The Use of Electric Cars in Short-Notice Evacuations: A Case Study of California's Natural Disasters

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Abstract

As Electric Vehicles (EVs) become more widely adopted by consumers, their use in emergency evacuation situations becomes a more relevant challenge. Short-notice evacuations, such as those caused by wildfires and earthquakes, may lead to stall-outs, resulting in increased traffic and accidents. To avoid this, EV charging stations need to be located far enough away from emergency sites but within the range of an average charge to prevent stall-outs. California is the state that has the largest number of EVs and the largest number of wildfires annually. The objective of this study is to analyze the state of California's current EV charging capacity in emergency situations by applying existing methodology while focusing on a new aspect.

Keywords
Electric Vehicles, Simulation, California, Evacuations, Natural Disasters

1. Introduction

1.1 Background

One of the drawbacks of EVs is that they generally have a smaller driving range than a gas-powered car. Most electric vehicles have a range between 100-200 miles, which is at least 100 miles less than the average gas-powered car. In addition, recharging to full capacity can take anywhere from 3 to 12 hours, with "fast charges" to 80% still taking at least 30 minutes (fueleconomy.gov). This can create serious problems in evacuations because of the large disparity between refueling a gas-powered car and recharging an EV. Stalled EVs will create huge traveling delays for the people using them and even increased traffic if a stalled EV is blocking a lane.

In 2019, EVs made up 1.9% of the United States vehicle market share, with the largest concentration of EVs located in the state of California (energy.gov, 2019). With EVs making up such a small percentage of the current vehicle market, the problem of publicly available charging stations does not affect a significant percentage of the population. However, in 2020, Gavin Newsom, the governor of California, issued an executive order that requires all new cars sold in the state to be EVs by 2035 (Newsom, 2020). If this executive order continues to be upheld by successive California governors, within the next 30 years, EVs will see a significant increase in market share, presenting a problem for charging station capacity. Governor Newsom's executive order contains no mandates about the installation of publicly available charging stations.

California's two main natural disasters are earthquakes and wildfires. Both are short-notice events that have the potential to knock out the power grid with no warning, making it especially difficult, if not impossible, to charge a Battery Electric Vehicle (BEV). Over 2 million properties in California are at extreme risk from wildfires, making up about half of all properties at extreme risk from wildfires (Verisk, 2020). Additionally, the occurrence of wildfires has increased greatly in recent years, with 2020 seeing 5 out of the 6 largest California wildfires ever (McGough, 2020). This has continued to be proven true in 2021, with the Dixie fire becoming the largest single fire, and the second-largest fire ever in California's history, spreading through four counties, two national forests, and a national park and destroying over 1,000 buildings (AP, 2021). Wildfire evacuation will become a bigger problem with a wider spread adoption of EVs if the power grid is not at full capacity.

1.2 Objectives
With the amount of EVs set to more than triple in the next 15 years and the number of severe natural disasters increasing as well, the objective of this model was to determine the minimum number of publicly available charging stations that need to be installed for every electric vehicle in the area to be able to safely evacuate.

2. Literature Review
2.1 Capacity Modeling with Queuing
While there have been significant contributions to the problem of optimal locations for EV charging stations, very little research has been directed at the capacity of charging stations. Aveklouris et al. (2017) examine charging station and parking capacity through M/M/c queues during a non-evacuation situation. This means their arrival distribution is different from the one that would be seen during an evacuation. In particular, they focus on slow charging or charging where the owners are not waiting for the car to be charged and are instead doing something else. In this model, time is not of the essence. Bayram et al. (2013) and Yudovina and Michailidis (2013) focus on fast charging, which is more in line with emergency situations but does draw significantly more power from the emergency grid.

Two previous papers have explored EV charging station capacity in relation to emergency evacuation situations. Adderly et al. (2017) examined EVs through hurricane evacuations in Florida, USA. They applied a basic capacity model, taking the ratio of average charging times and the number of EVs evacuating. MacDonald (2020) expands upon this initial research using a G/G/c/N queuing problem and applying this method to Prince George, British Columbia and the wildfires that occurred there in 2017.

2.2 Evacuation Volumes
In an evacuation situation, there are more cars on the road than normal. This means an increased number of cars in need of a charge. In short-notice situations, like the wildfires and earthquakes that are common in California, evacuation notices have very little or no time at all to be sent out. This means that little to no charging can be done at home. Archibald and McNeil (2012) found that during long-term hurricane evacuations, roads only filled to 79% capacity in Delaware, USA. However, Chang and Nojima (1999) examined the evacuation traffic after the 1995 Hyogoken–Nanbu earthquake in Japan and found that because of damage, traffic volume had to be reduced to 35-55% of pre-earthquake capacity, greatly increasing the times that people spent on the road trying to evacuate. In wildfires especially, this becomes dangerous if there is very little evacuation notice.

3. Methods
Several simulation software were evaluated, including SUMO and Anylogic. However, due to the size of the simulation and the assumptions made, it was determined that Excel would be used. An Excel Macro developed by Rutgers University called YASAI was used for this simulation. It was then run through Amazon Web Services due to the size of the simulation.

3.1 Assumptions
Several assumptions were made for the model. The most important one is that all EVs have enough charge to reach a charging station from wherever they are evacuating from. This was found to be reasonable due to the linear nature of EV charging between 20% and 80%. Most EV owners keep their vehicle's battery above 20% to increase the life of the battery (Mies et al., 2018). This leads to the assumption that EV owners will choose to evacuate safely rather than preserve their car's battery life and, if their car is around 20% charge, will choose to leave regardless, which was also determined to be reasonable.

It was also assumed that all cars would be evacuating the same distance, which can be input into the model and changed depending on the scenario. In addition, the number of cars purchased per year remains constant through 2035 in California was assumed, and that Tesla owners have adapters to be able to connect to non-Tesla charging ports which are widely available and relatively inexpensive. Additionally, it was assumed in this model that all publicly available charging stations would have a similar amount of traffic, and there would not be a few stations in much higher demand than all others. This was assumed because the exact addresses of EV owners are not publicly available information. Therefore it is difficult to determine where in the area the highest concentration of EVs would be found. Lastly, when the car exits the simulation, it is assumed to be safely evacuated. This, however, does not account for any traffic on the roads due to the evacuation and may not mean that the car has actually reached the evacuation point.

3.2 Constructing the Model

Before constructing the simulation model, a flowchart, shown in Figure 1, was created. When the vehicle enters the model, it is first determined whether it has enough charge to reach the evacuation point. The evacuation point is entered into the model in miles, which then determines the amount of charge needed to reach the evacuation point. If the vehicle has enough charge, it proceeds through the model without stopping and is counted as having been safely evacuated. If they do not have enough charge, the simulation then decides where the car will charge. If there are level 3 chargers available, then the model will choose to have the vehicle go to a Level 3 charger because of the much faster charging time. If not, then they will go to a Level 2 charger and wait a long time. When they reach the amount of charge needed to safely evacuate without stall-outs on the freeway, then the car exits the simulation and is assumed to safely evacuate.

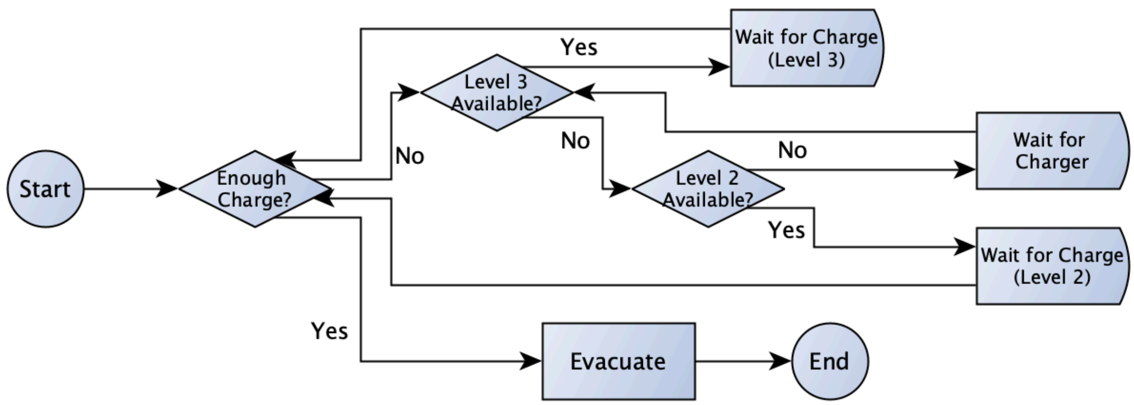

Figure 1: Flowchart followed by the model.

The charge of each car was determined by a normal distribution with a mean of 50% and a standard deviation of 15%. This was chosen because there is no way to determine when a wildfire will happen and when evacuations will start. Presumably, cars have the most charge in the morning if the owners have charged their cars overnight, but not every owner charges their car every day, and in the evenings after commuting to work and back, the average EV charge is at their lowest, with little time to recharge the vehicle.

The amount of charge per mile of 12 different EVs were averaged to determine the average charge needed to reach the evacuation point without going below 20%, shown in Table 1. Then the time needed to charge is calculated from Table 2. The charging times between 20% and 80% for lithium-ion batteries is linear, with Level 2 chargers adding 1% charge every seven minutes and Level 3 chargers adding 1% charge every 0.75 minutes.

Once the car has gone through the model, it is noted as whether it was charged by a Level 2 charger, Level 3 charger, or not charged. Those three numbers are added together and divided by the total number of cars in the simulation to get the percentage of cars able to evacuate the city. A dashboard was also added to the simulation so that it can be more easily adapted to other areas. Different evacuation times and distances can be easily changed as well as the current number of Level 2 and Level 3 chargers in the area.

Table 1: Percent charge needed to reach evacuation site

Evacuation Site	
Miles to Site	% of Charge Needed (Capped at 80%)
10	23%
20	27%
30	30%
40	33%
50	36%
60	40%
70	43%
80	46%
90	49%
100	53%
110	56%
120	59%
130	62%
140	66%
150	69%
160	72%

Table 2: Charging time in minutes to 80% charge

Charging Times (min)		
Previous Charge Level	Level 2	Level 3
20	423	45
30	352.5	37.5
40	282	30
50	211.5	22.5
60	141	15
70	70.5	7.5
80	0	0

4. Data

4.1 Case Study: Santa Rosa, CA

The case study of Santa Rosa, California, was used for the simulation. This was chosen for several reasons. First, it's a mid-sized city that is not in a densely packed urban area. It is about one hour north of San Francisco, CA. Their removal from the densely packed urban areas increases their risk of wildfires. They have been affected by multiple wildfires in the past 5 years, including the Tubbs Fire of 2017 and the Glass Fire of 2020, so the issue of evacuation is very relevant. Additionally, Santa Rosa has a higher number of EVs per capita than the average city in California and a higher number of publicly available charging stations.

The simulation was modeled using the scenario involving the 2017 Tubbs Fire. This was a fire that broke out in the fall of 2017, about 12 miles from the Santa Rosa city limits (NYT Staff, 2017). Due to high wind speeds, not uncommon for that time of year, the fire reached the outskirts of the city within three hours, and emergency services were underprepared due to the speed of the spread. At 1:12 AM, authorities warned that the fire would reach Santa Rosa within the hour, leaving little to no time to prepare or grab anything other than essentials. Between 2:00 AM and 3:00 AM, the fire was destroying homes within the very heart of the city and a densely packed neighborhood of over 1,000 homes called Coffrey Park. Most residents were forced to evacuate south, away from the fire to the closest city of Petaluma, CA, or farther to San Francisco, CA. This fire was chosen because of the profound impact it has had on that community.

4.2 Data Collection

The evacuation distance and time were taken from the Tubbs Fire. Currently, they have 120 Level 2 chargers, which are the chargers that take several hours to reach a full charge, and 31 Level 3 chargers, which are the ones that generally charge your car in under an hour but are more expensive (ChargeHub, 2021). Level 1 chargers are not publicly used because of their extremely long charging times.

Data regarding the number of EVs that will be in Santa Rosa in the year 2035 is more complicated. Currently, Sonoma County has 1.6% of all EVs in California which averages to approximately 3,000 EVs owned by residents of Santa Rosa (Brant, 2015). Assuming cars will be bought at a near-constant rate for the next 15 years, 896,000 cars will be bought annually in California, with 1.2% of them being bought in Santa Rosa (Carlier, 2021). The market share that EVs hold has been steadily increasing in the past few years and with the announcement of the new executive order, this can only be assumed to continue increasing.

If the number of new EVs bought in 2035 will be equivalent to the number of cars bought in 2035 and that the rate of adoption for new EV users will follow a sigmoid function, the following function can be used to describe the number of new EVs on the roads per year:

$$S(x) = \min + (max - min)\left(\frac{1}{(1 + e^{(-k(x-x_0)^a}}\right)$$

Where the min is the initial percentage of EVs in Santa Rosa, 1.6%, the max is 100% adoption of EVs, x is the year, and x0 is the mean of years. K is the parameter that controls the shape of the curve so the larger k is, the steeper the curve will be, while a is the parameter controlling the start of rapid growth. K = 1 for this model and a = 1. The rate of adoption is shown in Figure 2.

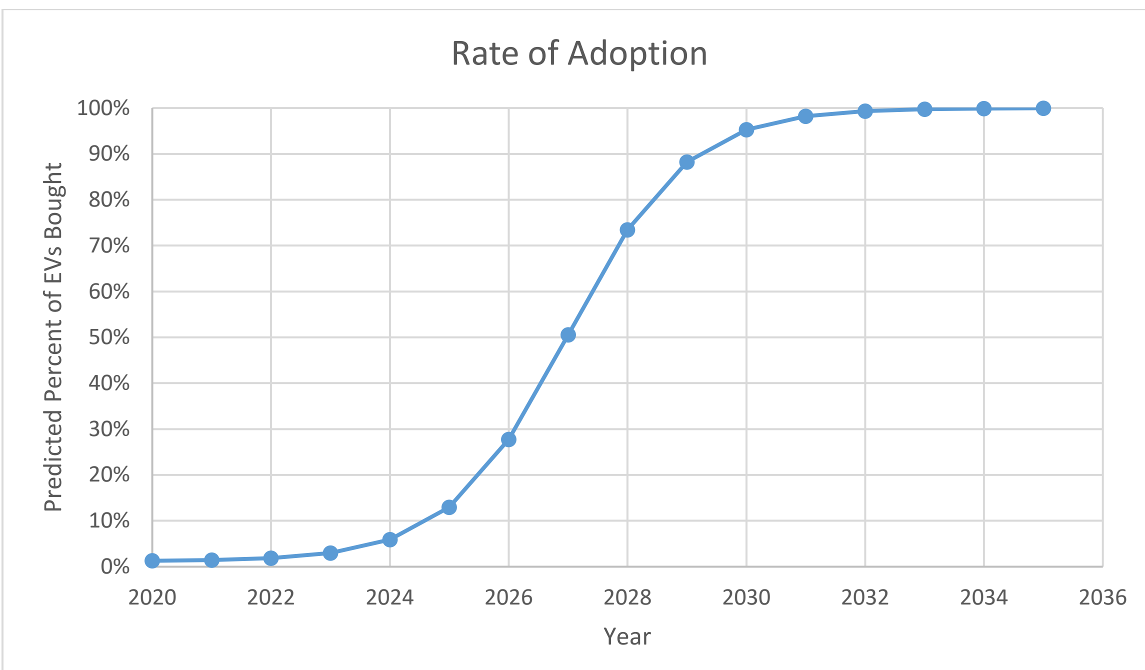

Figure 2: Predicted rate of adoption for EVs in Santa Rosa, CA.

These newly bought EVs are then added to the overall number of EVs since it is also assumed that a negligible amount of the population will buy a non-electric vehicle after owning an EV. Therefore, the total number of EVs predicted to be in Santa Rosa, CA by 2035 is shown in Figure 3.

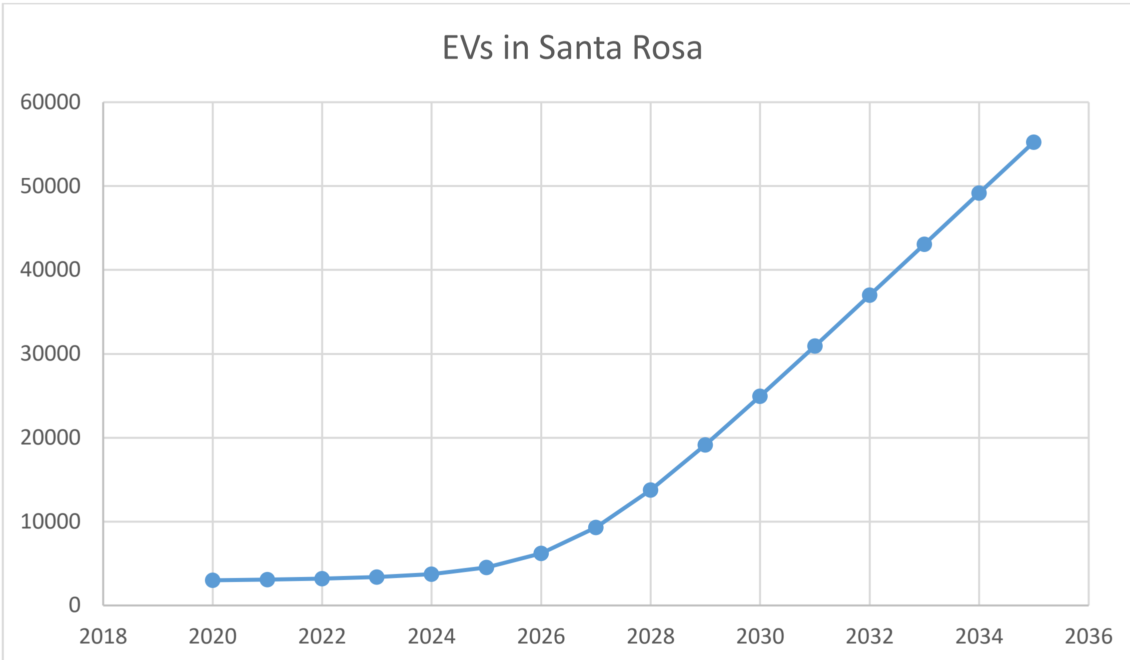

Figure 3: Approximate number of EVs in Santa Rosa, CA per year.

5. Results and Discussion

Three scenarios were analyzed as part of the results: One where 100% of the electric cars were forced to evacuate, one with 60% of the cars, and one with 40% of the cars. These were decided on to see the maximum number of chargers needed to ensure safe evacuations and the percentage of the population evacuated in the Glass Fires and the Tubbs Fire, respectively.

5.1 Numerical Results

The results from the three scenarios are displayed in Table 3. Currently, Santa Rosa almost has the infrastructure to support the 40% evacuation it saw in 2017 with the Tubbs Fire. However, in 2020 with the Glass Fire, they chose to evacuate more of the population earlier to avoid casualties as much as possible. Therefore, it would be prudent for Santa Rosa to continue to upgrade their charging infrastructure in the next 15 years.

Table 3: Results of three scenarios

Percentage of Cars Evacuating	Number of Level 2 Chargers to be Added	Number of Level 3 Chargers to be Added
100%	180	20
60% (Glass Fire)	12	4
40% (Tubbs Fire)	10	0

5.2 Proposed Improvements

There are several improvements that could be made to this model. First, constraints could be added based on the amount of money that a certain city, or area, is willing to invest in publicly available charging stations. For this model, it was not included because of the differences in the amount of money each area would be willing to invest in this public infrastructure project. It could vary depending on the amount that corporations or individuals would be willing to donate to the government to encourage the use of EVs. Second, it was assumed in this model that all publicly available charging stations would have a similar amount of traffic, and there would not be a few stations in much higher demand than all others because of the lack of information about the highest concentrations of EVs within a given area. This information would be able to identify the publicly available charging stations likely to experience a bottleneck and the ones that are being underutilized.

Additionally, the population growth patterns of Santa Rosa and California, in general, could be considered within the model. According to the California Department of Finance, the population of California is declining for the first time in a century (Hubler, 2021). A continued decline in the population could affect the results of the model when that data becomes available.

6. Conclusion

As expected, more publicly available charging stations need to be added in any scenario. What was surprising what that no level 3 chargers would need to be added to accommodate the evacuation of 40% of EVs in the city. This leads to the assumption that if less than 40% of the population of Santa Rosa needed to evacuate from a fire in 2035, the current level of publicly available charging stations would most likely be sufficient to support all residents safely evacuating, indicating that Santa Rosa is already in a good position to support electric vehicle evacuations.

Although the initial objective of this model was to determine the minimum number of charging stations that would need to be added to safely evacuate all EVs, it was found that to get the minimum number, they would need to all be level 3 charging stations. Level 3 charging stations are much more expensive than level 2 charging stations and put a greater burden on the electric grid, which is not a good thing in evacuation scenarios. Instead, an even balance of Level 2 and Level 3 chargers was found to help alleviate this issue.

Once the optimal number of publicly available charging stations has been identified, the next step is to identify where these new charging stations should be located. By looking at traffic patterns, proximity to neighborhoods and freeways, and the locations of currently existing charging stations, a simulation could be developed to find the optimal placement for the new charging stations. Additionally, further study into the everyday needs of publicly available charging stations in California under Governor Newsom's executive order could be investigated as well.

References

"2020 Verisk Wildfire Risk Analysis." *Verisk*, www.verisk.com/insurance/campaigns/location-fireline-state-risk-report/.

Adderly, Shawn A., et al. "Electric Vehicles and Natural Disaster Policy Implications." *Elsevier*, 5 Nov. 2017.

"All-Electric Vehicles." *Www.fueleconomy.gov - the Official Government Source for Fuel Economy Information*, n.d., www.fueleconomy.gov/feg/evtech.shtml.

Archibald, Erik and McNeil, Sue., "Learning from traffic data collected before, during and after a hurricane" IATSS Research., Vol. 36, Issue 1, pp. 1-10, July 2012.

Associated Press. "The Largest Wildfire in California's History in Continuing to Grow." *Time.com*, 11, Aug. 2021, https://time.com/6089742/california-wildfire/

Brant, Arthur et al. "Electric Vehicles in Sonoma County: White Paper on EV Status and Paths to Adoption". Center for Climate Protection, Aug. 2015., https://theclimatecenter.org/wp-content/uploads/2015/08/EVWhitePaper-SonomaCounty-Final.pdf

California, State of. "Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars & Drastically Reduce Demand for Fossil Fuel in California's Fight Against Climate Change." *California Governor*, 26 Apr. 2021, www.gov.ca.gov/2020/09/23/governor-newsom-announces-california-will-phase-out-gasoline-powered-cars-drastically-reduce -demand-for-fossil-fuel-in-californias-fight-against-climate-change/#:~:text=In%20the%20last%20six%20months,electric%20medium%2D%20and%20heavy%2Dduty.

Carlier, Mathilde. "Car sales in the United States by key state 2018." Statista.com. 4, Aug. 2021. https://www.statista.com/statistics/634072/us-car-sales-by-key-state/

Carpenter, Susan. "What It Will Take to Get to 100% EV Sales in California." *spectrumnews1.Com*, 6 Oct. 2020, spectrumnews1.com/ca/la-west/transportation/2020/10/05/what-it-will-take-to-sell-100--evs-in-california.

Chang, Stephanie and Nojima, Nobuoto. "Measuring Post-Disaster Transportation System Performance: The 1995 Kobe Earthquake in Comparative Perspective". 5 Sept. 1999. https://reader.elsevier.com/reader/sd/pii/S0965856400000033?token=31DB601808339F3CEA029E1AAF313D9

67A55B4A567C43E1310E01ECA4C8A0139B7C56B27183DAECA1FAA607FAE3D5F4B&originRegion=us-east-1&originCreation=20210815210416

ChargeHub, EV. “Santa Rosa, California EV Charging Stations Info.” *ChargeHub*, 2021, chargehub.com/en/countries/united-states/california/santa-rosa.html.

“Charging Plug-In Electric Vehicles at Home.” *Alternative Fuels Data Center: Charging Plug-In Electric Vehicles at Home*, US Department of Energy, 2021, afdc.energy.gov/fuels/electricity_charging_home.html#:~:text=If%20electricity%20costs%20%240.13%20per,to%20reach%20a%20full%20charge.

D. L. Donaldson, M. S. Alvarez-Alvarado and D. Jayaweera, "Power System Resiliency During Wildfires Under Increasing Penetration of Electric Vehicles," 2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), 2020, pp. 1-6, doi: 10.1109/PMAPS47429.2020.9183683.

E. Yudovina and G. Michailidis, "Socially Optimal Charging Strategies for Electric Vehicles," in IEEE Transactions on Automatic Control, vol. 60, no. 3, pp. 837-842, March 2015, doi: 10.1109/TAC.2014.2346089.

Executive Order. No. N-79-20, 2020.

Grid Integration Tech Team and Integrated Systems Analysis Tech Team. “Summary Report on EVs at Scale and the U.S. Electric Power System.” *Energy.gov*, Nov. 2019, www.energy.gov/sites/prod/files/2019/12/f69/GITT%20ISATT%20EVs%20at%20Scale%20Grid%20Summary%20Report%20FINAL%20Nov2019.pdf.

Guo, F., Yang, J., & Lu, J. (2018). The battery charging station location problem: Impact of users’ range anxiety and distance convenience. *Transportation Research Part E: Logistics and Transportation Review*, *114*, 1–18. https://doi.org/https://doi.org/10.1016/j.tre.2018.03.014

Hubler, Shawn. “A New Demographic Surprise for California: Population Loss.” *The New York Times*. 7 May 2021. https://www.nytimes.com/2021/05/07/us/california-population-loss.html

MacDonald, Craig. “Modeling Charging Network Capacity and Evacuation Route Capacity During Short-Notice Events.” *University of Calgary*, 2020.

McGough, Michael. “5 Of the 6 Largest California Wildfires in History Started in the Past 6 Weeks.” *Sacramento Bee*, 2020.

Staff, New York Times. “How Santa Rosa's Tubbs Fire Spread, Hour by Hour.” *Santa Rosa Press Democrat*, The Press Democrat, 28 Sept. 2020, www.pressdemocrat.com/article/news/how-santa-rosas-tubbs-fire-spread-hour-by-hour/.

Biographies

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