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Analysis and Projections of BEVs, Renewable Electricity, and GHG Reductions through 2050

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STEPS+ Energy Futures Working Paper

# Analysis and Projections of BEVs, Renewable Electricity, and GHG Reductions through 2050

UC Davis STEPS+ Energy Futures Research Program  
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July 30, 2019

**UC DAVIS**

**SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS**

*of the Institute of Transportation Studies*

Table of Contents

Executive Summary ..... 4

Introduction..... 5

Literature Review – United States ..... 7

    U.S. Transportation Today and Projections ..... 7

    U.S. Electric Power Today and Projections ..... 10

Literature Review - California ..... 13

California Scenarios for 2030 and 2050 ..... 17

    ZEV Scenario Development ..... 17

    California Electricity Scenario: Background for a VGI Optimization..... 20

    Taking the CA Scenario to 2030/2050: High EV use and High Electricity from Renewables ..... 24

Summary and Conclusions ..... 28

References ..... 30

## List of Figures

Figure 1. Light Duty Vehicle Sales and Stock, in 2018 and in three 2015 scenarios.....	8
Figure 2. White House's MCS Transportation Sector Energy Use .....	9
Figure 3. Primary energy consumption in 2015 (AEO 2019) .....	10
Figure 4. Energy use in the US in 2018 and projections to 2050, by AEO (total primary energy consumed) and NREL (net energy consumed) .....	11
Figure 5. Annual Electricity Consumption Projections by NREL EFS .....	12
Figure 6. Estimated Peak Load magnitude and seasonal timing by state for 2015 (left) and 2015 in NRE'sL High scenario (right).....	13
Figure 7. California greenhouse gas emissions by scenario.....	14
Figure 8. Statewide baseline annual electricity consumption .....	15
Figure 9. Statewide baseline annual non-coincident net peak demand.....	15
Figure 10. Electricity generation forecast by fuel type in high electrification scenario by E3 .....	16
Figure 11. Percent of new sales of light duty vehicles for high electrification scenario predicted by E3 study.....	16
Figure 12 Capacity expansion projection for 2050 for different electrification scenarios by E3 .....	17
Figure 13. California Scenarios, PEV Sales/stocks to 2050, S0 and S1 cases.....	19
Figure 14. Projections of battery capacity and electricity demand for CA, in the S2 scenario .....	19
Figure 15. Effect of V1G and V2G on load management and duck curve flattening .....	21
Figure 16. Effect of V1G and V2G on utilizing more battery capacity for VGI purposes.....	22
Figure 17. Optimized results for a smart grid V2G and G2V connection to the grid showing how duck curve changes by utilizing the EV battery capacity throughout the day. ....	23
Figure 18. 2017 California Load and electricity generation by VRE .....	24
Figure 19. 2030 simulation of California Load and electricity generation by VRE when renewable generation is about 60% of total electricity demand.....	25
Figure 20. 2050 simulation of California Load and electricity generation by VRE when renewable generation is about 100% of total electricity demand.....	26
Figure 21. 2050 simulation of California Load and VRE showing excess generation in September and lack of generation in January when renewable generation is about 100% of total electricity demand .....	27

## List of Tables

Table 1 Scenarios Included in this Literature Review.....	7
Table 2. PEV scenarios for analysis.....	18
Table 3. California Load and VRE comparison for the years 2030 and 2050 simulated results and actual 2017 .....	27
Table 4. EV Battery Available for VRE Penetration during highest excess of VRE and highest lack of VRE during year 2050.....	28

## Executive Summary

This report makes an initial investigation into the potential for combining very high penetration levels of electric vehicles with similarly very high penetration of variable renewable electricity (VRE) in California. A literature review is performed regarding the potential for high levels of EV sales and VRE penetration at both the U.S. and California level. Such scenarios have been developed by a number of researchers, such as U.S. national laboratories for the White House (under the Obama Administration), and by Energy and Environmental Economics, Inc. (E3) for the California Energy Commission. Such studies indicate that both of these “extreme” futures are entirely plausible and have the potential to coexist. However, none of the reviewed studies has undertaken detailed analysis of how large numbers of EVs could interact with and support a VRE-dominated system, and how these might interact in a useful way. This could include grid-to-vehicle (G2V) and vehicle-to-grid (V2G) movement of electricity, with vehicle batteries providing large scale electricity storage.

We undertake our own preliminary simulation for a 2030 and 2050 scenario for California, using an 8760 hours (full year) electricity demand profile and VRE generation example. We assume a ramp-up of VRE to 60% of all electricity generation by 2030 and 100% by 2050, with a similar increase in the EV share of new LDV sales, creating a significant stock (about 7 million) by 2030 and nearly complete transition (to over 20 million vehicles) by 2050. Using an “averages, peaks and valleys” analysis on the electric side, and a typical spare battery storage potential on the vehicle side, our simulation shows that by 2030 a large share of excess VRE electricity generation could be stored, and a large share of electricity shortfall from VRE could be provided, by electric vehicle batteries throughout the year, though there would be many cases where they cannot provide full coverage of these situations. However by 2050, if nearly 100% of the fleet were EVs, only about half of their available, spare capacity is needed to store the excess electricity from a full VRE system on the highest generation day and only about 40% would be needed to store and supply the shortage from lack of VRE generation on the highest shortfall day.

While these results are encouraging, a deeper simulation is needed to provide a true hour-by-hour assessment of battery use and the incidence of storage need compared to driving need. Management of charging times that could not be assessed here may also play a critical role. In addition, our initial assessment only covers a single day shortfall. Shortfalls could occur for longer periods, particularly if the VRE electricity system were sized to take better advantage of seasonal storage options. Vehicle batteries are best suited to very short duration storage and may not be adequate to keep the electricity reliable for many consecutive days of shortfall. Hydrogen (H<sub>2</sub>) has the potential to be a longer-term energy storage option and could be stored in fuel cell vehicle tanks (and the H<sub>2</sub> system associated with generating, storing and distributing H<sub>2</sub> to those tanks). The next stage of our research will involve running a full simulation using our (ITS-Davis) California ZEV power model (“CALZEV”), a version of the larger Message model, applied to consider both electricity and hydrogen (with large numbers of both of these types of vehicles) in order to: 1) gauge the relative storage potential and cost over a range of time frames and VRE scenarios, and 2) estimate the relative value and possible synergies in a system with both types of vehicles and fuels.

## Introduction

The UC Davis STEPS+ Energy Futures Program has conducted a study of the interactions between a high renewable generation grid and a high electric vehicle penetration, focused primarily on California (CA), and looking out to 2050. The goal is to understand how a full transition to zero- or near-zero light-duty vehicles—which include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell vehicles (FCEVs)—could interact with a transition to a high-renewable energy grid, and how this interaction might evolve and what kind of synergies might occur.

The study is focused on improving our understanding of the contribution of plug-in electric vehicles (PEVs, comprising BEVs and PHEVs) towards decarbonization, taking into account potential market penetration rates, patterns of use, and interactions with a changing electric grid. The scope is primarily California (although we consider recent research at the U.S. level), and the time frame is 2020 to 2050, with a decadal focus (potentials primarily for 2030, 2040, 2050). The analysis begins with a review of existing modeling literature in the U.S. and CA context to understand what is generally believed likely or possible into the future, and to help inform our calculations and projections of a range of possible scenarios. We then include new modeling work that provides a roughed-out representation of future scenarios for CA.

We combine two types of projections:

- 1) **ZEV outlook.** We develop a quantitative case study on different pathways for future battery-electric (and plug-in hybrid electric vehicles) to travel on a very high share of renewable electricity, and to the extent possible on 100% renewable electricity in the future. It will consider the following aspects and projections:
  - ZEV adoption rates (with specific adoption rates for BEV, PHEV, and FCEV) by year and by region
  - Renewable integration by year and by region and how recharging patterns may be matched to renewable electricity availability
- 2) **Grid electricity outlook.** What is the U.S. and CA renewable electricity outlook up to 2050, as well as the implications for average carbon intensity of the grid? How will this evolution likely occur, on a decade-by-decade basis? The investigation will consider the following aspects and projections:
  - Total amount and percentage in total electricity supply
  - Breakdown of the supply by different renewable sources

This report is organized in three parts:

1. **Literature review:** A review of recent literature on future potential BEV sales and usage scenarios, as well as on grid evolution from a technology, CO<sub>2</sub> and cost perspective. The review includes studies with a U.S. and CA scope, as well as international studies that include the U.S. as a region. The purpose of the review will be to understand the existing projections and scenarios, and the basis for these.

2. **Development of scenarios:**
  - a. Scenarios of ZEV (BEV, PHEV and FCV) sales: Several future scenarios of ZEV sales and use that are then linked to the electric power scenarios. Projections are made to 2050 using a low-sales (“business-as-usual”) scenario and several other scenarios with much higher ZEV penetrations, varying those of BEVs, PHEVs and FCVs by scenario.
  - b. Electric sector: One main high variable renewable electricity scenario is developed, hitting 60% generation share by 2030 and 100% by 2050, that provides electricity to all sectors, including to the plugged-in electric vehicles that are capable of storing some of this energy.
  - c. Combined scenarios: We combine scenarios a and b above to compare the capacity of EV batteries to the excess electricity generation from VREs and also to the shortfall of this power source on low generation days. These initial comparisons of BEVs to high VRE generation over a typical year can provide the basis for future, deeper analysis.
  
3. **Analysis, discussion and policy implications:** The analysis from the literature review and scenarios development above is discussed and the implications of the numerical and qualitative analysis will be described, with particular emphasis on the policy implications.

## Literature Review – United States

There have been a number of recent U.S. electric and fuel cell vehicle studies, and electricity grid decarbonization studies that include current status and future projections through 2050. We focus on three important, recent U.S. studies: the EIA’s Annual Energy Outlook 2019 (AEO2019)<sup>1</sup>, NREL Electrification Futures Scenarios (EFS)<sup>2</sup> and the White House Mid Century Scenarios (MCS)<sup>3</sup>. Table 1 indicates the particular scenarios considered.

*Table 1 Scenarios Included in this Literature Review*

EIA’s 2019 AEO	NREL EFS		White House MCS
Reference Case	Medium Electrification	High Electrification	Benchmark Scenario (80% CO2 reductions by 2050)

The EIA produces an Annual Energy Outlook (AEO) each year, with projections for the U.S. energy system out to 2040. The AEO’s Reference Case is traditionally considered a conservative (i.e., no major changes in existing trends) projection, and is treated as a “business-as-usual” (BAU) scenario in this analysis. NREL’s EFS produced a medium and high electrification scenario which represent higher electrification across economy sectors based on assumptions of faster declines in the price of electrification technologies. The White House MCS report includes numerous pathways to an 80 % reduction below 2005 levels in 2050. It also relies on the AEO for its reference case. Methodologies and scope vary across these scenarios. Thus, caution must be used when comparing the numbers presented in these reports.

### U.S. Transportation Today and Projections

In 2016, only 1% of the 16 million light duty cars and trucks sold in the U.S. were EVs. By 2018, this percentage rose to 2.5%. By 2050, AEO projects it to grow to 17%, while NREL envisions it could reach 69% and 95% in the medium electrification and high electrification scenarios, respectively (Figure 1). In 2018, EV stocks reached 1 million, or about 0.5% of the 255 million light duty cars and trucks on U.S. roads. By 2050, 13% of the light duty vehicles on U.S. roads could be EVs, if AEO’s Reference Case is to be realized. This number could raise to 65% and 84% if NREL’s medium and high electrification scenarios, respectively, materialize.



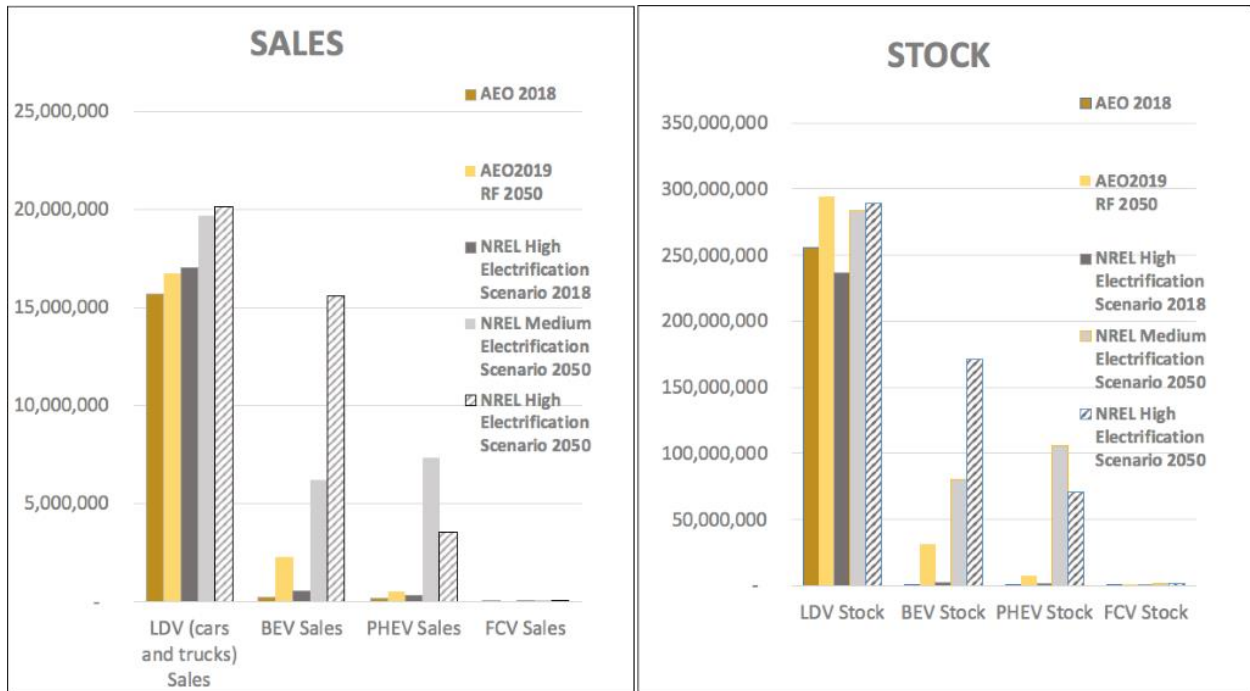


Figure 1. Light Duty Vehicle Sales and Stock, in 2018 and in three 2050 scenarios

In the U.S., fuel cell electric vehicles (FCEVs) have also increased in sales recently, though at much smaller volumes than EVs so far. This is in part because FCEVs have entered the market more recently, but may also relate to bigger constraints on their availability and, in particular, on availability of refueling infrastructure. Consumer awareness of FCEVs is also at a nascent state. It will be interesting to see if FCEVs increase their market share into the future, or do not make significant inroads. Any forecast would be highly uncertain at this point. Of the 16 million cars sold in 2016, only 0.01%, or 1,570, were FCEVs. Data from AEO shows that by 2018, FCEV sales grew three-fold to 5,000 that year, and basically doubled the FCEV stock, which stays at around 9,000. The Toyota Mirai, one of the world’s first mass-produced hydrogen FCEVs, makes up more than 80% of all hydrogen fuel cell vehicles in the United States<sup>4</sup>. FCEV in 2019. It appears Toyota made 1,700 deliveries of the Mirai in 2019, while Honda made 624 Honda Clarity in 2019. By 2050, FCEVs sales could constitute 0.3% of all light duty sales, and NRELS finds that it could grow to 0.5% in their medium and high electrification scenarios.

California has been one of the top markets for battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) through 2018. Together these plug-in electric vehicles (PEVs) have reached sales within the state of close to a 10% market share in late 2018, with stocks of over 500,000. However, whether this trend continues and how far it goes, is highly uncertain. Looking out to 2030, sales shares could keep climbing to 50% market share or higher or could become “stuck” at much lower percentages. This will depend on many factors: availability of vehicles, their attributes (such as driving range, performance and price), profitability for manufacturers, and available recharging infrastructure, among other things.

An interesting difference between NREL’s medium and high electrification scenarios is that the medium electrification sees more PHEVs than pure BEVs, whereas pure BEVs dominate in the

High Electrification scenario. Similarly, a medium electrification scenario also see slightly larger numbers of FCEV than a high electrification scenario.

In the White House MCS Benchmark scenario, large reductions in transportation energy use with a large share of electrification are projected by 2050, as part of attaining the 80% CO2 reductions relative to 2005 levels, across the energy economy (Figure 2). Although electrification is widespread in all economic sectors, it obtains these reductions through low or zero carbon fuels and a combination of higher carbon fuels combined with carbon capture and sequestration (CCS).

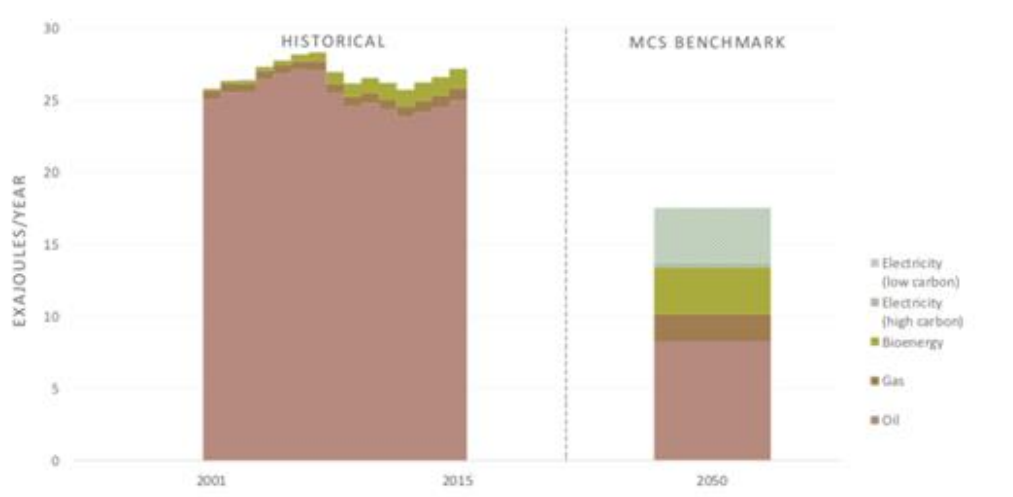


Figure 2. White House MCS Transportation Sector Energy Use

## U.S. Electric Power Today and Projections

In 2016, total U.S. electricity consumption amounted to 4,000 TWh. As shown in Figure 3, in 2015 electricity represented about 40% of the energy used in the U.S. The transportation sector was responsible for only 1% of this electricity. By 2050, overall energy consumption could be reduced in high electrification scenarios, despite population and economic growth, due to the higher efficiency of electric technologies; however, the demand for electricity will grow dramatically.

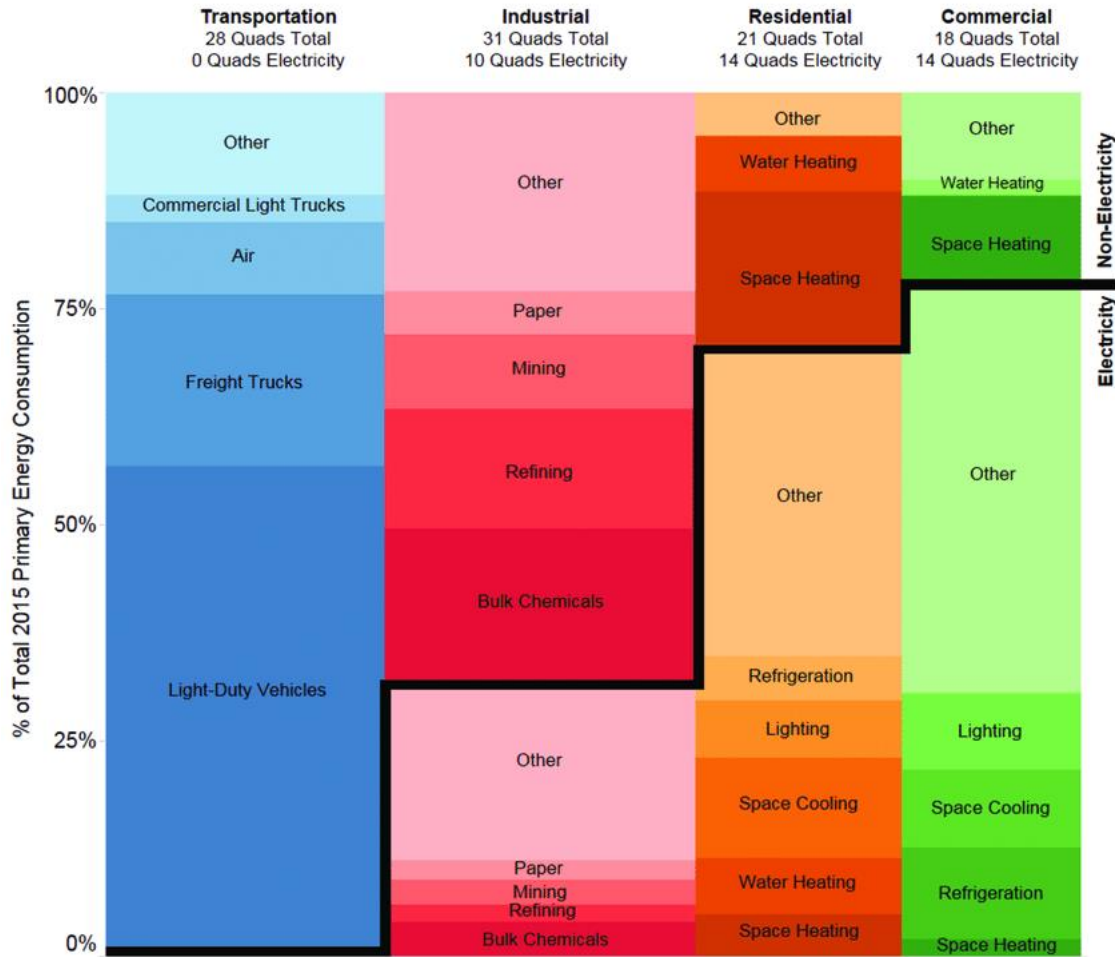


Figure 3. Primary energy consumption in 2015 (Electrification Futures Study 2018 NREL.)

In its Reference Case, the AEO projects a slight increase (6%) of total primary energy consumption by 2050 and electricity to grow proportionally (Figure 4). NREL, however, finds that total energy consumption could remain flat through 2050 but the energy mix would change, with electricity consumption basically doubling between 2018 and 2050, due primarily to a growth in electricity demand from the transportation sector (Figure 5). However, both AEO and NREL find that total transportation energy consumption will decrease, by 6% in the case of AEO and by 33% in the case

of NREL's projection. The greater energy efficiency of EVs results in a 21% reduction in the high electrification scenario.

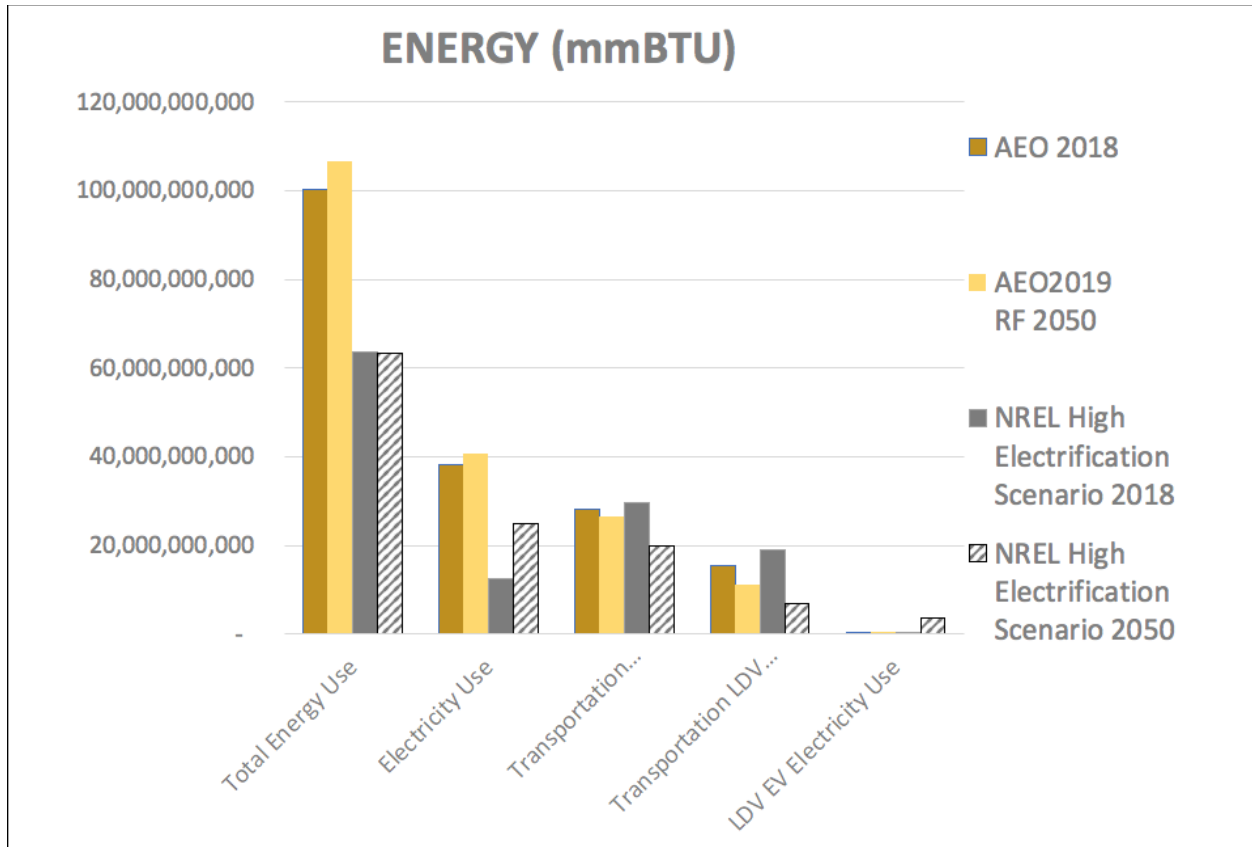


Figure 4. Energy use in the U.S. in 2018 and projections to 2050, by AEO (total primary energy consumed) and NREL EFS (net energy consumed)

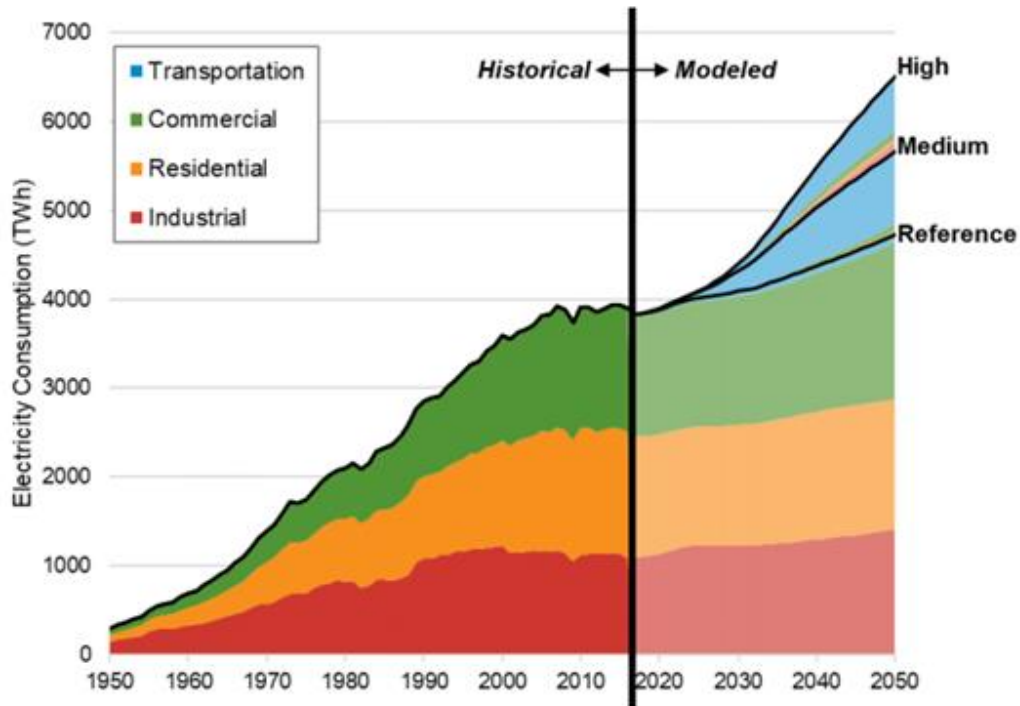


Figure 5. Annual Electricity Consumption Projections by NREL EFS

In 2015, all states excluding those in the Pacific Northwest were estimated to be primarily summer peaking, with a majority of the top 100 load hours falling in June, July, or August (Figure 6). Under NREL’s medium and high electrification scenarios, growth in winter electricity consumption outpaces consumption in non-winter months in many regions, in large part because of greater adoption of electric air source heat pumps in the Midwest and Northeast regions, which have colder climates.

The NREL study finds that while currently the U.S. experiences peak demand in the summer (due to electricity use for air-conditioning), by 2050, a separate peak demand could occur also in winter in a high electrification scenario where heating is electric. The size of both the summer and winter peak could also grow dramatically to 2050 in the high electrification scenario.

While transportation electrification has an outsized impact on annual electricity consumption compared with the other sectors, buildings electrification can dramatically change the characteristics of peak demand. Changes to peak load, and shifts to load shapes more generally, can be sensitive to the degree of demand-side flexibility, which we include in our modeling but only to a limited extent.

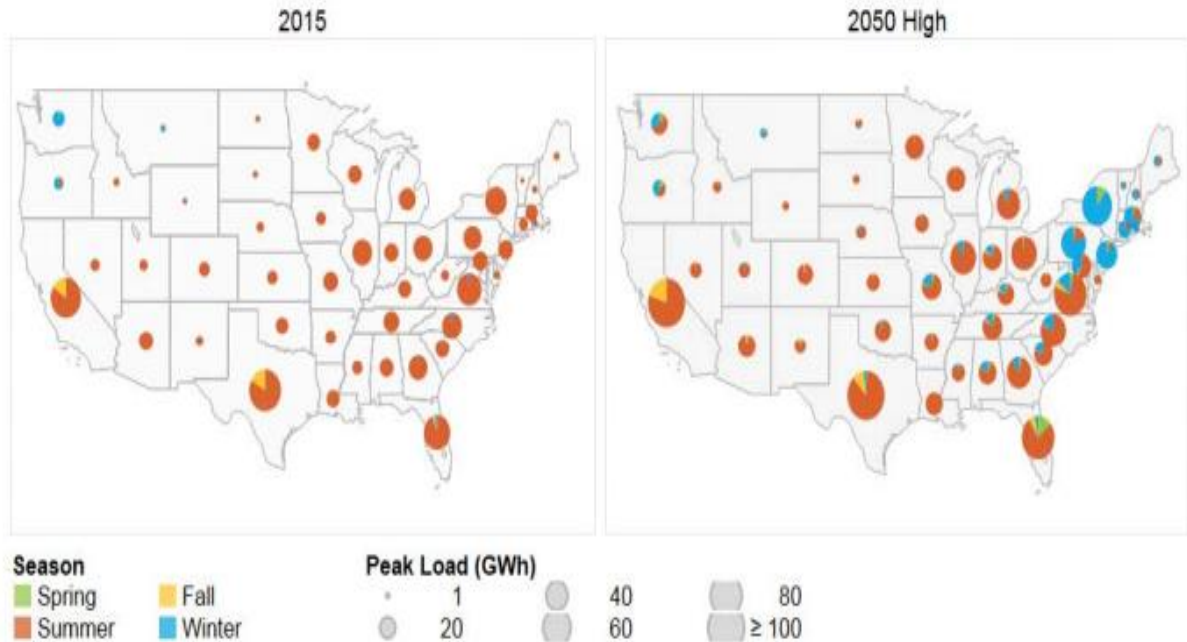


Figure 6. Estimated Peak Load magnitude and seasonal timing by state for 2015 (left) and 2050 in NREL's High scenario (right).

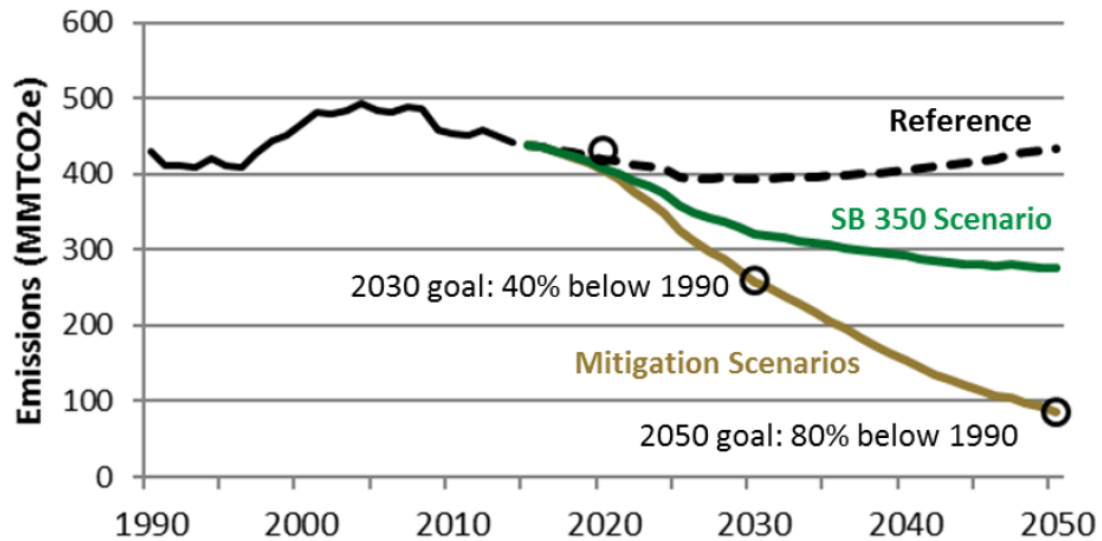
The NREL study finds that, for the U.S. to achieve 100% variable renewable electricity (VRE) it would require 150 million light duty EV vehicles, each with a total battery storage capacity of 100 kWh discharging 10% of their stored energy. This would provide 1.5 TWh of stored energy, sufficient to provide 3 hours of mean power demand in the U.S.

Finally, a study done by Shaner et al<sup>7</sup>, regarding electricity storage needed for U.S. nationwide to achieve 100% VRE is suggesting a scenario of 150 million light duty EV vehicles, discharging only 10% of the stored energy, each with a total battery storage capacity of 100 kWh, would provide 1.5 TWh of stored energy, sufficient to provide 3 hours of mean power demand in the U.S. As an extreme example, they have considered a scenario in which only wind and solar generation is deployed and only storage is used to increase reliability. For this case, storage totaling 12 hours of U.S. mean demand, would require 5.4 TWh of energy capacity.

## Literature Review - California

In this section we briefly review two relevant studies of EV sales and Electric Power projection for California. These are the California Energy Commission (CEC) Final Report on California Energy Demand 2018-2030 Revised Forecast<sup>5</sup> and also its Final Project Report on Deep Decarbonization in a High Renewables Future conducted by Energy and Environmental Economics, Inc. (E3)<sup>8</sup>.

As shown in Figure 7, California has CO<sub>2</sub> emission reduction goals of 80% below 1990 emissions by 2050 (Executive Order S-3-05) and 40% below 1990 levels by 2030 (Senate Bill 32). In figure 8 this scenario is compared with Senate Bill 350, which requires a 50% Renewables Portfolio Standard (RPS) by 2030 and a doubling of energy efficiency savings relative to historical goals. This reference scenario reflects policies prior to the passage of Senate Bill 350 (33% RPS from 2030 through 2050).

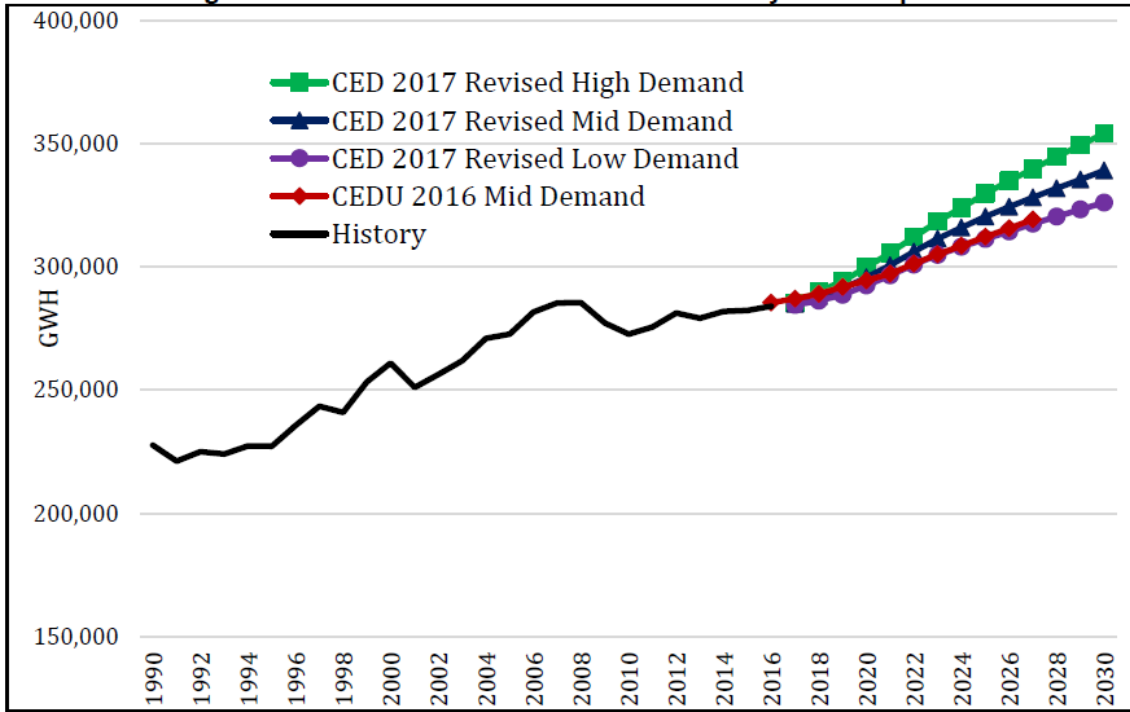


Million metric tons of CO<sub>2</sub>-equivalent

Source: E3

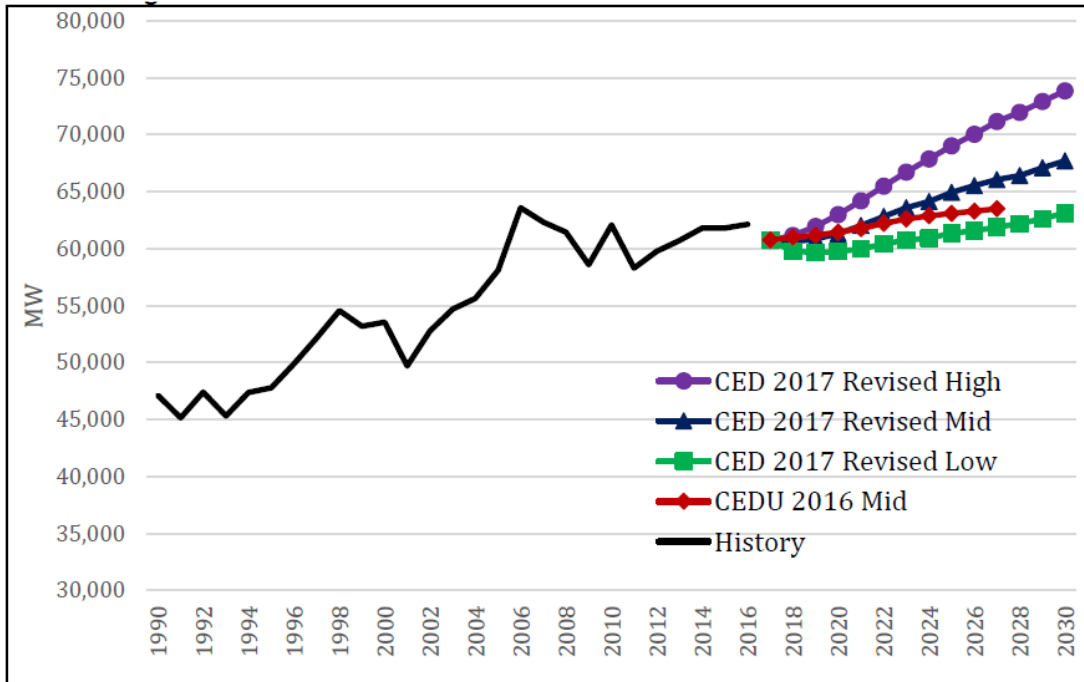
Figure 7. California greenhouse gas emissions by scenario

The CEC projects electricity growth in the state, in part in reference to this low CO<sub>2</sub> target, with increasing electrification related to stronger decarbonization scenarios. Referring to the CEC Final Report on Energy Demand 2018-2030 Revised Forecast, we consider the high case scenario of 1.5% per year load increase to be reflective of overall demand growth in this low CO<sub>2</sub> future. Figure 8 shows the statewide baseline annual electricity consumption and Figure 9 shows statewide baseline annual non-coincident net peak demand. This peak demand rises by about 25% between 2015 and 2030 in the high case.



Source: California Energy Commission, Energy Assessments Division, 2017.

Figure 8. Statewide baseline annual electricity consumption

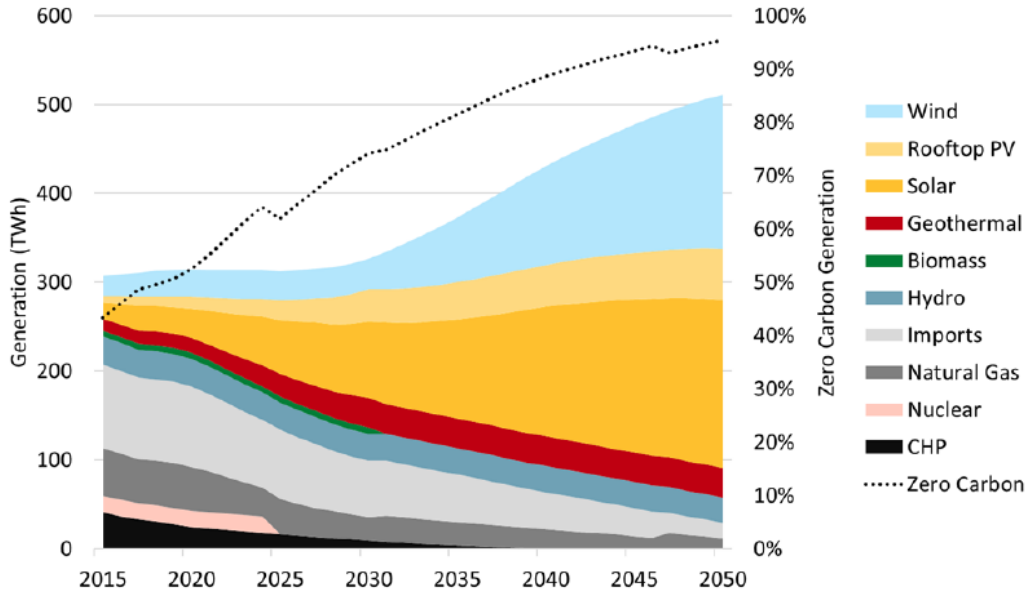


Source: California Energy Commission, Energy Assessments Division, 2017.

Figure 9. Statewide baseline annual non-coincident net peak demand



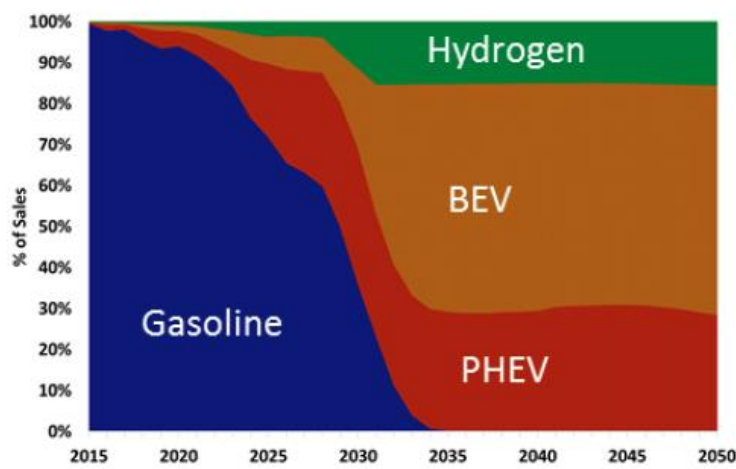
Looking out to 2050, Figure 10 shows a high electrification scenario electricity generation in California by fuel type including wind and solar from E3's projections. In this scenario, electricity generation is 75% decarbonized by 2030 and 95% by 2050, despite large increases in demand between 2030 and 2050.



Source: E3

Figure 10. Electricity generation forecast by fuel type in high electrification scenario by E3

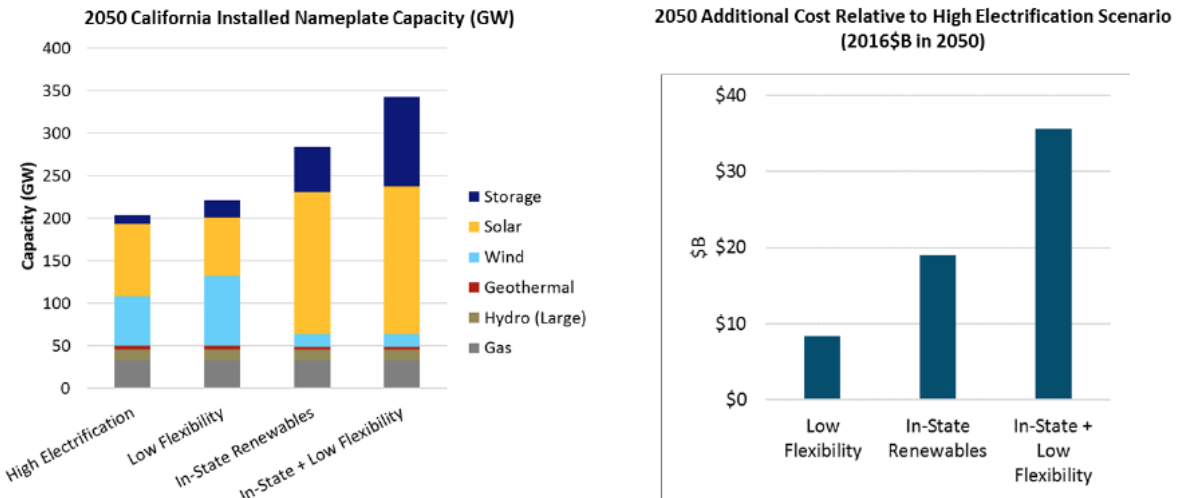
It should be noted that in this same E3 study, there is a very rapid penetration of ZEV vehicles between 2020 and 2035, completely displacing the sales of internal combustion engine (gasoline/diesel) light duty vehicles by that year (Figure 11). This reflects very rapid penetrations but also suggests that E3 considers this a plausible scenario.



Source: E3

Figure 11. Percent of new sales of light duty vehicles for high electrification scenario predicted by E3 study.

The increase in electricity demand, partly related to the rapid increase in ZEV sales and stocks, requires a rapid increase in both generation capacity and electricity storage capacity. Figure 12 shows the implications of an increasingly variable renewable (and especially solar-dominated) system in 2050, with lower and higher flexibility in the system. With high flexibility of load management, lower storage capacity is needed. This storage can include either vehicle batteries or generation of hydrogen. In the following section, we develop our own preliminary scenario for how vehicle energy storage could contribute to future expansion of VRE in California.



Results are based on RESOLVE modeling using electricity demands from the California PATHWAYS High Electrification Scenario

Source: E3

Figure 12. Capacity expansion projection for 2050 for different electrification scenarios by E3

## California Scenarios for 2030 and 2050

The following sections present our own scenarios for California, including projected electric and fuel cell vehicle sales, stocks, battery availability for electricity storage, and electric sector projections, focused on a scenario with rapid increases in variable renewable power, reaching 60% of generation by 2030 and 100% by 2050.

### ZEV Scenario Development

For this study, we have created a set of high sales growth scenarios to test the limits of what could happen out to 2050. As shown in Table 2, we have created 3 scenarios for both the U.S. and California (though only the CA scenarios are then utilized in this study). We also add a “business-as-usual” case for comparison. The BAU is calibrated to the Energy Information Administration reference projection of ZEVs in their 2019 Annual Energy Outlook. The other three scenarios are:

- S1: a balanced scenario, with high ramp up of each of the three main types of ZEV (and near-ZEV): 33% each of BEVs, PHEVs and FCEVs by 2050. The nature of this ramp up is shown further below.
- S2: a scenario where BEVs eventually completely dominate LDV sales by 2050.
- S3: a scenario where FCEVs eventually completely dominate LDV sales by 2050.

*Table 2. PEV scenarios for analysis*

	California				U.S.			
	ICE	BEV	PHEV	FCEV	ICE	BEV	PHEV	FCEV
S0 (BAU)	90%	5%	4%	1%	90%	5%	4%	1%
S1	0%	33%	33%	33%	0%	33%	33%	33%
S2	0%	100%			0%	100%		
S3	0%			100%	0%			100%

The nature of the ramp ups for this scenario are shown in Figure 14 for the S0 and S1 scenarios (S2 and S3 are similar to S1, except for the distribution of sales among the 3 types of ZEVs). With these sales projections, the resulting stock projections can be derived based on stock turnover assumptions. As shown, sales of ZEVs in S1 (and S2 and S3) reach about 50% of the market in CA by 2030, and close to 100% by 2040. This results in ZEV stock shares of about 25% in 2030 and 75% in 2040. Stocks reach 100% by 2050.

The results for the U.S. are similar to those for CA, with about 10x more sales and stock volumes but similar sales shares in those scenarios. This clearly assumes that the U.S. “catches up” with CA over time, since currently about 50% of EV sales within the U.S. occur within CA. The U.S. projections simply provide a point of comparison here, though could be useful for later research.

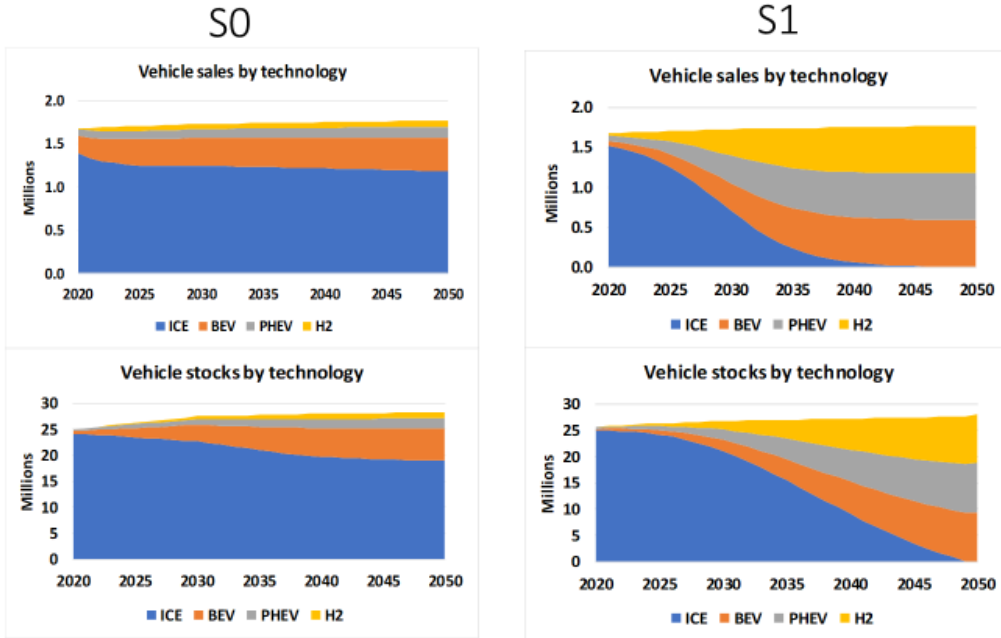


Figure 13. California Scenarios, PEV Sales/stocks to 2050, S0 and S1 cases

The growing sales and stocks of PEVs result in a growing sales and stocks of batteries on those vehicles as well. Based on a set of assumptions regarding the battery capacity of each vehicle, the aggregate capacity of those batteries for BEVs and PHEVs is shown in Figure 14. These grow to a combined level of about 1 billion kWh by 2050.

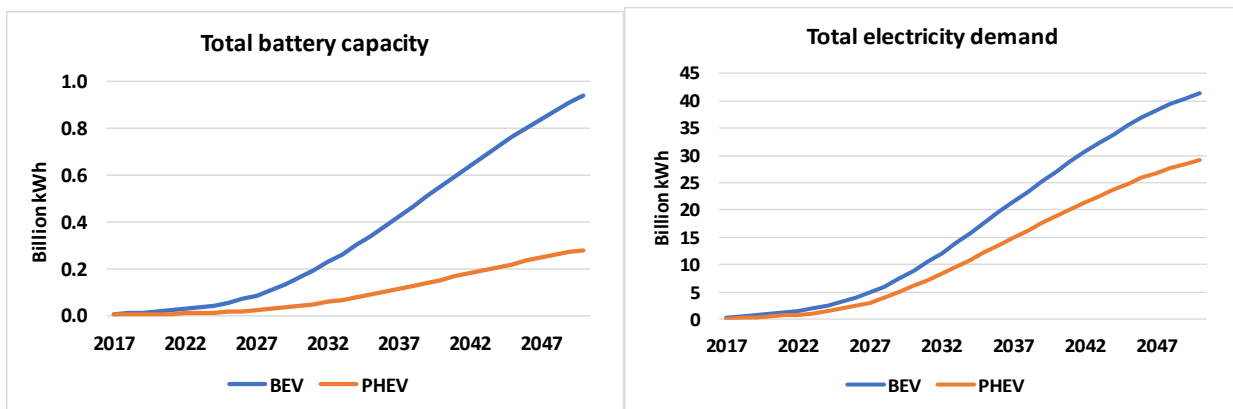


Figure 14. Projections of battery capacity and electricity demand for CA, in the S2 scenario

### California Electricity Scenario: Background for a VGI Optimization

California's Renewable Portfolio Standard (RPS) goals call for significant expansion of renewable electricity (wind and solar). This means a higher share of variable electricity generation that does not necessarily coincide with time of demand (i.e., not dispatchable). The net load (i.e., amount of electricity demand to be produced with dispatchable generators—mostly natural gas power plants) is affected by high levels of solar energy during midday and early afternoon, at a time of low electricity demand, followed by a decrease of solar output in the evening coinciding with a steep ramp up of demand. This produces the now infamous “Duck Curve”. There is a higher share of solar energy, relative to demand, during spring days than summer days. This trend is expected to increase as solar power capacity increases in California. Due to limited storage capacity, operators must curtail renewable power at its peak productivity in the middle of the day hindering the ability to reach renewable power goals.

Could distributed storage from electric vehicles be used to soften the mismatch between demand and supply? This seems promising, for example by having parked EVs charging during high solar periods such as noon/early afternoon, and using these parked EVs to recharge the grid in the evening, when electricity demand (and price) are highest. How viable is this? We evaluate changes of net load in a system with solar and forecasted levels of EV as distributed storage. We report on our detailed Message model runs for Southern California, and then consider more aggregate data for the state, going out into the future, to gain some rudimentary sense of how much EVs could contribute, if sold and used in very high volumes, as shown in the previous section (for Scenario 2).

Vehicle to Grid Interactions (VGI) occur either through G2V (Grid to Vehicle) or V2G (Vehicle to Grid). When there is no V2G, and only time of charging is optimized, it is called V1G. In Figure 14, the first graph shows the situation when charging is managed only as V1G, and the second graph shows it when there is the possibility of V2G as well. Although V1G (grid charging of vehicles, with no return of electricity from vehicles to grid) can flatten the load curve to some extent, it is obvious that how V2G (electricity moving both to and from vehicles to grid) can help much more in peak load reduction, and results in a much more flattened load.

It is notable that even with the relatively low numbers of EVs in 2020 that we assume (around 1.5% of the total stock of LDVs in Southern California), these vehicles can contribute significantly to grid load flattening. We report on our detailed Message model runs for Southern California, and then consider more aggregate data for the state, going out into the future, to gain some rudimentary sense of how much EVs could contribute, if sold and used in very high volumes, as shown in the previous section.

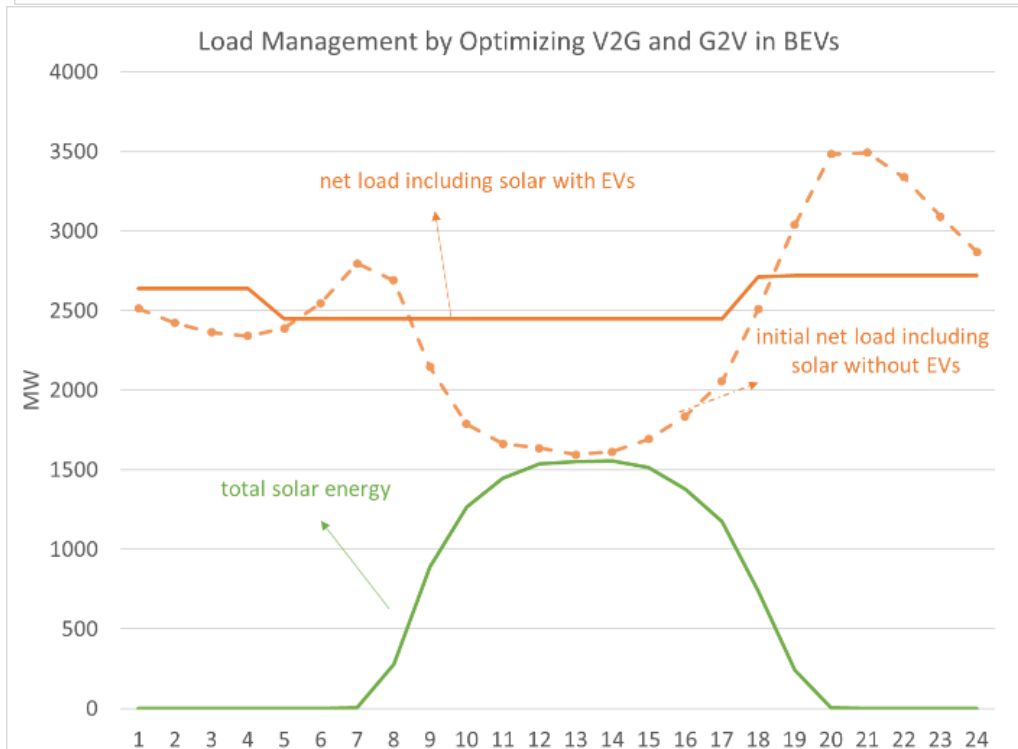
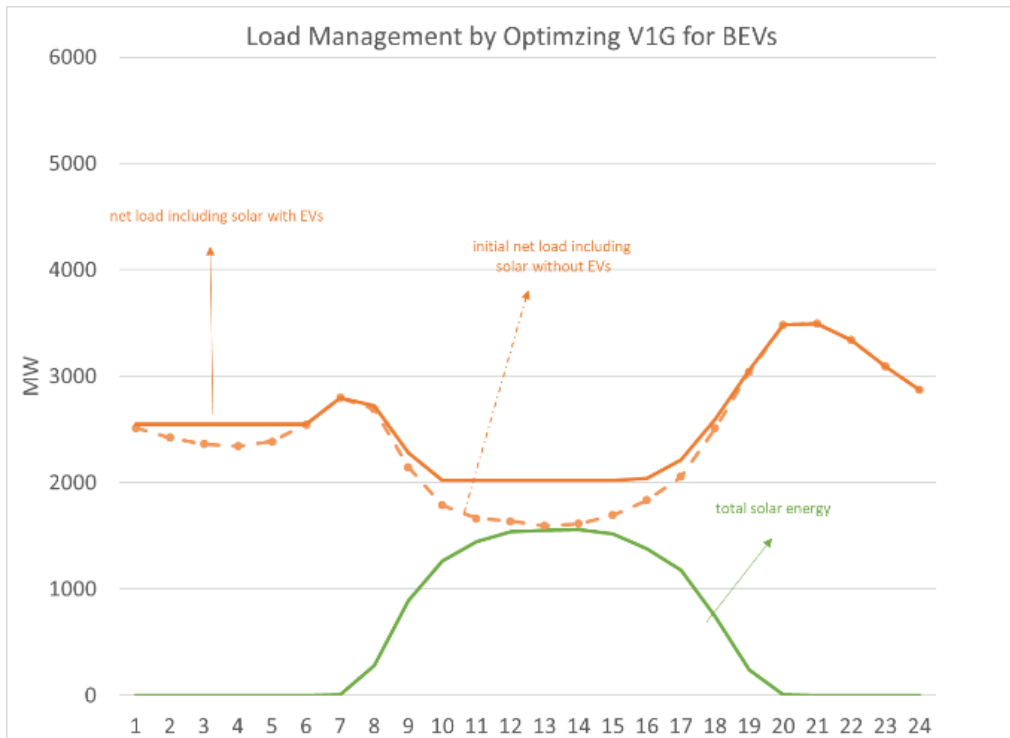


Figure 15. Effect of V1G and V2G on load management and duck curve flattening

In our analysis, driving energy needs are treated as having priority over grid access to the energy stored in the EV. Once parked, vehicles normally recharge. If there is time to use this stored electricity and return it to the vehicle before the next trip, we assume this is available to help with

grid management. In particular, we restrict the electricity coming from vehicles to ensure that the “state of charge” (SOC) never drops below 30%. Thus, if there is excess (i.e., more than 30% or as needed for daily trip) battery energy and the pricing is right, energy will be supplied from the EV to the grid. Inversely, when there is excess renewable generation capacity, the vehicle batteries will be charged up to 80% of full capacity, taking advantage of the faster charging rate to the 80% point with a near linear characteristic.

Figure 16 shows the state-of-charge pattern, along with charging and discharging, of all EVs in two scenario runs. The left graph shows the optimal operation of grid when only V1G is allowed. The right graph shows the optimal V2G and G2V interaction. As shown, in order to meet daily driving need, only 11.6kWh per vehicle energy is required which is a small fraction of total battery capacity. As V2G is allowed, more battery storage would be utilized to manage the grid load which still would be utilizing only 50% of the battery capacity for this purpose.

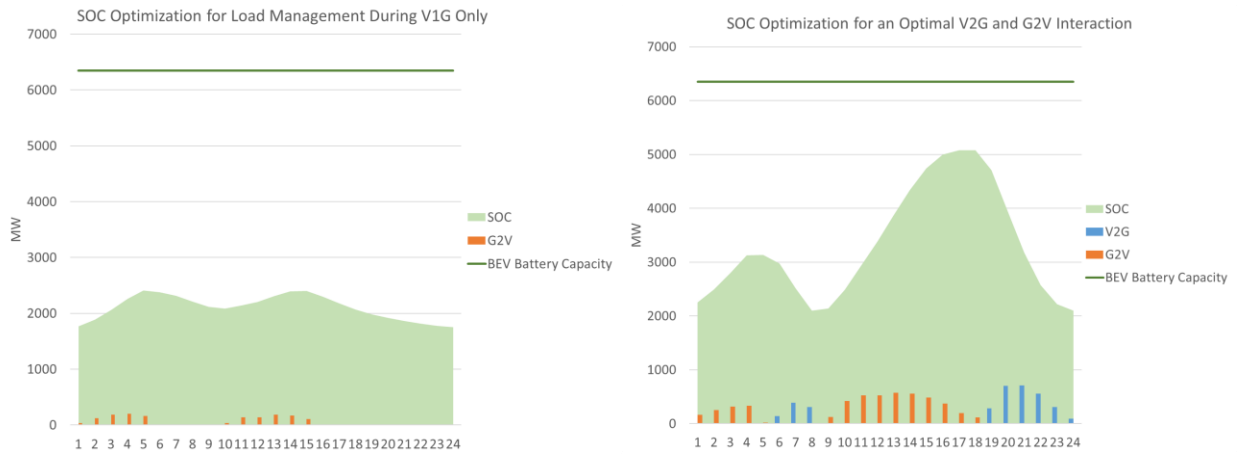


Figure 16. Effect of V1G and V2G on utilizing more battery capacity for VGI purposes

Figure 17 shows the optimized results for a smart grid V2G and G2V connection to the grid showing how duck curve changes by utilizing the EV battery capacity throughout the day. The yellow line refers to the right-hand y-axis in 1000 VMT, the other curves and bar graphs to the left-hand y-axis in MW and SOC in MWh.

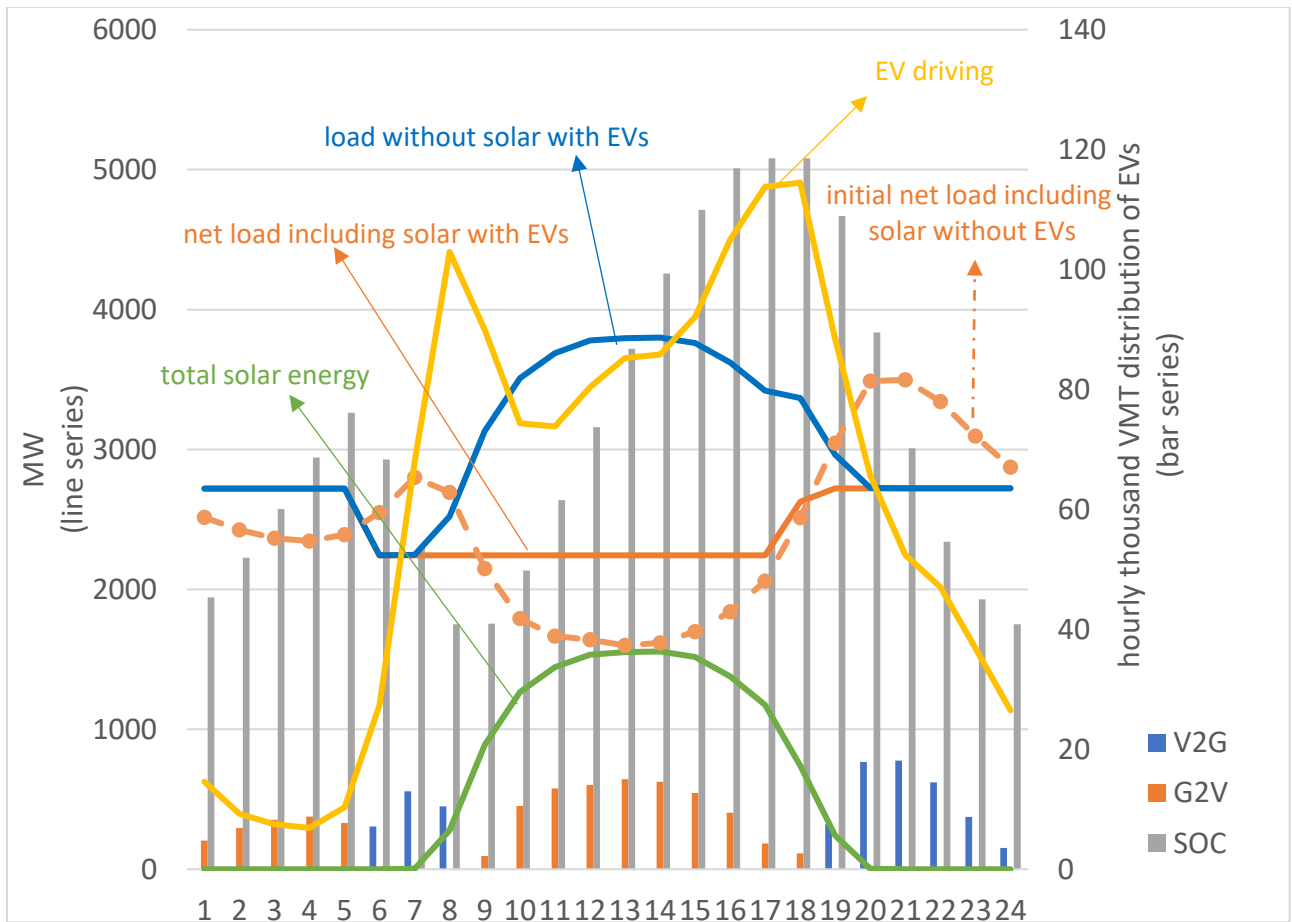


Figure 17. Optimized results for a smart grid V2G and G2V connection to the grid showing how duck curve changes by utilizing the EV battery capacity throughout the day.



## Taking the California Scenario to 2030/2050: High EV Use and High Electricity from Renewables

To simulate California’s electricity generation for years 2030 and 2050 and enabling the penetration of Variable Renewable Energy (VRE) up to 100% in California by 2050, we use a relatively simplified approach, without detailed grid modeling at this time (though that is planned in the future). We utilize a year 2017 hourly load pattern for California, with an hourly total wind and solar generation pattern overlaid on this, as shown in Figure 18. In this figure, dark blue is the hourly load and light blue is the VRE hourly electricity generation. In 2017, total electricity generated by wind and solar were only 14% of yearly electricity consumption with a maximum capacity of 14GW.

With 2017 as the base year and assuming some growth in load over time, consistent with the previously presented scenarios, we then compare this to a rapid increase in variable renewable energy penetration over time. We assume this share of average annual generation reaches 60% in year 2030 and 100% in year 2050. It could reach this level much sooner, given that CA has a requirement for a totally renewable grid by 2040, but there is also the possibility of higher levels of hydro power, pumped storage of that hydro, etc. By 2050, it seems reasonable to assume that VRE could account for close to 100% of power demand within the state. It is at least an interesting possibility to look at, in relation to grid-connected EVs.

Figure 19 shows the actual 2017 hourly load curve and the VRE generation level as a starting point for the analysis. VRE levels are typically well below half of the instantaneous load at this point in time.

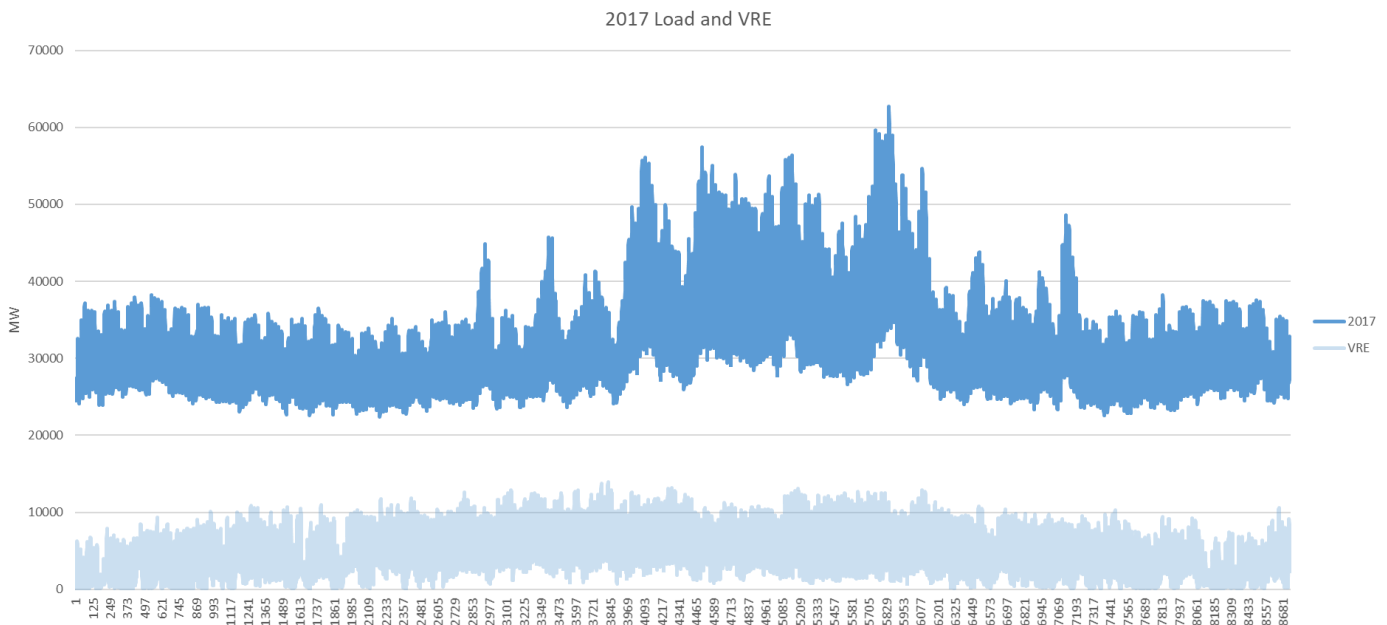
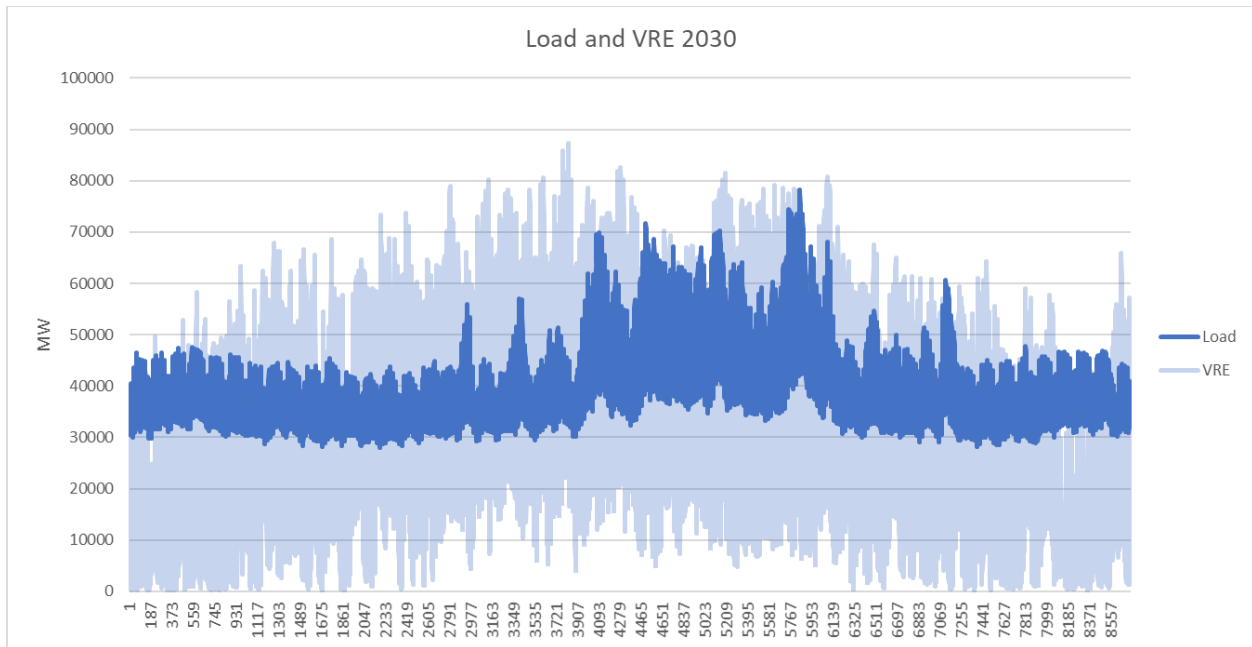


Figure 18. 2017 California Load and electricity generation by VRE

Figure 19 shows our simulated hourly load in California for year 2030 reflecting increases over time and overlays an average 60% generation share from VRE. In order to produce 60% of electrical energy demand from VRE, with demand patterns over the year similar to today's, we would need at least 87GW of total wind and solar generation capacity. We can see from the graph that as the capacity increases, the variability also increases such that there will be many hours of excess generation and also, many hours of insufficient VRE generation in different seasons, on particular days, and for certain hours of many days. The excess VRE would need to be shut in or used for new demands (such as charging EVs beyond base charging patterns), and the insufficient VRE production periods would benefit from a supply of electricity from stored devices, such as those very same EVs.



*Figure 19. 2030 simulation of California Load and electricity generation by VRE when renewable generation is about 60% of total electricity demand*

Figure 20 shows the same type of simulated hourly load and VRE situation for year 2050. By 2050 VREs reach 100% of required yearly electricity, but still there are many times when load and generation are not balanced. That means we have hours of excess and hours of lack of generation. To be able to avoid curtailment, we would still need significant electricity storage available in the system. How much storage would be needed, and how much could come from spare vehicle battery capacity? We address these questions next.

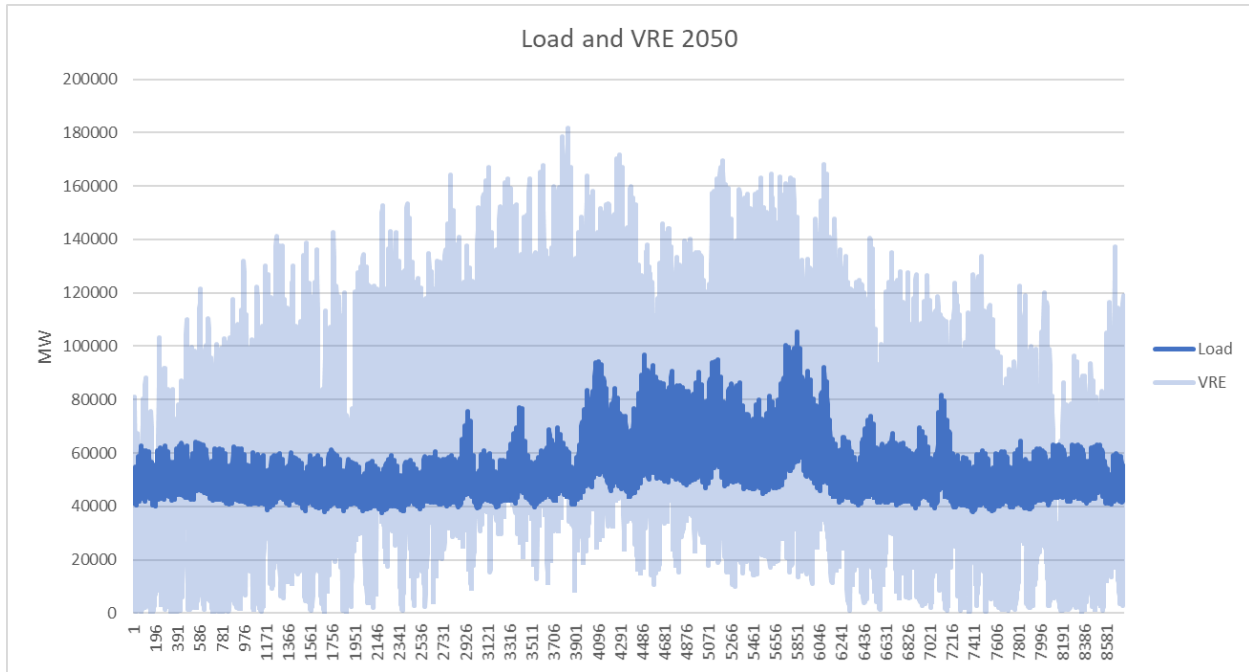


Figure 20. 2050 simulation of California Load and electricity generation by VRE when renewable generation is about 100% of total electricity demand

To what extent could the battery storage capacities of existing EVs be available for electricity storage and for returning that electricity to the grid during need periods? A detailed answer would require a full run of our Message (or similar) model, optimizing across all time periods and days in a year and tracking the availability of stored electricity on vehicles. Here we provide a simplified answer, which can indicate roughly how much of a role EVs can play.

In Table 3 we have compared the penetration of renewables in 2030 and 2050 with base year of 2017. On the EV side, we use the numbers of EVs included in our Scenario 2, which is on the order of 5 million by 2030 and nearly 30 million by 2050. By 2050, total battery capacity available in the EVs would increase from 30 GWh in 2017 to 480 GWh in 2030, to 2800 GWh in 2050. The 2050 level would represent a very large storage potential, more than twice the daily total electricity demand in the state. This should provide a considerable storage capacity for enabling renewable penetration, especially if V2G is possible.

In Figure 21 we show detailed hourly load and VRE generation obtained from Figure 9, but only showing for a few days in January and September as examples of lack of generation and excess of generation based on the time of day. To utilize the excess generation, considerable storage would be needed. EV batteries could be a practical source if V2G and G2V would be possible for grid interaction.

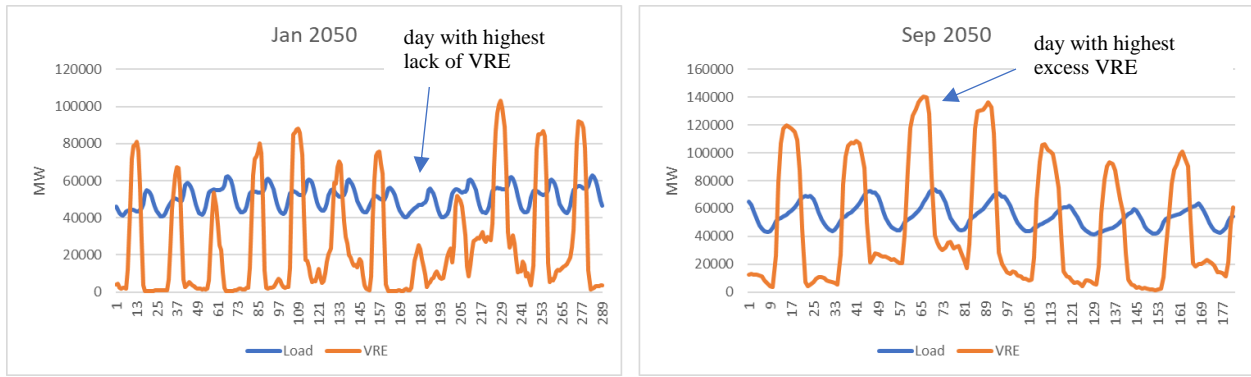


Figure 21. 2050 simulation of California Load and VRE showing excess generation in September and lack of generation in January when renewable generation is about 100% of total electricity demand

We have calculated the VRE generated in these two special days of the year in 2050 - one for the day with highest excess renewable generation and one for the day with highest lack of renewable generated. Table 3 shows the results of battery available for these two cases. The calculations are made for S1 (33% BEV) and S2 (100% BEV) scenarios explained above. Percentage of SOC required is calculated based on minimum storage required to store the excess VRE for later use or V2G energy required to compensate lack of electricity during that day after providing the daily driving demand for the EVs.

Table 3. California Load and VRE comparison for the years 2030 and 2050 simulated results and actual 2017

	2017	2030	2050
VRE Penetration	14%	60%	100%
EV Battery Capacity (GWh)	30	431	2,803
Electricity Demand (TWh)	283	353	477
Average Daily Electricity Demand (GWh)	775	967	1,307
VRE Capacity (GW)	14	74	168
VRE Average Daily Production (GWh)	109	575	1,302

In Figure 22 we have compared EV battery capacities, average daily renewable generation and average daily electricity demand for 2030 and 2050 simulations compared to 2017.

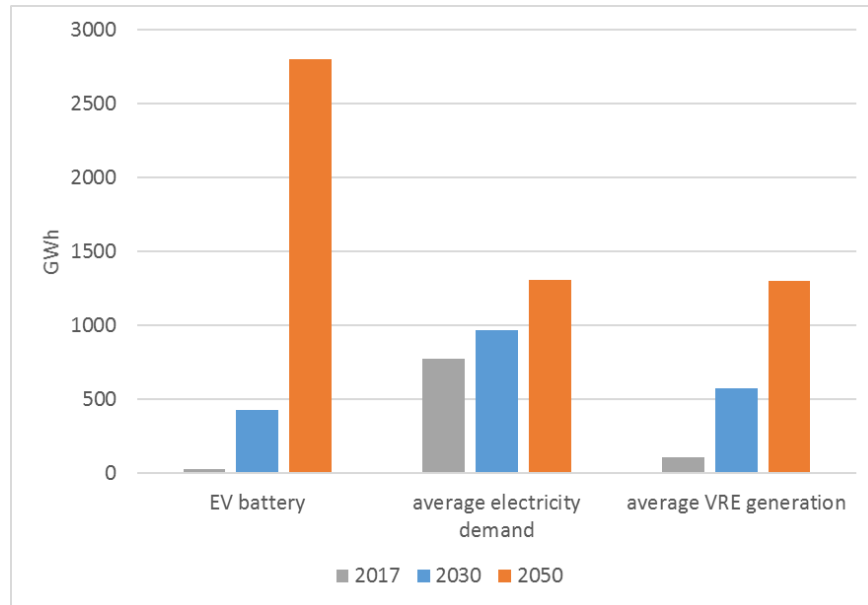


Figure 22. Comparison of EV batteries, average daily renewable generation and average daily electricity demand for 2030 and 2050 forecasts compared to 2017

Table 4 shows EV batteries available to be utilized during this year 2050 scenario, assuming 100% electricity is supplied by wind and solar in California. An interesting result is that with 100% of the fleet as EVs (S2 scenario), we would have 223% of battery capacity needed to provide sufficient storage to cover the highest renewables excess day and 246% of available battery capacity to provide energy for the biggest shortfall day. However, if only 33% of the fleet were EVs (S1 scenario), they could store only 74% of the excess energy on the highest day and generate only 82% of the daily energy required during the day with highest lack of energy.

Table 4. EV Battery Available for VRE Penetration during highest excess of VRE and highest lack of VRE during year 2050. S1 represents scenario 1 and S2 represents scenario 2. EV Battery Capacity is the capacity available from 0% to 100% of SOC

	Renewable Energy (GWh)	EV Battery Capacity (GWh)	Daily Driving (GWh)	Available battery capacity as a percentage of excess or insufficient VRE
Day with highest excess VRE (S2)	1,108	2,803	326	223%
Day with highest excess VRE (S1)	1,108	934	105	74%
Day with highest lack of VRE (S2)	1,005	2,803	326	246%
Day with highest lack of VRE (S1)	1,005	934	105	82%

## Summary and Conclusions

In summary, if all California light duty vehicles were relatively long-range BEVs in 2050, and the batteries on these vehicles are available for storage as we assume in this study, we can provide about 2.5 times the storage needed for the day with highest lack of VRE from these batteries to store and supply the lack of energy for the worst day of the year (highest lack of VRE), while we can absorb about 2.2 times the excess VRE with highest excess VRE and use it in a future day without

curtailing renewable energy. This does not take into account all the driving and charging the vehicles will do during the day, and how this available capacity could be best allocated to electricity storage and return to the grid (we will need a full cost/benefit analysis to better address this question). But it does suggest that batteries could play an important role in managing a VRE dominated system.

Further, although this amount of battery storage can help on a daily basis and for two or more consecutive days, this type of storage probably is not appropriate to store electricity over longer periods, to ensure grid reliability over consecutive days or longer. Seasonal variability is a particular issue needing longer term storage systems. The better the seasonal storage in the system, the lower the overall capacity and generation levels needed in the VRE system itself, which can produce important savings and reliability benefits.

As an example, our simulation results show that, despite assuming very high VRE capacity in 2050, in December there would be 22 consecutive days with a net shortage of VRE generation relative to daily load. If all stored in batteries (and still allowing cars to drive as needed), the total battery capacity required for these 22 days would be 13TWh, far beyond that available even with a complete stock of BEVs. Vehicle batteries are not well suited to multiday storage, but dedicated hydrogen storage within a hydrogen system, built to provide fuel to vehicles and other purposes, might serve this purpose well.

For these reasons, an integrated study including both electricity and hydrogen vehicles and infrastructure is necessary to provide a more holistic and integrated assessment of a technically and economically optimal solution to reach high levels of VRE penetration and pollution in the future, such as for 2030 and 2050. This additional study is in development, and the current study's report will be used as a basis for undertaking the full analysis.

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