SCHOOL OF SUSTAINABLE ENGINEERING AND THE BUILT ENVIRONMENT

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California High Speed Resilience to Climate Change

Elizabeth Barnes

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LCA Project: California High Speed Resilience to Climate Change

Elizabeth Barnes

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Executive Summary:

This LCA used data from a previous LCA done by Chester and Horvath (2012) on the proposed California High Speed Rail, and furthered the LCA to look into potential changes that can be made to the proposed CAHSR to be more resilient to climate change. This LCA focused on the energy, cost, and GHG emissions associated with raising the track, adding fly ash to the concrete mixture in place of a percentage of cement, and running the HSR on solar electricity rather than the current electricity mix.

Data was collected from a variety of sources including other LCAs, research studies, feasibility studies, and project information from companies, agencies, and researchers in order to determine what the cost, energy requirements, and associated GHG emissions would be for each of these changes. This data was then used to calculate results of cost, energy, and GHG emissions for the three different changes.

The results show that the greatest source of cost is the raised track (Design/Construction Phase), and the greatest source of GHG emissions is the concrete (also Design/Construction Phase). This is because raising track is very costly, estimated at about $247 million per mile, and the cement in the concrete accounts for 75% of the GHG emissions. However, the GHG emissions would be even greater if 100% cement was used in the concrete mixture. By substituting 25% of the cement with fly ash, the GHG emissions were reduced by 15%, or the equivalent of consuming about 2 million gallons of gasoline. Substituting in fly ash for cement also decreases the cost of cement by about 15%, or almost $2 million.

Another major result within the LCA was the fact that solar was slightly cheaper than the current electricity mix by about $80 per trip, which was not expected. Although $80 is a small difference, this difference does add up in the long run. The reason solar is slightly cheaper is because it is subsidized, but the cost is steadily decreasing with increased performance in solar technologies. All solar electricity, as expected, had much less associated GHG emissions than the current electricity mix.

This LCA showed that fly ash as a substitute for cement and renewable energy to power the HSR would be the most feasible options for making the CAHSR more resilient to climate change. Further research into increasing the amount of fly ash that can be substituted for cement and other renewable energy sources would be the most beneficial to this project. Fly ash and renewable energy both had major impacts on decreasing the amount of GHG emissions associated with the project during both phases, and fly ash also contributed to decreasing costs during just the design/construction phase.

Introduction:

The high population of California has lead to transportation within cities and between cities to be a difficult and time consuming process, which is why there has been a proposal to construct high speed rail (HSR) in California between the major cities. The proposed line will eventually run from San Diego to Sacramento with stops in other major cities like Los Angeles and San Francisco. This has been done in other high population areas like Europe and East Asia for quicker and/or easier transportation between cities as well as for reducing air pollution and greenhouse gas emissions. With climate change set to cause some serious consequences in California like extreme precipitation during shorter periods of time, increased wildfires, higher temperatures, and flooding due to sea level rise, new and existing infrastructure should be modified to be resilient to these consequences.

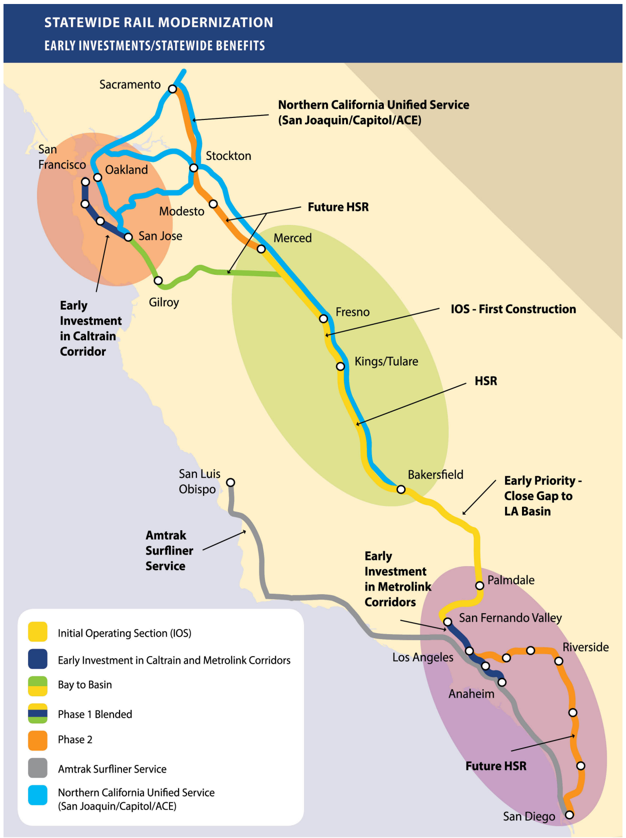


Figure 1: Map of Proposed CAHSR

This attributional LCA looks at what changes can be made to the proposed HSR line's track and energy infrastructure in California, as well as the cost and energy required to implement these changes and the greenhouse gas emissions that will be avoided by implementing these changes.

The changes that were looked at in this LCA were: raising the HSR track, using fly ash in place of concrete, and switching from the current electricity mix in California to all solar. Raising the HSR track was looked into because it is the easiest solution to flooding at this time since the project is just proposed and is not being constructed yet. Raised track is usually utilized in large cities, especially those by large bodies of water, because it allows for existing development below the track to stay in that area. Fly ash is becoming more popular as a substitute for cement in concrete due to the lower GHG emissions associated with the product, and the lack of processing needed since it is a byproduct of burning coal and not a virgin material. In this LCA, this change could potentially decrease the amount of GHG emissions associated with this project, which will in turn help with efforts to stop climate change. The current electricity mix in California is not only high in GHG emissions, but is also at risk every year when wildfire season occurs. By switching to solar, there is the possibility of decreased GHG emissions (which helps with the growing concern of climate change), as well as another option for electricity when wildfires can potentially put the current electricity at risk for blackouts. Solar was chosen since it is greatly improving each year, and California has the perfect climate for reliable solar electricity.

The system boundary of this project is the geographical boundary of California. Obviously the entire track is located in the state of California, but it is assumed that the electricity needed to power the HSR will also be included in the state of California. Only changes made to the infrastructure systems during the Design/Construction and Maintenance/Use phases will be taken into account. The functional unit of this LCA is miles of usable HSR track.

Methodology:

The focus of this LCA is to calculate the cost and energy associated with implementing raised track, using fly ash, and switching to solar energy as well as the greenhouse gas emissions avoided by making these changes during the Design/Construction phase or Use phase. This LCA is based mostly on the work done in Chester and Horvath's CAHSR LCA of 2012, but data was also found from other LCAs regarding information on energy and concrete, feasibility studies, and research and government sources.

Data from Chester and Horvath's article (2012) was the starter for this LCA, and helped with basic information on the proposed CAHSR along with information on electricity needs and concrete. Their LCA was mostly used to look further into energy use for the HSR since it gave information on electricity requirements for different sizes of trains. This LCA will assume the future train will be 1200 seats, which has an electricity requirement of 36 kWh/VKT. This data was used to determine what the electricity requirements would be for the entire HSR line, as well as the differences in greenhouse gas emissions between the current electricity mix and solar electricity running the HSR line.

With the knowledge of the electricity requirements of the train, the actual electricity mix of California is necessary, as well as data on solar electricity. The Energy Almanac (n.d.), run by the California Energy Commission, has data on the current system in California. This data was used to determine the current electricity mix, and apply it to the HSR project. The mix was given as a breakdown of electricity sources as percentage of the total system, so it was assumed that the HSR would run on that same mix. Next, the cost of the current energy mix was determined by using the average cost of electricity for the transportation sector, as determined by the U.S. Energy Information Administration (2014). This was given in cost per kilowatt-hour. In order to determine the cost of solar energy, data from SRP (n.d.) on commercial solar electric systems and data from Go Solar California (2014), run by the California Energy Commission and California Public Utilities Commission, was used. This data was also given in cost per kilowatt-hour. Since the electricity need to power the HSR line is known from Chester and Horvath's LCA (2012), this data was used to determine the cost for the current electricity mix as well as all solar.

Data on greenhouse gas emissions (GHG) was acquired from the Intergovernmental Panel on Climate Change (IPCC) (2011) and the National Renewable Energy Laboratory (NREL) (n.d.), under the Department of Energy. Specifically, the IPCC report gave information on all electricity sources, and the NREL report gave information on solar energy. Each report has data on GHG emissions as g CO_2 eq/kWh. This data was used alongside the electricity data from Chester and Horvath's LCA and the California Energy Commission to determine the GHG emissions associated with each electricity source.

In order to show the extreme outcome, the maximum GHG emissions possible from the data was used in this analysis.

Cal-Adapt (2014) is another resource that was utilized in this LCA. This site combines data from numerous research units and government agencies on sea level rise, precipitation, wildfires, and temperatures to show impacts on the entire state of California. This site uses data from the U.S. Geological Survey (USGS) and the Pacific Institute on sea level, which was used in this LCA to determine how much track would need to be raised, and in what areas. This data is available for GIS as well as Google Earth. In this LCA, both applications were used to map out what sections were at risk of flooding from sea level rise. Although there is potential flooding in both Southern and Northern California, the HSR is only at risk for flooding in the San Francisco Bay Area. This is because the HSR starts inland in Southern California and will not be affected by sea level rise according to the future models. Data on raised track was gathered from public data on proposed HSR or other train transit projects in and around the US, including a project proposed in Canada (TransLink, 2013) and a project proposed in Hawaii (Light Rail Now, 2010). Future projects were preferable since those projects took into account future costs, and the location had to be close enough to California for the costs to be similar.

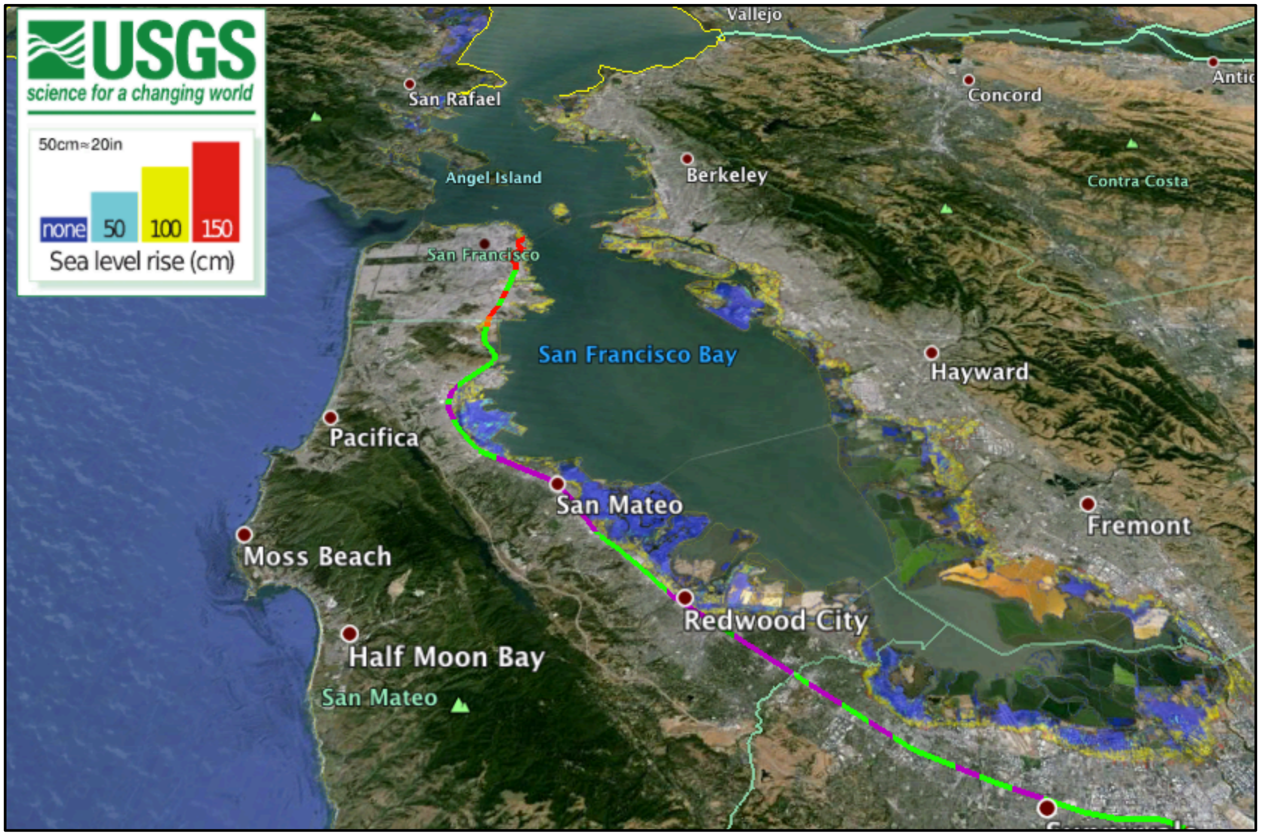


Figure 2: Google Earth Map – USGS sea level rise data and proposed CAHSR

Different resources were used to determine the cost, energy, and GHG emissions associated with cement and fly ash. First off, the amount of cement and fly ash had to be determined. Rocla Concrete Tie, Inc. (n.d.) sells concrete ties specifically for HSR, so the dimensions of these concrete ties were used to determine the amount of concrete, cement, and fly ash needed for the entire 800 miles of track. Cement was assumed to be 15% of the mix (maximum amount of cement in most mixes), and fly ash was assumed to replace 25% of the cement in the mix (also a maximum specification in most states). A study done by Perkins + Will (n.d.) was used to determine GHG emissions for each material, given in kg CO_2 eq/ton, and another study done by the EPA was also consulted for this information. A study done by the Transportation Development Foundation (2011) had national average data on cost per ton of cement and fly ash, so that was used to determine the cost of all 800 miles of track with just cement and with a combination of cement and fly ash. The embodied energy of cement and fly ash needed for the project was determined through data from a study for the World of Coal Ash Conference (2011).

Preliminary Data and Calculations:

The following preliminary data was used for calculations in Excel. Some calculations are shown below; additional calculations are in Appendix A. The results of these calculations follow in the "Results" section as charts and tables.

While many projects were found with raised tracks, two projects were the most related to this proposed project – one in Hawaii and one in Vancouver. Both are not completed, and both are occurring in cities known for a higher cost of living, which leads to higher construction costs. The two costs from these projects were averaged to reach the $247 million per mile used for this project. Using GIS and Google Earth, the length of the track that would need to be raised it about 28 miles. The value was rounded to account for error and to make it a whole number that is easier to work with during calculations and discussion. One trip is equal to 800 miles.

	Current electricity mix	**All solar**
Electricity required (one trip) in kWh	46,368	46,368
Electricity required in MJ	166,925	166,925
Cost per kWh	7.97 cents	7.8 cents

Table 1: Current electricity and solar costs

Sample Calculation of cost of electricity: 46,368 kWh * $0.0797/kWh = **$3,695.53**

Electricity Type	**Percent**	**kWh**	**GHG emissions (kg CO_2eq/kWh)**
Coal	7.50%	3477.6	1.689
Hydro	8.53%	3955.1904	0.043
Natural Gas	43.40%	20123.712	0.930
Nuclear	9.00%	4173.12	0.220
Biomass	0.35%	162.288	0.075
Geothermal	0.68%	315.3024	0.079
Solar	0.14%	64.9152	0.089
Wind	0.97%	449.7696	0.081
Unspec. (assume oil)	16.40%	7604.352	1.170

Table 2: Current electricity mix breakdown

Calculation of GHG emissions of current electricity mix =

(3477.6*1.689)+(3955*0.043)+(20124*0.93)+(4173*0.22)+(162*0.075)+(315*0.079)+(65*0.089)+(450*0.081)+(7604*1.170) = **34,653.26 kg CO_2 eq**

	All cement	Fly Ash (25%)	Cement (75%)
Weight (tons)	140,026	35,007	105,019
Weight (kg)	127,029,487	31,757,826	95,271,662

Table 3: Amount of cement and fly ash required

	Cement	Fly Ash
Cost per ton	$92	$40
GHG emissions (kg CO_2eq/ton)	844	336
Embodied energy (MJ/ton)	3900	31

Table 4: Comparison between cement and fly ash

Calculation of 100% cement cost = (140,026 tons)*($92/ton) = **$12,882,392**

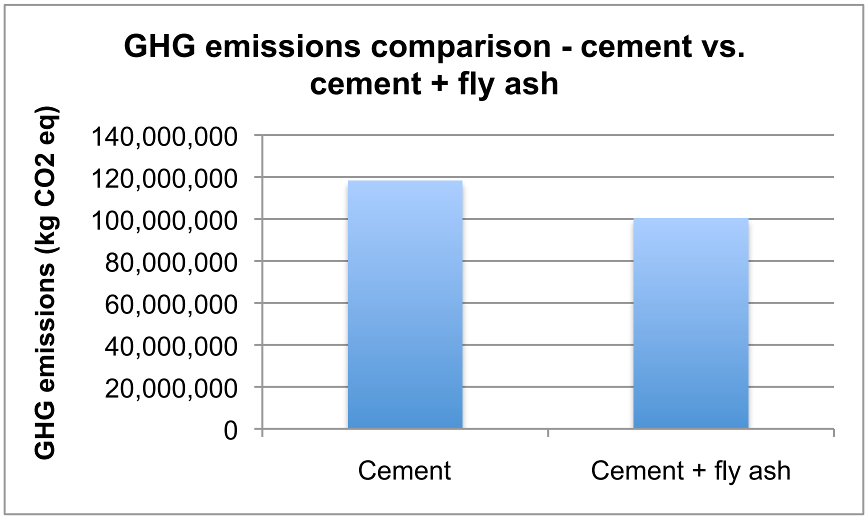
Calculation of 100% cement GHG emissions = (140,026 tons)*(844 kg CO_2 eq/ton) = **118,137,226 kg CO_2eq**

Calculation of 100% cement embodied energy = (140,026 tons)*(3900 MJ/ton) = **546,101,400 MJ**

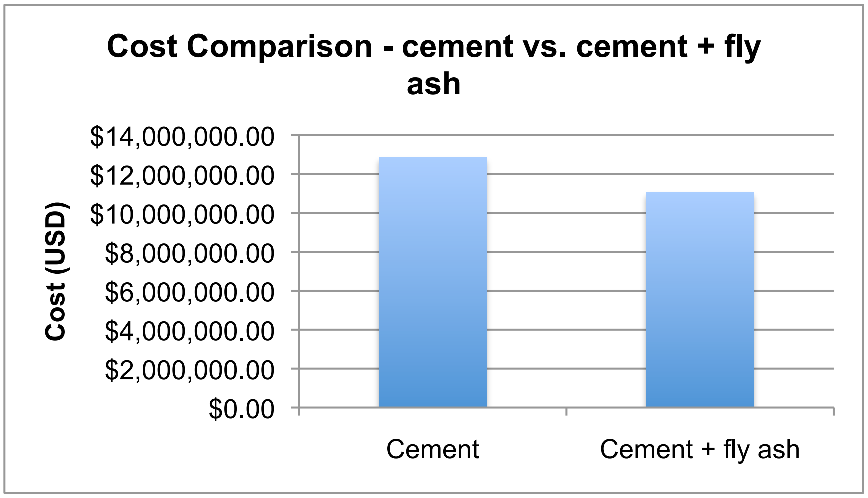
Results:

The data from Tables 3 and 4 were used in calculations to get the results in Graphs 1, 2, and 3.

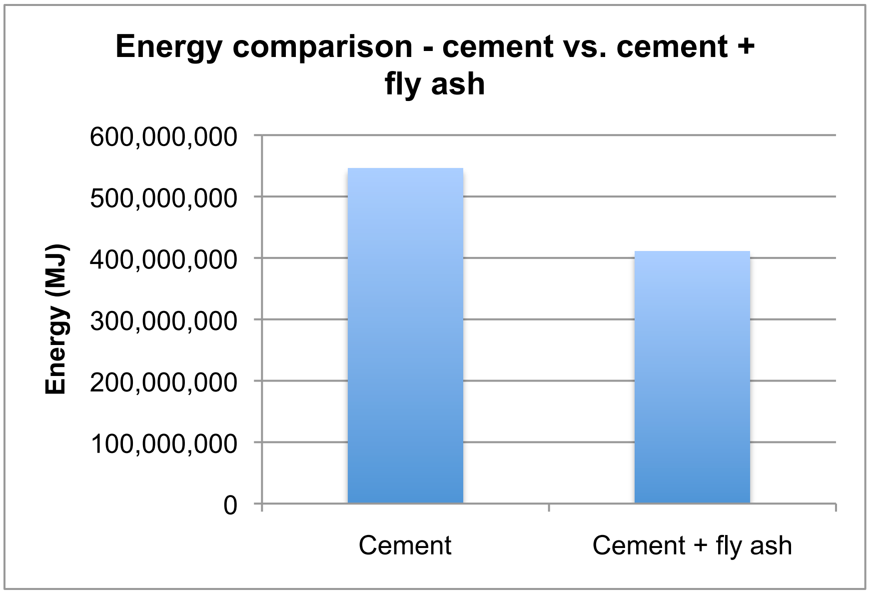
Graph 1: GHG emissions comparison – cement vs. cement +fly ash



Graph 2: Cost comparison – cement vs. cement + fly ash



Graph 3: Embodied energy comparison – cement vs. cement +fly ash



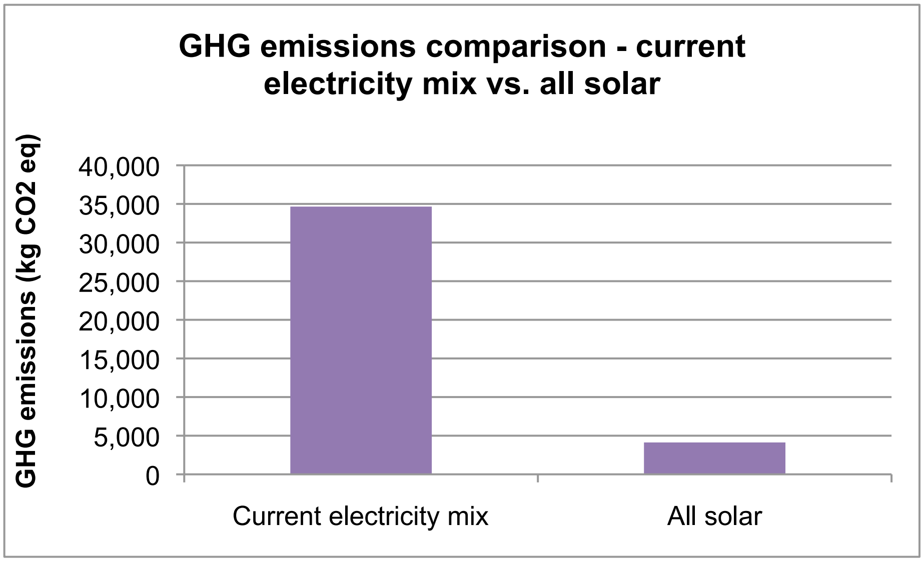
	GHG Emissions (kg CO_2eq)	Cost ($)	Energy (MJ)
Cement	118,137,226	$12,882,392	546,101,400
Cement + fly ash	100,416,642	$11,062,028	410,659,317

Table 5: Summary of results for Cement and Cement +Fly Ash

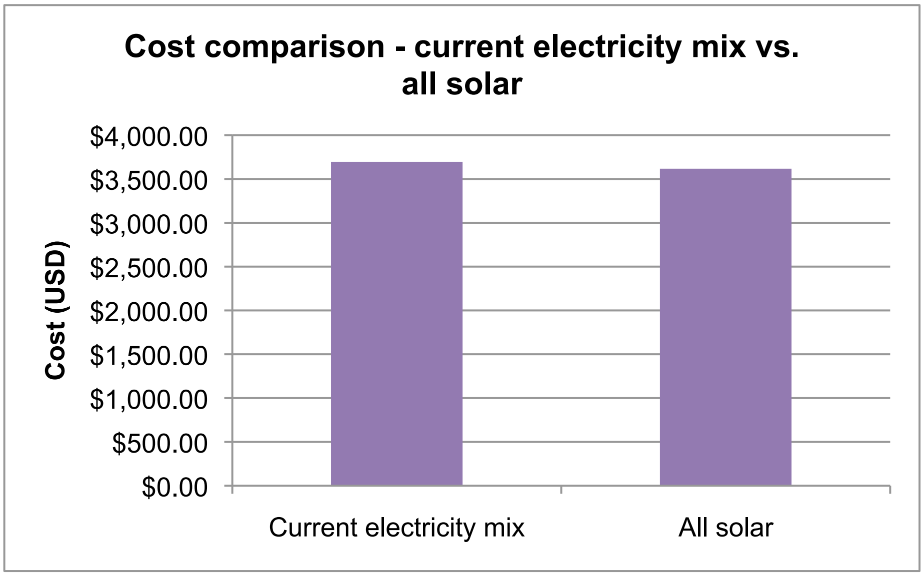
There is about a 15% decrease in GHG emissions, a 15% decrease in cost, and a 25% decrease in embodied energy when fly ash replaces 25% of the cement in the concrete mix.

The data from Tables 1 and 2 were used in calculations to get the results in Graphs 4 and 5.

Graph 4: GHG emissions comparison – current electricity vs. solar



Graph 5: Cost comparison – current electricity vs. solar



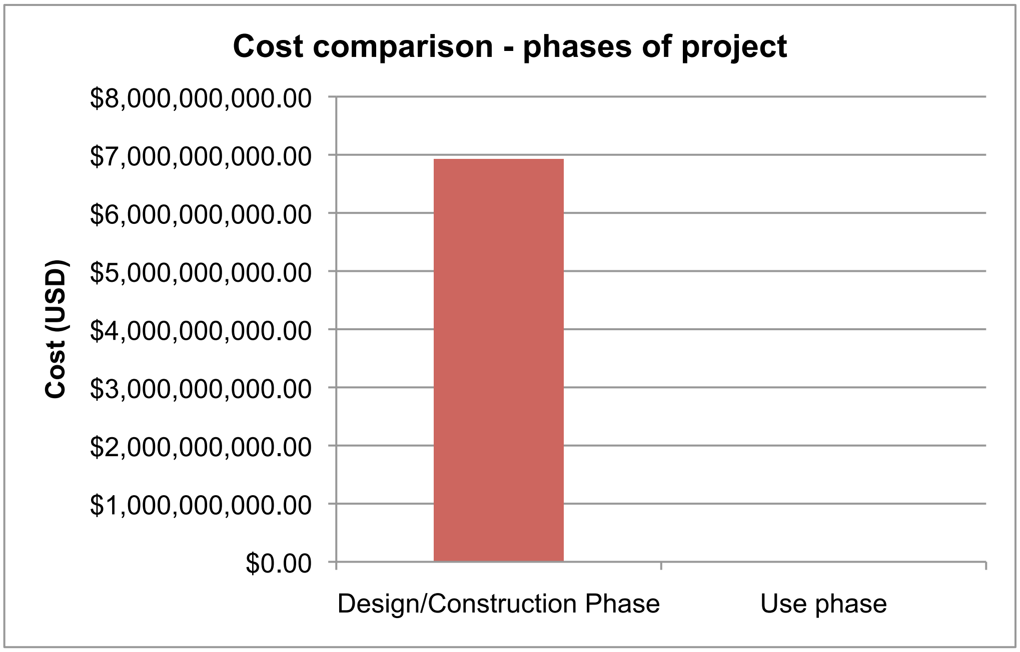
	GHG emissions (kg CO_2eq)	Cost ($)
Current electricity mix	34,653.26	$3,695.53
All solar	4,126.75	$3,616.70

Table 6: Summary of results for current electricity vs. solar

There is about an 88% decrease in GHG emissions, and only about a 2% decrease in cost when switching from the current electricity mix to all solar.

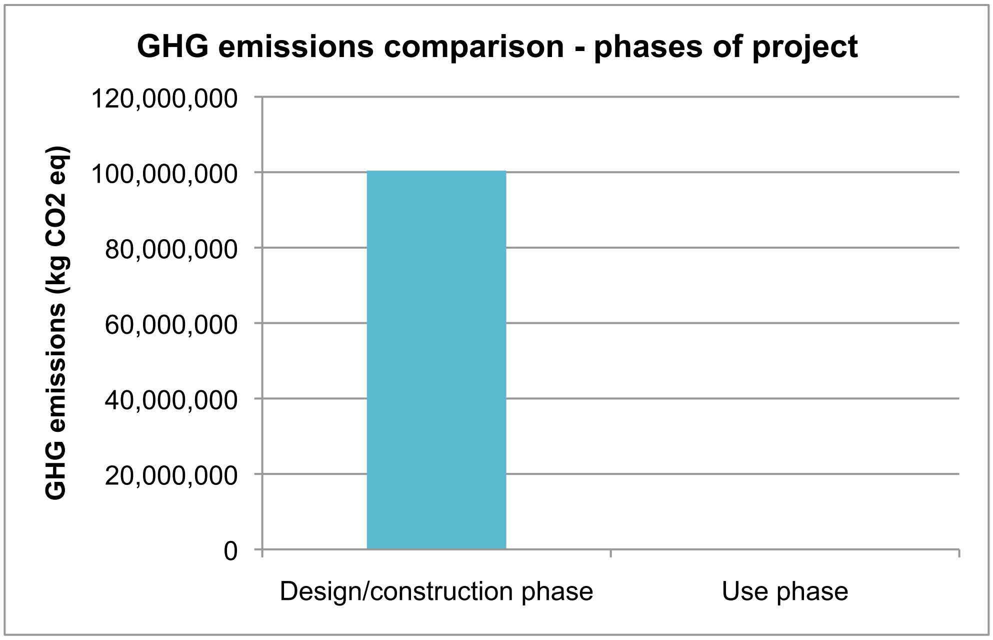
Graphs 6 and 7 combine data from the previous tables and graphs. Design/Construction phase includes raising the track and cement with fly ash, while the Use phase only includes electricity (all solar). These graphs only show the changes, not the current state.

Graph 6: Cost comparison between two phases of project



Only the cost of raising the track is seen in Graph 6 since the cost of cement and fly ash is very small compared to the cost of raising the track. The cost of electricity is also not visible since it is also much smaller than the cost of raising the track.

Graph 7: GHG emissions comparison between two phases of project



Only the GHG emissions associated with the cement and fly ash is shown because solar electricity has very little associated GHG emissions compared to the cement and fly ash.

	Design/construction phase	**Use phase**
Cost ($)	$6,925,276,705	$3,616.70
GHG emissions (kg CO_2eq)	100,416,642	4,126.75

Table 7: Summary of results between two phases

There is a difference of $6,925,273,088 between the two phases in terms of cost, and a difference of 100,412,525.3 kg CO_2 eq between the two phases in terms of GHG emissions.

Discussion:

First off, Graphs 6 and 7 show that changes made during design/construction like switching to cement and fly ash and raising track really dominate the cost and GHG emissions associated with making all these changes to make the HSR more resilient to climate change. Within that, cost is dominated by raising track, which makes sense since the estimated cost is about $247 million per mile. However, the GHG emissions are dominated by the cement and fly ash, with most of the emissions from cement. This makes sense since cement is only about 15% of the concrete mixture, but accounts for as much as 75% of the associated GHG emissions. By including fly ash in the mixture, there is a reduction in GHG emissions of 15%, which is equivalent to taking almost 4,000 passenger vehicles off the road or not consuming almost 2 million gallons of gasoline. So, switching to just 25% fly ash is very impactful considering the consequences of just using cement in this project would be even greater.

In terms of the cost of 100% cement versus 75% cement and 25% fly ash, it was expected that cost would decrease since fly ash costs almost 60% less per ton than cement. Embodied energy also decreased as expected since cement is a virgin material that required a lot of processing whereas fly ash is a byproduct.

Looking at the results of comparing the current electricity mix and all solar electricity, it is not a shock that GHG emissions decrease since solar is known to have much less GHG emissions associated with it since there is no combustion occurring like with gasoline. A decrease in 30,526.51 kg CO_2eq means that each trip the HSR takes on all solar electricity is equivalent to taking about 7 passenger vehicles off the road or not consuming almost 3,500 gallons of gasoline. The major result when looking at current electricity and solar is that solar actually costs less than the current electricity mix. It is only by about $80 per trip, but that does add up in the long run. This decrease in cost is mostly due to subsidies in place for solar electricity, and the assumption that solar will eventually get cheaper without the help of subsidies as it continues to improve.

Based on these results, making the HSR resilient to climate change will be costly, but planning for these costs in advance is easier than trying to make these changes farther down the road when it is being constructed or is completely finished. The major takeaway from these results is that at full capacity, this HSR will decrease the amount GHG emissions from transit because people will switch from driving their personal vehicles, or even flying between these cities to taking the HSR. Plus, by making the proposed changes to electricity and concrete, GHG emissions related to the project will be decreased even more.

Conclusions:

There is some uncertainty associated with these results especially from the data and assumptions made about the data. All data was secondary, tertiary, etc. because the data was either taken from an agency or study that gathered the data or from a study that gathered the data from other studies and so on. Therefore, the data might not be completely correct, or might not be correct for this type of project in this location. Although some data was specific to California, most was not, so there could be error related to the location. California likely won't be at the national average for any data point, so using an average value could not represent this situation properly. A lot of the data used in calculations was assuming the extreme situation – maximum 15% cement, maximum 25% fly ash, maximum GHG emissions for type of electricity, etc. This was so the project can be planned for the worse possible scenario rather than the average scenario, with a chance that the effects could be worse than average. A major part of uncertainty stems from the future models that predict sea level rise and other consequences of climate change. These models were used to show the areas of the HSR at risk, but if they are not correct, this means there could be errors with calculating how much track would need to be raised.

Solar electricity was assumed to be coming from a tower or trough power plant instead of PV panels. This is because PV currently has more GHG emissions associated and there are issues with storing energy produced at a solar PV power plant compared to a tower or trough power plant. Another assumption made during this project was assuming the "Unspecified" electricity source (shown in Table 2) was oil. This is because things that are powered by some type of oil are the least likely to be specified when asking an owner of a building. Since this section was fairly large compared to the rest of the electricity sources, the fact that it was assumed to be oil made a large impact on the GHG emissions associated with the current electricity mix. Another assumption made was that the cost to raise track would be close to the cost to raise track in Hawaii and Vancouver. Since these areas are known for higher costs in general, it was a safe bet that transit built in California would also be as expensive as these areas. Vancouver and Hawaii also have limited land in the major parts of the cities, much like the major cities in California (most of which the HSR would stop in). An average between the two projects was used in this LCA, but the cost could change depending on inflation, cost of concrete, cost of land needed for the track foundations, etc. Since this project is only in the proposal stage, any of these costs could change and affect the cost of raising track.

Based on the above results, fly ash should definitely be used when using concrete as a building material since it is helpful in decreasing GHG emissions and cost during the entirety of the project, but especially in the design/construction phase. More research could also go into increasing the amount of fly ash substituted in place of cement in order to decrease costs and GHG emissions even further. Research on renewable energy powering the HSR would also be useful considering solar is also very beneficial to decreasing costs and GHG emissions during the use phase of the project. A mixture of renewable energy could lead to even less cost and/or GHG emissions depending on how far renewable energy technology goes over the next few years. Raising track is obviously a very costly part of the project, but it is also not really part of the project that can be ignored. With rising sea levels expected all along the coast of California, the HSR is at risk especially in the San Francisco Bay Area since there is a chance of sea levels rising up to 5 feet in that area. Other options like retaining walls could be researched further in order to determine which option is more feasible cost-wise and risk-wise. Another issue that was not looked into is the potential for flooding inland (rivers, streams, etc.) due to rising sea level rise. This would likely lead to raising more than 28 miles of track, which would increase the project cost by much more. Overall, the major recommendations as a result of this LCA would be to use more fly ash as a substitute of cement, and to look into renewable energy powering the CAHSR.

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Appendix A: Additional Calculations

kWh/VKT to kWh: 36 kWh/VKT (1 VKT/0.62 VMT) = 57.94 kWh/VMT * 800 miles = **46,368 kWh**

Cost of 75% cement and 25% fly ash = (35,007 tons fly ash)($40/ton) + (105,019 tons cement)($92/ton) = **$11,062,028.00**

GHG Emissions of 75% cement and 25% fly ash = (35,007 tons fly ash)(336 kg CO_2eq/ton) + (105,019 tons cement)(844 kg CO_2eq/ton) = **100,416,642 kg CO_2 eq**

Embodied Energy of 75% cement and 25% fly ash = (35,007 tons fly ash)(31 MJ/ton) + (105,019 tons cement)(3900 MJ/ton) = **410,659,317 MJ**