RESEARCH REPORT

Institute of
Transportation
Studies

UNIVERSITY
OF
CALIFORNIA

Green Charging of Electric Vehicles Under a Net-Zero Emissions Policy Transition in California

Alan Jenn, Ph.D., Assistant Director, Institute of Transportation Studies, University of California, Davis
Austin Brown, Ph.D., Director, Policy Institute for Energy, Environment, and the Economy, University of California, Davis

August 2021

ITS UCDAVIS
INSTITUTE OF TRANSPORTATION STUDIES

Report No.: UC-ITS-2020-08 | DOI: 10.7922/G28P5XTH

Technical Report Documentation Page

1. Report No. UC-ITS-2020-08	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Green Charging of Electric Vehicles Under a Net-Zero Emissions Policy Transition in California		**5. Report Date** August 2021
		6. Performing Organization Code ITS-Davis
7. Author(s) Alan Jenn, Ph.D., https://orcid.org/0000-0003-4232-0697 Austin Brown, Ph.D., https://orcid.org/0000-0002-5454-1465		**8. Performing Organization Report No.** UCD-ITS-RR-21-41
9. Performing Organization Name and Address Institute of Transportation Studies, Davis 1605 Tilia Street Davis, Ca 95616		**10. Work Unit No.** N/A
		11. Contract or Grant No. UC-ITS-2020-08
12. Sponsoring Agency Name and Address The University of California Institute of Transportation Studies www.ucits.org		**13. Type of Report and Period Covered** Final Report (October 2019 – September 2020)
		14. Sponsoring Agency Code UC ITS
15. Supplementary Notes DOI:10.7922/G28P5XTH		

16. Abstract

California has many aggressive climate policies, primarily aimed at individual sectors. This study explores untapped policy opportunities for interactions between sectors, specifically between the transportation and the electricity grid. As electric vehicles become more prevalent, their impact on the electricity grid is directly related to the aggregate patterns of vehicle charging. Even without vehicle-to-grid services, shifting of charging patterns can be a potentially important resource to alleviate issues such as renewable intermittency. This study compares, through modeling, projected emissions reductions from managed vs. unmanaged charging. The lion's share of emissions reduction in the light-duty transportation sector in California will come from electrification, with a cumulative 1 billion tons of CO_2 reduction through 2045. Decarbonization of the current grid leads to an additional savings of 125 million tons of CO_2 over the same time-period. Potential state policies to exploit synergies between transportation electrification and grid decarbonization could reduce cumulative emissions by another 10 million tons of CO_2. These policies include strategic deployment of charging infrastructure, pricing mechanisms, standardizing grid interaction protocols, and supporting grid infrastructure requirements.

17. Key Words Decarbonization, electric grids, electric vehicles, electric vehicle charging, emissions, carbon dioxide, policy analysis		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 49	**21. Price** N/A

Form Dot F 1700.7 (8-72) Reproduction of completed page authorized

About the UC Institute of Transportation Studies

The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

Acknowledgments

This study was made possible through funding received by the University of California Institute of Transportation Studies from the State of California through the Public Transportation Account and the Road Repair and Accountability Act of 2017 (Senate Bill 1). The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project.

Disclaimer

Green Charging of Electric Vehicles Under a Net-Zero Emissions Policy Transition in California

Alan Jenn, Ph.D., Assistant Director, Institute of Transportation Studies, University of California, Davis
Austin Brown, Ph.D., Director, Policy Institute for Energy, Environment, and the Economy, University of California, Davis

August 2021

ITS UCDAVIS INSTITUTE OF TRANSPORTATION STUDIES

Report No.: UC-ITS-2020-08 | DOI: 10.7922/G28P5XTH

Table of Contents

Table of Contents

List of Figures

Glossary

CALN	Northern California
EV	electric vehicle
GHG	greenhouse gas
GOOD	Grid Optimized Operation Dispatch
IID	Imperial Irrigation District
LADW	Los Angeles Department of Water and Power
LCFS	Low Carbon Fuel Standards
RPS	Renewable Portfolio Standard
SCE	Southern California Edison
SDGE	San Diego Gas and Electric
SF	San Francisco
TOU	time-of-use
WECC/WEC	Western Electricity Coordinating Council
ZEV	zero emission vehicle

Executive Summary

Executive Summary

California is one of the most progressive governments combatting climate change with aggressive policies. Under the framework of Assembly Bill 32, the Global Warming Solutions Act of 2006, which requires an 80% reduction of greenhouse gases below 1990 levels by 2050, the state has passed multiple pieces of legislation and regulation to reduce carbon emissions across all end-use sectors. Decarbonization of the electricity sector is largely driven by Renewable Portfolio Standards, which enacts requirements to generate electricity from renewable sources of energy, such as wind and solar. Under current legislation, California is required to produce 60% of their electricity from renewables by 2030 and all electricity must be carbon free by 2045. This transition is crucial not only to clean the current generation of electricity but also to fully decarbonize other sectors that are seeking to electrify, such as residential and transportation. In the transportation sector, California is heavily pushing for electrification of its vehicles through regulations targeted towards automakers and consumers. For automakers, examples of regulations include the Zero Emissions Vehicle rule and the Advanced Clean Trucks Act; for consumer, they include the Clean Vehicles Rebate Program and credits awarded through the Low Carbon Fuel Standard.

While the state has a plethora of activities targeting specific sectors, our study explores untapped policy opportunities for interactions between sectors, specifically between the transportation and electricity grid. As electric vehicles (EVs) become increasingly prevalent, their impact on the electricity grid is directly related to the aggregate patterns of vehicle charging. Even without vehicle-to-grid services (where electric vehicles provide electricity back to the grid), shifting of charging patterns can be a potentially important resource to alleviate issues such as renewable intermittency. This study employs forecasts of both future EV adoption rates and changes to the capacity mix of the electricity grid in California, to determine how the emissions related to charging EVs change over time. We employ vehicle adoption results from a recent study conducted by the University of California for the California Environmental Protection Agency (Brown et al., 2021) as the baseline forecasts for our modeling—adoption of zero emission vehicles reaches 100% of the fleet mix by 2045. The electricity grid operation for the Western Electricity Coordinating Council region is simulated using the Grid Operation Optimized Dispatch (GOOD) model, an electricity grid model developed at the University of California, Davis. Our model includes changes in capacity mix over time to meet the state regulatory requirements as well as high-resolution location-based hourly solar and wind profiles.

The results of this study indicate a potential emissions benefit to managed charging. However, based on the magnitude of emissions savings, our findings also highlight and re-emphasize the critical role of transport electrification in California's decarbonization strategy. The lion's share of emissions reduction in the light-duty transportation sector in California comes from electrification, with a cumulative 1 billion tons of CO_2 reduction through 2045. Decarbonization of the current grid leads to an additional savings of 125 million tons of CO_2 over the same time-period. As the state moves towards these objectives through existing (and potential future) policies, we point to additional policy mechanisms including strategic deployment of charging infrastructure, pricing mechanisms, standardizing grid interaction protocols, and supporting grid infrastructure requirements.

The additional policies to exploit synergies between transportation electrification and grid decarbonization has the potential to reduce cumulative emissions by a further 10 million tons of CO_2. While these emission benefits are small relative to the reductions seen from simply electrifying the transport sector, there are many co-benefits on the electricity grid that can be simultaneously realized.

Contents

1 Introduction

One of the largest problems facing the world today is the existential threat of climate change. Countries around the world have already pledged to combat climate change as evidenced by their signing of the Paris Climate Agreement[1] in 2015. This accord is a non-binding resolution that pledges countries to confront climate damages through mechanisms of mitigation and adaptation. Measures to reduce emissions of greenhouse gases (GHGs) such as carbon dioxide and methane have begun to accelerate worldwide, following the passage of the Paris agreement. Yet for some governments, this agreement is merely a continuation of a legacy of climate policies aimed at fighting climate change. The State of California is one such government that has had a history of strong climate policies, beginning with the Global Warming Solutions Act of 2006[2] and since then spanning a breadth of regulations that cover carbon pricing (Cap-and-Trade Program[3]), renewables adoption (Renewable Portfolio Standard [RPS] Program[4]), clean fuels (Low Carbon Fuel Standards [LCFS][5]), and vehicle electrification (Zero Emissions Vehicle [ZEV][6] and Advanced Clean Trucks[7] Programs).

The transportation sector represents the largest source of GHG emissions in California—producing 41% of the total emissions in 2018.[8] While the state has many aggressive policies to decarbonize transportation (including the aforementioned policies such as the ZEV mandate and LCFS program), there are additional policy opportunities that can help to ease and accelerate decarbonization efforts in the transition. Many of California's regulatory policies are sector specific, but as the transition towards transport electrification continues, the opportunities for synergies between transportation and the electricity grid continue to grow. This study demonstrates the necessity for policy that addresses the intersection of these two sectors. Design of sustainable charging measures can decrease cumulative emissions impacts, address intermittency issues from renewable power sources, and decrease reliance on grid storage.

The remaining report is divided as follows: Section 2 provides a literature review; Section 3 describes the future of EV adoption in California and associated charging behavior; Section 4, how we simulate the electricity grid of the Western Interconnect, Section 5, how the grid operates in response to EV charging events, Section 6, the emissions impacts of EVs, and Section 7, policy issues and conclusions.

---

[1] United Nations. "Paris Agreement". 2015

[2] https://ww2.arb.ca.gov/resources/fact-sheets/ab-32-global-warming-solutions-act-2006

[3] https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program

[4] https://www.cpuc.ca.gov/rps/

[5] https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard

[6] https://ww2.arb.ca.gov/our-work/programs/zero-emission-vehicle-program

[7] https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks

[8] California Air Resources Board. "California Greenhouse Gas Emissions for 2000 to 2018: Trends of Emissions and Other Indicators". 2020. https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2018/ghg_inventory_trends_00-18.pdf

2 Literature Review

While policies supporting the growth of EVs and renewable power have already been developed in California, the same cannot be said for policies that take advantage of interactions between these technologies. It is critical to understand the dynamic relationship between EVs and the operation of the power sector, to develop policies that can decrease costs, improve grid resilience, and enhance services to the electricity sector. In the academic literature, these topics are well studied, and in the following section we review the body of relevant research in this area.

Most studies of EV-to-grid interactions are focused on understanding specific operational aspects of the electricity grid. However, there are several studies that examine more generalized impacts. For example, Kasputin and Grushevenko provide a comprehensive overview of automaker plans for EV deployment, to demonstrate a simple forecast of global electricity demand resulting from scenarios of EV adoption with increases as large as 10,000 TWh annually in 2040 (Kapustin & Grushevenko, 2020). These results do not provide any operational details of the grid, but the size of demand is a strong indication of the large impact EVs will have on the grid. The demand requires a significant number of upgrades in the power sector, but as many studies demonstrate, can potentially be an important asset as well. In a more nuanced study focused on residential power demand, Muratori also conducts forecasts of EV adoption in the United States and reveals that additional electricity demand from uncontrolled EV charging can have important local impacts on the grid's distribution system. These include increases in both average and peak load demand on transformers of 50% once market share reaches 100% (Muratori, 2018).

Many of these issues can be ameliorated and even serve as a benefit to the grid. Before delving into the body of literature on this topic, we first highlight a study by Thompson and Perez that provides a comprehensive overview of the energy services, value streams, and policy implications of connecting vehicles to the grid (Thompson & Perez, 2020). The study demonstrates 16 possible value streams across sectors of wholesale generation, utilities, and end customers for both power and energy services. These streams are estimated to range between $20 to as high as $250 per kW-year on average—a massive market opportunity when considering EVs in aggregate. However, the authors also conclude that regulatory action is essential for vehicle-to-grid value to be captured through allowing aggregator access to energy markets, developing technology-agnostic services, and providing incentives for actors to reveal costs to be compensated for their services. Likewise, a study by Freeman et al. also found that the participation of EVs in grid-services can lead to savings, however the savings they predict are smaller than those predicted by Thompson and Perez. Importantly, Freeman et al. investigate several scenarios that include a carbon tax which lead to larger savings—indicating a synergistic opportunity to mitigate carbon emissions (Freeman et al., 2017).

Many studies indicate that the specific problem with increased load is in power availability, as opposed to energy availability. Increased peak load means that more generation assets need to be deployed, which also leads to an increase in costs as less economically efficient generators are dispatched. In a case study of EVs in the midwestern United States, Zhang et al. show that while uncontrolled charging can increase peak load by 8 GW (a 10% increase over the baseline), unidirectional controlled charging can reduce this increase to 2% while bidirectional controlled charging can reduce the peak by upwards of 30% (Zhang et al., 2020). This result is similar to that of another case study of controlled charging via demand response in Germany where the authors find vehicles in 2030 can reduce system load by 2.8% compared to an uncontrolled charging scenario (Gnann et al., 2018). These examples are generally consistent in magnitude with literature on load shifting and peak shaving for future scenarios of EV adoption.

However, beyond general shifts in electricity load, EVs are potentially a powerful asset for integrating with renewable generation. As climate mitigation efforts shift the grid towards a larger proportion of renewable energy, there are several important issues that arise for meeting load demand. These include intermittency and the timing of renewable resource availability. The inherent flexibility of EV charging may help to mitigate these issues. Rahbari et al. demonstrate, through modeling, a technical example of bi-directional charging to integrate EVs into the grid. In this study, the authors are able to match the renewable energy profile of both wind and solar generation units to EV charging throughout the test bus area using only flexibility in charging—even without the presence of any permanent grid storage resources (Rahbari et al., 2017). Similar work was published examining integration to reduce costs of solar systems and help to manage uncertainty in the generation portfolio of these systems by employing bi-directional charging with EVs (Mehrjerdi & Rakhshani, 2019). An application of these grid systems was conducted in a study of several small European countries (Spain, Ireland, Hungary, and Sweden). Their primary findings revealed massive cost-savings when employing bi-directional charging—upwards of 10 EUR per kWh of battery capacity annually. One of the common themes of these studies is the use of electric grid simulation models—due to the complex nature of grid operation, these models are necessary to realize the benefits from integrating EVs with renewable energy systems (or any electricity system). Our work is a continuation of these studies at a much larger scale—rather than simulating a hypothetical power bus system, we simulate power supply to all of California with scenarios that extend to 100% adoption of both EVs and renewable power generation.

Already there exists some work examining policy opportunities to integrate EVs with renewable energy. One example of policy application in China found that bi-directional charging could obtain a large value in reducing costs of solar energy in the long run by using EV battery capacity as distributed storage on the demand side (Liu & Zhong, 2019). The authors recommend support of this potential through the implementation of time-of-use (TOU) tariffs, lowering wholesale market thresholds for EVs and distributed storage resources, and upgrading metering infrastructure to enable EVs to provide high quality regulation services. Likewise, our study measures the benefits of EV grid integration measures in California and discusses the policy mechanisms to help realize these benefits.

3 Forecasting Vehicle Adoption and Charging Behavior

The following steps are taken to develop forecasts of aggregate vehicle charging loads in California:

1. Vehicle adoption forecast
2. Charging simulation approach based on vehicle adoption
3. Generation of different charging patterns and magnitudes (based on seasons, uncontrolled vs smart charging, and differences in charging between years)

We employ a vehicle adoption model known as the EV Toolbox, developed by the Plug-in Hybrid and Electric Vehicle Research Center at the University of California, Davis. The charging simulation is based on bootstrapping the charging behavior of vehicles from empirical data on charging behavior. This technique closely follows the procedure described in a study by Jenn et al., 2020. We allocate the demand from the EV Toolbox model across a full year, randomly distributing the charging events across each day of the year, using a uniform distribution. Our study considers two “bookend” scenarios of charging: a baseline of “regular” charging behavior (simulated exogenously to the grid operation) and an advanced flexible “smart” charging behavior (determined endogenously by the grid model). The regular charging scenario determines charging behavior by assigning charge timing distributions to each of the charging categories determined by the EV Toolbox (home, work, public, and DC fast public charging). These timing distributions are derived from empirical observations from EVs outfitted with loggers in a separate study by researchers at the Plug-in Hybrid Electric Vehicle Research Center at UC Davis (Tal et al., 2020) combined with public charging service provider infrastructure data (Jenn et al., 2020).

This bootstrapping procedure is repeated for all years of analysis from 2020 through 2045. A sample of the simulated charging behaviors can be seen in Figure 1–Figure 3 across several days in the summer of 2020 (for both regular and smart charging scenarios) and in the summer of 2045 (for smart charging). In Figure 1, we observe that the bootstrapping procedure introduces some variation in day-to-day charging, but the overall pattern is fairly uniform throughout the day, with a single peak in charging over the course of the day. The peak charging load demand varies between about 400 kW to as high as 40 MW depending on the region in California. At an aggregate level, this represents a very small proportion of the total load demand—at the wholesale generation and transmission level these EV charging volumes would not be difficult for the grid to meet. However, in Figure 2 we immediately observe a stark difference in charging behavior under a smart charging scenario where vehicles are provided flexibility to charge at the best times for the electricity grid to reduce costs. In this scenario, the peaks are substantially larger: between 8 MW to as high as 1 GW (25 times higher than the regular charging scenario). As shown later in Section 5, this charging provides a substantial amount of relief to the grid during sudden reductions in renewable resources, thus decreasing ramping requirements on natural gas generators and reducing curtailment during periods of excess renewables. These results are further expanded in later years as shown in Figure 3, which shows the charging patterns corresponding to a smart charging scenario in 2045. There are substantially more peaking events throughout the day, corresponding to the intermittency in renewable generation. Several areas experience lengthier peaks (as seen in the Southern California Edison [SCE] and San Francisco [SF] regions). Note that the magnitudes of the peaks are also substantially larger due to the high volume of EVs on the road. While smaller regions in Southern California (such as Imperial Irrigation District) experience peaks of approximately 600 MW, other areas in the state reach peaks in excess of 20 GW (similar in magnitude to baseload demand in 2020). The stark difference in charging patterns between regular and smart charging is a strong indication of the opportunity costs that can be captured by introducing flexibility in charging patterns. We later quantify these benefits in terms of both social costs and emissions.

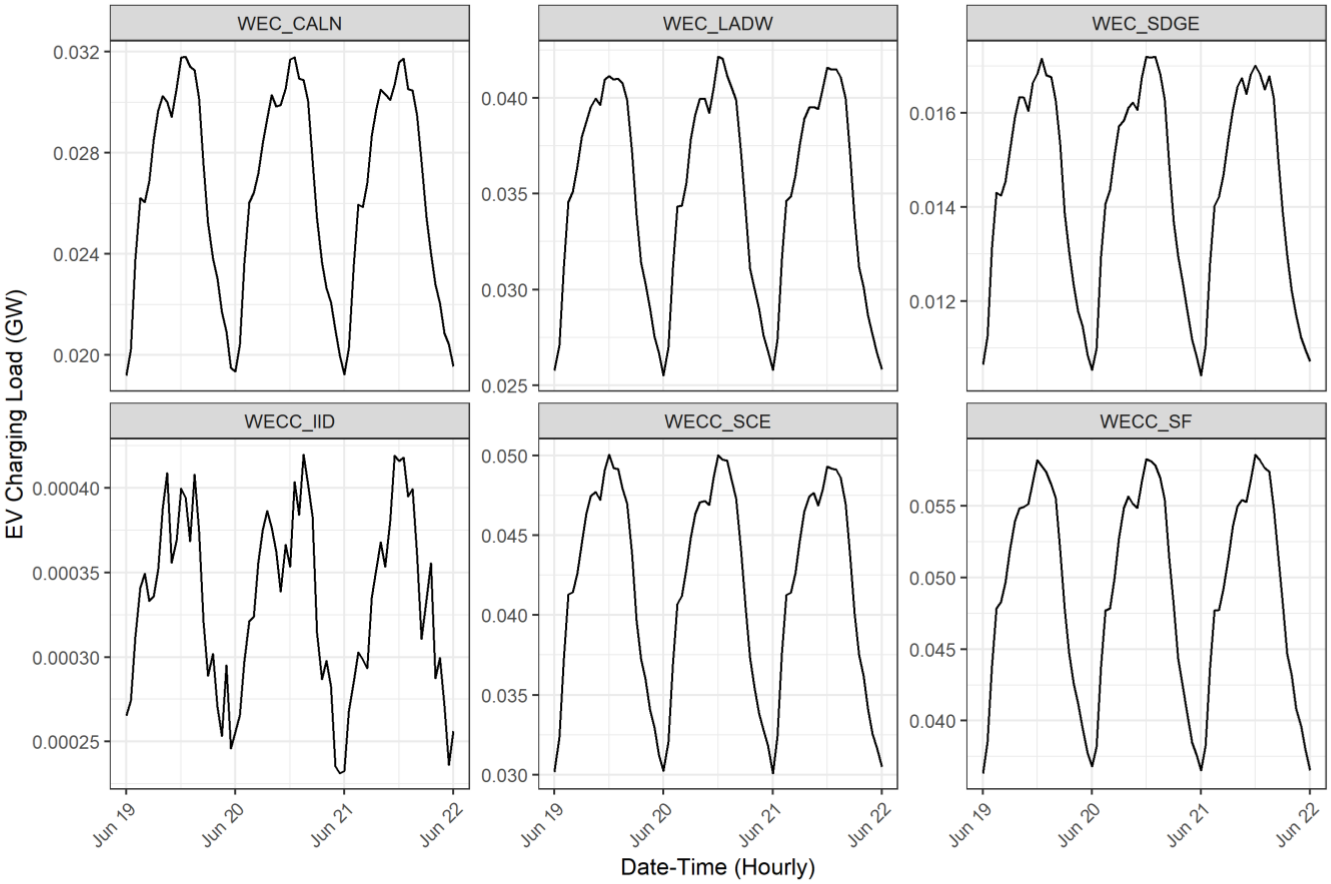

Figure 1. Sample of three days of hourly charging profiles of all EVs in California in the summer of 2020 with regular charging patterns. The relative magnitude of charging remains fairly constant (on the order of hundreds of kW up to tens of MW in load demand depending on the region) but with noticeable variation from day to day. (CALN, Northern California; LADW, Los Angeles Department of Water and Power; SDGE, San Diego Gas and Electric; IID, Imperial Irrigation Department; SCE, Southern California Edison; SF, San Francisco)

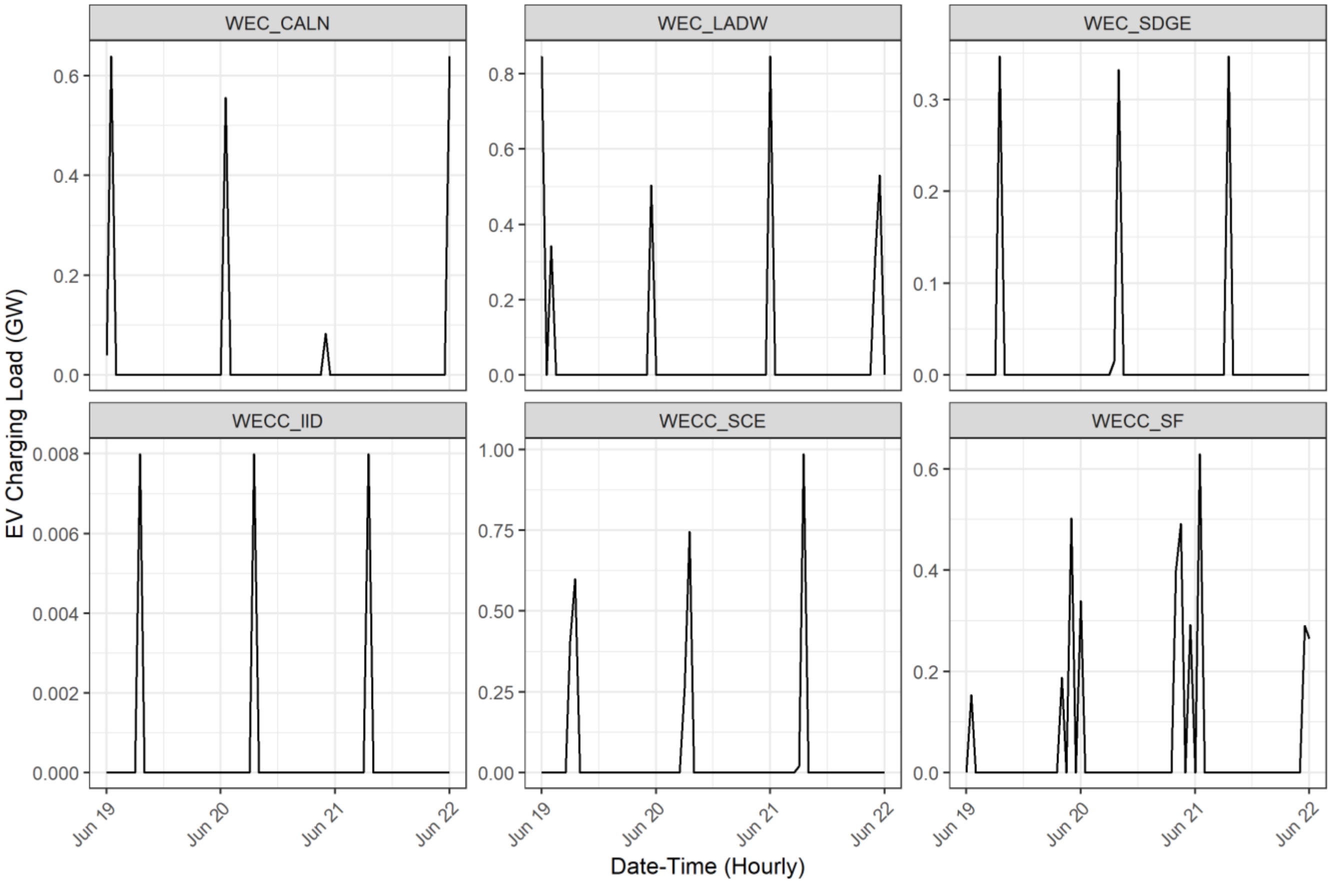

Figure 2. Sample of three days of hourly charging profiles of all EVs in California in the summer of 2020 with smart charging. The magnitude of the charging events remains fairly small but with large spikes indicating a preference for a particular time of day. (CALN, Northern California; LADW, Los Angeles Department of Water and Power; SDGE, San Diego Gas and Electric; IID, Imperial Irrigation Department; SCE, Southern California Edison; SF, San Francisco)

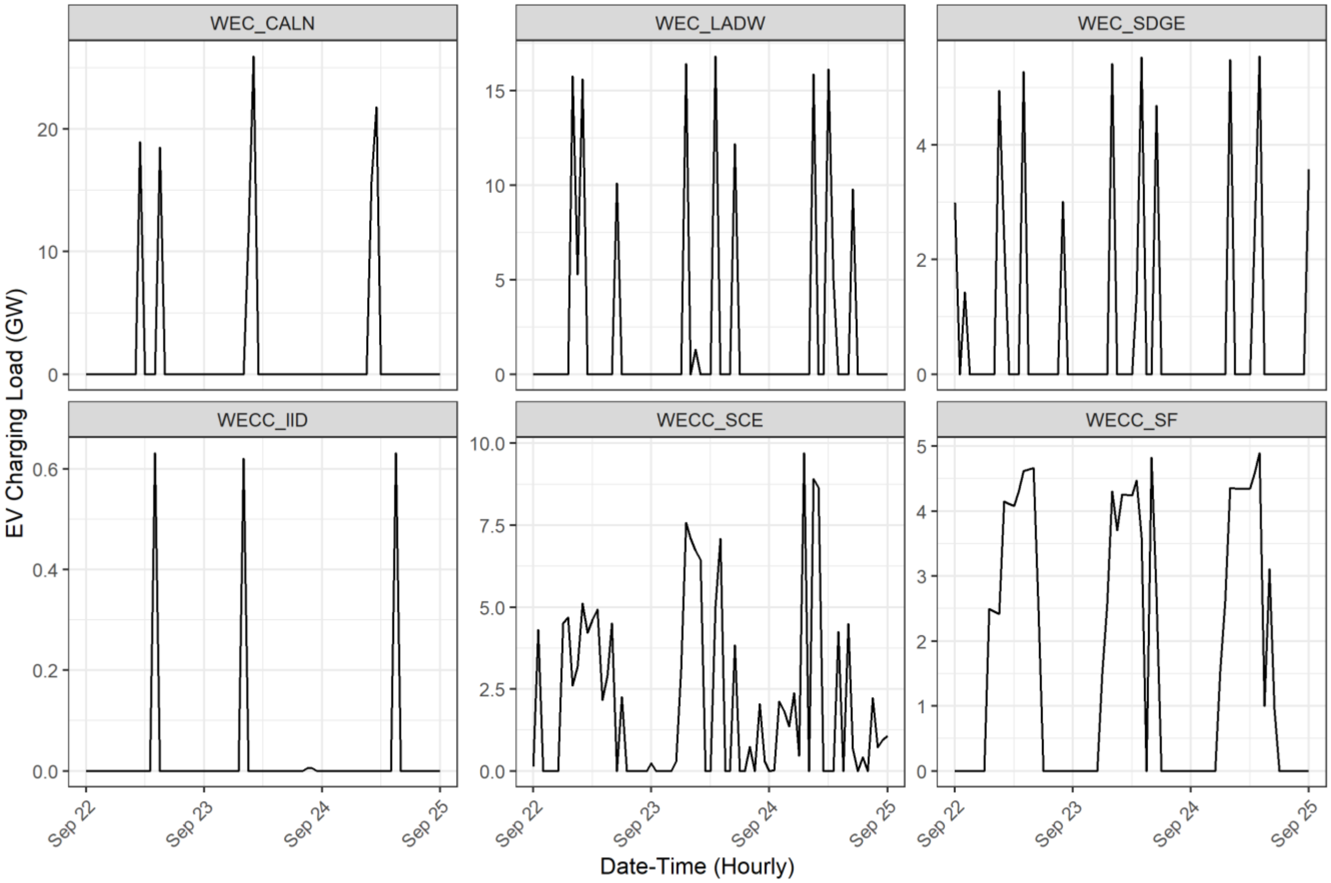

Figure 3. Sample of three days of hourly charging profiles of all EVs in California in the summer of 2045 with smart charging. In the presence of 100% renewable generation, charging behavior is still fairly spikey, but in comparison to the 2020 run there are several sudden charging spikes throughout the day (in addition to being substantially larger in magnitude) that are indicative of addressing renewable intermittency issues. (CALN, Northern California; LADW, Los Angeles Department of Water and Power; SDGE, San Diego Gas and Electric; IID, Imperial Irrigation Department; SCE, Southern California Edison; SF, San Francisco)

4 Simulating the WECC Electricity Grid

This study employs a modified version of the Grid Optimized Operation Dispatch (GOOD) model, an economic dispatch model that simulates the operation of individual power generators to meet load demand and several other constraints of the power system across a single calendar year (Jenn et al., 2020; Sheppard et al., 2020). The extent of the GOOD model for this study covered the Western Electricity Coordinating Council (WECC) interconnect region (divided into 16 balancing zones) and all power generating assets contained within this region (see Figure 4). While the focus of our analysis is California, it is necessary to include the larger interconnect region to accurately capture the import and export of electricity in and out of the state. The grid model is slightly modified from previous versions as it includes simple representations of capacity expansion for renewables and storage as it moves forward in time (on a yearly basis). Rather than creating an economic capacity expansion, it is constrained by California's Renewable Portfolio Standards and required to generate a certain proportion of renewables in-state that can only be achieved through the installation of renewable generation assets such as solar and wind. Below, we provide the full formulation of the GOOD model as deployed for this study.

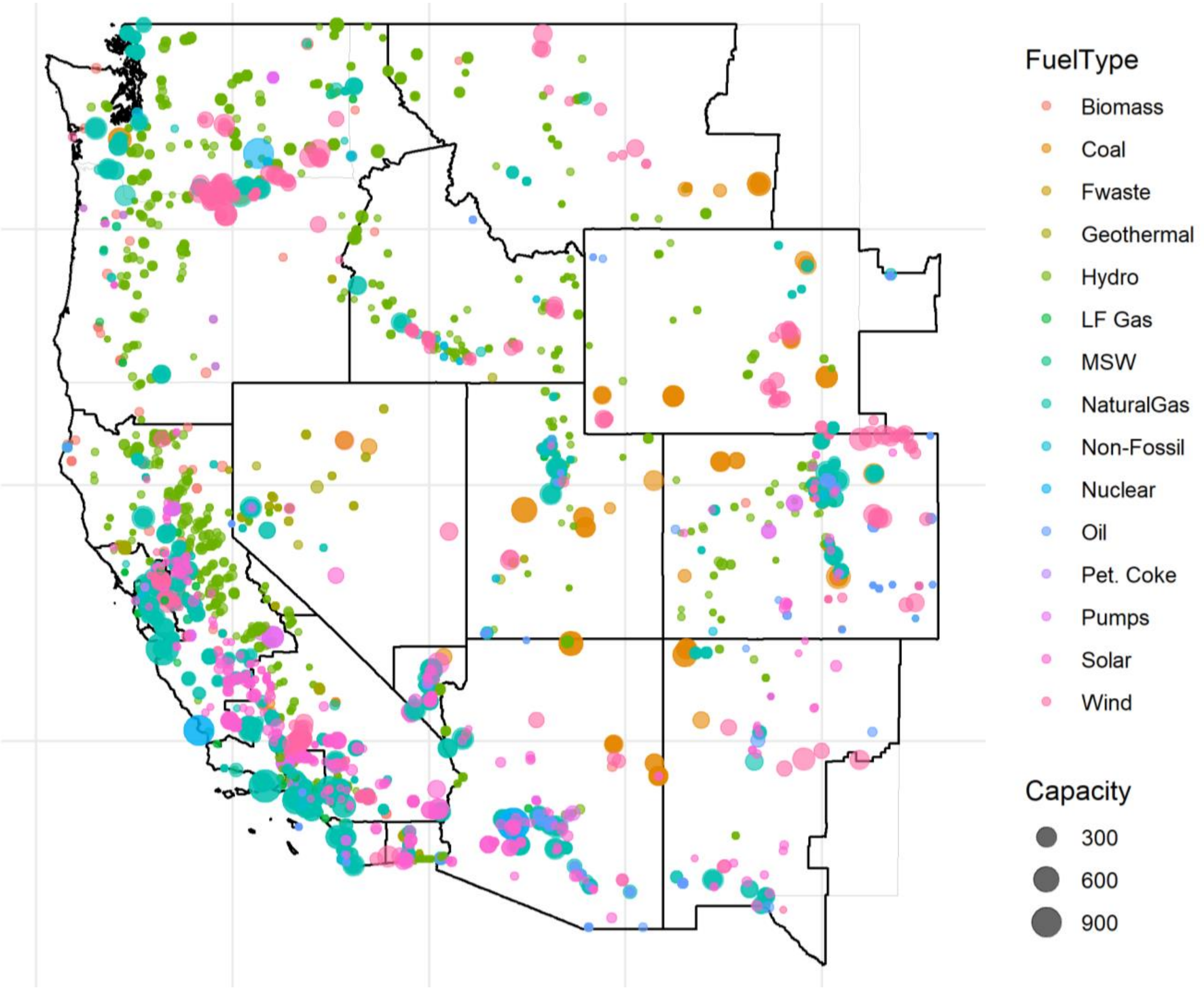

Figure 4. Breakdown of regional balancing zones within the Western Interconnect electricity grid system along with the individual power generation assets. Each generator is distinguished by its color (fuel type) and size (capacity [MW]). (Fwaste, food waste; LF Gas, landfill gas; MSW, municipal solid waste; Pet. Coke, Petroleum Coke)

4.1 Objective Function: Total cost of the system

The objective function describes the total marginal system cost of the electricity system across all generators *g*, time periods *t*, and regions *r* (with alias set *o*). The total marginal system cost consists of the cost of electricity generation, wheeling charges related to transmission of electricity across different balancing zones, and the levelized cost to install new solar, wind, and storage capacity. The total cost in the system varies as a function of: (a) how generators are dispatched; (b) how much electricity is imported/exported from different regions; (c) the charging load patterns from EVs; (d) the new capacity of solar, wind, and storage assets; and (e) the operation of grid storage—all of which are determined endogenously by the GOOD model.

$$\min_{\substack{x_{gt}^{\text{gen}},\, x_{rto}^{\text{trans}},\, x_{rt}^{\text{ev.flexLoad}},\\ x_{r}^{\text{new.solar}},\, x_{r}^{\text{new.wind}},\\ x_{r}^{\text{storage.cap}},\, x_{rt}^{\text{storage.soc}},\\ x_{rt}^{\text{storage.in}},\, x_{rt}^{\text{storage.out}}}} \begin{pmatrix} \sum_{g}\sum_{t} x_{gt}^{\text{gen}} c_{g}^{\text{gen.cost}} + \sum_{r}\sum_{t}\sum_{o} x_{rto}^{\text{trans}} c_{ro}^{\text{trans.cost}} + \\ \sum_{r} x_{r}^{\text{new.solar}} c^{\text{solarCost}} + x_{r}^{\text{new.wind}} c^{\text{windCost}} + x_{r}^{\text{storage.cap}} c^{\text{storageCost}} \end{pmatrix} \tag{1}$$

Constraint 1a: Generation must equal load with regular charging behavior

This constraint is active when modeling the scenario with “regular” EV charging behavior. In each time period *t* and region *r*, the generation (plus net import/exports and net storage input/output) of electricity must meet the total demand load. The demand load consists of two exogenous parameters: baseload demand and charging load demand from EVs, as determined by the mobility portion of our modeling system.

$$\begin{pmatrix} \sum_{g \in gtor_{gr}} x_{gt}^{\text{gen}} + \sum_{o} x_{otr}^{\text{trans}} c^{\text{transLoss}} - \sum_{p} x_{rtp}^{\text{trans}} - \\ x_{rt}^{\text{storage.in}} + x_{rt}^{\text{storage.out}} c^{\text{storage.out}} - \left(c_{rt}^{\text{demandLoad}} + c_{rt}^{\text{evHourlyLoad}}\right) \end{pmatrix} = 0, \forall t, r \tag{2}$$

Constraint 1b: Generation must equal load with smart charging behavior

This constraint is active when modeling the scenario with “smart” EV charging behavior. It is identical to 1a, except that the charging load demand from EVs is now a decision variable (the GOOD model determines the best time that EVs should charge).

$$\begin{pmatrix} \sum_{g \in gtor_{gr}} x_{gt}^{\text{gen}} + \sum_{o} x_{otr}^{\text{trans}} c^{\text{transLoss}} - \sum_{p} x_{rtp}^{\text{trans}} - \\ x_{rt}^{\text{storage.in}} + x_{rt}^{\text{storage.out}} c^{\text{storage.out}} - \left(c_{rt}^{\text{demandLoad}} + c_{rt}^{\text{evFlexLoad}}\right) \end{pmatrix} = 0, \forall t, r \tag{3}$$

Constraint 2: Maximum solar generation

This constraint takes information about representative solar profiles across all regions *r* in all time periods *t* and limits the maximum generation from all solar resources in the model based on the maximum initial capacity of solar generators plus newly installed capacity of solar resources in the year being run by the GOOD model.

$$\left(c_{rt}^{\mathrm{maxSolar}} \sum_{solar \in gtor_{solar,r}} c_{solar}^{\mathrm{maxGen}} + x_{r}^{\mathrm{new.solar}} c_{rt}^{\mathrm{maxSolar}} - \sum_{solar \in gtor_{solar,r}} x_{solar,t}^{\mathrm{gen}} c_{solar}^{\mathrm{maxGen}} \right) \geq 0, \forall t, r \tag{4}$$

Constraint 3: Maximum wind generation

This constraint takes information about representative wind profiles across all regions *r* in all time periods *t* and limits the maximum generation from all wind resources in the model based on the maximum initial capacity of wind generators plus newly installed capacity of wind resources in the year being run by the GOOD model.

$$\left(c_{rt}^{\mathrm{maxWind}} \sum_{wind \in gtor_{wind,r}} c_{wind}^{\mathrm{maxGen}} + x_{r}^{\mathrm{new.wind}} c_{rt}^{\mathrm{maxWind}} - \sum_{wind \in gtor_{wind,r}} x_{wind,t}^{\mathrm{gen}} c_{wind}^{\mathrm{maxGen}} \right) \geq 0, \forall t, r \tag{5}$$

Constraint 4: Balancing flexible EV load under an EV smart charging scenario

This constraint provides guidance on how often the GOOD model must fulfill the aggregate charging demand from EVs. The hourly demand is allowed to be determined endogenously but the aggregate demand must be fulfilled within a larger time window.

$$\sum_{t \in ttod_{td}} x_{rt}^{\mathrm{evFlexLoad}} - c_{rd}^{\mathrm{evDailyLoad}} \geq 0; \forall r, d \tag{6}$$

Constraint 5: Renewable Portfolio Standards renewable generation requirement

This constraint specifies the proportion of in-state (within California) generation that must be fulfilled by renewable resources.

$$\sum_{ca,t} \left(\sum_{solar \in gtor_{solar,ca}} x_{solar,t}^{\mathrm{gen}} + \sum_{wind \in gtor_{wind,ca}} x_{wind,t}^{\mathrm{gen}} \right) - c^{\mathrm{RPS}} \sum_{ca,t} \left(\sum_{g \in gtor_{g,ca}} x_{gt}^{\mathrm{gen}} \right) \geq 0 \tag{7}$$

Constraint 6: Tracking storage state of charge

This constraint tracks the aggregate energy state of grid storage batteries. In each time period, the energy balance is achieved by adding the energy input minus the energy output to the previous time period's energy level.

$$x_{rt}^{\text{storage.soc}} - x_{r,t-1}^{\text{storage.soc}} - x_{r,t-1}^{\text{storage.in}} c^{\text{storageLoss}} + x_{r,t-1}^{\text{storage.out}} = 0; \forall r, t \tag{8}$$

Constraint 7: Maximum storage capacity

This constraint specifies the maximum amount of energy that can be stored in the grid battery storage based on the installed capacity of storage.

$$x_{r}^{\text{storage.cap}} - x_{rt}^{\text{storage.soc}} \geq 0; \forall r, t \tag{9}$$

Constraints 8 & 9: Storage input/output limits

This pair of constraints limits the amount of energy that can be transferred in and out of the grid storage within one time-period. Based on the performance of current lithium-ion batteries, we allow for a charging/discharging limit equal to 25% of the total capacity of the storage device.

$$.25x_{r}^{\text{storage.cap}} - x_{rt}^{\text{storage.in}} \geq 0; \forall r, t \tag{10}$$

$$.25x_{r}^{\text{storage.cap}} - x_{rt}^{\text{storage.out}} \geq 0; \forall r, t \tag{11}$$

The addition of renewable resources to simultaneously meet additional load from EVs and California's RPS requirements can be seen in Figure 5. It is here that some of the benefits of smart charging become evident: while the amount of renewable capacity installed is similar between the charging scenarios, the required storage to deal with intermittency is substantially smaller in the smart charging scenario (compare the size of storage (green bars) in the regular charging scenario (left) vs. the smart charging scenario (right) in Figure 5). Note that the smart charging is simply flexible load and does not include vehicle discharge back to the electricity grid—yet the flexibility is so substantial that it can reduce the necessary storage capacity by an order of magnitude. In 2040, the regular charging scenario requires over 22 GWh of storage capacity whereas the smart charging scenario requires a mere 1.2 GWh of storage. In 2045, due to the RPS requirements for 100% generation from renewables, storage capacity must increase dramatically to meet the requirements—nevertheless the regular charging scenario (requiring 143 GWh of storage) is still much higher than in the smart charging scenario (requiring 110 GWh of storage).

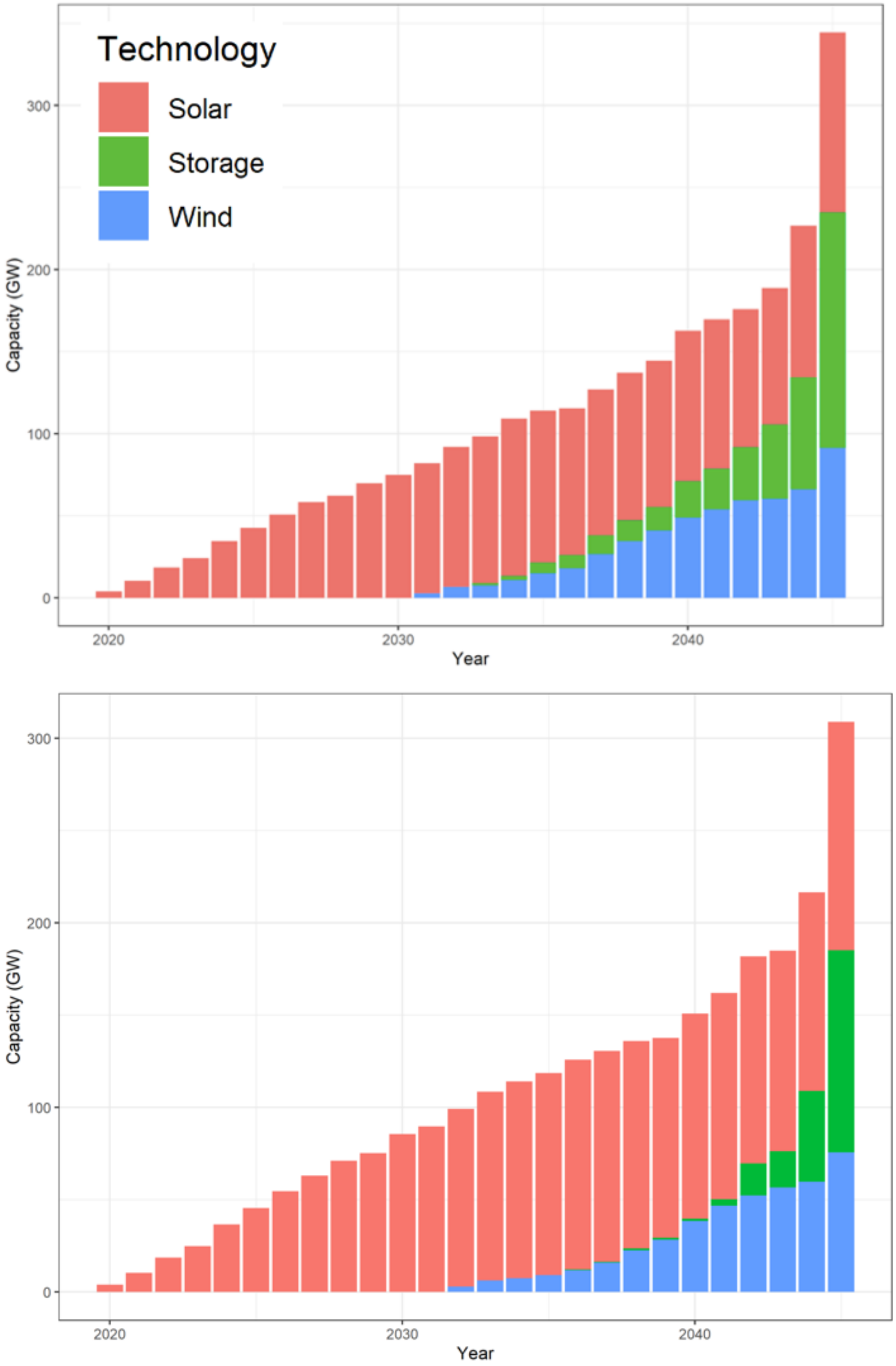

Figure 5. Renewable energy and grid storage capacity growth over time to meet demand requirements and California's Renewable Portfolio Standards. Capacity expansion is shown for two scenarios: regular charging behavior for EVs (left) and smart charging behavior for EVs (right).

Figure 6 shows the change in annual generation of energy in California by fuel type over time in the regular charging scenario. As California's Renewable Portfolio Standards increase in stringency over time, non-renewable sources of generation experience a corresponding decrease. Over the first decade starting in 2020, solar power experiences the most growth, which is later matched by wind power. Solar power experiences growth first, because it is slightly cheaper than wind power. Then, as solar power saturates the load demand over the hours when it is able to provide electricity, wind power (and later storage) must be installed to meet the remaining demand and RPS requirements simultaneously. Note that the bulk of overall load growth from approximately 250 TWh in 2020 to upwards of 400 TWh in 2040 is almost entirely from growth in load demand due to charging of EVs.

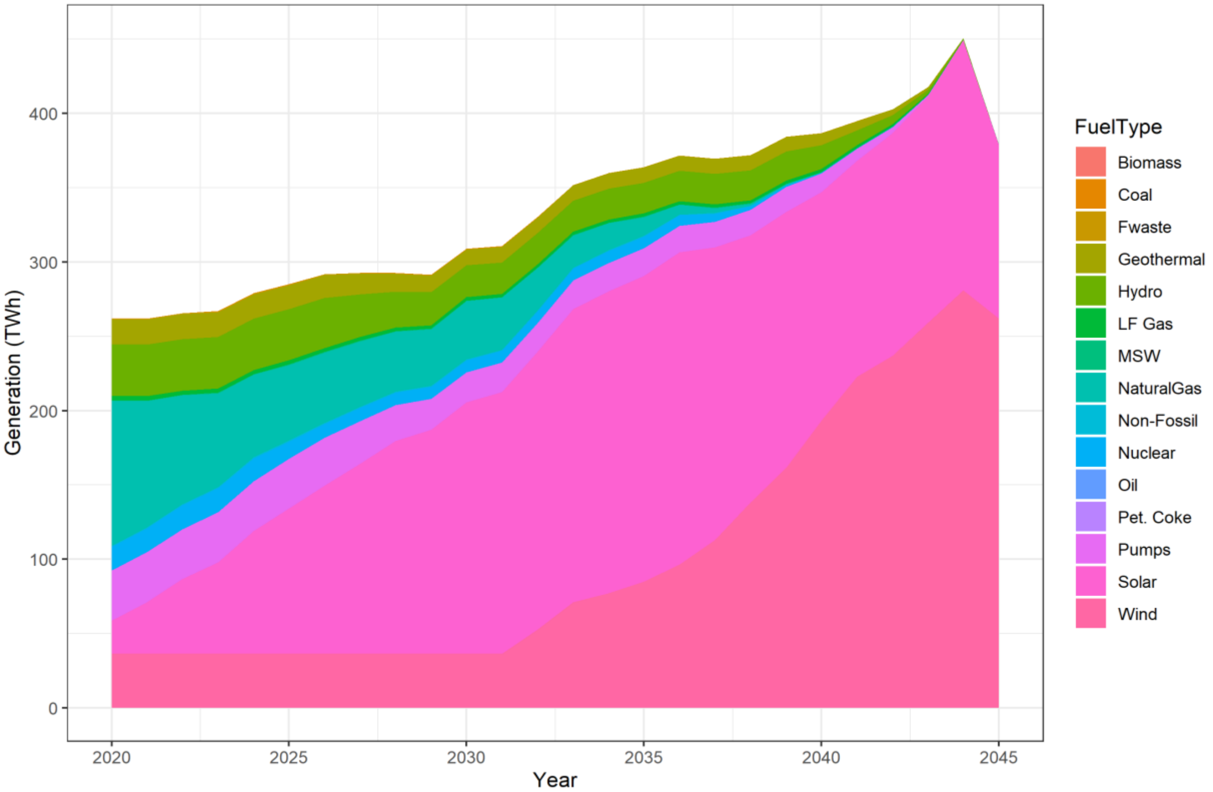

Figure 6. Shift in capacity mix over time in California from 2020 through 2045 as the electricity system simultaneously meets constraints for increased demand load from charging EVs and Renewable Portfolio Standard requirements (note that storage capacity is not included).

While many of the specific capacities and generation figures depend heavily on cost and operational assumptions, the general trend of the results is robust across sensitivities of these parameters. The most critical finding of our study indicates that there are substantial benefits to the electricity grid by capturing flexibility from charging of EVs. EV load becomes a resource that helps stabilize the grid against the intermittency of renewables, a resource that is sorely needed when considering the aggressive nature of California's RPS requirements. Additionally, the benefits of reducing the capacity expansion of renewable resources and grid storage resources can lead to a tremendous reduction in social costs. These results point not only to the importance of policy to enable this flexibility—but also necessitates the urgency of pursuing flexible charging standards as soon as possible, since the benefits accrue cumulatively over time.

5 Meeting EV Demand

In this section we show the operational results of the GOOD model's simulation of the power system to meet the baseload demand of electricity and the charging demand coming from EVs. In Figures Figure 7 to Figure 9 we show dispatch curves across a sample of three days in the spring in several different years (2020, 2035, and 2045) and across different scenarios of charging behavior (regular and smart charging). There are several notable features of generator operation changes over time and between charging behavior profiles.

The overall generation composition of California's grid consists of solar, wind, natural gas, and hydro as the dominant resources. As seen in Figure 7, there is a diversity in the shape of the dispatch curves between different regions, though these generation curves do not necessarily reflect the demand load in that region due to electricity imports and exports. There are several large peaks in generation that tend to correspond with electricity exports and dealing with intermittency in renewables. In Los Angeles Department of Water and Power (LADW), San Diego Gas and Electric (SDGE), Southern California Edison (SCE), and San Francisco (SF) regions, load that is unmet from renewables tends to be met from natural gas, while in Imperial Irrigation District (IID) it is met with geothermal, and in Northern California (CALN) it is met with a combination of natural gas and hydro.

As EV load increases and the grid integrates more renewables, we observe a very different dispatch in 2035, as seen in Figure 8. Over the period shown, the majority of generation is now coming from renewable resources with a relatively small amount of generation from natural gas, hydro, and geothermal filling in gaps due to renewable intermittency. While the magnitude of peaks in certain regions remain relatively unchanged, there are some notable differences in peak size. In several regions, the production of renewable resources is significantly larger, leading to peaks: in LADW the peak is nearly four times higher, at 12 GW in 2035; in SDGE the peak is twice as large at 6 GW; and in SF the peak is four times higher at 2 GW. We do observe a decrease in magnitude in SCE going from about 10 GW in 2020 down to 8 GW in 2035. Again, these peaking events correspond to renewable intermittency events, allowing the grid to both reduce curtailment and meet sudden spikes in charging demand. We are also able to compare the difference in dispatch between the regular charging (Figure 8) and the smart charging (Figure 9) scenarios in 2035. The most notable difference is the dispatch of solar power in the LADW, CALN, and IID regions where there is substantially more consistent solar generation during the daylight hours. Under a smart charging regime, the load is better able to accommodate the intermittency from renewables and reduce the curtailment of both solar and wind.

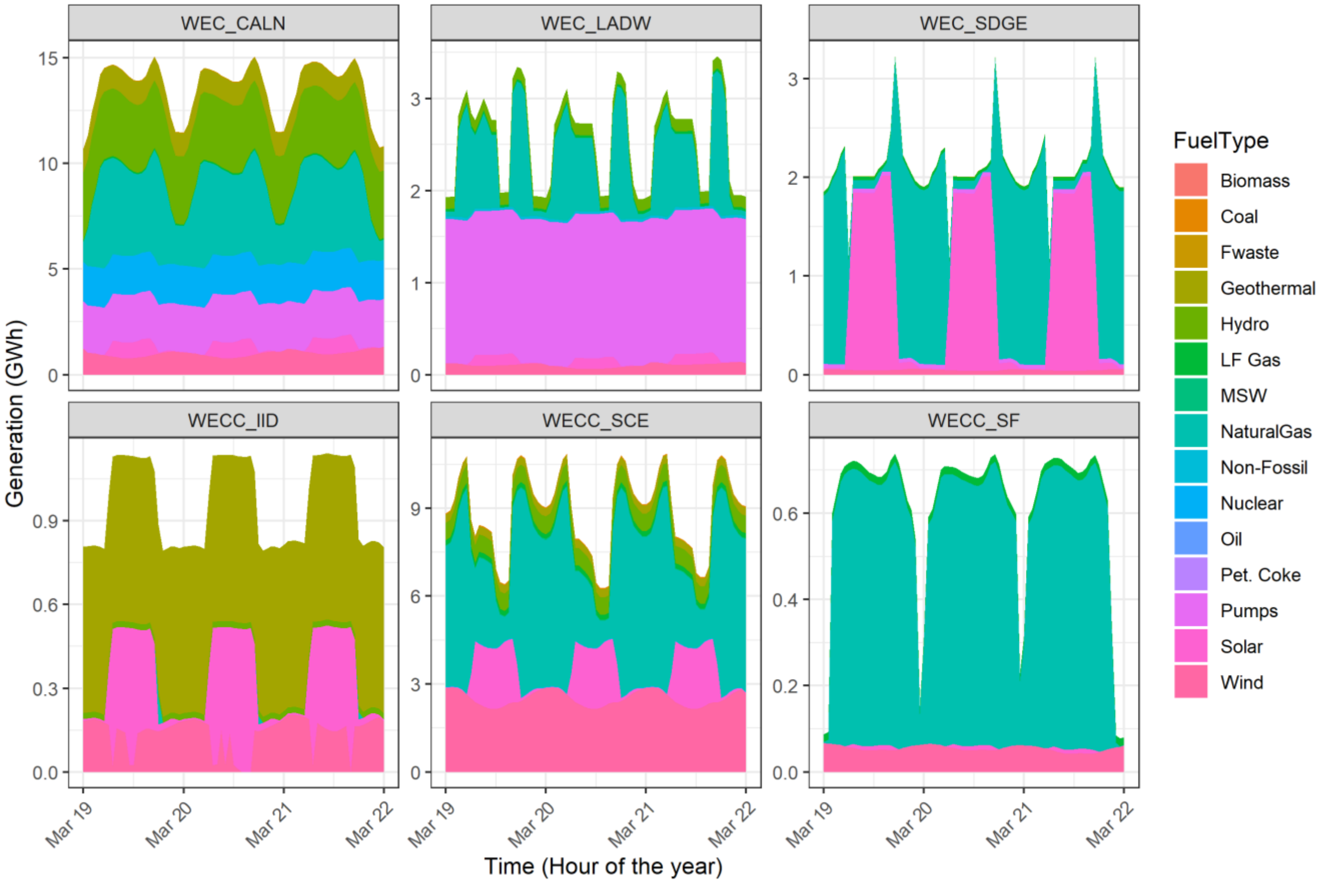

Figure 7. Generation dispatch curves for California across a sample of three days in the spring of 2020. Load curves include baseload demand and demand from regular charging patterns of EVs.

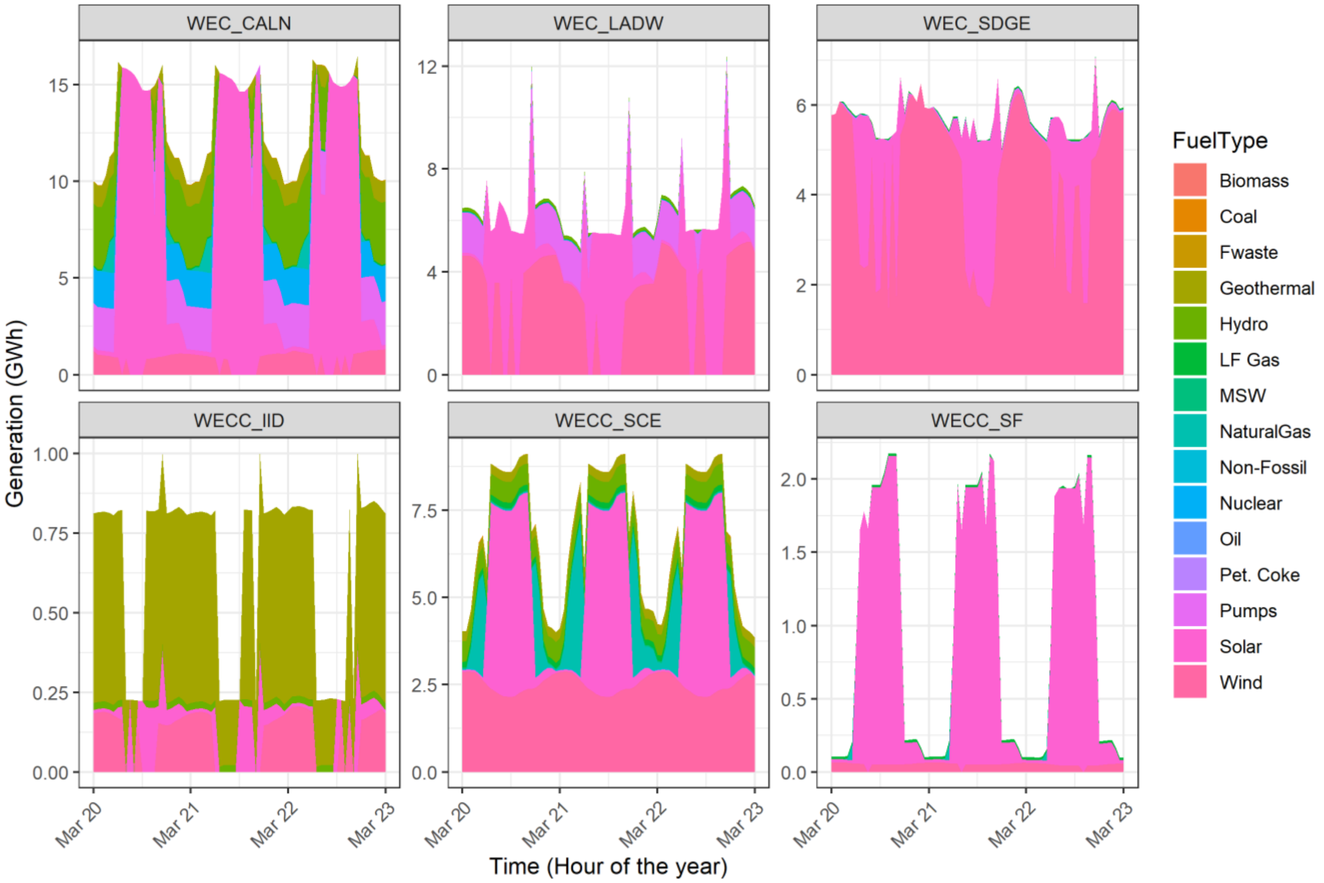

Figure 8. Generation dispatch curves for California across a sample of three days in the spring of 2035. Load curves include baseload demand and demand from regular charging patterns of EVs.

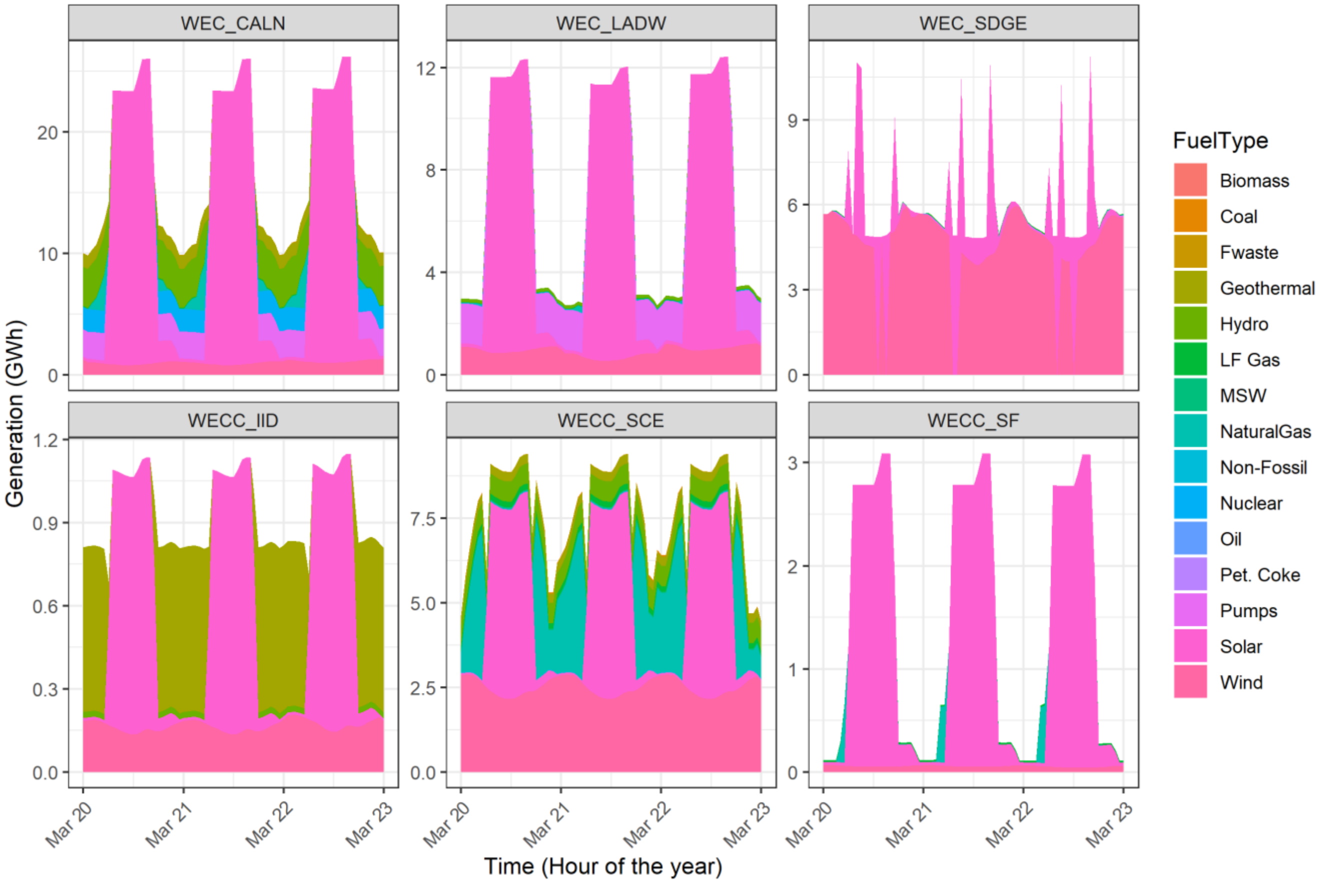

Figure 9. Generation dispatch curves for California across a sample of three days in the spring of 2035. Load curves include baseload demand and demand from smart charging patterns of EVs.

Aside from reducing the required renewable capacity expansion, the smart charging scenario, as compared to the regular charging scenario, also significantly reduces the total amount of curtailment (Figure 10). While the regular charging scenario begins to experience significant growth in curtailed energy (nearly 50 TWh by 2033), the rate of growth is much slower in smart charging scenario (not reaching 50 TWh until 2039, 6 years later). Over the course of the entire period of study, the smart charging scenario has nearly 35% lower curtailed energy from renewables than the regular charging scenario. One particularly interesting feature is the decline in curtailment (despite higher adoption of renewables) in the smart charging scenario past 2042. The increased volume of EVs participating as flexible load begins to overcome the effect of renewable intermittency. These results point to additional benefits of charging flexibility and the importance of supporting policy to raise the utilization rates of renewable resources. This becomes especially important at higher volumes of solar and wind penetration where intermittency and uncertainty in demand load can lead to large economic losses due to curtailment.

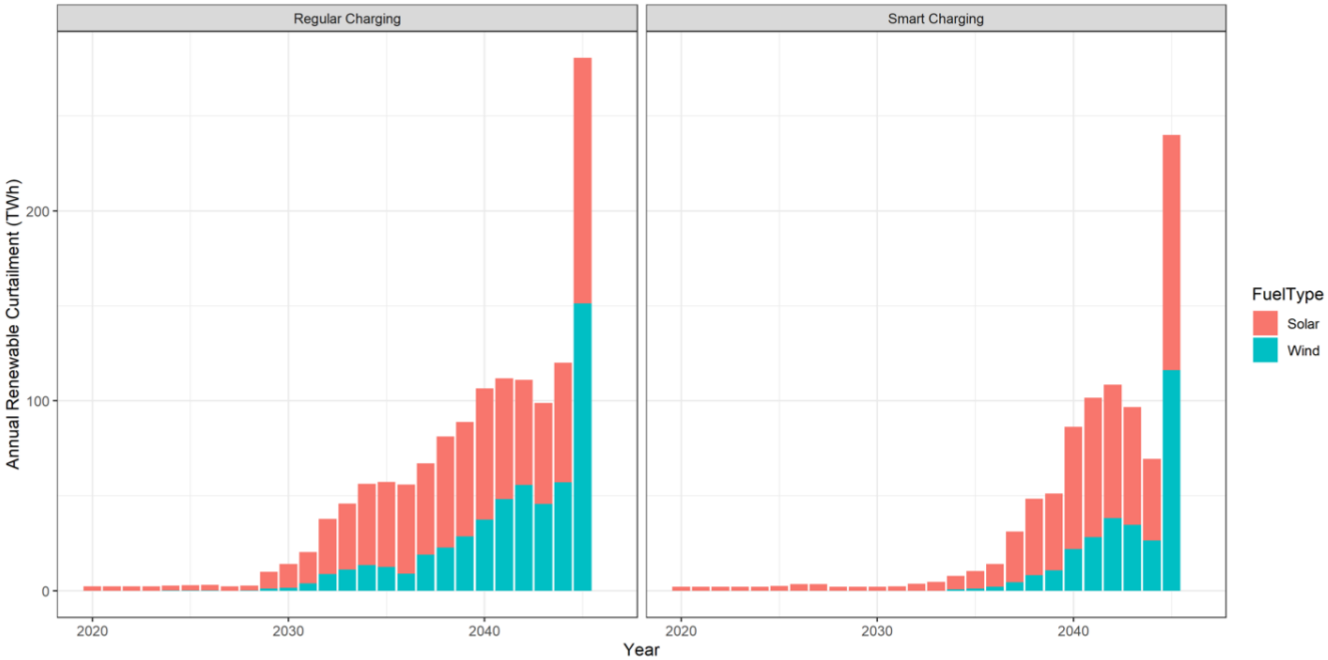

Figure 10. Annual curtailment from solar and wind renewable resources as RPS requirements increase year to year. Curtailment is shown for two scenarios: regular charging behavior (left) and smart charging behavior (right).

The electricity grid is also able to install grid-scale storage to: better absorb excess generation of renewable resources (hence reducing curtailment), offset capacity increase requirements for periods with low or no solar/wind availability, and help smooth intermittency. We can compare the operation of grid storage in regular versus smart charging scenarios in Figure 11 and Figure 12. Overall, the lower peaks in the smart charging scenario indicate lower requirements for storage capacity compared to the regular charging scenario. The depth of discharge of the grid storage is also lower in the smart charging case—leading to more efficient operation and longer lasting storage overall. We also note that despite fairly large fluctuations in the peak load demand throughout the year, we do not observe much seasonal storage occurring due to the fact that the capacity of renewables has been carefully balanced to avoid underutilization of storage that is often associated with seasonal utilization (though storage across a period of several days is not unusual).

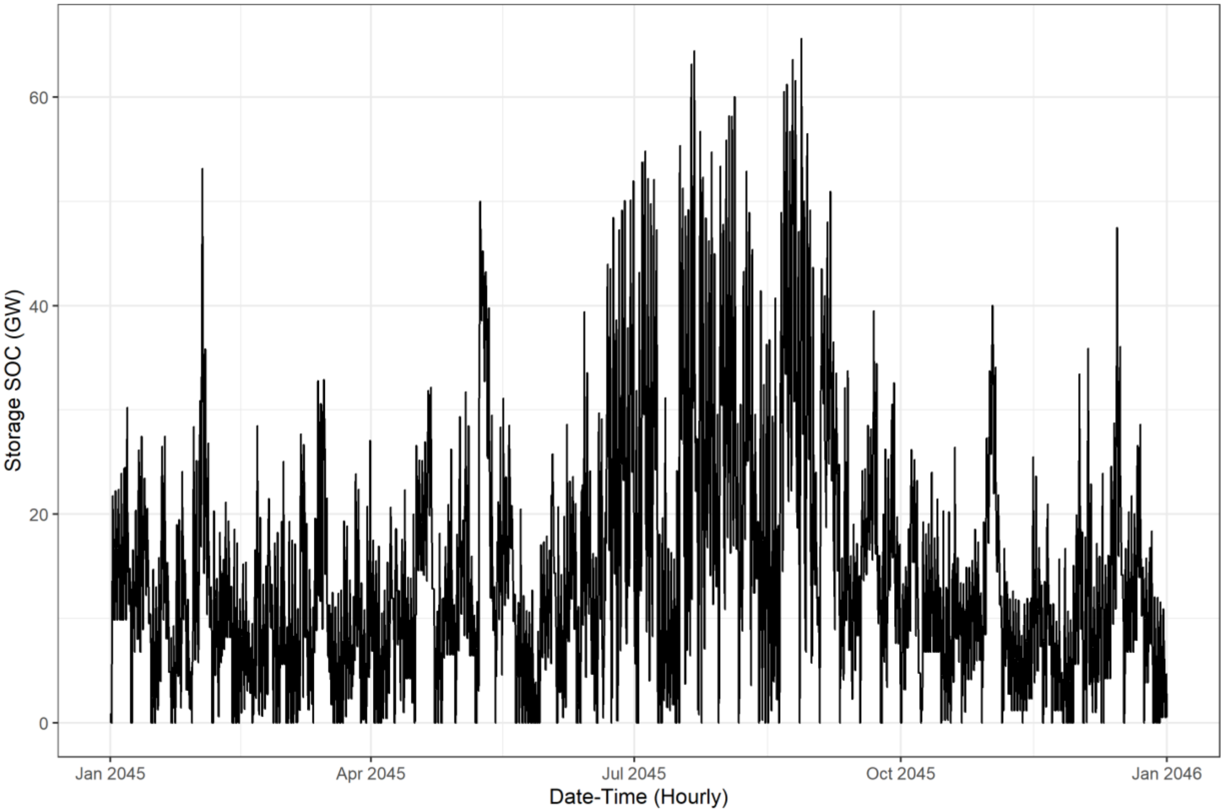

Figure 11. Aggregate view of total grid battery storage operation across California in 2045. The depicted scenario is for regular charging patterns for EVs throughout the state. Peak capacity of the storage is slightly over 60 GWh with peak state-of-charge (SOC) events happening regularly throughout the summer months and several peaks reaching 80% SOC in the remaining seasons.

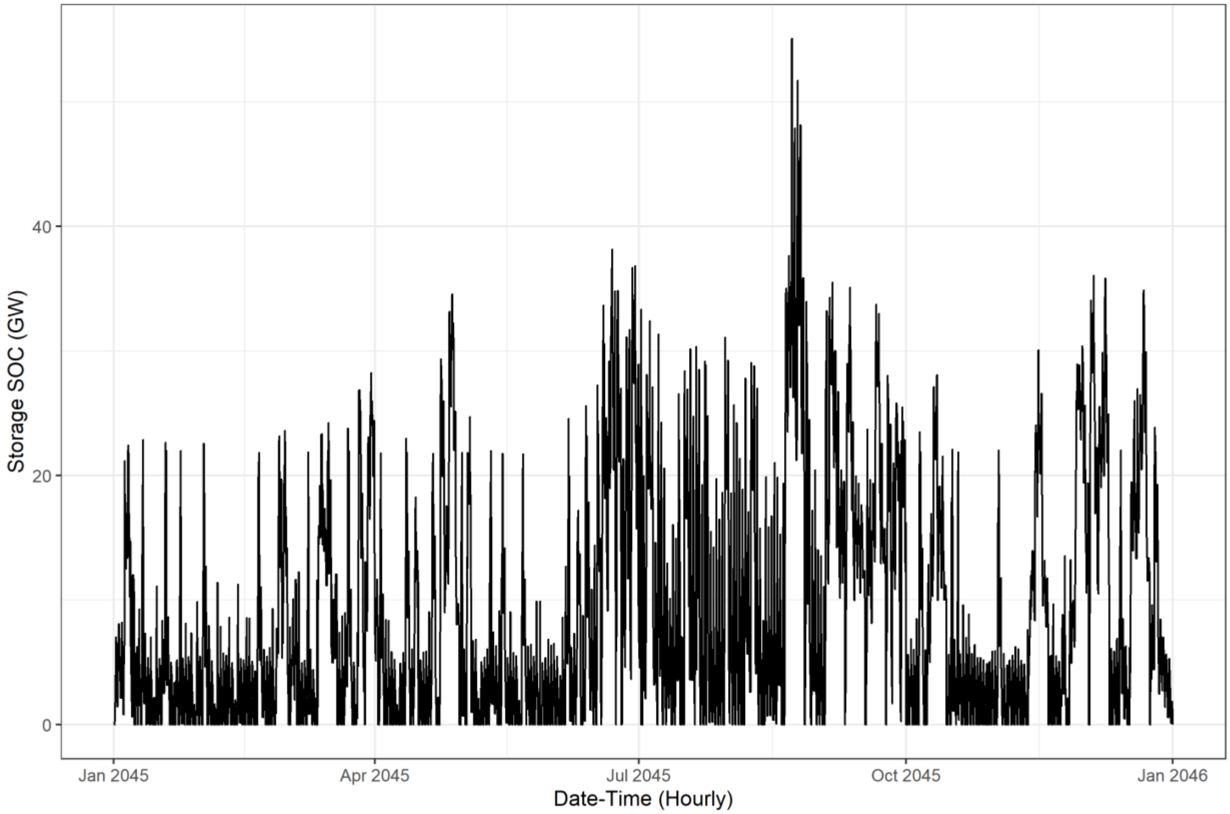

Figure 12. Aggregate view of total grid battery storage operation across California in 2045. The depicted scenario is for smart charging patterns for EVs throughout the state. Peak capacity of the storage is slightly over 50 GWh with peak events happening only once throughout the year in a summer event. Throughout the remainder of the year, there are no events that reach 80% of state of charge (SOC).

6 Emissions Impacts of EVs

The long-term adoption of EVs will help to reduce direct emissions from the transportation sector but may actually increase emissions from the electricity sector as greenhouse gases from the combustion of gasoline (from internal combustion engine vehicles) is shifted to upstream emissions related to power production. The GOOD model can identify these upstream emissions attributable to EV charging events. In Figures Figure 13 and Figure 14 we show the difference in hourly emissions corresponding to charging demand load for EVs between two scenarios of behavior (regular charging in Figure 13 and smart charging in Figure 14). Note the substantially lower magnitude of hourly emissions in the smart charging scenario compared to the regular charging scenario.

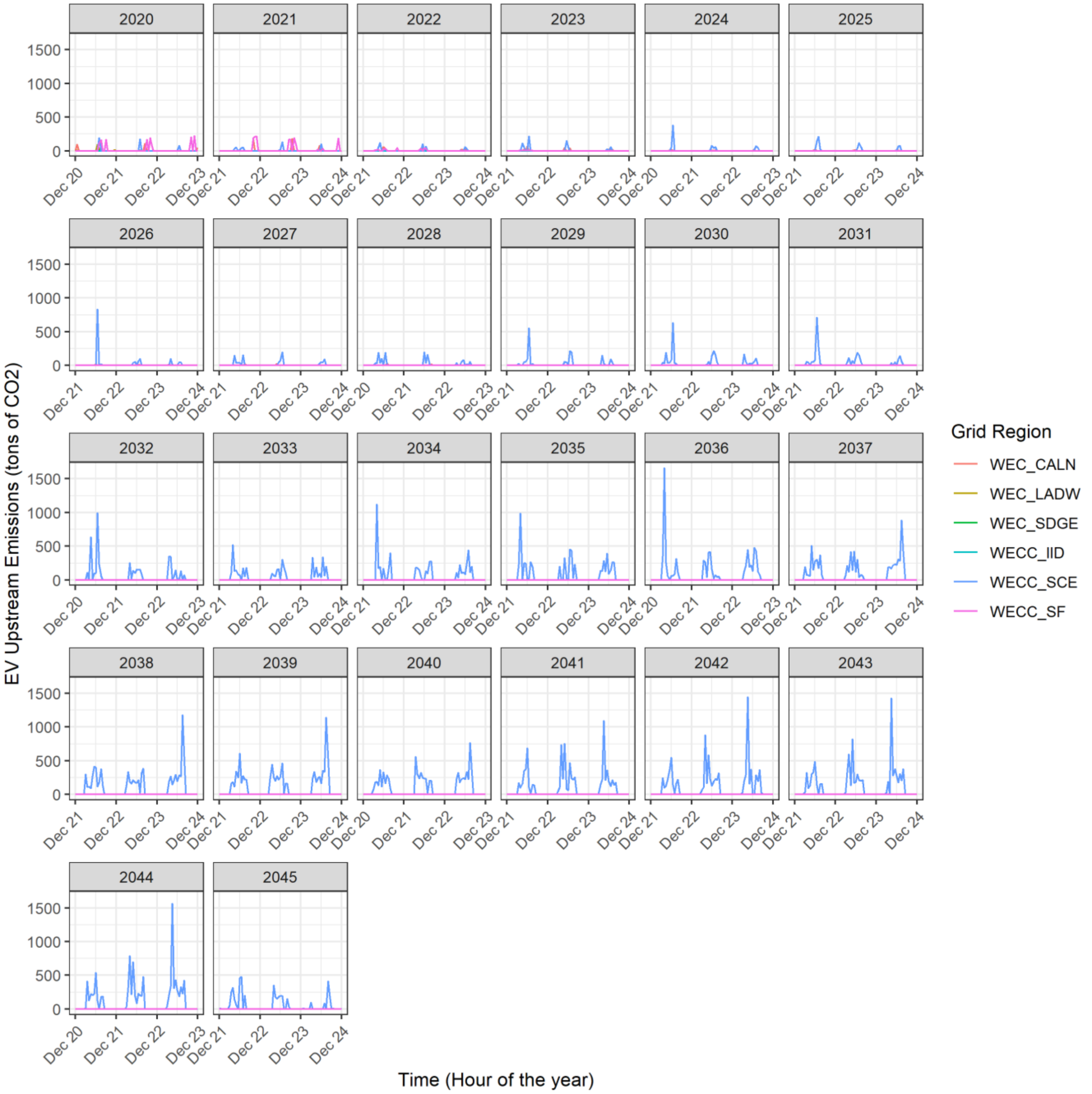

Figure 13. Sample of hourly emissions from EV charging with regular charging behavior over 3 days in the winter in six California grid regions. There are two countervailing factors that lead to different emissions trajectories: greater numbers of EVs on the road leads to higher emissions over time but this is opposed by an increase in the proportion of renewable energy generation on the electricity grid over time. The EV trend tends to outweigh the cleaning of the grid until 2045, which leads to a non-linear decrease at a

100% renewable energy requirement.

Figure 14. Sample of hourly emissions from EV charging with smart charging behavior over 3 days in the winter in six California grid regions. In comparison to a scenario with regular vehicle charging seen in Figure 13, in this scenario the peak emissions are nearly three times lower—leading to substantially lower emissions overall.

While EV upstream emissions per mile are already lower than those from gasoline vehicles, there is further potential for emissions reduction as the electricity grid powering EVs becomes cleaner through the RPS requirements in California. In Figure 15, we observe a decrease from over 175 kg CO_2/MWh in 2020 down to nearly 0 kg CO_2/MWh in 2045 due to the penetration of renewable resources (note that while 2045 has a 100% renewable requirement, there are some emissions occurring due to the presence of facilities like concentrated solar power, which may be supplemented with gas generators/turbines for operational reasons).

Despite the difference in capacity expansion of renewable generation (Figure 5) between scenarios of EV charging behavior, we do not observe a substantial difference between the two charging scenarios in average grid emissions rate. However, as a larger proportion of grid electricity is satisfied by renewable power at certain times, the timing of meeting demand can begin to have a greater influence on the emissions rate—in other words, if we examine the average emissions rate at specific hours of the day or days of the year, a larger difference can be observed. It is for this reason that we observe a difference in total emissions between the two charging scenarios.

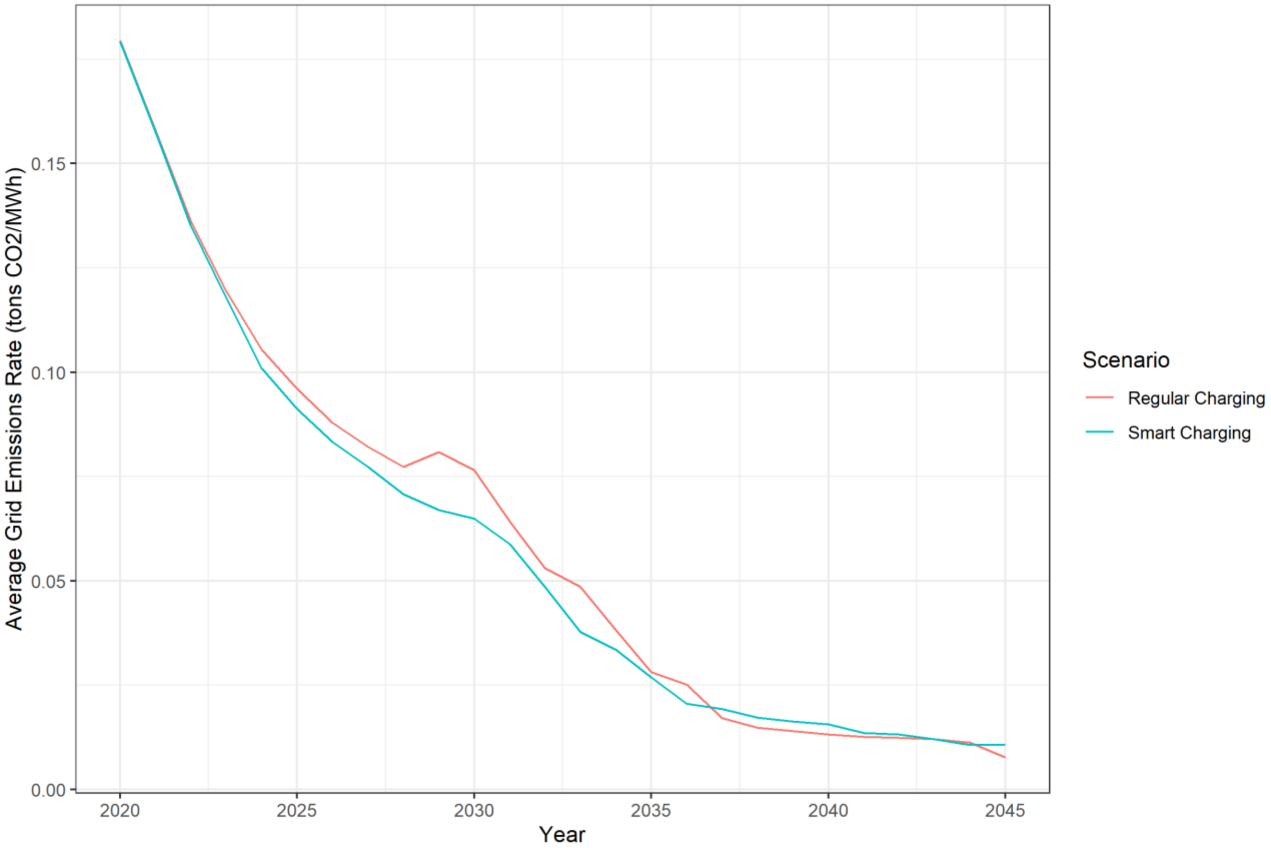

Figure 15. Average emissions rate of the electricity grid from 2020 through 2045 in California. The decrease in grid emissions rate is due to the required increase in renewable energy utilization from the Renewable Portfolio Standards with a 100% requirement in 2045. Two scenarios of regular versus smart charging behavior in EVs lead to slightly different grid compositions.

As we estimate the emissions from EV charging over time, there are two countervailing factors that can influence the trend in total emissions from EVs over time. The first is the RPS which will lead to a decrease in emissions as the regulation forces more renewable generation onto the grid (thus replacing carbon emitting fossil plants with zero carbon renewable sources). However, at the same time the total emissions from EVs will increase as more of the vehicles are adopted. Regardless of the charging scenario, the latter effect dominates at the start of the study period, and we observe annual emissions from EVs increasing through 2030 for regular charging or 2040 for smart charging. Despite the fact that the inflection point for the emissions trend occurs later in the smart charging scenario, the magnitude of the emissions is substantially lower than in the regular charging scenario. When considering the impact on climate change, it is the cumulative emissions that matter most, and the smart charging scenario leads to over 30% total lower emissions than the regular charging scenario over the period of study. It is critical to note that we are not discussing a counterfactual measurement, this is simply an accounting of the emissions coming from EVs. When considering EV replacement of gasoline cars, the trend in total emissions is always a substantial decrease (see Figure 17).

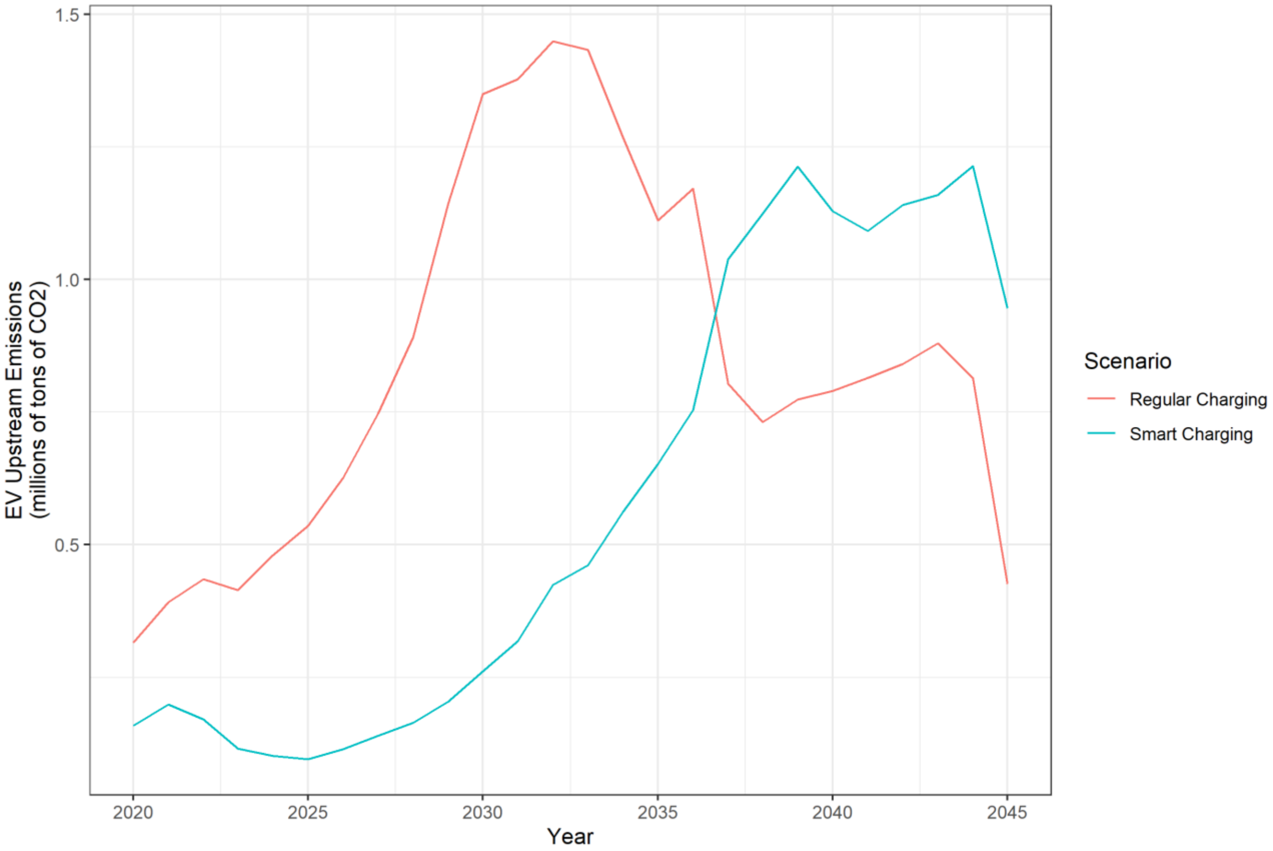

Figure 16. Total upstream annual emissions from the electricity grid for EV charging in two scenarios of charging (regular versus smart charging behavior).

7 Policy Discussion and Conclusions

In this section we provide a high-level overview of our results, focusing specifically on a series of outcomes between the two charging scenarios in this study. We then conclude with a discussion of the importance of policies to help direct California's transport and electricity sectors towards realizing some of the potential benefits from our modeling.

One of the primary outcomes of interest are the emissions associated with EVs. Our findings demonstrate how these annual totals will grow over time as the passenger fleet becomes more electrified. However, we do not want our results to be misconstrued as statement that EVs will lead to an overall increase in emissions in the passenger transport sector. In fact, we quantify the relative benefits of various transport scenarios in California in Figure 17. As can be seen, even without any improvements to the electricity grid, the lion's share of emissions reduction occurs from transitioning from gasoline to EVs. Even with a fairly aggressive efficiency standard with an annual 5% improvement in the fuel economy of new cars (mimicking the intent of the original Corporate Average Fuel Economy [CAFE] standards passed under President Obama's administration), the emissions benefits are dwarfed by an order of magnitude when electrifying passenger vehicles in California. Nevertheless, the focus of our work is the additionality of benefits that can be achieved even if all vehicles were electrified. A direct comparison of the measures can be seen in Figure 18 and include transitioning to a cleaner electricity grid and enabling smart charging of EVs. Fortunately, California already has policies promoting higher penetration of renewables (RPS) and adoption of EVs (ZEV rule). However, by promoting policies that can realize the potential of flexible charging, cumulative emissions from EVs can be further reduced by over 31% from 22 million tons of CO_2 down to 15 million tons.

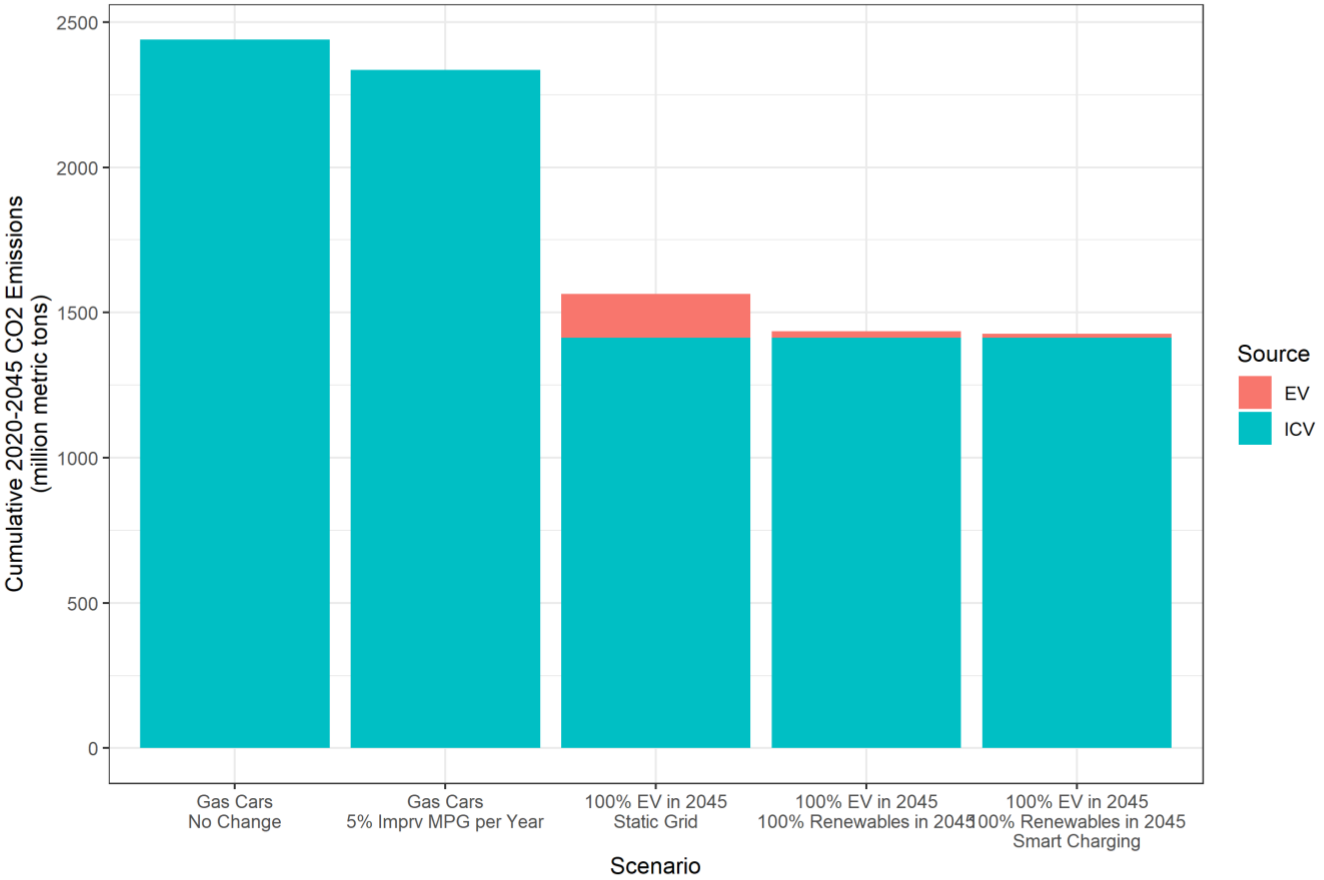

Figure 17. Cumulative greenhouse gas emissions from the passenger transportation sector (divided into emissions from EVs and gasoline vehicles) in California from 2020 through 2045 across five different scenarios (left to right): 1) business-as-usual scenario with no change in vehicle technology, 2) a scenario with no adoption of EVs but with a 5% improvement in fuel efficiency for new gasoline vehicles sold each year (in line with CAFE standards), 3) a transition to 100% passenger EVs by 2045 but with no improvements from the electric grid in 2020, 4) a transition to 100% passenger EVs and 100% renewable generation on the grid by 2045, and 5) a transition to 100% passenger EVs and 100% renewable generation on the grid as well as entirely smart charging behavior by 2045. (EV, electric vehicle; ICV, internal combustion engine vehicle)

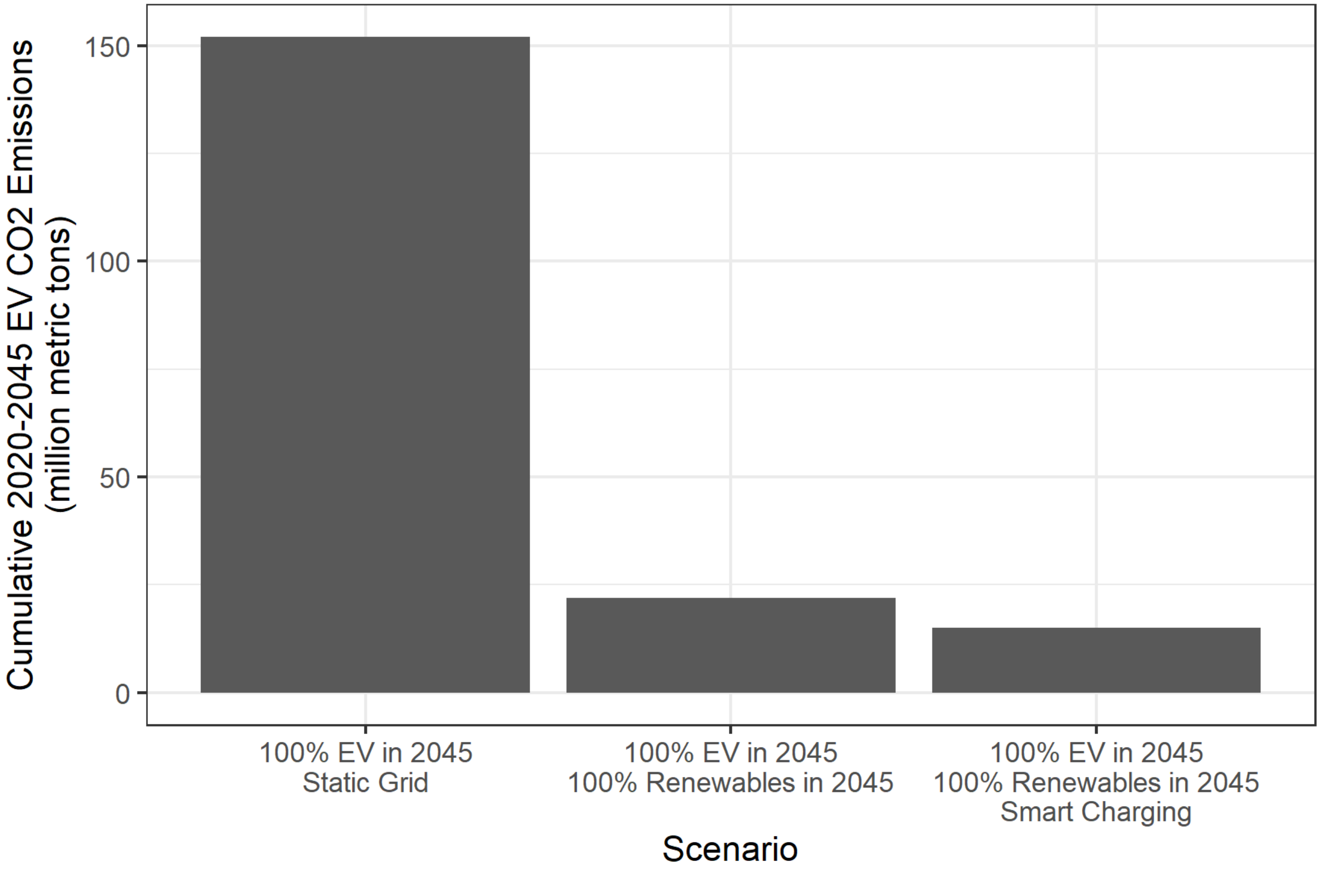

Figure 18. Cumulative greenhouse gas emissions from passenger EVs in California from 2020 through 2045 across the last three scenarios in Figure 17.

In addition to the emissions benefits, smart charging provides other systemic benefits. As we show in Figure 10, the increased flexibility of charging loads allows for a greater uptake of renewable generation (shifting charging demand to times with overgeneration by solar or wind resources). By reducing curtailment of renewables, both solar and wind generators operate more economically efficiently—effectively lowering the cost of those resources. In the breakdown of costs shown in Table 1, the smart charging scenario leads to slightly lower costs (though many of the benefits in the latter scenario will continue to accrue past 2045), saving nearly $30 billion in costs over the period of our study from 2020 through 2045. The smart charging takes advantage of slightly lower costs in solar capacity and deploys less wind capacity while leveraging the flexibility of EV charging to capture solar power generation.

Table 1. Cost breakdown of modeling scenarios

	Regular Charging Scenario	Smart Charging Scenario
Generation Costs	$65.3 billion	$67.2 billion
Solar Capacity Costs	$154 billion	$172 billion
Wind Capacity Costs	$264 billion	$227 billion
Storage Capacity Costs	$79.5 billion	$67.7 billion
Total Costs	**$563 billion**	**$535 billion**

From the perspective of emissions and system costs to the grid, taking advantage of EV charging flexibility is a win-win situation leading to both lower emissions and costs. The main deterrent to achieving this scenario is often thought of as behavioral, since, at low volumes of EVs, it may require shifting the charging times of EVs to times they may not be available (or that inconvenience owners). However, this problem is substantially reduced at larger volumes of EVs, since the intersection of vehicle flexibility over the entire fleet of vehicles often exceeds the need for demand shifting. As a result, simply providing some signal to differentiate better times to charge may suffice in capturing many of the benefits shown in this study. Following the results of our study, we suggest a broad set of policy objectives that consider the interactions of the transportation and electricity systems such that 1) synergies can be effectively enabled between EVs and a renewable energy transition, and 2) impacts of a simultaneous transformation can be addressed.

7.1 Supporting synergies between EVs and the electricity grid

7.1.1 Strategic deployment of charging infrastructure

As renewables become prevalent, it can be beneficial to shift charging load to certain times of the day to prevent curtailment and increase the uptake of solar or wind energy. The use of different types of charging infrastructure (public and workplace chargers versus residential chargers) is heavily correlated with the time of the day (Hardman et al., 2018; McLaren et al., 2016). One way to enable shifts towards charging at specific hours of the day is to provide opportunity and access to chargers for drivers. For example, deployment of workplace chargers can help increase uptake of midday solar energy peaks. By targeting specific outcomes for chargers, the infrastructure deployment can be made to better align with emission reduction targets in California.

7.1.2 Pricing signals to incentive strategic charging

Charger availability must also be coupled with pricing signals that lead to shifts in behavior (Chakraborty et al., 2019). Strategically pricing the cost of charging based on the time of day can lead to an increase in charging events at desirable times (midday for solar power and evening for wind power). Pricing of EV charging is currently regulated by the California Public Utilities Commission (CPUC). Integrating an emissions or renewables uptake goal into commercial EV charging rate setting would allow utilities and charging service providers the ability to rate recover while simultaneously aligning with sustainability outcomes. While rate recovery calculations would increase in complexity because providers would need to account for behavioral shifts in response to price changes, this tradeoff allows prices to be explicitly set to meet California's climate change goals.

7.1.3 Developing and standardizing smart charging and vehicle-to-grid protocols

One of the benefits of a large-scale adoption of EVs is the massive potential benefit for the electricity grid in the form of vehicle batteries that can double as energy storage for the grid. If California's approximately 25 million light-duty vehicles were to electrify, assuming a 150 to 200-mile range, there would be about 1,250 GWh of storage capacity. This is a substantial amount of storage considering peak electricity demand load in California is around 50 GW. Well-designed policy can streamline the ability of electric grid operators to take advantage of these storage resources from EVs, increasing uptake of renewable energy, decreasing curtailment, and reducing the total necessary capacity to meet peak loads.

Regulation is crucial in the standardization of protocols for communication of grid operators and/or utilities with vehicles and drivers. These protocols must be applied to a broad array of new technologies that include the charging infrastructure and the vehicles and must dictate what type of information they receive from the grid, how this information is transmitted and how and what type of information is conveyed between technologies. Such requirements would ensure that all vehicle models, regardless of the automaker, would be able to participate in a vehicle-to-grid system. This would also facilitate aggregators to create systems where participants can elect to allow their vehicles to participate as a grid resource for financial compensation. At large enough volumes, vehicle batteries can potentially mitigate many of the intermittency issues related to high penetration rates of renewable generation.

7.1.4 Public awareness campaigns to guide charging behavior

Most vehicles spend most of the time parked rather than moving. In theory this translates to an abundance of flexibility for when drivers choose to charge their vehicles. We have outlined several policy mechanisms that could help shift behavior, including requiring the installation of an abundance of chargers at the right locations and pricing strategies for these chargers. However, explicit messaging directly to consumers may also prove to be an effective avenue of shifting charging behavior. Drawing upon the success of the "Flex Your Power" program in California, which led to upwards of a 90% decrease in energy use during peak hours and over a 10% decrease in overall energy consumption in several California regions, an analogous program could be designed for EVs—particularly as the new technology begins to reach a critical mass.

7.2 Addressing impacts of a simultaneous transition

7.2.1 Supporting grid infrastructure requirements

Widespread charging infrastructure can lead to challenges for the electricity grid, particularly within the localized distribution infrastructure (Clement-Nyns et al., 2010). For a household, a single Level 2 charger can drastically increase the peak power demand—as these chargers become more widespread, they can stress the capacity of transformers and accelerate degradation. Similarly, for heavy-duty trucks, extreme charging requirements can potentially reach as high as 1 MW for a single charger. This would require a substantial amount of infrastructure to support. At the same time EVs are becoming increasingly popular, utilities must accelerate upgrades and rollout of distribution infrastructure in their respective territories. The California Public Utilities Commission must carefully consider the costs of additional infrastructure due to EVs, as well as how these costs can be recovered.

8 References

Brown, A., Sperling, D., Austin, B., DeShazo, J., Fulton, L., Lipman, T., Murphy, C., Saphores, J. D., Tal, G., Abrams, C., Chakraborty, D., Coffee, D., Dabag, S., Davis, A., Delucchi, M. A., Fleming, K. L., Forest, K., Sanchez, J. C. G., Handy, S., … Yang, A. (2021). *Driving California's Transportation Emissions to Zero*. https://doi.org/10.7922/G2MC8X9X

Chakraborty, D., Bunch, D. S., Lee, J. H., & Tal, G. (2019). Demand drivers for charging infrastructure-charging behavior of plug-in electric vehicle commuters. *Transportation Research Part D: Transport and Environment*, *76*(February), 255–272. https://doi.org/10.1016/j.trd.2019.09.015

Clement-Nyns, K., Haesen, E., & Driesen, J. (2010). The impact of charging plug-in hybrid electric vehicles on residential distribution transformers. *IEEE Transactions on Power Systems*, *25*(1), 371–380.

Freeman, G. M., Drennen, T. E., & White, A. D. (2017). Can parked cars and carbon taxes create a profit? The economics of vehicle-to-grid energy storage for peak reduction. *Energy Policy*, *106*, 183–190. https://doi.org/10.1016/j.enpol.2017.03.052

Gnann, T., Klingler, A. L., & Kühnbach, M. (2018). The load shift potential of plug-in electric vehicles with different amounts of charging infrastructure. *Journal of Power Sources*, *390*, 20–29. https://doi.org/10.1016/j.jpowsour.2018.04.029

Hardman, S., Jenn, A., Tal, G., Axsen, J., Beard, G., Daina, N., Figenbaum, E., Jakobsson, N., Jochem, P., Kinnear, N., Plötz, P., Pontes, J., Refa, N., Sprei, F., Turrentine, T., & Witkamp, B. (2018). A review of consumer preferences of and interactions with electric vehicle charging infrastructure. *Transportation Research Part D: Transport and Environment*, *62*. https://doi.org/10.1016/j.trd.2018.04.002

Jenn, A., Clark-Sutton, K., Gallaher, M., & Petrusa, J. (2020). Environmental impacts of extreme fast charging. *Environmental Research Letters*, *15*(9). https://doi.org/10.1088/1748-9326/ab9870

Kapustin, N. O., & Grushevenko, D. A. (2020). Long-term electric vehicles outlook and their potential impact on electric grid. *Energy Policy*, *137*(April), 111103. https://doi.org/10.1016/j.enpol.2019.111103

Liu, J., & Zhong, C. (2019). An economic evaluation of the coordination between electric vehicle storage and distributed renewable energy. *Energy*, *186*, 115821. https://doi.org/10.1016/j.energy.2019.07.151

McLaren, J., Miller, J., O'Shaughnessy, E., Wood, E., & Shapiro, E. (2016). CO2 emissions associated with electric vehicle charging: The impact of electricity generation mix, charging infrastructure availability and vehicle type. *Electricity Journal*, *29*(5), 72–88. https://doi.org/10.1016/j.tej.2016.06.005

Mehrjerdi, H., & Rakhshani, E. (2019). Vehicle-to-grid technology for cost reduction and uncertainty management integrated with solar power. *Journal of Cleaner Production*, *229*, 463–469. https://doi.org/10.1016/j.jclepro.2019.05.023

Muratori, M. (2018). Impact of uncoordinated plug-in electric vehicle charging on residential power demand. *Nature Energy*, *3*(3), 193–201. https://doi.org/10.1038/s41560-017-0074-z

Rahbari, O., Vafaeipour, M., Omar, N., Rosen, M. A., Hegazy, O., Timmermans, J. M., Heibati, S., & Bossche, P. Van Den. (2017). An optimal versatile control approach for plug-in electric vehicles to integrate renewable energy sources and smart grids. *Energy*, *134*, 1053–1067. https://doi.org/10.1016/j.energy.2017.06.007

Sheppard, C. J. R., Jenn, A. T., Greenblatt, J. B., Bauer, G. S., & Gerke, B. F. (2020). Private Versus Shared, Automated Electric Vehicles for U.S. Personal Mobility: Energy Use, Greenhouse Gas Emissions, Grid Integration and Cost Impacts. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3575130

Tal, G., Raghavan, S., Karanam, V., Favetti, M., Sutton, K., Lee, J. H., Nitta, C., Chakraborty, D., Nicholas, M., & Turrentine, T. (2020). Advanced plug-in electric vehicle travel and charging behavior-final report. *California Air Resources Board Contract*, 12–319.

Thompson, A. W., & Perez, Y. (2020). Vehicle-to-Everything (V2X) energy services, value streams, and regulatory policy implications. *Energy Policy*, *137*(July), 111136. https://doi.org/10.1016/j.enpol.2019.111136

Zhang, C., Greenblatt, J. B., MacDougall, P., Saxena, S., & Jayam Prabhakar, A. (2020). Quantifying the benefits of electric vehicles on the future electricity grid in the midwestern United States. *Applied Energy*, *270*(February), 115174. https://doi.org/10.1016/j.apenergy.2020.115174