The Hidden Emissions of Electric Vehicles

Astoria Ho, Clara Hu, Josh Everts
Advisor: Professor Marti Hearst
MIMS Capstone Project, 2023
https://eee-capstone.github.io/MIMS-Capstone/templates/index.html

Table of Contents

I. Summary

Our project, The Hidden Emissions of Electric Vehicles, examines the sustainability of zero emissions vehicles and highlights barriers to EV adoption and use in California. Through an interactive website and vehicle emissions tool, called Emissions Explorer, we break down how and why EVs still emit, and let people explore how different factors – charging location, vehicle type, and mileage – all impact emissions. Our Emissions Explorer allows a user to input almost any vehicle (gas, hybrid, or electric) and outputs the lifetime emissions of that vehicle, along with useful context about how that vehicle compares to its peers. We built our emissions model calculations using data from the GREET model, created by Argonne National Laboratory (ANL), and vehicle emissions and weight data from the EPA. Emissions Explorer models the production, use, and end-of-life emissions for a vehicle, and is the first tool to integrate these calculations into a digestible, consumer-facing product.

The Hidden Emissions of Electric Vehicles and Emissions Explorer, were ideated, designed, and built by three students from the School of Information at UC Berkeley as a capstone project for the Master of Information Management and Systems program.

Our project can be found here: **LINK**
Quicklink to Emissions Explorer: **LINK**

II. Introduction

A. What makes this an Information project?

Climate change is a complex issue that cross-disciplines from environmental science, social science, health, law and policy, and agriculture. Environmental scientists are studying how our Earth has changed, is changing, and will change in the future while social scientists are determining who climate change affects and how the consequences of climate change disproportionately affect minority groups. Combining the knowledge being discovered and created from researchers of all different backgrounds and translating them into understandable and digestible concepts to be shared with the public is complicated. This can be in the form of transforming large datasets into interactive visualizations, or drawing connections between relationships between policy, science, and social issues. We believe that information sciences can play a role in bridging this gap of communication.

B. Project Goals

The transition towards zero-emission vehicles and electrification to reduce emissions has become a key topic in environmental policy. In 2020, California Governor Gavin Newsom signed Executive Order N-79-20 which mandates that by 2035, 100 percent of all sales of new passenger cars and trucks in California be zero-emission. In 2021, the White House published their long-term strategy to reach a goal of net-zero emissions by 2050. Their plan includes decarbonizing electricity, transitioning to clean transportation fuels, and scaling CO2 removal.

Our project intends to inform people about what “zero emission vehicles'' are, what makes them zero-emission, and what the sustainability of these vehicles are. We explain the concepts of a vehicle’s lifetime emissions and the connection between the electrical grid and electric vehicles.

III. Related Work

A. Zero Emission Vehicles

In California, transportation emissions accounted for 38 percent of total greenhouse gas emissions (369.2 MMT CO_2e) in 2020, in-state electricity power production contributed to 11 percent, and imported electricity contributed to 5 percent as shown in Figure 1 (California Air Resources Board, 2021).

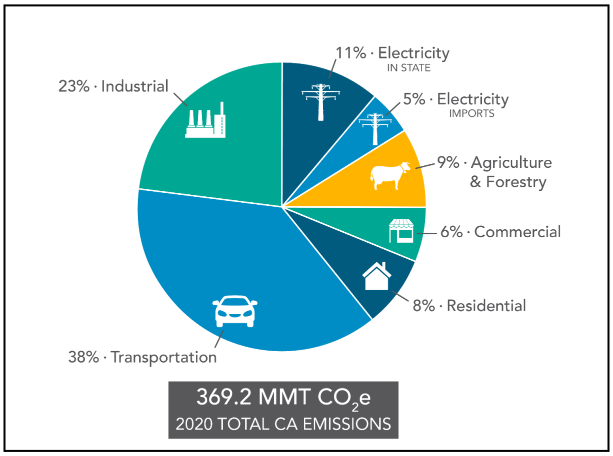


Figure 1. California greenhouse gas emissions in 2020 by economic sector (California Air Resources Board, 2021).

Greenhouse gas emissions from transportation occur through burning fossil fuels for vehicles including cars, trucks, trains, ships, and planes and are also called tailpipe emissions (U.S. Environmental Protection Agency, 2022-c). Cumulatively, about half of greenhouse gas emissions in California are related to well-to-wheel emissions (Caltrans, 2021). Well-to-wheel emissions include all emissions related to fuel production, refinement, distribution or transportation of the fuel, and fuel usage by vehicles (U.S. Department of Energy, n.d.-a). Carbon dioxide makes up 99 percent of tailpipe emissions, but vehicles fueled by gasoline or diesel also release harmful air pollutants including sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), formaldehyde (HCHO), particulate matter (PM), and other carbon containing compounds which make up smog (U.S. Environmental Protection Agency, 2022-b). Poor air quality caused by pollutants is detrimental to the environment and has also been proven to have negative health outcomes such as increased risk of asthma, dementia, lung cancer, and heart disease (Schraufnagel, 2019). Reducing greenhouse gas and toxic air pollution would make a great difference in the air quality and ultimately improve population health, especially in disadvantaged communities. In order to reduce emissions and combat climate change California is taking actions through environmental restoration projects, promoting renewable energy, and regulating pollution. One such initiative California is taking to be more climate-friendly is through restriction on fossil fuel usage, emphasis on public transportation, new incentives to Zero Emission Vehicles (ZEVs), and focus on sustainable energy.

Two of California's landmark environmental policies passed are: Executive Order N-79-20 (2020) and the Advanced Clean Cars II Rule (2022), which requires all sales of new passenger vehicles in California to be zero-emission by 2035. They recognize multiple types of zero-emission vehicles: full battery-electric (BEV), hydrogen fuel cell electric (FCEV), and plug-in hybrid electric vehicles (PHEV). Plug-in hybrid electric vehicles must have an all electric range of at least fifty miles, and no more than 20 percent of the zero-emission vehicles sold may be plug-in hybrids (California Air Resources Board, 2022-a).

Zero emission vehicles are vehicles that produce zero exhaust emissions in any mode and condition (U.S. Department of Energy, n.d.-b). The goal of transitioning to ZEVs is to reduce carbon emissions in the air, reduce smog-forming and greenhouse gas pollutant emissions, and ultimately improve air quality. Conventional internal combustion vehicles apply high pressure on fossil fuels in a heat engine to power the engine, which releases greenhouse gasses as exhaust emissions, while ZEVs eliminate the combustion engine related exhaust emissions.

While zero-emission vehicles have virtually no tailpipe emissions during operation, they do contribute to emissions elsewhere in their life cycle (Figure 2). Indirect emissions should also be taken into account when considering the sustainability of zero-emission vehicles. Some of these emissions may arise from battery production as well as sources of electrical energy that vehicles draw from for power - fuel supply.

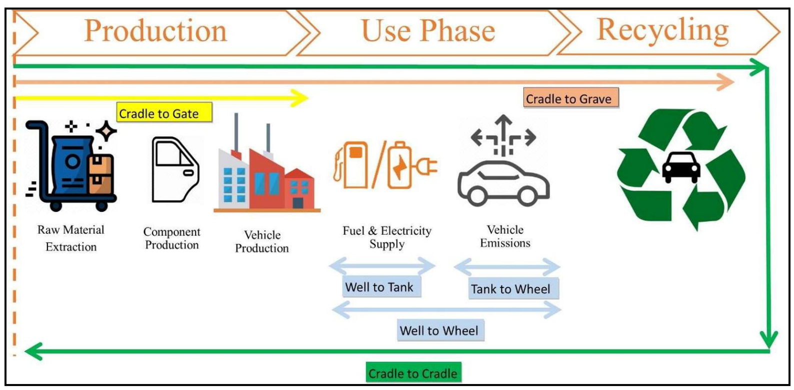


Figure 2. Stages of a vehicle's life cycle (Verma, 2022).

ZEVs are generally powered by lithium-ion batteries which are larger than the lead-acid batteries that equivalent-sized ICE vehicles use to start their engine. These larger lithium-ion batteries require higher amounts of raw materials and energy to produce, which can result in higher carbon emissions during the manufacturing stage of ZEVs. In 2015, a study by the Union of Concerned Scientists found that manufacturing a mid-sized electric vehicle would produce 15 percent more manufacturing-related emissions than an equivalent conventional gasoline vehicle, while for longer ranged electric vehicles, the emissions, the manufacturing emissions could be up to 68 percent higher (Neiler, Reichmuth, and Anair, 2015). Carbon emissions generated from battery production can potentially be reduced through lithium-ion battery recycling, which reduces the need for new raw materials. Lithium-ion battery recycling can potentially reduce energy consumed for battery manufacturing by between 10 and 17 percent (Nealer, Reichmuth, and Anair, 2015) and carbon emissions by 54 percent (Dunn, Gaines, Sullivan and Wang, 2012). However, technologies to recycle vehicle lithium-ion batteries are still being developed and face many challenges such as fluctuating material prices and design complexity, making it difficult and economically unjustified (Jacoby, 2019).

Although ZEVs may contribute to higher manufacturing emissions than ICE vehicles, the additional emissions may potentially be offset over the lifetime of the vehicle because of the lack of tailpipe emissions, but how much of ZEV emissions are compensated for also depends on indirect emissions coming from electricity generation for the vehicles during their usage.

Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are reliant on electricity, which may have varying levels of associated emissions depending on the primary source of electric generation in the geographic area where the vehicles are being charged. Electricity may be generated from mainstream fossil fuels or from alternative sources that may be cleaner with less associated carbon emissions. Globally, associated electric vehicle carbon emissions can range from being comparable to that of conventional gasoline vehicles in carbon heavy countries to having a vast reduction in carbon emissions in carbon light countries (Wilson, 2022). In addition, for countries that rely heavily on fossil fuels for electricity generation, conventional hybrid vehicles are likely to produce lower emissions than electric vehicles (International Energy Agency, 2019). Because of this, when talking about cumulative emissions from ZEVs, it is also important to consider the local electrical grid.

B. Electrification in California

In 2021, California was second in the country, after Texas, in terms of total electricity generation from renewable resources as well as second to Texas in total energy consumption (U.S. Energy Information Administration, 2022-a). California was the top electricity producer from solar, geothermal, and biomass resources; fourth in hydroelectric power; and sixth in wind energy. In addition to renewable energy sources, California generates electricity from thermal and non-renewable sources including fossil fuels (coal, natural gas, oil, waste heat, and petroleum coke) as well as nuclear, and large hydro. Electricity that is consumed in California may be generated in-state or from imported electricity. The daily energy supply mix, including both in-state and imported generation, and the daily renewable energy supply mix is shown in the figures below. Electricity that is from unspecified sources include resource types that are not traceable to specific generating facilities and may be from spot market purchases, wholesale energy purchases, or other purchases (California Energy Commission, 2022-a).

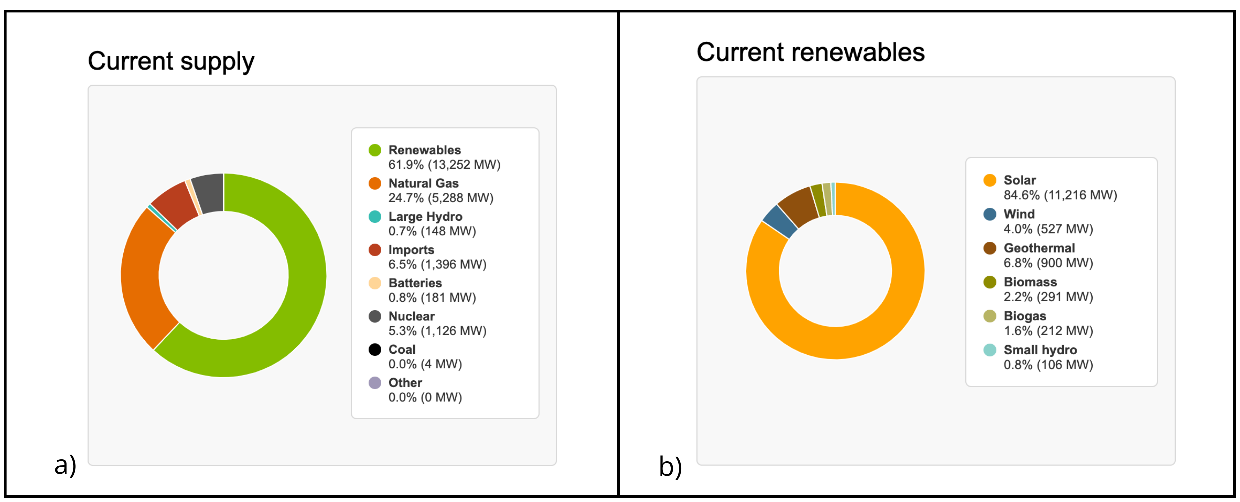


Figure 3. The a) daily energy supply mix and b) daily renewable energy supply mix in California on October 30, 2022 (California ISO, 2022-a).

Demands for electricity in California vary throughout the year, and thus results in varying levels of greenhouse gas emissions that are required to generate enough electricity to serve California ISO loads. The varying levels of demand often relate to heating and cooling demands that correlate with weather. Generally, greenhouse gas emissions from electricity generation are highest in the months of July, August, and September and lowest in April and May (Figure 4).

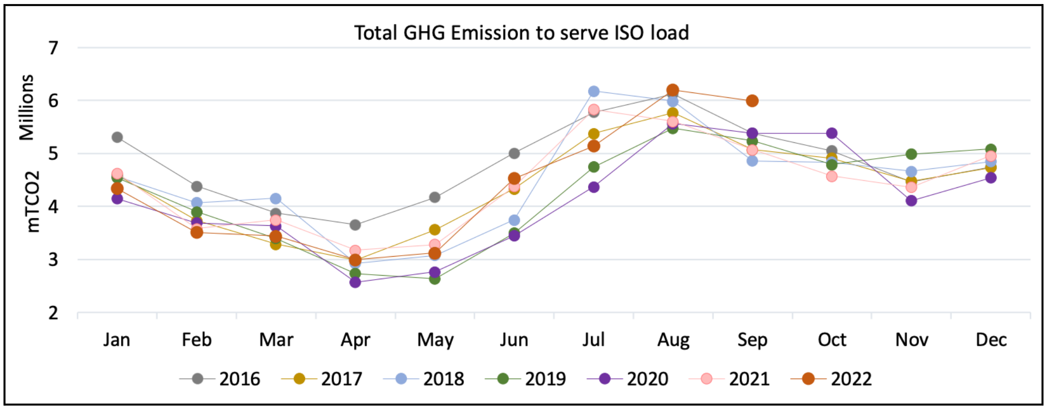


Figure 4. Greenhouse gas emissions from electricity generation by month in California from 2016 to 2022 (California ISO, 2022-a).

California has been pushing for cleaner energy resources and legislation has passed to promote using more renewable energy sources. The 100 Percent Clean Energy Act of 2018 made updates to California's Renewables Portfolio Standards so that 60 percent of California's electricity is renewable by 2030; the Act also sets a goal for renewable energy and zero-carbon resources to supply 90 percent of all retail electricity sales by 2035, 95 percent by 2040, and 100 percent by 2045 (California Energy Commission, 2021). In order to reach these goals, the California Energy Commission estimated in 2021 that California would need to triple its electricity grid capacity and increase new renewables and storage resources by 6 gigawatts annually in comparison to its historical increase of 1 gigawatt of utility solar and 300 megawatts of wind per year. The Clean Energy, Jobs, and Affordability Act of 2022 creates a roadmap to reach the goals outlined in the 100 Percent Clean Energy Act of 2018 in addition to designating greater accountability to California electric sector for their climate commitments through encouraging greater transparency and information sharing between California Public utilities Commission (CPUC), California Energy Commission, and California ISO (Stapler, 2022). The Clean Energy, Jobs, and Affordability Act of 2022 takes effect on January 1, 2023.

As California attempts to create a more reliable and sustainable energy system, stresses on the system may cause roadblocks and affect access to electricity. Climate change and extreme weather conditions exacerbate stresses on the energy system (Penn, 2022). For example, during heatwaves, California's grid can become overwhelmed as demand for electricity spikes as households are turning on their air conditioning systems. However, supply may be low during heat waves because risk of wildfires is extremely high causing power shut-offs to occur. In the case that wildfires do occur, wildfire smoke and cloud covers may also reduce solar energy supply. In addition, in extreme heat, natural gas plants can become overwhelmed and need to be shut off for periods of time, causing a further decrease in supply. This combination of high demand and low supply increases stress on the energy system. Because California imports energy from surrounding regions that participate in the Western Energy Imbalance Market (WEIM) as well, variable conditions in those regions that cause them to produce less energy may also affect energy supplies in California.

In addition to climate change and more frequent extreme weather events increasing stress on electricity infrastructure and energy systems in California, the impact that increased ZEVs may have on energy systems should also be considered. With recent regulations promoting the sale of new ZEVs and banning the sale of conventional gasoline vehicles, the number of electric vehicles on the road in California is bound to rise rapidly in the coming decade. These EVs rely on electricity to charge their batteries, which may become an added burden on California's electric grid.

💡Read our full Literature Review and Background Research Report here: **LINK**

C. Modeling Vehicle Emissions

There are many different approaches to quantifying emissions for Electric Vehicles (EVs) and for Internal Combustion Engine (ICE) vehicles, which are also called "Life Cycle Assessment" or LCA. These different LCA approaches use estimates of the emissions created during each step of a manufacturing process in order to provide an estimate for the overall global emissions of a vehicle over its lifetime. For both ICE and EVs, there are emissions associated with the manufacturing process of the vehicle chassis, which includes the body structure, suspension components, interior components, as well as lights, windows, and wheels. EVs also have emissions associated with battery production and manufacturing, while ICE cars have emissions associated with the production of an engine/transmission.

To get a picture of the true lifetime emissions from a vehicle, it is also necessary to estimate the emissions produced when the vehicle is driven. For ICE cars, this includes a modeling of the emissions created from gasoline combustion, as well as the emissions involved with the production/transportation of that gasoline. For EVs, this necessitates a modeling of the grid mix they are charged with, and the associated emissions from that grid mix. Because the grid mix changes from location-to-location, especially from state-to-state within the US, this is an emissions modeling factor that depends on geographic location. Furthermore, the lifetime emissions of both gasoline vehicles and EVs depend on the amount they are driven. Finally, the emissions created during the lifetime of a vehicle is proportional to the vehicle's energy efficiency. In the US, we typically see this represented as MPG or MPGe (for EVs).

Finally, there are ancillary factors which are present in some form for both EVs and ICEs that contribute to a vehicle's emissions over time. These ancillary factors include the oil, fluids, and lubricants a vehicle uses as well as other consumables such as brakes and tires. Brakes and tires are used over the lifetime of a vehicle for both ICEs and EVs and have emissions associated with their production as well as direct emissions produced from brake and tire dust respectively when they are used. These emissions are not usually included in existing vehicle emissions models.

D. Existing Tools related to Vehicle Emissions and Energy

Communicating concepts such as vehicle emissions and electricity generation are difficult, so learning from tools that already exist and are published by major environmental organizations is important.

Six tools related to vehicle emissions and energy generation were evaluated based on its usability and understandability (Table 1). In addition to learning about currently existing tools, this was an opportunity to see what models and data the tool used to make these estimations. Here, our team was able to see what designs both the user interface and the representation of the results.

Table 1. List of Tools Evaluated

Vehicle Comparison Tools	
DriveClean Vehicle Search	Source: https://driveclean.ca.gov/search-vehicles Published by: California Air Resources Board
Argonne National Laboratory, Car Webtool "EVOLUTION"	Source: https://evolution.es.anl.gov/vehicle-inputs.php Published by: Argonne National Laboratory
Vehicle Emission Calculator Tools	
Beyond the Tailpipe Emissions Calculator	Source: https://www.fueleconomy.gov/feg/Find.do?action=bt2 Published by: Oak Ridge National Laboratory for the U.S. Department of Energy and E.P.A
How Clean is Your Electric Vehicle	Source: https://evtool.ucsusa.org/ Published by: Union of Concerned Scientists
Electricity Generation Tools	
Power Profiler, eGrid	Source: https://www.epa.gov/egrid/power-profiler#/ Published by: EPA, last updated in April 2022
Electricity Sources and Emissions Tool	Source: https://afdc.energy.gov/vehicles/electric_emissions.html Published by: ADFC, resource of the U.S. Department of Energy's Vehicle Technologies Office

From our analysis, we gained key insights and found potential approaches to creating an effective tool design. One takeaway was to provide context around filters, terms, and categories. Tools used sustainability metrics that were not well known, making it necessary to explain to the user what the metric is, how it is measured, and how to interpret it. An example of this is the "GHG and Smog score" used by the California Air and Resources Board in their DriveClear Vehicle Search Tool where a vehicle is given a score of 10 (Figure 5). This leaves the user with many unanswered questions. Is 10 a good score or a bad score? What does it mean? Why does it matter?

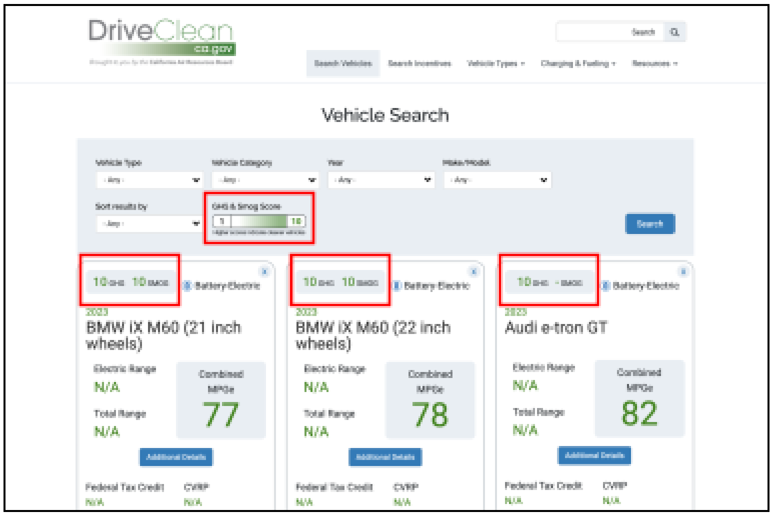
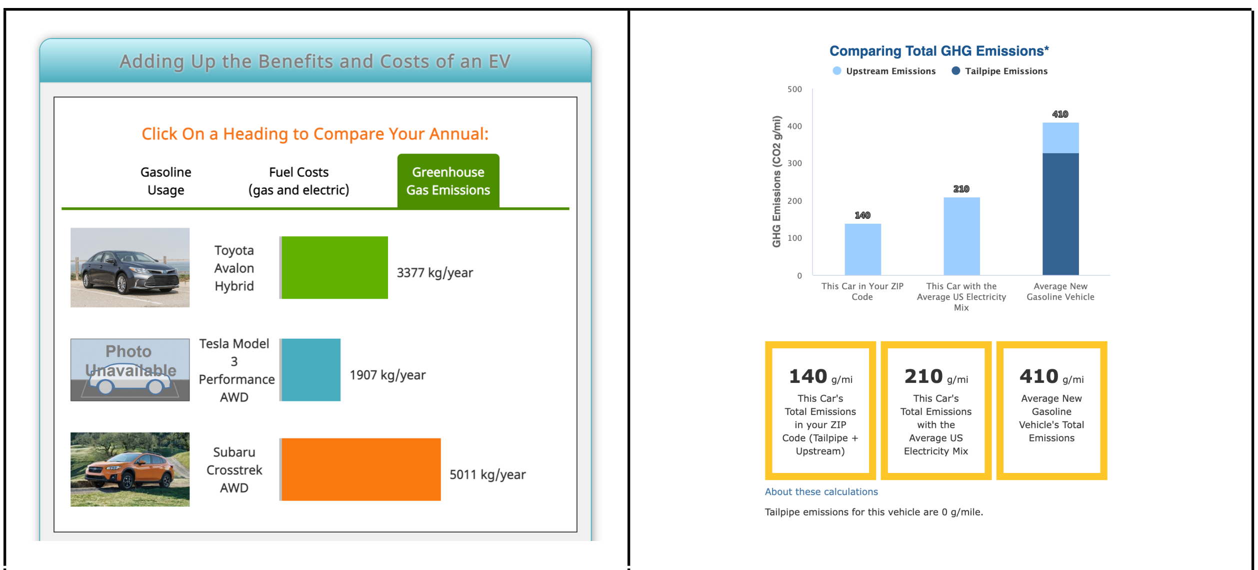
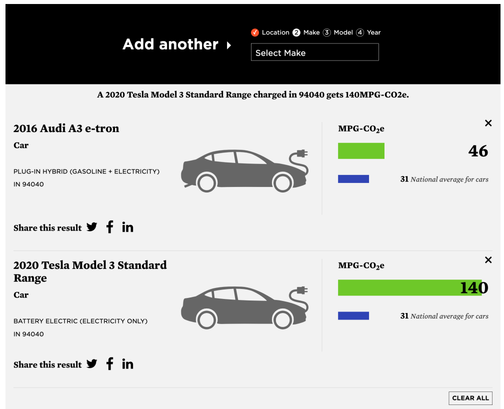


Figure 5. Screenshot of Vehicle Search Results, Highlighting GHG and Smog Scores (2022).

The tools we analyzed all showed their results as the raw number of emissions– in units of kg/year, CO2g/mi, and MPG-CO2e– with no context on what the value meant (Figure 6). This led to the takeaway of the importance of user-relevant results, and prompted us to keep questions about presenting results to users in mind. How does the tool communicate its results to the user? How can the result carry more meaning and relatability than a large number?



a) b)



c)

Figure 6. Outputs of Existing Tools (Accessed 11/29/2022) a) Car Webtool "EVOLUTION" by Argonne National Laboratory, b) Beyond the Tailpipe Emissions Calculator by Oak Ridge National Laboratory, c) How Clean is Your Electric Vehicle by Union of Concerned Scientists.

To improve the outputs of these emissions estimator tools, we turned to digestible outputs. While we were conducting background research, we found that the EPA created a tool called the Greenhouse Gas Equivalencies Calculator which converts emissions or energy units to concrete concepts such as the number of smartphones charged, household electricity use for one year, and wind turbines running for a year. In addition to providing a raw emissions number, more accurate interpretation of output can come from contextualizing it to units that are easily grasped.

💡Read our full Existing Tool Analysis Here: **LINK**

IV. Information Visualization Development

A. Introduction

Explaining complex concepts around climate change and emissions related to vehicles is difficult, and the aid of information visualizations necessary in order to communicate information that is poorly received in plain text, images, or tables. For example, when communicating sources of emission associated with different phases in a vehicle's lifetime emissions, a visualization is needed to color code the different phases and draw connections between the source and phase. Additionally, visualizations can help explain concepts for better understanding. When comparing the difference between lifetime emissions of internal combustion engine vehicles and all-battery electric vehicles, we wanted to show *where* emissions were occurring differently in the life cycle that caused all-battery electric vehicles to have overall less lifetime emissions. This information could be communicated through writing lengthy paragraphs explaining the differences, but creating a stacked bar chart comparing the two vehicles would be much more effective.

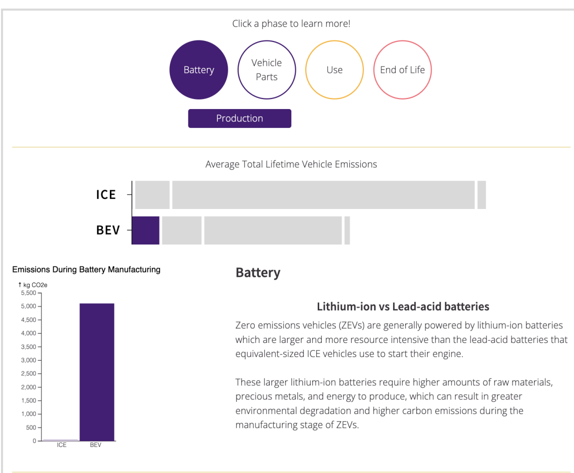
Information visualizations were a primary focus of our project, and from the initial background research stages we were curious and brainstorming ways to visualize different concepts and ideas. We wanted to create a variety of flat and interactive visualizations from line charts and bar charts to radar charts and dashboards linking multiple charts together.

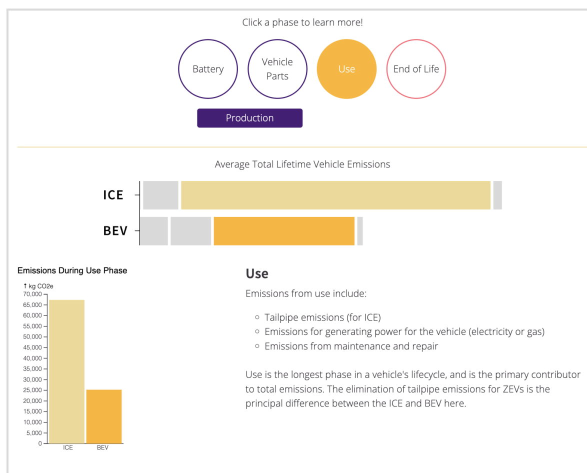
The process to create our visualizations began in the background research phase. During our literature review, we took note of current visualizations that were used to communicate similar concepts like sources of electricity and vehicle life cycles, and began compiling a list of databases that we could create our visualizations from. After our literature review, we drafted a site map of the flow of our narrative and began brainstorming where visualizations could go and what the visualization could look like. Thinking about our visualizations in the context they were going to be placed in was extremely important. What information does the viewer need to know to interpret the visualization correctly? What is the purpose of this visualization? And how is it playing a role in forwarding our narrative? From our brainstorming sessions, sketches, and inspiration visualizations, we then developed them in D3.js and Figma. And continued iterating on them after team critiques, expert reviews, and usability tests.

B. Technical Implementation
Flat visualizations were designed on Figma.

Interactive visualizations were developed using D3.js on Observable. Links to the Observable notebooks are found in the description of each visualization.

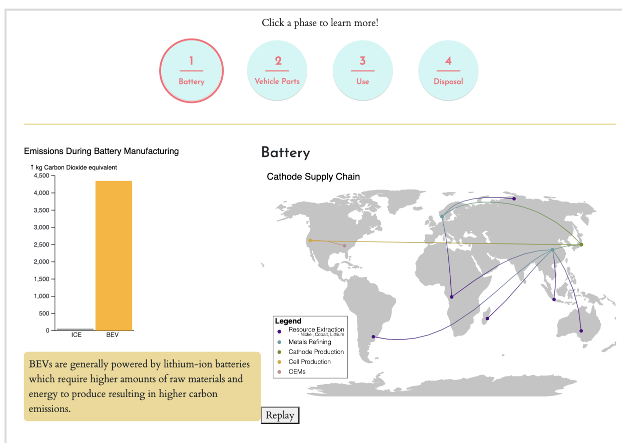
C. Visualization Walk-Through

<table>
<tr><td colspan="2">Explore Associated Emissions in a Vehicle's Life cycle</td></tr>
<tr><td colspan="2">


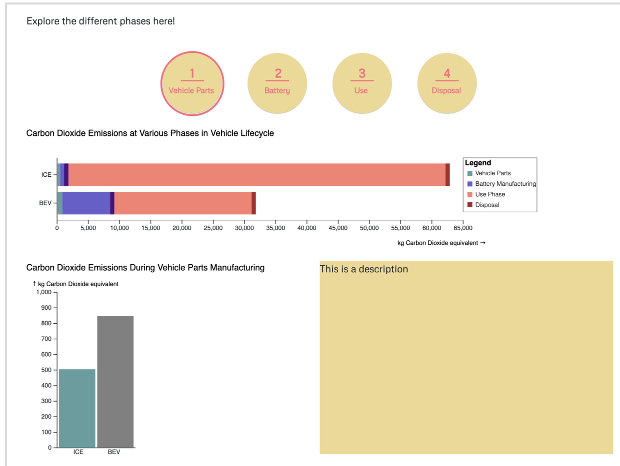


</td></tr>
<tr><td>Description</td><td>This visualization is a breakdown of vehicle lifetime emissions into four phases. The goal was to show the difference in emissions during vehicle life cycle phases between an internal combustion engine vehicle (ICE) and an all battery electric vehicle (BEV). While the total emissions of an average BEV is less than an average ICE, its production phase has more emissions than ICEs.
When the user clicks on the phase button, two charts will change and a description of the phase will appear. We have both a stacked bar chart to show the phase within the context of total lifetime emissions, and a bar chart showing the comparison between ICE and BEV. Here users can interact with the phases,</td></tr>
</table>

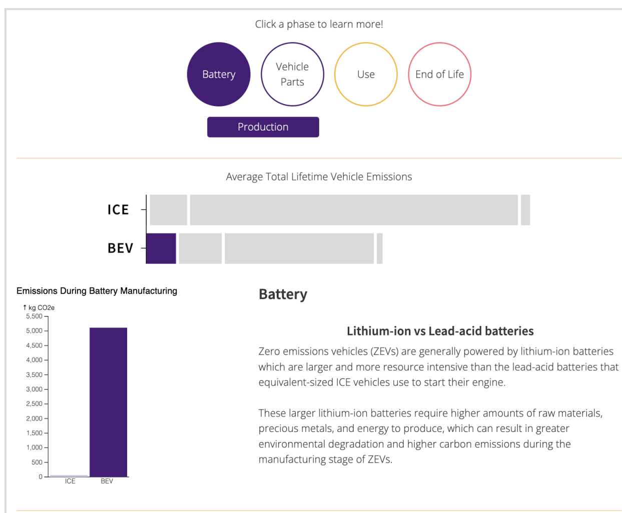
<table>
<tr><td></td><td>learn more about where emissions come from in each phase, and understand in what stages BEVs are more sustainable than ICEs.
From the stacked bar chart, users can see where the primary source of lifetime emissions is from (use phase) and from the bar chart they can compare the difference of emissions between the average ICE and average BEV.
Before this section, we introduce the vehicle lifetime emissions through a flat visualization and continue using the same colors for each phase to be consistent.</td></tr>
<tr><td>Link</td><td>https://observablehq.com/d/4c5ebaf4cb125f27</td></tr>
<tr><td>Data Source</td><td>Data was sourced from calculations from our tool, which calculates both total vehicle emissions and emissions from specific phases.
The ICE data is from the 2023 Subaru Forester AWD, and the BEV data is from the 2023 Subaru Solterra AWD. These vehicles are comparable, outside of type, because they are models released in the same year, same model, and both SUVs.
For the BEV, the average U.S. grid mix was used to calculate the associated fuel emissions for the Use Phase.</td></tr>
<tr><td>Iterations</td><td>We iterated on this section many times by refining what charts to include, color of the charts, and placement of the charts.



Version 1: We began with just the comparison bar chart to show the difference of phase emissions for ICEs and BEVs. However, this fails to show the phase emissions in context of total lifetime emissions.</td></tr>
</table>

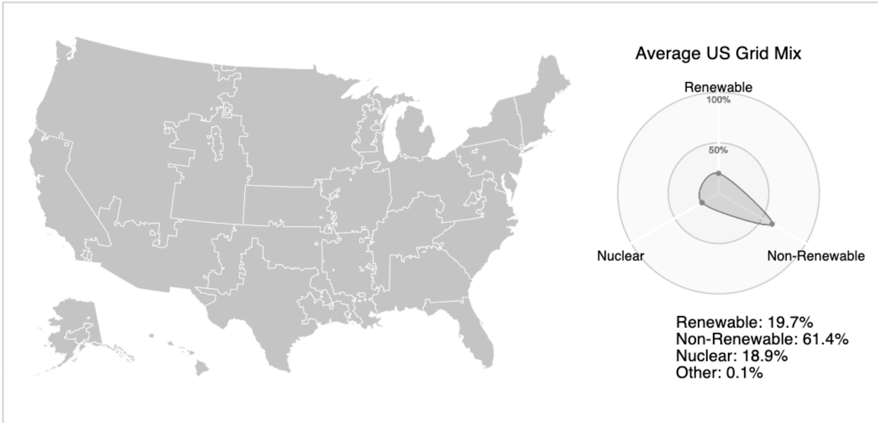


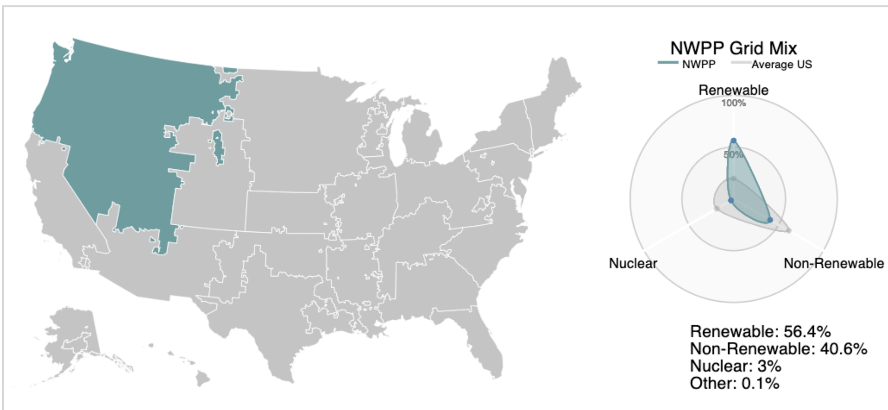
Version 2: Then we added a stacked bar chart to show each phase's emissions individually but also compared to total lifetime emissions. But the charts felt disjointed from each other and there was too much going on in terms of axes and colors.



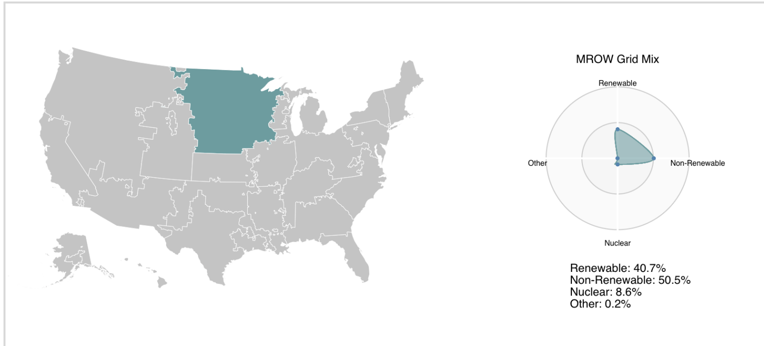
Final Iteration: We kept the layout of the charts but emphasized only the section of the stacked bar chart that the phase covered. In addition we repeated the colors associated with the phases from a previous chart and continued them throughout this section. Battery and Vehicle Parts are the same color of purple, so we added a bar beneath the label to show they are both part of the production phase.

Grid Mix by Region

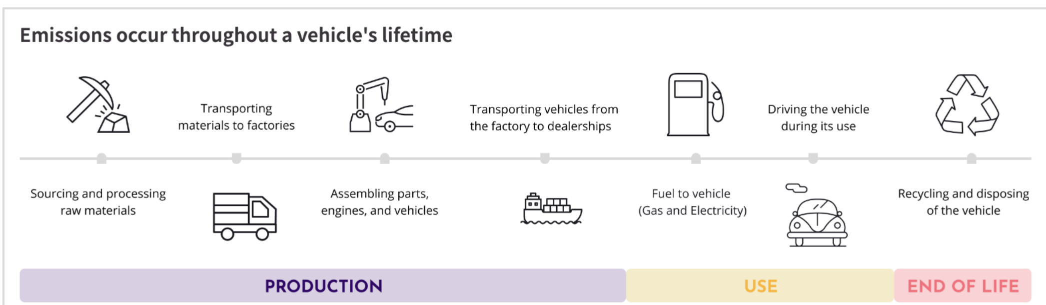


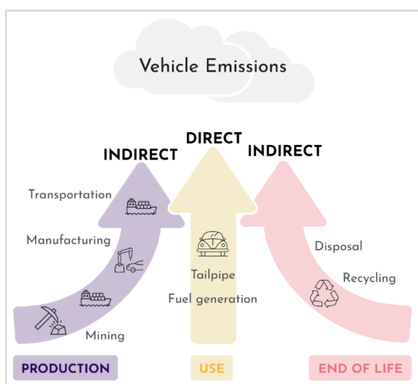


Description	This is an interactive radar chart where clicking on a region, will show the grid mix sources. Not only do users see a radar chart but also can see the percent breakdown for more detail. The goal of this chart is to show that depending on where you live, the sources of electricity are different. In previous iterations we had an additional source called Other but it was removed because it had minimal contributions and was distorting the radar chart.
Link	https://observablehq.com/d/d2acbd3b5d70efa1
Data Source	EPA (2023). Emissions & Generation Resource Integrated Database (eGRID). U.S. Environmental Protection Agency. Data Updated April 2023. https://www.epa.gov/egrid.

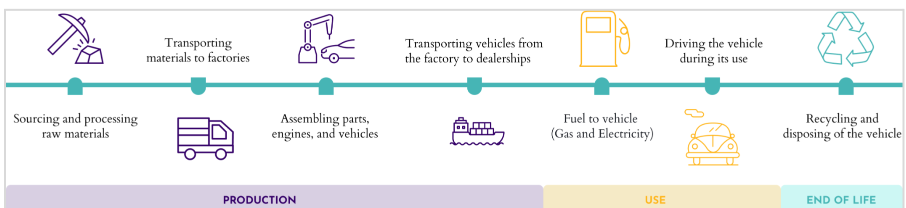
<table>
<tr><td>Iterations</td><td>

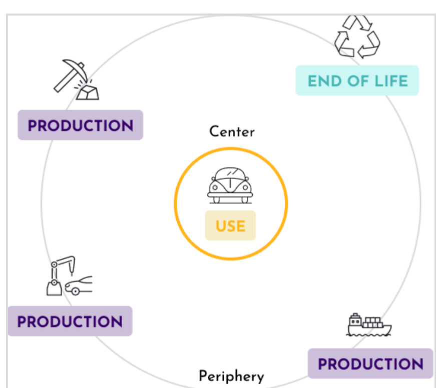
In our first iteration, we included the Other source as part of the radar chart. In addition, we felt that the radar chart needed more context. How does this grid mix compare to other regions? What about the average U.S. grid mix?</td></tr>
</table>

<table>
<tr><td colspan="2">Flat Infographic Visualizations on Vehicle Lifetime Emissions</td></tr>
<tr><td colspan="2">


</td></tr>
<tr><td>Description</td><td>These flat visualizations are essentially to our project in helping users understand where emissions are occurring throughout a vehicle’s lifetime. We split lifetime emissions into three categories: production, use, and end of life.
Understanding the concept of vehicle lifetime emissions is integral to understanding fuel-to-vehicle emissions but also the concept of our lifetime emissions estimator tool.
In addition to knowing what emissions occur, it is also relevant to know where</td></tr>
</table>

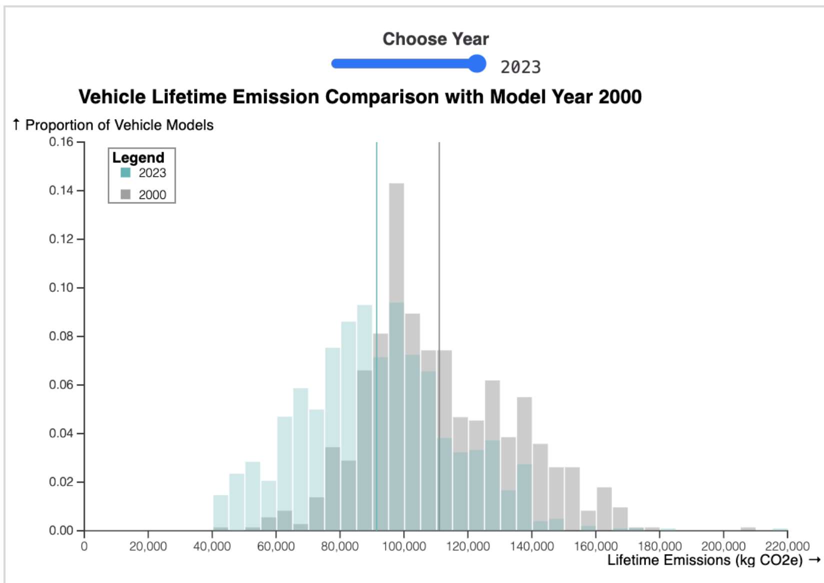
<table>
<tr><td></td><td>these emissions are occurring. We use the concept of Scope 1, 2, and 3 emissions to demonstrate how for each phase, these emissions are direct or indirect to the driver of the vehicle. Consequences of emissions occurring at the factory where the vehicle is built are not felt by the vehicle driver (production phase), where tailpipe emissions (use phase) does directly affect the vehicle driver.
For both of these visualizations, we remained consistent both with the colors used and iconography.</td></tr>
<tr><td>Data Source</td><td>Verma, Shrey, Gaurav Dwivedi, and Puneet Verma. “Life Cycle Assessment of Electric Vehicles in Comparison to Combustion Engine Vehicles: A Review.” Materials Today : Proceedings. Vol. 49. Elsevier Ltd, 2022. 217–222. Web.</td></tr>
<tr><td>Iterations</td><td>


In the first iteration of the lifetime emissions, we had longer descriptions and images of where emissions are occuring. The intention behind the images was to demonstrate that the emissions are not invisible but very real. All of the shipping containers of materials and finished cars waiting at the dock need to be transported around the world, and cause significant emissions.


However, we decided that using icons would have a cleaner appearance and allow us to re-use this timeline throughout our site and other materials. The photos, while impactful, are distracting from understanding the different phases. Initially, the icons followed the same color scheme as the phase colors, but we removed this in the final iteration because it did not add much value.


Our first iteration of communicating where emissions occur was through the</td></tr>
</table>

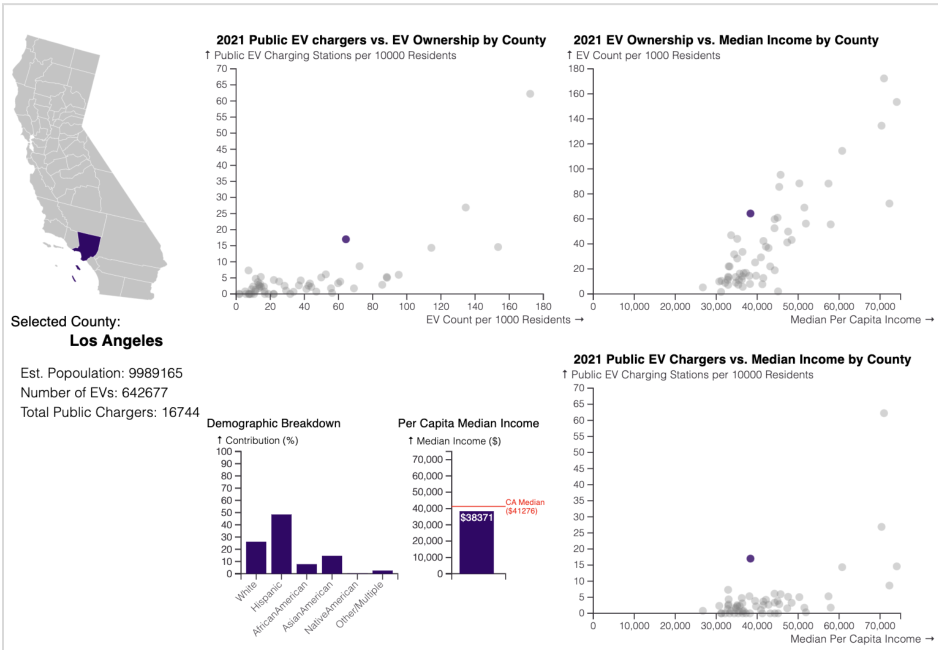
	concept of center and periphery. For the vehicle driver, the emissions that affect them are central while the emissions happening outside of their geographic location are in the periphery. In the same way, people primarily think and center their attention around usage emissions, but do not recognize or acknowledge other emissions because it is out of scope. This design was intended as a target, but we ultimately decided to change to direct and indirect emissions, because those concepts are more well known.

<table>
<tr><td colspan="2">Vehicle Lifetime Emissions over Time</td></tr>
<tr><td colspan="2">


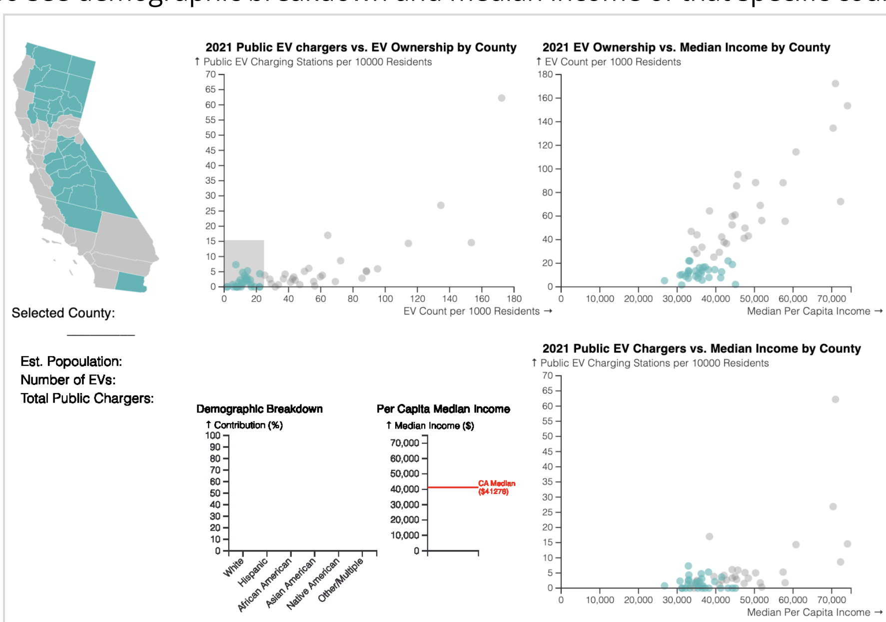
</td></tr>
<tr><td>Description</td><td>This interactive histogram allows users to see how the lifetime emissions of vehicles have changed over time from 2000 to 2023.
From our tool’s vehicle data, we wanted to create a visualization to serve as a summary or overview. We felt like a histogram of lifetime emissions would be interesting to explore whether vehicle lifetime emissions have decreased generally. We added a line representing the mean to better see the change over time. The user can use the slider to drag to see the histogram of different years. We were surprised that the average lifetime emissions did not decrease very much, but the histogram clearly shows the shift towards decreased vehicle lifetime emissions from 2000 to 2023. Also the bell curve in 2023 is much flatter than 2023, showing greater distribution of vehicles with less than average total lifetime emissions.
The inspiration behind this histogram is Vallandingham.me’s visualization of distribution of animal drawing times. As the user hovers on a section of the histogram, the sketches from that drawing time are shown. In future iterations, we could narrow the scope of our histogram to a type of car or make of car to also be able to show images of a car's physical evolution over time.</td></tr>
</table>

Link	https://observablehq.com/d/f6ad9ee9c08fc9bd
Data Source	Our Emissions Explorer Vehicle data. Original vehicle data is from the EPA Vehicle Data: https://www.fueleconomy.gov/feg/download.shtml

Dashboard of Public EV chargers in California



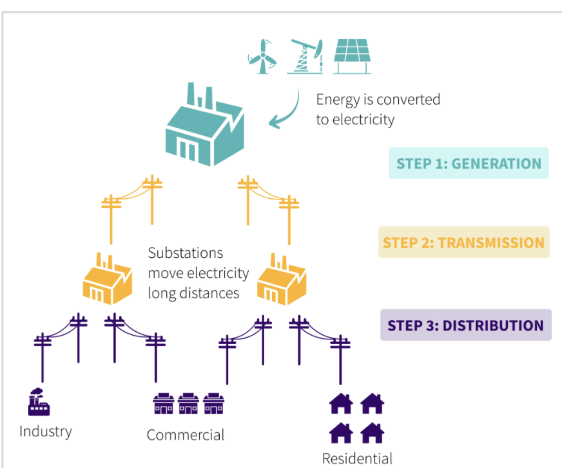
Click on a county in California to see where it stands on EV ownership and charging. Users can also see demographic breakdown and median income of that specific county.

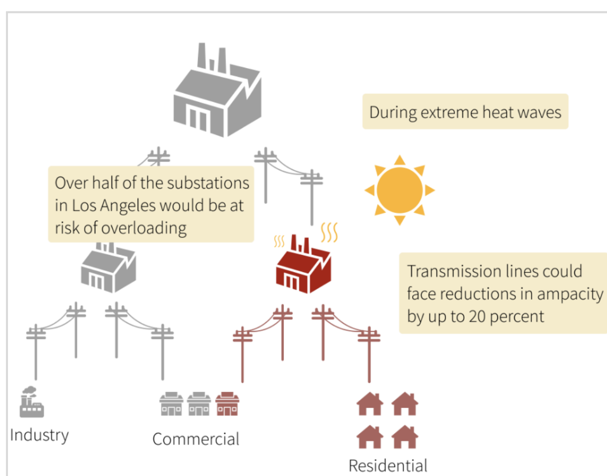


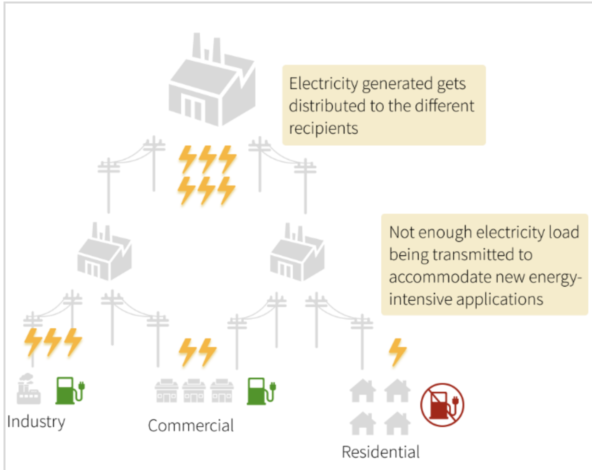
Brush on any scatter plot and data is linked on the map of California and other scatter plots.

Description	This dashboard was created to allow users to explore distribution of electric vehicle ownership and public electric vehicle charging in the state of California. Access to public charging affects the adoption of electric vehicles and other zero-emission vehicles. People who need public charging include: those who live in apartments with limited charging, those without off-street parking, or those who have range anxiety. With this dashboard, users can see the trend that electric vehicle ownership increases when median income increases, and that the number of public electric vehicle chargers also increases when median income increases. In addition to trends, users can view a specific county (where they live or picking an outlier on the scatterplot) to see the demographic breakdown, median income, and where the county stands on electric vehicle adoption and number of EV chargers. This dashboard was inspired by a paper written in 2021 by Hsu and Fingerman that found public electric vehicle charger access generally increases with income, and gaps in public electric vehicle access exist among different racial groups.
Link	https://observablehq.com/d/747cf5be98c1e86c
Data Source	California Energy Commission (2023). Electric Vehicle Chargers in California. Data last updated January 2023. https://www.energy.ca.gov/zevstats California Energy Commission (2023). Light-Duty Vehicle Population in California. Data last updated December 2022. https://www.energy.ca.gov/zevstats State of California Franchise Tax Board (2023). Personal Income Tax Data. https://data.ftb.ca.gov/stories/s/2it8-edzu#california-median-income-by-county United States Census Bureau (2022). Population and Housing Unit Estimates Datasets. https://www.census.gov/programs-surveys/popest/data/data-sets.html

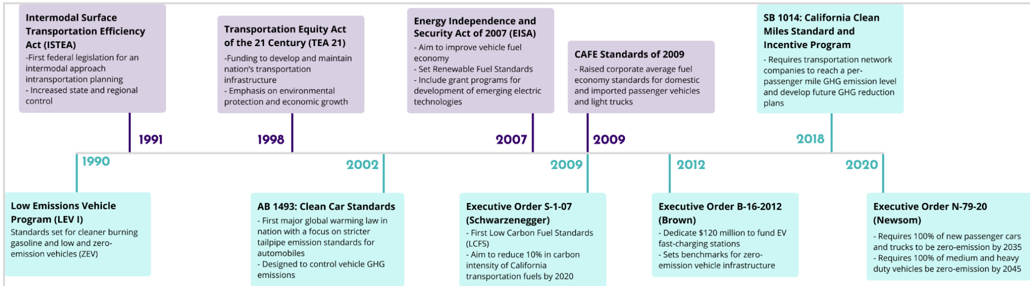
Flat narrative visualizations on energy infrastructure

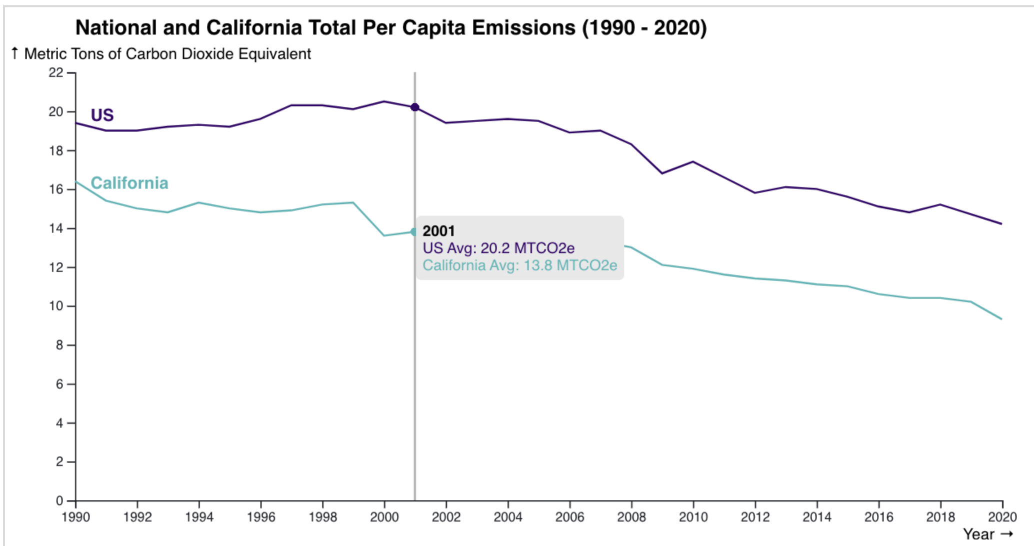






Description	On our webpage on accessibility zero emission vehicles, we discuss access to charging but also the ability for our electrical grid infrastructure to adapt to increased load of charging electric vehicles. In order to explain this concept, we needed to create a diagram explaining how the electrical grid works. We chose the most simplified version with three tiers/steps: generation, transmission, and distribution. We used three different colors to separate these steps and iconography to represent what these steps looked like. We also used an icon of electrical grid lines to connect the steps together to further this analogy. Once the base diagram was created of the electrical grid infrastructure, the outline of the three tiers was used as backbone for the rest of the infographics for the rest of the page. This allowed for better understanding because of the repetition and continuity throughout the page. Icons were de-emphasized in gray to focus the viewer on what the diagram was conveying.
Data Source	Yu, Xinghuo & Cecati, Carlo & Dillon, Tharam & Simoes, Marcelo. (2011). The New Frontier of Smart Grids. Industrial Electronics Magazine, IEEE. 5. 49 - 63. 10.1109/MIE.2011.942176. Burillo, D., Chester, M. V., Pincetl, S., and Fournier, E. (2019). Electricity infrastructure vulnerabilities due to long-term growth and extreme heat from climate change in Los Angeles County. Energy Policy, 128, 943-953. Brockway, A. M., Conde, J., & Callaway, D. (2021). Inequitable access to distributed energy resources due to grid infrastructure limits in California. Nature Energy, 6(9), 892-903.

<table>
<tr><th colspan="2">Key Policies and Emissions over Time</th></tr>
<tr><td colspan="2">




</td></tr>
<tr><td>Description</td><td>As an introduction to emissions and actions taken to reduce emissions, we wanted to share key policies passed by the federal government and California over the past 30 years. In addition, we created a timeline of per capita emissions over the same 30 years looking at the trend but also the difference between California and the US.
The goal of these charts are to show that with all of these key policies passed, the per capita emissions are decreasing but not significantly.
Originally the key policies were included into the line chart. The intended interaction was that while the user was following the emissions trend, they could also see the policies that were passed at the time. However, the narrative of the visualization was not clear and after many iterations we decided to separate the visualization into two separate parts.
However, we continued to use the same colors for California and the U.S. to show continuity and have consistency in this section.</td></tr>
<tr><td>Link</td><td>https://observablehq.com/d/cc45001d41e8b130</td></tr>
<tr><td>Data Source</td><td>CARB (2007) GHG 1990–2004 Inventory & Documentation. https://ww2.arb.ca.gov/ghg-1990-to-2004.</td></tr>
</table>

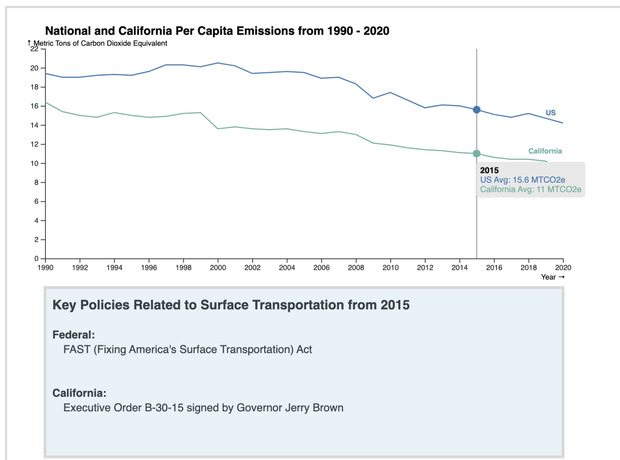
<table>
<tr>
<td></td>
<td>

CARB (2022) California Greenhouse Gas Emissions for 2000 to 2020 Trends of Emissions and Other Indicators. California Air Resources Board. https://ww2.arb.ca.gov/ghg-inventory-data.

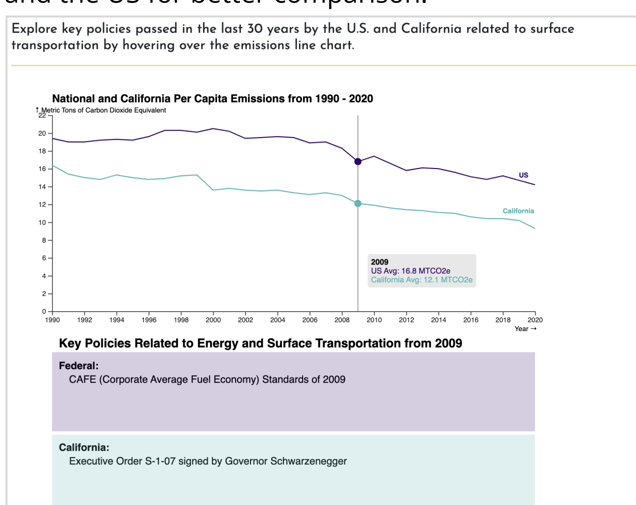
EPA (2022) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020. U.S. Environmental Protection Agency, EPA 430-R-22-003. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissionsand-sinks-1990-2020.

United States Census Bureau (2022) Population and Housing Unit Estimates Datasets.https://www.census.gov/programs-surveys/popest/data/data-sets.html.

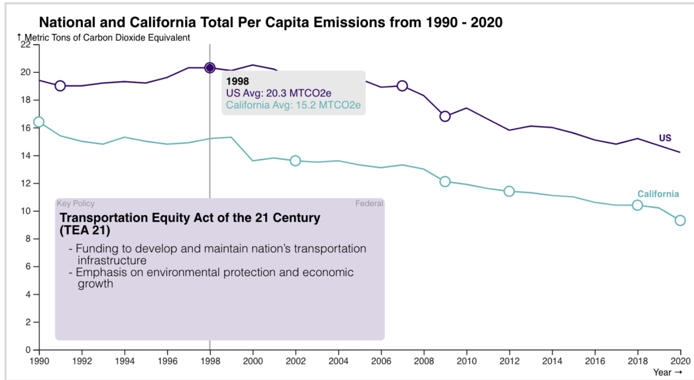
</td>
</tr>
<tr>
<td>Iterations</td>
<td>



This is the first iteration of our timeline. We had the placement of the policies at the bottom and we attempted to have a policy for every year passed by either the U.S. or California. There was also a tooltip that showed the exact value of CO2e for both California and the US for better comparison.



In this second iteration, we made the distinction between California and the U.S. clearer by repeating the color of the lines in the policy section. We also created two different boxes in the policy section, instead of having a combined section.
</td>
</tr>
</table>

<table>
<tr>
<td></td>
<td>


From the last iteration, it was difficult to see which years had policies associated with them. Here we reduced the number to only the key policies passed and added points so viewers could see which years to hover on. Instead of a separate box below the line chart, we positioned it inside the line chart.
</td>
</tr>
</table>

V. Emissions Explorer Tool Development

A. Introduction

<u>What is our tool?</u>

While it is generally understood that transportation remains the single-largest contributor to greenhouse gas emissions, and that consumer vehicles contribute a large percentage of this, identifying and understanding the emissions impact of any one vehicle is extremely difficult. This latter challenge is what we have focused on with our Emissions Explorer tool, as it is relevant to both consumers who are looking to purchase, rent or lease a vehicle, as well as for anyone looking for accurate model-specific information regarding vehicle emissions.

Our Emissions Explorer tool addresses this information need by 1) providing a quantitative estimate of a vehicle's emissions estimate over its lifetime (more on this below) and 2) contextualizing this emissions estimate by comparing it to vehicle averages and by providing emissions equivalencies (see visualization section above). The Emissions Explorer provides these numerical and visual estimates by taking into account both emissions produced while the vehicle is in use, and the emissions inherent in vehicle manufacturing, disposal, and transportation.

<u>How we make our estimate: general overview</u>

We can represent the total emissions of a vehicle as being encompassed by two parts: *usage emissions* and *embodied emissions*. We define usage emissions to be the emissions released when the vehicle is driven. We define embodied emissions to be emissions released during all other processes involved with the vehicle's life. This includes emissions related to the mining, transport, and shipping of materials involved in the vehicle's production, emissions involved with vehicle assembly and transportation, emissions involved with battery material mining, manufacturing and transport, and finally emissions associated with vehicle disposal and recycling. In other literature, embodied emissions are also referred to as "cradle-to-gate" emissions, while embodied and usage emissions together are referred to as "cradle-to-grave" emissions.

Estimating usage-phase emissions is relatively straightforward. For gas-powered cars, fuel is combusted in the engine and emissions are released from the tailpipe. For electric vehicles we must take into account where the energy used to charge the vehicle comes from: depending on where a user charges their vehicle (based on zip-code), we calculate the associated emissions with the regional electricity mix. If the electricity used to charge the vehicle comes primarily from coal, for example, the emissions released during the use phase is relatively high. Correspondingly, if the local electricity grid is primarily renewable energy, the emissions released during use can be close to zero. The details of this calculation are outlined in the next section.

Estimating embodied emissions is more complex: one must in theory identify the emissions associated with the mining, processing, transport, and assembly of every material involved in a vehicle's manufacture. It would not be possible for us to provide estimates of all these numbers, so we turned to an existing life cycle assessment (LCA) model: GREET. Greenhouse Gasses, Regulated Emissions and Energy Use in Transportation (GREET), is the gold-standard LCA model available to the public. Created by Argonne National Laboratory (ANL), GREET synthesizes both original research and outside estimates from LCA literature into one comprehensive software package (hosted in Excel). For our project, we used GREET estimates of emissions associated with particular materials, as well as GREET assumptions regarding the material proportions that make up both a vehicle's chassis and batteries. In addition, we used the GREET model to inform our emissions estimates for vehicle disposal and recycling. While we could have used the GREET Excel model to directly calculate embodied emissions estimates for particular vehicles, entering numbers in Excel is tedious and difficult to automate and scale. For this reason we ported the relevant sections of GREET into our own python backend to generate our emissions estimates. For specific implementation details see the next section.

B. Technical Implementation

Procedure:

1. Define our overarching model: what parameters to include, what assumptions to make.
2. Identify data sources for vehicle and emissions information
    a. EPA vehicle efficiency data
    b. EPA vehicle battery data (*estimated from EV range)
    c. EPA vehicle weight data
    d. GREET data (material emissions values, material percentages, misc. vehicle emissions assumptions)
    e. eGRID grid emissions data
3. Develop minimal python script to estimate usage-phase emissions
4. Clean, process, and join data
5. Incorporate data into python functions
    a. Estimate embodied emissions
        i. Estimate EV battery size, PHEV emissions
        ii. Distinguish between LI/NIMH batteries
        iii. Account for Hydrogen emissions (FCVs)
    b. Estimate usage emissions
        i. Use grid-mix based on zip code to calculate EV emissions
        ii. Account for charging loss, grid losses
        iii. Account for upstream fuel emissions (Well-to-Wheel)
6. Error-check and test code functionality

7. Validate emissions estimates against existing literature values
8. Integrate into the website form and perform further validation

Gathering data:

We identified the data we needed to gather based on the inputs we expected in our model. The key inputs we knew we needed included vehicle efficiency (MPG/MPGe), vehicle weight, vehicle battery weight and capacity, and the grid mix at a user's zip code. The EPA releases extensive data regarding both vehicle testing results and additional information about each vehicle tested. Unfortunately, neither one of these datasets contains all the information we need, necessitating a join between the two. Once we had identified the test data we downloaded the data in a .csv format, then downloaded each year of the EPA vehicle information data (which includes the vehicle weight), also in a .csv format.

We searched extensively for accurate and standardized data regarding EV battery weight and capacity. Our search led us to communications with both creators of similar emissions models and with the EPA directly. Unfortunately the EPA informed us that there is not yet a standardized source of battery weight information; there are, however, separate information sheets and spreadsheets that contain limited information about EV battery capacity and specifications which could be used to back-calculate the battery weight. Because there was no standardized data available, we chose to estimate battery weight using parameters already available to us in the EPA data: vehicle efficiency and vehicle highway range.

Finally, we found datasets which identified emissions associated with different grid regions (eGRID) as well as a lookup table that allows conversion from a zip-code to grid region. These data were downloaded in .csv format.

Cleaning data:

We performed data cleaning steps on each dataset separately. For EPA vehicle information it was necessary to join the different EPA datasets, one containing most of the information we needed, the other containing vehicle weight information. Because this join had no consistent primary-key to foreign-key relationship, the join of this data proved a challenge. Details on our join process are detailed in a standalone section below.

Once the EPA data was joined, we removed data that was creating duplicate models in our dataset. These data differed only in test procedure, but the key information we required was the same, allowing us to safely remove them. We removed data which contained duplicate values across the following columns: year, make, model-name, cylinder count, transmission type, and displacement. This was to avoid providing duplicate models to the user when the form is accessed. We also removed vehicles which run on compressed natural gas since we determined this fuel type was in very minor use, both past and present, and was outside the scope of the project. Finally, we removed unneeded columns from the dataset before storing it as a final, cleaned .csv file.

The zip code and grid-emissions data was fairly easy to clean. We converted zip code values from strings to integers and removed leading zeros from the numbers. We removed extraneous columns from the grid mix data before placing them into our model.

<u>Putting together the model:</u>
As outlined previously, the Emissions Explorer model partitions the emissions calculation into two phases: usage and embodied. In other words:

$$\textbf{Eq1: } E_{total} = E_{usage} + E_{embodied}$$

Usage emissions are calculated separately for ICEVs/HEVs, PHEVs, EVS, and FCVs, as each relies on a different combination of energy sources. We can write the general usage emissions calculation as follows:

$$\textbf{Eq2: } E_{usage} = \epsilon_{vehicle} d_{lifetime} c_{energy}$$

where $\epsilon_{vehicle}$is the vehicle efficiency (energy consumed/mile driven), $d_{lifetime}$is the lifetime vehicle mileage, and c_{energy} is the carbon intensity of the energy source in grams carbon (gC)/mile.
Joining EPA Data. For gasoline vehicles, we assume a standard emissions intensity of 8870 gC/mile; for EVs we use the user's zip code and eGRID data to calculate the emissions intensity in gC/kWh for electricity used to charge the vehicle. For FCVs we assume a CA-standard mix of hydrogen sources and associated carbon intensities (see assumptions below). Usage emissions for plug-in hybrid vehicles which use both gasoline and grid electricity are calculated as follows:

$$\textbf{Eq3: } E_{PHEV} = \frac{1}{1/(\epsilon_{vehicle} d_{lifetime} c_{grid}) + (1 - UF_{vehicle})/(\epsilon_{vehicle} d_{lifetime} c_{gasoline})}$$

Eq.3 employs a Utility Factor (UF), which represents the mileage fraction driven on pure electricity. Note in Eq.3 we take the harmonic mean of the gasoline and electric efficiencies as a typical geometric mean does not estimate the correct value when dealing with distance-based rates such as mpg.
For FCVs, we assume that the hydrogen conforms to CA hydrogen standards, as nearly all FCVs are currently driven in CA. See the assumptions section for more details.

Embodied emissions are calculated differently. We define embodied emissions as all emissions tied to the vehicle less usage phase emissions. We consider the following contributions:

$$\textbf{Eq4: } E_{embodied} = E_{chassis} + E_{battery} + E_{batt\ assembly} + E_{vehicle\ disposal} + E_{battery\ recycling} + E_{consumables}$$

Chassis emissions and battery emissions utilize GREET model assumptions regarding material makeup of vehicle chassis and batteries, while battery assembly and recycling emissions also depend on battery chemistry and makeup as outlined in GREET. Vehicle disposal emissions and consumable-emissions are considered constant, as we detail further in the assumptions section below. For chassis and battery emissions, we use emissions values associated with specific materials and the proportions of those materials expected in a chassis or battery pack. These proportions, which we use as weights, are multiplied by the associated emissions intensity of each material, before being multiplied by the weight of the vehicle chassis or battery. The general calculation can be represented as follows:

$$\textbf{Eq 5: } E_{embodied} = m \sum_{j}^{m} \sum_{i}^{n} GWP_{j} \epsilon_{i,j} w_{i}$$

In Eq. 5, GWP is the global warming potential of a greenhouse gas, defined as the equivalent concentration of CO2 necessary to cause the same global warming effect. Because GWP is a function of time, we have opted to use a GWP for greenhouse gasses at 100 years, also called GWP100. Methane, for example, has a GWP100 of about 25 times CO2. Then, for every greenhouse gas we consider, we multiply the emissions intensity in gC/kg by the GWP and by a corresponding weight. We multiply each weighted sum by the overall weight of the vehicle chassis or battery (represented as m) to get an overall embodied emissions estimate. For battery assembly, we perform a simple calculation using values from GREET:

Eq 6: $E_{batt\ assembly} = C_{battery} \sum_{j}^{m} GWP_j \epsilon_{assembly_j}$

Where C is the capacity of the battery in kWh, and the $\epsilon_{assembly}$ is the emissions intensity of the battery assembly per kWh. For battery disposal we assume a weighted average of different battery recycling methods (more details in assumptions below). This is represented as:

Eq 7: $E_{batt\ recycling} = m_{batt} \sum_{j}^{m} \sum_{i}^{n} GWP_j \epsilon_{recycling_{i,j}} w_i$

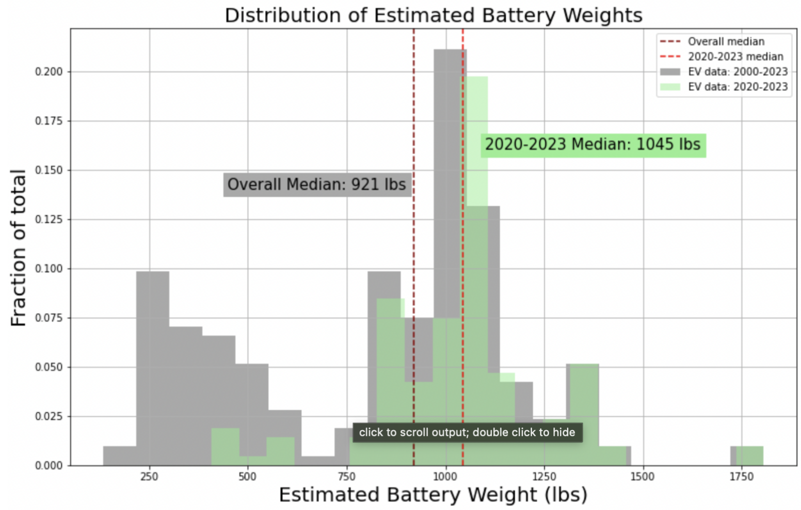
For vehicle chassis disposal and recycling we assume a constant value for all vehicles, as the GREET model values did not depend much on vehicle type or weight. We also assume constant value for lead-acid batteries in all vehicles and for oil, brake, and transmission fluids depending on vehicle type (outlined further in the assumptions section). Finally, we will also cover how we estimate the mass and capacity of the vehicle battery, as these are not values which the EPA currently records in their main dataset. The range an EV travels depends on many factors, including how fast it is driven, whether it is driven in a city or highway setting, and other conditions like temperature and humidity. However, in general the following relationship holds:

Eq 8: $C_{battery} = \epsilon_{vehicle} d_{max}$

Where C,ϵ, are as defined previously and d is the maximum distance the vehicle can travel on a single charge. Since the EPA data contains both vehicle efficiency, and estimated range for EVs, we can directly estimate the battery capacity, C. For this calculation we use the highway efficiency and range of the vehicle as these values are not affected to the same degree by factors like driving style, traffic conditions, or regenerative braking capacity. We can then calculate the battery mass using an assumption for the average energy density of a lithium battery; we assume 0.2 kWh/kg. Eq. 9 shows this calculation.

Eq 9: $m_{battery} = 0.2C_{battery}$

This assumption yields the battery weight distribution below:



Estimated battery weights have a wide, bi-modal distribution. This is primarily down to two factors: 1) earlier models have much smaller batteries as the vehicles were intended primarily as city-transport and 2) the assumption that energy density is a constant 0.2kWh/kg. We delve into why we make this assumption and the effects it has on our results in the assumptions section. Upstream emissions adjustments are also incorporated into the model. We define "upstream emissions" to be the emissions associated with fuel and electricity production that are not directly captured in the emissions estimate. For gasoline vehicles, this includes emissions released during the extraction, refining, and transport of petroleum. For grid-mix electricity, this includes energy losses in the energy distribution and vehicle charging process. These upstream factors are included in our calculation in the following general way:

Eq. 10: $$E_{adjusted} = f_{upstream} E_{unadjusted}$$

We calculate $f_{upstream}$ for gasoline using the GREET WTW calculator values, and for the grid-mix using the most recent reported literature values for the US average. For gasoline, this multiplication factor is 1.27, and for EV charging this multiplication factor is 1.25.

<u>Data join:</u>

To combine EPA vehicle weight data with other data about the vehicle, like efficiency, range, and utility factor (relevant for PHEVs) it was necessary to join datasets. Since no primary-key foreign-key relationship exists between these datasets we were forced to look to alternative joining methods. Across the datasets, three variables of interest stood out: year, make, and model. However, across the datasets and across years, the entered make and model vary significantly and in sometimes unexpected ways. For example, the make "Mitsubishi" can also be entered as "Fuji Heavy Industries" in the other dataset. For this reason, rather than attempting to provide a manual accounting of every possible make-to-make combination, we focused on joining vehicles based solely on the year of manufacture and the vehicle model.

While vehicle models did vary between the datasets, we were able to use them as a join-key using a fuzzy-matching approach. The fuzzy matching algorithm we implemented uses a combination of Jaro-Winkler and Levenshtein string similarities. Then, for every string in the left EPA dataset (containing everything but vehicle weight), we search all the strings of the right EPA dataset (containing vehicle weight). When the similarity of the match is above a certain threshold (validated on subsets of the data), and if the year of manufacture is matching, we conclude that the row of the right dataset is a candidate match for the row of the left dataset. We then save the indices of the candidate join. For certain makes and models, we provide a set of manual data cleaning rules which help ensure the accuracy of the join. Finally, we are left with a set of fuzzy-matched join indices which we can now perform a traditional inner-join on. We were careful to validate this approach, and found that around 98 percent of the total data (assuming a perfect inner join on the original datasets) was captured. Of the data that was captured, we validated the join accuracy on random subsets of the data and found an accuracy of 96 percent. While this is not a perfect join, and some weight information is off, it does not have any real impact on the validity of the model results because the weight information we are using is already rounded by the EPA. Therefore we estimate that any error caused by the join is within the rounding error already present within the dataset (which ranges from 2-10 percent depending on the vehicle).

Writing functions:
We developed our script to calculate usage-phase emissions and embodied emissions separately, in order to keep it as modular as possible. Additionally we designed our functions to be as future-proof as possible; we calculate the emissions for each type of vehicle (ICE, HEV, PHEV, EV, FCV) in different functions in order to maintain modularity. Additionally, different steps of each calculation are broken into separate functions: for example, we calculate vehicle chassis and battery emissions separately for EVs. This should make it relatively easy to update the model over time as values change or estimates are made more accurate.

Coding the front-end app:
The final tool is coded in HTML and javascript with output visualizations created using D3.js. The functionality of HTML and javascript are appropriate for our tool, and does not require an additional external hosting service, which helped to simplify the development of our tool. In order to collect user inputs for the tool, we used HTML form elements that walk the user through each necessary input. Because entering inputs may be repetitive and feel tedious for some users, we defined preset inputs to increase the ease of use and so that changing those inputs can become optional for the user. From the user inputs, lifetime emissions are calculated using a series of javascript functions. These javascript functions were adapted from python code that we had previously implemented to calculate emissions.

While we ended up using javascript and HTML to create our tool, we initially created a backend for the project in Django, which is considered the standard python-based web framework. We also initially pursued Django because it offers scalability and built-in security features. We originally pursued Django as we believed it would let us integrate the data, model script, and front end form most efficiently. However, we found that Django had a steep learning curve, especially when it came to integrating the form with our backend functions. Certain form features, like creating a chained dropdown menu often end up using javascript files to enhance functionality anyways. With this in mind, we decided to move our entire form into a javascript file as it greatly simplifies the backend. In addition it allows us to display our website on github without hosting it on a server, like Heroku.

C. Validating Tool Outputs

When creating the tool we used the most recent available data and models, and wherever possible, tried to make the most prudent assumptions. To see where our model estimates fall within the literature, we performed a validation coupled with a literature review. This literature review separately considers the estimates for usage phase emissions, which are easier to obtain and more widely reported, and embodied emissions due to vehicle manufacturing, which have much greater variability and are difficult to find outside of environmental and industrial research papers. Below, we compare outputs of our model with the outputs of other's models and reported literature values. Overall, we find that our values for both usage and embodied emissions fall within the expected range of values; where our values disagree, it is usually due to our model taking into account additional factors that others have left out.

We previously discussed how we estimate emissions. To summarize, we use the GREET model to adjust for emissions related to vehicle fluids as well as vehicle assembly, disposal and recycling. Finally, we use the emissions values for CO2, CH4, and N20 to calculate a combined CO2 equivalent emissions value which combines the global warming effects of each greenhouse gas into an equivalent amount of CO2. Then, we sum the CO2e contribution from each phase of the vehicle life cycle to create a lifetime emissions estimate for the vehicle.

Note: Queries and code used to calculate the numbers below are in the Testing directory in our github repository.

Averaging usage emissions for the 2021 model year:

Source	Emissions Estimate	Upstream Estimate	EV treatment
EPA	~347 gCO2/mi	Not Included	Zero Emissions
Emissions Explorer	~469 gCO2e/mi	Included	Non-Zero Emissions

Our usage-phase emissions estimate is about 35% higher.

Reasons for this difference:

1. The biggest reason for this difference is that the EPA estimate does not include upstream emissions from fuel production and transport. We estimate that upstream fuel emissions and production in the US add about 27% to the “tailpipe CO2” value the EPA reports.
2. The EPA calculates “tailpipe CO2” emissions which are 0 for EVs and low for PHEVs. We calculate “usage phase” emissions which include the emissions associated with charging EVs/PHEVs based on a driver's local grid emissions.
3. The EPA uses an estimated “real-world” fuel economy value that differs slightly from the “compliance fuel economy” value that they report. We weight our city/highway emissions using the standard 55/45 weighting, while EPA adjusts its tailpipe values to use a 43/57 weighting. For most vehicles (especially non-hybrid vehicles) this will result in slightly lower emissions estimates.

4. We calculate CO2e using data from the GREET WTW calculator. While CO2e should be similar to CO2 for gasoline vehicles, it will still be slightly higher.

Together these differences account for our estimate being about 35% higher than the EPA estimate. Note that if the EPA estimate is multiplied by our upstream CO2e factor for fuel production we get ~441 gCO2e which isn't far off our Emissions Explorer estimate (only 6% less), the remainder of the difference being accounted for by the factors above.

Usage-phase for EVs:
In their appendix, the EPA does delve into usage-phase emissions for some EVs and PHEVs:

Table E.4. Model Year 2022 Example EV and PHEV Upstream CO_2 Emission Metrics (g/mi)

Manufacturer	Model	Fuel or Powertrain	Tailpipe + Total Upstream CO_2			Tailpipe + Net Upstream CO_2		
			Low	Avg	High	Low	Avg	High
Ford	F-150 Lightning	EV	136	211	369	35	110	267
GM	Bolt	EV	76	117	204	25	66	153
Hyundai	Ioniq 5	EV	81	125	218	26	70	163
Nissan	Leaf 62 kWh	EV	84	130	228	30	76	173
Tesla	Model 3 LR AWD	EV	69	107	188	10	48	128
BMW	X5 xDrive	PHEV	323	378	494	230	285	401
Ford	Escape	PHEV	154	185	251	97	129	195
Stellantis	Pacifica	PHEV	217	254	332	134	171	250
Toyota	Prius Prime	PHEV	134	154	196	86	106	148
Average Sedan/Wagon			**338**	**338**	**338**	**270**	**270**	**270**

Comparing the usage value for our EV/PHEVs to their average usage value:
Averaging PHEV/EV usage emissions:

Source	Emissions Estimate	Upstream Estimate	EV treatment
EPA	~184.6 gCO2/mi	Included (Avg Grid)	Non-Zero Emissions
Emissions Explorer	~185.0 gCO2e/mi	Included (Avg Grid	Non-Zero Emissions

Comparing the EPA's usage emissions estimates for the subset of EV/PHEV vehicles they provide to our average usage phase emissions for EV/PHEV vehicles from 2021 we find a difference of 0.2%. This is negligible compared to the measurement and rounding error for the measured fuel economy and grid mix values.

Embodied Emissions (Battery):

Battery Production:
Peters et al (2017) estimate that battery production for NMC chemistry (assumed for lithium batteries in the tool model) is approximately 0.160 kgCO2e/Wh. The International Energy Agency also provides two battery manufacturing/assembly estimates: 2.6 tCO2e (low) and 4 tCO2e. They assume a 40 kWh battery and NMC622 chemistry. Converting to kgCO2e/kWh: (Estimate*1000*(1/40)) gives a low estimate of 60 kgCo2e/kWh and a high estimate of 100 kgCo2e/kWh

The ICCT also provides a meta-analysis of estimated emissions intensities.

Source	Emissions Estimate	Chemistry (Lithium)
Emissions Explorer	~107 kgCO2e/kWh	NMC111
Peters et. al (2017)	~160 kgCO2e/kWh	NMC (all chemistry)
IEA (2022)	[60-100] kgCO2e/kWh	NMC622
ICCT (2018)	[30-494] kgCO2e/kWh Studies 2017 and later: [56-200] kgCOe2/kWh	All chemistries

Overall, the Emissions Explorer value lands on the lower side of the estimate range in the existing literature. Since each paper assumes different battery chemistries, different energy sources during production, and different transportation and mining-related emissions the estimates vary considerably.

Embodied Emissions (Vehicle Chassis):

IEA provides an estimate of ICE vehicle manufacturing of 6 tCO2e and EV vehicle manufacturing (not including the battery) of 5.4 tCO2e. For the ICE vehicle this is 6000 kgCO2e. Buberger et al. complete a vehicle LCA using a Volkswagen internal estimate of 4.56 kgCO2e/kg of vehicle weight. Applying this value to our average ICE weight yields an estimated emissions of ~8700 kgCO2e.

Source	Emissions Estimate	Vehicle Size
Emissions Explorer	~8100 kgCO2e	All Sizes (ICE)
Emissions Explorer	~7200 kgCO2e	“Mid-Size” (3000-4000 lbs) (ICE)
Buberger et al. (2019)	~8700 kgCO2e	N/A
IEA (2018)	~6000 kgCO2e	“Mid-Size” (ICE)

The Emissions Explorer is outputting values within range of these results. Once comparing similar size vehicles, Emissions Explorer outputs a value about 20% higher than the IEA estimate and about 17% lower than the Buberger et al. estimate. This is understandable because we are using different datasets and have made different assumptions about the underlying emissions intensities of production. In our case we are also using the most up-to-date numbers from a standardized source (GREET 2) whereas Buberger et al. report an industry value and IEA use the emissions estimate for a single vehicle (which is not specified). Note that whether or not we are using ICE vehicles shouldn't matter since we assume ICE and BEV chassis to be composed similarly. However, other papers cite values for ICE vehicles so for the sake of consistency (and to keep vehicle weights comparable) we select only ICE vehicles from our dataset.

Overall, the results of our analysis suggest that the Emissions Explorer model is reporting accurate values for both usage and embodied emissions. We expect that the usage emissions will be higher than the EPA's average value because we take into account additional factors like upstream emissions due to fuel production and also include the emissions from EVs in our analysis (which the EPA considers to be zero in the calculation for their estimate).

D. Assumptions and System Boundaries

Assumptions behind consumables:
Consumables include the fluids a vehicle uses over its life, not including gas (for ICE cars). For most vehicles this includes brake fluid, transmission fluid and grease, differential oil, washer fluid, and coolant. For ICE vehicles, this estimate also includes engine oil. We use the GREET model assumptions for lifetime vehicle fluid use. These are outlined below:

Comparison	ICE	HEV	PHEV	EV	FCV
Emissions (gC)	634,200	634,200	571,000	167,000	82,000

These values assume the average vehicle life in the US of 178,000 miles. While these values should vary from vehicle-to-vehicle depending on factors like engine size, transmission type, braking system type, amongst others, we expect the primary difference to appear between vehicle drivetrains; this is captured well in the above assumptions. Depending on the other embodied and usage emissions in a vehicle, and how long it is driven for, these constant values make up a small percentage of the total emissions estimate, often no more than 1-2 percent.

Assumptions behind vehicle composition:
We assume the standard vehicle composition that is outlined in GREET. Specifically, we assume the "Conventional" composition, which involves a vehicle largely composed of steel, aluminum, glass, and plastic. Since most vehicles today are manufactured from steel, aside from exotic or ultra-luxury vehicles, we believe this assumption to be reasonable. In the future we would like to find ways of adjusting this material composition on a model-specific basis. The specific weight vector we assume is located within our emissions join script on Github.

Assumptions behind vehicle assembly, disposal, recycling:

We assume that vehicle assembly, disposal, and recycling (ADR) is captured by a constant assembly and recycling term for the chassis, and a separate capacity-dependent term for battery assembly and recycling. We assume a constant chassis term of 874,000 gC/vehicle, and use GREET estimates for battery assembly and recycling emissions. For battery recycling, we assume a weighted average of different recycling processes which GREET models: 25 percent pyro-recycling, 30 percent inorganic hydro-recycling, 30 percent organic hydro-recycling, 15 percent direct recycling. We assume these values based on reports of new battery recycling plant types (American Chemical Society, 2022) – which should reflect how batteries will be recycled (if they are at all). We assume that direct emissions will play a small role in the near future, since this method is the most difficult and expensive, though it is the least emissions intensive.

Assumptions regarding EVs: no battery replacement, constant grid mix:
For our emissions estimate, we assume that EV batteries do not require a replacement over the vehicle's lifetime. We make this assumption because little data exists on this topic, and it is safer to assume that EV-owners will accept range degradation on the order of 10-20 percent than elect to completely replace the battery (Argue, 2020). However, we should emphasize that this assumption can greatly impact the emissions estimates for EVs and it is something that we plan on researching further in the future.

We also assume that the electric grid-mix will remain constant over a vehicle's life. While this assumption simplifies our calculations considerably (otherwise we would have to model a time-varying component of emissions from zip-region to zip-region over time, requiring many more assumptions) it also has the potential to increase usage-phase emissions estimates for EVs. We are researching methods to integrate a time-varying component into our grid emissions estimate, and plan to integrate it once finished.

Assumptions regarding Hybrid vehicle battery type:
Regular hybrid vehicles (HEVs) which contain a gas engine and small onboard battery, which cannot be plugged in, have battery emissions which are difficult to estimate well. This is because little data exists on HEV battery weight, and it is not possible to back-calculate battery emissions as we do with EVs since electric-only range data is not reported by the EPA for HEVs. However, by researching HEV battery replacement options we were able to determine typical battery weights for HEVs, as well as typical chemistries (besthybridbatteries.com, 2023). We found that EV batteries before 2020 were typically NIMH, and after were typically Lithium chemistry. We also found that the HEV battery weight varied with vehicle weight. Since no structured dataset was available, we assumed three battery weight subsets. We believe these capture NIMH battery weight well. Note that the overall difference these assumptions make in the final estimate is small, around 1 percent at most.

Vehicle Weight (lbs)	More than 4000	Between 3300 and 4000	Less than 3300
Battery Weight (lbs)	75	120	150

Assumptions regarding FCV fuel type:
Because FCVs are the least common vehicle type, there is little data about hydrogen fueling available. We assume that hydrogen fueling must comply with California standards: 33 percent renewable hydrogen. Specifically, we assume that 67 percent of hydrogen is from Steam Methane

Reformation (SRM) processes, while the remaining third is evenly split into renewable SRM and renewable hydrolysis. For each source, we multiply each weight by its corresponding emissions intensity, reported by CARB (2018). We believe these estimates reflect the current most common hydrogen sources in California.

System Boundaries: What do we not take into account:

System boundaries can be thought of “where we draw the line” on what factors and emissions to include in our model, and what factors and emissions we currently consider outside the model scope. Below we outline some factors that matter when estimating emissions, but which we do not currently have the data or modeling capacity to take into account. We expect most of these factors to have user-specific impacts (for example, if someone lives in a very cold place or charges using a home-solar array) but they should not have large impacts on our overall emissions estimates.

Driving style and location:

Driving style varies between people and is hard to quantify, but it has an impact on usage-phase emissions regardless of vehicle type. People who drive more aggressively, at higher speeds, or brake unnecessarily will have higher emissions than those who drive at lower speeds, brake less, and coast when possible. Efficient driving techniques depend on vehicle drivetrain type and can even be engine specific; they are outside the scope of this report.

Location also matters when determining usage-phase emissions. Driving in a hillier area reduces efficiency, since more energy is lost to braking. Driving in cities reduces efficiency for the same reason. The amount these factors matter depends on vehicle type and weight and understanding exactly how they impact usage emissions is complex and outside the scope of our model.

Weather and climate:

Temperature and humidity both impact air density, which affects vehicle efficiency, especially in highway settings. In addition, cold weather impacts vehicle efficiency and performance since the vehicle takes longer to heat up and additional energy may be required to heat the cabin. ICE and EVs are impacted differently, as ICE vehicles use residual heat from the battery to heat the passenger cabin, while many, but not all, EVs use resistive heaters to heat the cabin, reducing overall efficiency. On-road accumulation from rain, snow, sleet, or hail also impacts rolling resistance and therefore efficiency. These impacts can be very significant depending on the severity of the conditions and proportion of vehicle lifetime spent in such conditions. We would like to integrate some of these effects into our model in the future as a user-interactive feature.

Home solar panels or generators:

We assume that plug-in vehicles are charged using the grid-mix corresponding to the user’s zip-code. However, if a vehicle is charged on home-solar or other non-grid sources of electricity this will greatly change the emissions estimate. These possibilities are outside our system boundary.

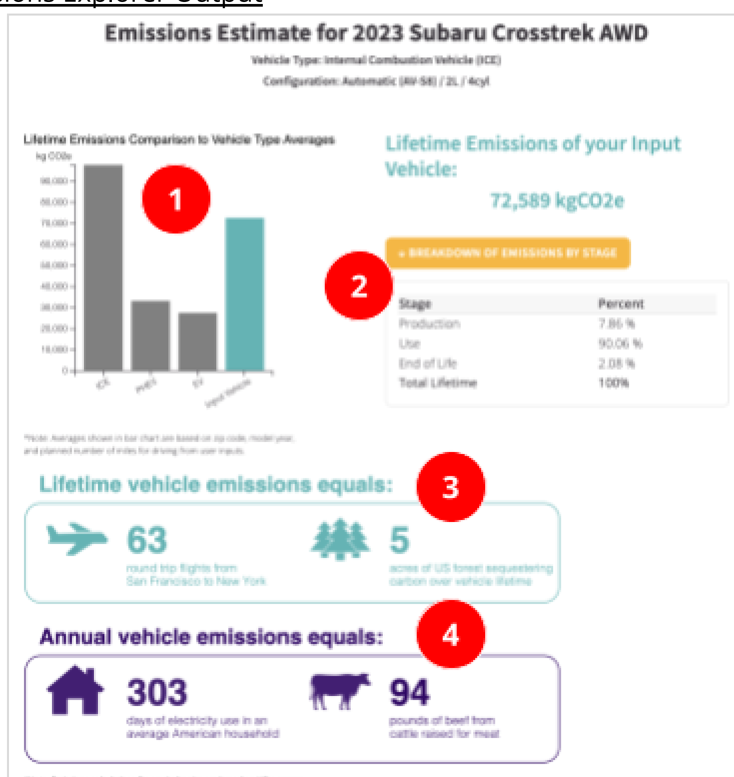
Biofuels/Efuels:

Biofuels and Efuels are hydrocarbon fuels which are not generated from fossil fuels, instead generated from plants, waste products, or chemically synthesized. While some Biofuels and Efuels have the potential to make usage-phase emissions of ICE vehicles carbon neutral or even carbon negative, the exact impact depends on the fuel used and how it is sourced. Corn ethanol, for example, is present in most US fuel mixes, but it does not have any real positive impact on fuel emissions, often having an overall larger impact than the fossil fuel it displaces. For these reasons we have left the estimation of alternative fuel carbon intensity out of the model for now.

E. Designing Digestible Outputs

From our existing tool analysis, our primary takeaway is the importance of having outputs that are understandable and relatable to our users. The lifetime emissions of a vehicle can range from 40,000 to 180,000 kg CO2e (CO2 equivalent). There are two issues with this output: how can we conceptualize such a large number, and what does this unit mean for people who are not commonly familiar with environmental measures? We needed to build a mental model for our users to conceptualize this output. We can visualize scale in many ways such as animations that zoom-in or out (such as Powers to Ten), analogies (making comparisons between objects or space), or unitization (redefining the object into a new type of object). Chevalier et al. calls for the re-expression of complex scales, such as extreme magnitude and unfamiliar units (our output is both), to easier to grasp measures– concrete scales (Chevalier, 2013). Chevalier writes that "what is a good unit" is difficult to determine, but the unit should be understandable without extra explanation and should have little room for interpretation. For example, a bowl of soup is a poor unit because depending on a person's mental model a bowl of soup could be many sizes and there is no consistency between interpretations. Hullman et al, builds on this by creating a list of criteria for effective re-expression of objects. Aspects of a good unit include: concreteness, countability, rigidity, object familiarity, measure familiarity, low measure variance, measure closeness, and object similarity (Hullman, 2018). Our output attempts to apply these concepts of re-unitization and adding familiar context to create interesting and understandable results to the user.

Description of Emissions Explorer Output



Output of our Emissions Explorer Tool

1	**Lifetime Emission Comparison** The first part of our output section is a bar chart that shows the user's vehicle lifetime emissions compared to the average gas-powered vehicle, plug-in hybrid electric vehicle, and electric vehicle – all calculated with the same geographic region, miles driven, and model year. Here we used the strategy of comparison to contextualize the lifetime emissions with different types of vehicles. Users can see that their vehicle's lifetime emissions is more than the lifetime emissions of an average but less than the lifetime emissions of an average gas-powered vehicle.
2	**Breakdown of Emissions by Stage** Under the raw value of the user's vehicle lifetime emissions, we inserted a dropdown that allows the user to click to see the lifetime emission breakdown into the three phases that were introduced on our site (production, usage, and end of life). Breaking this down by percent was the most clear way of communicating this because giving a raw breakdown would force the user to calculate the numbers in their head. This is also hidden by default to reduce clutter on the output visualization overall.
3	**Lifetime vehicle emissions equals:** Our re-unitization begins with comparisons to units that a user might be more familiar with than CO2e. We compare the vehicle's lifetime emissions to the emissions from X round-trip flights from SFO to NYC. We also show that the vehicle's lifetime emissions are equal to the carbon sequestering of X acres of U.S. forest over the vehicle's lifetime. We chose flights because it was another mode of transportation which brings both object familiarity and measure closeness to the topic. People commonly know that flying on a plane has high associated emissions, so comparing that to driving a car is relatable. On the other hand, carbon sequestration of forests is a measure that is well-known in the environmental sciences. We wanted to add a specific comparison for users who are familiar in this domain and are looking for an exact equivalency.
4	**Annual vehicle emissions equals:** Because conceptualizing the emissions of a vehicle over its entire life time which can be well over 10 years, we break this into a smaller increment – annual. Because the users input total years planned on driving, we are able to divide the lifetime emissions into average annual emissions. Here we are also able to use smaller units of measure that would have been too large for lifetime emissions. The units we chose were: emissions from X days of electricity use in an average American household and emissions from X pounds of beef from cattle raised from meat. Both of these units are familiar to the user and scales appropriately. We thought about a concrete measure such as charging a smartphone, running the washing machine, or powering AC – but the vehicle emission value is so large that than these units that the converted order of magnitude would be so large that it would be meaningless and unrealistic.

Equivalency Calculations:

Round trip plane from San Francisco to NYC	
Calculation	- In 2018, 88g CO_2/revenue-passenger-kilometer - Multiplier of 1.9 to account for the non-CO_2 climate effects of flying - Flight distance from SFO to JFK – 4,151.79 km (Round trip = 8303.58km) **1.9 x 88g CO_2/passenger-kilometer x 8303.58km/round trip flight x 1kg/1000g = 1388.26 kg CO_2/passenger/round trip flight**
Sources	Graver, Brandon et al. "CO2 emissions from commercial aviation, 2019." INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION, 2019. Web. "2018 GOVERNMENT GHG CONVERSION FACTORS FOR COMPANY REPORTING: Methodology paper for emission factors: final report, 2018." Department for Business, Energy, & Industrial Strategy, 2018. Web.

Acres of US forest sequestering carbon	
Calculation	- 206 metric tons of carbon stored per hectare → 0.57 metric tons of carbon sequestered per hectare per year (1 hectare = 2.47105 acres) → 0.23 metric ton C/acre/year - 44 units CO_2/12 units C - 0.23 metric ton C/acre/year x 44 units CO_2/12 units C = 0.84 metric ton CO_2/acre/year sequestered annually by one acre of average U.S. forest - Multiplied by years in vehicle lifetime for final calculation
Sources	https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Home electricity use per day	
Calculation	- 2019 US household average–11,880 kWh of delivered electricity per year - eGRID U.S. national annual average CO_2 output rate to convert kilowatt-hours of energy use into units of carbon dioxide emissions; counting transmission and distribution losses of 7.3% – 953.7 lbs CO_2 per megawatt-hour for delivered electricity - 4.33 × 10-4 metric tons CO_2/kWh - 11,880 kWh per home × 953.7 lbs CO_2 per megawatt-hour delivered × 1 MWh/1,000 kWh × 1 metric ton/2,204.6 lb = 5.139 metric tons CO_2/home/year - 5139 kg CO_2/home/year / 365 = 14.08 kg CO_2/home/year

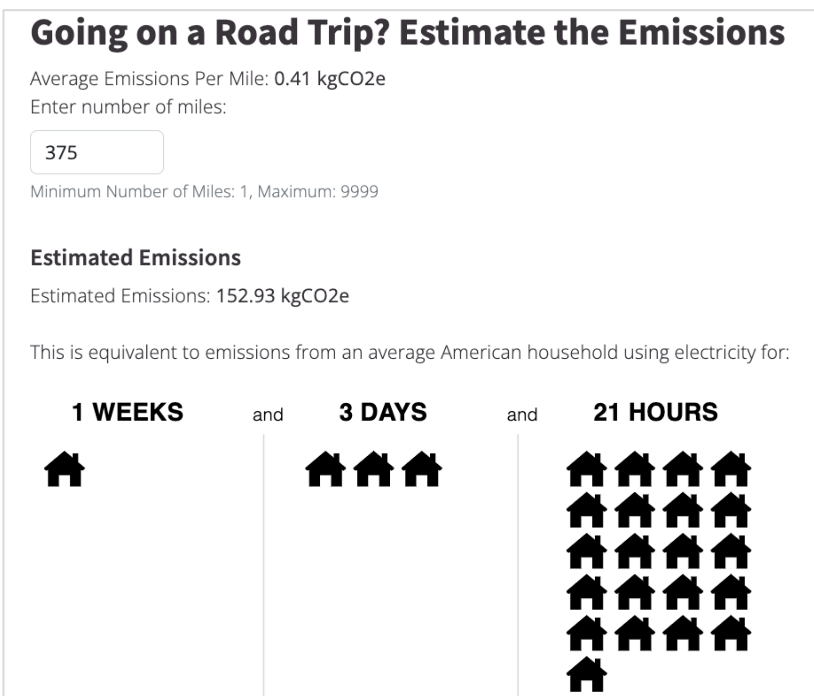
Sources	https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Pounds of Beef	
Calculation	- Global mean emissions of 1kg of beef from non-dairy beef herds (meaning the herds were raised for meat industry): 100 kg CO2e - 1lb = 0.453592kg - 100 kg CO2e / 1kg beef x 0.453592kg/1lb = 45.3592 kg CO2e / lb of beef
Sources	https://ourworldindata.org/carbon-footprint-food-methane

Road Trip Emissions Estimator

In addition to breaking the lifetime emissions into average annual emissions, we were also able to calculate the average emissions per mile. With this information, a user can see their specific vehicle's emissions based on how long their trip is. For example if a user wants to take a road trip from Berkeley, CA to Los Angeles, CA - they can see that the emissions from driving the car that distance is equal to the emissions of an American household using electricity for 1 week and nearly 4 days.

We thought that this would be an interesting way for users to conceptualize their vehicle's emissions by customizing the distance that their vehicle is driven - whether it be the distance to their grocery store, distance to work, or distance on a road trip they've been wanting to take.

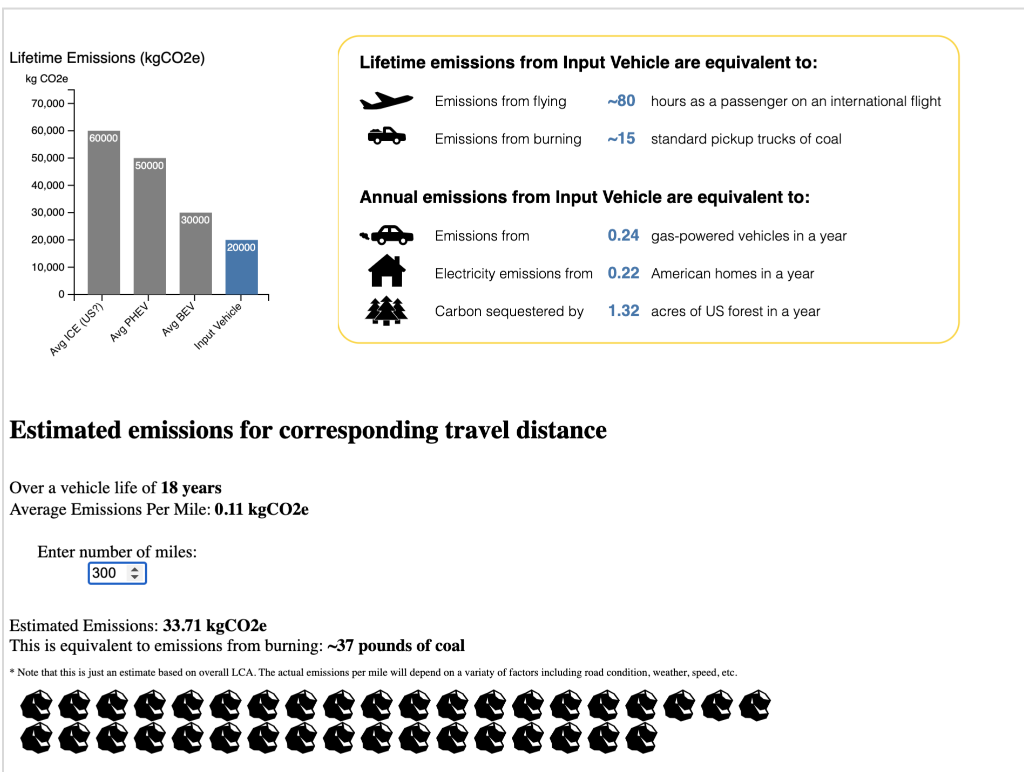


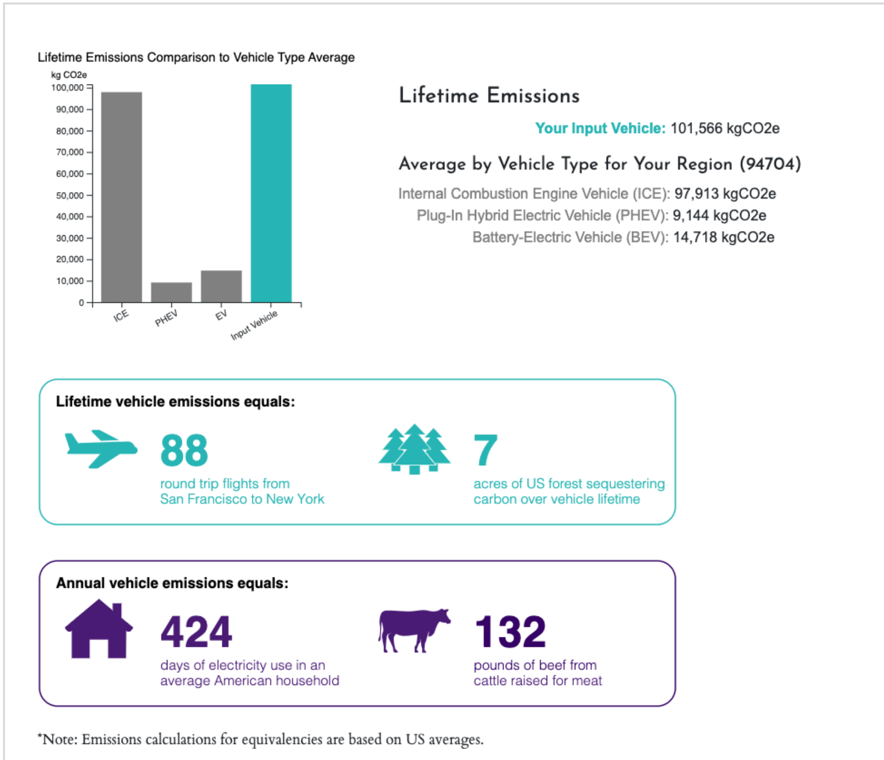
Going on a Road Trip? Estimate vehicle emissions based on number of miles driven.

Developing this calculator was difficult because we needed to find an appropriate unit that would scale a wide range and would still be realistic and relatable to the user. We thought about setting breakpoints throughout our range of miles and changing the unit of comparison depending on the breakpoint. For example, if the miles was less than 50 the unit comparison would be emissions from running a washing machine, but if the miles was over 5,000 the unit comparison would be emissions from hours of international flight. However, this was not a good idea because now the units of measure were not consistent.

Ultimately, we decided to use the emissions from an American household using electricity for a X amount of time. Here we could scale the amount of time to digestible categories like weeks, days, and hours. On a short trip, the vehicle's emissions are comparable to the emissions of a household's electricity for hours, while on a long trip, the vehicle's emissions may be more comparable to the emissions of a household's electricity for weeks.

Iterations:

Iterations of Output

This is the first iteration of our outputs. Here we had pounds of coal as our unit of comparison in our trip calculator. This was scalable because we could convert pounds of coal to bags of coal and pick-up trucks of coal. However, this unit is not well-known and it is difficult to conceptualize burning truckloads of coal. In addition, participants from usability testing were misinterpreting lifetime emissions and annual emissions and not recognizing the distinction.



In this iteration, we split the lifetime emissions and annual emissions into two separate boxes. But when shown to participants, they still were not able to correctly recognize that one was lifetime and the other is annual.
Additionally, under the raw value of lifetime vehicle emissions, we added the lifetime emissions values of the average vehicle types so users can examine the differences more closely. However, we found that this was not a useful addition and users would rather see the breakdown of their vehicle's lifetime emissions by life cycle phase.

V. Final Product Overview

A. Site Map

Our final deliverable is an information website split into 3 parts:

1. Emissions and Vehicle Life Cycle Emissions
2. Emissions Explorer Tool
3. Accessibility to Zero Emission Vehicles

<u>Emissions and Vehicle Life Cycle Emissions</u>

- Overview of emissions and transportation's contribution to overall emissions
- Alternative transportation options exist and are currently being pushed for
  - What is a zero-emission vehicle?
- All vehicles, including zero-emission vehicles, have associated emissions.
  - Introduction of vehicle lifetime emissions
  - Breakdown of vehicle lifetime emissions into stages:
    - Production Phase

        - Use Phase
        - End of Life Phase
    - Where do these emissions occur?
        - Direct and indirect emissions
- Emissions when fueling Zero-Emission Vehicles
    - While ZEVs have zero tailpipe emissions, there are associated emissions to generate electricity to charge these vehicles
    - What are the sources used to generate electricity?
    - Introduction of grid mix
- There are many ways to reduce transportation emissions
    - In addition to shifting towards clean energy generation and driving ZEVs. We can also
        - Drive less in general, choose to walk/bike/public transportation
        - Drive a smaller passenger, like a scooter or compact car

<u>Emissions Explorer Tool</u>

- What is Emissions Explorer
    - What are lifetime emissions?
    - What is estimated?
    - What data is used?
    - What makes our tool unique?
- Factors that affect the lifetime emissions of a vehicle
- Emissions Explorer Tool
    - Form
    - Outputs
        - Digestible outputs
        - Going on a Road Trip? Estimate Emissions by mile

<u>Accessibility to Zero Emission Vehicles</u>

- Transitioning to Zero Emission Vehicles is more complicated than people purchasing these vehicles. The infrastructure needs to be put in place to sustain ZEV usage.
- Stress to the electrical grid can hinder ZEV adoption
    - Extreme weather causes stress
        - Risk of wildfires and overuse of cooling during heat waves will limit electricity
        - Storms and severe winds can damage grid infrastructure limiting electricity
    - At-home charging causes stress
- Access to public charging can hinder ZEV adoption
    - Who needs public charging
    - Who currently has access to public charging? Who does not?
- Consumer choice can hinder ZEV adoption
    - Factors that affect vehicle choice
        - Cost of ownership
        - Societal factors
        - Psychological factors

B. Usability Testing

The purpose of usability testing was to understand the effectiveness of our visualizations and to test the ease of use and digestibility of our Emissions Explorer tool.

The information visualizations, both flat and interactive, on our website are placed throughout as a mode to explain and communicate concepts around lifetime emissions, sustainability of different types of vehicles, and accessibility of these vehicles and associated infrastructure. The goal of testing these visualizations was to ensure that information is presented effectively, clearly, and engaging.

Our primary goal of testing the Emissions Explorer tool was to test the effectiveness of our digestible outputs. Are users able to grasp the concept of the equivalencies used?

Overall, we wanted to answer the following questions. Does the visual hierarchy of our website make sense? Are users able to connect the different concepts of each page to each other?

<u>Screening Criteria:</u>

1. California residents
    a. We chose California residents because our project focuses on California specific topics such as energy infrastructure and policies passed around zero emissions vehicles.
2. Planning on purchasing a passenger vehicle in the next 2-3 years
    a. The target audience for this project are people who are planning on purchasing a new vehicle (brand new or used) in the next few years and want to better understand the types of vehicles available and the sustainability of internal combustion engines (ICEs) and zero emissions vehicles (ZEVs).

<u>Usability Test Procedure:</u>

This test procedure asks the participants to evaluate two parts:

1. Information visualizations
2. Emissions Explorer tool

Based on the time constraints of the participants, they would either complete both portions of the usability test or only the Emissions Explorer tool portion

1. Obtain consent from the participant and welcome them to the usability study.
2. Introduce the prototype and provide some background information about the topic to the participant.
    a. Our prototype focuses on emissions and the sustainability of passenger vehicles.
3. Begin the interview by asking the participant background questions including demographic questions, and their background knowledge in zero emissions vehicles.
4. Provide the participants with the instructions of how the usability study will be conducted as they explore the design.
    a. The participants will freely explore the design for 2-3 minutes and they will be directed to think aloud and explain their initial reactions.
    b. A deeper dive into 4 key visualizations will be conducted to test that they are effective. The participants will more closely interact with the visualizations, provide feedback, and be able to ask questions on the visualizations. They will then respond with what they have learned and the key takeaways they have from the visualization.
        i. Visualization #1: Explore Key Policies over Time
        ii. Visualization #2: Explore Associated Emissions at Different Phases of a Vehicle's Lifecycle

iii. Visualization #3: Sources of Electricity Generation
iv. Visualization #4: Factors that Affect Vehicle Lifetime Emissions - Year
c. Evaluation of the Emissions Explorer tool. We will test the ease and clarity of user inputs, and digestibility of the outputs.
5. Conclude the study with an interview consisting of wrap up questions. The participants will be asked for a summary of their takeaway from the prototype and any additional feedback they have for the design.

💡Read our Usability Test Script found in Appendix 2: **LINK**

Key Findings:
We had eight participants be a part of our usability tests. We gathered interesting observations from participants' interacting with the tool, learned about what parts of the website were most interesting, and finally caught errors on our visualizations to improve comprehension.

At the end of the usability test session, we asked the participants what their overall takeaway was, and a majority of participants discussed the complexity of vehicle emissions and factors that play into vehicle emissions. One participant said, “Although everyone knows that ‘cars are not good for the environment,’ there are a lot more intricacies that come into play”.

We were interested in seeing how participants interacted with the Emissions Explorer on their own. What vehicles did they choose to evaluate? Why did they pick that vehicle? What digestible outputs were interesting and relevant to them? We found that participants did not have a consensus of a single equivalency that made the most sense to them. Participants resonated with one particular output because of their background and lifestyle. For example, one of our participants said that the flight equivalency was most meaningful to them. However they said that having round trip flights to locked destinations made it more difficult to apply the emissions compared to their current travel behavior. They said: “I want to compare my vehicle lifetime emissions to my regular flight hours. To go home I fly an international 32 hour round trip. Domestic flights don’t mean much to me.” Another participant has a background in environmental science so the acres of US forest sequestering carbon make the most sense to them. They noted how this seemed somewhat actionable where they could spend money to reforest to offset their emissions. Finally, a participant, with an agricultural and environmental policy background, found the equivalency of emissions from pounds of beef to be the most interesting because of the novelty. They made a comment about how for someone who avoids meat for environmental purposes, this equivalency shows how the emissions from cars is far above the emission from producing meat.

When observing their behavior with the Emissions Explorer Tool, users chose to input 3 types of vehicles:
1. A vehicle they or someone in their family owns
2. A vehicle that they are interested in owning the future
3. The first vehicle on the dropdown list

Additionally, having more eyes on our visualizations and sites, we were able to catch many small visualization errors and learn where we needed to add more context. Some of the errors that we made note of and iterated upon included: labeling the line of the histogram that showed average, added context behind the radar charts, the ability for users to input negative numbers on the Emissions Explorer tool form, font being too small for flat and interactive visualizations, and not being able to tell that elements on the site were clickable/buttons.

Iterations of our visualizations can be found in our Visualization Walk-Through Section and iterations of our emissions explorer tool can be found in our Designing Digestible Outputs Section.

VI. Discussion

Future Work

While developing our Emissions Explorer model we gained a greater appreciation for the deep complexity involved with life cycle assessment and emissions estimates. While we are happy with our model results, and our validation has shown the Emissions Explorer model to be within range of literature values, there are many elements we plan to integrate in the future:

1. Time-dependent grid-mix
2. Cold-weather driving effects
3. Improved battery weight estimation

These factors will benefit the precision and granularity of the model, and also help to future-proof it.

Information Access

We began this project hoping to provide the first consumer-friendly tool to estimate vehicle emissions in a complete and accurate way. With our website and tool, we have made steps towards that goal. Since much life cycle assessment work is buried in government reports and academic papers, a key feature of this project involved performing the background research necessary to incorporate into our model. In doing so we hope we have made this information more digestible and therefore more impactful to a broader audience.

Reducing Vehicle Emissions

While the primary goal of our project was to investigate and model emissions from electric vehicles, our secondary goal was to help consumers understand how to reduce their emissions with any vehicle, regardless of type. As discussed in our website and illustrated through the Emissions Explorer, the most important factor influencing vehicle emissions is driving distance. By driving less and/or using alternatives such as bikes, scooters, or public transit, anyone can reduce their emissions, sometimes even drastically. Our model results show that while electric vehicles do have a large role to play in the transition to a more sustainable transportation system, "sustainability" is not directly or exclusively tied to "Electric Vehicles." Instead, a combination of factors– reducing dependence on fossil fuels, walking, biking, and riding public transport, purchasing smaller vehicles, and yes, switching to EVs– can all make a significant impact on consumer vehicle emissions. Embracing change in each of these areas, rather than focusing solely on any one, is required to meet the pressing demands of climate change.

VII. Acknowledgements

We would like to thank our usability test participants, iSchool peers, and iSchool faculty who provided feedback on our project.

We would like to specially thank our capstone advisor, Professor Marti Hearst, for advice and guidance on our project scope and design.

VIII. Works Cited

American Chemical Society (2022), "Lithium-Ion Battery Recycling: Overview of Techniques and Trends."
https://pubs.acs.org/doi/pdf/10.1021/acsenergylett.1c02602. ACS Energy Lett. 2022, 7, 712−719

Argue, Charlotte. "What 6,000 EV batteries tell us about EV battery health." Geotab, 2020. Web. https://www.geotab.com/blog/ev-battery-health/

Arun Tejasvi Chaganty, and Percy Liang. "How Much Is 131 Million Dollars? Putting Numbers in Perspective with Compositional Descriptions." arXiv.org. Ithaca: Cornell University Library, arXiv.org, 2016. Web.

Browning, Catherine Cronquist. "Why we need data science in the fight for climate justice." Berkeley Blog. University of California, Berkeley, 2019. Web.

Buberger, Johannes, et al. "Total CO2-Equivalent Life-Cycle Emissions from Commercially Available Passenger Cars." Renewable and Sustainable Energy Reviews, vol. 159, 2022, p. 112158., https://doi.org/10.1016/j.rser.2022.112158.

California Air Resources Board. (2018). CA-GREET3.0 Lookup Table Pathways. Technical Support Documentation.
https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/ca-greet/lut-doc.pdf

California Air Resources Board. (2021). Current California GHG Inventory Data. California Greenhouse Gas Emission Inventory Program. https://ww2.arb.ca.gov/ghg-inventory-data

California Air Resources Board. (2022-a, August 25). California moves to accelerate to 100% new zero-emission vehicle sales by 2035. Release Number 22-30. https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii

California Air Resources Board. (2022-b, May 13). States that have Adopted California's Vehicle Standards under Section 177 of the Federal Clean Air Act. https://ww2.arb.ca.gov/sites/default/files/2022-05/%C2%A7177_states_05132022_NADA_sales_r2_ac.pdf

California Energy Commission. (2022-a). 2021 Total System Electric Generation. https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2021-total-system-electric-generation

California Energy Commission. (2022-b). New ZEV Sales in California. Data last updated October 18, 2022. https://www.energy.ca.gov/zevstats

Chevalier, Fanny, Romain Vuillemot, and Guia Gali. "Using Concrete Scales: A Practical Framework for Effective Visual Depiction of Complex Measures." IEEE transactions on visualization and computer graphics 19.12 (2013): 2426–2435. Web.

Dunn, J. B., Gaines, L., Sullivan, J., & Wang, M. Q. (2012). Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive lithium-ion batteries. Environmental science & technology, 46(22), 12704-12710.

"Effects of Battery Manufacturing on Electric Vehicle Life-Cycle." ICCT, ICCT, https://theicct.org/sites/default/files/publications/EV-life-cycle-GHG_ICCT-Briefing_09022018_vF.pdf.

Hullman, Jessica et al. "Improving Comprehension of Measurements Using Concrete Re-Expression Strategies." Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. ACM, 2018. 1–12. Web.

"Hybrid Battery Repair, Replacement, and Reconditioning Services." Hybrid Battery Replacement and Repair - Best Hybrid Batteries, https://www.besthybridbatteries.com/.

International Energy Agency. (2019). Global EV Outlook 2019: Scaling up the transition to electric mobility. https://www.iea.org/publications/reports/globalevoutlook2019/

International Energy Agency. (2022). "Comparative Life-Cycle Greenhouse Gas Emissions of a Mid-Size BEV and Ice Vehicle – Charts – Data & Statistics." IEA, https://www.iea.org/data-and-statistics/charts/comparative-life-cycle-greenhouse-gas-emissions-of-a-mid-size-bev-and-ice-vehicle.

Jacoby, M. (2019) It's time to get serious about recycling lithium-ion batteries. Chemical and Engineering News. (2019) Vol.97-28.

Nealer, R., Reichmuth, D., and Anair, D. (2015) Cleaner Cars from Cradle to Grave: How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions, Union of Concerned Scientists. https://www.ucsusa.org/sites/default/files/attach/2015/11/Cleaner-Cars-from-Cradle-to-Grave-full-report.pdf

Penn, I. (2022, September 25). Dodging blackouts, California faces new questions on its power supply. The New York Times. Retrieved November 18, 2022, from https://www.nytimes.com/2022/09/25/business/energy-environment/california-energy-grid-heat.html

Peters, Jens F., et al. "The Environmental Impact of Li-Ion Batteries and the Role of Key Parameters – a Review." Renewable and Sustainable Energy Reviews, vol. 67, 2017, pp. 491–506., https://doi.org/10.1016/j.rser.2016.08.039.

Schraufnagel, D. E. et al. (2019). Air pollution and noncommunicable diseases: A review by the Forum of International Respiratory Societies' Environmental Committee, Part 2: Air pollution and organ systems. Chest, 155(2), 417-426.

Stapler, R. (2022, September 16). Governor Newsom signs the clean energy, jobs, and Affordability Act of 2022. Senate District 17. Retrieved November 18, 2022, from https://sd17.senate.ca.gov/news/governor-newsom-signs-clean-energy-jobs-and-affordability-act-2022

"The EPA Automotive 2022 Trends Report." EPA Automotive Trends Report, EPA, https://www.epa.gov/system/files/documents/2022-12/420s22001.pdf.

U.S. Department of Energy. (2022-a). Electric Vehicle Chargers in California. Alternative Fuels Data Center. https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/electric-vehicle

U.S. Department of Energy. (2022-b). TransAtlas. Alternative Fuels Data Center. https://afdc.energy.gov/transatlas/#/?state=CA&view=percent&fuel=ELEC

U.S. Energy Information Administration. (2022-a, March 17). California State Profile and Energy Estimates. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php

U.S. Energy Information Administration. (2022-b). Electricity in the United States is produced (generated) with diverse energy sources and technologies. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php

U.S. Energy Information Administration. (2022-c). How much carbon dioxide is produced per kilowatthour of U.S. electricity generation?. https://www.eia.gov/tools/faqs/faq.php?id=74&t=11

U.S. Environmental Protection Agency. (2022-a, April 14). Inventory of U.S. Greenhouse Gas Emissions and Sinks. Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

U.S. Environmental Protection Agency. (2022-b, June 29). Light Duty Vehicle Emissions. Green Vehicle Guide.https://www.epa.gov/greenvehicles/light-duty-vehicle-emissions

U.S. Environmental Protection Agency. (2022-c, August 5). Sources of Greenhouse Gas Emissions. Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Verma, Shrey, Gaurav Dwivedi, and Puneet Verma. “Life Cycle Assessment of Electric Vehicles in Comparison to Combustion Engine Vehicles: A Review.” Materials Today : Proceedings. Vol. 49. Elsevier Ltd, 2022. 217–222. Web.

Wilson, Lindsay. (2022) Shades of Green: Electric Car Emissions – 2022, Shrink that Footprint. https://shrinkthatfootprint.com/electric-car-emissions/

IX. Appendices

A. Appendix 1: Table of Reports and Documents outside this Report

Document Name	Hyperlink
Literature Review and Background Research	**LINK**
Analysis of Existing Tools	**LINK**
Usability Testing Raw Notes	**LINK**

B. Appendix 2: Usability Testing Script

Usability Testing Script

- Introduction to the project
  - This project focuses on exploring the sustainability of electric vehicles (EV) and factors that contribute to the vehicles’ environmental impact.
- Introduction Questions
  - Demographic information has already been collected from the screening process.
  - As someone who is interested in purchasing a car in the next few years, what factors into your decision making process?

        - Who are the players (family, friends, online resources) that would affect your decision making?
        - Was there any information that you wanted but couldn't find?
    - PRE: What factors into the sustainability of a vehicle?
    - How did you weigh sustainability in your decision making process?
        - 1 – Not at all important
        - 2 – Low importance
        - 3 – Slightly important
        - 4 – Neutral
        - 5 – Moderately important
        - 6 – Very important
        - 7 – Extremely important
- Instructions
    - We want your feedback on this design so:
        - Think out loud
        - Explain your initial reactions, what you are thinking, what are you drawn towards.
        - This could sound like "The first thing my eyes are drawn to is X because of X" or "I am not sure why this X is here, do I click on it?".
    - Your feedback both positive and negative are important to ensuring that this design is understandable for anyone who visits.
    - Since we are familiar with the designs and content of this project, it is key for us to have new eyes to catch aspects that we may have overlooked.
    - This is how our usability testing session with go:
        - First, you will have a chance to review the design on your own. Feel free to interact with anything you are drawn to. We will not be directing you on this task. This is a chance for us to capture your first impressions.
        - Second, we will walk you through specific visualizations on our design and ask you more specific questions.
        - Finally, we will conclude with a summary and gather your overall feedback.
- Visualizations
    - Steps of the Usability Test – Visualizations
        - Explore: participants will have about 3-5 minutes to explore the page.
            - Goal: gather initial reactions, catch any critical design errors, observe what attracts their attention and why
        - Diving Deeper into Visualizations:
            - Initial Exploration of Visualizations
                - Goal: gather initial reactions, catch any critical design errors, observe what attracts their attention and why
            - Visualization 1: Explore Key Policies over Time
                - What is this visualization telling you?
                - What is a key takeaway that you have from this visualization?
            - Visualization 2: Explore Associated Emissions at Different Phases of a Vehicle's Lifecycle
            - Visualization 3: Sources of Electricity Generation
            - Visualization 4: Factors that Affect Vehicle Lifetime Emissions - Year
    - Takeaways – Visualizations

    - What are one or two takeaways that you have from these visualizations?
    - Which visualization stood out to you the most and why?
    - Is there anything you think is missing from the visualizations?
    - Who do you think this visualization would be most helpful for?
- Emissions Explorer Tool
  - Explore: participants will have about 3-5 minutes to explore the tool.
    - Similar to exploration of the visualizations. Are there any critical design errors, what is attracting their attention? What types of vehicles are they inputting into the tool?
  - Diving Deeper into the Tool:
    - Input
      - What vehicle did you submit in the form?
      - Why did you choose that vehicle?
    - Output
      - What are the inputs telling you?
      - What is the primary takeaway of these outputs?
      - Which output stood out the most to you and why?
  - Takeaways – Tool
    - What are one or two takeaways that you have from the tool?
    - Who do you think this tool would be most helpful for?
- Conclusion
  - Wrap Up Questions
    - Visualizations
      - Which visualization stood out to you the most and why?
      - Is there anything you think is missing from the visualizations?
      - Who do you think this visualization would be most helpful for?
    - Can you summarize in one sentence what this prototype is about?
    - POST: What factors into the sustainability of a vehicle?