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Mitigating Urban Greenhouse Gas Emissions: Decarbonization Frameworks for Portland and Delhi

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Abstract

Climate change poses one of the most serious challenges to our planet, with urban areas contributing significantly to the greenhouse gas (GHG) emissions that drive this crisis. Although cities occupy only about 2% of the Earth's land, they are responsible for over 70% of global GHG emissions and account for two-thirds of worldwide energy consumption. By 2050, an estimated two-thirds of the global population will live in cities. Therefore, reducing emissions within urban landscapes is essential to combine climate change. The United States and India rank among the top global emitters of carbon, so reducing emissions in these nations is essential to achieving international climate targets. Currently, 82% of Americans and 35% of Indians reside in urban areas. With India's rate of urbanization accelerating, projections indicate that by 2050, 60% of the country's population will be living in cities. Delhi, the focal city in this study, is expected to become the world's largest city by 2028. Such urban expansion will demand considerable infrastructure investment, and prioritizing sustainable, climate-conscious development will be vital to achieving lasting GHG reductions. While urbanization in the United States may be slower than in India, American cities like Portland (the second city analyzed in this study) still make a substantial contribution to both national and global GHG emissions, with per capita emissions significantly higher than those of India and other rapidly developing nations. This study outlines various deep decarbonization strategies for Delhi and Portland, examining specific technology and policy measures. To approach urban decarbonization, it is helpful to consider seven key infrastructure sectors: food, water, buildings, energy, transportation and connectivity, waste and sanitation, and public spaces. These combined sectors represent 88% of global GHG emissions. Following this framework, the study begins with an analysis of each city's current carbon footprint, an essential step in crafting effective decarbonization strategies. Using a community infrastructure footprint (CIF) method, which employs a life cycle assessment (LCA) across these seven sectors, this approach includes emissions beyond city boundaries for a comprehensive emissions overview.

Keywords

Climate Change, Carbon Footprint, Urban Greenhouse Gas Emissions, Energy Consumption, Sustainable Development

1. Introduction

1.1. Delhi Baseline Conditions

Delhi has been involved in climate action planning for several years, with their most recent plan released in 2017 as part of India's broader commitment to reducing its country's carbon intensity by 33-35% below 2005 levels by 2030, part of the Paris Climate Accords. We calculate Delhi's current carbon footprint to be 53 million metric tons of carbon dioxide-equivalent (CO2e) per year 3.3 metric tons of CO2e per person per year. This is roughly 33% greater than the footprint reported by Chavez et al. in 2009, which was 40.3 Gt CO2 per year or 2.3 t CO2e on a per capita basis. We attribute this observed increase to population and infrastructure growth over the 11 years elapsed as well as different assumptions we made with certain emissions factors, especially for wood burning[1]. We find that building electricity, residential fuel combustion for cooking, food production, and transportation sectors contribute the most to the city's carbon footprint (**Figure 1**). Asterisks refer to transboundary impacts.

1.2. Portland Baseline Conditions

Portland, similar to Delhi, has had a deep investment into climate change mitigation. For the past 20 years Portland has worked to cut carbon emissions under the 1993 Carbon Dioxide Reduction Strategy, the nation's first local carbon reduction plan (City of Portland and Multnomah County, 2001).

In 2015, Portland released the city's 2015 Climate Action which aims to reduce carbon emission by 80% below 1990 levels by 2050 (City of Portland and Multnomah County, 2015). Due to this early involvement in mitigation efforts, the greater area of Multnomah County, in 2013 carbon emissions were already 14 percent below 1990 levels. We calculate Portland's current carbon footprint to be 13.137 Megatons of carbon dioxide-equivalent (CO2e) per year 19 metric tons of

[1]While carbon accounting frequently considers wood to be a carbon neutral fuel, we do not consider it as such because of the potential for its overexploitation, particularly in Delhi with its rapid population growth. Bailis et al. (2015), from which we draw our wood emissions factor, found that only 30% of the CO2e released from wood harvesting in India was subsequently sequestered. We fear that even less is sequestered in such a large city as Delhi. Thu, to be overly conservative in our footprint, we assume 0% sequestration.

CO2e per person per year. We verified our results by comparing it to the report, which calculated 19.5 metric tons of CO2e per person per year. From all the sectors studied, we found transportation, building electricity, agriculture, building natural gas, and fuel processing, to be the top five sectors to contribute the most to the city's carbon footprint (Figure 2).

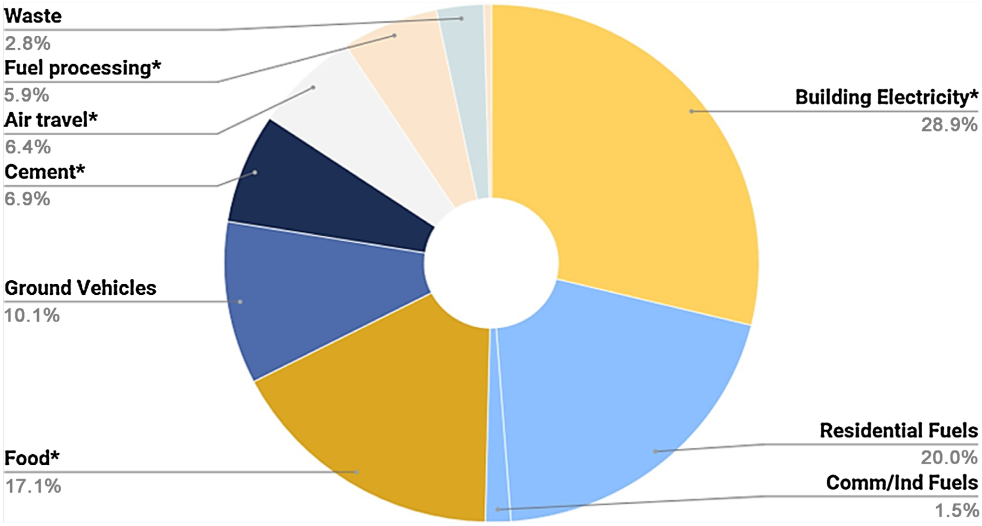

Figure 1. Carbon footprint breakdown for Delhi, India, by sector.

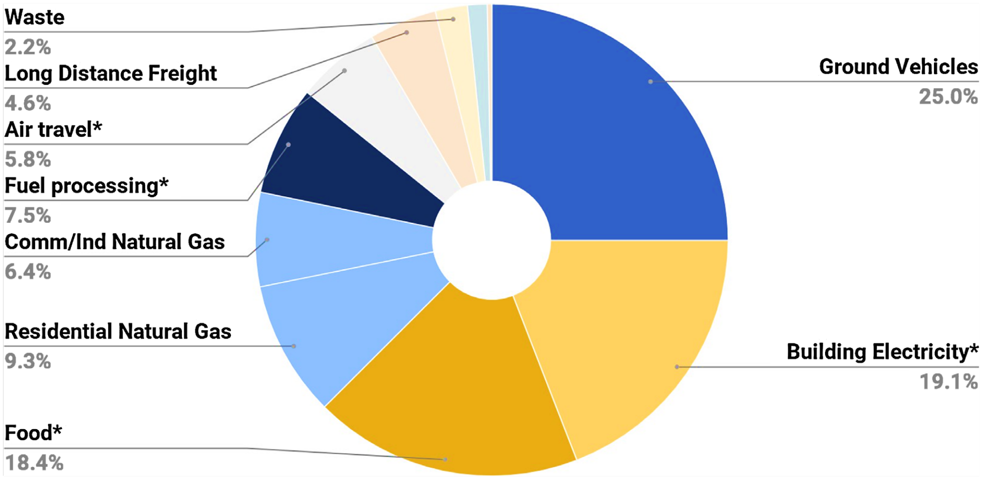

Figure 2. Carbon footprint breakdown for Portland, USA, by sector.

For both Delhi and Portland, we focus on five strategies that address the highest-emitting sectors that are also the easiest to decarbonize and bring along important co-benefits. Our strategies include fuel switching for residential cooking, vehicle electrification, low-carbon heating and cooling, carbon capture sequestration, and rooftop photovoltaics. These five strategies can benefit public health, improve air quality, help households save money on energy, generate additional energy, and create thousands of well-paying jobs, respectively (WHO, 2018).

2. Decarbonization Strategies and Co-Benefits

2.1. Cooking Fuel Switching

Cooking fuel is an essential part of every household in the world, and targeting its usage is a key component to achieving full decarbonization everywhere due to its prevailing necessity. Given the close proximity of cooking fuel in users's lives and its daily consumption, the use of dirty fuels for cooking creates indoor and outdoor air pollution and has significant adverse health effects, especially the less refined the fuels are. Around three billion people are still lacking access to clean cooking fuels, using open fire or "stoves fueled by kerosene, biomass, and coal" worldwide, creating harsh impacts on health equity (. Unlike other carbon mitigation problems, cooking can be done with a purely electrical solution, the induction stove, which allows for pathways to non-zero emissions (Kypridemos et al., 2020).

However, due to the immense dependence of people's livelihoods on cooking and the vast range of cooking technology from the simple burning of wood to warm up food to electromagnetic fields, adoption of new technologies when "old" technologies are cheaper and more familiar poses additional challenges. Accessibility to new technologies also poses difficulty as more refined fuels such as liquified petroleum gas (LPG) require transportation and refueling infrastructure and electric stovetops require consistent and reliable electricity every day to instill confidence and transition end-users (PMUY) (Sen, 2019).

Though this infrastructure is far from present in a vast majority of the Global South, the push from policy makers from Cameroon to Indonesia to transition from dirty traditional fuels such as wood and kerosene to LPG show an awareness of the health and climate effects of these fuels. As governments and countries create greater infrastructure, the carbon mitigation potential of cooking fuel switching becomes increasingly clear. In order to fully decarbonize, this essential household utility will eventually need to be electrified along with a clean up of energy grids with renewable energy sources. Overall, transitioning away from traditional fuels has huge impacts on billions of underprivileged people as well as an immense environmental impact to mitigate climate change, deforestation, and pollution (Business Today, 2018).

2.1.1. Delhi

In Delhi, 85.14% of households were using LPG and 1.82% of households were using firewood as the primary source of cooking as of 2010. Since then, many national government schemes directed at adopting LPG have contributed to the now 97.5% LPG penetration rate across India such as the Pradhan Mantri Ujjwala Yojana (PMUY). The PMUY provides a subsidy of Rs 1,600 to state-owned fuel retailers in order to provide free gas connections to poor Indians as well as many underprivileged groups such as Scheduled Caste and Tribe households and more (Business Today, 2018). Yet traditional cooking fuels like wood and chips still contribute a significant portion of carbon emissions for Delhi given their increased carbon emission rate as well as decreased efficiency, requiring more burning of fossil fuel for the same heating. Additionally, many consumers use both LPG and firewood in conjunction, offsetting the benefit of using LPG (Thomas, 2020).

Further, Delhi is considered one of the, if not the most, air polluted cities in the world. As the city continues to develop, Delhi's Climate Action Report predicts that energy intensity and usage of households will increase, and a combination of a dirty grid and dependence on fossil fuels will continue to Delhi's pollution. This pollution has clear health impacts, being described as smoking "44 cigarettes a day". Given the pollution that burning wood causes, transitioning away from these traditional, dirty fuels is necessary to mitigate these health and environmental harms (Wu, 2017).

The decision to transition from traditional fuels to LPG rather than an electric solution comes from a variety of economic, cultural, and technological reasons. Despite Delhi's rapid urbanization, large sectors of Delhi remain rural. This rapid urbanization has also caused an increase in the slum population of Delhi. In these rural and/or non-permanent settlements, the availability of traditional fuels make them a convenient fuel, especially since these fuels are often collected for free. Wood burning is more prevalent in these areas, where possibilities of piped natural gas or electric connections are more difficult. Furthermore, direct transitions from firewood to electric induction stoves in a study of rural households in Himachal Pradesh showed an only 5% adoption rate, even with high levels of electrification (Kadian et al., 2007). Widespread belief in the necessity of an open flame for cooking due to traditional cooking methods have also prevented the adoption of electric stoves, as well as basic lack of electricity. Meanwhile, programs such as PMUY to switch households to LPG exclusively have been effective.

By enacting a full transition of wood and chips used for cooking purposes to LPG in Delhi, GHG emissions are reduced ~62% percent from the baseline, which constitutes a 4% footprint reduction. By calculating the heat demand from wood and chips and finding the equivalent LPG usage, the reduction in carbon emissions can be calculated.

However, achieving this full-scale reduction of firewood cooking will pose many difficulties: price, cultural factors, government inefficiency, and lack of education have been contributing to fuel stacking—the use of solid fuels and LPG jointly. Current government subsidies and schemes focus on providing LPG connections, but many recipients never receive subsequent refuels due to having to pay out of pocket. Many people do not have access to those subsidies in the first place, despite eligibility, due to lack of proper paperwork. A continuation of wood burning of neighbors also reinforces the use of wood burning. Further, a lack of understanding of the health effects of wood burning prevents consumers from seeing the need to transition (Banerjee et al., 2016).

In order to further this adoption, discussions between policymakers, bureaucrats, utility and gas companies, and end-users will need to be conducted. Policy makers will have a variety of incentives, including improving health and air quality. Gas companies and policymakers will need to establish an agreeable subsidy along with taking into account the relationship between LPG pricing and adoption rate. Bureaucrats will need to reform LPG subsidy implementation to improve accessibility. Utility companies will need to pair with government health departments or non-profits to better explain the health impacts of a transition to decrease fuel stacking. See Policy Roadmap for more details (Gould et al., 2020; Gould & Urpelainen, 2018).

2.1.2. Portland

Unlike Delhi, Portland relies mainly on piped natural gas and electricity as stove fuels, with the Pacific West census region having a 41% usage of natural gas and a 43% usage of electricity for cooking fuels in 2015. This data compares to a 63% usage of electricity and 33% usage of natural gas for cooking fuels nationally, showing the potential for natural gas reduction. Given the prevalence of natural gas in homes, a transition from natural gas stoves, which rely on piped fossil fuels and are only ~40% thermally efficient, to induction stoves, which rely on the electric grid and are ~90% thermally efficient, create the opportunity for zero carbon cooking depending on the emission factor of the grid. Nationally, 59% of households use the same type of fuel for cooking and heating, so improvements in cooking fuel could lead to significant mitigation of heating emissions, too (EIA, 2020).

Despite the vast improvements in efficiency and safety (induction stovetops lack an open flame and only heat the pot or pan not the stove itself reducing chances of burns), induction stove tops are still very uncommon. Given that induction stovetops are a much newer technology than natural gas stoves and that appliance replacements are "unplanned expenses," induction stoves are usually only adopted once an existing appliance breaks. Even if a stove breaks, the relatively higher cost and unfamiliarity of induction prevents consumers from switching (Sweeney & Worrell, 2014). However, through increased education of health impacts, rebates and innovation bringing the price of induction stoves down, and the spillover effect of modern home designs can increase the adoption of induction stoves in Portland. As any transition away from fossil fuels, natural gas utilities will pose significant opposition, as natural gas is key to cooking and electricity generation in Portland. Policy makers, scientists, and utilities will need to find pathways to encourage adoption amidst that opposition (See Policy Roadmap.).

By estimating that the percentage of residential natural gas used for cooking is 10% (from the U.S. Energy Information Administration), the cooking fuel heat demand from natural gas can be calculated, as well as the equivalent electricity to power an induction stove. By factoring in the grid emission factor of 370 g CO_2e/kWh, a reduction of 11% from the baseline can be established. However, this modest reduction is heavily influenced by the dirty grid of Portland as imported coal and natural gas constitutes the majority of the grid. Evaluating the reduction with a cleaner grid, for example, France's with an emission factor of 32 g CO_2e/kWh, CO_2e reduces by 92%. Of course, the potential of a net-zero electricity grid would achieve a 100% reduction in emissions from cooking fuel (Lynch, 2019).

2.1.3. Co-Benefits

Cooking fuel transitions boast numerous benefits to a variety of health, environmental, and economic Sustainable Development Goals set out by the UN. SDG 7: Affordable and Clean Energy directly targets the availability of clean, reliable sources of fuel, particularly cooking fuel, since it is a fuel that all humans rely on every day (Portland General Electric, 2019). Cleaner cooking fuels also have the co-benefit of reducing indoor and outdoor pollution, which decreases morbidity of women and children in particular. Household air pollution causes nearly 3 - 4 million premature deaths. In Portland, recent wildfires, air pollution, and winter cold is causing many homeowners to shut their windows, causing the indoor air from natural gas stoves to become unhealthy as reported by local Portland news. In India in particular, transitioning from wood to LPG has even more co-benefits. Close to 482,000 Indians die prematurely from household air pollution alone; "as compared to combustion of traditional biomass, the combustion of LPG only generates a negligible amount of byproducts that are noxious to human health," which promotes Goal 3 of Good Health and Well-being (Health Effects Institute, 2019).

The decrease in carbon emissions aids in SDG13: Climate Action wherever a cooking fuel transition is implemented. Given that the task of collecting firewood is usually solely done by women and children, transitioning to infrastructure-based cleaner fuels positively impacts SDG 5: Gender Equality by allowing more freedom and opportunity for women and girls in India. The less demand for firewood also reduces deforestation, which has large benefits for SDG15: Life on Land (Chalmers, 2020).

2.2. Transportation Electrification

Transportation drives everything we do, from carrying agricultural products and manufactured goods to cities, to simply taking people to and from work every day. It is therefore inherently multi-sector, facilitating the operation of several other of the eight provisioning sectors, such as food supply and waste/sanitation transport. It is also clearly multi-scale, where many goods are carried into cities from halfway across the country or the globe. Thus, to mitigate greenhouse gas emissions, the transportation sector needs to be addressed. Electrifying the transportation sector means increasing the number of electric vehicles on the road. These electric vehicles can be as small as motorcycle and passenger vehicles or larger-sized like transit buses and even tractor trailers for long-distance freight trucking. The size of the vehicle affects the scale of transport it provides. Three types of electrical vehicles exist: battery electric vehicles (powered by electricity in battery pack), plug-in hybrids (powered by a gasoline or diesel engine with an electric motor and large rechargeable battery), or fuel cell vehicles (powered by splitting electrons from hydrogen molecules that produce electricity to run the motor). (*Electric*

Vehicles Are Not Just the Wave of the Future, They Are Saving Lives Today., 2020).

Not only is transportation multi-scale and multi-sector, it is also inherently multi-actor. Oil company lobbyists may want to stop electric vehicles from proliferating because it threatens their sale of petrol products and may use their power and wealth to slow the implementation of this strategy. Thus, it is pivotal that policy makers be prepared for such resistance and maybe attempt to work together with oil companies to gain their support for a successful transition. Other policy actors may desire electric vehicles strongly for their health benefits, highlighting the multi-objective nature of this strategy. As electric vehicles (EVs) reach a higher penetration of the car sector, cities will need to provide publicly accessible charging stations to meet the charging demand of people who do not have access to a private charging spot like a personal garage (Sheth & Patel, 2024b).

Switching to electric vehicles would "clean" the air both nationally and within the city itself. It is therefore important that when carrying out this net-zero carbon strategy, the objectives of different actors are considered as this strategy impacts more sectors than simply the transportation sector (City of Portland and Multnomah County, 2015).

Overall, electrifying the transportation sector is an attractive strategy for city decarbonization as it can impact lives and sectors beyond those directly involved in transportation. The focal point of this strategy is to look at the effects of electrifying the transportation sector within Portland and Delhi under three different scenarios: electrification with each city's grid kept the same, electrification with a "greener" energy grid, and electrification with a net-zero emissions grid. These scenarios will provide insight on how to ensure an effective and meaningful electrification process (Go Electric Oregon, n.d.).

2.2.1. Portland

In Portland, electrification of the transportation sector is a goal at the forefront of Portland's 2015 Climate Action Plan. Within this plan, Portland's 2030 Object 7A Electric Vehicles, is an effort to reduce the lifecycle carbon emissions from transportation fuels by 20%. Also, Oregon's Go Electric Oregon through Executive Order 17-21 vows to have 50,000 electric vehicles on the road by the end of 2020. The most pivotal, Portland's 2017 Electric Vehicle strategy, outlines a path to electrification of the transportation sector through public transit, shared and private vehicles; ultimately having 50,000 EVs by 2030. EVs include electric and plug-in hybrid cars, and electric bikes, scooters, trucks, buses and freight vehicles. This surge towards electric vehicles has also been supported by non-policy actors. For example, Portland General Electric provides discounted 2020 Nissan Leafs to customers. Lastly, current infrastructure within Portland supports electric vehicles as there are 7 charging stations within the Portland metropolitan area (*Electric Avenue: Everywhere Is Possible*, n.d.).

Within Portland, there are 477,950 registered passenger vehicles (Oregon Department of Transportation—Driver Motor Vehicle Registrations by County, 2019). This makes up about 70% of all registered vehicles within the whole city. As well, overall in Oregon, light-duty vehicles have the highest vehicle travel, 2.75 trillion miles in 2017, compared to heavy duty trucks, air travel, buses, freight, and domestic marine (Oregon Department of Energy, 2018). Using the current Portland grid, electrifying all passenger vehicles would generate a carbon footprint reduction of 10%, 1.32 Megatons of CO2e/year.

This was calculated using a 2020 Nissan Leaf with an average VMT of 22 miles/day/person. Using a more renewable grid, such as France's, and a net-zero emissions grid will result in a carbon footprint reduction of 13% and 13.3% respectively. This minimal increase in reduction is in part due to Portland's existing grid being relatively "clean."

Since Portland saw its major reductions from just electrification, increasing EVs usage is critical for decarbonization. Therefore, going forward, policy actors and infrastructure designers need to make EVs more attractive to infrastructure users through electric vehicle subsidies and rebates. (see Policy Roadmap for more detailed policy).

2.2.2. Delhi

Similarly in Delhi, the local government has actively pushed for the adoption of electric vehicles in the transportation sector. At large, India is a member of the Electric Vehicle Initiative, a policy forum focused on promoting the rapid deployment of electric vehicles. In Delhi's 2017 Climate Action Plan Delhi vowed to mitigate carbon emissions within the transportation sector through the adoption of Delhi's Electric Vehicle Policy of 2018. This policy led to the foundation of Delhi's Electric Vehicle Policy of 2020, a progressive policy intended to boost the economy and reduce air pollution through encouraging the usage of electric vehicles. More specifically the policy aims to have 25% of new registered vehicles be battery operated-by 2024 (*Electric Vehicles Initiative*, n.d.). The policy includes a subsidy of Rs 5000 per kilowatt/hour of battery capacity for all two-wheelers, subsidy of Rs 10,000 per kilowatt/hour of battery capacity for first 1000 e-four wheelers, while also removing the road tax and registration fee for all battery EVs. Lastly, current infrastructure within Delhi supports electric vehicles as there are 72 different charging stations around the city.

Delhi's transportation sector includes a diverse fleet ranging from e-Rickshaws, mopeds, buses, three wheelers to name a few. However, M-Cycle/Scooters and Motor Cars make up 95% of all registered vehicles; with 6,957,223 and 3,132,839 registered, respectively. As well, these two vehicle types have the third highest VKT in Delhi with only 51% in use. Using the current Delhi grid, electrifying all M-Cycle/Scooters and Motor Cars would generate a carbon footprint reduction of only 6%, 3.75 Megatons of CO2e/year. This small reduction can be attributed to Delhi's "dirty grid." Here, the EVs fuel requirement was 7 kWh/100 km for M-cycle Scooters and 10 kWh/100 km for Motor Cars, as the Delhi EV Policy 2020 has subsidy requirements for scooters and a subsidy for the TATA Motors Exon EV (*Delhi EV*, n.d.). As well, an average VKT of 42 km/day/person was used. Using a more renewable grid, such as France's, and a net-zero emissions grid will result in a carbon footprint reduction of 15.3% and 16% respectively. This maximum increase in reduction once a renewable grid is implemented highlights the importance of the electricity source on electrifying transportation (DTE Staff, 2020).

Delhi saw its major reductions from electrification plus the usage of a more renewable grid. Therefore, increasing EVs usage will not be significant on it's own. Going forward it will be pivotal for policy actors and infrastructure designers to make EVs more attractive to infrastructure users through electric vehicle subsidies and rebates but focusing most efforts on transitioning to a greener grid (see Policy Roadmap for more detailed policy).

2.2.3. Co-Benefits of Transportation Electrification

As briefly mentioned earlier, electrifying the transportation section generates a series of economic, health, environmental, and social co-benefits. Within both Portland and Delhi, low income communities disproportionately suffer from air pollution. As well, they tend to own less fuel efficient vehicles which when combined with longer commutes leads to higher proportion fuel and transportation costs. The transition to EVs can benefit these underserved communities as the increase in demand for EVs can drive the price down and make them more affordable, improve air quality, and reduce fuel costs. Simultaneously, this can accomplish the UN's Sustainable Development Goal (SDG) #3 of promoting good health and well-being for all ages and SDG #10 of reducing inequalities within and amongst countries. Overall, electrifying the transportation sector can create economic opportunities through the EV industry, constructing infrastructure for EVs, and transitioning to a greener electricity grid; while accomplishing SDG #7 of affordable clean energy for all and SDG #8 of decent work and economic growth. Overall, this strategy can also help achieve the World Research Institute's Three Steps to Zero Carbon Cities of "electrify and decarbonize".

2.3. Low-Carbon Heating and Cooling

Sustaining comfortable temperatures is a necessary element of everyday functioning making heating and cooling are central components of almost all buildings. In Portland, 15.7% and 19.1% of the carbon footprint is attributed to natural gas usage and building electricity respectively, significant portions of these are used for heating and cooling. In Delhi, building electricity accounts for 19.1% of the carbon footprint, up to 44% of this has been attributed to heating and cooling purposes (Stewart & Mackres, 2019).

Across varying climates and cultures, efficient heating and cooling practices drastically differ so this strategy requires an examination and consideration of the current infrastructure and environmental conditions of the heating and cooling in place. Portland and Delhi will need to take drastically different steps to make their heating and cooling more efficient. Addressing heating and cooling is an essential step in the World Research Institute's Three Steps to Zero Carbon Cities framework's optimization and electrification (*Energy Star*, n.d.).

2.3.1. Portland

While many homes in the US still use traditional heating methods, heat pumps are growing in popularity because of their high efficiency and cost-effectiveness. Heat pumps combine heating and cooling into one system that instead of generating hot and cool air, function by transferring heat between inside and outside buildings. Because heat pumps are more energy efficient than most traditional heating methods, they allow residents to yield savings in heating and cooling costs relative to furnaces and boilers; this contributes to SDG #7 Affordable and Clean Energy. Additional co-benefits for users include humidity control, quiet operating noise, and typically safer conditions because heat pumps aren't prone to gas leaks or explosions.

There are three types of heat pumps: air, water, and ground source. Air source heat pumps work by transferring heat through the air and is the most common type because it can be installed in almost any building. Water source and ground source heat pumps are geothermal heat pumps and function by transferring heat between nearby water sources and the ground, respectively. While geothermal heat pumps cost most to install, and are only suitable for certain areas, they are typically more efficient than air source heat pumps because of the relatively constant ground and water temperatures (EIA, 2015).

Residents within Portland are currently eligible for a variety of preexisting incentives for efficient residential energy use. The U.S. Environmental Protection Agency's Energy Star Program offers a few programs incentivizing heat pumps. Energy Star certified heat pumps purchases are eligible for $300 tax credits, and home builders are eligible for $2000 tax credit for homes with high energy efficiency in heating and cooling (although these are not heat pump specific). Portland General Electric (PGE) offers a $200 discount on any PGE-approved contractors. The Energy Trust of Oregon also offers cash incentives up to $700 for installations of heat pumps that meet efficiency standards. However, these incentive programs do not offset the costs of installation of heat pumps which on average range from $3625 to $22,000 to install. In Portland only 6.7% of homes already use heat pumps as their main source of heating (assumption by the main heating's choice by region, marine region 1.2 million households/17.9 million households = 0.067).

By installing air source heat pumps in 95% of homes, Portland has the potential to reduce its carbon footprint from heating by 352,693 metric tons of CO2e per year and from cooling by 31,903 metric tons of CO2e per year. Additionally, savings can be even greater when switching from to ground and water source heat pumps, but because they are not suitable for all housing, we do not assume their installation (GRIHA India, n.d.).

2.3.2. Delhi

In Delhi, because of their lack of space heating practices and high population residing in slums we decided that heat pumps would not be equitable and also not as effective as in the US. Instead, for Delhi our strategy is to integrate the existing Green Rating for Integrated Habitat Assessment rating system into policy that requires all new construction to meet standards for a green building. The GRIHA Council is a non-profit organization jointly set up by The Energy and Resources Institute (TERI) and the Ministry of New and Renewable Energy of Government of India to promote and administer green buildings in India (Sunref India, n.d.).

The GRIHA system emphasizes green features, vernacular architecture and climate responsive planning during the design phase such as local material use and passive cooling. One five star rated GRIHA project in New Delhi the FBN and Plexus Production House uses Thermally Reinforced Insulated Concrete (TRIC) on the outer envelope to reduce thermal mass. Another New Delhi five star building, the Engineers India Ltd Campus was designed so that regularly occupied spaces such as open office, and cabins are placed along the north side for glare free natural light and south side has been used for service areas and buffer spaces such as restrooms, and conference rooms, meeting to minimize the heat gain into the building (*The 17 Sustainable Development Goals*, n.d.).

Currently, the process of becoming GRIHA certified requires the project must apply, pay fees and must have an area of 2500 m^2, by mandating the GRIHA certification for all new buildings and eliminating fees all new projects will have a focus on green design even before certification. The GRIHA rating system grants 1 to 5 stars based off 100-points separated into 10 sections: Sustainable Site Planning, Construction Management, Energy Efficiency, Occupant Comfort, Water Management, Solid Waste Management, Sustainable Building Materials, Life Cycle Costing, Socio-Economic Strategies, Performance Metering and Monitoring, and an extra section: Innovation. The process involves registration, workshops, site visits, evaluation, and renewals every five years.

Currently there are incentives for 4 and 5 star rated GRIHA affordable housing projects provided by the Sustainable Use of Natural Resources and Energy Finance (SUNREF)—India such as financing the project, training, marketing and co-branding, reimbursement of certification costs, and technical support. Our strategy builds and expands on these programs and rating system.

New green building standards will require all new construction projects to register and receive support in order to get at least 25% of the points within each section of the rating. The SUNREF—India incentive program will also be expanded to offer more support to all project types and gives further incentive for projects to aim for a 4 or 5 star rating.

Because GRIHA standards cover a wide range of areas, there are many additional co-benefits in addition to more efficient heating and cooling such as, prevention of destruction to the local natural habitat and biodiversity, reuse of the construction waste material to the maximum possible extent, reduction of energy and water demands, reduction of air and water pollution loads on the community, limited waste generation due to recycling and reuse, increased occupant productivity and enhanced marketability for the community as a whole. These benefits contribute to SDG #7 affordable and clean energy, SDG #9 industry, innovation and infrastructure, SDG #11 sustainable cities and communities, and SDG #15 life on land (C2ES, 2017).

The current impact of the 422 GRIHA rated projects is a 2.5 million tCO2 emission offset, with potential impact at a 24 million tCO2 emission offset. The carbon mitigation in Delhi will depend on the amount of growth and is subjective based on the needs of different buildings.

2.4. Carbon Capture and Sequestration

More than 40% of CO2 emissions in the United States and 33.7% of emissions in India are from electric power generation. Although the availability of alternative sustainable energy sources is increasing, fossil fuels are expected to meet the world's energy demands for the next several decades, and accelerating the deployment of carbon capture technology is essential in reducing emissions from these power plants. Carbon capture stops additional carbon emissions from entering the atmosphere, and provides more time for transitions to more sustainable energy practices before exceeding a 2 degree Celsius global temperature increase from pre-industrial days. Over half the models cited within the IPCC's Fifth Assessment Report demonstrate that carbon capture technologies are necessary to meet this goal. Delhi's energy sector is one of it's dirtiest, and one of the first steps the city could take to changing this is the installation of CCS in its two coal powered plants. While Portland has been more successful in implementing cleaner technologies into its power grid, CCS would help the city continue to move forward with its emissions reductions (EIA, 2020).

While carbon capture technology is not new, as it has been employed in multiple industrial projects in North America dating back to the 1970s, its application to power generation is more novel. Current CO2 capture technologies in power stations include pre-combustion capture, oxyfuel carbon capture, and newly developing chemical looping combustion. However, post-combustion carbon capture is the main method used in retrofits of existing power plants, which would be ideal for both Delhi and Portland. In this method, chemical or physical solvents or sorbents (and sometimes semi-permeable materials as a membrane) are used to capture carbon dioxide from a flue gas after combusting a carbon-based fuel, such as coal or natural gas.

After the carbon is captured, it must be transported through pipelines to a storage site, where it can be injected into geological formations, including oil/gas reservoirs, deep saline formations, coal beds, and basalt formations, or it can be used in other industrial processes such as enhanced oil recovery, food and beverage manufacturing, or metal fabrication.

2.4.1. Delhi

Delhi currently has two coal and four natural gas power stations (with a combined installed capacity of 840 MW and 2,519 MW respectively) that provide energy to the city, which is rapidly increasing in population. Delhi residences use over three times the national average of energy consumption, and to support this, newly introduced sustainable energy sources will likely not meet demand for several decades to come. In order to reduce emissions from the energy sector immediately, the installation of post-combustion carbon capture at both coal plants and the highest capacity natural gas plant would substantially cut emissions, while allowing for the city to continue its current level of power consumption. Although natural gas makes up a larger percentage of the power provided by fossil fuel energy, coal power plants produce over twice as much carbon dioxide emissions per thermal unit than does natural gas, making the installation of CCS units in coal powered stations first imperative. Based on the assumptions, we found that Delhi could potentially reduce its carbon footprint by up to 5.89 million metric tons of CO2e, which is 11.1% of the city's overall carbon footprint.

2.4.2. Portland

Although Portland has the goal of reducing the carbon intensity of energy supplies by phasing out coal produced power and increasing energy provided by hydroelectric, solar, and wind sources, the two electric companies that provide energy to Portland, Portland General Electric and Pacific Power, still source about 21% of their energy from coal plants and 35% from natural gas plants in the Northwestern United States (City of Portland and Multnomah County, 2015). While sustainable energy sources continue to grow, these fossil fuel plants still provide over half of the energy used by Portland, and likely will continue to contribute energy to the Portland grid for at least the next couple of decades, even as they are phased out. To reduce emissions from the energy sector immediately, CCS installation in all of the coal plants sourced by PGE and Pacific Power would make a large difference. The economic feasibility of solar PV has seen remarkable improvements due to ongoing technological advancements. According to the National Renewable Energy Laboratory (NREL), the levelized cost of energy from solar PV has significantly decreased, from about 10 units in 2015 to approximately 3 units in 2018. Despite these advancements, challenges such as the limited efficiency of solar cells and their comparative reliability issues against fossil fuels remain. However, the long-term benefits are undeniable. For example, a 3 kW solar PV system, though initially expensive, can achieve a return on investment within three to four years. Post this period, the system generates significantly more energy than the initial investment, thanks to the solar panels' 25-year lifespan (Swami, Sheth, & Patel, 2024). Although natural gas makes up a larger percentage of the power provided by fossil fuel energy, coal power plants produce over twice as much carbon dioxide emissions per thermal unit than does natural gas, making the installation of CCS units in coal powered stations first imperative. Based on assumptions, we can estimate that Portland could potentially reduce its carbon footprint by up to 1.40 million metric tons of CO2e, which is 10.7% of the city's overall carbon footprint.

While the percentage of footprint reduction is similar for Portland and Delhi, it is important to note that Delhi's actual emissions reduction is 4 times the size of Portland's (EIA, 2020).

2.4.3. Co-Benefits

One of the potential co-benefits of the installation of CCS units at power plants is the generation of additional power, as geologically stored CO2 can be used to extract geothermal heat from the same locations in which it's injected, ultimately producing renewable geothermal energy. Captured CO2 can also be used to strengthen concrete, which would lead to increased infrastructure durability. Additionally, the captured CO2 can be used in other industrial processes to make chemicals and plastics, such as polyurethanes that are used to create soft foams like those used in mattresses, or in enhanced oil recovery (EOR), food and beverage manufacturing, pulp and paper manufacturing, and metal fabrication. Finally, CCS would create more jobs, since the more CCS operations that are implemented, the more skilled technicians would be needed to manage them.

2.5. Rooftop PV

Rooftop solar photovoltaics (PV) are growing in popularity around the world as a way to decarbonize electricity supplies. This is important for Delhi and Portland, where building electricity is the first and second highest emitting sector, respectively. Integrating more renewable energy will thus be an important part of cleaning up these cities' electricity grids.

Rooftop PV is also a chance for homeowners to generate their own electricity while saving (and, in some cases, even earning) money by selling excess electricity back to the grid through a program known commonly as net metering. In locations with aggressive rooftop solar incentives, enormous penetrations of the technology have been observed. In Australia, for instance, 1 in 4 homeowners have installed solar PV on their roofs, largely due to the cost savings from net metering. This comes despite Australia's deeply conservative leanings politically, which have prevented the country from taking widespread climate action. Thus, rooftop solar can serve as a bridge between political ideologies, driving emissions reductions when political inertia is difficult to overcome (Albert-Ripka & Penn, 2020).

Across the globe, nations are increasingly adopting solar PV, recognizing its potential to significantly contribute to their energy mix. Particularly in regions within the tropics, where sunlight is abundant, solar PV presents an unparalleled opportunity to harness this natural resource. The International Solar Alliance, comprising over 120 countries, exemplifies this global commitment. This alliance aims to mobilize USD 1 Trillion by 2030 to achieve both the Paris climate goals and the United Nations Sustainable Development Goals (SDGs), underscoring the pivotal role of solar energy in global sustainability efforts (Sheth & Patel, 2024a).

Rooftop solar also comes with the added co-benefit of increased resiliency.

Relying on self-generation of solar energy can shelter homeowners from the high volatility of fossil fuels prices in the electricity grid. Additionally, during emergencies and natural disasters when the grid may be out of commission, homeowners can disconnect and rely solely on their panel.

2.5.1. Delhi

In Delhi, several strong local and national government policies have driven rapid deployment of rooftop PV, including an India-wide National Solar Mission to install 40 GW of rooftop solar across the country by 2022 and a Delhi-specific "Solar City" goal to install 1 GW of rooftop solar by 2020 and 2 GW by 2025. Solar PV is mandated for all government and public building rooftops, and for the private sector, economic incentives have included a 30% capital investment subsidy and a Delhi-specific Rs 2.00/kWh generation-based incentive (GBI) on rooftop solar energy exported to the grid (ETI, 2016).

Actual installations of rooftop solar have lagged these goals, however, for multiple reasons. As of last year, Delhi had installed a total of 146 MW of rooftop PV, compared to its 2019 "Solar City" benchmark goal of 606 MW. Most installations so far have been in the commercial and industrial sectors because of the greater access to capital and more favorable economies of scale. Residential customers, whose rooftops represent more than half of the total solar PV potential, have been less able to access quality, low-cost capital. There has also been some cultural resistance and lack of awareness of existing subsidies and incentives, as well as delays in permitting. Greater consumer education is needed, as are more creative financing schemes that open up solar to lower-income households (ETI, 2017).

Assuming that greater adoption of rooftop solar becomes feasible through creative policymaking (which we outline in our Policy Roadmap section), we estimate that Delhi has the potential to reduce its carbon footprint by up to 3.06 million metric tons of CO2e, or 20% of its total electricity-related footprint (6% of total footprint) if rooftop solar is deployed on all available rooftop space (Gillard et al., 2018).

2.5.2. Portland

The city of Portland, through its 2015 climate action plan, has set a goal to get 10% of its energy from within city boundaries using renewable sources, including an additional 15 MW of rooftop solar. A number of grassroots campaigns like Solarize Portland and Solar Forward have tried to boost public awareness and adoption of solar systems, and multiple incentives exist on the state and national level, including a federal Investment Tax Credit (ITC) of 26%, set to expire by 2022 (SEIA, n.d.); a solar + storage rebate program with up to $5000 for rooftop PV and 25% of funds reserved for low- and moderate-income households; and additional utility incentives of up to $2400 for household systems plus up to an additional $9000 for LMI households. Similar to Delhi, rooftop PV installations have lagged the goals set, mainly due to lack of public awareness and fluctuation of incentives.

Sustaining these incentives and building out more awareness will be key (Energy Trust of Oregon, n.d.).

Based on assumptions, we estimate that Portland has the potential to reduce its carbon footprint by up to 808,470 metric tons of CO2e per year, 1/3 of its electricity-related footprint and roughly 6.22% of its overall carbon footprint. This percentage of city footprint is actually very comparable to that achieved in Delhi, notably.

2.5.3. Co-Benefits of Rooftop PV

In addition to the co-benefits listed earlier on household resiliency, rooftop solar PV offers several additional environmental, social, and economic benefits. For one, by covering roofs with solar panels instead of heat-absorbent roofing material often used in the United States, households can achieve lower temperatures in the summer and higher temperatures in the winter via better insulation. The rooftop solar industry can also create well-paying jobs—a 2013 Greenpeace report on solar energy in Delhi found that adding 2557 MW of rooftop solar could lead to the creation of 62,000 jobs. A third co-benefit is the reduction in air pollution from relying on fossil fuel generation. This is particularly important for Delhi, which consistently ranks among the top 10 most polluted cities in the world. Delhi in particular can also benefit from the price stability of rooftop solar electricity. Electricity tariffs in the city have been rising steadily over the past decade because of increased fuel costs for coal and diesel as well as upgrades to the grid required for 24/7 power. With electricity demand increasing across India, prices are projected to rise even more as supply becomes more strained. Having households rely on rooftop solar could help reduce their electricity prices while also easing up pressure on the electricity grid to perform at peak capacity during warm, sunny days. Energy produced from rooftop solar PV panels can also be utilized directly onsite, reducing electricity lost along transmission and distribution lines, including from energy line theft, which is a significant problem in India (Energy Trust of Oregon, n.d.).

Table 1. Summary of emissions reductions.

Technology	Delhi	Portland
Cooking Fuel Switching	2.03 million metric tons CO2e (4% of footprint)	6164 metric tons CO2e (0.05% of footprint)
Transportation Electrification	3.75 million metric tons CO2e (6% of footprint)	1.32 million metric tons CO2e (10% of footprint)
Low-Carbon Heating/Cooling	n/a	384,596 metric tons CO2e (2.9% of footprint)
Carbon Capture Sequestration	5.89 million metric tons CO2e (11.1% of footprint)	1.40 million metric tons CO2e (10.7% of footprint)
Rooftop Solar PV	3.06 million metric tons CO2e (5.96% of footprint)	808,470 metric tons CO2e (6.22% of footprint)

3. Policy Roadmap

Policy	Details & Timeline for Implementation	Relevant Stakeholders
Transportation Electrification		
Continue and expand the subsidies and rebates for electric vehicles	Portland: Work w/PGE to extend rebates to customers to include EVs other than the 2020 Nissan Leaf to support different financial situations Delhi: Increase the number of Four-Wheeler EVs approved for subsidies from 14 to 28 by 2024	U.S.: City of Portland (government), Pacific Power and Portland Gas & Electric (utilities), Oregon state government India: Delhi municipal government, national government
Lower grid emissions factor by increasing reliance on "green" energy sources	Portland: Increase renewable owned net generation from 2.5 million MWh to 5 by 2030 to reach 2050 goals; can provide economic opportunities. Delhi: drastically increase reliance on renewables through investments in green startups and national funding	U.S.: City of Portland (government), Pacific Power and Portland Gas & Electric (utilities) India: Delhi municipal government, three DISCOMs (utilities)
Fund a pilot program to determine the efficiency and effectiveness of EV charging stations on electricity poles in effort to support all EV users (regardless of socioeconomic background)	Portland: Currently doing this with the Clinton Neighborhood Pilot program (Basics of Charging, n.d.) Delhi: work to complete pilot by 2024 to support new EVs in Delhi EV 2020 Policy	U.S.: Portland Gas & Electric (utilities) India: Delhi municipal government, three DISCOMs (utilities), national government
Rooftop Solar PV		
Establish a solar PV residential outreach and education program, particularly for LMI households.	Reach 30% of households by 2023 and 100% of households by 2030. Outreach programs should walk households through the process of installing rooftop PV, including quantifying long-term cost benefits.	U.S.: City of Portland (government), Solar Oregon (nonprofit), Pacific Power and Portland Gas & Electric (utilities) India: Delhi municipal government, three DISCOMs (utilities)
Maintain levels of subsidies and tariffs for rooftop PV. Continue to lobby for	Delhi: Rs 2/kWh generation-based incentive, 30% CAPEX subsidy (national level) Portland: solar + storage rebate	U.S.: Pacific Power and Portland Gas & Electric (utilities), Oregon state government, federal

strong national-level subsidies (particularly in the U.S., where federal ITC is set to expire by 2022).	program (state-level) and utility-level rebate through Energy Trust of Oregon	government India: Delhi municipal government, national government
Streamline and expedite the permitting process for the installation of rooftop PV.	Portland already has done this, establishing permitting experts on residential solar in their city government2. Delhi can look to this as an example.	U.S.: City of Portland (government), Pacific Power and Portland Gas & Electric (utilities) India: Delhi municipal government, three DISCOMs (utilities)
Pursue creative residential financing options, especially for LMI households. Increase financing access through low-interest loans backed by the local governments.	These can include expanding the RESCO model in Delhi and power purchase agreements in the U.S. (in both of these, residential customers do not pay upfront costs but instead pay a set tariff over time to a third party like an electric utility) as well as community aggregations to reduce costs through economies of scale.	U.S.: City of Portland (government), Pacific Power and Portland Gas & Electric (utilities) India: Delhi municipal government, three DISCOMs (utilities)
Low-Carbon Heating and Cooling		
Establish heat pump installation outreach program (Portland)	Reach 30% of households by 2023 and 100% of households by 2030. Outreach program should inform households on the different types of heat pumps, the eligibility of their house, and inform the potential savings.	U.S.: City of Portland (government), Pacific Power and Portland General Electric (utilities), local heating and cooling contractors
Fund heating and cooling contractors partnership (Portland)	Connect with local heating and cooling contractors to subsidize the cost of heat pump installations.	U.S.: City of Portland (government), local heating and cooling contractors
Increase incentives through Energy Trust of Oregon (Portland)	Expanding the current Energy Trust of Oregon discount so that 75% of the heat pump costs are covered (currently set price of $700)	U.S.: City of Portland (government), Energy Trust of Oregon,
Integrate the GRIHA rating green building standards for all new construction (Delhi)	Green building policy will require all new construction to score at least 25% of points for each section of the GRIHA rating system	India: Delhi municipal government, GRIHA Council, SUNREF-India
Expand Affordable Green Housing	Expand existing program to aid all new 4 or 5 star-rated projects	India: Delhi municipal government, SUNREF-India

SUNREF Program (Delhi)	in financing the project, training, marketing and co-branding, reimbursement of certification costs, technical support and all other current initiatives	
Cooking Fuel Transition		
Continue and expand LPG adoption subsidies (India)	Expand access to PMUY to more rural women	India: Ministry of Petroleum and Natural Gas, Oil Marketing Company
Reduce mistargeting of LPG subsidies (India)	Remove subsidy for high earning population and expand "Give It Up" campaign	India: Delhi municipal government, national government
Further subsidies for LPG after adoption (India)	Reduce price of LPG from market rate for rural and poor recipients of PMUY subsidy	India: Ministry of Petroleum and Natural Gas, Oil Marketing Company
Greater education directed at women to understand health impacts of LPG (India)	Tie government services and PMUY installation with information campaign to elucidate health impacts of LPG	India: Ministry of Health, non-profits
Increased education on induction stoves (U.S.)	Create information campaign to homeowners to explain induction stoves	US: Pacific Power and Portland Gas & Electric (utilities), Oregon state government, federal government
Establish incentives for induction stove switching such as rebates (U.S.)	Establish rebate program for homeowners to incentivize greater adoption of induction stoves	US: Pacific Power and Portland Gas & Electric (utilities), Oregon state government, federal government
Carbon Capture and Sequestration		
Investment support	Grants and/or provision of debt or equity capital until risks surrounding the technology diminish and the regulatory and policy framework become better established and understood—then investors will be more willing to commit funds without capital support	US: Pacific Power and Portland General Electric (utilities), Oregon state government, federal government India: Dellhi municipal government, three DISCOMs (utilities), national government
Operating support through subsidizing abatement	Incentives to provide additional revenue for each unit of output in stations where CCS units are operational to offset higher operating costs	US: Pacific Power and Portland General Electric (utilities), Oregon state government, federal government India: Dellhi municipal government, three DISCOMs

		(utilities), national government
Promotion of CCS technologies	Government involvement can facilitate learning opportunities and promote coordination between firms, which will facilitate more efficient infrastructure development.	US: Pacific Power and Portland General Electric (utilities), Oregon state government, federal government India: Delhi municipal government, three DISCOMs (utilities), national government

4. Conclusion

This study presents a comparative decarbonization framework for Delhi and Portland, two cities representing distinct socio-economic and infrastructural paradigms, yet facing similar imperatives to reduce greenhouse gas (GHG) emissions. By evaluating emissions contributions across core infrastructure sectors—transportation, buildings, energy, waste, and public spaces—we identified targeted, high-impact strategies to achieve significant carbon reductions while addressing systemic inequities and promoting co-benefits such as improved public health, economic opportunity, and energy resilience.

Our analysis indicates that cooking fuel switching in Delhi, supported by the Pradhan Mantri Ujjwala Yojana (PMUY), offers the potential for a 4% carbon footprint reduction, particularly by addressing fuel stacking and enhancing education about health impacts. In contrast, Portland's transition to induction stoves can reduce 11% of cooking-related emissions under a cleaner grid scenario, highlighting the role of grid decarbonization in achieving deeper reductions.

Transportation electrification emerged as a cornerstone strategy for both cities. In Delhi, vehicle electrification reduces GHG emissions by 6% under the current grid and up to 16% with a net-zero energy grid. However, infrastructure investment and grid decarbonization remain critical challenges. In Portland, electrification of passenger vehicles yields a 10% reduction with its relatively clean grid, underscoring the importance of incentives and infrastructure for electric vehicle adoption.

For the buildings sector, low-carbon heating and cooling strategies diverge significantly between the two cities. Portland can achieve a 2.9% footprint reduction by scaling up heat pump installations, benefiting from existing incentive frameworks. Meanwhile, Delhi's integration of GRIHA-certified green building standards for new construction offers a systemic, equity-driven solution to reduce emissions while enhancing urban resilience.

Carbon capture and sequestration (CCS) offers immediate emissions reductions for energy sectors dependent on fossil fuels. In Delhi, retrofitting CCS technology to coal plants could reduce 11.1% of the city's total carbon footprint, while Portland could achieve a 10.7% reduction by targeting its coal-based power imports.

Lastly, rooftop photovoltaics (PV) provide a dual benefit of emissions reduction and energy self-sufficiency. In Delhi, rooftop PV deployment on all available residential rooftops has the potential to mitigate 6% of total emissions while alleviating energy grid pressures. Portland, despite its lower solar resource, can achieve a comparable 6.22% reduction, showcasing the scalability and adaptability of this technology across geographies.

In conclusion, while Portland and Delhi present distinct challenges, their shared pathway to deep decarbonization underscores the universal principles of electrification, renewable energy integration, and infrastructure innovation. By adopting the proposed strategies, cities can serve as leaders in mitigating urban GHG emissions, driving progress toward global climate targets while fostering resilient, equitable urban futures.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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