Research Statement

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The global challenge of climate change requires a fast, large-scale transition to low-carbon, sustainable, and environmentally just energy systems. The goal of my research is to contribute feasible solutions to this challenge. My doctoral research in energy science and engineering aims to design zero-emission energy systems that improve air quality and affordability while ensuring environmentally just outcomes. Of special interest is decarbonizing the transportation sector which has high health consequences in urban areas due to air pollution, disproportionately affecting socio-economically marginalized groups. I also explore the electricity sector, and its interaction with transportation through electrification.
I build spatially explicit, data-driven models that delve into the complexity and trade-offs that arise when fossil and zero-carbon resources co-exist during the energy transition. My background in materials science and mechanical engineering has provided technical depth to my work, and my graduate studies have equipped me with an appreciation for the nuances of decision-making for climate policies. I also utilize methods from systems engineering, data science, lifecycle analysis, demography [1], and air quality modeling.

Long-term research goals: My long-term research interests are in:
(i) reducing environmental externalities of transportation
(ii) preparing the electricity grid for electrification of technologies
My research group will provide decision-makers involved in the energy transition – policymakers, ratepayers, adopters, and utilities – with solutions and actionable takeaways. These solutions will be **place-based**, incorporating regional resource constraints; **equitable**, mitigating the unequal burden of pollution and extractive industries on socio-economic minorities; and **cost-effective**, incentivizing new technologies without exacerbating system costs and unaffordability. I highlight three interconnected areas of interest, with past and future work, as well as my long-term research goals below:

1. Realistic decarbonization solutions to address climate, health, and environmental justice consequences of transportation choices: Transportation contributes to 34% of greenhouse gases, 45% of NO_X, and 20% of particulate matter emissions in the United States. This pollution disproportionately affects socio-economically marginalized groups and is a significant environmental justice concern. In my work, I have weighed the use of electric vehicles or highly efficient gasoline hybrids as two possible strategies to reduce air emissions from light-duty vehicles. I used a spatially resolved life-cycle assessment approach along with air quality modeling to compare the climate, health, and air pollution consequences of these choices. I modeled the on-road efficiency as it depends on vehicle and travel characteristics along with a detailed electricity model to understand air emissions associated with vehicle use and charging. This work led to important regional conclusions. For example, in two pieces (one currently under review in *Nature Scientific Reports*, and the other undergoing revisions at *Environmental Research Letters*), we find that electric vehicles reduce greenhouse emissions, criteria air pollutants, and their related inequities in most parts of the country. The largest reductions in health damages occur in densely populated metropolitan areas, suggesting a tailored approach for electric vehicle adoption that prioritizes cities. With our detailed modeling of the grid, we were able to recommend fifty coal power plants with the highest sulfur dioxide emissions that should be retired or retrofitted with carbon capture and storage that would ensure electric vehicles reduce damages from climate change and air pollution when compared to the most efficient gasoline vehicles. Most of these plants are in the Ohio Valley and the Southern United States.

Realistic decarbonization strategies will need to consider **consumer preferences**. My research group will work on the longer-term environmental and economic consequences of increasing vehicle weight and footprint, travel behavior, and multiple vehicle ownership in households. Consumer preferences will influence how the transportation fleet and its emissions evolve. For instance, heavier and larger vehicles such as light-duty trucks – electric or conventional – require more energy to move and produce more greenhouse gas emissions and fine particulate matter (tire and brake wear), currently unaccounted for in transportation decarbonization pathways. I also plan on growing a research agenda focused on solutions for the **hard-to-decarbonize marine sector**. Marine vessels, though responsible for roughly 1% of total greenhouse gas emissions in the United States, often operate in highly populated port cities. It has also been historically weakly regulated compared to other transportation sectors, though that has changed in the last few years. I plan to assess the viability of different decarbonization strategies, and their efficacy, as they differ by marine fleet, the proportion of commercial versus passenger operations, technology substitutes available, and the regional electricity grid.

2. The role of retirement policies in accelerating electrification. Increasing sales of zero-emissions vehicles has been the primary policy to decarbonize transportation. However, conventional vehicles sold today and, in the future, will remain a part of the fleet for a long time. The average lifetime of light-duty cars and trucks is around 20 years, but research to find the most effective ways to retire and replace our highest-emitting vehicle stock is lacking. In two papers, currently in review in *Science*, we use a fleet-turnover and retirement model for light-duty and heavy-duty transportation for California to find cost-effective retirement strategies in pursuance of the state's goal to achieve net-zero emissions by 2045. Importantly, we find that even if the state achieves 100% zero emissions sales by 2035, 20% and 35% of fossil light-duty and heavy-duty vehicles will remain on the road. Retiring light-duty vehicles above 10 years – which currently contribute to more than 70% NOx emissions, disproportionately affecting Black and Latino Californians – and replacing them with electric vehicles could yield a 35-50% reduction in cumulative greenhouse gas emissions and a 23-50% reduction in cumulative mortality between now and 2045.

My research group will study other policy designs to retire and replace the most damaging fossil-fueled vehicles in the fleet cost-effectively. For example, enabling the transition of **gasoline superusers** – a small set of users that disproportionately have higher gasoline consumption and drive more – towards more sustainable strategies may help reduce the emissions from the light-duty sector by 30%. These superusers have lower incomes than the median and spend upwards of 25% of their monthly income on gasoline and maintenance (as is the case in California). This research agenda will model the total cost of ownership and charging requirements if gasoline superusers adopt electric vehicles. I'm also interested in modeling the interactions between the **used vehicle market** and the retirement of vehicles. Current policies that target new vehicles disincentivize the scrappage of older, more polluting vehicles. My research group will model alternative policies such as higher registration fees or more stringent pollution testing for older vehicles that can accelerate the fleet turnover to zero-emissions vehicles.

3) Electrification of end-uses with affordable electricity rates. Transportation and electricity sectors are becoming increasingly intertwined. Electricity prices and rate design will play an important role in consumer bill savings and the adoption of electric vehicles as well as other technologies such as heat pumps, and distributed energy resources (DER, rooftop solar and storage). For the past century, electricity rates have usually consisted of a small, fixed customer charge along with a volumetric (per-kilowatt hour) rate which recovers costs of electricity generation, distribution & transmission, and public purpose programs. While generation costs have declined in recent years, network and wildfire mitigation costs have increased, putting upward pressure on residential electricity rates. The two-fold challenge of rising electricity system costs and integration of controllable resources provides a unique opportunity to design retail rates that benefit both the adopters and the electricity grid at large.

I have **two ongoing projects**[1] in this research theme detailing how different retail rate designs influence customer bills and adoption of DER, particularly for low-income and renter communities. We simulate the consequences of different retail rate designs -- tiered, time-of-use, rates with and without income differentiated fixed charges -- on adopters and non-adopters across climate zones, income, housing type (single vs. multifamily), and utilities (investor-owned vs. publicly owned). We also estimate the benefits of DER for the electricity grid and environment through avoided costs and emissions. This work **extends** to other controllable resources and settings such as the adoption of heat pumps, virtual power plants, and vehicle-to-load technologies.

Collaboration and outreach: My group will build engineering tools and models to inform equitable and affordable climate policy. We will prioritize providing decision-support tools in the form of open-source code, datasets, and applets, and present research findings through research briefs, popular writing, and community-centered workshops. I'm eager to extend these research questions to other geographic settings, particularly in countries with fossil-heavy electricity grids and high health damages like South Asia and Southeast Asia. I aim to create a systemic approach to understanding the decarbonization of increasingly intertwined transportation and electricity sectors while improving equity, air quality, and affordability. I hope to significantly advance methods of inquiry within energy systems engineering and policy to help society take rapid action to address the climate crisis.

[1] **M. Singh**, "How Differential Privacy Will Affect Estimates of Air Pollution Exposure and Disparities in the United States," *Findings*, May 2023, doi: 10.32866/001c.74975.
[2] **M. Singh**, T. Yuksel, J. Michalek, and I. M. L. Azevedo, "How clean does the U.S. electricity grid need to be to ensure electric vehicles reduce greenhouse gas emissions when compared to hybrid gasoline vehicles?" (in review, *Nature Scientific Reports*)
[3] **M. Singh**, C. W. Tessum, J. D. Marshall, and I. M. L. Azevedo, "Distributional impacts of fleet-wide change in light duty transportation: mortality risks of PM2.5 emissions from electric vehicle and tier 3 conventional vehicles." (Revise and Resubmit, *Environmental Research Letters*)
[4] E. M. Hennessy, **M. Singh**, S. Saltzer, and I. M. L. Azevedo, "Pathways to Zero Emissions in California's Heavy-Duty Transportation Sector." (In submission, *Science*)
[5] **M. Singh**, E. M. Hennessy, S. Saltzer, and I. M. L. Azevedo, "Pathways to Zero Emissions in California's Light-Duty Transportation Sector." (In submission, *Science*)

[1] working papers available at https://madalsa.org/