charges, and EV-specific TOU rates becoming more popular, later in this paper we do include discussion of how utility price signals and an emissions signal might interact.

Baseline "dumb" charging begins at the time the EV is plugged in and continues uninterrupted until the battery is full, blind to the emissions intensity of the grid over that time. Emissions-optimized smart charging waits for times of cleaner electricity, pausing EV charging at moments when the grid is dirtier. This analysis assumes the emissions-optimized smart charging is part of a full AER software package that also still fully recharges the battery by the end of the allotted charge window, while doing so with lower associated emissions (see Figure 2).

The higher mileage scenario requires more of the charge window to fully recharge the battery, but still allows room for emissions optimization (see Figure 3).

FIGURE 2

Baseline vs. Emissions-optimized Charging Behavior

Average Mileage Scenario

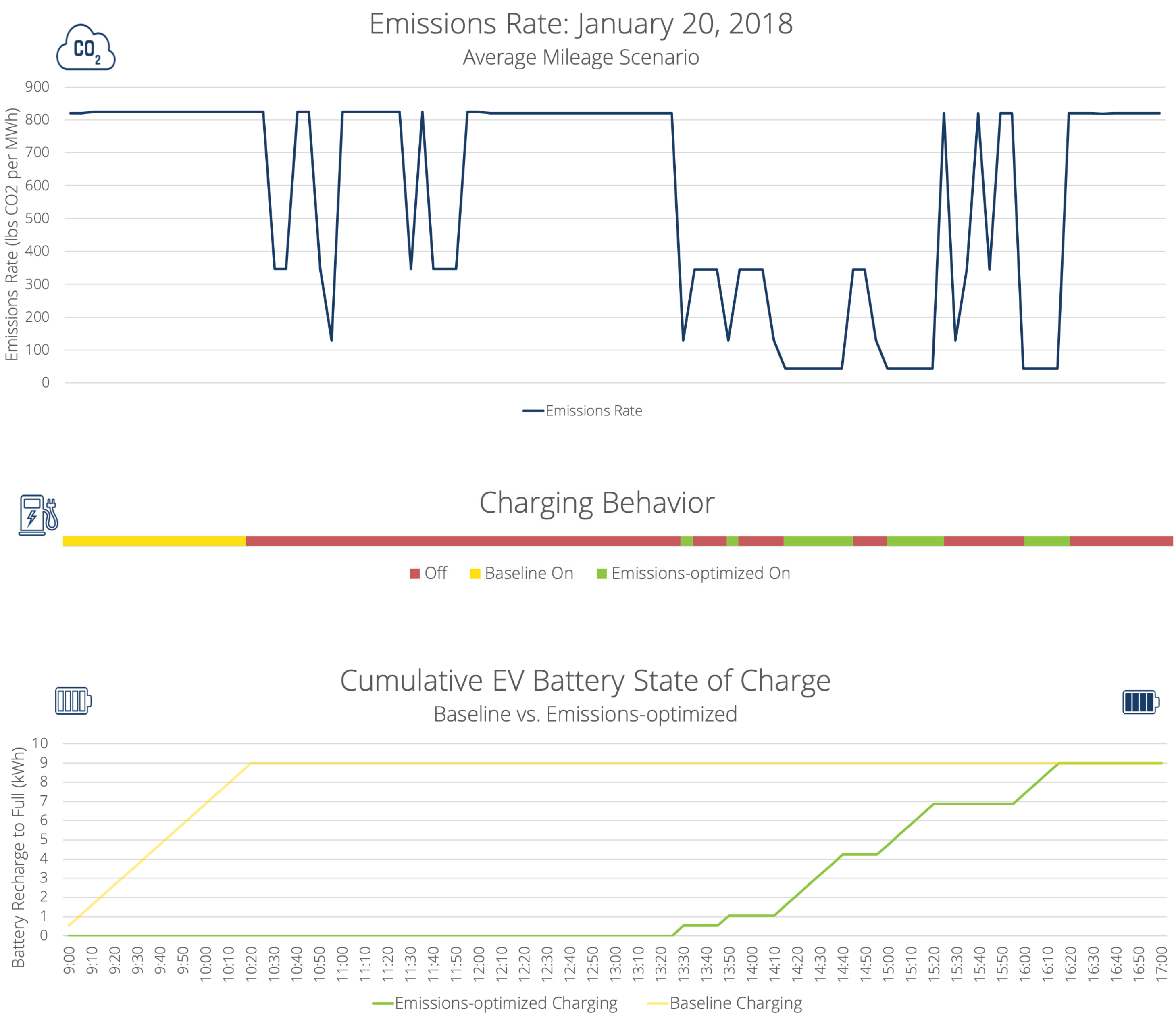
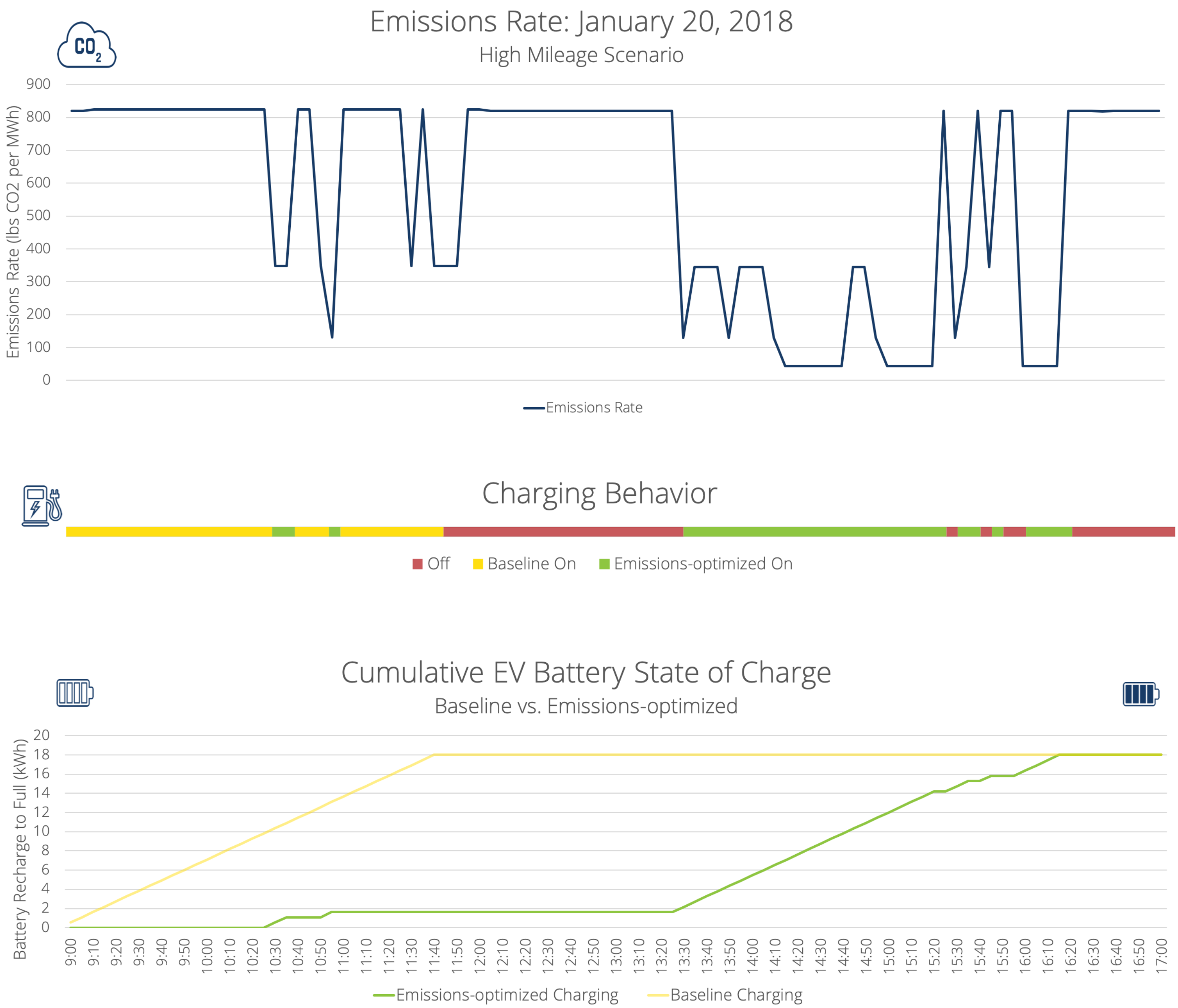


FIGURE 3

Baseline vs. Emissions-optimized Charging Behavior

High Mileage Scenario



GRID REGIONS

We examined EV charging in four U.S. regional grids. The four representative grid balancing areas we analyzed covered a spectrum of a coal-heavy grid, a natural gas-heavy grid, a mix of renewables and coal, and a mix of renewables and natural gas (see Figure 4).

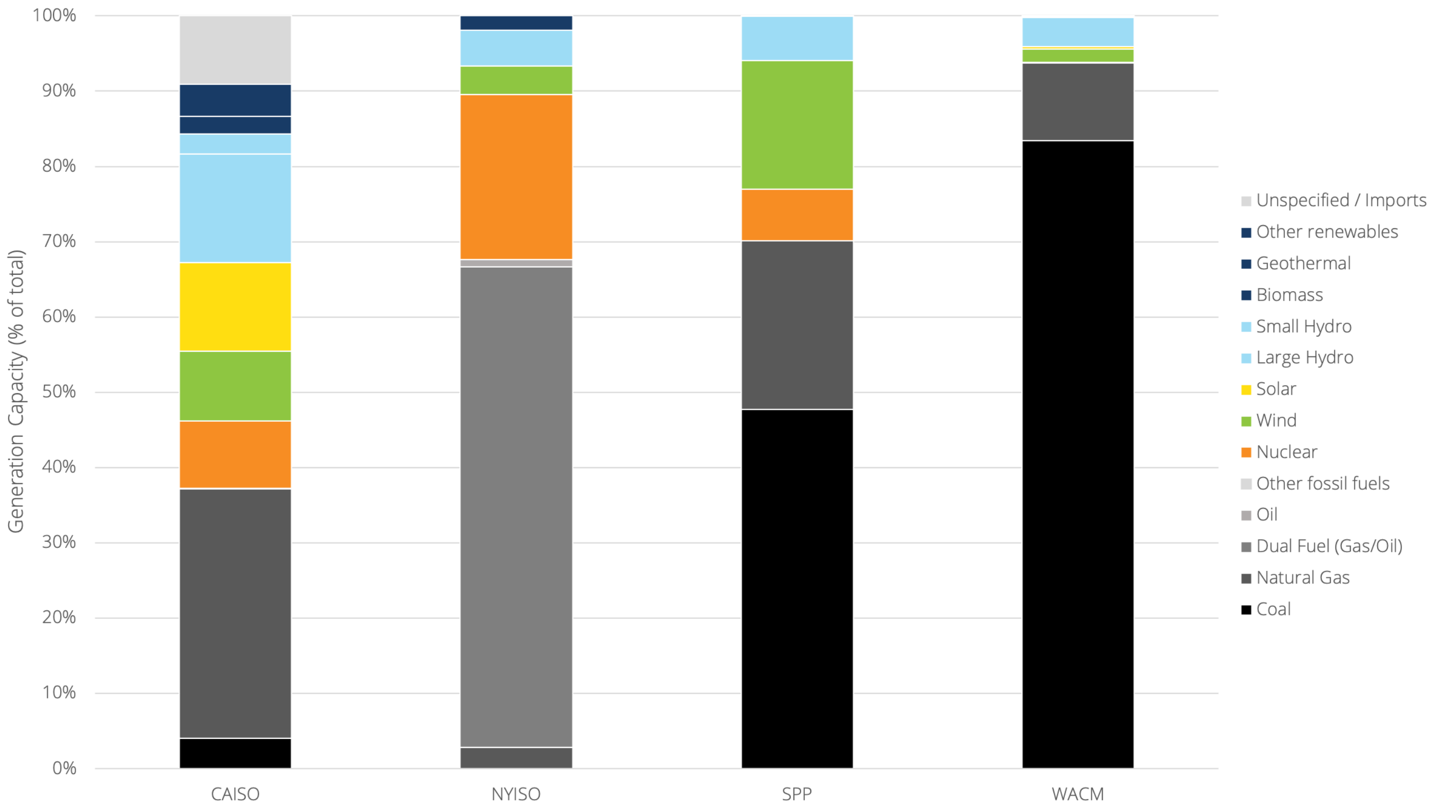
- **A coal-heavy grid**
  (WAPA Rocky Mountain Region: WACM)
  This balancing authority covers portions of Colorado and Wyoming, where the grid's generation mix is coal-heavy *and* coal tends to be the marginal generator much of the time. The grid's emissions may oscillate slightly depending on the balance of more-efficient vs. less-efficient coal, but the overall daily profile is relatively flat and the dirtiest of the four scenarios.

- **A natural gas-centric grid**
  (NYISO: New York City Zone)
  This balancing authority covers the New York City area in downstate New York, where natural gas dominates the grid's generation mix (despite solar and wind making modest inroads to the state's overall mix, thanks in part to natural gas replacing the state's declining coal-fired generating capacity).[11] With the transition to natural gas, the emissions intensity is cleaner than coal but still dirty relative to renewables-rich grids. It also remains relatively flat with only modest variability over time.

- **A grid with renewables and coal**
  (SPP: Reserve Zone 5)
  This balancing authority covers North and South Dakota, which has a high penetration of installed renewable capacity (especially wind) *and* dirty coal. It represents a grid in transition. This is a grid of extremes, where the emissions rate can swing wildly from very clean (due to wind's contributions) to very dirty (due to coal's influence). These large and highly variable changes in emissions rates theoretically unlock the most compelling opportunities to optimize EV-associated emissions from charge timing.

- **A grid with renewables and natural gas**
  (CAISO_NP15)
  This balancing authority covers Northern California, which has a high penetration of installed renewable capacity *and* some natural gas. It represents a more-mature grid in transition; one that has evolved further down the clean energy pathway. Overall, this is the cleanest of the four grid mixes. However, because of the diversity of the mix (zero-carbon and fossil-fueled generation), such grids also offer compelling opportunities to leverage the variability in their emissions rates to make EV charging even cleaner—thanks to the changing relative contributions of each resource to the overall mix, whether surplus renewables are being curtailed, and which generators are on the margin (renewables vs. natural gas).

FIGURE 4
Grid Generation Mix by Region



Results

Emissions-optimized smart charging makes ALL EV charging cleaner, but has the most opportunity on grids with highly variable emissions rates.

Emissions-optimized smart charging makes *all* EV charging cleaner. However, the magnitude of the incremental additional emissions reductions depends heavily on the variation of the regional grid mix.

The greatest emissions reductions can be achieved on grids with large swings in marginal emissions rates (i.e., very clean to very dirty, and vice versa), such as coal-and-wind-rich SPP and gas-and-renewables-rich CAISO (see Figure 5).[12]

Even on grids with relatively stable emissions rates (e.g., coal- and gas-heavy grids), AER can tap into smaller emissions-rate variations between more- and less-efficient fossil-burning power plants to seize smaller but still significant emissions-reduction opportunities (see Figure 6).

FIGURE 5

Emissions Rates for Four Representative U.S. Grid Balancing Areas

April 7, 2019

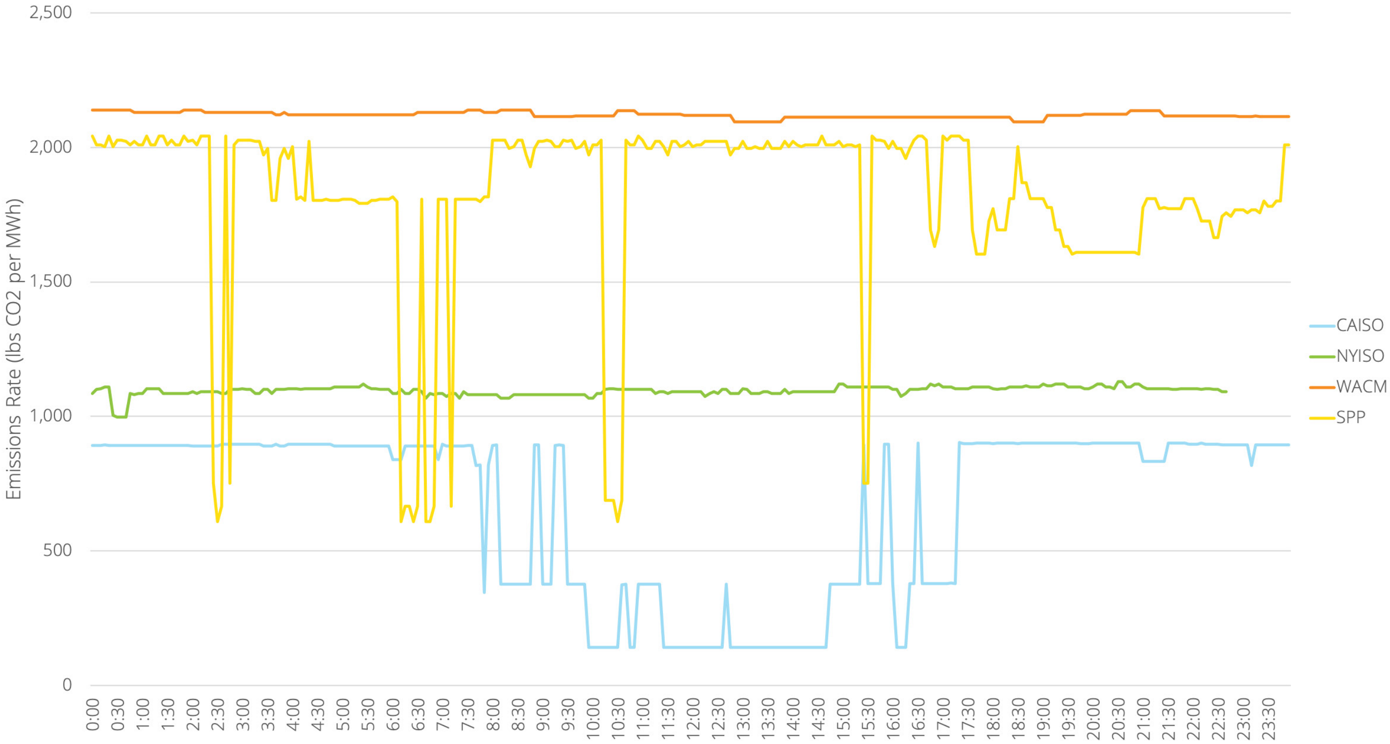
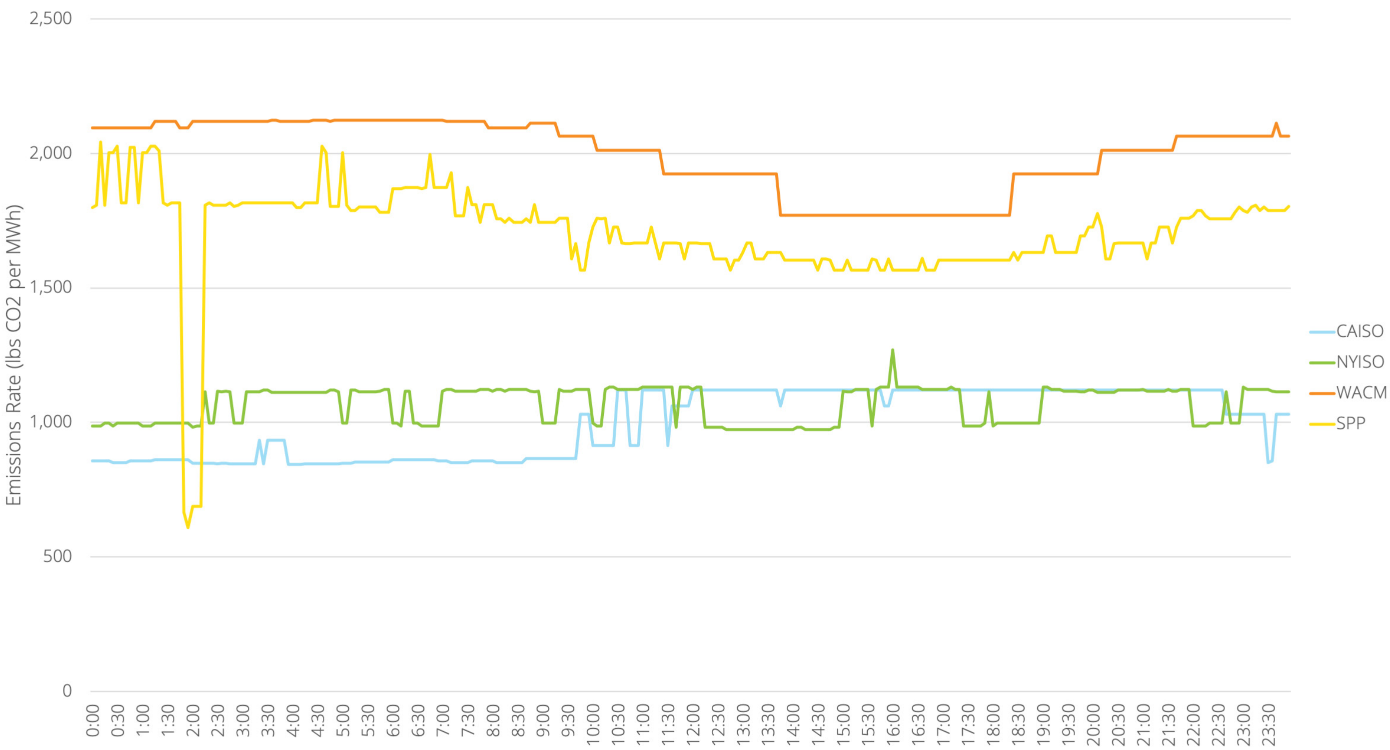


FIGURE 6

Emissions Rates for Four Representative U.S. Grid Balancing Areas

August 7, 2018



Emissions-optimized EV charging can reduce ANNUAL associated grid emissions by up to 18% vs. baseline.

Emissions-optimized EV charging can reduce associated grid emissions by up to an additional 18% vs. baseline charging (see Figures 7 and 8). As expected, the greatest incremental emissions reductions are possible on grids with the most variability and the largest emissions-rate swings between times of dirty vs. clean energy (i.e., CAISO and SPP). Further, the best emissions-reduction opportunities become possible when the charging profile is well-matched to the local grid mix, such as daytime charging in California when solar and wind are at risk of curtailment and nighttime charging in the Southwest Power Pool where overnight wind is most abundant.

Not surprisingly, emissions-optimized EV charging reduces the per-mile emissions intensity of driving and charging an EV (see Figures 9 and 10). The deepest reductions in per-mile emissions intensity come in regions with dirty-but-variable generation, such as SPP's mix of coal and wind. Meaningful reductions are also achievable in regions with cleaner-but-variable generation, such as CAISO's mix of renewables and natural gas.

From another perspective, emissions-optimized EV charging is like giving an instant "MPGe boost" to EVs, without ever having to touch the electric powertrain's efficiency (see Figures 11 and 12). For example, an EV charged during the day in CAISO with an emissions-optimized protocol can supercharge its MPGe from ~75 to more than 85+. Similarly, an EV charged overnight in SPP with an emissions-optimized protocol can increase its MPGe from <35 to 40+.

In essence, emissions-optimized EV charging partially de-couples powertrain efficiency (Wh/mile) from associated emissions (CO_2/mile) in MPGe calculations. The U.S. EPA notes that 1 gallon of gasoline is equivalent to 33.7 kWh of electricity consumption and that 1 gallon of gasoline contains 19.7 pounds of CO_2.

But while any given internal combustion automobile will have its MPG efficiency and tailpipe carbon emissions essentially locked in a fixed ratio, an EV's powertrain has fixed efficiency but can have variable grid emissions rates, based on how clean or dirty the grid is (which is why EV analyses such as those of the Union of Concerned Scientists note different MPGe values for EVs in different regions of the country, thanks to the influence of the local grid mix).

Yet emissions-optimized EV charging delivers the same total amount of kWh (and therefore, the same added range) as baseline EV charging. By that measure, they achieve equal MPGe on a range-added basis. For example, under either charging scenario, an EV with a powertrain efficiency of 0.30 kWh per mile (30 kWh per 100 miles) will start with a full battery and a 112 MPGe. Yet the two modes of charging can do so for potentially vastly different associated emissions. The emissions-optimized EV will be able to drive the same number of miles for fewer total associated emissions, just like driving a car with a better MPG.

FIGURE 7

Incremental Additional Emissions Reduction (Annual)

Average Mileage Scenario - Emissions-optimized vs. Baseline EV Charging

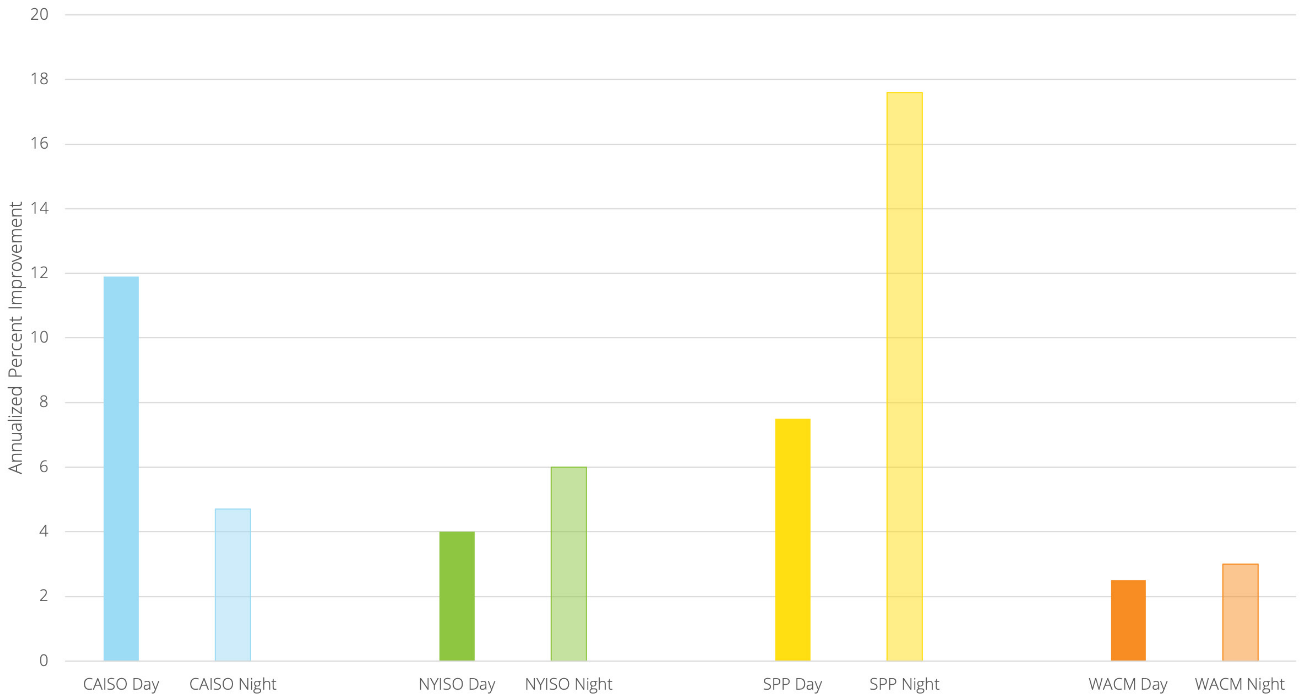


FIGURE 8

Incremental Additional Emissions Reduction (Annual)

High Mileage Scenario - Emissions-optimized vs. Baseline EV Charging

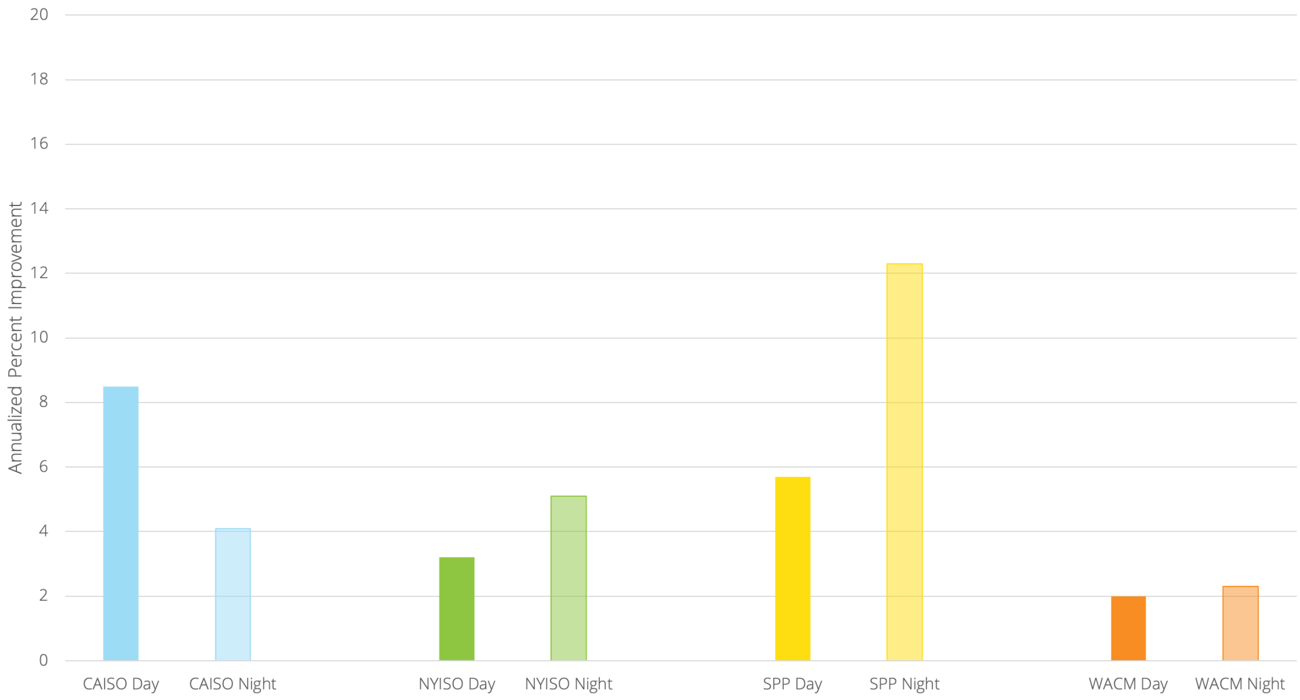


FIGURE 9

CO_2 Emissions per Mile

Average Mileage Scenario

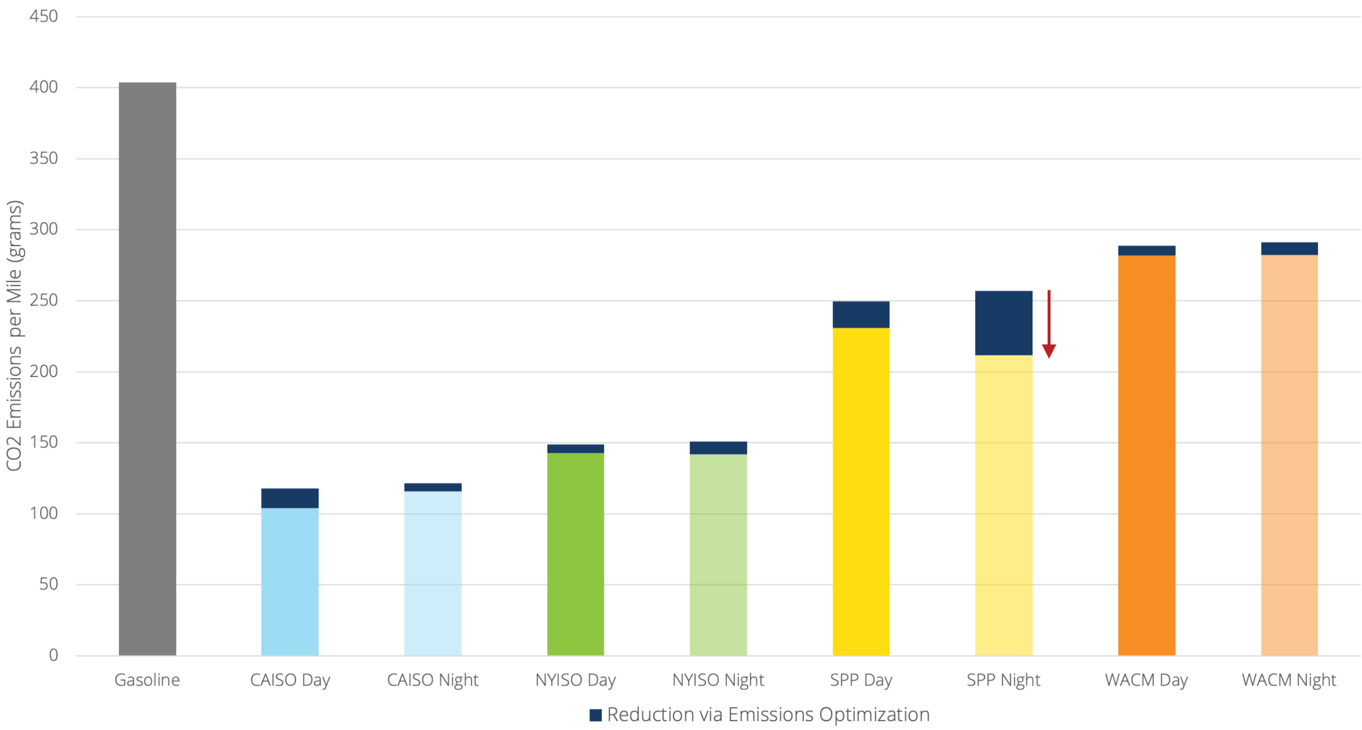


FIGURE 10

CO_2 Emissions per Mile

High Mileage Scenario

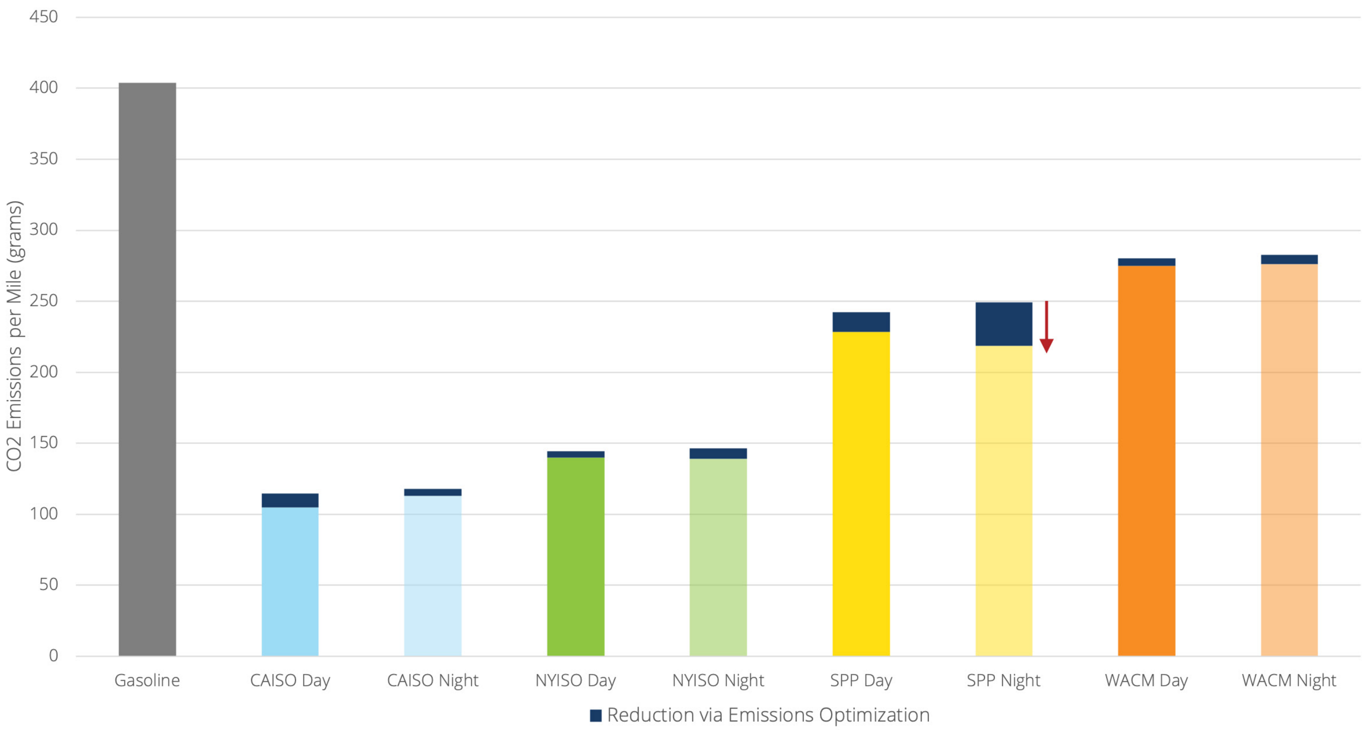


FIGURE 11

Emissions-optimized MPGe 'Boost' to Baseline EV Charging

Average Mileage Scenario

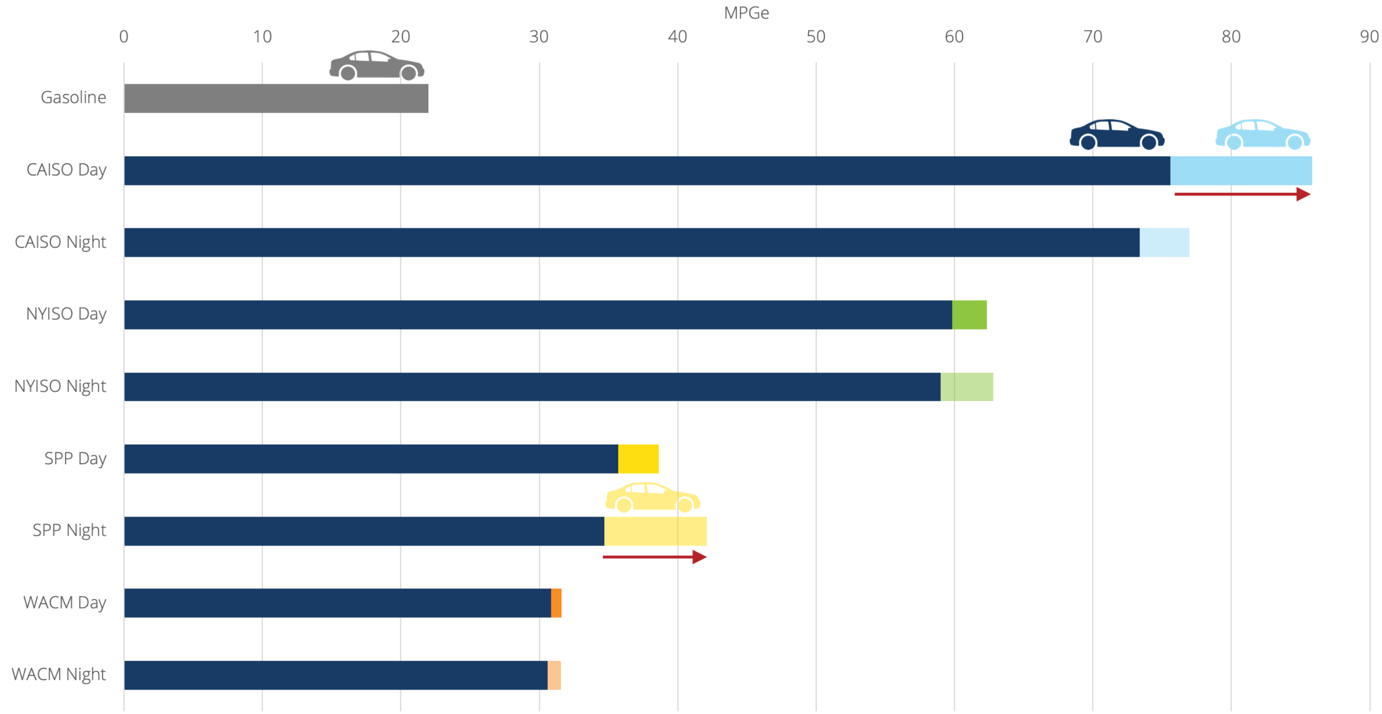
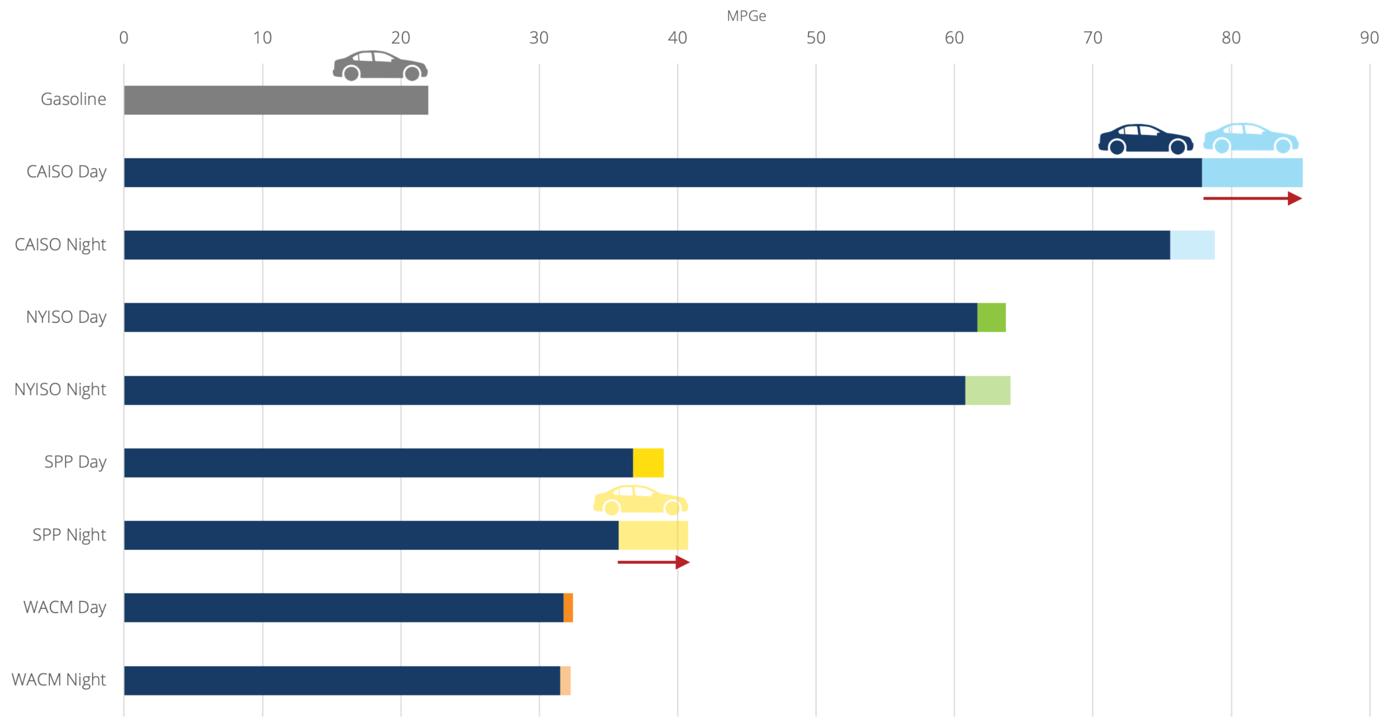


FIGURE 12

Emissions-optimized MPGe 'Boost' to Baseline EV Charging

High Mileage Scenario



Emissions-optimized EV charging can reduce DAILY associated grid emissions by more than 90% vs. baseline on select days.

Because some days experience more emissions variability than others, emissions-optimized EV charging can achieve additional emissions reductions exceeding an impressive 90% vs. baseline on select days (see Figures 13 and 14). In addition to helping maximize overall total annual emissions reductions, such profound daily opportunities suggest important possibilities as well, such as addressing regional air quality concerns on alert days and aiding renewable energy grid integration during times of excessive curtailment / surplus renewable generation.

High-mileage drivers see a slightly reduced opportunity for additional, incremental emissions reductions (on both a daily and annual basis), because more of their charging time window is required to recharge the vehicle battery. However, as discussed later, high-mileage drivers still offer compelling aggregate emissions-reductions opportunities, since their slightly lower per-mile emissions reductions are more than compensated for by their higher total miles.

FIGURE 13

Incremental Additional Emissions Reduction (Daily)

Average Mileage Scenario - Emissions-optimized vs. Baseline EV Charging

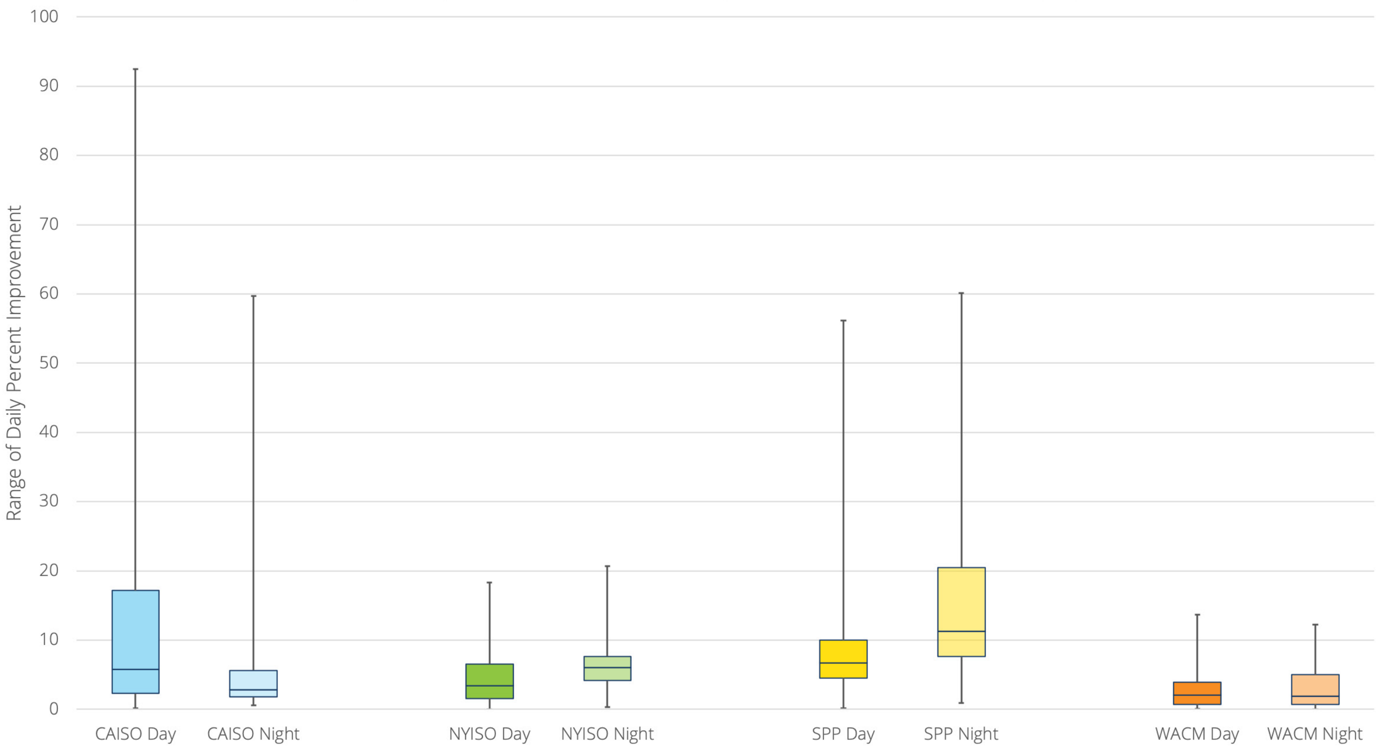
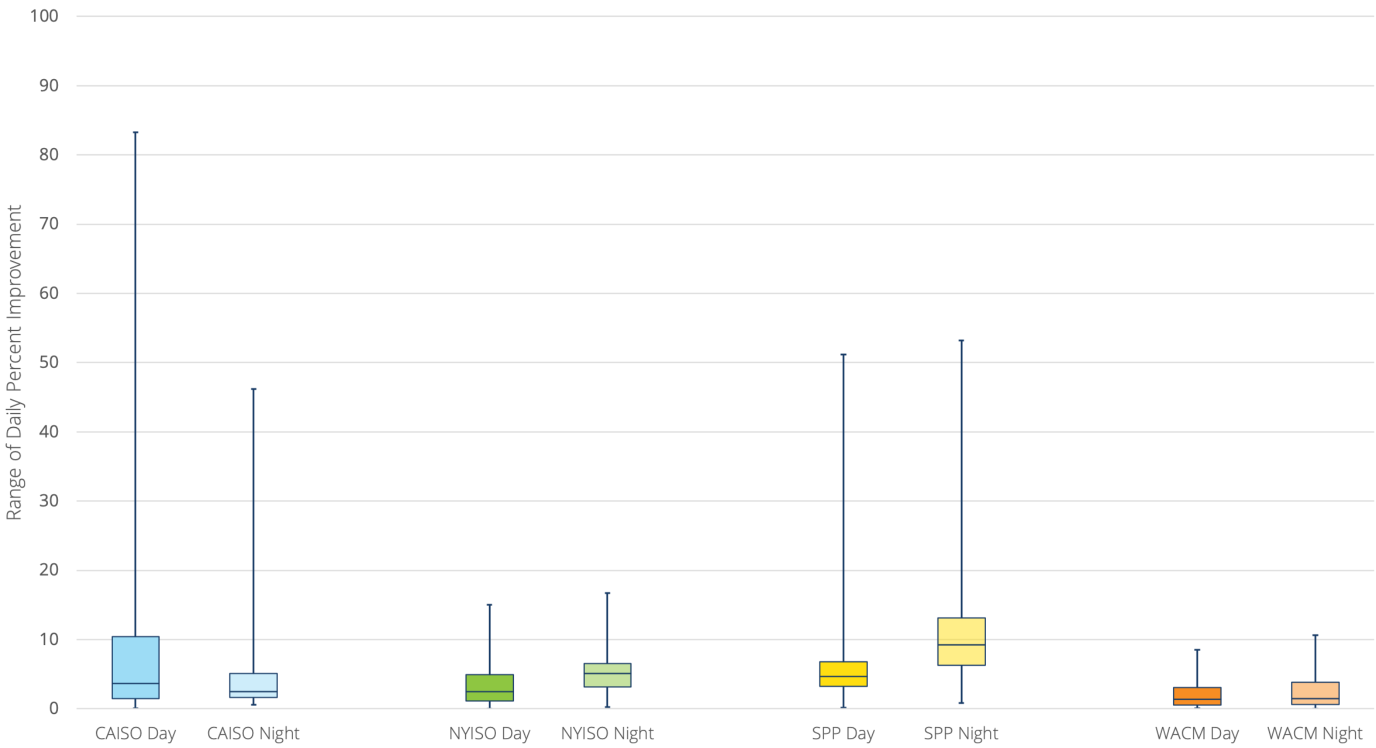


FIGURE 14

Incremental Additional Emissions Reduction (Daily)

High Mileage Scenario - Emissions-optimized vs. Baseline EV Charging



Emissions-optimized EV charging will become increasingly effective—and increasingly important—as grids change, including for flexibility and renewable energy grid integration.

The four grids chosen for this analysis represent a grid at different stages of energy transition and renewable energy integration.

CAISO is the furthest along in this transition, and is beginning to see increasing amounts of renewable energy curtailment. Renewable energy curtailment in CAISO territory occurs about 15% of the time. EVs can help pull that number back toward zero.[13]

One of the main strategies for reducing renewable energy curtailment is introducing increased flexibility into the system, from both the demand and supply side.[14] Electric vehicles—especially those using level 2 charging infrastructure—represent a large and nimble source of demand-side flexibility. In fact, flexible EV charging is listed as one of the CAISO's eight solutions to renewable curtailment.[15]

Moreover, the potential to reduce emissions using emissions-optimized charging increases as renewable energy penetration increases and grids' emissions rates become increasingly variable. In variable grids like CAISO and SPP, there are days where emissions can be reduced by 60–90%. Overall, these same grids also present the greatest opportunity for annual overall emissions reductions (see Figures 15 and 16). We should expect more grids across the country and around the world to exhibit emissions variability and emissions-reduction opportunities as they add more renewables to legacy fossil-fueled systems—until, of course, grids reach near-100% renewable energy and no longer exhibit dirty periods when coal or natural gas power plants are responding to demand.

Incorporating emissions-based optimization before and during the renewable energy transition will enable variable renewable energy sources to be integrated cheaper and quicker.

FIGURE 15

Emissions-optimized EV Charging Waterfall

Average Mileage Scenario - SPP Night

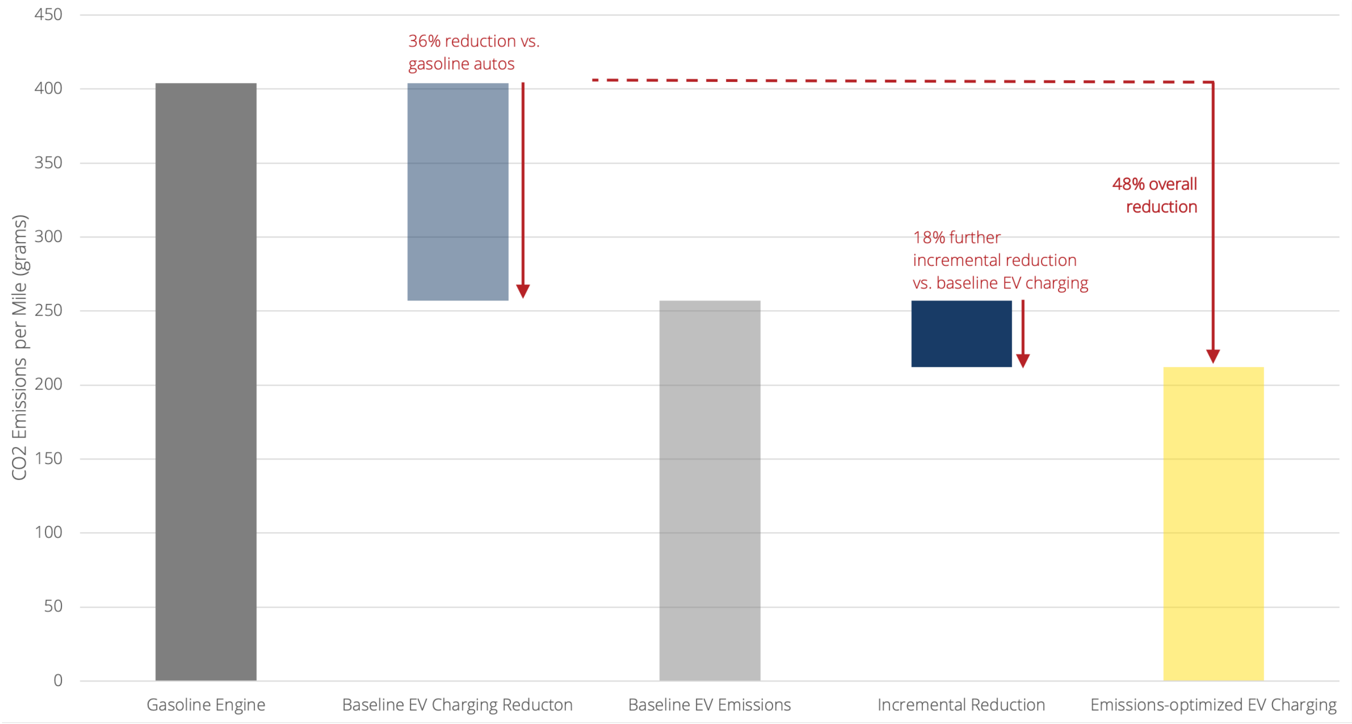
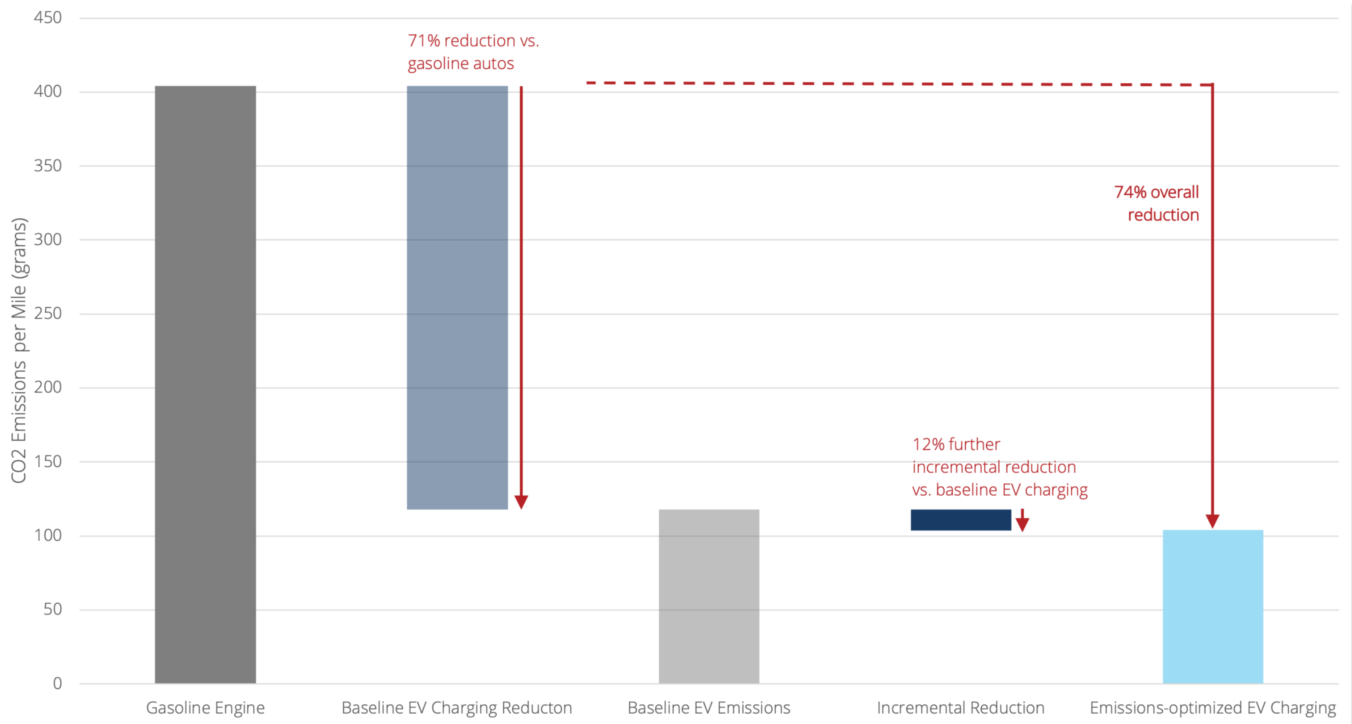


FIGURE 16

Emissions-optimized EV Charging Waterfall

Average Mileage Scenario - CAISO Day



Adopted at scale, emissions-optimized EV charging could yield very large aggregate, absolute emissions reductions given EV adoption forecasts.

If adopted at scale, emissions-optimized EV charging could yield very large aggregate emissions reductions, given certain states' aggressive EV adoption targets and forecasts (see Figures 17 and 18). These emissions savings are incremental *above* and *beyond* emissions savings of baseline EV charging vs. tailpipe emissions from internal combustion engine (ICE) autos.[16]

For example, California has a statewide zero-emissions vehicle (ZEV) goal of 5 million on the state's roads by 2030.[17] Assuming that the bulk of ZEVs will comprise battery electric vehicles (BEVs) and daytime EV charging well-matched to California's grid profile, annually the incremental additional emissions savings would be the equivalent of taking more than 180,000 ICE cars off the road under the average mileage scenario.

Similarly, New York has a statewide electric vehicle target of 2 million by 2030.[18] With emissions-optimized charging deployed at scale and with nighttime charging well-matched to New York's grid profile, annually the incremental additional savings would be the equivalent of taking nearly 48,000 ICE cars off the state's roadways under the average mileage scenario.

FIGURE 17

Aggregate Annual Incremental Emissions Savings

Average and High Mileage Scenarios - CA & NY 2030 EV Targets

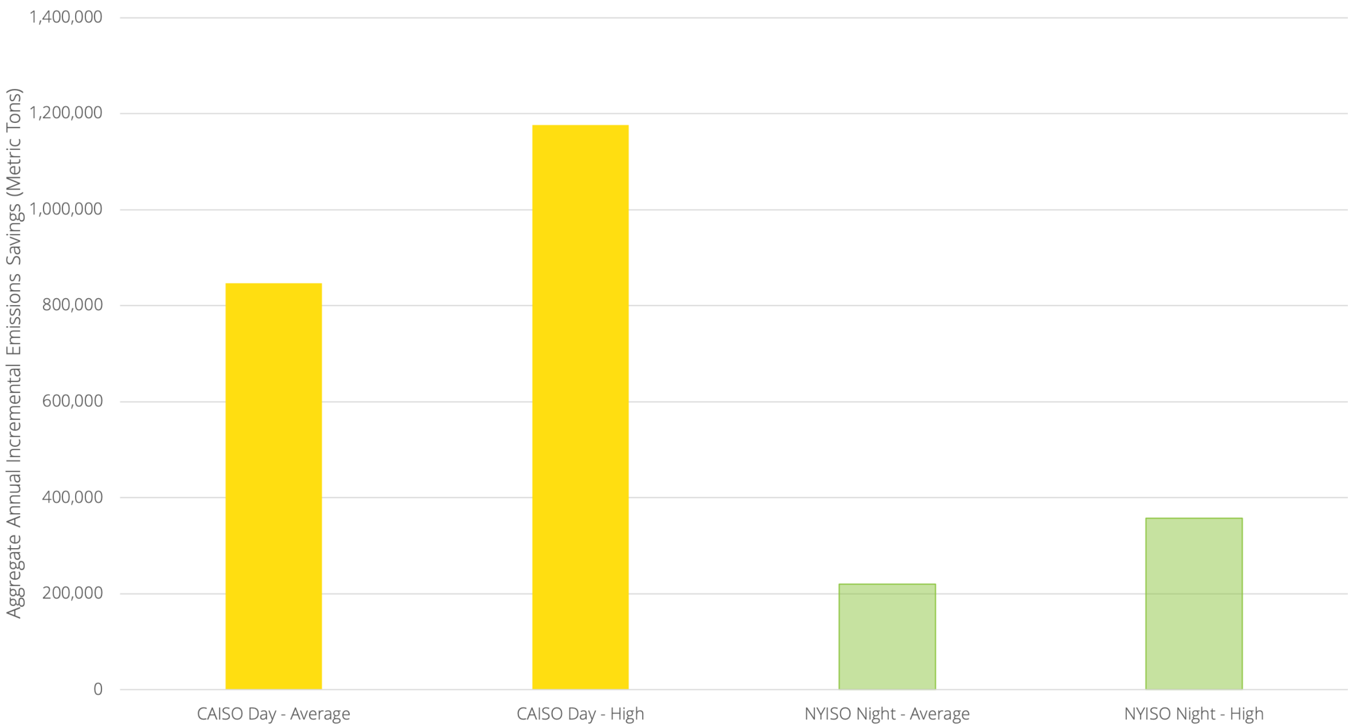
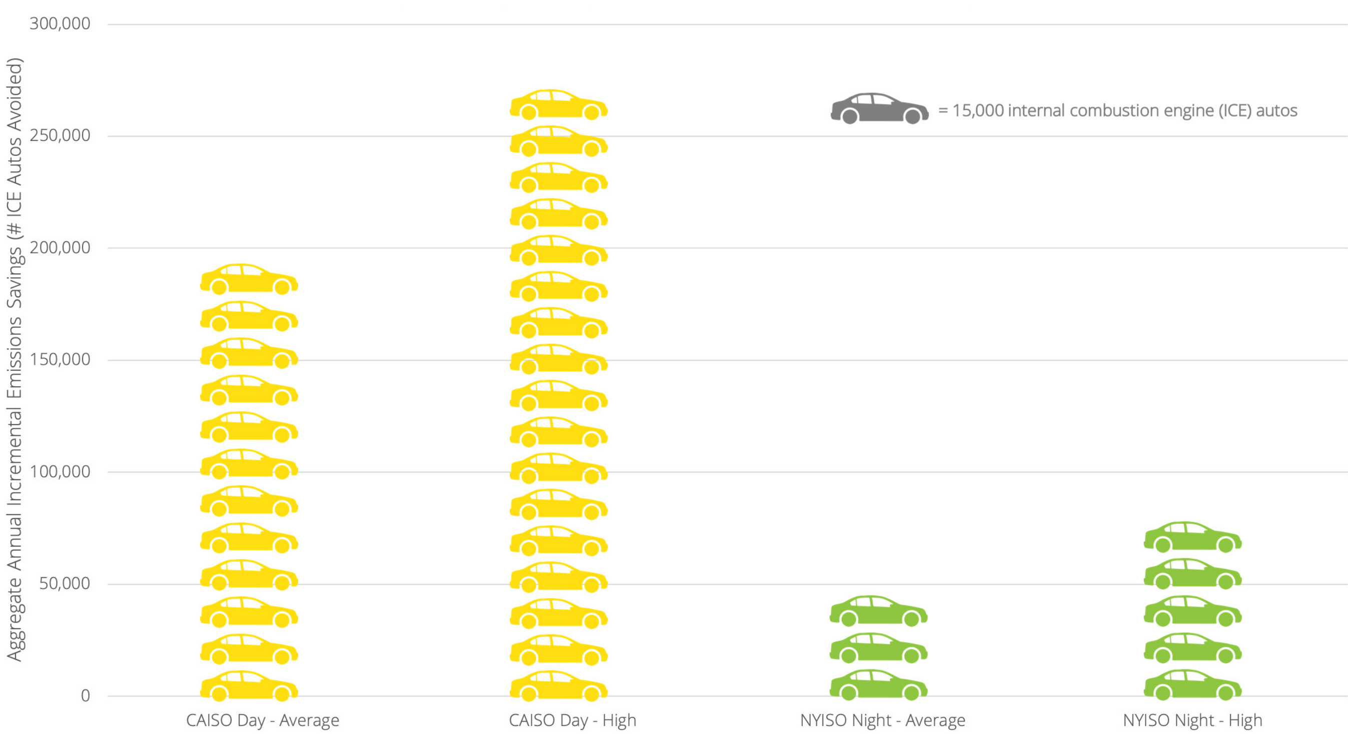


FIGURE 18

Aggregate Annual Incremental Emissions Savings

Average and High Mileage Scenarios - CA & NY 2030 EV Targets



Further Discussion

As more grids adopt more renewables, emissions rate variability will grow. Meanwhile, accelerating electric vehicle adoption will add significant amounts of new, often-flexible load to the grid. This presents a huge opportunity for emissions-optimized EV charging, but must be done thoughtfully to ensure that technologies, policies, programs, and utility rate structures align to meet the needs of the grid, the environment, and consumers.

Potential (mis)alignment of emissions rates and utility TOU rate structures

Utilities, recognizing their role in the electric vehicle revolution, are moving fast on creating charging programs and time-of-use (TOU) rates that help their customers reduce charging costs, incentivizing electric vehicle adoption (see Figure 19).[19]

However, it is not a foregone conclusion that peak TOU pricing also aligns with peak emissions rates, creating potential misalignment between the two (see Figure 20). Even when peak TOU pricing does generally align with emissions rates, TOU blocks usually lack the necessary granularity to take advantage of briefer swings in emissions rates to enable even deeper emissions reductions (see Figure 21).

Thus getting TOU rate design and emissions-optimized charging protocols "right" from the outset is valuable, especially for IOUs, whose extensive regulatory frameworks often limit fast iteration.

Emissions-based smart charging gives EV drivers what they want while delivering against battery energy storage policy goals

Smart charging is currently also a smart business move. Two-thirds of EVSE manufacturers are offering smart charging capabilities, and the number of smart charging software programs available has tripled in the past two years.[20] Emissions-based smart charging gives EV drivers more of what they want, since emissions, climate impact, and concern for the environment are an important motivator behind EV purchase decisions.[21]

For now, these companies are building their optimization strategies to focus on cost— both behind and in front of the meter. And while cost can *sometimes* be a good proxy for emissions, cost-based optimization does not always result in reduced emissions. A 2007 Yale-UNC joint study found that in many grids, real-time pricing actually *increased* emissions when not paired with an emissions signal.[22] Follow-on studies such as the 2017 evaluation by Itron of the California Public Utilities Commission's Self Generation Incentive Program (SGIP) continue to find that price-arbitrage optimization schemes often increase grid emissions associated with battery energy storage charge / discharge protocols.[23] This finding provides a good warning signal: relying on price-optimization alone may not have the intended emissions effects.

FIGURE 19

CAISO Emissions vs. EV Time-of-Use Rate

August 25, 2018

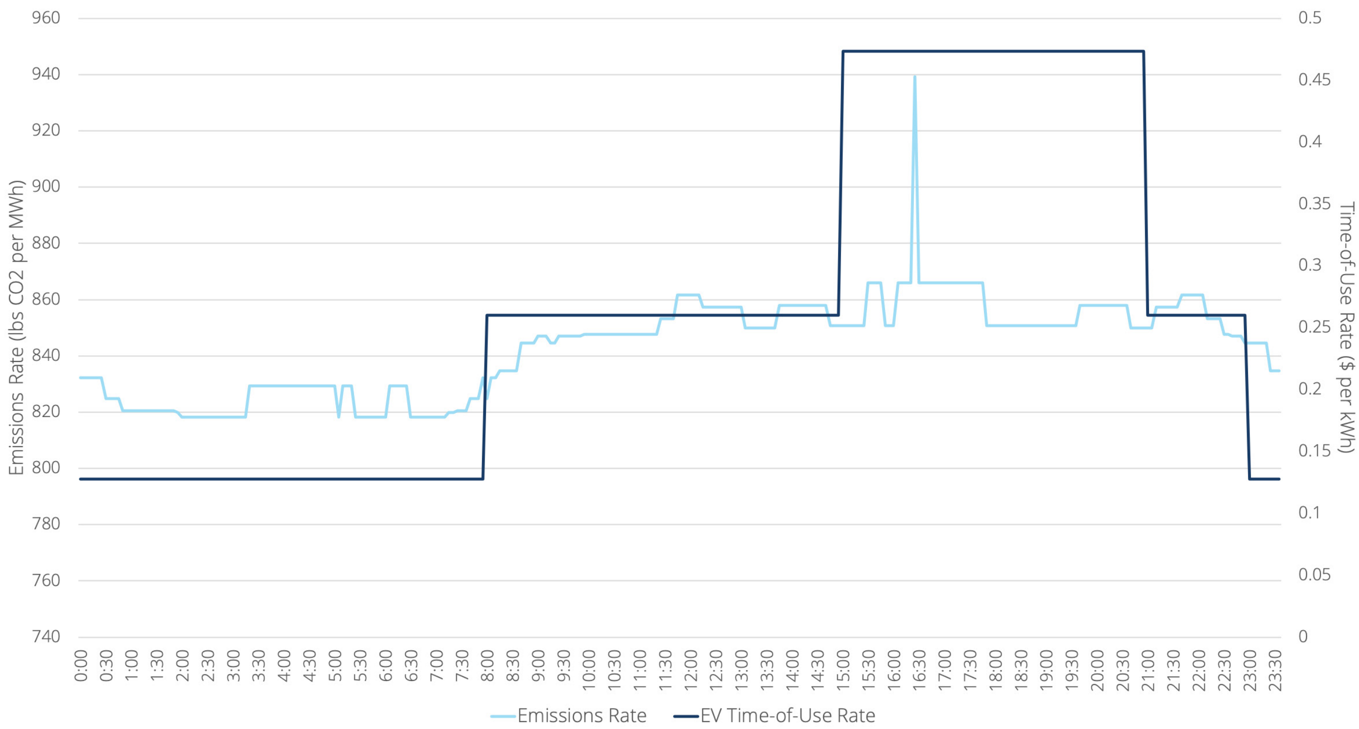


FIGURE 20

SPP Emissions vs. EV Time-of-Use Rate

August 25, 2018

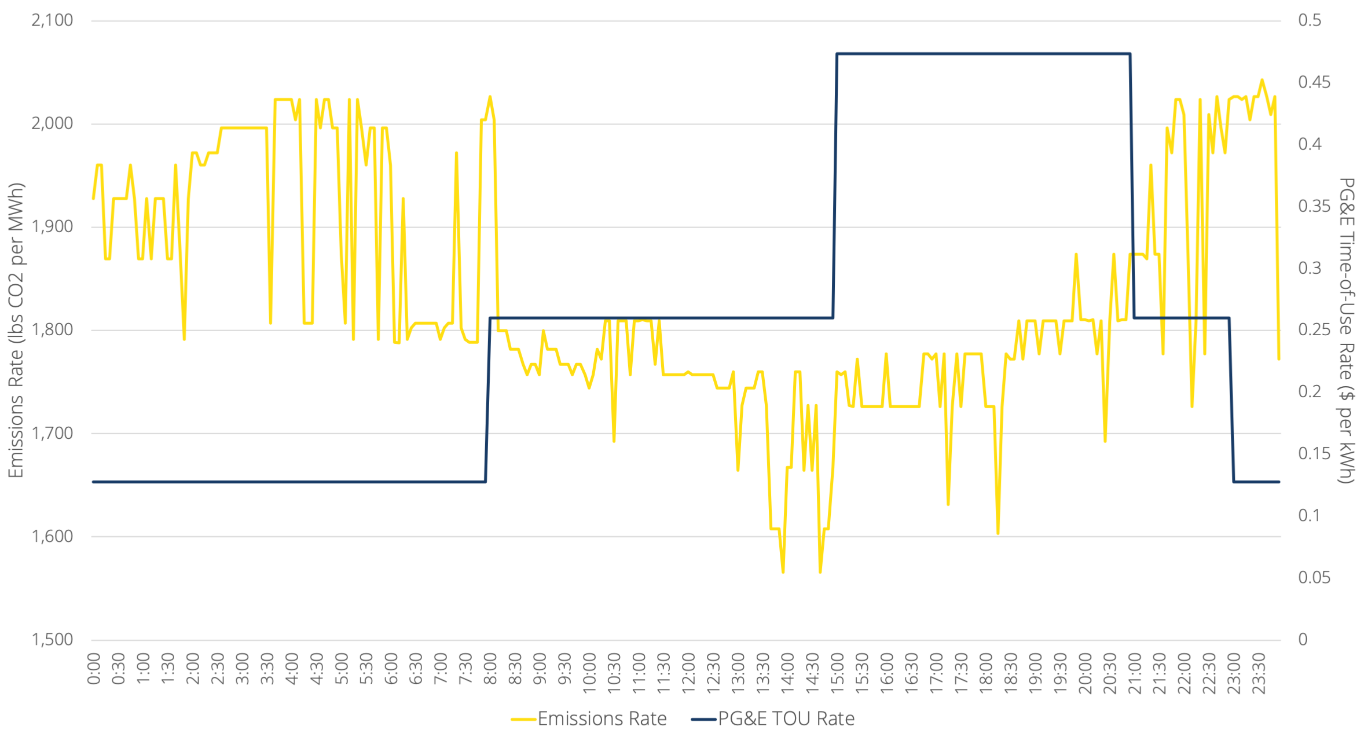


FIGURE 21

NYISO Emissions vs. ConEd Time-of-Use Rate

August 25, 2018

Conclusion

Three trends are rapidly converging: a) accelerating electric vehicle adoption in the United States, b) the growth of smart, level 2 EV charging, and c) increasingly variable grid emissions rates thanks to renewable energy additions to traditionally fossil-fueled grids. The timing is right to integrate time-based emissions signals into EV charging protocols. Doing so can help make clean EVs even cleaner, help states and utilities achieve policy goals (e.g., grid balancing, climate, emissions), meet consumer demand, and aid further renewable energy grid integration.

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