Applied Energy 339 (2023) 120974

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Emissions of electric vehicles in California’s transition to carbon neutrality

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HIGHLIGHTS

- California’s decarbonization strategy will lead to 1 billion tons of CO_2 saved in the light-duty transportation sector.
- Grid decarbonization can further decrease emissions by over 100 million tons of CO_2 in California.
- The majority of emissions savings in the technology transition comes from vehicle electrification rather than grid decarbonization.
- Smart charging can potentially decrease grid costs in a full renewable transition by about 5%

ARTICLE INFO

Keywords:
Electric vehicles
Emissions
Electricity grid
Smart charging
ZEV
California

ABSTRACT

California has a many activities targeting specific sectors to mitigate climate change. This study models several scenarios of future electric vehicle emissions in the state and explores untapped policy opportunities for interactions between sectors, specifically between the transportation and 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 involved the creation of a model to predict the potential emissions benefits of managed vs. unmanaged charging. The study finds that 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. This figure represents a decrease of about 4 tons CO_2/capita/year from the average operation of Californian passenger vehicles in 2020 to about 40 kg CO_2/capita/year in 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, additional policies to exploit synergies between transportation electrification and grid decarbonization could reduce cumulative emissions by another 10 million tons of CO_2.

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 (GHG) 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]), vehicle electrification (Zero

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[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.

https://doi.org/10.1016/j.apenergy.2023.120974
Received 12 September 2022; Received in revised form 6 March 2023; Accepted 10 March 2023
Available online 20 March 2023
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Emissions Vehicle [ZEV][6] and Advanced Clean Trucks[7] Programs).

The transportation sector represents the largest source of GHG emissions in California at 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 both 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 synergies between transportation and the electricity grid likewise 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.

While this study focuses on impacts of California's policy landscape, the work will serve as a foundation of the emissions in other regions both in the US and internationally if they follow similar policy trajectories. In fact, there is tremendous precedent for California policies to reach broader stages: 10 other states have also adopted California's Zero Emission Vehicle regulation as have countries such as China, Canada, and South Korea [1]; Renewable Portfolio Standards (RPS) are prevalent in many states and countries around the world [2]. As other regions are influenced by California's aggressive policies [3], the benefits examined in this study can serve as a foundation for quantifying emissions impacts for other policymakers.

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 the body of relevant research in this area is reviewed.

Most studies of electric vehicle 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, in a study by Kasputin and Grushevenko, the authors 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 20% global electricity consumption annually in 2040 [4]. 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 as high as 50% once market share reaches 100% [5].

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, a study by Thompson and Perez provides a comprehensive overview of the energy services, value streams, and policy implications of connecting vehicles to the grid [6]. 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 examines value streams from participation in grid-services from electric vehicles can lead to positive savings. While their findings are smaller than those found in the Thompson study, their conclusion remains the same: economic benefits can be captured by participating in grid services. Importantly, they investigate several scenarios that include a carbon tax which lead to larger savings—indicating a synergistic opportunity to mitigate carbon emissions [7].

Many studies point to a specific problem with increased load as a grid issue in power availability (as opposed to energy). 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 electric vehicles in the midwestern United States, Zhang et al. show that while uncontrolled charging can increase peak load 8 GW (a 10% increase over the baseline), unidirectional controlled charging can reduce this increase to 2% while bidirectional controlled charging can actually reduce the peak by upwards of 30% [8]. This is similar in result to 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 [9]. Likewise, smart charging with heavier-duty application vehicles can reduce impacts on the grid down to the distribution level [10]. These examples are generally consistent in magnitude with literature on load shifting and peak shaving for future scenarios of electric vehicle adoption.

However, beyond general shifts in electricity load, electric vehicles 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 electric vehicle charging may help to mitigate these issues. Rahbari demonstrates a technical example of bi-directional charging to integrate electric vehicles into the grid. In this study, the authors are able to match the renewable energy profile of both wind and PV generation units throughout the test bus (a hypothetical power system to represent the simulation of a portion of the electricity grid) area using only flexibility in charging—even without the presence of any permanent grid storage resources [11]. 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 electric vehicles [12]. 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 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 electric vehicles with renewable energy systems (or any electricity system). This work is a continuation of these studies at a much larger scale—rather than simulating a hypothetical power bus system, it simulates all of California with scenarios that extend to 100% adoption of both electric vehicles and renewable power generation.

Beyond renewable integration, several studies have also attempted

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[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.

to examine the long-term upstream emissions impacts of electric vehicle adoption. These studies range in coverage from local city-level impacts such as Los Angeles [13], to larger regions such as the European Union [14], up to worldwide impacts [15,16]. The work in this paper expands the approaches from these studies in several ways: the resolution of electric vehicle adoption is at a substantially higher resolution backed by empirical data and the treatment of the electricity grid moves beyond marginal emissions estimates or static grid factors. Accounting for the evolution of the grid allows for an improved integration with dynamic shifts in the power sector that happen over time—a crucial factor missing from much of the existing literature.

There already exists some work examining policy opportunities to integrate with renewables. 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 utilizing EV battery capacity acting as distributed storage on the demand side. 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 [17]. Likewise, this study measures the benefits of EV grid integration measures in California and discusses the policy mechanisms to help realize these benefits.

The remaining report is divided as follows: Section 4 describes the future of electric vehicle adoption in California and their associated charging behavior, Section 4.2 describes how to simulate the electricity grid of the Western Interconnect, Section 5 reveals how the grid operates in response to electric vehicle charging events, and finally Section 6 concludes with a discussion of the findings and policy implications of this work.

3. Data and methods

3.1. Forecasting vehicle adoption and charging behavior

The study employs a vehicle adoption model known as the EV Toolbox, developed by the Plug-in Hybrid and Electric Vehicle Center at the University of California, Davis [18]. The modeling approach consists of the following procedures:

1. Vehicle adoption forecast (levels and method)
2. Charging simulation approach (bootstrapping)
3. Difference in pattern and magnitude (season, uncontrolled vs smart charging, over time)

The adoption forecast in Fig. 1 originates from a University of California-wide study examining the required trend of electric vehicle adoption needed to decarbonize the transportation sector in California [19]. The projection closely aligns with the California Air Resources Board's projections for new electric vehicle sales necessary to meet the recently passed Advanced Clean Cars II rule[9], specifying all new light-duty vehicles (covering both passenger cars and light-duty trucks) sold in California must be zero emissions by 2035.

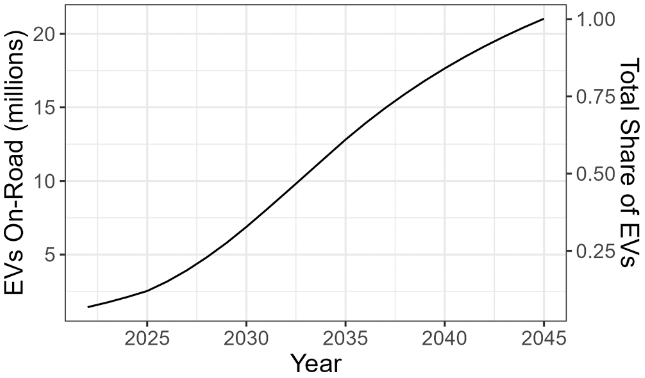

Fig. 1. Projection of electric vehicle adoption in California.

The charging simulation is based on a bootstrapping the charging behavior of vehicles from empirical data from observed charging patterns (this technique follows closely to the procedure described in a study by [20]). The demand is allocated from the EV Toolbox model across a full year, specifically randomly distributing the charging events across each day of the year using a uniform distribution. The charging patterns within a given day are then bootstrapped from empirical observations of charging behavior. The 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 its 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 electric vehicles outfitted with loggers in a separate study by researchers at the Plug-in Hybrid Electric Vehicle center at UC Davis [21] combined with public charging service provider infrastructure data [20].

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 Figures Figs. 2-4 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 Fig. 2, 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 electric vehicle charging volumes do not present any difficulty to the grid to meet. However, in Fig. 3 there is 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. This effect occurs because renewable resources are not dispatchable, therefore having flexible load resources (such as those offered from EVs involved with smart charging) can match over or under-supply of electricity generation. These results are further expanded in later years as shown in Fig. 4, 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 electric vehicles on the road. While smaller regions in Southern California (such as the Imperial Irrigation District [IID]) 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 very strong

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[9] California Air Resources Board. "Advanced Clean Cars II Regulations: All New Passenger Vehicles Sold in California to be Zero Emissions by 2035." https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii.

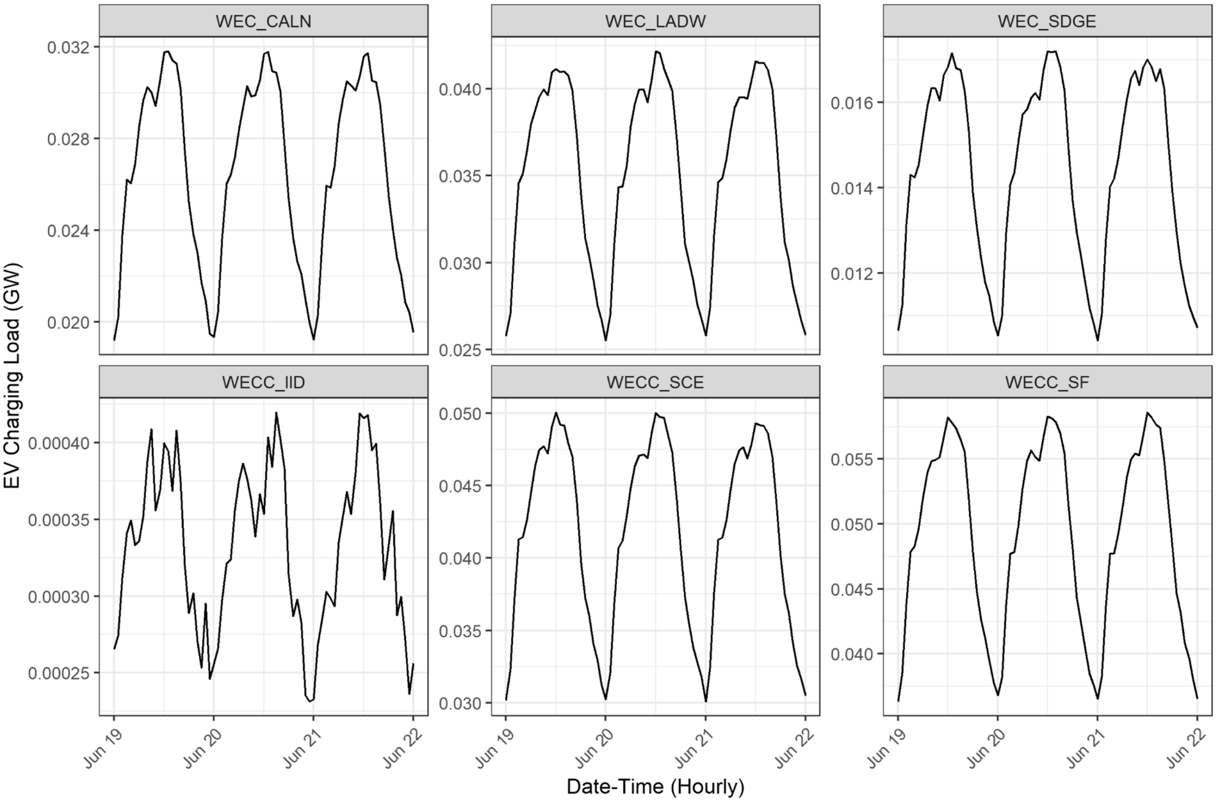

Fig. 2. Sample of three days of hourly charging profiles of all electric vehicles in California in the summer of 2020 with regular charging patterns. The relative magnitude of charging remains fairly constant (on the order of hundreds of kW up to tens of MW in load demand depending on the region) but with noticeable variation from day to day.

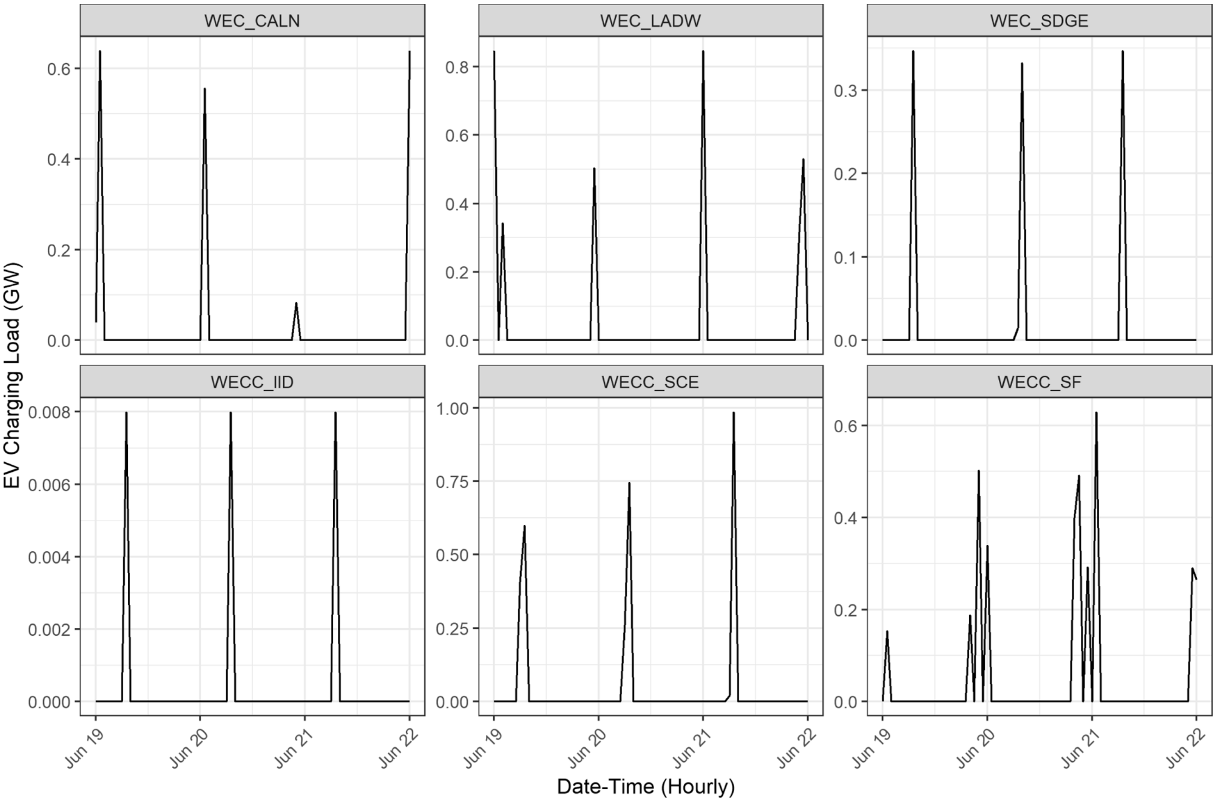

Fig. 3. Sample of three days of hourly charging profiles of all electric vehicles in California in the summer of 2020 with smart charging. The magnitude of the charging events remains fairly small but with large spikes indicating a preference for a particular time of day.

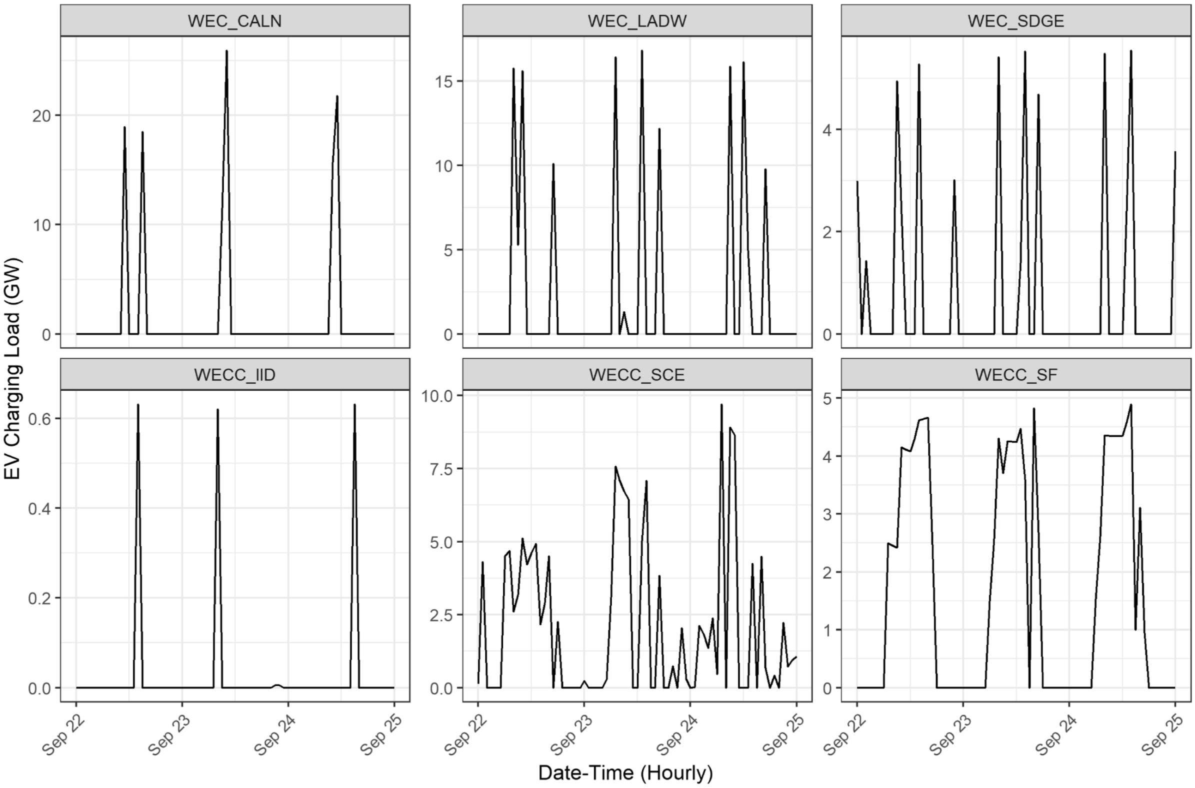

Fig. 4. Sample of three days of hourly charging profiles of all electric vehicles in California in the summer of 2045 with smart charging. In the presence of 100% renewable generation, charging behavior is still fairly spikey, but in comparison to the 2020 run there are several sudden charging spikes throughout the day (in addition to being substantially larger in magnitude) that are indicative of addressing renewable intermittency issues.

indication of the opportunity costs that can be captured by introducing flexibility in charging patterns. These benefits are quantified in terms of both social costs and emissions.

3.2. *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 [20,22]. The extent of the GOOD model for this study covered the Western Electricity Coordinating Council interconnect region (divided into 16 balancing zones) and all power generating assets contained within this region (see Fig. 5). While the focus of the 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, the full formulation of the GOOD model is provided.

3.3. *Objective function: Total cost of the system*

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

$$\min_{\substack{x_{gt}^{\text{gen}},x_{rto}^{\text{trans}},x_{rt}^{\text{ev.flexLoad}},\\ x_r^{\text{new.solar}},x_r^{\text{new.wind}},\\ x_r^{\text{storage.cap}},x_{rt}^{\text{storage.soc}},\\ x_{rt}^{\text{storage.in}},x_{rt}^{\text{storage.out}}}} \left(\begin{array}{c} \sum_g \sum_t x_{gt}^{\text{gen}} c_g^{\text{gen.cost}} + \sum_r \sum_t \sum_o x_{rto}^{\text{trans}} c_{ro}^{\text{trans.cost}} + \\ \sum_r x_r^{\text{new.solar}} c^{\text{solarCost}} + x_r^{\text{new.wind}} c^{\text{windCost}} + x_r^{\text{storage.cap}} c^{\text{storageCost}} \end{array} \right) \tag{1}$$

3.3.1. *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 is comprised of two exogenous parameters: baseload demand and charging load demand from electric vehicles as determined by the mobility portion of the modeling system.

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

3.3.2. *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 electric vehicles is now a decision variable (the GOOD

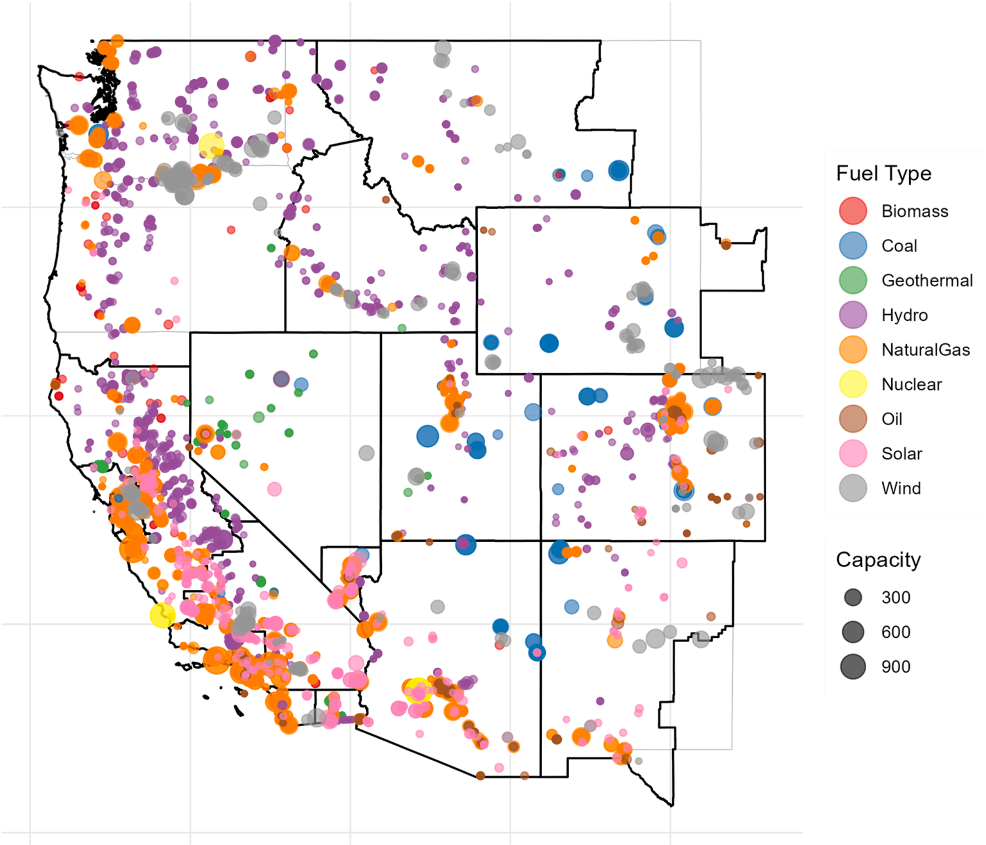

Fig. 5. Breakdown of regional balancing zones within the Western Interconnect electricity grid system along with the individual power generation assets. Each generator is distinguished by its color (fuel type) and size (capacity [MW]).

model determines the best time that EVs should charge).

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

3.3.3. *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.

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

3.3.4. *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.

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

3.3.5. *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 electric vehicles. The hourly demand is allowed to be determined endogenously but the aggregate demand must be fulfilled within a larger time window.

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

3.3.6. *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.

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

3.3.7. *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.

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

3.3.8. *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.

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

3.3.9. *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, the charging/discharging limit is set equal to 25% of the total capacity of the storage device.

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

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

Parameter values for input assumptions in the GOOD model include generator and transmission infrastructure attributes, costs (fuel costs for generators, transmission wheeling costs, capacity costs), and renewable capacity factors. These inputs are derived from the latest data from EPA's Emissions & Generation Resource Integrated Database (eGRID)[10] and their Power Sector Modeling Platform NEEDS v6[11].

The addition of renewable resources to simultaneously meet additional load from electric vehicles and California's RPS requirements can be seen in Fig. 6. It is here that some of the benefits of smart charging become evident: while the amount of renewable capacity installed is fairly similar between the charging scenarios, the required storage to deal with intermittency is substantially smaller in the smart charging scenario. 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).

Fig. 7 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 the resource is slightly cheaper than wind power and as it saturates the load demand over the hours where it is able to provide electricity, wind power then must be then installed (and later storage) in order 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 electric vehicles. The decrease in overall generation in California in the final period of analysis is due to the RPS requirement reaching 100% of total generation. The side-effect of this policy is a massive increase in storage capacity which induces a corresponding increase in electricity imports, hence leading to lower generation within the state.

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 this study indicates that there are substantial benefits to the electricity grid by capturing flexibility from charging of electric vehicles. Electric vehicle 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.

4. Results

4.1. *Meeting EV demand*

In this section the operational results of the GOOD model's simulation of the power system are shown to meet both the baseload demand of electricity as well as the charging demand coming from electric vehicles. In Fig. 8 and Fig. 9, dispatch curves are shown 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 as well as 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 Fig. 8, there is a diversity in the shape of the dispatch curves between different regions, though it should be noted that 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 LADW, SDGE, SCE, and SF regions, load that is unmet from renewables tends to be met from natural gas, while in IID it is met with geothermal, and in CALN it is met with a combination of natural gas and hydro.

As electric vehicle load increases and the grid integrates more renewables, dispatch differs in 2035 as seen in Fig. 9. 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 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. There is 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. Differences in dispatch are shown between the regular charging (Fig. 9) and the smart charging (Fig. 10) 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.

Asides from reducing the required renewable capacity expansion, the smart charging scenario also significantly reduces the total amount of curtailment compared to the regular charging scenario (Fig. 11). 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 electric vehicles 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

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[10] https://www.epa.gov/egrid/download-data.

[11] https://www.epa.gov/power-sector-modeling/power-sector-modeling-platform-v6-november-2018.

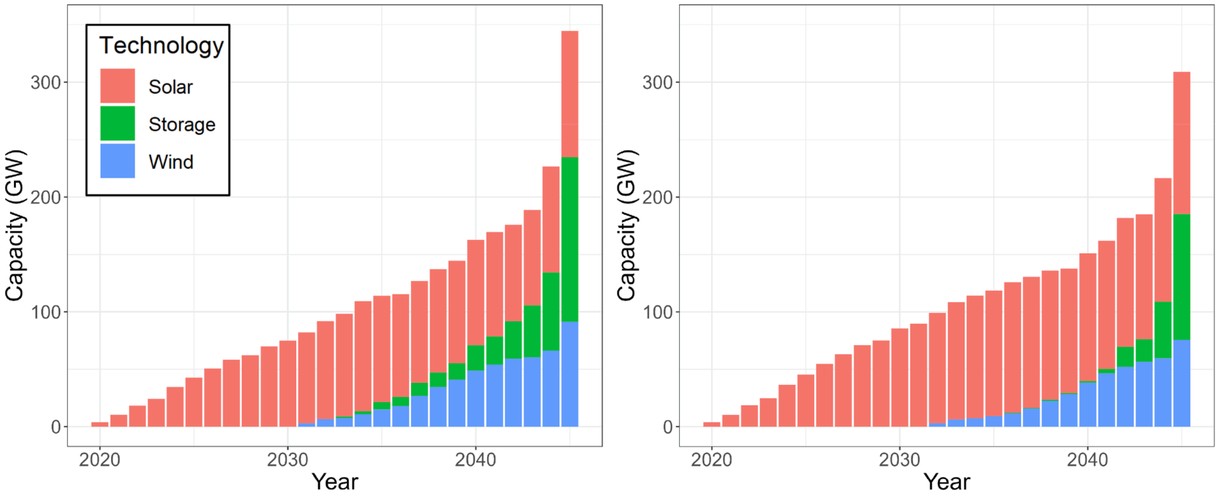

Fig. 6. Renewable energy and grid storage capacity growth over time to meet demand requirements and California's Renewable Portfolio Standards. Capacity expansion is shown for two scenarios. regular charging behavior for electric vehicles (left) and smart charging behavior for electric vehicles (right). The current installed capacity in California is approximately 80 GW.

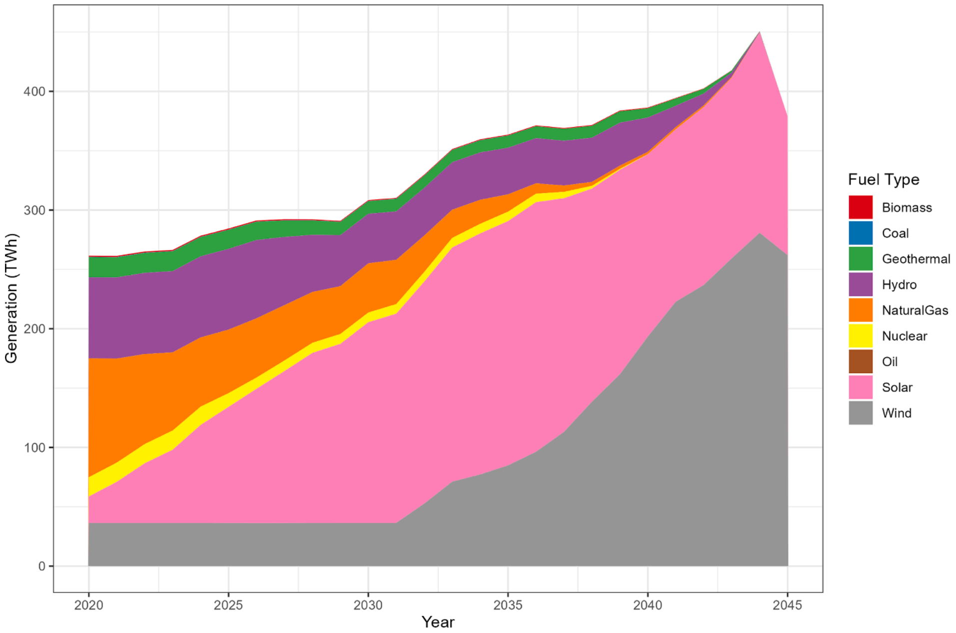

Fig. 7. Shift in generation mix over time in California from 2020 through 2045 as the electricity system simultaneously meets constraints for increased demand load from charging electric vehicles and Renewable Portfolio Standard requirements (note that storage capacity is not included).

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 loses due to curtailment.

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 to help smooth intermittency. A comparison of the operation of grid storage in regular versus smart charging scenarios is shown in Fig. 12 and Fig. 13. 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. Despite fairly large fluctuations in the peak load demand throughout the year, there is not 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).

4.2. Emissions impacts of EVs

The long-term adoption of electric vehicles 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 electric vehicle charging events. While electric vehicle upstream emissions per mile are already lower than those from gasoline vehicles, there is further potential for emissions reduction as the electricity grid powering electric

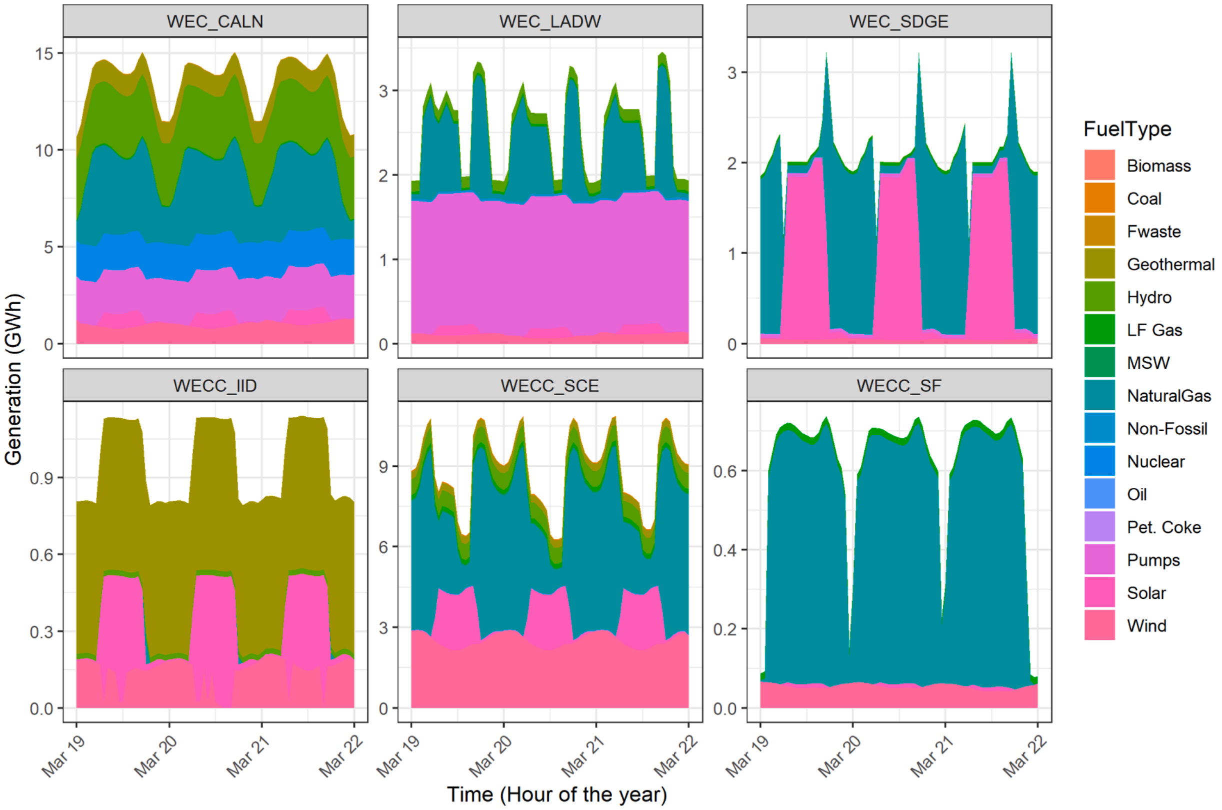

Fig. 8. Generation dispatch curves for California across a sample of three days in the spring of 2020. Load curves include both baseload demand as well as demand from regular charging patterns of electric vehicles.

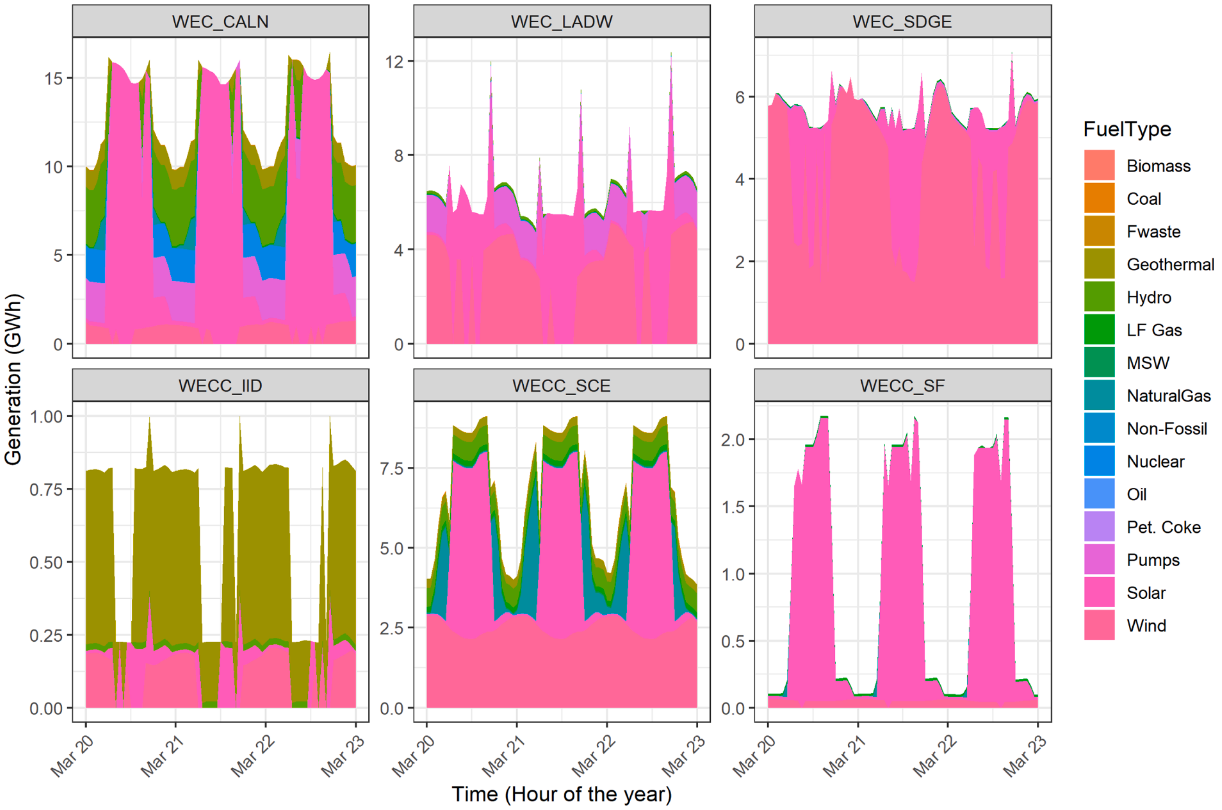

Fig. 9. Generation dispatch curves for California across a sample of three days in the spring of 2035. Load curves include both baseload demand as well as demand from regular charging patterns of electric vehicles. Spring 2035 regular.

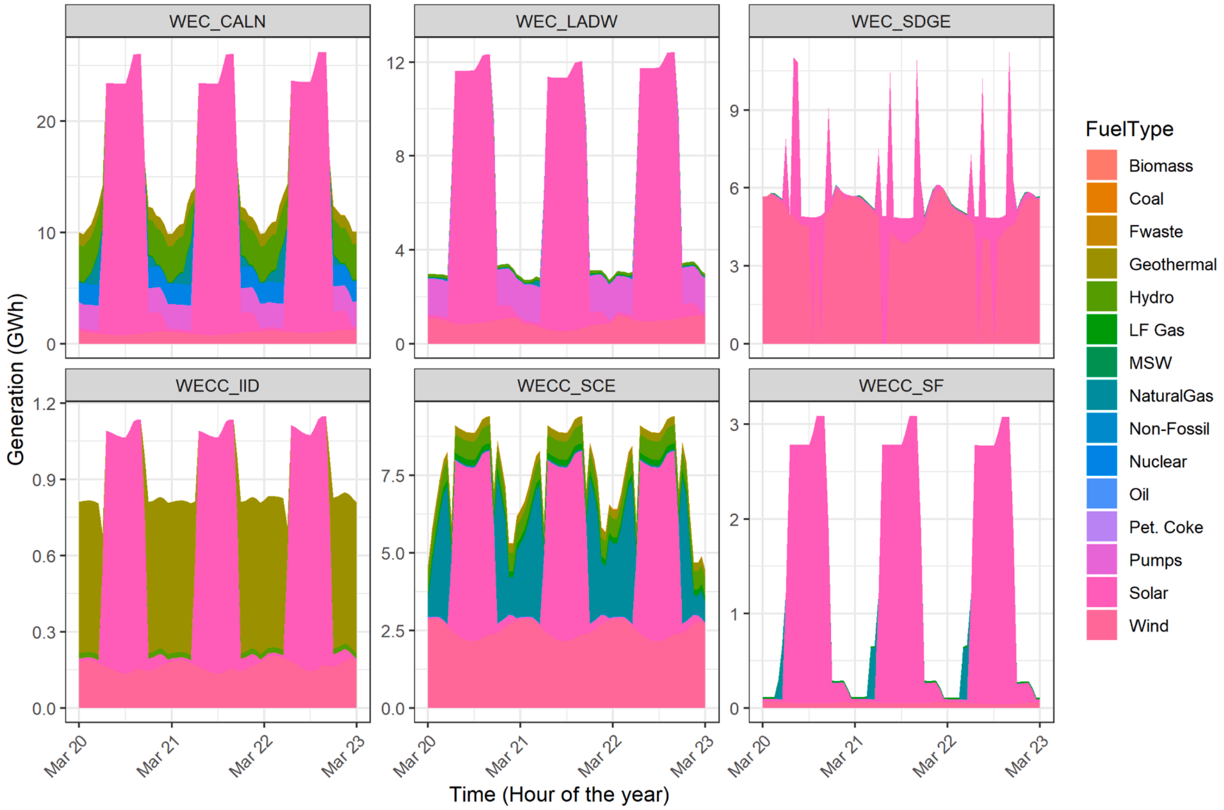

Fig. 10. Generation dispatch curves for California across a sample of three days in the spring of 2035. Load curves include both baseload demand as well as demand from smart charging patterns of electric vehicles.

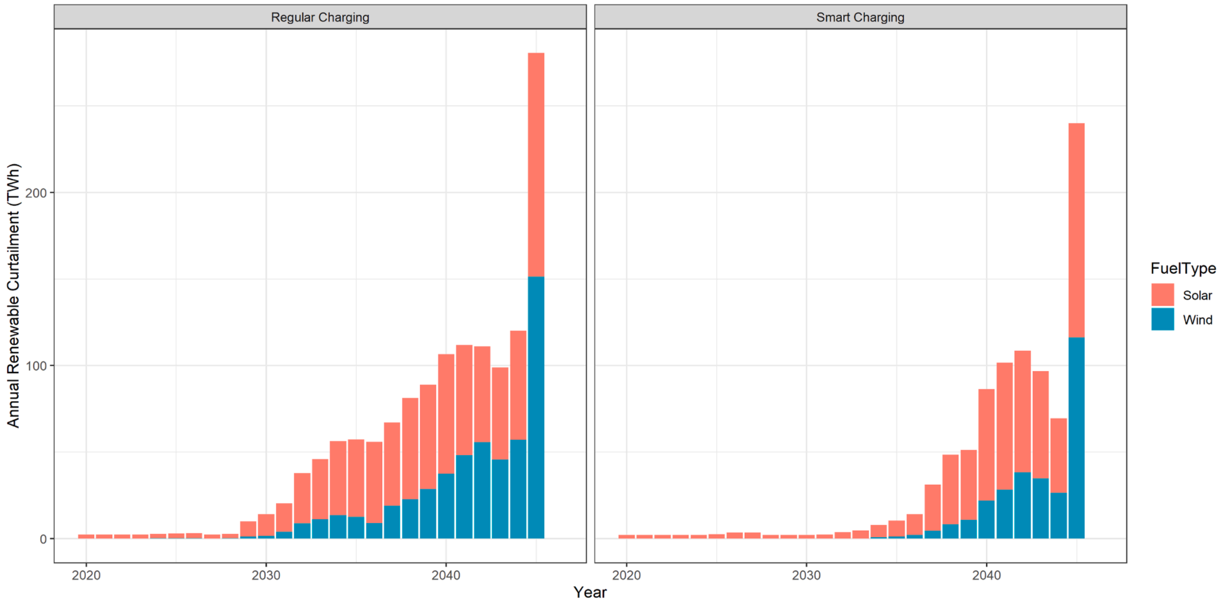

Fig. 11. Annual curtailment from solar and wind renewable resources as RPS requirements increase year to year. Curtailment is shown for two scenarios. regular charging behavior (left) and smart charging behavior (right).

vehicles becomes cleaner through the RPS requirements in California. In Fig. 14, there is 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 (Fig. 6) between scenarios of electric vehicle charging behavior, there is not a substantial difference between average grid emissions rate of the two charging scenarios (Fig. 15). 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 a larger difference can be observed between

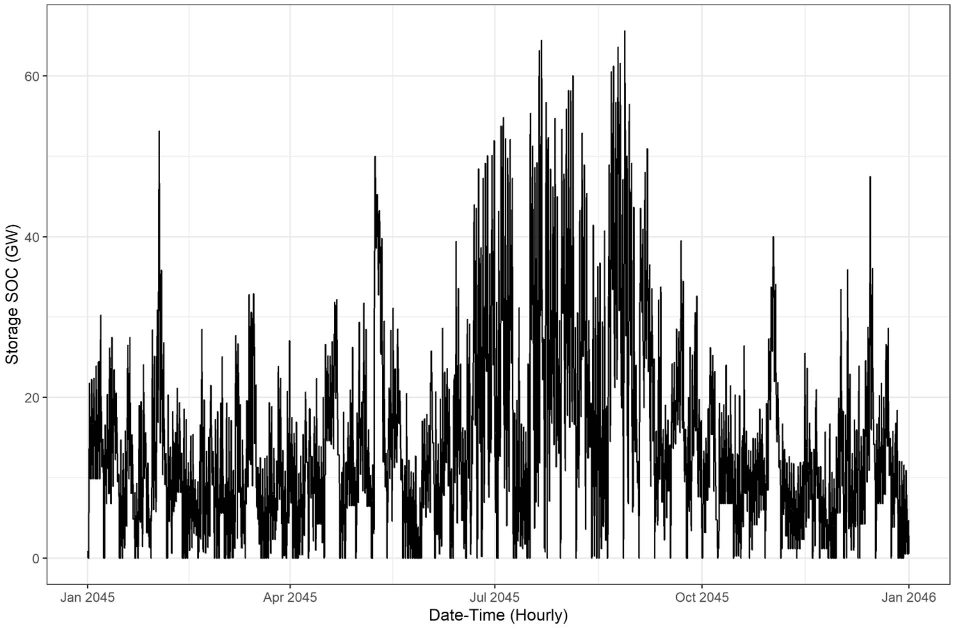

Fig. 12. Aggregate view of total grid battery storage operation across California in 2045. The depicted scenario is for regular charging patterns for electric vehicles throughout the state. Peak capacity of the storage is slightly over 60 GWh with peak SOC events happening regularly throughout the summer months and several peaks reaching 80% SOC in the remaining seasons.

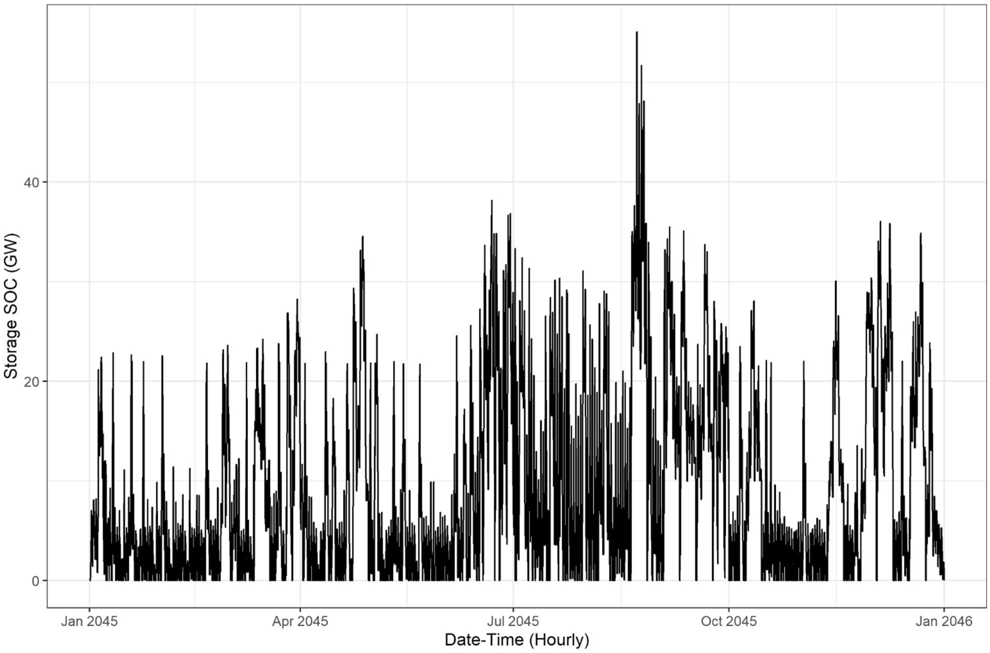

Fig. 13. Aggregate view of total grid battery storage operation across California in 2045. The depicted scenario is for smart charging patterns for electric vehicles throughout the state. Peak capacity of the storage is slightly over 50 GWh with peak events happening only once throughout the year in a summer event. Throughout the remainder of the year, there are no events that reach 80% of SOC.

average emissions rate at specific hours of the day or days of the year. This is the primary reason for the difference in total emissions between the two charging scenarios. Nevertheless, the overall grid emissions mix is not substantially affected by charging scenarios—its decrease is driven primarily by the increase in renewable capacity (even if the emissions associated with the charging events themselves maybe associated with different emissions rates).

As emissions from electric vehicle charging changes over time, there are two countervailing factors that can influence the trend in total emissions from electric vehicles over time. The first is the Renewable Portfolio Standards 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 electric vehicles 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 annual emissions from electric vehicles increases through 2030 for regular charging or 2040 for smart charging. Despite the fact that the inflection point for emissions trend occurs later in the smart charging scenario, the magnitude of the emissions is substantially lower

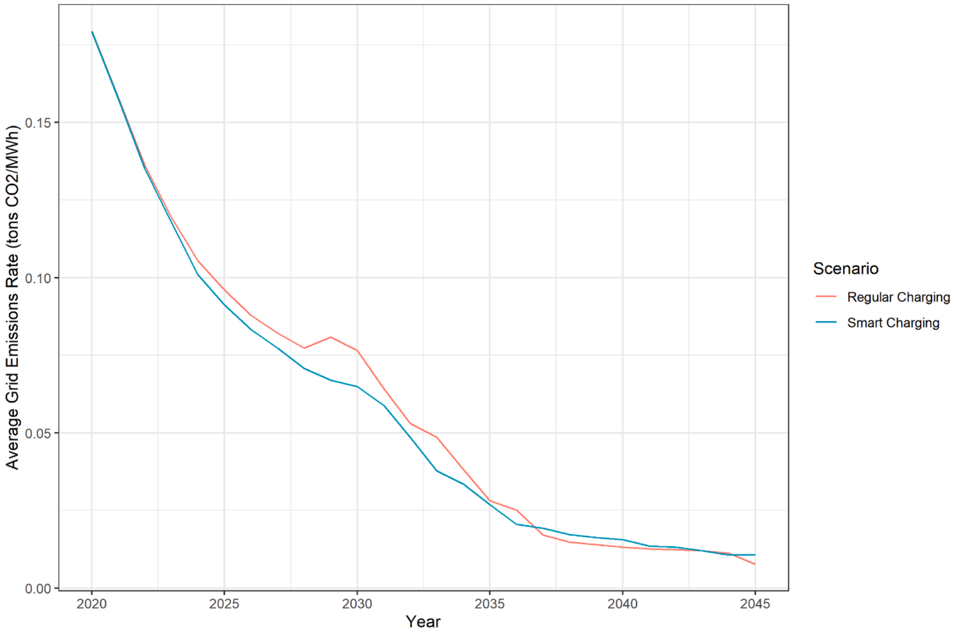

Fig. 14. Average emissions rate of the electricity grid from 2020 through 2045 in California. The decrease in grid emissions rate is due to the required increase in renewable energy utilization from the Renewable Portfolio Standards with a 100% requirement in 2045. Two scenarios of regular versus smart charging behavior in electric vehicles lead to slightly different grid compositions.

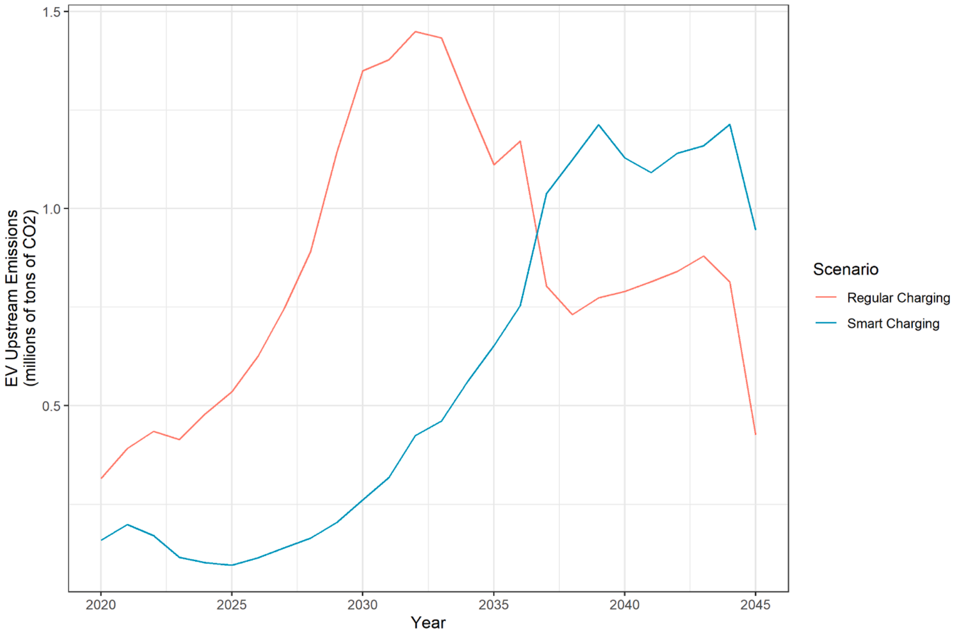

Fig. 15. Total upstream annual emissions from the electricity grid for electric vehicle charging in two scenarios of charging (regular versus smart charging behavior).

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 the study is not discussing a counterfactual measurement, this is simply an accounting of the emissions coming from electric vehicles. When considering electric vehicle replacement of gasoline light-duty vehicles, the trend in total emissions is always a substantial decrease (see Fig. 17).

5. Policy discussion and conclusions

This section provides a high-level overview of the results, focusing specifically on a series of outcomes between the two charging scenarios in this study. It then concludes 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 the modeling.

One of the primary outcomes of interest are the emissions associated with electric vehicles and the findings demonstrate how these annual totals will grow over time as the passenger fleet becomes more electrified. However, the results should not be misconstrued as a statement that electric vehicles will lead to an overall increase in emissions in the passenger transport sector. In fact, the relative benefits of various transport scenarios in California are substantive as seen in Fig. 16 and Fig. 17. Even without any improvements to the electricity grid, the lion's share of emissions reduction occurs from transitioning from gasoline to electric vehicles. Even with a fairly aggressive efficiency standard with an annual 5% improvement in the fuel economy of new light-duty vehicles (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 the 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 Fig. 16 and Fig. 18 and include transitioning to a cleaner electricity grid and enabling smart charging behavior from electric vehicles. Fortunately, California already has policies promoting higher penetration of renewables (RPS) and adopting electric vehicles (ZEV rule). However, by promoting policies that can realize the potential of flexible charging, cumulative emissions from electric vehicles can be further reduced by over 31% from 22 million tons of CO_2 down to 15 million tons.

In addition to the emissions benefits, smart charging also provides other systemic benefits. As shown in Fig. 11, 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.

From the perspective of emissions and system costs to the grid, taking advantage of electric vehicle charging flexibility is a win–win situation leading to both lower emissions and costs captured within the GOOD model. The main deterrent to achieving this scenario is often thought of as behavioral, since at low volumes it may require shifting the charging of electric vehicles to times they may not be available (or are inconvenienced in doing so). However, this problem is substantially reduced at larger volumes of electric vehicles 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 the study, a broad set of policy objectives should consider the interactions of the transportation and electricity systems such that 1) synergies can be effectively enabled between electric vehicles and a renewable energy transition and 2) impacts of a simultaneous transformation can be addressed. However, it is important to note that policy itself must supplement both socio-economic and techno-economic factors to ensure a successful transition to a decarbonized transportation system.

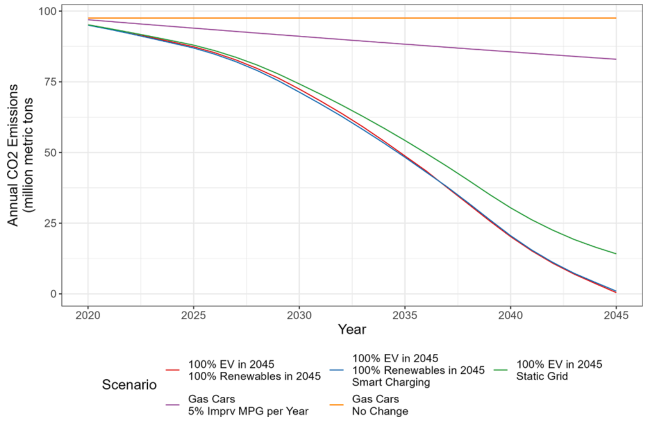

Fig. 16. Annual greenhouse gas emissions from the transportation sector in California from 2020 through 2045. Five scenarios are represented. 1) business-as-usual scenario with no change in vehicle technology, 2) a scenario with no adoption of electric vehicles but with a 5% improvement in fuel efficiency for new gasoline vehicles sold each year (in line with CAFE standards), 3) a transition to 100% passenger electric vehicles by 2045 but with no improvements from the electric grid in 2020, 4) a transition to 100% passenger electric vehicles and 100% renewable generation on the grid by 2045, and 5) a transition to 100% passenger electric vehicles and 100% renewable generation on the grid as well as entirely smart charging behavior by 2045.

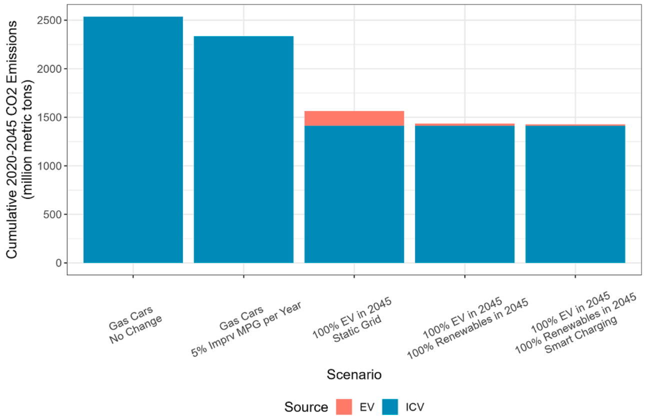

Fig. 17. Cumulative greenhouse gas emissions (area under the curve in Fig. 16) from the passenger transportation sector (divided into emissions from electric vehicles and gasoline vehicles) in California from 2020 through 2045 across five different scenarios (left to right). 1) business-as-usual scenario with no change in vehicle technology, 2) a scenario with no adoption of electric vehicles 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 electric vehicles by 2045 but with no improvements from the electric grid in 2020, 4) a transition to 100% passenger electric vehicles and 100% renewable generation on the grid by 2045, and 5) a transition to 100% passenger electric vehicles and 100% renewable generation on the grid as well as entirely smart charging behavior by 2045.

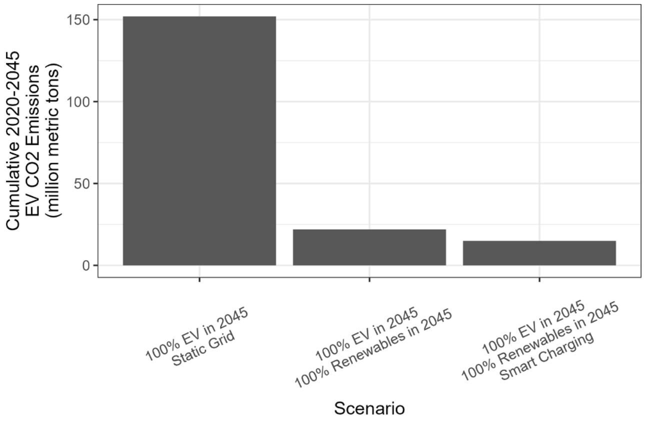

Fig. 18. Cumulative greenhouse gas emissions from passenger electric vehicles in California from 2020 through 2045 across the latter three scenarios in Fig. 17.

There are several limitations of this study. This work relies on assumptions that the California vehicle market will comply with CARB's ACCII regulations and shift to a heavily electrified technology. Simultaneously, the modeling also assumes that the grid will evolve in accordance with California's climate goals—leading to a fully decarbonized grid by 2045. The farther these assumptions stray from these outcomes, the less likely the emissions benefits found in the results of this study will be realized. Additionally, the model simulates the operation of the entire Western Interconnect, but the evolution of the electricity grid outside of California is fairly static—if other state policies evolve over time to shift the mix of their respective generation capacity, the results from the GOOD model could shift. Lastly, the study does not include a full accounting of the embodied emissions from the production of electric vehicles, which would ultimately decrease the cumulative emissions savings from the EV transition. With modern day emissions related to vehicle and battery production, as well as end-of-life, these savings could be decreased by anywhere between about 11% up to 35% [23–26], though this does not include any improvements in upstream emissions.

5.1. Supporting synergies between EVs and the electricity grid

5.1.1. Strategic deployment of charging infrastructure

As renewables become increasingly 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 [27,28]. 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 to 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.

5.1.2. Pricing signals to incentive strategic charging

Charger availability must also be coupled with pricing signals that lead to shifts in behavior [29] (Chakraborty citation). 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 during the evening for wind power). Pricing of electric vehicle 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.

5.1.3. Developing and standardizing smart charging and vehicle-to-grid protocols

One of the benefits of a large-scale adoption of electric vehicles 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 between grid operators and/or utilities with vehicles and drivers. These protocols must span a broad array of new technologies including for the charging infrastructure (what type of information it receives from the grid, how this information is transmitted), the vehicle (interface with the vehicle telematics system), and the linkage between the two (how and what type of information is conveyed). 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.

5.1.4. Public awareness campaigns to guide charging behavior

Most vehicles spend the majority of the time parked rather than moving, in theory this translates to an abundance of flexibility for when drivers choose to charge their vehicles. There are several policy mechanisms that could help shift behavior including an abundance of chargers at the right locations and pricing strategies. 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 electric vehicles—particularly as the new technology begins to reach a critical mass.

Addressing impacts of a simultaneous transition.

5.1.5. Supporting grid infrastructure requirements

Widespread charging infrastructure can lead to challenges for the electricity grid, particularly within the localized distribution infrastructure [30]. 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 electric vehicles, as well as how these costs can be recovered.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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) under grant UC-ITS-2020-08. 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.

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