This Master’s Project

Evaluating the transition to zero-emission vehicles and the impact on clean electricity demand under the effects of climate change in San Francisco

by
Tamara G. Totah

is submitted in partial fulfillment of the requirements for the degree of:

Master of Science
in
Environmental Management
at the
University of San Francisco

Submitted: ___________________________ Received: ___________________________

_________________________________ ___________________________
Tamara Totah Date Amalia Kokkinaki, Ph.D. Date
Abstract

California is considered a global leader in environmental policy relating to climate change and greenhouse gas emission mitigation. The state has implemented policies to limit greenhouse gas emissions and phase-out the use of fossil fuels in transportation. The transportation sector is one of the major emitters of greenhouse gasses in California. In 2020, Executive Order N-79-20 established the goal of having 100% of in-state sales of new light-duty passenger vehicles and trucks to be zero emission by 2035. The use of electric vehicles has reduced greenhouse gas emissions from transportation, but we need to be able to power these vehicles while also keeping emissions down. The need for renewable and emission-free electricity is growing, especially since climate change has caused more severe storms, high winds and heat waves that increase demand for air conditioning and cause disruptions in the electrical system. This paper conducted a review of how increased electric vehicle use will impact the demand of electricity, while considering climate changes’ effects on the electric grid. The generation, distribution, and transmission of electricity is impacted by climate change on a state and local scale. California policies shape the transition to clean electricity generation and sustainable transportation and San Francisco has adapted strategies to achieve California's climate mitigation goals. Electrical demand will impact San Francisco’s transition to electric vehicles and renewable electricity generation. This review found that the quantity, shape, and timing of demand will also change depending on technological and environmental factors. Electrical supply can be altered to meet demand for individual cities and the state. San Francisco relies on hydropower to generate half the city's electricity, but California’s drought conditions could impact generation in the future. Diversifying state and local energy mix and increasing grid resilience to climate change will strengthen the system. Additional investments in energy storage, increased use of other renewable or clean sources and further researching vehicle to grid integration are some of the ways electrical supply can meet demand from vehicle electrification. Electrical supply can be enhanced by increasing investment in energy storage to support the increased use of solar and wind power. Reconsidering closures of nuclear power plants until reliance on renewable electricity supply and storage is consistent. The development of vehicle to grid (V2G) integration and bi-directional charging will support vehicle electrification and the grid’s transition to renewable and emission-free sources.
Table of Contents

1. *Introduction* 7

2. *Methods* 11

3. *Background* 13

3.1. *California Policies & Programs* 13

3.2. *The Electric Grid and California’s Energy Mix* 14
   - In-state Electricity Generation in California 15
   - California’s Electricity Imports 16

3.3. *Reliability of Emission-Free Sources* 18

3.4. *Impact of Climate Change on the Electric Grid* 20
   - Electricity Generation in California 21
   - Electricity Transmission and Distribution in California 22
   - Electricity Demand in California 23

4. *Results and Discussion* 25

4.1. *San Francisco’s Transportation Sector* 25
   - Electricity Generation in San Francisco 28
   - Climate Change Impact in San Francisco Bay Area 29
   - Shift to Sustainable Transportation in San Francisco 30
   - Role of Zero-Emission Vehicles in Sustainable Transportation 31
   - Current Charging Demand from Electric Vehicles in San Francisco 33

4.2. *Zero-Emission Vehicles in California, Los Angeles, and San Francisco* 33
   - Electric Vehicles Projected Impact on Future Demand in California 35
   - Projected Future Demand from Electric Vehicles in Los Angeles 38
   - Comparing California and Los Angeles Demand Projections to San Francisco 40

4.3. *Strategies to Balance Electrical Supply and Projected Demand* 41
   - Strengthen grid resiliency against climate change 42
   - Invest in energy storage technology for renewable integration 43
   - Invest in Smart grid and Develop Vehicle to Grid integration 43


Alter Timing of Electrical Demand .............................................. 43
In case of Energy surplus .......................................................... 44

5. Recommendations and Conclusion ........................................ 45

References .............................................................................. 49
List of Figures

Figure 1: U.S. Greenhouse Gas Emissions Overview and Sources in 2020 (EPA, 2022). ______ 7
Figure 2: California greenhouse gas emissions by sector in 2019 (CARB, 2021). _____________ 9
Figure 3: California in-state electricity generated by source in 2021 (California Energy Commission, 2022). _____________________________ 16
Figure 4: State net electricity exports and imports in 2019 (U.S. Energy Information Administration [EIA], 2020). _____________________________ 17
Figure 5: Imported Electricity by Generation Type (CARB, 2021). _____________________________ 18
Figure 6: Duck curve comparing solar and wind generation to electric loads with and without variable generation (Denholm et al., 2015). _____________________________ 19
Figure 7: Capacity Factor by Energy Source in 2020 (U.S. Energy Information Administration, 2022). _____________________________ 20
Figure 8: Comparison of 2020 Monthly Hydroelectric Generation to Historical Highs and Lows in California (CEC, 2022). _____________________________ 21
Figure 9: San Francisco’s greenhouse gas emissions by sector in 2019 (San Francisco Department of Environment, 2021). _____________________________ 25
Figure 10: Transportation emissions by sub sector in San Francisco for 2019 (San Francisco Department of Environment, 2021). _____________________________ 26
Figure 11: Transportation emissions by type and source (San Francisco Department of the Environment, 2022). _____________________________ 27
Figure 12: San Francisco Public transportation emissions by type and Source (San Francisco Department of the Environment, 2022). _____________________________ 27
Figure 13: San Francisco electricity generation and consumption by Source in 2019 (San Francisco Department of the Environment, 2022). _____________________________ 29
Figure 14: The Sustainable Transport Hierarchy (Action Net Zero CIC, 2022). _____________ 30
Figure 15: Weekday time of day Charging demand in San Francisco (Schey et al., 2012). _____________ 33
Figure 16: Population Density, PEV Density and Public Chargers by County (Alexander et al., 2021). _____________________________ 34
Figure 17: California Annual Light-duty zero-emission vehicle sales and Market share from 2011-2021 (Javanbakht et al., 2022). _____________________________ 34
Figure 18: Light-duty vehicle energy consumption for 2020 and 2035 (Javanbakht et al., 2022).

Figure 19: Projected Statewide power for light-duty charging for 8 million ZEVs on a typical 2030 weekday in California (Alexander et al., 2021).

Figure 20: Possible impacts of electric vehicle charging on total electricity demand (Muratori & Mai, 2021).

Figure 21: Annual electricity consumption by projection-year and sector for Los Angeles (Hale et al., 2021).

Figure 22: Assumed new electric vehicle share and stock in San Francisco from 2015 to 2050 (Hsu et al., 2020).

Figure 23: Feedback loops associated with climate change, and the relation to electric vehicles and the electric grid.

List of Tables

Table 1: Wildfires caused by electric power accounted for 19% of acres burned from 2016 to 2020 (California State Auditor, 2022).

Table 2: Total Light-duty Vehicles end of 2021 Comparison of California, Los Angeles, and San Francisco. Data from https://www.energy.ca.gov/zevstats

Table 3: LA100 Customer Demand (Load) Projections, including Examples of Distinctions among the Projections regarding Efficiency, Electrification, and Demand Response (Hale et al., 2021).
1. Introduction

Climate change caused by the excessive amounts of greenhouse gas emissions being emitted by human activity is a growing global concern. These emissions include carbon dioxide, methane, and nitrous oxides. Carbon dioxide emissions account for 79% of the United States total greenhouse gas emissions in 2020 (Environmental Protection Agency [EPA], 2022). Greenhouse gas emissions from transportation contribute to climate change, global warming and worsens public health. The transportation industry includes cars, buses, trucks, airplanes, trains, ships, ferries, and any other vehicles used to facilitate the movement of people and goods. Transportation is an essential part of society, but it is causing harm.

In the United States, the transportation sector was the largest contributor of greenhouse gas emissions, making up 27% of all emissions in 2020 (EPA, 2022). Transportation is also responsible for 33% of the United States’ carbon dioxide emissions (EPA, 2022). Traditionally, vehicles have relied on the burning of fossil fuels, such as gasoline, diesel, and other petroleum-based products to power internal combustion engines, which contributes to these emissions. About 57% of greenhouse gas emissions come from light-duty vehicles and approximately 26% come from medium and heavy-duty trucks (EPA, 2022). The increase amounts of greenhouse gas emissions contribute to climate change, pollution and poor air quality which impacts both environmental and human health.

Figure 1: U.S. Greenhouse Gas Emissions Overview and Sources in 2020 (EPA, 2022).
One of the main sources of greenhouse gas emissions in California is transportation (i.e., cars, trucks, buses, planes, trains, and ships). California’s transportation sector accounts for about 40% of the states’ greenhouse gas emissions (California Air Resources Board, 2021). In California, climate change contributes to extreme weather events (e.g., wildfires, storms, heatwaves, drought, coastal erosion, and sea level rise). These environmental changes will significantly affect the economy, industrial sector and energy infrastructure impacting diverse communities throughout California (Shonoff et al., 2011). To reduce emissions from transportation, there has been multiple policies and programs introduced that encourage the electrification of transportation and the adoption of zero emission vehicles.

In 2020, Governor Newsom signed Executive Order N-79-20 which established the goal of having 100% of in-state sales of new light-duty passenger vehicles and trucks to be zero emission by 2035 (Executive Department State of California, 2020). California Assembly Bill 1218 was introduced in 2021, this bill would require the state to develop and adopt the goals stated in Executive Order N-79-20 (California State Legislature, 2021). Passenger vehicles contributed the most emissions in the transportation sector (see Figure 2). Electric-powered vehicles can help achieve greenhouse gas mitigation, air quality, and climate change goals. Achieving these goals through policy regulations creates sustainable communities that are more resource-efficient (Sperling & Eggert, 2014).

Electrification of transport will help phase-out fossil fuels used in the transportation sector while promoting the transition to all renewable and low-carbon generation of electricity in the state. Electricity production is the second largest source of emissions and is responsible for 25% of the United States’ greenhouse emissions (EPA, 2022). California has the most registrations of zero emission vehicles in the United States (Alternative Fuels Data Center, 2022). The phase-out of gasoline-powered vehicles increases reliance on electric-powered vehicles causing increased demand for electricity. Encouraging the switch to electric vehicles will have many benefits but the impact of increased electrical demand on the electrical grid needs to be addressed especially for individual cities and communities in California. Climate change has already caused many issues for the state’s electric grid but increased demand from electric vehicles will cause additional stress.
The objectives of this research are to assess how increased use of electric vehicles will impact electric demand considering the switch to renewable generation sources. I will look at the state of California as a whole and compare two California cities, San Francisco, and Los Angeles. My research objective is to see if San Francisco’s current electrical supply can handle increased demand for electricity from the adoption of electric vehicles. Privately owned vehicles contribute to about 96% of transportation related emissions in the city (San Francisco Municipal Transportation Agency [SFMTA], 2022). Public transit (e.g., buses, trains, and ferries) has already transitioned to using electricity or renewable diesel (SFMTA, 2022). Switching from traditional gasoline and diesel-powered private vehicles to zero-emission vehicles would further

This figure breaks out 2019 emissions by sector into an additional level of sub-sector categories. The inner ring shows the broad Scoping Plan sectors. The outer ring breaks out the broad sectors into sub-sectors or emission categories under each sector.

*The transportation sector represents tailpipe emissions from on-road vehicles and direct emissions from other off-road mobile sources. It does not include emissions from petroleum refineries and oil extraction and production, which are included in the industrial sector.

Figure 2: California greenhouse gas emissions by sector in 2019 (CARB, 2021).
reduce emissions. Increased demand for renewable electricity can put additional strain on the local grid which already experiences power fluctuations and grid instability from climate change. San Francisco has experienced power outages due to storms, high winds and wildfires which are becoming more frequent due to climate change. San Francisco needs to be able to generate enough electricity from low carbon and renewable resources to power electric vehicles in the transportation sector.

I expect that San Francisco will need more electricity supply to meet the growing demand to power both private and public transportation vehicles in the city. Improvements in electricity generation are going to be needed if electric vehicles are going to be the main type of transportation in the city. I also expect that the electrification of transportation is not viable for transportation vehicles that need to cover a large range (i.e., heavy-duty trucks). Addressing local power supply issues to meet demand for clean electricity from transportation is also important. If electric-powered vehicles are not currently sustainable for certain types of transportation modes other vehicle types need to be considered.

First question is to assess how California policies and climate change influence San Francisco's transition to clean electricity generation and sustainable transportation. To address issues on a local scale, I will be looking at San Francisco’s greenhouse gas emissions, transportation, sustainability goals, and generation sources of electricity. A look at the local sources of renewable electricity generation while considering the effects of climate change on the local power supply will provide important information for probable issues in the future. Second question is to find out how future electrical demand from electric vehicles will impact the electrical supply and the transition to renewable electricity generation. To assess the impact electric vehicles will have on electricity demand from renewable sources, I looked at the relationship between climate change, electric vehicles, and California’s electric grid. Assessment of California’s electricity generated from renewables and emission-free sources will provide information about the state of the current electric grid. My last question is to see how the electrical supply can be altered to meet demand for the state and individual cities. Recommendations to support transportation electrification and the transition to renewable sources in electricity generation for both state and local levels are provided.
2. Methods

This report investigates the relationship between climate change, electric vehicles and electricity generated from renewable and emission-free sources in the context of San Francisco’s electrical vehicle transition. A literature review of California’s policies relating to emission reductions, electricity generation and electric vehicles was conducted. Policy and regulation information from the California State Legislature, State of California’s Executive Department, California Air Resources Board (CARB), and other federal agencies. A summary of California’s energy mix and reliability of electricity generation from renewable and emission-free sources was examined.

Data was collected, from the California Energy Commission website, regarding the state’s electrical generation sources and energy mix which includes imports. I also assessed the impact climate change has on the electric generation, transmission, distribution, and demand in California by reviewing peer-reviewed journals on the topic. These articles were found using the following keywords: climate change, electric generation, and electric grid. The reliability of emission-free sources including solar, wind, hydroelectric and nuclear power was summarized and compared. The scholarly articles reviewed for this paper were obtained by a thorough search of the online databases including Scopus, Google Scholar, the University of San Francisco’s online library, and the web search engine Google. Other references were called to my attention from my professors and colleagues.

To assess the local impact California polices have on an individual city, I looked at the electrification of transportation vehicles (i.e., private, and public) in San Francisco. City information found on the San Francisco Department of the Environment and City and County of San Francisco websites provided information about energy generation, consumption, and emissions from private and public transportation. San Francisco’s Climate Storyboard, found on the San Francisco Department of the Environment’s website, provided valuable figures and illustrations showing emission and electricity trends in the city.

A case study was written on transportation electrification’s impact on the local electricity supply while considering climate changes' effect on the electricity generation in San Francisco. Information on climate changes’ impact on the San Francisco Bay Area came from California’s Fourth Climate Change Assessment, San Francisco Bay Area regional summary report. An
analysis of San Francisco's transportation electrification goals, government reports, City Action Plans, federal and city government websites relating to emissions were collected by searching Google. The book, *Three Revolutions: Steering Automated, Shared, and Electric Vehicles to a Better Future*, by Daniel Sperling provided information about increase electric vehicle use, the benefits, and ways to create a sustainable transportation system in the long term.

A review of future projections of demand in Los Angeles and California was conducted and compared to San Francisco. Assessment of California’s transition to 100% clean electricity came from the 2021 Senate Bill 100 Joint Agency Report: Achieving 100 Percent Clean Electricity in California: An Initial Assessment provided by the California Energy Commission (CEC), California Public Utilities Commission (CPUC), and the California Air Resources Board (CARB). Demand projects for California were provided by the California Energy Commission report on Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment: Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030. Information from, The Los Angeles 100% Renewable Energy Study, Chapter 3: Electricity Demand Projections from the National Renewable Energy Laboratory, provided insight about the transition to clean electric generation on a city and local level. The impacts of increasing electric vehicle use on the electricity supply and demand were identified. Information was provided by joint agency reports and government assessments from the California Energy Commission, California Air Resources Board, California Public Utilities Commission, the National Renewable Energy Laboratory, and other agencies.

The timing of electricity demand for charging electric vehicles for a 24-hour period in the present was compared to future demand projections for a typical 2030 weekday in California. Strategies to balance electrical supply and future demand were found in government assessments, reports, and peer-reviewed journals. The California Energy Commission’s 2021 Final Integrated Energy Policy Report (IERP) provided information on the state’s transition to electric vehicles and the impact on electrical demand. The main sections focused on were the 2021 IERP’s Volume II: Ensuring Reliability in a Changing Climate, Volume III: Decarbonizing the State’s Gas System, and Volume IV: California Energy Demand Forecast.
3. Background

3.1. California Policies & Programs

In California multiple policies have been implemented to reduce greenhouse gas emissions worsening climate change. In 2004, the California Air Resources Board approved the Pavley regulation, which required automakers to lower the amount of greenhouse gas emissions from car models from 2009-2016 (CARB, 2022). California’s Assembly Bill 32, called the Global Warming Solutions Act of 2006, was implemented to reduce greenhouse gas emissions from all sources throughout the state (California Energy Commission [CEC], 2022). Senate Bill 350, the Clean Energy and Pollution Reduction Act of 2015, was also created to reduce greenhouse gas emissions, promote clean air and energy generation (CEC, 2022). In 2020, Governor Gavin Newsom announced that California will ban the sale of new gasoline powered passenger cars and trucks starting in 2035. Executive Order N-79-20 established the goal of 100% of in-state sales of new light-duty passenger vehicles be zero emission vehicles by 2035 and sales of medium and heavy-duty vehicles be zero emission by 2040, where feasible (Executive Department State of California, 2020). In 2021, Assembly Bill 1218 was introduced, which would require 100% of new passenger and light-duty vehicle sales be zero-emission vehicles by 2035 in California. Another policy related to reducing emissions from transportation in California is the Advanced Clean Truck (ACT) regulation which was approved on June 25, 2020 (California Air Resources Board [CARB], 2022). This regulation promotes the development and large-scale transition of medium and heavy-duty trucks to emission-free vehicles. Many medium and heavy-duty trucks use diesel and gasoline resulting in the release of greenhouse gas emissions. The Innovative Clean Transit (ICT) regulation is another policy that requires public transit agencies to transition to zero-emission buses starting in 2029 (CARB, 2019). The goal of this regulation is to reduce greenhouse gas emissions, and pollution which would lead to better air quality and protect public health (CARB, 2019). These statewide policies aim to reduce greenhouse gas emissions by promoting the use of zero-emission electric vehicles.

California Senate Bill 100, also known as, the 100 Percent Clean Energy Act of 2018, requires all electricity to be produced from 100% renewable energy and zero-carbon sources by 2045 (Gill et al., 2021). To complement Senate Bill 100, an additional microgrid bill, California Senate Bill 1339, was enacted. Its goals are to enhance system resilience to climate stress and
shocks, support the commercialization of microgrids and expands the distribution of electricity (California State Legislature, 2018). Senate Bill 1339 also encouraged utilities and communities to start creating more microgrid projects, one example of this is Pacific Gas & Electric Company’s Community Microgrid Enablement Program (CMEP). Executive Order B-55-18, signed by Governor Jerry Brown in 2018, also created the goal to achieve a 100% carbon neutral economy in California by 2045 (Gill et al., 2021). In December 2020, Senate Bill 67, the 24/7 Clean Energy Standard bill, was introduced which would require that 100% of California’s electrical load be supplied by eligible clean energy resources, at all times (California State Legislature, 2020). It would also require utilities to purchase clean electricity during harder-to-serve times for the state.

3.2. The Electric Grid and California’s Energy Mix

The electric grid is an interconnected system that relies on multiple agencies and balancing authorities. The Federal Energy Regulatory Commission (FERC) is an independent agency, that oversees the interstate transmission of electricity, natural gas, and oil, and regulates hydropower projects in the United States (FERC, 2022). North American Electric Reliability Corporation (NERC), a non-profit organization, is responsible for improving the reliability and security of electricity generation facilities and the high-voltage transmission system, which creates and transports electricity across North America (NERC, 2013). FERC and NERC have granted responsibly to regional entities and the largest is overseen by the Western Electricity Coordinating Council (WECC, 2015). The Western Electricity Coordinating Council (WECC) is responsible for compliance monitoring and enforcement of reliability planning and assessments in the region called the Western Interconnect, which extends from Canada to Mexico and includes California and 13 other western states (WECC, 2015). The California Independent System Operators (CAISO) is the largest balancing authority in the Western Interconnect (CAISO, 2022). They are responsible for balancing supply and demand by coordinating the bulk electric power system, maintaining grid reliability, and facilitating infrastructure planning (CAISO, 2022). They also manage the electric flow for about 80% of California and a small part of Nevada (CAISO, 2022). Elements of grid reliability include transmission stability, distribution reliability, resource adequacy, operational reliability, and resilience (Frick et al., 2021). The three main utility companies in California, Pacific Gas and Electric (PG&E), San Diego Gas and
Electric (SDG&E) and Southern California Edison (SCE), are responsible for electrical
distribution and transmission to end-use users (California Energy Commission [CEC], 2015).
Approximately, three quarters of California’s electricity demand are served by these three utility
companies (CEC, 2015).

In-state Electricity Generation in California
California’s in-state electricity generation can be split into two categories: renewables and non-
renewables. Sources that are part of the renewables category include: hydroelectric, solar, wind,
geothermal and biomass. Renewables generated about half of the electricity in California for
2021. Hydroelectric power contributed to about 7.5% of electricity generated in California. Solar
power contributed 17.1% of the total while wind power accounted for 7.8%. Geothermal energy
generated 5.7% of the total in-state electricity. Geothermal energy comes from The Geysers
Geothermal Complex, which is the world’s largest geothermal fields, located in the Sonoma,
Lake, and Mendocino counties of California (California Energy Commission [CEC], 2021).
Biomass contributed 2.8% of the total in-state generated electricity in 2021. This includes the
combustion and decomposition of organic matter and waste.

Non-renewables include coal, oil, natural gas, and nuclear energy. Coal and oil contributed less
than 1% of the total electricity generated in 2021. California currently relies on natural gas to
generate most of the electricity for the state (see Figure 3). Although natural gas is less carbon
intensive than oil and coal, it still produces emissions. If California wants to reach the goal of
100% clean electricity, set by Senate Bill 100, we need to move away from fossil fuels. Nuclear
power provided 8.5% of California’s total in-state electricity in 2021 (see Figure 3). In 2018, the
state announced it would shut down the two nuclear reactor units at the Diablo Canyon nuclear
plant, which is the last operating power plant in California, by 2024 and 2025 (California State
Legislature, 2018). This is because operating costs to keep the plant open are becoming too
costly. Senate Bill 1090, the Diablo Canyon nuclear plant closure bill, was approved in 2018 but
in August 2022, a proposal to keep the plant’s two reactors operational until 2029 and 2030 was
revealed (California State Legislature, 2022). This decision was prompted by rolling blackouts
experienced across California during the heatwaves of 2020. If the Diablo Canyon nuclear plant
shuts operations that would cause the loss of emission-free generated electricity in California.
This would impact the total amount of electricity generated, slowing progress towards a 100% renewable and emission-free generation in the state. As of September 2022, Senate Bill 846, was passed which would give Pacific Gas & Electricity, a $1.4 billion loan to keep the Diablo Canyon nuclear plant operational until 2030 (California State Legislature, 2022).

![Total California In-state Electricity Generation, 2021](image)

*Figure 3: California in-state electricity generated by source in 2021 (California Energy Commission, 2022).*

**California’s Electricity Imports**

California imports power from neighboring states and countries. In 2019, California was the largest importer of electricity in the United States (U.S. Energy Information Administration [EIA], 2020). The California Energy Commission splits imports into two categories based on location: Northwest and Southwest Imports. Northwest Imports comes from Idaho, Montana, Oregon, South Dakota, Washington, Wyoming and the Canadian provinces of Alberta, and British Colombia (California Energy Commission [CEC], 2022). Southwest imports include Arizona, Colorado, New Mexico, Texas, Utah, Baja California, and Mexico (CEC, 2022). Electricity imports account for about 30% of California’s electrical energy mix (CEC, 2022). Net
imports increased by 2.5% in 2021 to offset the decreased electrical generation in-state from hydroelectric power in California (CEC, 2022).

![State net electricity exports and imports (2019)](chart)

*Figure 4: State net electricity exports and imports in 2019 (U.S. Energy Information Administration [EIA], 2020).*

Generation sources of imports are a mix of renewable and non-renewable sources including solar, wind, hydro, nuclear, natural gas, coal, and diesel (See Figure 5). The energy resources are sorted by decreasing greenhouse gas intensity. Generation types with the least greenhouse gas emissions are on the top (solar, wind, nuclear and hydro). In 2019, imports from low-emission sources including hydro, solar, wind and nuclear grew 9% (CARB, 2021). Renewable and low-emission sources have nearly tripled when compared to 2011 levels (CARB, 2021). Reliance on coal energy had decreased by 67% since 2011 and fossil fuel generated electricity continues to decrease (CARB, 2021). If Senate Bill 67, the 24/7 Clean Energy Standard bill, is passed all future imports must be from zero-emission and renewable sources (California State Legislature, 2020).
3.3. Reliability of Emission-Free Sources

Reliability under changing grid conditions requires balancing the supply for electricity with demand (CAISO, 2016). Electricity generated from solar, and wind are intermittent, and the amount of power generated throughout the day fluctuates. Changes in cloud coverage and wind patterns causes, output from these energy sources to change. Solar generation increases in the morning, peaks in the middle of the day, slows during the early evening and then decreases at night. Electricity generated from wind complements solar generation since wind power is mostly generated at night, this helps balance the decrease of solar output. The duck curve shows the difference between electricity load and generation from solar power throughout the day (Denholm et al., 2015). As more solar panels are installed there is a risk of having an overgeneration of solar power during the day, when electric demand is low. Energy storage is used to reduce the amount of lost power generated from renewable energy sources. Backup power for wind and solar usually depend on the combustion of fossil fuels because this is less expensive than energy storage (Brook et al, 2014).
Hydroelectric generation is not intermittent and can be used to buffer the intermittencies of generation from renewables (Chang et al., 2013). Since solar power dominates daytime electrical generation, hydropower can support electrical demands at night, which can decrease reliance on generators (Chang et al., 2013). Hydroelectric dams are considered by environmentalists to be non-renewable sources of energy because they cause damage to the ecosystem (Rahman et al., 2022). Hydroelectricity is produced by building a dam which prevents the migration of fish and alters species interactions between indigenous plants and animals (Rahman et al., 2022). Dams also alter the temperature, water flow, sediment distribution, and chemical properties of the water, effecting water quality and changing the surrounding ecosystem (Rahman et al., 2022). Drought conditions in California also impacts the reliability of hydroelectric supply (Erne et al., 2022).

Nuclear power is one of the most reliable sources of energy on the grid since it generates continuously and has the highest capacity factor out of all sources of energy (see Figure 7). The capacity factor is the ratio of the actual amount of electric energy produced by a unit for a certain period of time compared to the amount that could have been produced if the unit was operating at full capacity in the same time frame (U.S. Energy Information Administration, 2022). Energy output is rarely down with nuclear power since the plants can operate
continuously throughout the day (Brook et al, 2014). The high-capacity factor makes nuclear energy an ideal candidate for replacing fossil fuels. Nuclear energy is the only emissions-free conventional energy source that can replace fossil fuels since it is reliable, efficient, and developed (Brook et al, 2014). Nuclear energy use also reduces the need for storage capacity (Michaelides & Michaelides, 2020).

Phasing-out of using nuclear energy will create energy gaps and relying on renewables like wind and solar is not enough. When generation from renewable sources is low the combustion of non-renewable energy sources, often natural gas, is relied on to fill in gaps (Brook et al., 2014). Replacing fossil fuels with renewables such as solar and wind power also causes a supply-demand mismatch in terms of timing (Michaelides & Michaelides, 2020). Use of renewables and nuclear energy would provide a cleaner alternative to using fossil fuels in the generation of electricity and meet the goals of Senate Bill 100.

![Capacity Factor by Energy Source in 2020](image)

*Figure 7: Capacity Factor by Energy Source in 2020 (U.S. Energy Information Administration, 2022).*

### 3.4. Impact of Climate Change on the Electric Grid

Due to climate change, California and many Western states have more extreme weather conditions like high winds, wildfires, drought, and storms that have contributed to power outages and changes in the electricity supply. Electrical generation, transmission, distribution, and
demand are all impacted by climate change. Having an insufficient power supply and unstable electric grid impacts the decarbonization of transportation. Without a reliable supply of electricity California cannot support the increased use of electric vehicles.

**Electricity Generation in California**

Dry conditions and drought in the state means that electricity generation from hydroelectric sources are impacted. Kern et al., 2020 found that drought periods in California from 2012 to 2016, caused low streamflow leading to reduced hydropower availability. In 2019, renewable sources produced 57% of the in-state generation of electricity but in 2020, they contributed to 51% (California Energy Commission [CEC], 2021). This reduction of electricity production was caused by dry conditions effecting generation by hydroelectric sources (CEC, 2021). These conditions continued into 2021, causing additional loss of hydroelectric generated electricity in the state. Hydroelectric generation in California for 2021 dropped by 32% from 2020 levels (CEC, 2022). The generation of electricity from solar and wind power is affected by temperature, humidity, cloud coverage, and precipitation (Vine, 2012). Thermoelectric generation is water intensive and may be impacted by changes in precipitation, runoff and elevated water temperatures caused by climate change (Vine, 2012).

![Comparison of 2020 Monthly Hydroelectric Generation to Historical Highs and Lows](image)

*Figure 8: Comparison of 2020 Monthly Hydroelectric Generation to Historical Highs and Lows in California (CEC, 2022).*
States neighboring California are also affected by the impacts of climate change. Hill et al., 2021, found that the United States West Coast power system is affected by air temperature changes in California and altered streamflow patterns in the Pacific Northwest caused by climate change (Hill et al., 2021). In addition to this, climate related impacts in one regional power system can spill over to others (Hill et al., 2021). Increased local electrical demand and decreased generation from hydroelectric power in the summer months means California cannot count on large transfers of hydropower from the Pacific Northwest (Vine, 2012). This means California cannot always rely on electricity imports when there is a decrease in the amount of renewably generated electricity in the state. Tarroja et al., 2019, compared scenarios of drought in California found that to compensate for the shortfall in hydropower generation, reliance on natural gas combined cycle (NGCC) plants could increase. Investment in natural gas combined cycle plants would increase generation efficiency and address the supply shortage issue (Tarroja et al., 2019). But reliance on natural gas will not support the long-term decarbonization goals and achieve 100% renewable and emission-free electricity generation in-state by 2040.

**Electricity Transmission and Distribution in California**

California Independent System Operators (CAISO) runs the California electric grid, while Pacific Gas & Electric Company (PG&E) oversees distribution of electricity in Northern California. In the past few years, California has experienced unplanned power outages and power grid emergencies caused by severe weather conditions. Climate change disrupts electricity transmission and distribution and other elements of infrastructure (Vine, 2012). The location of power plants and other infrastructure along the coast maybe impacted by erosion caused by sea level rise (Vine, 2012). California’s ongoing drought, elevated temperatures and dry vegetation have also increased wildfire concerns in the state. Wildfires impacts electric system infrastructure and effects the grid’s ability to meet electric demand. Equipment failures due to overheating also increases the risk for wildfires. Wildfires caused by electric power accounted for 19% of acres burned from 2016 to 2020 (California State Auditor, 2022). Three of the largest utilities in California reported 3,550 utility caused fire incidents from 2015 to 2020 (California State Auditor, 2022).
Table 1: Wildfires caused by electric power accounted for 19% of acres burned from 2016 to 2020 (California State Auditor, 2022).

<table>
<thead>
<tr>
<th>YEAR</th>
<th>TOTAL WILDFIRES</th>
<th>TOTAL ACRES BURNED</th>
<th>NUMBER</th>
<th>PERCENT</th>
<th>ACRES BURNED</th>
<th>PERCENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>2,816</td>
<td>245,000</td>
<td>270</td>
<td>10%</td>
<td>3,000</td>
<td>1%</td>
</tr>
<tr>
<td>2017</td>
<td>3,470</td>
<td>467,000</td>
<td>408</td>
<td>12%</td>
<td>250,000</td>
<td>54%</td>
</tr>
<tr>
<td>2018</td>
<td>3,504</td>
<td>1,063,000</td>
<td>297</td>
<td>8%</td>
<td>247,000</td>
<td>23%</td>
</tr>
<tr>
<td>2019</td>
<td>3,086</td>
<td>130,000</td>
<td>304</td>
<td>10%</td>
<td>84,000</td>
<td>65%</td>
</tr>
<tr>
<td>2020</td>
<td>3,501</td>
<td>1,459,000</td>
<td>335</td>
<td>10%</td>
<td>59,000</td>
<td>4%</td>
</tr>
<tr>
<td>Totals</td>
<td>16,377</td>
<td>3,364,000</td>
<td>1,614</td>
<td>10%</td>
<td>643,000</td>
<td>19%</td>
</tr>
</tbody>
</table>

Note: These data consist primarily of wildfire incidents within the Cal Fire direct protection area responded to by Cal Fire personnel.

In 2020, severe heatwaves and wind caused California utilities to order outages due to the insufficient supply. Utilities implement Public Safety Power Shutoffs (PSPS) when weather conditions are considered dangerous (California State Auditor, 2022). The power shutoffs are effective in preventing fires caused by broken equipment and hazards during windy conditions (California State Auditor, 2022). Consumers are also told to conserve electricity from utility providers issuing public Flex Alerts during hours of 4PM to 9PM Pacific Standard Time (PST). The goal of conserving power is to prevent outages caused by equipment failures due to overheating. Consumers being asked to conserve power and utilities needing to ration the current power supply during climate emergencies is a problem. Utilities need to make improvements to power lines and other infrastructure to withstand severe weather conditions until this is done, power shutoffs will continue (California State Auditor, 2022). California’s electric grid needs to adapt to climate change and become more resilient to ensure electricity access. The ability of the electric generation system to withstand climate change’s impact on transmission and distribution will determine if an all-electric powered future is feasible.

Electricity Demand in California

California’s electrical grid cannot meet the increased demand for power caused by climate change. Record high temperatures and ongoing drought in California has caused demand for electricity to increase. Drought periods from 2012 to 2016 combined with elevated temperatures, caused an increase in electricity demand, to provide air conditioning and cooling for buildings (Kern et al., 2020). Higher summer demands in California due to future extreme heat could
impact the reliability of the Pacific Northwest power system (Hill et al., 2021). Another study on the observed and future projected climate scenarios showed that there is a significant asymmetry in the summer-time temperature response of electricity demand in all three utility service regions in California which includes, Pacific Gas and Electric (Kumar et al., 2020). To decrease electrical demand from buildings, improvements in energy efficiency and building design are going to be needed. To reduce the magnitude of increased demand from air conditioning in the summer, increased building efficiency and a higher level of insulation and window glazing is recommended (Vine, 2012). The use of heat pumps for buildings will also reduce demand from buildings (Nadel, 2019). Knowing that California’s electricity grid is currently impacted by climate change, means that increased electric vehicle use in the future may put additional strain on the grid.
4. Results and Discussion

This section presents the results of this study. Section 4.1 will go over San Francisco’s transportation sector, emission, and electricity generation sources. The impact climate change has on the San Francisco Bay Area and the city’s shift to sustainable transportation are also mentioned. Section 4.2 reviews zero emission vehicle trends in California, Los Angeles, and San Francisco. Projections of demand from electric vehicles in California and Los Angeles shows that the quantity and timing of demand will be impacted. Section 4.3 will go over ways electrical supply can meet future demand from increased electric vehicle use in transportation.

4.1. San Francisco’s Transportation Sector

San Francisco is a metropolitan city that is considered, one of the greenest cities in California. Despite this there are still challenges when trying to reduce emissions from transportation. In San Francisco, 47% of greenhouse gas emissions in 2019 came from transportation (San Francisco Department of Environment, 2021). Cars and trucks produce the majority of emissions since they rely on petroleum-based fuels. Gasoline and diesel are the main sources of emissions in the city’s transportation sector. The use of gasoline contributed to 72% of the city’s emissions and diesel contributed 21% (see Figure 10).

![Figure 9: San Francisco’s greenhouse gas emissions by sector in 2019 (San Francisco Department of Environment, 2021).](image)
Transportation in San Francisco can be split into two categories: private and public. Private transportation makes up most of the city’s emissions and includes cars & trucks, maritime ships & boats, and off-road equipment (see Figure 10). Cars and trucks account for 72% of the city’s emissions. Maritime ships and boats are responsible for 19% of San Francisco’s emissions from transportation. Off-road equipment contributed 6% of the city’s total transportation emissions. Executive order N-79-20, set the goal of having all sales of off-road vehicles and equipment be 100% zero emission by 2030 (Executive Department State of California, 2020).

Figure 10: Transportation emissions by sub sector in San Francisco for 2019 (San Francisco Department of Environment, 2021).
Figure 11: Transportation emissions by type and source (San Francisco Department of the Environment, 2022).

Public transportation accounts for 3% of San Francisco's emissions (San Francisco Department of Environment, 2021). Many parts of the public transportation in the city already have transitioned to using alternatives to internal combustion engine vehicles or alternatives to petroleum-based fuels. The Bay Area Rapid Transit (BART), Caltrain, Muni are already relying on zero and/or low-emission vehicles. In 2020, the contracted electricity supply to power BART trains was generated from 100% greenhouse emission free sources (Bay Area Rapid Transit District, 2020). The Caltrain electrification project aims to switch out diesel-powered trains for electric-powered ones by September 2024 (Caltrain, 2022). San Francisco cable cars and Muni buses are powered by electricity generated from the hydroelectric Hetch Hetchy Water and Power System (SFMTA, 2022). Ferries use renewable diesel which is why they are the main emitters of greenhouse gases in the public transportation sector of the city (see Figure 12).

Figure 12: San Francisco Public transportation emissions by type and Source (San Francisco Department of the Environment, 2022).

The city originally had the goal of achieving 100% renewable electricity by 2030, but with Mayor Breed’s announcement the timeline to reach this goal has been pushed up to 2025 (City and County of San Francisco, 2022). San Francisco also wants to become a net-zero emission
city by 2040 and be carbon neutral by 2045. To reach these goals, there is a push to switch to zero-emission vehicles in the transportation sector, especially for private vehicles.

**Electricity Generation in San Francisco**

The generation and distribution of electricity in San Francisco is impacted by environmental, structural, and financial issues. Environmental impacts on power supply include climate change, heatwaves, storms, sea level rise, drought, and winds. San Francisco and the Greater Bay Area has experienced planned power shut offs and unplanned outages because of weather and environmental issues. Local operators of the city’s power include the San Francisco Public Utilities Commission which operates two retail electricity services: Hetch Hetchy Power and CleanPowerSF (City and County of San Francisco, 2022). In 2022, San Francisco’s mayor London Breed announced that CleanPowerSF will provide 100% renewable electricity to customers by 2025, which is ahead of the city’s original goal to achieve 100% renewable electricity generation by 2030 (City and County of San Francisco, 2022).

Electricity generated from renewables has increased over the years. In 2019, renewable sources generated 83% of the electricity in the city. Most of the electricity in San Francisco is generated through hydroelectric power (see Figure 13). The combined amounts from small and large hydroelectric power provided 50% of San Francisco’s electricity. The hydroelectric dam run by Hetch Hetchy Power is responsible for generating and distributing emission-free electricity to San Francisco. Electricity generated from wind power accounts for 18% while solar power contributes 6% of the city’s electricity. As previously mentioned, electricity generated from solar, and wind is intermittent and changes depending on the time of day. Geothermal electricity, from The Geysers’ geothermal fields, made up 6% of the electricity generated (CEC, 2022). Although, nuclear is not a renewable source of electricity generation it is emission-free and makes up 10% of the electricity consumed by the city. Total amount of electricity used in San Francisco for 2020 was 5025.70 GWh, Millions of kWh (CEC, 2022).
Figure 13: San Francisco electricity generation and consumption by Source in 2019 (San Francisco Department of the Environment, 2022).

Climate Change Impact in San Francisco Bay Area

The San Francisco Bay Area is affected by the impacts of climate change in multiple ways. The three-way relationship between land use, transportation infrastructure and energy systems are vulnerable to climate impacts in the Bay Area (Ackerly et al., 2018). Transportation infrastructure including airport, roads, railways is along the coast where flooding from sea level rise and storms can cause disruptions of the transportation system. There are challenges in managing the electric grid due to the changes in daily and seasonal energy demand combined with an increased reliance on solar and wind power (Ackerly et al., 2018). The electrical grid in the Bay Area is located both above and below ground making neighborhoods vulnerable to power outages during wildfires and wind events (Ackerly et al., 2018). Increased summer energy demand in coastal cities and higher building energy demand for inland regions impacts energy consumption (Ackerly et al., 2018). Under the Environmental Code Chapter 30, Ordinance 220-19, San Francisco requires large commercial buildings to switch to 100% renewable electricity (San Francisco Department of the Environment, 2022). Most of the power generated in San Francisco relies on hydroelectric generation, which is impacted by lack of precipitation and drought conditions in California. Climate change’s impact on energy consumption and distributed generation in the Bay Area will affect the electrification of transportation.
Shift to Sustainable Transportation in San Francisco

In San Francisco there are two main strategies used to reduce emissions from transportation: encouraging alternatives to driving and shifting to electric vehicles. Sustainable transportation is organized into a hierarchy (see Figure 14). The mobility options at the top are the most sustainable and include walking and biking. The least sustainable transportation options are on the bottom, the use of private vehicles is not considered sustainable when compared to other options. One component of the San Francisco Planning’s Transportation Sustainability Program, completed in 2017, was to encourage sustainable travel by supporting alternatives to driving (San Francisco Planning, 2022). The main goal is to shift away from private cars and encourage the use of bikes, public transit, and walking. Reducing vehicle miles travelled by private vehicles is critical for reducing California’s greenhouse gas emissions (Ackerly et al., 2018). The San Francisco Planning’s Transportation Sustainability Program is an example of shifting consumers to use more sustainable transport options. Public transportation in San Francisco has already made the switch to zero-emission vehicles or use alternative fuels. The creation and availability of travel choices will lead consumers to give up on using personal vehicles (Sperling, 2018).

![Sustainable Transport Hierarchy](image)

*Figure 14: The Sustainable Transport Hierarchy (Action Net Zero CIC, 2022).*

Private vehicles contribute the majority of emissions out of all transportation types. To address the problems with private vehicles and transportation, Sperling (2018), created a concept of the
three revolutions: electric, automated, and shared vehicles. The three mobility revolutions are a proposed solution to the problems associated with private vehicle ownership and will help lead society to a sustainable transportation future (Sperling, 2018). An assessment on understanding the adoption of shared, electric transportation in San Francisco Bay Area found that market penetration of electric vehicles may be increased by helping already interested groups, such as those in the younger generation (Spurlock et al., 2019). Sustainable transportation will also enable the transition to a clean electricity grid (Coignard et al., 2018). Electric vehicles are one part of a sustainable transportation system but reducing use of personal vehicles and encouraging public transportation use is also important (Perujo & Ciuffo, 2010). The city’s investments in electric-powered transportation will rely on a consistent supply of clean electricity. San Francisco’s reliance on hydropower to generate most of the city’s electricity, while California is experiencing drought may cause supply issues. If there is a large decrease in hydropower the back-up alternative is burning fossil fuels which would go against the zero-emission goals of the city.

**Role of Zero-Emission Vehicles in Sustainable Transportation**

San Francisco’s shift to electric vehicles can change the transportation industry and support the transition to sustainable transport. A combination of policies has a substantial impact on electric vehicles sales (Nadel, 2019). Vehicle electrification is being pushed by federal, state, and local policies instead of consumer demand (Sperling, 2018). There are four reasons for growing electric vehicle use: environmental impact, technological impact, design flexibility and vehicle electrification is good for consumers (Sperling, 2018). Electric vehicles provide the most environmental benefits when electricity used to power them is generated from renewable and emission-free sources, including wind, solar, hydropower and nuclear (Sperling, 2018). Zero-emission vehicles (ZEVs) include: plug-in hybrids, pure battery plug-ins and hydrogen fuel cell electric vehicles. The shift to electric vehicles will reduce greenhouse gas emissions by reducing fossil fuel consumption (Ackerly et al., 2018). Pure battery and hydrogen fuel cell electric vehicles emit no pollution and gases, but plug-in hybrid electric vehicles have zero emissions only when operating on electricity (Sperling, 2018).
Electric vehicles’ technological impact includes advancements in vehicle technology that creates design opportunities and allows design flexibility in terms of different models (Sperling, 2018). Electric vehicles have fewer moving parts and reduced weight, which is huge advantage in terms of energy efficiency (Sperling, 2018). Vehicle electrification is good for consumers since the dependence of foreign oil will decrease leading to economic independence (Sperling, 2018). Adoption of zero-emission vehicles produce public health benefits including reduction of air pollutants (Ackerly et al., 2018). The transition to vehicle electrification is gradual for three reasons: consumer caution, high initial cost of manufacturing and push back from vested interests including oil companies (Sperling, 2018). We know the transition to electric vehicles is going to happen but what is less clear is how fast the transition will be (Sperling, 2018).

Solely relying on electric-powered vehicles in San Francisco when the electric supply is variable from during climate emergencies can lead to long-term sustainability issues. One article found that it is not possible to choose one sustainable transportation option (i.e., electric, hybrid, or hydrogen/fuel cell drive) as being the best (Jorgensen, 2008). All three types of electric vehicles will help decrease transportation emissions, but they alone are not sufficient to create sustainable and emission-free transportation (Sperling, 2018). In general battery electrification is also best suited for cars, buses and trucks used for short routes (Sperling, 2018). The switch to electricity and hydrogen for large trucks, trains and ships will be slow (Sperling, 2018). Because of this, one recommendation is to diversify the types of sustainable transportation being offered and used for private and public transportation in San Francisco. Renewable gas and hydrogen can potentially be cost-effective alternatives in the long-term for hard to electrify gas uses (Jones et al, 2022). Hydrogen fuel has the potential to power vehicles that need to cover a large range (Jorgensen, 2008). Using green hydrogen fuel to power heavy duty transportation vehicles (i.e., ships, trucks, trains, and planes) may be a better option. Biofuels will also eventually replace oil (Sperling, 2018). There may be opportunities for biofuel and hydrogen to play a role in the transportation shift of medium and heavy-duty vehicles (Southern California Edison, 2019). San Francisco's use of renewable diesel to power ferries is an example of an alternative to fossil fuels. Investing in alternatives to electric-powered vehicles like green hydrogen fuel-cell vehicles would also reduce the demand for electricity while also meeting transportation needs.
Current Charging Demand from Electric Vehicles in San Francisco

As of 2019, electric vehicles in San Francisco make up 12% of market share (Hsu et al., 2020). In San Francisco, 90% of the Electric Vehicle Supply Equipment (EVSE) was found in regions operated by PG&E (Schey et al., 2012). Demand for electricity to charge electric vehicles is highest at night and lower during the day. Charging demand is also higher during the fourth quarter of the year due to seasonal holidays like Thanksgiving and Christmas. In San Francisco demand spikes at midnight during weekdays and weekends but peak demand occurs at 1:00 AM (Schey et al., 2012). This is because EV Project participants in San Francisco have the option to charge their vehicles at a specific time since they have a time-of-use rate plan offered from their utilities. The financial incentives offered by PG&E seem to work in off-setting demand during peak hours but the lack of diversity in charging time may be an issue for utilities since there is a surge of demand at night during off-peak hours (Schey et al., 2012). An assessment by the California Energy Commission, also reported that the projected surge in demand at around midnight during off-peak hours may strain local electricity distribution and infrastructure (Alexander et al., 2021).

![Figure 15: Weekday time of day Charging demand in San Francisco (Schey et al., 2012).](image)

4.2. Zero-Emission Vehicles in California, Los Angeles, and San Francisco

California has the most registered electric vehicles in the United States, accounting for 39% of the country’s total (Alternative Fuels Data Center [AFDC], 2022). Hsu et al., 2020 compared 50 metropolitan cities in the United States, found that the top five cities with the highest electric vehicles shares are in California. The top five cities with the highest electric vehicle share were San Jose, San Francisco, San Diego, Los Angeles, and Sacramento (Hsu et al., 2020). These cities also have the most state, city and utility actions promoting electric vehicles (Hsu et al.,
Both the San Francisco Bay Area and Los Angeles area have a high population density and number of public chargers for electric vehicles (Alexander et al., 2021). A comparison of the population density, and public chargers for electric vehicles in California is shown in Figure 16.

Figure 16: Population Density, PEV Density and Public Chargers by County (Alexander et al., 2021).

Figure 17 shows significant increase in light duty zero-emission vehicles sales and market share in California from 2011 to 2021 (Javanbakht et al., 2022). The trends indicate continued growth of zero-emission vehicles for the upcoming years. Many California policies also push for the increased use of zero-emission vehicles in the transportation sector.

Figure 17: California Annual Light-duty zero-emission vehicle sales and Market share from 2011-2021 (Javanbakht et al., 2022).
As of 2021, there are approximately 29.9 million registered light-duty vehicles in California but only 3% are zero-emission vehicles (California Energy Commission [CEC], 2022). According to the California Energy Commission, there were 425,296 registered light-duty vehicles in San Francisco County and 6,903,230 registered in Los Angeles County at the end of 2021 (CEC, 2022). San Francisco’s zero-emission light-duty vehicle population was 5.5% of the total registered light-duty vehicles by the end of 2021. This is higher than the total percentage in the state (3%) and Los Angeles County (2.95%). Battery electric vehicles are the most registered type of zero-emission vehicle in California, Los Angeles, and San Francisco. Plug-in hybrid and hydrogen fuel cell vehicles are the least registered zero-emission vehicle types.

Table 2: Total Light-duty Vehicles end of 2021 Comparison of California, Los Angeles, and San Francisco. Data from https://www.energy.ca.gov/zevstats

<table>
<thead>
<tr>
<th></th>
<th>California</th>
<th>Los Angeles County</th>
<th>San Francisco County</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-ZEVs</td>
<td>29,104,630</td>
<td>6,903,230</td>
<td>425,296</td>
</tr>
<tr>
<td>ZEVs</td>
<td>837,887</td>
<td>209,205</td>
<td>21,822</td>
</tr>
<tr>
<td>Total Light-duty vehicles</td>
<td>29,942,517</td>
<td>7,112,435</td>
<td>447,118</td>
</tr>
<tr>
<td>Battery Electric (BEV)</td>
<td>1.7%</td>
<td>1.76%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Plug-in Hybrid (PHEV)</td>
<td>1.0%</td>
<td>1.14%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Fuel Cell (FCEV)</td>
<td>0.03%</td>
<td>0.05%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Total Percent of zero-emission vehicles</td>
<td>3%</td>
<td>2.95%</td>
<td>5.5%</td>
</tr>
</tbody>
</table>

Electric Vehicles Projected Impact on Future Demand in California

In California, electric vehicle charging currently accounts for 0.4% of consumption during peak hours (Javanbakht et al., 2022). Policies encouraging the adoption of more electric vehicles means electrical consumption and demand will be impacted. California’s goals established in Executive order N-79-20, signed by Gavin Newsom, are to have 100% of in-state sales of new passenger vehicles be zero emission by 2030 and 100% of medium and heavy-duty trucks sales be zero emission by 2040, where feasible (Executive Department State of California, 2020). It
also set the goal of 100% zero emission off road vehicles and equipment by 2030 (Executive Department State of California, 2020). Assembly Bill 2127 requires assessments of electric vehicle charging infrastructure to identify investment needs to support the goal of having 5 million zero emission vehicles on California roads (Alexander et al., 2021). Executive order B-48-18 signed in 2018, set a target of 5 million zero emission vehicles to be on California roads by 2030 (Gill et al., 2021). A report from the California Energy Commission, states that California needs 1.2 million shared electric vehicle chargers to reach the 2030 goal of 5 million zero-emission vehicles (Alexander et al., 2021).

More electric vehicles on California roads will cause the use of gasoline to decrease, but electricity demand will increase. Figure 18 compares gasoline, electricity, and diesel consumption from light-duty vehicles in 2020 to a forecasted high energy demand case in 2035 (Javanbakht et al., 2022). The study created three energy demand cases, low, mid, and high, depending on economic and demographic projections, electricity and gas rates, electrical vehicle adoption and self-generation of energy and storage options (Javanbakht et al., 2022). The light-yellow in Figure 18, shows the amount of gasoline consumption that was avoided by using plug-in electric vehicles (Javanbakht et al., 2022). Transportation electrification is projected to reach 12% of load by 2035 in California (Javanbakht et al., 2022).

Figure 18: Light-duty vehicle energy consumption for 2020 and 2035 (Javanbakht et al., 2022).
Charging more electric vehicles will impact the timing of electrical demand. Figure 19 shows the daily projected statewide impact of charging 8 million zero-emission vehicles on the road by 2030 in California (Alexander et al., 2021). The 2021 report published by the California Energy Commission, projects that electricity consumption from 8 million zero-emission vehicles in 2030 could increase electricity demand by 20% at 10 AM and 25% at midnight (Alexander et al., 2021). More than 60% of the total charging energy will be demanded at night when electricity generation from solar power is low (Alexander et al., 2021). There is a peak of electrical demand at midnight for residential charging for both levels one and two (Alexander et al., 2021). This is because consumers typically charge their vehicles at night when they are home. Public and direct current (DC) fast charging peaks mid-day when consumers are at work.

![Figure 19: Projected Statewide power for light-duty charging for 8 million ZEVs on a typical 2030 weekday in California (Alexander et al., 2021).](image)

Electricity supply, including generation and energy storage, must match the demand at all times to ensure reliability. Understanding the shape of electricity loads and the complex dynamic feedback loop between charging electric vehicles and the power system affects planning and operations (Muratori & Mai, 2021). Transport electrification will impact electricity demand and change the load shape (Muratori & Mai, 2021). Electric vehicle charging can possibly impact total electricity demand in four ways: (a) assumption, (b) complexity, (c) integration and (d) flexibility (see Figure 20). The shape of demand depends on the generation source of electricity,
the time of charging and charging location (i.e., home or work). Vehicle electrification will increase electricity demand, not only in terms of quantity but it will also change the shape and timing of consumption impacting the energy system (Muratori & Mai, 2021). Timing is more important for a future electrical grid with higher amount of renewable generation (Powell et al., 2022).

![Diagrams showing possible impacts of electric vehicle charging on total electricity demand](image)

**Figure 2.** Possible impacts of EV charging on total electricity demand: (a) assuming that EV charging leads to a simple scaling up of current load (current assumption in many models); (b) considering mobility-based modeling of alternative EV charging profiles, leading to two possible total loads that are significantly different; (c) highlighting interaction between EV profiles and variable renewable production; and (d) illustrating the effect of coordinated and optimal EV charging. Load (non-EV) and PV data is from [69] for a summer day in CAISO for a system with 30% annual PV penetration. The different EV charging patterns illustrated in the figure result from different charging strategies, but the green areas (total EV use and charging energy) are the same across all panels.

**Figure 20:** Possible impacts of electric vehicle charging on total electricity demand (Muratori & Mai, 2021).

### Projected Future Demand from Electric Vehicles in Los Angeles

The San Francisco Bay Area and Los Angeles region are both metropolitan areas located in California. Looking at demand projections for Los Angeles provides insight into the feasibility of meeting climate mitigation goals for local regions. Assessments for Los Angeles will also show
possible challenges for cities, like San Francisco, may face in the future. The 100% renewable energy study of Los Angeles found that achieving Senate Bill 100 goals of reliable, 100% renewable power by 2035 is feasible. The study conducted modeling of three different scenarios based on the Los Angeles Green New Deal sustainability plan of 2019 (Hale et al., 2021). The three projected scenarios have various levels of energy efficiency, electrification, and demand flexibility and are categorized as: Moderate, High, and Stress (see Table 3).

Table 3: LA100 Customer Demand (Load) Projections, including Examples of Distinctions among the Projections regarding Efficiency, Electrification, and Demand Response (Hale et al., 2021).

<table>
<thead>
<tr>
<th>Load Projection</th>
<th>Moderate Description</th>
<th>High Description</th>
<th>Stress Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>The Moderate load projection assumes easy, low-hanging-fruit electrification and above-code improvements to energy efficiency and demand response. Significant change, but short of the Mayor’s Office’s Green New Deal 2019 pLAN goals.</td>
<td>The High projection is designed to match most of the electrification and energy efficiency goals set forth in the 2019 pLAN, and it includes 80% light-duty vehicle electrification by 2045 and significant demand response potential. Very high electrification results in significantly more demand, even with high levels of energy efficiency.</td>
<td>High electrification combined with low energy-efficiency improvements and demand response to create worst-case load conditions.</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>Sales distributed across available efficiency levels; 80% of new and retrofit equipment is 5 years ahead of Title 24 commercial building energy-efficiency code-minimum</td>
<td>100% sales at highest efficiency levels</td>
<td>LADWP’s 2017 SLTRP 10-year efficiency goals³³</td>
</tr>
<tr>
<td>Electrification</td>
<td>30% electric light-duty vehicle share of market in 2045</td>
<td>100% electric sales share by 2030 (incl. HVAC and water heating; 100% electric homes by 2050</td>
<td>Same as “High”</td>
</tr>
<tr>
<td>Demand Response</td>
<td>75% access to residential charging; 25% access to workplace charging</td>
<td>60% access to residential charging; 50% access to workplace charging</td>
<td>90% access to residential charging; 15% access to workplace charging</td>
</tr>
</tbody>
</table>


A comparison of three different climate scenarios in Los Angeles found that the electricity demand and consumption from the transportation sector will significantly increase, primarily
because of electric vehicle charging (Hale et al., 2021). All projections and model years are also impacted by weather related cooling demand (Hale et al., 2021). Both peak and annual demand for electricity grows in all projections but the peak demand grows at a slower rate than the annual demand (Hale et al., 2021).

Figure 21: Annual electricity consumption by projection-year and sector for Los Angeles (Hale et al., 2021).

Comparing California and Los Angeles Demand Projections to San Francisco

Projected electricity demand increases from electric vehicles for California and Los Angeles, likely means San Francisco will also experience an increase in electrical demand as the electric vehicle population grows. Electric vehicles are expected to make up 50% of all new registrations in San Francisco by 2025 (see Figure 20). By 2030, vehicles registrations are supposed to be 100% electric (Hsu et al., 2020). Knowing that the number of electric vehicles in San Francisco will increase means the amount of electricity needed to power them will also increase. In Milan, Italy one study found that scenarios with high percent of electric vehicle integration, 20-25% of market share, could heavily impact the daily demand of electric power requested (Perujo & Ciuffo, 2010). Electric vehicle charging in San Francisco currently spikes at midnight and peaks at 1 AM (Schey et al., 2012). The projection for light-duty charging for 8 million ZEVs on a typical 2030 weekday in California indicates that San Francisco will likely experience a second
peak of demand during the day, due to public charging. Preparing for additional peaks of demand throughout the day is important when trying to match supply and demand.

![Assumed new electric vehicle share and stock in San Francisco from 2015 to 2050](hsuetal2020)

**Figure 22: Assumed new electric vehicle share and stock in San Francisco from 2015 to 2050 (Hsu et al., 2020).**

4.3. Strategies to Balance Electrical Supply and Projected Demand

To meet future demand projections, altering the electric supply is necessary. As mentioned previously, the electric supply has natural fluctuations in electrical generation daily, seasonally, and yearly. Climate change has already impacted electrical generation, distribution, and demand. Increased demand from electric vehicle use could put additional strain on the local grid. A joint agency report published in 2021, states that California’s electric grid will need to be closely monitored to coordinate the planning between the power supply and electric demand from transportation (Gill et al., 2021). Another assessment also states that California must align public electric vehicle charging (PEVs) with renewable energy generation and pursue greater vehicle-grid integration (Alexander et al., 2021). California’s current electric supply relies on imports and the burning of natural gas to meet increases in demand. The impact of climate change and projected demand from electric vehicles puts California’s current electric generation system and grid at risk. Knowing that climate change will continue to impact the electric grid during the
transition to electric vehicles means improvements in the electric system are needed. High level of infrastructure is required to support California’s zero emission vehicle future (Alexander et al., 2021). There needs to be a stable and reliable generation of electricity from renewable and low emission sources, on a local scale, to support the electrification of transportation in San Francisco. Adaptation strategies for the electric sector in California include mitigation, adaptation, technological development, and research (Vine, 2012). Two ways the electric sector can respond to peak demand are to reduce the magnitude of increased demand through energy efficiency programs and by increasing resiliency of the electric production system (Vine, 2012).

**Strengthen grid resiliency against climate change**

Enhancing the local electric grid against climate related weather events is necessary to power sustainable transportation. In California, about half of the electricity is already generated using non-emitting sources like wind, solar, hydropower and nuclear (Sperling, 2018). The remaining electricity is generated by natural gas, we need to shift to renewable and emission-free sources to achieve the state goals in Senate Bill 100. California struggles with increased electrical demand from air conditioning in the summer and it is difficult to meet peak demand with hydropower (Vine, 2012). In San Francisco about 50% of electricity is generated from hydropower (San Francisco Department of the Environment, 2022). Diversifying the energy mix can mitigate future issues that arise from depending on a single type of power source. The decision by the California State Legislature to pass, Senate Bill 846, to keep the Diablo Canyon nuclear power plant open until 2030, was prompted by the need for reliable clean electricity. Reconsidering closures of other nuclear power plants until the grid has enough storage to support the transition to 100% renewables maybe necessary. Another way to strengthen the electric grid against climate change would be to integrate better infrastructure design, use of more resilient materials and change the location of equipment. This can help prevent transmission and distribution equipment from damage and overheating. A review of 15 post-fire event reports in California found that 11 of them cited wind-related damage and broken power poles with direct contact to vegetation (California State Auditor, 2022). Burying powerlines would prevent contact with vegetation lowering wildfire risk. Ackerly et al., 2018, found that the location of infrastructure in the San Francisco Bay Area is impacted by climate change which effects the electric grid’s reliability.
**Invest in energy storage technology for renewable integration**

To support the increase in electric vehicle adoption more grid storage is needed (Powell et al., 2022). California also needs to invest in battery storage technology and have a back-up power supply for climate emergencies (i.e., heatwaves). Renewable energy fluctuation plays an important role when evaluating and integrating renewable energy storage technologies into the grid (Dallinger et al., 2013). To address the reliability issues with the large-scale integration of wind, water and solar (WWS) energy, different types of storage can be used including batteries for short- and long-term storage, compressed air, hydroelectric dams, and pumped hydro storage (Jacobson, 2015).

**Invest in Smart grid and Develop Vehicle to Grid integration**

Vehicle-grid integration would allow electric cars to help manage loads on the grid (Gill et al., 2021). Vehicle to grid (V2G) integration and flexible or ‘smart’ vehicle charging could mitigate charging issues and support the grid (Muratori & Mai, 2021). Smart charging is defined as the ability of electric vehicles to change their electricity demand in response to supply needs (Muratori & Mai, 2021). Bi-directional charging also called vehicle to grid or V2G, involves the ability of electric vehicles to supply electricity to the grid (Muratori & Mai, 2021). Electric vehicles can supply electricity back to the grid during climate emergencies due to their battery storage.

**Alter Timing of Electrical Demand**

Time of use (TOU) charging can be a first step in reducing peak loads and promote off-peak charging for plug-in electric vehicles (Dallinger et al., 2013). The daily pattern of photovoltaic generation is favorable for charging plug-in electric vehicles depending on the location of charging infrastructure and where vehicles are parked during the day (Dallinger et al., 2013). To match electricity supply and demand, electric vehicle charging can be aligned with solar generation by ensuring access to workplace charging infrastructure (Hale et al., 2021).
Electric vehicle charging during the day, could reduce the solar duck curve and overnight (i.e., home) charging could reduce wind curtailment (Muratori & Mai, 2021). Charging electric vehicles in the day will also help offset the increased demand at night (Powell et al., 2022). Utilities offering time of use rates and smart charging discounts for consumers influences the time of charging (Nadel, 2019).

**In case of Energy surplus**

If the state accumulates a surplus of energy, we can export it for other states and regions to use. Excess electricity can also be used to produce green hydrogen, an alternative clean power source, which can be used to phase-out the use of fossil fuels. Green hydrogen is produced by water electrolysis using renewable generated electricity from solar, wind and hydropower and is carbon-free (Yu et al., 2021). Because of California’s drought seawater can be used in the production process. Yu et al., 2021 states that producing green hydrogen from solar and wind is an important route to a renewable generation system. Green hydrogen is also an energy carrier and can be used for temporary storage for green electricity (Yu et al., 2021). Liquid green hydrogen can also be imported. Green hydrogen can be used to power hydrogen fuel cell vehicles like heavy-duty trucks, ships, trains, and airplanes. Hydrogen fuel cell vehicles only by product is water vapor. Green hydrogen can also be used as a fuel in generators to supply power during climate emergencies. Using hydrogen fuel cell vehicles can also help reduce demand for electricity while still meeting transportation needs. Recently, California Senate Bill 1075, was approved and filed with the Secretary of State on September 16, 2022 (California State Legislature, 2022). It would require the California Air and Resources Board, California Energy Commission and California Public Utilities Commission to assess the role of green hydrogen and consider its use for decarbonization and reducing greenhouse gas emissions (California State Legislature, 2022).
5. Recommendations and Conclusion

**Continue to implement policies to strengthen decarbonization of the grid**

Implementation of policies and regulations that monitor and limit greenhouse gas emissions helps California achieve greenhouse gas reduction goals and improves air quality. To achieve 100% renewable and low-carbon electricity generation by 2045, California needs to implement additional policies to support existing legislature. Senate Bill 67, the 24/7 Clean Energy Standard bill, was introduced in December 2020, it would require that 100% of California’s electrical load be supplied by eligible clean energy resources at all times (California State Legislature, 2020). It would also require utilities to purchase clean electricity during harder-to-serve times for the state (California State Legislature, 2020). Passing this policy would help California increase clean electricity supply which will help meet demand from powering electric vehicles. The state grid also needs to adapt to changing environmental conditions caused by climate change. Having a climate resilient grid will ensure that California has a steady supply of power for electric vehicles. State policymakers must also continue to create and implement regulations for vehicle emissions.

**More research to inform state and local policymakers**

The impact of increased electrical demand from electric vehicles, and climate change must be considered on a local level. This can be done by creating reports similar to the Los Angeles 100% Renewable Energy Study for other cities and counties. Information found would help assess the local impacts climate change has on electricity generation and distribution. Which is important for metropolitan areas that have high population and transportation demand. Many papers assess issues about charging infrastructure, costs, accessibility, and equity but there is a lack of papers connecting electric vehicle charging to the electricity supply and availability in individual cities. More research for specific cities and states is important since each individual region is affected differently from climate change and have their own policies. Charging infrastructure, technology advancement and rate of electric vehicle adoption will be different for each city, state, and country. Charging solutions must be tailored to local and community needs to ensure zero-emission vehicle access for all (Alexander et al., 2021). Assessing impact on
cities’ local systems will help inform policymakers about potential issues and prevent local supply emergencies.

Limitations of Study

This paper was written within a time frame of a few months, some topics are beyond the scope of this paper. In addition to the time limit, the topics of climate change, state policies and adoption of electric vehicles is currently developing, and new proposals and information are continuously being published. Some topics that were beyond the scope of this paper include the cost of building electrical grid infrastructure, electricity generation, battery storage, and chargers. Financing state and local electric vehicle charging infrastructure projects was also not assessed. The environmental impact of mining for battery materials, and cost of electric vehicle manufacturing was also not mentioned. Lastly, accessibility and equity issues surrounding electric vehicle adoption must also be considered.

Conclusion

Climate change is a global issue that must be addressed by federal, state, and local governments with research, policy implementation and monitoring. Emissions from the transportation sector are primarily responsible for most of the greenhouse gas emissions in California. Many California polices about reducing emissions from transportation and electricity generation have been passed. These policies prompt the shift to electric vehicles. Transportation electrification is an effective greenhouse gas mitigation strategy since emissions are being reduced but powering transportation must also be clean and sustainable for the long-term. The switch to electric vehicles coincides with the transition to renewable and emission-free electricity generation in the state. These changes will impact the availability of green electricity, especially during climate emergencies.

San Francisco is shifting to sustainable transportation by encouraging alternatives to driving and switching to electric vehicles. Cars and trucks are responsible for most of the city’s emissions. Alternatives to driving such as walking, biking, and using public transit will reduce miles travelled by private passenger vehicles. Walking, biking, and using public transit are more sustainable than using private vehicles and creates a more sustainable transportation system.
Public transportation in San Francisco already uses zero-emission vehicles and alternatives to fossil fuels. The switch to zero-emission private vehicles is being pushed by state and local polices. But the impact of increased use of electric vehicles on electrical demand must be addressed to ensure a smooth transition especially since there is an increased reliance on renewable sources to generate most of the electricity.

Projections of demand from Los Angles and California found that increased electric vehicle use will affect the quantity and timing of electricity demand. The timing of demand is important especially since the timing of electrical generation from renewables like wind and solar is intermittent. Matching the timing of renewable electrical generation with the charging demand time throughout the day is the main challenge. To match electrical supply and demand in the future, more investments in storage and charging is needed. Improvements in local electricity grid are needed to support transportation electrification and the transition to clean electricity generation. Creating more climate resilient systems by diversifying the energy mix and improving design and location of electrical equipment would prevent damage. Vehicle to grid (V2G) integration and bidirectional charging allows electric vehicles to support the electric grid during climate emergencies.

Overall, this paper reviewed the dependencies between transportation electrification, the electric grid and climate change. Figure 23 shows how climate change influences California polices relating to electric vehicle adoption and the transition to clean electricity. Increased use of electric vehicles and clean electricity generation will reduce the amount of greenhouse emissions which contribute to climate change. Climate change effects the generation, distribution, and transmission of electricity. Generation from hydropower, wind and solar are affected by climate change. Climate change events like heatwaves also influences electrical demand from the grid. With these feedback loops in mind, this work identified opportunities for increasing the resiliency of the electric grid against the impacts of climate change. It also identified ways to strengthen the supply and demand relationship between electric vehicles and the electric grid.
Figure 23: Feedback loops associated with climate change, and the relation to electric vehicles and the electric grid
References


Brook, B. W., Alonso, A., Meneley, D. A., Misak, J., Blees, T., & van Erp, J. B. (2014). Why nuclear energy is sustainable and has to be part of the energy mix. Sustainable Materials and Technologies, 1-2, 8-16, doi: https://doi.org/10.1016/j.susmat.2014.11.001.


