Impact of Electric Vehicle Adoption on Electricity Consumption and Generation: Evidence from California

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Abstract

The market share of electric vehicles (EV) is growing in the USA, and there are substantial numbers of federal, state, and county-level incentives for EV consumers. These incentives are in place primarily due to environmental concerns. This study focuses on two different but interrelated aspects of EV adoption. First, using monthly county-level data from 2010 to 2019, this study reveals that electric vehicles and their supportive infrastructures, such as charging stations, have a significant effect on residential and commercial electricity consumption in California. Second, analyzing electricity generation information by county, I find a significant negative relation between electricity usage and the share of electricity that comes from renewable sources. Although electric vehicles emit lower greenhouse gases than conventional vehicles, they require a significant amount of electricity for charging. If the electricity generation does not involve renewable or cleaner sources, public spending on EV adoption may not contribute to a cleaner environment as much as expected.

Keywords: Electric vehicle adoption, Residential and Commercial electricity consumption, Renewable electricity generation

JEL category: D04, Q58

1 Introduction

The United States is the third-largest electric vehicle (EV) market, following China and Europe. The State of California alone accounted for half of all new 2019 electric vehicle sales in the USA. Federal and state-level actions, including regulations, financial and non-financial incentives for consumers, charging infrastructure development, and consumer awareness programs, are playing an essential role in increasing EV adoption. These incentives are important because upfront purchase cost is a barrier (Bui et al., 2020). Apart from federal incentives, 40 states currently have their own EV incentive, rebate, or emission control programs (Alternative Fuel Data Center, 2020). The government is trying to promote electric vehicles, mostly due to environmental concerns. The U.S. Department of Energy (DOE) report states that increasing passenger vehicle efficiency and reducing the use of petroleum-based fuels can reduce consumers' fuel costs, support the domestic industry, minimize pollution, and increase energy security (DOE, 2014, p.7). The DOE supports EV as a solution for the challenge of providing affordable, clean, secure transportation. The government also supports plug-in-hybrid vehicles (PEVs) that are powered at least in part by electricity. On September 8, 2011, Energy Secretary Steven Chu announced the Clean Cities Community Readiness and Planning for Plug-In Electric Vehicles and Charging Infrastructure awards. These awards helped communities forge public-private partnerships to take strategies to support the adoption of PEVs and charging infrastructure installation. These 16 awards, totaling $8.5 million, helped prepare 24 U.S. states and the District of Columbia to adopt PEV technologies to reduce U.S. petroleum dependence and build the foundation for a clean transportation system (DOE, 2014).

While the changes towards electric energy sources represent a positive change, that progress is diminished by the fact that coal, natural gas, and nuclear fuels are still the most-used electricity generation sources nationwide. Natural gas and, to a certain extent, and shale oil remains relatively cheap and reliable energy sources. Despite the prevalence of non-renewable fuels, electric power can also be derived from renewable sources, including wind power, hydropower, and solar power (U.S. Energy Information Administration [EIA], 2020). Below two figures show the energy generation share and trend by sources.

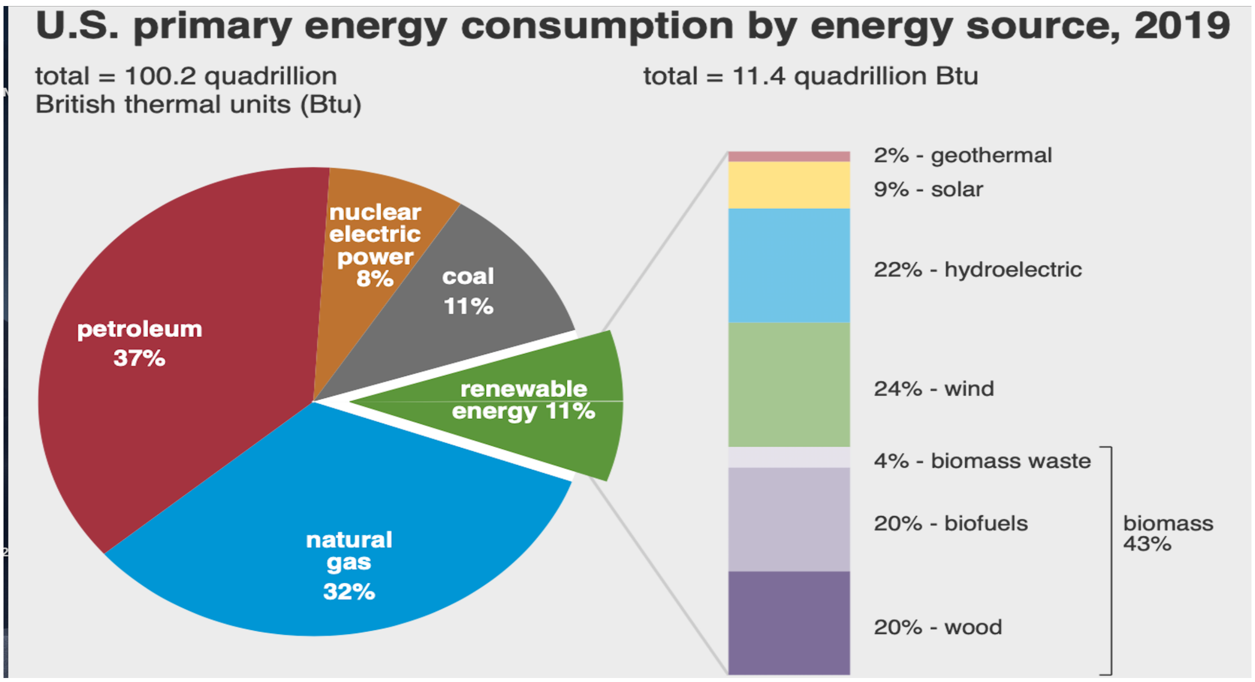

Figure1. U.S primary consumption of electricity share[1] by sources in 2019.

[1] Sum of the components may not equal to 100% due to independent rounding
1 Btu= 0.293071 Watt-hour
Source: U.S Energy Information Administration, *Monthly Energy Review,* Table 1.3 and 10.1, April 2020, Preliminary data

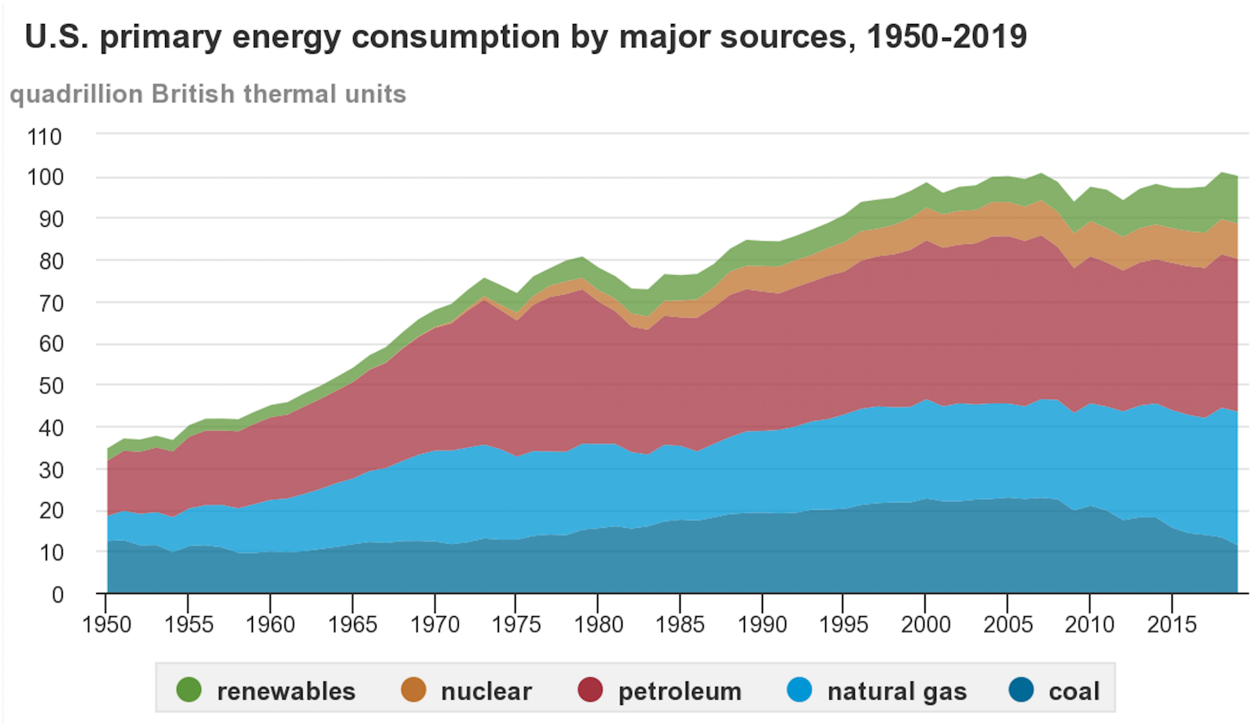

Figure 2. U.S primary energy consumption by major sources from 1950 to 20The above

The above figures show that electricity generation still relies mainly on fossil fuel, primarily responsible for emitting the major air pollutants in the USA. US Department of Energy report contends, "Power plants are the largest source of sulfur dioxide (SO2) emissions in the United States... Power generation from fossil fuels, biomass, and waste contributes to air pollutants that adversely impact human health and the environment" (Oak Ridge National Laboratory, 2017, p vii). This has policy implications regarding EV adoption, which may increase electricity consumption.

This study aims to examine the impact of EV adoption on electricity consumption and, eventually, on electricity generation from renewable sources. As stated by the DOE website, an average EV's electricity consumption is 0.34 kWh/km, and an average American drives 46 km daily. So, per capita, monthly electricity consumption due to EV is roughly 470 kWh for an EV driver. In the USA, the average residential electricity consumption per person is 909 kWh each month (DOE, 2020); this data suggests a person's electricity consumption due to EV could be on the order of 50% of one's residential electricity consumption. The DOE website also states that, based on the national average of 12.6 cents/kWh, fully charging an all-electric vehicle with a 100-mile range and depleted battery would cost about the same as operating an average central air conditioner for six hours. These estimates indicate that EVs can cause an increase in electricity demand, and so that electricity generation sources should also be analyzed.

This study consists of two major parts. First, using county-level monthly data from California for the year from 2010 to 2019, I estimate the effect of EV adoption on residential and commercial electricity consumption. By employing fixed-effect panel regression, this study finds that each electric vehicle charging station significantly increases the residential and commercial electricity consumption per county by 0.12%. Second, after establishing the relationship between EV adoption and electricity consumption, this study explores the electricity generation pattern by sources, especially whether there is any significant relationship between excess electricity consumption and renewable electricity generation. By analyzing ten years of electricity generation information in California, this study finds a increased electricity consumption significantly reduces renewable energy share.

The rest of this study is organized as follows: first, I give a brief literature review in section 2. Section 3 presents an overview of the data, and section 4 discusses the model specification. I offer the result of our analysis in section 5 before concluding in Section 6, along with discussions of the limitations of this study.

2 Literature review

Analysis of electricity consumption due to electric vehicles' adoption is absent in the economics literature so far. Most studies about EV adoption focused on purchasing patterns due to incentives using various consumer choice models. However, studies about electricity consumption due to the adoption of new technologies are available. Su (2019), in his research about residential electricity demand in Taiwan, found that the effects of urbanization and energy poverty have a significant positive impact on energy consumption. He used Air cooler (AC) as an exogenous variable to account for the differences between urban and rural areas. Hung and Huang (2015) also estimated the same relationship using dynamic panel data.

Holtsmark et al. (2014) studied Norwegian subsidy policies for EV purchasers and concluded that the sales of EVs in Norway increased rapidly as a result of these policies. Due to the subsidies, driving an EV implies very low costs to the owner on the margin, probably leading to more driving at the expense of public transport and cycling. Moreover, because most EVs' driving range is low, the policy gives Norwegian households incentives to purchase a second car, again stimulating the use of private vehicles instead of public transport and cycling. This study also analyzed the emission level due to the production of two models of EVs and their batteries. All of these lead to more pollution. The authors concluded that the EV policy could not be justified.

There are several environmental engineering fields of studies that address this question with different aspects. For instance, Foley et al. (2012) examined the Irish government's target in 2008 that 10% of all vehicles in the transport fleet be powered by electricity by 2020. The study confirms that off-peak charging is more beneficial than peak charging and that charging EVs will contribute 1.45% energy supply to the 10% renewable energy in transport target, which also contributes to a certain amount of CO_2.

Muratori (2018) found that even if the total PEV market share remains limited, high PEV adoption clusters can be found in certain areas. The results show that the introduction of one single PEV in a residential distribution network consisting of six households can potentially increase the distribution transformers' peak load factor if Level 2 (a type of EV charger) charging is considered, which can lead to a significant decrease in the expected transformer life. In general, the higher charging level significantly exacerbates the impact of PEV charging on the residential distribution infrastructure.

However, Rolim et al. (2012) collected information about driving behavior by interviewing eleven EV drivers in Lisbon, Portugal, with onboard diaries, including km traveled, kWh charged, and the number of trips per day for five months duration. Results indicate that the EV's adoption impacted everyday routines on 36% of the participants, and 73% observed changes in their driving style. Compared to conventional internal combustion engine vehicles running on gasoline or diesel, EV reveals considerable reductions in energy consumption and CO2 emissions.

Nicholas et al. (2015) estimate to what extent PEVs are more environmentally friendly, than conventional passenger cars in Texas, controlling for the emissions and energy impacts of battery provision and other manufacturing processes. Results indicate that PEVs on today's grid can reduce some types of pollutants in urban areas but generate significantly higher emissions of

SO_2 than existing light-duty vehicles. A primary concern for PEV growth is the use of coal for electricity production, but there is a benefit of electrified vehicle miles' energy security.

3 Data

This study examines empirical data to estimate the effect of EV adoption on electricity consumption and the relationship between electricity generation by renewable sources. Primarily, I use California's county-level monthly data for the year 2010-2019 to find the effect on electricity consumption. California's EV rebate program also started at the beginning of 2010. California has 58 counties, so, there are 6960 monthly observations in the dataset. I have collected electricity consumption and revenue data for different sectors from the California Energy Commission. I then use this information to calculate electricity prices also.

I have to use a proxy variable for the EV adoption data because original EV registration data is not publicly accessible. California state has a rebate program for EV purchasers, which started in 2010. The California Air Resources Board's Clean Vehicle Rebate Project (CVRP) provides rebate checks to California individuals, businesses, and government agencies to purchase or lease eligible clean vehicles, including plug-in hybrid, all-battery, and fuel-cell electric vehicles. According to the CVRP website, rebated vehicles constitute a majority (74%) of new clean-vehicle sales in the state (Center for Sustainable Energy, 2015). We assume that there are no differences in rebate rates across counties. I discuss more detail about this CVRP program and other incentives for electric vehicle supply equipment (EVSE), such as charging stations, in Appendix A.

EV charging Station information is provided by the U.S. Department of Energy and National Renewable Energy Laboratory. In the data set, there is information about the opening date of each station or charging ports. I aggregate the numbers of active stations at the monthly level of each county. In this study, I use connectors and stations interchangeably. In one station, there might be more than one connector to charge more vehicles at a time. I use the number of total connectors. Currently, there are three types of charging stations available. Level 1, level 2, and DC fast. These three settings require different volts and amps and take a different range of times to charge EV. In my model, however, I do not differentiate these types of stations since this study focuses on electricity consumption as a whole, not the intensity of the electricity flow at particular times.

Information on different housing units like single-unit, multi-unit, and the mobile unit, are collected from the California state association of counties. I collect per capita personal income, population, and employment data from the Bureau of Economic Analysis (BEA), and U.S. Department of Commerce website. I collect average monthly temperature per county information from the National Centers for Environmental Information of National Oceanic and Atmospheric Administration (NOAA).

The maps below show by county the population density, the average total electricity consumption of ten years, average per capita electricity consumption, total electric vehicle, and charging station adoption level at the end of 2019. The last one shows the percentage of electricity that comes from renewable resources in each county.

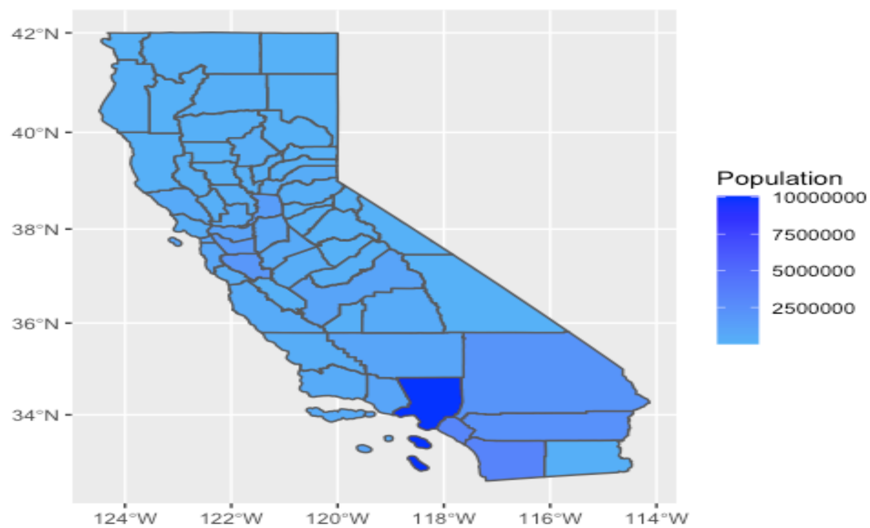

Figure 3. The average population by county in California.

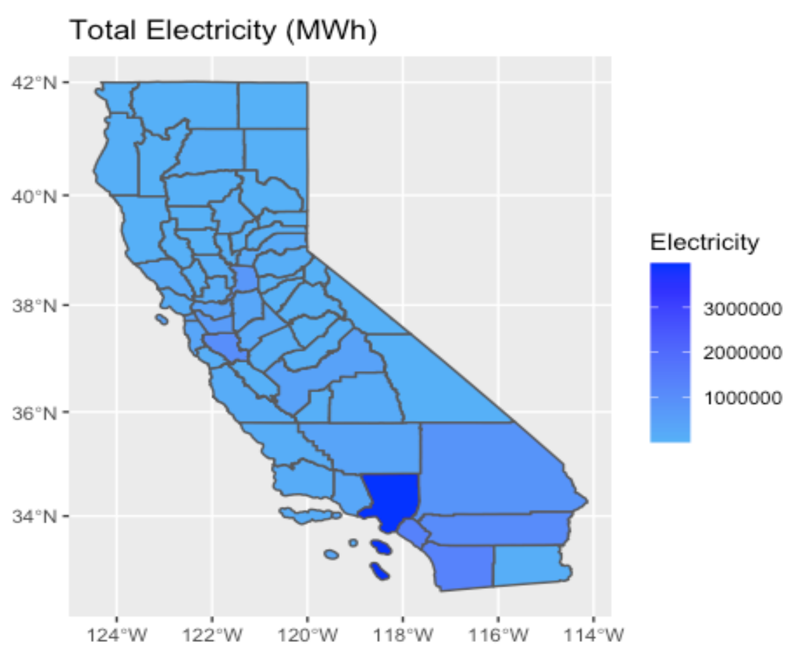

Figure 4. Average electricity consumption by counties

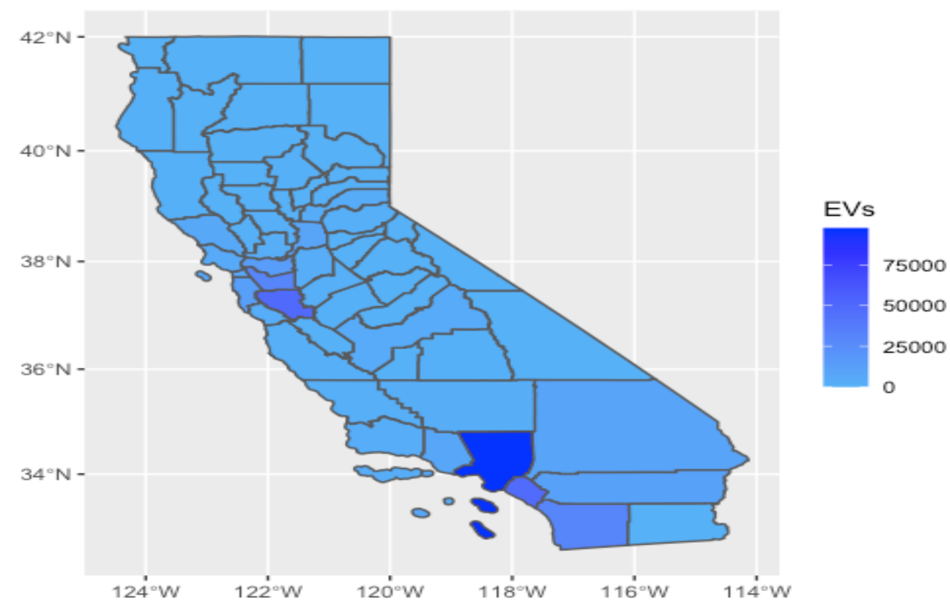

Figure 5. Total EV adoption at the end of 2019 by counties.

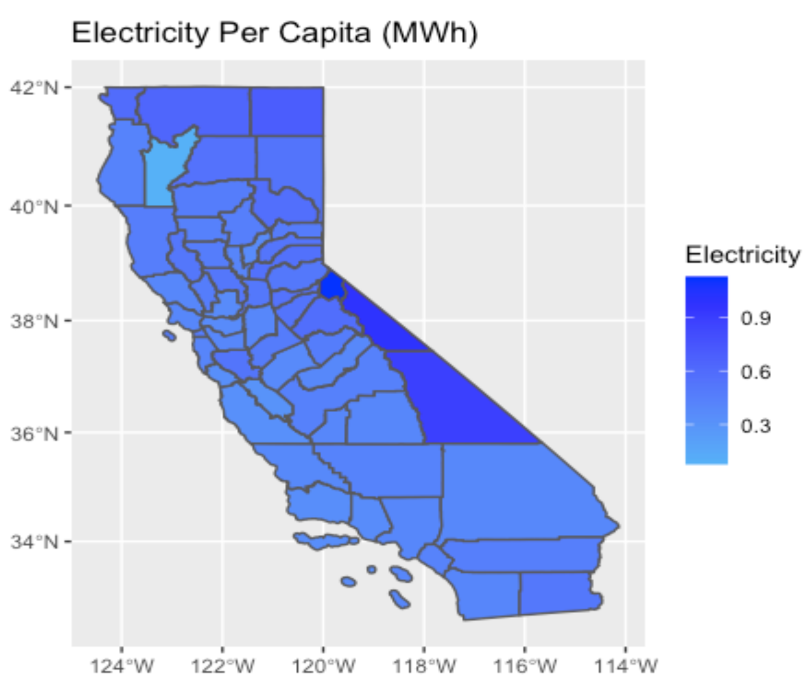

Figure 6. Per capita average electricity consumption by counties.

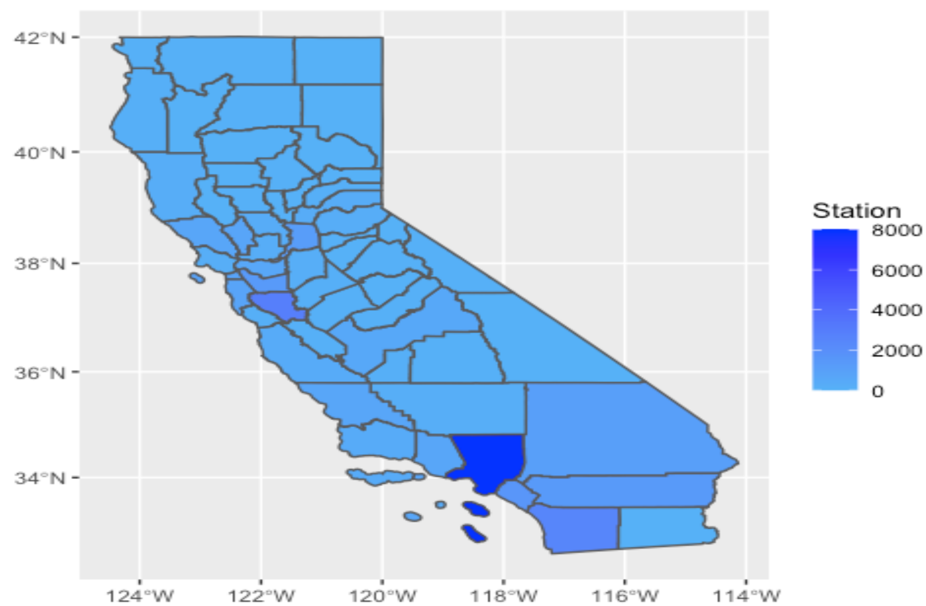

Figure 7. Total charging station at the end of December 2019 by counties.

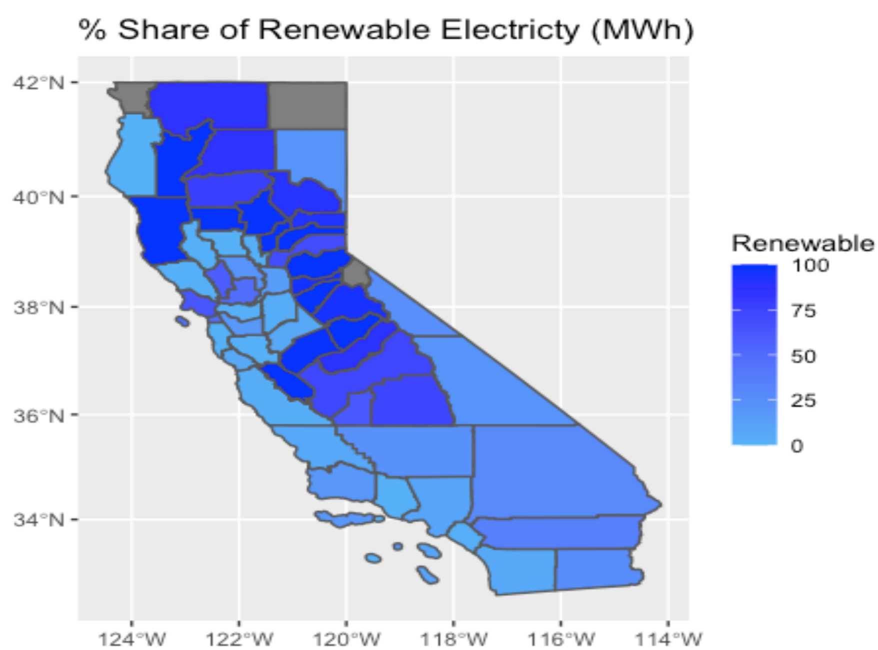

Figure 8. Percentage of electricity comes from renewable sources.

Although I did not control for anything to depict the intensity of EV adoption, station constructure, and electricity consumption, these maps might give a general idea about the relationship considered here. Table 1 shows the summary statistics of the variables I use in this study. Table 2 represents the average per capita electricity consumption for ten most EV adopting counties and ten least EV adopting counties annually for the study period.

Table 1. Summary table

Variables	Mean	St Dev	Min	Max
EV	2052.90	7428.94	0	97538
Station	147.7	494.12	0	8016
Income ($)	49061	18090.95	26717	141735
Population	665831	1441469	1047	10105708
Employment	382226	879935.8	970	6685737
Residential Electricity (MWh)	130518.40	257371.51	328.60	2555402.70
Commercial Electricity (MWh)	149504	336388.80	93	2746909
Residential Electricity Price ($)	159.83	38.77	0.0105	1200.34
Weighted Average Price ($)	151.70	34.36	35.5	635.3
Single housing	155818	292312.52	1049	1965018
Multi housing	74368	205912.60	106	1545580
Mobile housing	9654	14608.09	32	80315
% of Electricity share from Renewable source (MWh)	46.93	40.08	0.000	293.58
Number of observation (N)= 6960				

Table 2. Per capita average electricity consumption (mwh) of ten highest and ten lowest EV adopting counties.

	Per capita Electricity Consumption	
Year	Highest ten EV Adopting Counties	Lowest ten EV Adopting Counties
2010	5.196	7.729
2011	5.203	7.449
2012	5.237	7.351
2013	5.169	7.819
2014	5.181	7.276
2015	5.114	7.279
2016	5.061	7.558
2017	5.133	7.713
2018	4.988	7.450
2019	4.954	7.673
Welch Two Sample t-test: t = -34.764, p-value = 3.568e-14		

Moreover, I have collected electricity generation data of California at the yearly level by counties for 2010 to 2019 from the California Energy Commission to estimate the effect of EV adoption on the types of electricity generation by renewable sources. In California, primary electricity sources are coal and natural gas. Major renewable electricity sources are Hydroelectric, solar, and wind. Figure 9 shows the electricity generation trend by sources in

California as a whole for the past ten years, and Table 3 shows the summary statistics of the electricity sources.

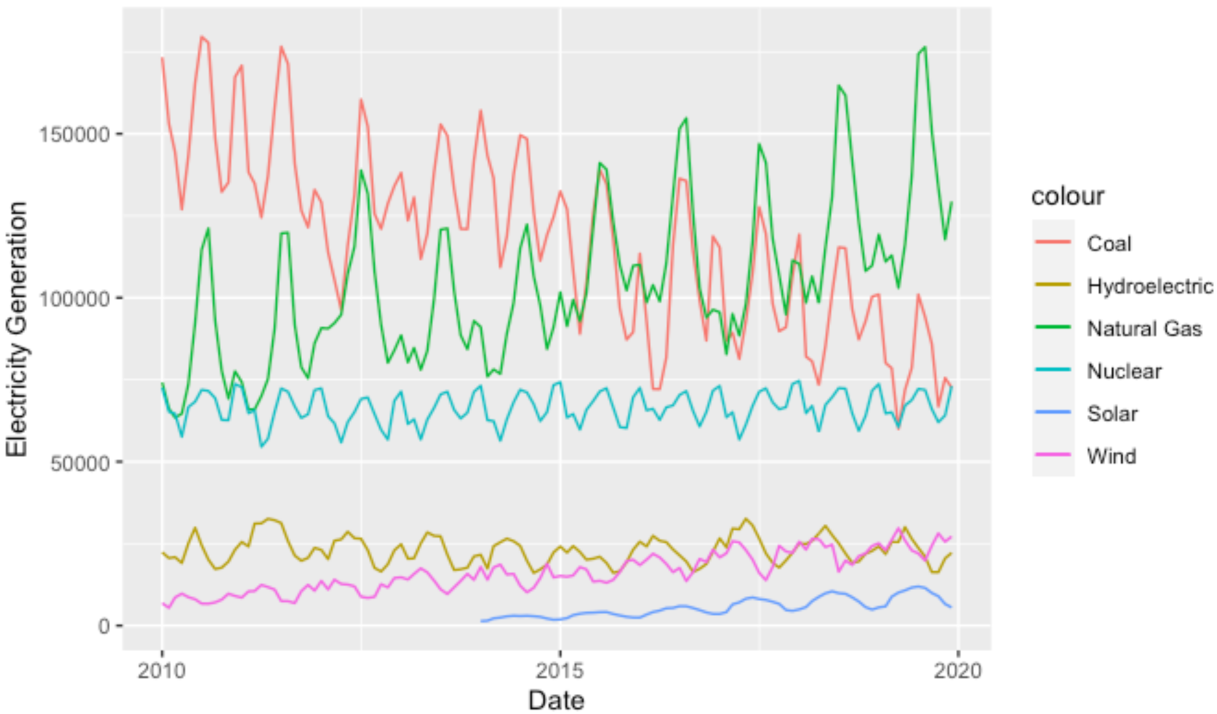

Figure 9. Electricity generation of California by sources. Three major sources are non-renewables (Source: EIA, 2020)

From Figure 9, we can see that solar production did not start in California until December 2013. Renewable electricity share in the total electricity production is relatively low in these ten years in California.

Table 3. Summary statistics of electricity generation by sources.

		Non-Renewable			Renewable		
	All Fuel	Coal	Natural Gas	Nuclear	Hydroelectric	Solar	Wind
Minimum	287,800	60,008	63,431	54,547	16,074	1,375	5,432
Average	340,978	118,088	104,483	66,475	23,060	5,566	16,249
Maximum	418,693	179,600	176,458	74,649	32,607	11,941	29,711
Number of observation (N) = 580							

According to this data, in December 2019, total electricity generation in California was 337253.09 thousand MWh. Hydroelectric, solar, and wind combined generated 54929.56 thousand MWh electricity, only 16% of the total electricity generation. The other three sources, coal, natural gas, and nuclear, contribute the most to California's electricity production. Table 4 shows the average percentage share of electricity from renewable resources in the ten most EV adopting and ten least EV adopting counties.

Table 4. EV adoption and renewable electricity generation for ten highest and lowest EV adopting counties.

Highest EV adopting counties				Lowes EV adopting counties			
County	% of renewable electricity	EVs	Station	County	% of renewable electricity	EVs	Station
Los Angeles	9.686	379,538	27,958	Modoc	NA	0	20
Santa Clara	0.8831	208,307	8,430.2	Sierra	92.75	18.7	11
Orange	1.6723	176,010	5,160.6	Alpine	NA	13.60	61.7
San Diego	6.1137	116,925	10,552	Lassen	20.979	23.1	24.8
Alameda	17.7320	118,198	4,713	Trinity	100	46.50	25.0
Contra Costa	0.64937	55,773	1,123.8	Colusa	0	46.0	23
San Mateo	0	54,804	1,797.6	Glenn	100	59.70	0
Riverside	34.184	36,840	5,231	Mono	24.40	51.50	380.6
San Bernardino	27.99	29,062	3,606	Plumas	89.50	57.30	28.9
Sacramento	13.575	27,828	6,185	Inyo	20.706	78.60	43.2

4 Methodology

4.1 EV adoption on electricity consumption

This study constructs a two-way fixed-effect linear regression model where the dependent variable is the monthly electricity consumption over time. I look at residential and commercial electricity because, according to the California Energy Commission, electricity consumption due to EV charging is mostly under residential and commercial sectors. People charge their EVs either at home or at the charging stations. Apart from public charging stations, there is a number of private charging stations in California, and many EV owners adopt relatively simple Level 1 EVSE or the slightly more complex Level 2 EVSE at their residents. People in nearby residents also share the charging facilities with neighbors using mobile apps. For example, California-based startup EVMatch and ampUp are these types of initiatives, which by using people can share their residential charging connectors with others and earn money (CVRP, 2020). So, in my model, I exclude other sectors like the agricultural sector, industrial sector, etc., from this analysis. The electricity consumption for county i at time t is specified as-

$$\begin{aligned} \text{Log}(\text{ELECTRIC}_{it}) = {} & b_0 + b_1 \text{ Log}(\text{EV}_{it}) + b_2 \text{ Log}(\text{STATION}_{it}) + b_3 \text{ Log}(\text{POP}_{it}) + \\ & b_4 \text{ Log}(\text{SINGLE}_{it}) + b_5 \text{ Log}(\text{EMPLOY}_{it}) + b_6 \text{ Log}(\text{INCOME}_{it}) + \\ & b_7 \text{ Log}(\text{HOTMONTH}_{it}) + b_8 \text{Log}(\text{COLDMONTH}_{it}) \\ & + b_9 \text{ Log}(\text{PRICE}_{it}) + \delta_t + \phi_i + u_{it} \end{aligned} \tag{1}$$

Here, ELECTRIC is the monthly residential and commercial electricity consumption for each county. EV is the number of electric vehicle rebate application numbers in a specific county and month, and this is our primary variable of interest. In the dataset, there is information about the application date. I take the cumulative sum of the numbers of applications for each county at the monthly level. In my model, I am assuming people file their applications in the same month they purchase EV.

Moreover, the term STATION represents the charging stations of EVs in each county. Apart from installing charging connectors at home, many EV owners charge their cars at a station rather than their homes, primarily because of its fast-charging capacity. So, this variable should also have a positive relationship with the outcome variable. In my data, I have the opening date of each station or charging connector. Like the EV variable, I take the cumulative sum of the number of stations for each county at the monthly level. However, in my model, I primarily use the STATION variable and EV variable separately as they both should account for the EV adoption. However, I also use these two variables together to see the EV effect while controlling for STATION and vice versa.

The remaining variables are control variables. The term SINGLE is the percentage of single housing in each county. There are three types of housing available, which are Single, Multi, and Mobile housing. Households with a different number of members may have a different electricity-consuming pattern. People living in the same household can share their electricity services, such as cooking or watching TV together. Thus, if the demand-side economies of scale exist, the effect of different types of households should have different effects on electricity consumption.

HOTMONTH and COLDMONTH are two separate variables representing the climate factors, like average hot/cold degree months when people use more electric appliances like air coolers and heaters would positively influence electricity demand. I consider 86 degrees Fahrenheit or more temperature as hot days and 32 Degree Fahrenheit or less as cold days (Alberini et al., 2017). So, if the average monthly temperature is above 86 degrees, the

HOTMONTH variable would be equal to 1, otherwise 0. Similarly, if the average monthly temperature is below 32 degrees, the COLDMONTH variable would be equal to 1, otherwise 0.

The term PRICE is the weighted average electricity price of the residential and commercial sectors, which I calculated from electricity consumption and the revenue information. The term INCOME is the per capita personal income for each county. Based on the demand theory, the price effect is expected to be negative, while the income effect is expected to be positive on electricity demand. The term POP represents the population for each county, which is the number of potential electricity users. This variable also controls the size of each county. A county with more residences will consume more electricity, so the population's effect would be positive. The variable EMPLOY is the total employment in each county, which controls for any unobserved economic activity for electricity consumption and purchasing EVs.

δ and ϕ stand for county fixed effect and time fixed effect, respectively. More specifically, time fixed effects account for the year- month level in this model.

4.2 Renewable electricity generation due to EV adoption

To address the second question of this study, I again employ the two-way fixed-effect model. The electricity from renewable sources in county i and year t would be,

$$RENEWABLE_{it} = b_0 + b_1 \, Log(ELECTRIC_{it}) + b_2 \, Log(NCOME_{it}) + b_3 \, Log(POP_{it}) + b_4 \, Log(SINGLE_{it}) + b_5 \, Log(EMPLOY_{it}) + b_6 \, Log(PRICE_{it}) + \delta_t + \phi_i + u_{it} \quad (2)$$

Here, RENEWABLE is the percentage share of the electricity generation that comes from renewable sources in a specific county and year. Other variables are the same as the first specification, except the I do not add temperature control here since that should not affect the source of electricity. Electricity generation is supposed to be independent of temperature.

5 Result

5.1 Effect of EV adoption on electricity consumption

Table 5 represents the results of the unlogged analysis of the effect of EV adoption on both residential and commercial sectors together. I use a weighted average price for these two sectors. The three separate columns in the table represent different model specifications. In the first column, I use EV as my explanatory variable without the charging station in it. I use the charging station as my explanatory variable without EV in it in the second column. In the third column, I keep both EV and charging station as an explanatory variable. Although charging stations and EVs should be correlated, it is worth looking at the EV effect while controlling for the charging station and vice versa. As we know, least EV adopting counties might also want to build more stations for travelers. This study adopts a two-way fixed-effect model where I control for county-fixed effect and year-month fixed effect. We can see that, in column (2), the charging station has a coefficient of 29.71, and this result is highly significant, which means one extra charging station or connector can increase monthly electricity consumption by 29.71 MWh. In column (3), while accounting for both EV and Station, this coefficient is 27.16. The population has a significant positive result on consumption while Employment has negative impacts. Hot degree months have a highly significant positive effect.

Table 5. Effect on residential & commercial consumption

Variables	(1)	(2)	(3)
EV	0.695 (0.447)	×	0.318 (0.701)
Charging Station	×	29.71*** (7.49)	27.16*** (9.93)
Income	0.231 (0.310)	0.819** (0.401)	0.772* (0.412)
Population	0.418*** (0.074)	0.613*** (0.097)	0.608*** (0.098)
Weighted Price	134.74** (55.16)	174.97** (78.68)	171.91** (79.72)
Single HH	7,885.49 (720.71)	9,493.09 (7176.01)	10,160.81 (7358.46)
Employment	-0.123*** (0.0431)	-0.297*** (0.056)	-0.308*** (0.059)
Hot Months	169,478.93*** (11725.16)	192,259.71 (13742.45)	191,572.84*** (13843.41)
Cold Months	17,198.96 (12,556.87)	24,458.90 (15,029.43)	25,233.86 (16,430.62)
County Fixed effect	✓	✓	✓
Time Fixed effect	✓	✓	✓

*Notes: *** p<.001, ** p<.0, * p<.05. standard errors reported in parenthesis*
Number of observations = 6960

Table 6 shows the logged analysis, which represents the primary results of the effect of EV adoption on both residential and commercial sectors together. In this specification all the predictor and the outcome variables are log-transformed. For the weather control, this time, I use numbers of dummy variables with a range of 5° bins for both hot and cold months. I had to drop one of these dummies because none of these months fall under the range of 30-35° Fahrenheit.

Table 6. Robustness check specifications for electricity consumption on EV adoption

Variable	(1)	(2)	(3)
Log (EV)	0.0062	×	0.0006
	(0.0042)		(0.0079)
Log (Station)	×	0.0105***	0.0118***
		(0.0037)	(0.0039)
Log (Income)	0.0299	0.1909**	0.1536*
	(0.0712)	(0.0847)	(0.0843)
Log (Population)	0.6727***	0.8640***	0.8324***
	(0.1592)	(0.1986)	(0.2056)
Log (Weighted price)	0.0947***	0.1021***	0.0984***
	(0.0142)	(0.0175)	(0.0176)
Log (Employment)	0.1077	0.0831	0.0915
	(0.1055)	(0.1247)	(0.1318)
Log Single HH	0.8180*	1.3947***	0.0195**
	(0.4259)	(0.4580)	(0.0084)
Factor (80-85)	0.1833***	0.1921***	0.1879***
	(0.0128)	(0.0138)	(0.0136)
Factor (>90)	0.4467**	0.4529***	0.4465***
	(0.0358)	(0.0406)	(0.0400)
Factor (25-30)	0.2557***	0.3325***	0.3145***
	(0.0321)	(0.0329)	(0.0363)
Factor (20-24)	0.5465***	0.5751***	0.5781***
	(0.1233)	(0.1181)	(0.1163)
County Fixed Effect	✓	✓	✓
Year Fixed Effect	✓	✓	✓

*Notes: *** p<.001, ** p<.01, p<.05. standard errors reported in parenthesis*
Number of observations = 580

In this specification charging station again shows a significant positive effect on electricity consumption. We can interpret that a 1% increase in charging station installation increases the electricity consumption by 0.012%. According to our average county-level electricity usage data, this 0.012% would yield 33.04 MWh electricity consumption per country per month. This time, single housing unit shows a positive effect. All the temperature variables are positively significant at a 1% level.

Table 7 represents the result for the residential electricity consumption only. As before, In the first column, I use EV as my explanatory variable without the charging station in it, and in the second, I use the charging station as my explanatory variable without EV in it. Column (3) shows the result for both EV and charging stations. This model is also a two-way fixed-effect model. In column (2), Station shows a coefficient of 18.22 for residential electricity consumption. This result is significant at a 1% level. So, one extra charging station adoption can cause 18.22 MWh residential electricity consumption monthly. The population has a significant positive result on consumption, employment has a significant negative effect, and hot degree months have a significant positive impact as we expected. In column (3), EV does not have any significant effect, but charging station is still highly significant and has a positive effect on residential electricity consumption.

Table 7: Effect on residential consumption only

Variables	(1)	(2)	(3)
EV	0.152 (0.294)	×	-0.179 (0.461)
Charging Station	×	18.22*** (4.92)	20.13*** (6.53)
Income	-0.003 (0.202)	0.279 (0.262)	0.289 (0.269)
Population	0.245*** (0.049)	0.393*** (0.064)	0.392*** (0.064)
Residential Price	7.257 (22.88)	16.16 (32.45)	16.74 (32.77)
Single HH	6,525.89* (3,754.08)	7,330.94 (4,709.09)	6,972.81 (4,828.14)
Employment	-0.058** (0.028)	-0.191*** (0.037)	-0.189*** (0.039)
Hot Months	137,806.95*** (7,707.42)	158,027.64*** (9,029.48)	157,450.91*** (9,093.58)
Cold Months	4,888.51 (8,247.63)	8,853.32 (9,871.24)	9,288.32 (10,790.26)
County Fixed effect	✓	✓	✓
Time Fixed effect	✓	✓	✓

*Notes: *** p<.001, ** p<.01, p<.05. standard errors reported in parenthesis*
Number of observations = 6960

5.2 Electricity generation in California

Natural gas, coal, nuclear, hydroelectric, solar, and wind are the primary electricity generation sources in California. Among these, hydroelectric, solar, and wind are considered clean, renewable sources. As California State is concerned about the environment and trying to impose public policies to reduce pollutants, it is worth looking at the electricity generation pattern and whether the EV adoption policies are accompanied by more secure and cleaner power plants. To analyze the relationship between EV adoption and renewable energy sources, I construct a variable: the percentage share of electricity that comes from renewable sources in each county. Then, I run a two-way fixed-effect model to see the effect. This time, the data is yearly. So, the time fixed effect represents the year fixed effect. Other variables remain the same.

In California, most renewable electricity comes from hydroelectric power. Solar and wind follow hydroelectricity. There are some biomass and geothermal electricity production as well.

Table 8 shows the result of the impact of EV adoption on renewable sources of energy. In the table, column (1), (2), (3), and (4) shows the logged analysis of variables. Column (5) shows the result for unlogged variables. In the first three columns, I use EV and Station as an explanatory variable. However, it seemed more logical to have Electricity itself as the explanatory variable, shown in the column (4), and (5), as high electricity demand or usage should affect the energy mix of the electricity generation decision. According to the U.S. Energy Information Administration, electricity demand is one factor that influences the mix of energy sources for electricity generation. Intermediate load generating units (rather than Baseload units, which supply electricity at a nearly constant rate) comprise the largest generating sector and provide load responsive operation between baseload and peaking service. In general, the demand profile varies over time, and intermediate sources are technically and economically suited for following changes in load. Natural gas-fired combined-cycle units, which currently provide more generation than any other technology, generally operate as intermediate sources.

The result shows that neither EV adoption nor Station increases renewable electricity generation. Instead, when I use Electricity as the explanatory variable, it shows a significant negative impact on renewable energy sources. In this specification, the dependent variable, the percentage of electricity from renewable sources, is not log-transformed, but all the predictor variables are log-transformed. We can interpret that a 1% increase in electricity consumption decreases the renewable energy share by 0.34%. This negative effect is crucial for the policy perspective. It means more EV adoption, or in other words, more electricity usage is accompanied by decreased adoption of renewables sources.

Table 8. Effect of electricity usage on renewable energy source

	(1)	(2)	(3)	(4)	(5) (Unlogged)
Log (Electric Vehicle)	0.3217 (1.55)	×	-2.40 (2.89)	×	×
Log (Charging Station)	×	0.5540 (1.51)	0.8954 (1.60)	×	×
Log (Electricity)	×	×		-34.78 (21.05) *	-0.0000085** (0.0000036)
Log (Population)	-20.12 (61.50)	5.23 (82.50)	-21.30 (85.44)	-9.08 (54.31)	0.000016*** (0.0000036)
Log (Income)	-36.15 (25.35)	-59.65* (32.63)	-68.78** (33.79)	-4.51 (22.66)	0.000022 (0.000015)
Log (Weighted Price)	-1.87 (6.66)	0.9975** (9.81)	0.0235 (9.85)	-0.0906 (5.94)	-0.0055 (0.0039)
Log (Employment)	120.97* ** (42.60)	121.81 (51.00)	144.80** (56.02)	139.65 (39.85)	-0.0000024* (0.0000012)
Log (Single HH)	-43.18 (151.93)	-34.87 (178.57)	0.2921 (181.66)	125.79 (148.02)	2.55 (3.01)
County Fixed effect	✓	✓	✓	✓	✓
Year fixed effect	✓	✓	✓	✓	✓

*Notes: *** p<.001, ** p<.01, p<.05. standard errors reported in parenthesis*
Number of observations = 580

6 Discussion and conclusion

In addition to the rebate programs for EV and EVSE, California has enacted several other incentives to adopt electric vehicles, including HOV lane access, zero-emission transit bus tax exemption, and nine other regional incentive programs. The state rebate program for EVs alone has already spent $823 million since 2010 (California Public Utilities Commission, 2020). Nikolewski (2019) provides the breakdown of California's all EV incentive programs' total spending, which is $2.46 billion for approximately ten years. As I stated earlier, all of these incentives have been introduced in response to environmental concerns. In general, experts agree that electric vehicles are cleaner than other conventional vehicles powered by diesel or gasoline while driving because EVs emit fewer pollutants in the atmosphere. Nevertheless, the increased electricity demand due to EV and its supporting infrastructure is an important part of the policy discussions. If this issue is not addressed correctly, there will be unintended consequences on public spending and, most importantly, on the environment. Although California is trying to reduce its coal-based power plants in recent years, coal is still one of its primary electricity sources, along with natural gas and nuclear energy. These power plants emit a significant amount of greenhouse gas and other pollutants, as discussed earlier. Besides, hydroelectricity is the major source of renewable options in California. Solar and wind exist to a limited extent. So, there are rooms for renewable resources to be escalated as one of the primary electricity production sources.

This study has some limitations. California is the biggest importer of electricity as well. In 2018, almost one-third of California's electricity supply came from generating facilities outside the state. In this study, I cannot account for the imported electricity sources, which would be the scope for future research. Another interesting aspect of this research could be analyzing the adoption of small-scale customer-sited solar photovoltaics (PV) in California, known as a behind-the-meter generation, a predominant technology in residential solar PV. In 2019, solar PV self-generated about 16,000 GWh of energy (California Energy Commission, 2019, slide 8). But there is no data available right now at the county level to see the relationship of EV adoption with PV adoption.

However, this study finds that EV adoption significantly increases electricity consumption in residential and commercial sectors, and energy usage is accompanied by a lower adoption of renewable power plants. Considering the average number of charging stations per county, EV adoption increases monthly residential and commercial electricity consumption by 0.012%. Based on California's average energy generation, this would yield 33.04 MWh. Besides, a 1% increase in electricity consumption is associates with 0.34% of the decrease in the renewable electricity share. These results should be an essential viewpoint for policymakers. Evaluating government EV incentives' true environmental impact should weigh the reduced gasoline engine emissions against the increased fossil fuel or nuclear consumption during electricity generation. Unless California adopts cleaner sources of power plants, billions of dollars of public spending on EV adoption will not be as effective as it would be if accompanied by increased adoption of renewable energy sources.

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A. Appendix

A.1 Clean vehicle rebate project

The Clean Vehicle Rebate Project (CVRP) promotes clean vehicle adoption by offering rebates of up to $7,000 for the purchase or lease of new, eligible zero-emission vehicles, including electric, plug-in hybrid electric, and fuel cell electric vehicles. Until funds are available, eligible California residents can follow a simple process to apply for a CVRP rebate after purchasing or leasing an eligible vehicle. The Center for Sustainable Energy (CSE) administers CVRP throughout the California Air Resources Board (CARB) state. [17] In my dataset, there are a total of 371892 rebate application records.

Income Eligibility

- Income Cap: Higher-income consumers are not eligible for CVRP rebates if their gross annual incomes are above the income cap. The income cap applies to all eligible vehicle types except fuel-cell electric vehicles. The present income cap is mentioned below-
    1. $150,000 for single filers
    2. $204,000 for head–of–household filers
    3. $300,000 for joint filers
- Increased Rebate: Consumers with household incomes less than or equal to 300 percent of the federal poverty level are eligible for an increased rebate amount. Increased rebate amounts are available for fuel-cell electric vehicles, battery electric vehicles, and plug-in hybrid vehicles.

Rebate Limit

Individual and business applicants are not eligible to receive more than one CVRP rebate either via direct purchase and/or lease as of December 3, 2019. Traditional rental and car share fleets are subject to limits of 20 rebates per calendar year. Public fleets are limited to 30 rebates per calendar year.

Vehicle Eligibility

Eligible vehicles must meet requirements that include, but are not limited to, the following:

- Be on the list of Eligible Vehicles which meet required emission standards.
- Be new as defined in the California Vehicle Code (CVC) Section 430 and manufactured by the original equipment manufacturer (OEM) or its authorized licensee. Vehicles considered new vehicles solely for the determination of compliance with state emissions standards are not eligible.
- Be registered as new in California. Vehicles may not be purchased, leased, or delivered out of state. Purchases/leases must be made via a California purchase or lease contract. Vehicles ordered online and delivered outside of California are not eligible. The seller's address, as reflected on the purchase or lease agreement, must be in California.
- Have an odometer reading below 7,500 miles at the time of purchase or lease.

Funding Availability

If funds are not available at the time of application, people may still apply and be placed on a rebate waitlist. Rebates for approved applications on the waitlist will be issued if additional funding from the state of California becomes available.

A.2. charging station rebate

Rebates for Residential Level 2 Charging Stations

Numbers of California utility providers and air districts[2] offer rebates to make home Level 2 charging stations more affordable. Some of the rebates also help offset the cost of installing the charging station at the EV owner's home if additional electrical work is required. The minimum rebate amount is $400, and the maximum is $4000 based on the location and EVSE type. In California, the most popular charging is Level 2 charging. The median installation cost of a Level-2 charger is $1,200 (Idaho National Laboratory, 2015).

Rebates for Commercial EV Charging Stations

Property owners can get rebates for installing commercial charging stations for public use and thus generate a new revenue stream (charging fees). In California, there are nineteen separate utility incentives and ten air district incentives for the commercial installation of an EV charging station

[2] Air districts refer to county or regional agencies throughout California that have primary responsibility for controlling air pollution from stationary sources and administer various air pollution-related rebate programs and initiatives. California has 23 Air Pollution Control Districts (APCDs) and 12 Air Quality Management Districts (AQMDs).