Methodology:

Growing to Its Potential: The Value of Urban Nature for Communities, Investors, and the Climate

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About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

Table of Contents

INTRODUCTION

This methodology accompanies the report, *Growing to Its Potential: The Value of Urban Nature for Communities, Investors, and the Climate*. It is divided into four sections:

- **Quantifying the Value of Urban Nature** – Our methodology for the global analysis of the investment costs and benefits of urban nature (associated with chapter 4 of the main report).
- **Buildings** – Our methodology for modeling urban nature's energy, emissions, and cost benefits for buildings in the cities of Abidjan, Côte d'Ivoire, and Sacramento, California (associated with chapters 5 and 6 of the main report).
- **Stormwater Management** – Our methodology for modeling urban nature's emissions and cost benefits for stormwater management in the cities of Ahmedabad, India, and Houston, Texas (associated with chapters 5 and 7 of the main report).
- **Transportation** – Our methodology for modeling urban nature's energy, emissions, and cost benefits for transportation in the cities of Austin, Texas, and Curitiba, Brazil (associated with chapters 5 and 8 of the main report).

All economic values are inflation-adjusted to 2022 US dollars based on the US Consumer Price Index. Any value not in US$ was converted to US$ in the estimate's year and adjusted to be in US$ 2022. Analysis was completed by June 2022.

METHODOLOGY: QUANTIFYING THE VALUE OF URBAN NATURE

This analysis estimates the future investment costs and benefits of urban nature globally in monetary terms.

Step 1: Review Literature

We began with a review of the relevant literature on the investment potential of urban and nonurban nature, as well as costs and associated benefits. This included global estimates, meta-analyses, and case studies on the costs and benefits of urban nature projects in individual cities.

The most relevant sources and their findings include the following:

- *BiodiverCities by 2030: Transforming Cities' Relationship with Nature* (World Economic Forum, Arup, and Alphabeta, 2022): Estimates the investment opportunity and business value generated by 11 categories of nature-based solutions to meet urban biodiversity need, based on the World Economic Forum's *Future of Nature and Business* report. The report estimates the total investment value of urban nature-based solutions (NbS) to be $113 billion/year (US$ 2019), creating $231 billion/year (US$ 2019) in annual business value in 2030. It was used in this analysis to inform estimates for green roofs, coastal wetlands, and bodies of water. Additionally, the report downscales the *State of Finance for Nature*'s estimate of the current NbS investment in cities to be $28 billion/year (US$ 2019). However, this is a likely an underestimation because it includes only water resources, conservation and land management, pollution control, and other natural resources ($17 billion), and pollution abatement, wastewater management, and environmental protection ($11 billion) (see *State of Finance for Nature* for more information).[1]

- *Identifying Biodiversity Threats and Sizing Business Opportunities – Methodological Note to the New Nature Economy Report II: The Future of Nature and Business* (AlphaBeta, 2020): Presents the methodology and estimates for the business value of 59 nature-positive business opportunities globally, 10 of which are relevant for urban areas and form the basis for the estimates included in *BiodiverCities by 2030: Transforming Cities' Relationship with Nature.*[2]

- *State of Finance for Nature: Tripling Investments in Nature-Based Solutions by 2030* (UNEP, WEF, ELD, and Vivid Economics, 2021): Estimates the current global financial flow into nature to be $133 billion/year (US$ 2020) and the future investment potential of four categories of nature to be $536 billion/year or $8.1 trillion cumulatively. The report includes reforestation/afforestation, mangrove restoration, peatland restoration, and silvopasture but does not explicitly estimate urban nature or include types of nature commonly found in cities such as green roofs or parks.[3]

- *How Can Investment in Nature Close the Infrastructure Gap?* (IISD, 2021): Estimates the future global infrastructure need and the percentage that can be met through nature as opposed to grey infrastructure (11%). A $241 billion investment in nature-based infrastructure would create $489 billion in value. The report does not identify the share that would occur in urban areas.[4]

- *Financing Nature: Closing the Global Biodiversity Financing Gap* (The Paulson Institute, The Nature Conservancy, and the Cornell Atkinson Center for Sustainability, 2020): Estimates the biodiversity conservation funding needs in urban areas to be $72.6 billion to $72.7 billion per year (US$ 2019). The report does not classify this estimate by type of urban nature.[5]

- *A Catalogue of Nature-Based Solutions for Urban Resilience* (The World Bank, 2021): A compendium of 14 types of NbS commonly found in urban areas. For each NbS type, the catalogue introduces considerations for their costs and provides examples of project costs in cities around the world.[6]

- *Planting Healthy Air* (TNC, 2016): Estimates the maximum potential investment in urban street trees in 245 cities — home to 910 million people — to be $3.2 billion/year (US$ 2015) and estimates the associated health, temperature, energy, and carbon savings.[7]

- *Financing the Earth's Assets: The Case for Mangroves as Nature-Based Climate Solution* (Earth Security, 2020): Estimates an opportunity to invest $11.1 billion over 20 years in global mangrove restoration. The report identified that 65.6% of the 728,421 hectares of restorable mangroves are located in urban areas (477,844 hectares). It estimates $9,500 per hectare in initial costs for restoration over five years, followed by an additional $1,900 every five years.[8]

- *Beyond the Source: The Environmental, Economic, and Community Benefits of Source Water Protection*: Estimates the costs and benefits of investing in urban source water protection to improve, enhance, and protect drinking water for over 1.4 billion urban dwellers in more than 4,000 cities. Benefits include water treatment cost savings, carbon sequestration and storage, biodiversity, and health and well-being. These investments would benefit 4.4 billion people living in source watersheds (including those living in nonurban areas).[9] The report is the basis for estimating the investment potential of bodies of water to supply urban areas identified in *BiodiverCities by 2030* and this analysis.

- *The Economic Value of Nature-Based Solutions in European Cities* (Naturvation, accessed 2022): According to Naturvation, the total value of nature-based solutions in European cities is $1.52 billion annually.[10]

- *Urban Nature Atlas*: A collection of over 1,000 examples of urban nature-based solutions globally, including costs.[11]

Step 2: Define Urban Nature Taxonomy

We include seven types of natural features commonly found in cities for which data is available to include in this analysis: green roofs, bodies of water (including those outside cities that supply water to cities), coastal wetlands, mangroves, street trees, urban forests, and grassy parks and open green spaces.

This analysis does not explicitly include urban farms and food forests, linear parks, grasslands, gardens, green facades, bioretention areas, river floodplains, soil and fungi, or fauna as distinct categories. Some of these may be implicitly included in certain cases (e.g., the flora and fauna captured under biodiversity benefits).

Step 3: Identify Investment Size and Costs for Each Type of Urban Nature

We identify the potential investment size and costs of each urban nature type using one of the following three approaches (in descending order of preference) depending on the data available. For each type of urban nature, we could implement the following:

1. Use a literature-provided estimate of global urban investment potential for an urban nature type.
2. Use a global estimate of investment potential to derive an estimate of the urban share.
3. Estimate the urban share of a type of nature by using case studies to estimate the median cost and apply it to the urban share.

The annual investment size (amount of urban nature that needs to be restored, protected, or enhanced and the associated cost) and time frame identified are based on the source literature. Where the source literature did not specify the period of investment, we estimate the time frame for investment based on other available literature.

We divide costs into two categories: initial and ongoing costs. Initial costs reflect up-front investments to establish urban nature projects. Ongoing costs include maintenance and upkeep. Estimates for costs were identified in the literature. Where we could not find a robust global estimate, we assume the annual ongoing costs are 10% of the initial investment cost. The total ongoing costs increase as more urban nature is developed.

Step 4: Estimate Value of Benefits of Investments in Urban Nature

The following benefits are included in the analysis:[i]

- Direct economic benefits: job creation, business value created, direct sales, and direct cost savings
- Environmental benefits: reductions in air pollution, reduction in greenhouse gases, carbon storage and sequestration, increased biodiversity, improved stormwater management, and climate resilience
- Health benefits: reduced healthcare spending and lives saved, largely due to reduced temperature, reduced pollutants, and increased physical activity
- Social benefits: aesthetic value, cultural value, and recreation

Benefits are included for each type of urban nature based on their applicability and data availability (i.e., size of the benefit that would be created and its monetary value).

For each type of urban nature, we identify which benefits can be quantified based on the source literature. We then assess the magnitude and dollar value of the benefit that would be created in cities across the globe based on the investment identified in step 3. For each type of urban nature, we could implement the following:

1. Calculate the magnitude of the benefit (e.g., number of metric tons of CO_2 avoided) that would be created based on the investment identified in the previous step.
2. Estimate the dollar value of the benefit in cities globally based on one of the three approaches in descending order (depending on the data available for each benefit stream); we calculate this for each type of urban nature included in the analysis. If possible, we use an estimate of a benefit from the same sources that provide investment size and cost.
    a. Use a literature-provided estimate of the dollar value of the benefit in cities across the world.
    b. Multiply a literature-provided estimate of the dollar value of the benefit per unit (e.g., social cost of carbon) by the magnitude of the benefit found above to estimate the dollar value of the benefit in cities globally.
    c. Use case studies to estimate the median dollar value of the benefit per unit in cities globally. Multiply the median dollar value by the investment size to estimate the dollar value of the benefit in cities across the world.

We assume each benefit increases over time as investments increase and projects reach maturity. Where the source literature does not identify a time frame for a benefit's accrual, the team estimated it based on the available literature. Exhibit 2 details the benefits we include and how they accrue for each type of urban nature.

To monetize the benefits of reducing carbon emissions and the benefits of carbon sequestration and storage, we use the social cost of carbon for a 3% average discount rate identified by the Interagency Working Group on Social Cost of Greenhouse Gases, United States Government.[12]

[i] All categories of benefits produce economic value but often indirectly; we use the "direct economic benefits" category for direct benefits.

Exhibit 1: Average Annual and Cumulative Costs and Benefits of Urban Nature

Average Annual Costs and Benefits of Urban Nature

Billions of $

	2023–2030	2031–2040	2041–2050	2023–2050
Initial costs	140	89	78	98
Ongoing costs	51	160	240	160
Benefits	960	2,600	3,200	2,400
Net benefits	770	2,400	2,900	2,100

Note: All values are in May 2022 dollars. Totals do not sum due to rounding.

Source: RMI Analysis

Cumulative Costs and Benefits of Urban Nature

Trillions of $

	2023–2030	2031–2040	2041–2050	2023–2050
Initial Costs	1.1	0.9	0.8	2.7
Ongoing Costs	0.4	1.6	2.4	4.4
Benefits	7.7	26	32	66
Net Benefits	6.2	23	29	59

Note: All values are in May 2022 dollars. Totals do not sum due to rounding.

Source: RMI Analysis

Exhibit 2: Analysis by Type of Urban Nature

Type of Urban Nature	Investment Size and Cost (2023–2050)	Benefits and Value (2023–2050)
Bodies of Water for Urban Water Supply	Potential to provide drinking water to 1.4 billion urban dwellers by protecting urban bodies of water and source watersheds for initial costs of $18 billion on average per year. Ongoing costs are 12% of the initial costs.[13] **Initial costs:** $512 billion **Ongoing costs:** $1.38 trillion	Benefits included: Cost savings compared with similarly performing grey infrastructure and carbon sequestration attributable to city investment (7.5% of the total carbon sequestration provided).[14] Benefits reach 100% of their value 10 years after investment. **Total benefits:** $5.1 trillion **Net benefits:** $3.3 trillion
Coastal Wetlands	Potential to restore coastal wetlands in cities for initial costs of $5.7 billion on average per year. Ongoing costs are 4% of the initial costs.[15] **Initial costs:** $159 billion **Ongoing costs:** $86 billion	Benefits included: Business value, reduced insurance payouts.[16] Benefits reach 100% of their value 10 years after investment. **Total benefits:** $1.25 trillion **Net benefits:** $1 trillion
Grassy Parks and Open Green Spaces	Potential to create 8.5 million hectares (ha) of parks by 2050 to accommodate existing and new urban residents at a median initial cost of $160,000 per ha or $49 billion on average per year. Ongoing costs are 16% of the initial costs.[17] Costs do not include land acquisition or development of park amenities such as sports courts and swimming pools. **Initial costs:** $1.4 trillion **Ongoing costs:** $2.5 trillion	Benefits included: Less air pollution, stormwater management, improved health, tourism, cultural value, community cohesion.[18] Benefits reach 100% of their value one year after investment. **Total benefits:** $6.5 trillion **Net benefits:** $2.6 trillion
Green Roofs	Potential to spend $12.5 billion on average per year on new urban green roofs. Ongoing costs modeled are 2% of the initial costs.[19] **Initial costs:** $350 billion **Ongoing costs:** $95 billion	Benefits included: Business value, acoustic noise insulation, reduced air pollution, stormwater management, avoided cost of one roof replacement.[20] Benefits reach 100% of their value one year after investment. **Total benefits:** $5.7 trillion **Net benefits:** $5.2 trillion
Mangroves	Potential to restore 478,000 ha of coastal mangroves in cities by 2030 (approximately 65% of the world's total restorable mangroves) for an initial cost of $183 million on average per year. Ongoing costs are 20% of the initial costs every five years.[21] **Initial costs**: $5 billion **Ongoing costs:** $3 billion	Benefits included: Coastal protection, recreation and tourism, water and air purification, reduced flood damages, carbon sequestration.[22] Benefits reach 100% of their value 10 years after each investment as mangrove trees mature. **Total benefits:** $214 billion **Net benefits:** $205 billion
Street Trees	Potential to plant street trees in existing and growing urban areas to provide 90% of the air pollution benefits. Values scaled up from a study of 245 cities (home to 912 million people) to all urban population. In just 245 cities, spending $1.5 billion per year will provide over 90% of the benefits of urban street trees compared with 100% benefits for $3.2 billion per year (values in US$ 2015). Ongoing costs are 8% of the initial costs.[23] **Initial costs:** $294 billion **Ongoing costs:** $297 billion	Benefits included: Lives saved from improved air quality and reduced temperatures, energy savings, carbon emissions reduction, carbon sequestration and storage.[24] Benefits reach 100% of their value 10 years after each investment as street trees mature. **Total benefits:** $37.7 trillion **Net benefits:** $37.1 trillion
Urban Forests	Potential to reforest and afforest 10.9 million ha of urban forest by 2030 at a median cost of $3,700 per ha or $5 billion per year. Ongoing costs are 8% of the initial costs.[25] Costs and benefits are likely underestimated because they do not include the potential of forest conservation inside new and growing cities. **Initial costs:** $40 billion **Ongoing costs:** $75 billion	Benefits included: Less air pollution, carbon sequestration and storage, stormwater reduction, energy savings, temperature reduction, positive health effects, culture value, recreation and amenity services, local climate regulation.[26] Benefits reach 100% of their value 10 years after each investment as trees mature. **Total benefits:** $9.5 trillion **Net benefits:** $9.4 trillion

Source: RMI

Variation in Results

There is significant potential for additional value not included in this analysis. Including other types of urban nature, increasing investment sizes or costs, and including additional benefits would change the results of the analysis.

Benefits

If we use the upper end of the benefit size range for the number of lives saved, tons of emissions reduced and sequestered, and kilowatt-hours (kWh) of energy saved, the cumulative net benefits could be as high as $79 trillion, or $2.9 trillion on average per year. This would increase the total benefit–cost ratio to 12-to-1.

For example, we exclude benefits that are difficult to monetize or apply the monetary value of globally. These include increased property values and certain aesthetic or scenic benefits. Some estimates do exist for changes to property values. For instance, a study on the economic costs and benefits of green roofs in Canada found they may raise property values by up to $43 per square meter, which may translate to over $6,500 on a standard residential roof. If scaled globally, this translates to an additional $16 billion in added benefits from urban nature annually, or over $440 billion cumulatively by 2050. However, we exclude such values because variations in real estate markets would complicate estimating a meaningful global value.

Additionally, many of nature's benefits are intangible. For example, while it is possible to assess the aesthetic value, cultural value, or quality of life, individual preferences and value assigned will vary.

Costs

Investment costs for urban nature could vary depending on the assumption used for the size of the investment. For example, one study estimates the maximum number of street trees different cities could add. Instead of using that maximum number, we use the number of street trees that would provide at least 90% of the potential benefits related to air pollution mitigation and temperature reduction. Increasing annual spending (initial and ongoing) to provide 100% of the benefits from $21 billion to $45 billion on average would increase net benefits from $59 trillion to $80 trillion cumulatively and yield a benefit–cost ratio of 11-to-1, compared with nine-to-one for the lower investment figure.

Investment costs related to urban forests could be higher when including areas that will urbanize between now and 2050. There is an additional investment opportunity to create protected urban forests in peri-urban and newly developing areas.

Urban investments in bodies of water include surrounding watersheds that supply water to cites. Considering only the inside of a city's municipal boundaries would yield a small investment size and reduced benefits.

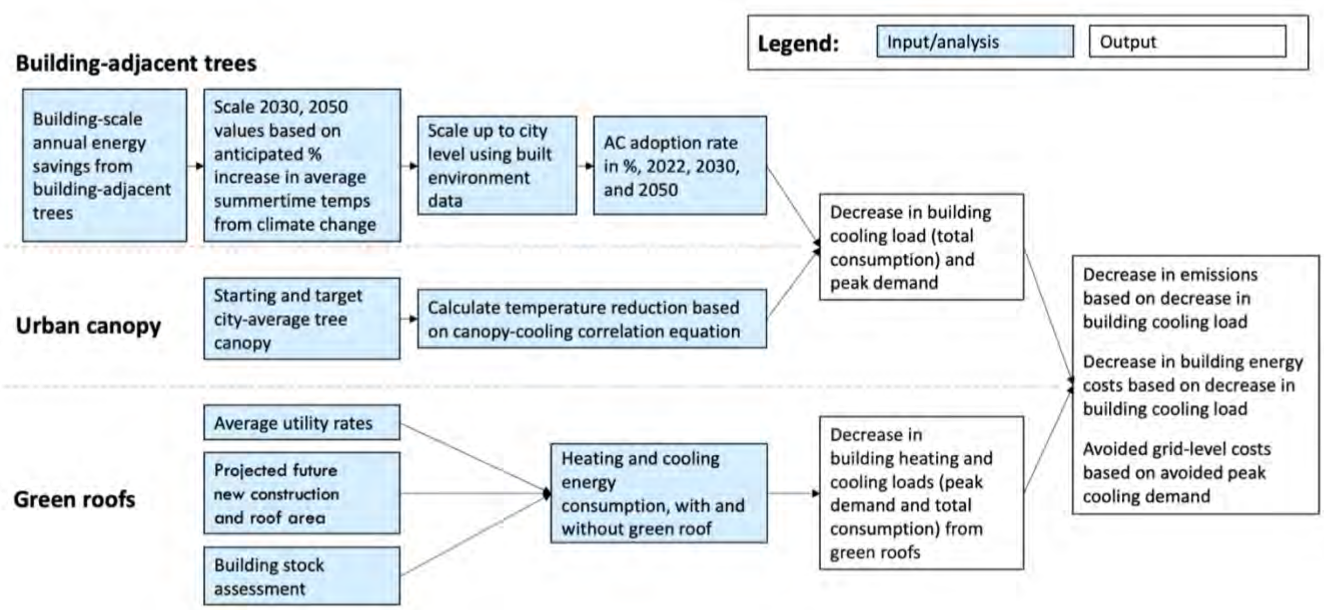
While our analysis is global, there is a need to further understand how costs and benefits vary in different city typologies. Factors including population, development stage, and local policy environment shape urban nature deployment and potential returns. Local conditions such as climate, terrain, water availability, and ecosystem health influence up-front and lifetime costs and ability to realize full benefits.

METHODOLOGY: BUILDINGS

Buildings Model Overview and Purpose

We develop a model to estimate the impact on building energy of three natural features — building-adjacent trees, overall tree canopy, and green roofs — in Abidjan, Côte d'Ivoire, and Sacramento, United States, through 2050. We use these estimates to derive the projected reduction in greenhouse gas emissions and cost, and compare saved costs to the expense of planting and maintaining urban trees and installing and maintaining green roofs in each city. Exhibit 3 visualizes the high-level methodology.

Exhibit 3: Schematic of Methodology to Estimate the Impact of Building-Adjacent Trees, Overall Urban Canopy, and Green Roofs in Abidjan and Sacramento



Source: RMI

We utilize several data sets; relationships from the literature; and existing tools, including i-Tree, the Green Roof Energy Calculator (GREC), and UrbanFootprint.[27] We use i-Tree to produce estimates of building energy savings from building-adjacent trees (annual kWh savings per building, classified by impact of shading, evapotranspiration, and windbreak) and GREC to produce estimates of building energy savings from green roofs.[28] Additionally, we use UrbanFootprint to collect building inventory data in Sacramento (including number of buildings, building age, building type, and building square footage as a percentage of parcel area) and Google Research Buildings Data for an estimate of building inventory in Abidjan (number of buildings and roof square footage). For ascertaining the impact of increasing tree canopy overall, we rely on relationships between canopy cover, urban temperature, energy consumption, and peak demand derived by Santamouris and Osmond, 2020, through their analysis of 55 global studies.[29] Exhibit 4 details the features we model.

Exhibit 4: Features Modeled for Building Analysis

Feature	Abidjan	Sacramento
Building-adjacent trees	Plant 8,000–16,000 south oriented, 10,700–21,300 west oriented, and 2,700–5,300 southwest oriented trees Species planted: Ivory Coast almond, big leaf mahogany, superb terminalia, cocoa, and raintree	Plant 25,400–50,900 south oriented, 22,900–45,800 west oriented, and 5,100–10,200 southwest oriented trees Species planted: interior live oak, valley oak, and blue oak
Increased urban canopy	Increase overall urban canopy from 14% to 30% by adding about 1.1 million trees	Increase overall urban canopy from 19% to 35% by adding about 628,000 trees
Green roofs	Add green roofs to 1.2 million square meters of new construction roofs through 2050	Add 1.4 million square meters (15 million square feet) of green roofs on about 400 existing buildings and 10,800 new construction roofs through 2050

Source: RMI Analysis

We chose Abidjan and Sacramento based on the level of thermal stress, forecast population growth, water availability, and overall geographic footprint. Abidjan is hot-humid ("tropical savanna" by the Köppen-Geiger climate-rating system), with rapid population growth and moderate-high water availability.[30] Sacramento is hot-dry ("hot-summer Mediterranean"), with low population growth and low water availability. Both cities have high thermal stress, but they are at different stages of urban growth and development and face different planning opportunities for incorporating urban nature into existing and future development. Exhibit 5 summarizes the most relevant characteristics.

Exhibit 5: Abidjan and Sacramento Typologies

Characteristic	Abidjan, Côte d'Ivoire	Sacramento, USA
Climate type	Tropical savanna[1]	Hot-summer Mediterranean[1]
Municipal area	422 square kilometers[2]	253 square kilometers[3]
GDP per capita	$5,500 (country-wide)[4]	$45,000[5]
Existing tree canopy	14%[6]	19%[7]
Municipal population	5.5 million[8]	503,000[9]
Projected 2050 municipal population	10 million[10]	630,000[11]
Mechanical cooling penetration	2.5%[12]	100%[13]
Projected mechanical cooling penetration, 2050	15%[14]	100%[15]

Table: RMI • **Source:** 1. Köppen Classification 2. Modeste Kameni Nematchoua and Sigrid Reiter, "Evaluation of Bioclimatic Potential, Energy Consumption, CO2-Emission, and Life Cycle Cost of a Residential Building Located in Sub-Saharan Africa; a Case Study of Eight Countries," *Solar Energy* 218 (April 2021): 512–24, doi:10.1016/j.solener.2021.02.052; 3. Google; 4. The World Bank, "GDP per Capita, PPP (Current International $) - Cote d'Ivoire," The World Bank Data, 2021, https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD?locations=CI; 5. Open Data Network; 6. GFW, "Area between Abidjan and Comoé, Côte d'Ivoire Interactive Forest Map & Tree Cover Change Data," Global Forest Watch, accessed April 22, 2022, https://tinyurl.com/ykhrybhy; 7. City of Sacramento, "Urban Tree Canopy Assessment Sacramento, CA," 2018, https://www.cityofsacramento.org/-/media/Corporate/Files/Public-Works/Maintenance-Services/Urban-Forest-Master-Plan/Copy-of-Sacramento-UTC-Assessment-20180515.pdf?la=en; 8. Dan Hoornweg and Kayla Pope, "Population Predictions for the World's Largest Cities in the 21st Century," *Environment and Urbanization* 29 (September 24, 2016), doi:10.1177/0956247816663557; 9. U.S. Census Bureau 10. Dan Hoornweg and Kayla Pope, 2016 (see 8); 11. State of California Department of Finance, "Projections | Department of Finance," CA.Gov, 2022, https://dof.ca.gov/forecasting/demographics/projections/; 12. IEA, *Africa Energy Outlook 2019*, IEA, November 2019, https://www.iea.org/reports/africa-energy-outlook-2019; 13. Jackie Cole, Conversation with Jackie Cole, Virtual, April 12, 2022; RMI analysis; 14. IEA, *Africa Energy Outlook 2019*; 15. Cole, Conversation with Jackie Cole; RMI analysis.

Estimating Reduction in Energy Consumption and Peak Demand from Natural Features

Building-Adjacent Trees

We model the **energy consumption savings** from building-adjacent trees starting with estimates from i-Tree, which builds off a study by McPherson and Simpson, 1999.[31] We use i-Tree calculations, obtained from the developers, to estimate savings from planting one building-adjacent tree 4.6 m (15 ft) from a building. Planted trees are five-year-old saplings (Exhibit 6 includes tree species and climate zones modeled), which grow in the model over time as per i-Tree species-specific estimates, allowing us to estimate year-by-year energy consumption savings between 2022 and 2050.

Exhibit 6: Modeled Tree Species in Abidjan and Sacramento

	Abidjan	Sacramento
Tree species and i-Tree species codes	Ivory Coast almond (Terminalia ivorensis, TEIV2), Big leaf mahogany (Khaya grandifoliola, KHGR), Superb terminalia (Terminalia superba, TESU2), Cocoa (Theobroma cacao, THCA), Raintree (Samanea Saman, PISA2)	Valley oak (Quercus lobata, QULO), Interior live oak (Quercus wislizenii, QUWI), Blue oak (Quercus douglasii, QUDO)
Climate zone	"Gulf Coast/Hawaii" climate zone	"Southwest" climate zone

Note: i-Tree has built-in climate zones primarily for the United States, so we selected the most comparable for Abidjan for this analysis (the "Gulf Coast/Hawaii" climate zone). In Abidjan, we add five species of native trees used in reforestation efforts in Côte d'Ivoire. In Sacramento, we model three species of trees currently used in local tree-planting campaigns: interior live oak, valley oak, and blue oak.

Table: RMI • **Source:** Nowak, David J. "Understanding I-Tree: Summary of Programs and Methods," 2020; Torin Dunnavant and Jessica Sanders, 2022.

We disaggregate the energy impact of each tree by its orientation to a building (south, southwest, and west) and type of impact (shading, evapotranspiration, and windbreak), focusing on the kilowatt-hours (kWh) saved in building cooling. In the northern hemisphere, building-adjacent trees provide the most cooling when planted to the west, south, or southwest of the building because of the shade they provide. Given the building data availability for scaling, we further disaggregate by building vintage type (pre-1950, 1950–80, post-1980) for Sacramento and use an average for Abidjan.

Specific data on the **peak demand reduction** of building-adjacent trees is more limited. We base our projection on a Sacramento-based estimate in Akbari et al., 1997, deriving approximations for various orientations and Abidjan's climate zone by evaluating the relationships in i-Tree estimates for energy consumption savings.[32] We modify this projection through 2050 using the i-Tree growth estimate for the height of the interior live oak tree species — a mature, tall tree provides more peak demand reduction than a small one.

We estimate the change over time in building-level peak demand and energy consumption reduction using **climate change forecast data** from the Copernicus Climate Data Store.[33,ii] We assume a one-to-one change: 1% increase in temperature would lead to 1% increase in energy savings. We compare three different climate scenarios — SSP1-1.9 (i.e., 1.9 watts per square meter, correlating to 1.5ºC temperature rise by 2100), SSP2-4.5, and SSP3-7.0 — using the average percentage change in the temperatures in warm months (June through September) for scaling energy consumption savings and the percentage change in peak temperatures in warm months for scaling peak demand reduction.[iii] While the higher-emissions scenarios (SSP2 and SSP3) lead to higher estimates of energy savings, the difference between the scenarios is small; the results in the report reflect the more ambitious SSP1 scenario for clarity.

With the final building-level estimates, we **scale up to the city level using built environment data** from both cities, assuming one to two trees planted per identified building parcel.[34] For Abidjan, we identify 53,255 buildings citywide by averaging the two data sets available from a Google satellite-derived building map.[35] For Sacramento, we identify over 136,000 buildings through

[ii] We specifically considered the near-surface air temperature (averaged at 2 m above ground) in the GFDL-ESM4 (USA) model using location-specific forecasts: 38.5 N, 121.875W for Sacramento and 5.5 N, 4.375W for Abidjan.
[iii] Shared Socioeconomic Pathways are narrative descriptions of socioeconomic trends for the 21st century. Representative Concentration Pathways describe different levels of radiative forcing (W/m^2). SSP1-1.9 is a low-emissions scenario where sustainability-focused growth and equality limit temperature increase to 1.5ºC (1.9 W/m^2). SSP2-4.5 is a moderate-emissions scenario where socioeconomic trends follow historical pathways and warming is limited to 2.7ºC (4.5 W/m^2) by the end of the century. SSP3-7.0 is a high-emissions scenario where a fragmented world and rising nationalism hinder action to reduce emissions and temperature rises as much as 3.6ºC by 2100.

UrbanFootprint and its property assessor data. As we did not want to assume all building parcels have the capacity for planting trees, we filter out the buildings in Sacramento with ground square footage greater than two-thirds the parcel square footage. We also segment by age (to align with i-Tree building vintages: pre-1950, 1950–80, post-1980). Availability of filtering criteria for Abidjan is limited, but we ultimately narrow down eligible buildings by accounting for adoption rates of mechanical cooling (see below).

We then estimate how many of the eligible parcels could accommodate west, south, and southwest **tree orientation**. For Sacramento, we derive percentages from a study of street orientations, assuming 18% to west, 20% to south, and 4% to southwest.[36] As data for Abidjan is limited, we assume 20% to west, 15% to south, and 5% to southwest. Moreover, considering Abidjan, like Sacramento, is overall oriented north-south-west-east, achieving these proportions of tree orientations should be feasible even if certain areas are not on a perfect grid.

We apply the percentages derived for eligibility and orientation to a **forecast stock of new buildings**. We assume a one-to-one increase between percent population growth and percent growth in the number of buildings, recognizing this might be an overestimate where upward growth outpaces outward growth. For population growth in Sacramento, we rely on a Sacramento County forecast from the State of California Department of Finance.[37] For Abidjan, we refer to a Hoornweg and Pope study.[38]

Finally, we scale down citywide impact by accounting for the **adoption rates of mechanical cooling**, given that energy savings do not apply to buildings that rely on passive cooling. For Abidjan, we use International Energy Agency (IEA) *Africa Energy Outlook* data from 2019 to determine the current share of urban Côte d'Ivoire households with mechanical cooling (2.5% of the households) and increase this share through 2050 in line with the gross domestic product (GDP) per capita (5.3%–7.9% compound annual growth rate).[39] As Sacramento has effectively 100% mechanical cooling adoption according to local stakeholders, we keep it static through 2050.[40]

We end with a citywide estimate of energy consumption savings (kWh) and reduction in peak demand (kW) from building-adjacent trees for Abidjan and Sacramento.

Overall Urban Canopy

We model the impact of **increasing average citywide canopy** from current baselines — 14% in Abidjan and 19.2% in Sacramento — to targets of 30% and 35%, respectively.[41] The Sacramento goal aligns with the city's recently adopted tree canopy target of 35% by 2045.[42] Abidjan suffered drastic deforestation in the recent past; the Abidjan Autonomous District, which houses Abidjan, lost 40% of its tree cover from 2000 to 2021.[43] The modeled canopy increase represents nearly replacing this loss, at least in Abidjan.

The precise impact of canopy on urban heat and building energy use varies with a multitude of factors — canopy maturity, tree location and density, tree species, urban density, climate, etc. We rely on an equation derived by Santamouris and Osmond, 2020, based on 55 case studies from 39 cities globally.[44] The equation describes the relationship between citywide average temperature (at 3 p.m.) and change in tree canopy cover:

$$\Delta T_{15mean} = 0.00013\ \Delta GI^2 + 0.0079\ \Delta GI$$

Where ΔT_{15mean} is anticipated temperature change at 3 p.m. and ΔGI is change in tree canopy cover. Although this equation does not have a range of outputs built in, outputs among different cities and different approaches to increasing tree canopy will vary. A 2015 study from Santamouris et al. provides a comprehensive view of the nuance and range of possible outcomes, but our results follow this equation for simplicity.[45]

Santamouris and Osmond provide further relationships between **drop in temperature and cooling energy consumption savings** (0.7 kWh per meter-squared of city surface and degree of temperature decrease) and **peak demand reduction** (21 ±

10.4 W per person and degree of temperature decrease).[46] For the energy consumption savings equation, we use surface area values of 253 square kilometers (Sacramento) and 422 square kilometers (Abidjan).[47] For the peak demand reduction equation, we account for the same population growth forecasts as for building-adjacent trees. In both cities, all modeled trees are planted as five-year-old saplings in 2022.

We end with a citywide estimate of energy consumption savings (kWh) and reduction in peak demand (kilowatts or kW) from overall increase in canopy for Abidjan and Sacramento. This estimate is indicative but not predictive. A myriad of factors can fuel the error ranges present in the relationship. The range of our results accounts for these error ranges in addition to ranges in our other assumptions (for example, planting one versus two building-adjacent trees at identified buildings).

Green Roofs

Existing Building Stock Suitability for Green Roofs

Many existing buildings do not have the structural capacity to support the added weight of green roofs, especially buildings with light wood and steel framing. That said, old concrete and masonry buildings often have thick walls and increased structural capacity that could support green roofs. In the United States, the shift from heavy materials to lightweight members in building materials accelerated after the end of World War II.[48] We assess suitable existing buildings for Sacramento only, as we have insufficient information on the structural capacity of existing buildings in Abidjan to make accurate assumptions.

For Sacramento, we use assessor's data from the UrbanFootprint tool to identify old buildings that may be structurally suitable for added green roofs: commercial and multifamily residential buildings built before 1945. We exclude single-family residential and duplex buildings, industrial buildings, vacant lots and parking lots, and agricultural buildings. Of the buildings included, we apply a scaling factor of 36% to account for those with flat roofs, based on a regional average from Commercial Building Energy Consumption Survey (CBECS) data.[49] As the Sacramento assessor's data set excludes roof area, we use ground floor area as a proxy.

New Building Stock Suitability for Green Roofs — Sacramento

To estimate the potential of future green roofs in Sacramento, we again use assessor's data from UrbanFootprint. We identify the breakdown of building use types and estimate the roof area for each (again using ground floor area as a proxy). We exclude industrial buildings, parking lots, and agricultural buildings. For new building stock, we include commercial and single-family residential and duplex use types, as many modern residential buildings have flat roofs (we exclude industrial buildings, parking lots, and agricultural buildings). We apply a 60% scaling factor to account for 40% of the roof area needed for other purposes, such as access chimneys; heating, ventilation, and air conditioning (HVAC); and access for maintenance of roof elements. This would require approximately 362–1,290 green roof installations per year. This rate is likely higher than the number of green roofs currently being built in Sacramento, but it is feasible with supportive code and regulatory incentives.

To **estimate building stock growth over time**, we apply anticipated population growth rates for Sacramento County to the existing building ground floor area, assuming a one-for-one increase between population and number of buildings, to project how city ground floor area would increase over time with population growth.[50] As with building-adjacent trees, we recognize this may be an overestimate where upward growth outpaces outward growth.

New Building Stock Suitability for Green Roofs — Abidjan

To **estimate building stock growth over time**, we apply anticipated population growth rates from a Hoornweg and Pope study to the existing building ground floor area (using Google Research Buildings Data for an estimate of building inventory in Abidjan, including number of buildings and roof square footage).[51] In the case of Abidjan, we assume 30% of the new roofs could be suitable for green roofs under the right regulatory incentives. This estimate factors in the limited number of green roofs currently in Abidjan.

Estimating Energy Consumption Reduction from Green Roofs

For existing buildings and new construction, we **calculate energy savings from green roofs** compared with baseline dark-colored roofs using the Green Roof Energy Calculator (GREC 2.0) developed by Arizona State University.[52] GREC only has climate zones for cities in the United States and Canada, including Sacramento. For Abidjan, we run calculations for Miami, Florida, which is its closest Köppen Classification climate zone (Miami is part "tropical monsoon" and part "tropical savanna").

We run calculations in GREC for four building use types in Sacramento: existing commercial, existing residential, new commercial, and new residential. For Abidjan, we only run the two new construction use types. We run calculations twice for each use type — once assuming the green roofs would be irrigated and once assuming no irrigation — averaging those results.

For "Growing Media," we assume 11.4 cm (or 4.5 in, consistent with extensive green roof systems) and a "Leaf Area Index" of 2. The methodology in the *Delivering Urban Resilience* report from the Smart Surfaces Coalition informs these values.[53]

The assumptions for utility rates are in Exhibit 7.[54] Sacramento experiences cool winters, with buildings using energy for heating. Here, green roofs provide winter heating benefits in addition to summer cooling benefits, as they provide additional thermal mass to a building's roof. However, in Abidjan, mild winters mean buildings use little to no energy for heating. As green roofs do not provide winter heating benefits in Abidjan, we do not need local gas prices for our model.

Exhibit 7: Utility Rates Used for Sacramento and Abidjan Green Roof Energy and Emissions Estimates

City	Building Use Type	Electricity Rates	Gas Rates
Sacramento	New/Existing Residential	$0.1689 per kWh	$1.25 per Therm
Sacramento	New/Existing Commercial	$0.1689 per kWh	$0.91 per Therm
Abidjan	New Residential	$0.12 per kWh	N/A
Abidjan	New Commercial	$0.20 per kWh	N/A

Table: RMI • **Source:** Sacramento values come from US EPA state utility rate averages. Abidjan values from globalpetrolprices.com

For each calculation run, we assume a roof area of 930 square meters (10,000 square feet) and divide the output to get an energy savings estimate per square meter. As with building-adjacent trees, we scale building energy consumption reduction estimates using **climate change forecast data** from the Copernicus Climate Data Store.[55,iv] We assume a one-for-one scaling for the same three climate scenarios outlined in the *Building-Adjacent Trees* section above. Again, as the results do not significantly differ by climate scenario, the results in the report reflect the more ambitious SSP1 scenario for clarity.

Notes on Green Roof Trade-Offs with Other Roof Uses

While the shade from building-adjacent trees can limit the use of rooftop photovoltaics (PV), green roofs and PV can be compatible where budget and structural capacity allow. Green roofs cool the roof surface (sometimes by 17°C–22°C or 30°F–40°F) as well as the surrounding air, which can increase the yield of PV panels. Plants naturally filter the air and can reduce dust and pollution accumulation on panels, further increasing their efficiency. The shade from PV panels can support more diverse green roofs, providing opportunities for plants that grow in direct and indirect sun.[56]

[iv] We used near-surface (2 m above ground) air temperature in the GFDL-ESM4 (USA) model, using location-specific forecasts: 38.5N, 121.875W for Sacramento and 5.5N, 4.375W for Abidjan.

Notes on Unevaluated Green Roof Benefits

In our model, we do not quantify the full range of cobenefits associated with green roofs, such as stormwater retention, improved health, and employment. Our results focus on the energy and emissions benefits and, therefore, undervalue the benefits of green roofs and urban trees. Additionally, while we quantify the peak demand benefits for urban trees, we did not have the data to do the same for green roofs. Finally, green roofs provide more energy benefit in cool climates that see summer cooling savings and winter heating reductions from the added insulation. A more complete quantification of the benefits of green roofs would provide a stronger investment case than energy consumption savings alone.

Estimating Emissions Avoided, Cost Savings, and Return on Investment

Translating Reductions in Energy Consumption and Peak Demand into Emissions and Cost Savings

For each feature, we translate the reduction in energy consumption and peak demand into avoided greenhouse gas emissions and costs. For **greenhouse gas emissions**, we multiply the avoided energy consumption by average annual grid marginal emissions factors, as these savings, like most energy efficiency savings, would cut demand at the margins of grid generation. In Sacramento, we begin with current marginal emissions data for the California Independent System Operator (CAISO), given some interconnections with SMUD territory, and for broadly applicable takeaways. We forecast changes to the marginal emissions factor through 2050, bringing emissions to zero by 2050, in line with an RMI 1.5°C-aligned grid scenario and California's own plans for carbon neutrality.[57] In Abidjan, we average two IEA scenarios for Côte d'Ivoire's 2040 grid composition — going from a 2018 grid that is 25% hydro and 75% fossil gas to a 2040 grid that is 6% coal, 46% fossil gas, 2% oil, and 46% renewables (including hydro) and quantifying the emissions factors accordingly.[58]

To estimate **saved customer spend on electricity consumption** (all in US$ 2022), for Sacramento, we begin with California's average retail rate ($0.197/kWh in 2020) from the US Energy Information Administration (EIA) and forecast forward by extending the 2000–19 trends.[59] For Abidjan, we use the average of countrywide business and household power rates ($0.177/kWh in 2021) and scale them in line with California rate increases.[60]

The other cost-saving category we estimate is **avoided investment in new power generation** based on the reduction in peak demand we quantify for building-adjacent trees and overall canopy increase. While saved energy consumption costs repeat in our model every year, avoided generation investment is incremental and the timing depends on when the system operator invests in new generation. We collect typical capital costs per kW for various generation technologies from the EIA, averaging the cost of likely technologies for each geography.[61] For Sacramento, we average gas combustion turbines (typical peaker plants), onshore wind, and solar photovoltaics for an average cost of about $1,400 per kW.[62] For Abidjan, we average coal, gas combustion turbines, gas combined cycle, onshore wind, solar photovoltaics, and hydro for an average cost of about $2,200 per kW.[63] To compare avoided generation capacity to avoided peaker plant units, we consider the EIA unit capacity figures for gas combustion turbines and find mean and median capacities of 60–70 MW.[64]

Estimating the Cost of All Three Features

In addition to estimating energy cost savings, we estimate initial and ongoing costs for the features we model. For the two tree planting features, we assume an initial purchase cost of $36.51 per tree and an annual maintenance cost of $3.65 based on a recent study from IISD and conversations with stakeholders.[65] While the cost per tree for city-run tree planting programs can vary based on community outreach and education, involved labor, and other factors, we decided to narrow our cost scope to just the trees. All tree planting occurs in the first year in our model, but we also account for some tree mortality and necessary replacement through 2050. We assume mortality rates in line with i-Tree estimates (2%–3% depending on tree age).[66]

We multiply the per-tree costs by the number of trees. This number was defined in our building-adjacent tree planting feature but derived for overall canopy increase. To obtain this number, we assume each planted tree has a mature crown radius of 4.5 meters and area of 260 square meters on average. We then quantify the trees needed to fulfill the city's target canopy increase — for example, increasing Sacramento's canopy to 35% would mean planting trees to cover 16% of the 422 square kilometers and require roughly 1.06 million trees (inclusive of building-adjacent tree planting we model).[67]

To estimate the initial and maintenance cost of green roofs (as seen in Exhibit 8), we multiply the total area of green roofs by values for installation cost and annual maintenance cost. We use values from the *Delivering Urban Resilience* report, increased to account for inflation since the report was published in 2018, and accounting for anticipated decreases in installation and maintenance costs after 2025.[68] We use the same values for Abidjan due to lack of cost information on green roofs.

Exhibit 8: Cost of Green Roof Installation and Maintenance

Cost input	Price	Units
Installation (before 2025)	$17.46	US$ / ft^2
Installation (after 2025)	$11.64	US$ / ft^2
Maintenance (before 2025)	$0.54	US$ / ft^2 / year
Maintenance (after 2025)	$0.36	US$ / ft^2 / year

Note: Prices decrease after 2025 to reflect more experience and competition in the green roof market.

Table: RMI • **Source:** Price originally from *Delivering Urban Resilience* report (2018), adjusted to represent inflation.

Estimating the Present Value and Payback of All Three Features

To estimate the present value and payback, we compare cumulative costs against cumulative benefits for each feature individually and for combinations. All three features have initial and ongoing maintenance costs, and we quantify annual avoided energy consumption costs for all. For the two tree planting features, we also quantify avoided investment in new power generation on the benefits side. We compare costs and benefits without a discount rate given the long-term nature of the investments, nonlinear risks and tipping points involved, and our decision not to discount the costs future generations will have to bear.

Projecting Future Power Consumption, Demand, and Emissions

While not the core of our modeling, we project future power demand in our focus cities to better contextualize our results. In both cities, we consider two scenarios for increasing peak demand and overall energy consumption, contextualizing our results in chapters 5 and 6 between an average of the two.

For Abidjan, we built off the 2019 *Africa Energy Outlook* from the IEA.[69] Based on two data points — Côte d'Ivoire-wide 2018 per capita energy consumption of 275 kWh and a 2018 electricity access rate of 63% — we estimate a 2018 Abidjan-specific per capita consumption of 437 kWh (because electricity access is much more pervasive in the city). We then identify two scenarios of how this per capita consumption will change, one based on the IEA's Africa Case (3.8% annual growth in per capita consumption) and the other on the Stated Policies Scenario (1.5%). To get citywide electricity consumption, we multiply the forecast per capita consumption by the projected population.[70] We apply the same growth forecasts to citywide anticipated peak demand, assuming a 2020 Abidjan peak demand of roughly 960 MW (countrywide 2020 peak demand was 1,600 MW, and Abidjan makes up 60% of the country's GDP[71]). Our business-as-usual (BAU) consumption emissions forecast is based on the total anticipated power consumption and forecast marginal emissions factor, as explained above.

For Sacramento, SMUD's Integrated Resource Plan from 2019 projects power demand and power consumption through 2030 and subsequently estimates 1% annual growth.[72] The projection accounts for committed and achievable energy efficiency, behind-the-meter solar and storage, building electrification, and transportation electrification. To account for uncertainty, we derive a second scenario with less energy efficiency achieved, carving out SMUD's anticipated energy efficiency through 2030 and increasing the growth forecast from 1% to 2% beyond that. We apply a similar increase in the growth rate for peak demand estimates. As in Abidjan, our BAU consumption emissions forecast is based on total anticipated power consumption and forecast marginal emissions factor.

Notes on Summing Impact Across Features

In our model, the two tree planting features explicitly overlap in of costs and benefits. To avoid double-counting, we subtract the impact of building-adjacent tree planting from that of canopy increase. We first quantify the overlap: assuming each tree will have a mature crown radius of 4.5 meters and crown area of 260 square meters, we estimate the amount of canopy increase due to building-adjacent tree planting alone versus that from other tree planting. For Sacramento, for example, we model 52,441–106,882 building-adjacent trees. The total canopy increase we model (15.8%) would require just over 628,000 trees. This means building-adjacent trees constitute 8%–17%of the required tree planting, and we obtained the amount of benefit from the overall canopy increase when summing impact. The building-adjacent tree modeling covers this impact.

Limitations of the Modeling

The total effect of urban nature on reducing building energy use and associated emissions and costs is far greater than our results show; we only analyze the *incremental* effect from adding nature and not the effects of the existing urban nature.

We neither include all building-scale natural features such as green walls and facades or non-tree building-adjacent nature nor model potential reductions in the adoption or size of cooling systems or units due to reduced cooling needs. While we consider the financial savings from avoided new power generation, we exclude savings from avoided electric grid transmission and distribution infrastructure. Moreover, we do not account for future high-efficiency cooling, the potential increase in material size and embodied carbon in buildings to support the additional structural requirements of green roofs (which can be mitigated through better design), or the trade-off that can exist between tree shade and rooftop solar photovoltaics (PV) in some cases.

METHODOLOGY: STORMWATER MANAGEMENT

Stormwater Management Model Overview and Purpose

For Ahmedabad, India, and Houston, United States, we determine embodied carbon, cost, and runoff performance of green and grey infrastructure scenarios by determining the features needed for each scenario to capture sufficient stormwater runoff.

We developed models by using existing tools such as CLASIC and E^2STORMED (more information below) and creating an Excel model to determine the volume of runoff that would occur from location-appropriate design storms (hypothetical rainstorms with a specific intensity, frequency, and depth of rainfall that an urban infrastructure system is designed to withstand).[73] We analyze three different infrastructure scenarios for each city (green, hybrid, and grey scenarios for Houston and green, low-impact grey, and high-impact grey scenarios for Ahmedabad) and calculate the size and number of features required in each scenario to capture the estimated runoff. Finally, we compare the embodied carbon, cost, and runoff performance of the three stormwater management approaches to design green and hybrid scenarios that minimize embodied carbon and total costs relative to conventional concrete features while maintaining (or improving) stormwater runoff management.

City approaches to stormwater management vary by not only local climate, context, and stormwater management needs but also population density and anticipated population and geographic growth. Accounting for these differences, we determined two distinct and tailored stormwater management approaches to model for Ahmedabad and Houston.

City Typologies

We model Ahmedabad and Houston to give a range of precipitation intensity and frequency, population density (as a proxy for the space available to preserve and create high-quality natural areas for stormwater management), and forecast population growth. Both cities face challenges in stormwater management, experience groundwater depletion, and are projected to have high water stress by 2030.[74] Relevant characteristics of the cities are included in Exhibit 9.

Exhibit 9: Ahmedabad and Houston Characteristics

Characteristic	Ahmedabad, India	Houston, USA
Climate type	Hot semi-arid[1]	Humid subtropical[2]
Municipal area	466 square kilometers[3]	1,722 square kilometers[4]
Municipal population	8.3 million[3]	2.3 million[5]
Projected municipal population (by 2030)	12.4 million[3]	3.3 million[6]
Population density	10,500 people/kilometer[3]	1,352 people/kilometer[7]
Geographic location	Riverine[8]	Coastal/Riverine[9]
Projected water stress	Extremely high stress[10]	High stress[10]

Table: RMI • **Source:** 1. Sarkar Jayanta and J Chicholikar R., "Future Climate Change Scenario at Hot Semi-Arid Climate of Ahmedabad (23.04°N, 72.38°E), India Based on Statistical Downscaling by LARS-WG Model" (*Asian Journal of Water, Environment and Pollution*, 2016), https://content.iospress.com/articles/asian-journal-of-water-environment-and-pollution/ajw16000; 2. Weatherbase, "Houston, Texas Koppen Climate" (Weatherbase, 2022), https://www.weatherbase.com/weather/weather-summary.php3?s=34227&cityname=Houston,+Texas,+United+States+of+America; 3. Madhu Bharti and Shagun Mehrotra, "Scaling Up with Contiguous Replication of Town Planning Schemes," n.d., 43; 4. U.S. Census Bureau, "QuickFacts: Houston City, Texas; United States," U.S. Census Bureau, July 2021, https://www.census.gov/quickfacts/houstoncitytexas; 5. World Population Review, "Houston, Texas Population 2022" (World Population Review, 2022), https://worldpopulationreview.com/us-cities/houston-tx-population; "Population Projections 2000-2060," accessed July 25, 2022, https://www.houstontx.gov/planning/Demographics/demograph_docs/PopProjections.htm; 6. World Population Review, "Houston, Texas Population 2022" (World Population Review, 2022), https://worldpopulationreview.com/us-cities/houston-tx-population; "Population Projections 2000-2060," accessed July 25, 2022, https://www.houstontx.gov/planning/Demographics/demograph_docs/PopProjections.htm; 7. U.S. Census Bureau, "QuickFacts: Houston City, Texas; United States," U.S. Census Bureau, July 2021, https://www.census.gov/quickfacts/houstoncitytexas; 8. Ahmedabad Guide, "Ahmedabad Location," 2022, https://www.ahmedabad.org.uk/travel-tips/location.html; 9. Edgewater by Johnson Development, "Is Houston Considered a Coastal City? Yep!", 2022, https://www.edgewaterwebster.com/is-houston-a-coastal-city; 10. WRI, "Aqueduct Water Risk Atlas," accessed April 22, 2022, https://www.wri.org/aqueduct.

Future Rainfall and Climate Forecasts

The storms we model for Ahmedabad and Houston reflect their expected rainfall and flood risk, considering that neither total annual nor seasonal rainfall is projected to change significantly for either city through 2050.[75] Houston policy requires stormwater management infrastructure to capture and convey the rainfall from a two-year design storm (13 cm or 5.1 in over 24 hours), which has a 50% chance of occurring in a given year. We use this design storm when modeling all three scenarios in Houston.[76] Additionally, Houston's required designed storm — and therefore our model — reflects the most recent rainfall estimates from the National Oceanic and Atmospheric Administration (NOAA).[77] To reflect short periods of intense monsoon rainfall, our Ahmedabad design storm of 12.7 cm or 5 in of rain over 24 hours is in the 98th percentile of intensity (classified as very heavy rainfall) for the city over the past 40 years.[78] The Ahmedabad model also reflects post-2000 trends in rainfall.[79]

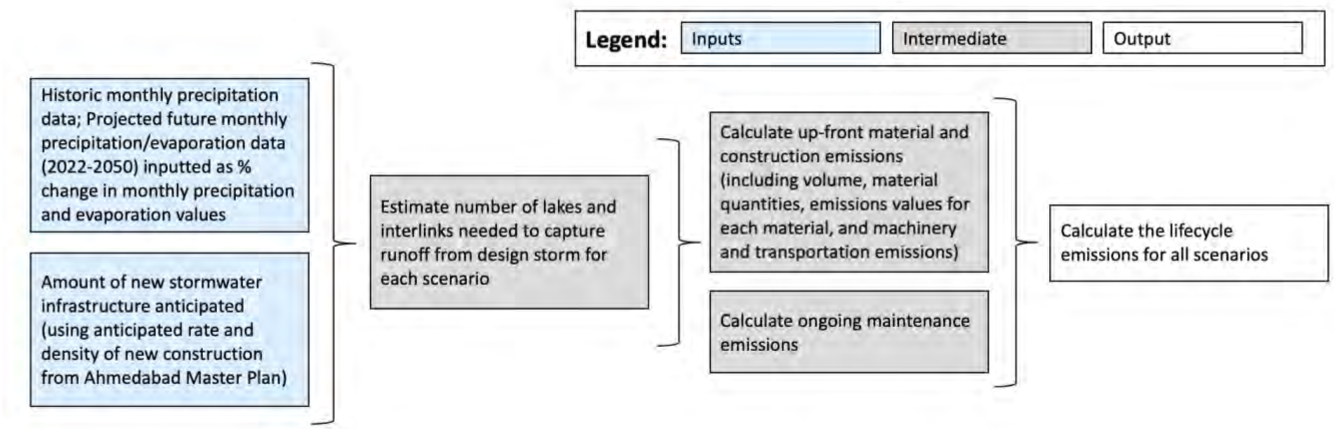
Ahmedabad Model Overview

For Ahmedabad, we compare the runoff, embodied carbon, and cost impact of developing and linking lakes to capture stormwater runoff across three scenarios: a baseline high-impact grey scenario, a low-impact grey scenario, and a green scenario (methodology in Exhibit 10; assumptions summarized in Exhibit 11).[v] We focus on an area in eastern Ahmedabad where development is currently minimal and urban expansion is likely, and project future development with population growth

[v] Embodied carbon describes the carbon emissions associated with a product's entire life cycle: material extraction and manufacturing, transportation, construction and annual maintenance, and disposal or rehabilitation at the end of life.

estimates.[80] We assume this growth would be of higher density — about 16,600 people per square kilometer — than the current average for Ahmedabad (10,500 people per square kilometer in 2017), resulting in a study area of 94 square kilometers.[vi,81]

Exhibit 10: Schematic of Methodology to Estimate Embodied Carbon and Costs of Stormwater Management Infrastructure in Ahmedabad



Source: RMI

[vi] While the density modeled (16,600 people per square kilometer) is higher than the current average for Ahmedabad, it is below the maximum density of 56,368 people per square kilometer in Ahmedabad in 2017.

Exhibit 11: Modeled Scenarios and Associated Features in Ahmedabad

Scenario	Feature	Details
Green	Pocket forests and parks	15% green cover 14 km^2
	Natural lakes	5 large (300m x 300m x 30m) 10 medium (150m x 150m x 18m) 68 small (50m x 50m x 18m)
	Waterways connected by open canals	79,600 meter length of canals 8,800 meter length of box drains 6,200 cubic meters of reinforced concrete
Low-Impact Grey	Pocket forests and parks	15% green cover 14 km^2
	Gabion (stone and wire mesh) lined lakes	5 large (300m x 300m x 30m) 10 medium (150m x 150m x 18m) 68 small (50m x 50m x 18m)
	Waterways connected with 2m x 2m box drains	88,400 meter length box drain 62,000 cubic meters of reinforced concrete
High-Impact Grey	Pocket forests and parks	15% green cover 14 km^2
	Concrete-lined lakes	5 large (300m x 300m x 30m) 10 medium (150m x 150m x 18m) 68 small (50m x 50m x 18m)
	Waterways connected with 2m x 2m box drains	88,400 meter length box drains 62,000 cubic meters of reinforced concrete

Example of green scenarios with natural lake walls (top), low-impact grey with gabion-lined lake walls (middle), and high-impact grey with concrete-lined lake walls (bottom). Credit: Rambilassingh via Wikimedia (CC-BY-SA-3.0); Leonard Bentley via Flickr (CC-BY-SA-2.0); Ansh Mishra via Wikimedia (CC-BY-SA-4.0).

Source: RMI Analysis

Our study uses an approach to stormwater management that Ahmedabad has taken historically — utilizing existing lakes and wetlands and interlinking the lakes to allow for stormwater conveyance during heavy rainfall for flood prevention.[82] As the city grows, new development fills and paves over existing lakes, ponds, and wetlands. We consider a roughly 250-square-kilometer area east of the city that is zoned for commercial, residential, and industrial development and that includes general agriculture land (not prime agriculture land), and we estimate about 250 existing water bodies (ponds, lakes, and wetlands). While some new lakes may be added where needed based on future development patterns, Ahmedabad has the opportunity to preserve these existing lakes for stormwater management and plan development around them.

For all scenarios, we assume 15% of the land is a green, natural cover aligning with Ahmedabad's 2025 green cover goal (excluding the area of the modeled lakes).[83] We assume the city will preserve existing lakes in the area of new development in all scenarios, thus requiring few new lakes. For the lakes, we assume the high-impact grey scenario would entail lining new and existing lakes with reinforced concrete and connecting them with reinforced concrete box drains. This scenario serves as a baseline in our study for cost and embodied carbon. The low-impact grey scenario utilizes gabions (wire mesh cages filled with rocks or stones). The green scenario assumes existing lakes in the study area are preserved, with some required to be regraded and interlinked via natural waterways and irrigation canals — some existing from agriculture in the area and some new. Where roads and infrastructure already exist, box drains would be needed for free-flowing waterways to accommodate the existing development. Therefore, we assume 10% of the total canal length in the green scenario would need to be box drains.[vii] For natural waterways and irrigation canals, we account for emissions from excavation and soil haul-off but assume no additional materials would be used.

Estimating Current and Future Stormwater Runoff

To estimate runoff, we first distinguish between different types of land cover in the expansion zone and use land cover data to estimate projected impervious development (buildings, roads, and parking lots) and existing natural land cover (grasslands, lakes, wetlands, parks, trees, etc.).[84] As we were unable to find geospatial modeling software for Ahmedabad, we use stormwater management criteria and equations published by the Washington, D.C., Department of Energy and Environment (DOEE) as the proxy to calculate resultant runoff in our design storm.[85] The equations help size detention basins for expected runoff based on criteria such as intensity of rainfall events and type of land cover. One limitation is that DOEE's equations are typically used for neighborhood-scale and parcel-scale modeling, whereas we apply the equation to a much larger area.

Our analysis period is 2022–50 and we base necessary stormwater management features on projected population growth in this time frame, linking annual population growth estimates with anticipated growth of impervious area.[86] Consistent with the city's own objectives in its zoning plan, we assume growth is compact and residents are connected to key activities through transit corridors. This will help preserve natural landscapes and prime agricultural areas through 2050, maintaining their ability to retain stormwater runoff and reduce flooding.

We size the lakes in all three scenarios to have enough capacity for the design storm's intense rainfall such that they could serve as the primary stormwater management feature. We model three lake sizes to reflect their heterogeneity in the existing landscape and allow flexibility for development based on local site conditions (number of lakes are those needed by 2050):

- Five large lakes (300m x 300m x 30m deep) to capture 65% of the runoff
- Ten medium lakes (150m x 150m x 18m deep) to capture 20% of the runoff
- Sixty-eight small lakes (50m x 50m x 18m deep) to capture 15% of the runoff

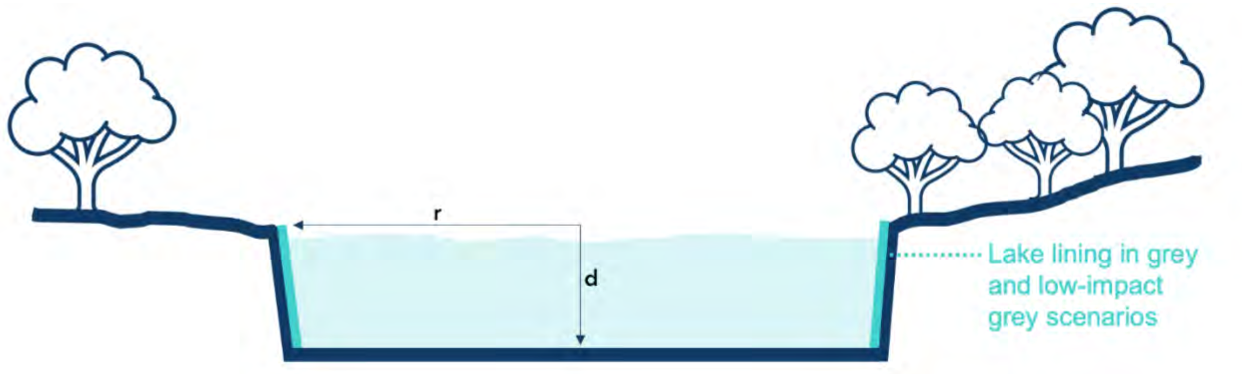
Considering the lakes' shape, we calculate the volume of water captured in each lake size using the formula for the volume of a cone's frustum. However, given that the lakes are wide rather than deep, we simplify the calculation using the following formula for the volume of a cylinder (the results for the cylinder approach are within 2% of the frustum approach; illustrated in Exhibit 12 below):

$$v = \pi * r_w * r_l * d$$

v = volume, π = pi, r_w = lake width radius, r_l = lake length radius, d = lake depth

[vii] 10% assumption based on a visual assessment using Google Earth and the Ahmedabad Urban Development Authority's 2021 Proposed Zoning map to estimate the amount of development and road infrastructure already in place in the study area in Ahmedabad.

Exhibit 12: Lake Section to Illustrate Volume Calculation and Wall Surface Area



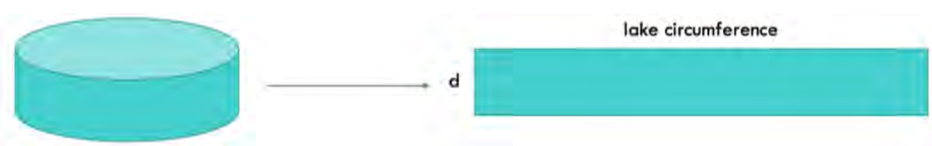
Source: RMI

Estimating Embodied Carbon of Stormwater Infrastructure for Each Scenario

We first calculate the total volume of material used in each scenario. The high-impact grey scenario assumes lake walls are lined with reinforced concrete (the lake bottom is unlined) (see Exhibit 12). We assume the walls would be 0.15 m (approximately 6 inches) thick with 5% reinforcement by weight. To simplify the calculation, we generalize that lakes would be round (same length as width). To calculate the surface area of the lake walls, we use a formula for the side surface area of a cylinder:

$$a = d * 2\pi r$$

a = wall area, d = lake depth, r = radius of lake



We calculate these dimensions for each size of lake and multiply by the total number of lakes needed to capture runoff from the design storm. As a result, the high-impact grey scenario requires a total volume of 62,000 m^3 of reinforced concrete. We repeat this process for the low-impact grey scenario, assuming the same 0.15 m (6 inches) thickness, again requiring 62,000 m^3 of gabions (river rocks in wire mesh). For the green scenario, we assume no lake wall lining (the natural lake walls would remain unchanged), requiring no additional materials. To estimate embodied carbon, we then multiply the total estimated volume of materials for each scenario by the embodied carbon of that material. We use embodied carbon values listed in Exhibit 13.[87] Industry average embodied carbon values were used due to limited data on the embodied carbon of materials manufactured in India.

Exhibit 13: Embodied Carbon of Materials Used in the Model

Material	Embodied Carbon	Units	Source
Concrete (average)[i]	284	$kgCO_2/m^3$	ICE[1]
Rebar (average)	0	$kgCO_2/lb$	EC3[2]
Wire mesh	384	$kgCO_2/100m^2$	Pathfinder (Athena)[3]
Stone	0	$kgCO_2e/kg$	ICE
Ordinary Portland cement (OPC) precast concrete (box drains)	353	$kgCO_2e/m^3$	ICE
Construction Process	**Embodied Carbon**	**Units**	**Source**
Soil off-hauling	12	$kgCO_2/m^3$	Pathfinder (Athena)
Regrading	1	$kgCO_2/m^2$	Pathfinder (Athena)

i - Assuming 305 kg cementitious content per m^3, a 1:3:3 mix with approx. 3000 psi.

Table: RMI • **Source:** 1. Inventory of Carbon and Energy (ICE); 2. Embodied Carbon in Construction Calculator (EC3); 3. Pathfinder - Climate Positive Design, using the Athena Sustainable Materials Institute database

To estimate the embodied carbon from connecting the lakes, we assumed a distance of 1,060 m between lakes (based on visual inspection using Google Earth). We multiply this by the amount of reinforced concrete in a 2m x 2m box drain (0.73 m^3 of reinforced concrete per meter per product specifications) and by embodied carbon values for material manufacturing.[88]

We also include construction emissions from machinery when regrading lakes, digging canals, and hauling soil and other materials off-site. We use Pathfinder to estimate the emissions from regrading lakes and hauling away soil. For a conservative estimate, we assume all three types of lake scenarios require regrading to achieve sufficient storage capacity, even the existing natural lakes. For all three sizes of lakes in each scenario, we multiply the respective surface area of the lake sides by Pathfinder's machinery emissions from regrading and by the number of lakes required for each lake size.

Calculating Maintenance Emissions

For the three types of basins in our scenarios, we use the American Society of Civil Engineers' recommendations for annual maintenance: 69 hours per hectare per year for retention ponds, 59 for detention ponds, and 51 for bioretention (i.e., natural lakes).[89] Using this suggested maintenance frequency, we estimate the number of annual trips required for the three features. To estimate transportation emissions for this maintenance, we use the methodology and values from the E^2STORMED tool, including typical transport distance (average round-trip urban distance) and vehicle fuel consumption (10.03 kWh/liter and 2.68 $kgCO_2$/liter).[viii,90]

[viii] We use an urban water management tool, E^2STORMED, that estimates embodied carbon, including from annual maintenance, selected for its unique capabilities to estimate carbon emissions across stormwater infrastructure's entire life span and because the tool is applicable in multiple countries.

Calculating Construction and Maintenance Costs for Stormwater Management Features

We calculate costs by multiplying the volume of total material by the per unit costs of material, labor, construction activity, and maintenance cost, as shown in Exhibits 14 and 15.

We estimate the cost of connecting lakes with 2m x 2m reinforced concrete box drains by using the cost of a previous lake interlinking project in Ahmedabad: 95 million INR (approximately US$1.2 million) for a total length of 2.4 km.[91] We multiply this cost (39.6 million INR/km or $496,400/km) by the total length of lake interlinking required in our modeling.

Exhibit 14: Construction and Material Costs for Stormwater Management Features

Material Cost	Cost	Unit	Source
Rebar	64	Rs/kg	Average from four Rebar 500 and 550 products available via IndiaMart
Ready-mix concrete	4,467	Rs/m^3	Average from three ready mix concrete products available via IndiaMart
Gabion stone (>200mm)	2,164	Rs/m^3	Kolkata Schedule of Rates (SOR) Highways 2020
Gabion hard drawn steel wire fabric	245	Rs/m^2	SOR for Buildings, Roads, Bridges Works of Ahmedabad District (2021-22)
Labor cost	**Cost**	**Unit**	**Source**
Gabion wall construction	2,414	Rs/m^3	Kolkata SOR Highways 2020
Laying rebar	58	Rs/kg	SOR for Buildings, Roads, Bridges Works of Ahmedabad District (2021-22)
Labor costs for slant slab concrete wall (water-retaining structure)	8,395	Rs/m^3	Gujarat Water Supply & Sewerage Board – SOR 2022-23
Construction costs	**Cost**	**Unit**	**Source**
Excavation 0–1.5 m deep	67	Rs/m^3	AMC (Jan. 2016) SPR for work of Drainage / SWD pipe line
Excavation 1.5–3 m deep	75	Rs/m^3	AMC (Jan. 2016) SPR for work of Drainage / SWD pipe line
Excavation 3–5 m deep	424	Rs/m^3	AMC (Jan. 2016) SPR for work of Drainage / SWD pipe line
Excavation 5+ m deep	15	Rs/m^3	AMC (Jan. 2016) SPR for work of Drainage / SWD pipe line
Earth moving costs	104	Rs/m^3	AMC (Jan. 2016) SPR for work of Drainage / SWD pipe line

Table: RMI • **Source:** "Rebar 500 - Indiamart," https://dir.indiamart.com/search.mp?ss=rebar+500&prdsrc=1; "Rebar 550 - Indiamart," https://dir.indiamart.com/search.mp?ss=rebar+550&mcatid=42729&catid=795&prdsrc=1; Government of West Bengal Public Works (Roads) Directorate National Highway Wing, "Addenda of New Items to Schedule of Rates 2019-20 Road & Bridge Works," February 1, 2020, http://wbpwd.gov.in/home/download/NjY1NzdjZDQ2YmU2NGIwOTc2YmU4MzllMTgyNDliYTJkNGMyYjQ4Yjk0OTc1YjhkOGQ5YWI4OGU1M2Q2OTA4NTc0ODE2NTc5MWFiYWVlZTQ1NjFhOTM4NGM3OWQxYWMwZjk2OWY0OGU1NDk0ZTRiOWRmMzUyYzYxMTdhNTUyOTlxS09tUkY2Zk1MWEwydWoybkFhVE1qQ3A4LzBqQndhSFBnS2N4d0pjdG45d3JCeDNqZTZEWWxCbGtoTjZ0amU4V1ppb2RYejRlTFJldE1PNnBPMFVVWkdVY3l4WDdzWlJRWUJiMUNXNXUzUT0=; Government of Gujarat - Roads & Buildings Department, "Schedule of Rates for Buildings, Roads & Bridges Works of Ahmedabad District," 2021, https://ahmedabadcity.gov.in/portal/jsp/Static_pages/dw_sor.jsp; Gujarat Water Supply & Sewerage Board, "Schedule of Rates Year 2022-23," 2022, https://gwilws.gujarat.gov.in/web/public/content/cms.portal.document/1019/document/SOR%2022%2023_%20GWSSB%20Civil%20(1)_compressed-compressed.pdf; Ahmedabad Municipal Corporation - Engineering Department, "SOR - (Jan. 2016) Rates for Work of Drainage / SWD Pipe Line," 2016, https://ahmedabadcity.gov.in/portal/jsp/Static_pages/dw_sor.jsp

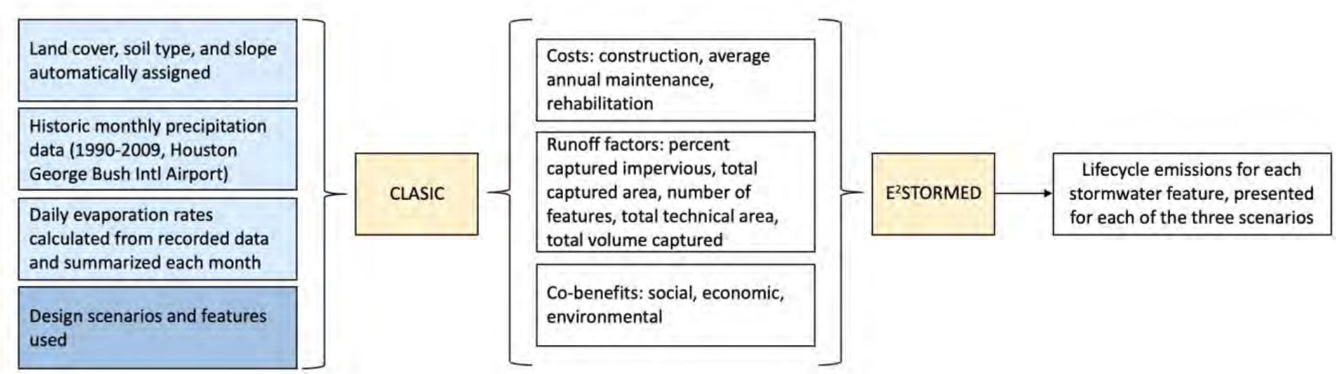
Exhibit 15: Maintenance Costs for Stormwater Management Features

Annual Average Maintenance Cost	Cost	Unit	Source
Retention Pond	8	$/ha/yr	American Society of Civil Engineers
Bioretention Pond	5	$/ha/yr	American Society of Civil Engineers

Table: RMI • **Source:** Houle et al., "A Comparison of Maintenance Costs, Labor Demands, and System Performance for LID and Conventional Stormwater Management"

Houston Model Overview

Exhibit 16: Schematic of Methodology to Estimate Embodied Carbon and Costs of Stormwater Management Infrastructure in Houston



Source: RMI

In Houston, low urban density allows the opportunity to study the impact of adding small, distributed features within the city's existing built landscape to capture stormwater runoff. We compare runoff, embodied carbon, costs, and cobenefits of distributed stormwater management features in Houston's existing built-up area across three scenarios: green, hybrid, and grey (summarized in Exhibit 17).

The features we model for each scenario are informed by discussions with city officials, local researchers, and local organizations. For example, our green scenario model focuses on rain gardens intended to emulate "pocket prairies" and "pocket wetlands," which are locally appropriate strategies used in Houston.[92]

Exhibit 17: Modeled Scenarios and Associated Features in Houston

Scenario	Feature	Details
Green	Rain gardens	188,956 gardens 93 square meters in surface area each, 17.6 square km total 45 cm deep 3–9 regional species (over half flowering) including trees
Hybrid	Rain gardens	75,583 gardens 93 square meters in surface area each, 7 square km total 45 cm deep 3–9 regional species (over half flowering) including trees
	Infiltration trenches	78,732 trenches 4.4 square km total 56 square meters wide by one meter deep each
	Sand filters	29,394 sand filters 93 square meters in area each, 2.7 square km total 0.5 meters deep 2.7 square kilometers total
	Small grass detention basins	7,256 small grass detention basins 696 square meters in top surface area each and 0.6 meters in depth, 5.1 square km total
Grey	Underground storage vaults	1,358 vaults 2,273 cubic meters each, 3.09 million cubic meters total
	Large concrete detention basins	1,200 basins 2,833 square meters in top surface area each and 1.2 meters in depth, 3.4 square km total
	Retention basins	907 basins 2,833 square meters in top surface area each and 2.7 meters in depth, 2.6 square km total

Example of rain garden in downtown Washington, D.C. (top). High water in a detention basin during heavy rains, Fairfax County, Virginia, US (middle). Under-parking stormwater storage tanks (bottom). Credit: Lindsay Rasmussen; Famartin via Wikimedia (CC BY-SA 4.0); Arbitrarily0 via Wikimedia (CC BY-SA 3.0).

Source: RMI Analysis

The hybrid scenario includes rain gardens and relatively small low-impact development features — nonliving features that mimic natural water infiltration and evaporation processes.[93] Modeled features in the hybrid scenario are infiltration trenches, sand filters, and small grassy detention basins. For the grey scenario, we model large, conventional high-impact grey infrastructure features: underground reinforced concrete storage vaults, large reinforced concrete detention basins, and large reinforced concrete retention basins.[94]

For this analysis, we use two existing stormwater management tools: CLASIC and E^2STORMED. CLASIC is an urban water management tool that defines land cover, soil type, slope, and historical monthly precipitation and evaporation rates for a given location in the United States. The tool combines detailed hydrological and financial modeling with cobenefit calculations.[95] E^2STORMED estimates embodied carbon — including from material extraction and manufacturing, construction, annual maintenance, and rehabilitation maintenance — for stormwater features.[96] The tool was built to model southern Europe but is also applicable elsewhere because it uses industry-standard specifications and values for stormwater infrastructure.

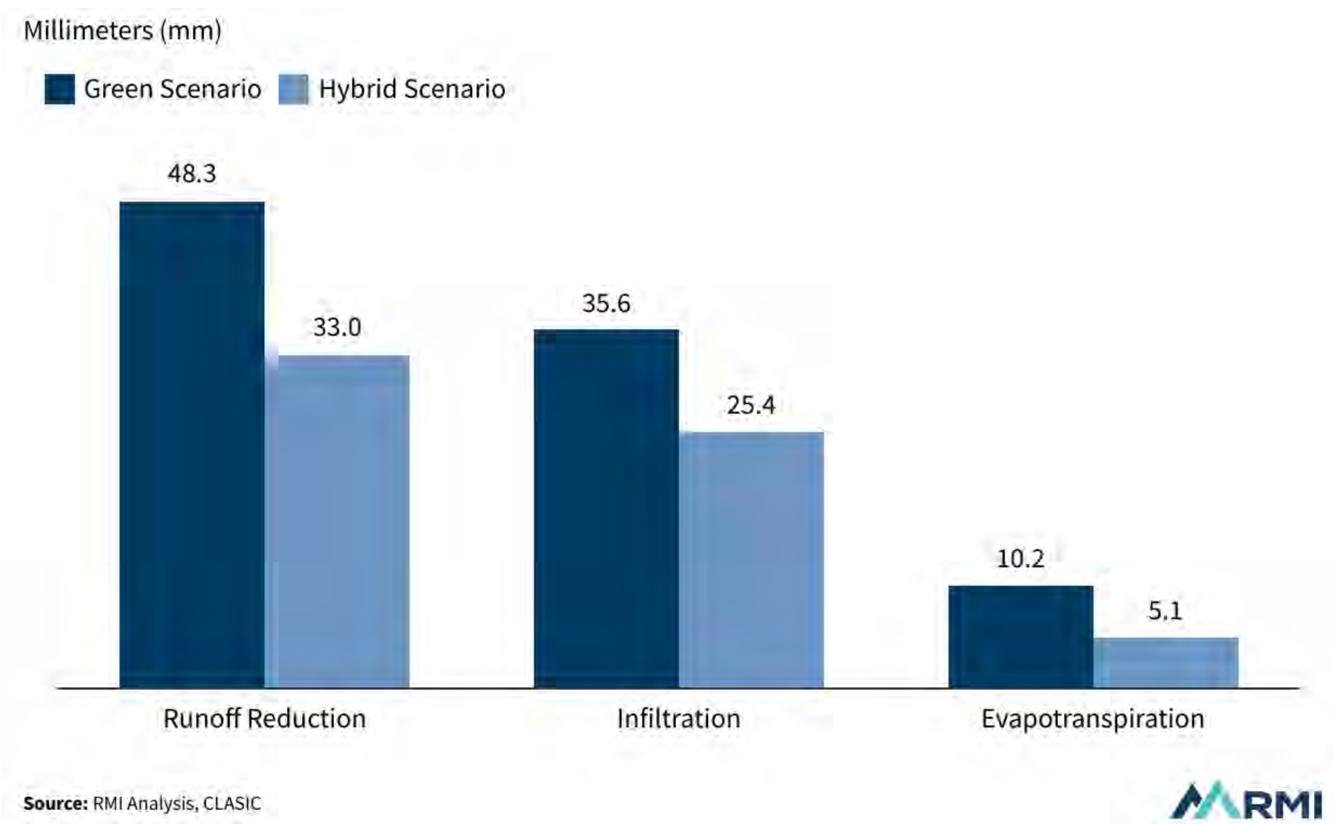
Estimating Current and Future Stormwater Runoff

Using CLASIC, we ensure each scenario meets Houston's policy requirement to capture the volume of initial stormwater runoff from a two-year design storm — 13 cm (5.12 in) rainfall over 24 hours. By 2050, all three scenarios will capture the runoff from 10% of Houston's impervious land cover area in this type of storm — the common benchmark across our scenarios — to then compare different outputs. Next, we use CLASIC to calculate all three scenarios' average annual runoff and infiltration and total cost (construction and maintenance).

CLASIC uses land cover type, soil type, impervious cover, and slope in Houston from the US National Land Cover database and US Soil Survey Geographic database.[97] We consider the generated landscape as Houston's existing "baseline," including for existing permeable area, impervious area, and stormwater features. CLASIC also uses historic monthly precipitation and evaporation data (1990–2009) to estimate the average annual runoff, infiltration, and evapotranspiration for the three design scenarios. As Houston is not projected to experience significant changes in annual or monthly rainfall through 2050, the historical record provides a reasonable estimate for future rainfall.[98]

CLASIC uses the two-year design storm to calculate the number of features required for successful runoff reduction across 10% of Houston's impervious area; CLASIC also uses land cover data to determine available space for stormwater features. The model's outputs include total captured area, number of features, total area required for those features, and total volume captured by the features. CLASIC finds that our green and hybrid scenarios show improved runoff, infiltration, and evapotranspiration performance compared with the grey scenario on an annual basis (Exhibit 18).

Exhibit 18: Runoff, Infiltration, and Evapotranspiration Compared with Grey Scenario



Estimating Embodied Carbon of Stormwater Infrastructure

E^2STORMED produces embodied carbon estimates for the green, hybrid, and grey scenarios based on material extraction and feature construction, annual maintenance, and periodic maintenance and rehabilitation.[ix] Embodied carbon values for each material in E^2STORMED come from the Inventory of Carbon and Energy (ICE) database.[99]

Separately from our modeled scenarios, we estimate the amount of embodied carbon in Houston's existing stormwater management infrastructure based on the city's data on stormwater pipe infrastructure, estimates of pipe material and size from Venkatesh et al., 2009, and embodied carbon data from the Inventory of Carbon and Energy database.[100] This estimate is only for materials, excluding construction and maintenance.

Calculating Maintenance Emissions

E^2STORMED calculates carbon emissions from routine annual maintenance and periodic, more intensive tasks that accompany rehabilitation or disposal. Routine maintenance emissions include vehicle emissions to visit the site, but they do not include fuel consumption for on-site tasks. The number of maintenance trips per year ranges from 1 to 12, depending on the feature (e.g., standard pavement requires one trip per year, whereas rain gardens require 12 trips a year). As these tasks are often more intensive than annual maintenance, their emissions intensity is higher.

Calculating Costs

CLASIC calculates construction costs, annual maintenance costs, and periodic rehabilitation costs. The tool does not include land purchase costs, but its construction costs include a percent of total cost allocated to engineering and contingency (20% total). CLASIC provides regionalized costs in the United States based on several sources.[101,x]

Calculating Cobenefits

CLASIC separately estimates social, economic, and environmental cobenefits on a scale of 1 (low benefit) to 5 (high benefit) based on an index of indicators. Social cobenefits include health impacts from air quality, mental health, thermal comfort, increased supply from harvested stormwater, public awareness of stormwater and water systems, and potential avoided social strain associated with nuisance flooding. Economic cobenefits include increased property values, avoided cost from illness, saved cost from combined sewer treatment, potential impact of nuisance floods, building energy efficiency, avoided water treatment, and employment opportunities. Environmental cobenefits include ecosystem services, groundwater flow increase, and carbon sequestration.[102]

Features We Do Not Model

Most major cities have an extensive network of underground stormwater and sewage pipes, but we did not model conveyance pipes. Ahmedabad has a separate stormwater and sewage treatment system; however, only 55% of the city is covered by a stormwater drain and pipe network, and roughly half of the sewage is disposed directly into the Sabarmati River. In some locations, stormwater enters and flows through the sewage network, and the wastewater treatment plant is often overwhelmed during monsoon season.[103] We model lakes to avoid challenges new stormwater conveyance pipes are likely to face.

[ix] For maintenance emission formulas, see the *Report on Energy in the Urban Water Cycle* (E^2STORMED Project) chapter on Construction and Maintenance.

[x] The University of Utah, Geosyntec Consultants, and Wright Water Engineers prepared a report for CLASIC that regionalized stormwater infrastructure costs. These organizations consulted multiple existing tools to develop the cost estimates, including the Water Environment Research Foundation's SELECT tool, a 2014 report from the National Cooperative Highway Research Program, and the Environmental Protection Agency's National Stormwater Calculator.

In Houston, we do not model green roofs because of their structural requirements. Green roofs provide a wide range of benefits and can be valuable given Houston's ongoing growth, particularly for new construction in dense locations where the ground area for green stormwater features is limited.

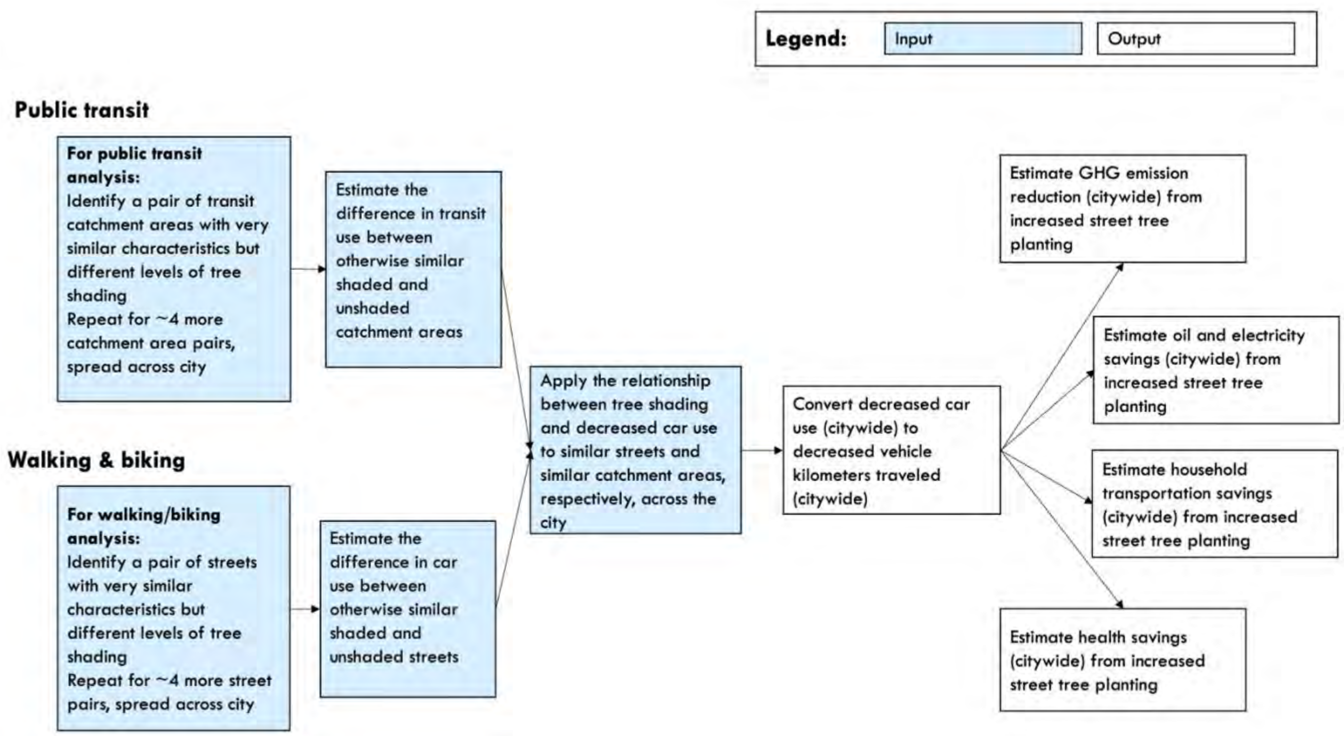
While we focus on embodied carbon, cities with combined stormwater sewer systems can see energy savings at the wastewater treatment plant by reducing stormwater runoff. Additionally, while we note the importance of stormwater infiltration for groundwater and aquifer recharge, we do not quantify how infiltration can potentially decrease the need for more carbon-intensive types of potable water sourcing, such as desalination, long-distance water transport, or the energy-intensive pumping required for a dropping water table. We also do not include the energy and emissions savings from reducing pumping during flooding events. If quantified, all these outcomes would further build the case for effective green stormwater infrastructure.

METHODOLOGY: TRANSPORTATION

Transportation Model Overview and Purpose

In our two-part analysis, we first find a relationship between street tree canopy cover and car mode share in Austin, United States, and Curitiba, Brazil. We then apply these findings to all under-shaded areas within the two cities that have good transportation infrastructure and are close to employment. We estimate the reduction in vehicle kilometers traveled (VKT) from shifting car usage to more biking, walking, and public transit. We also calculate the corresponding reduction in transportation emissions, increased household transportation savings, and increased health benefits for urban residents. Exhibit 19 outlines our methodology.

Exhibit 19: Schematic of Methodology to Estimate Transportation Mode Shift in Austin and Curitiba



Source: RMI

We study Austin and Curitiba because both cities have hot summers (when street trees can provide crucial thermal comfort) and relatively temperate winters (when noncar transportation remains comfortable for many people). Austin and Curitiba differ in their current mode split and development of noncar infrastructure. Curitiba has robust public transit and active transportation infrastructure and relatively low personal car use (22% mode share), while Austin is still expanding its bus, light rail, and active transportation infrastructure and has high personal car use (70%).[104] Curitiba's population density is over 3.5 times greater than that of Austin.[105] Exhibit 20 summarizes the key characteristics of these two cities.

Exhibit 20: Austin and Curitiba Characteristics

Characteristic	Austin, USA	Curitiba, Brazil
Climate type	Humid subtropical[1]	Subtropical highland[2]
Municipal area	771 square kilometers[3]	430 square kilometers[4]
Municipal population	964,000[5]	1.95 million[6]
Projected 2030 municipal population	1.2 million[7]	2.1 million[8]
Population density	1,250 people/square kilometer[9]	4,535 people/square kilometer[10]
Private car mode share	70%[11]	22%[12]
Public transit & active transportation mode share	7%[13]	70%[14]

Table: RMI • **Source:** 1. Weather.gov, "Austin Climate Summary," 2020, https://www.weather.gov/media/ewx/climate/ClimateSummary-ewx-Austin.pdf; 2. Geodiode, "Secrets of World Climate Chapter 3: Subtropical Highlands," 2022, https://geodiode.com/climate/subtropical-highlands; 3. U.S. Census Bureau, "QuickFacts: Austin City, Texas; United States," U.S. Census Bureau, July 2021, https://www.census.gov/quickfacts/fact/table/austincitytexas/LND110210; 4. Google Arts & Culture, "Curitiba," Google, 2022, https://artsandculture.google.com/entity/curitiba/m028mpr?hl=en; 5. City of Austin, "Austin's Population Continues Another Decade of Growth According to U.S. Census Bureau | AustinTexas.Gov," August 13, 2021, https://www.austintexas.gov/news/austins-population-continues-another-decade-growth-according-us-census-bureau-0; 6. Google Arts & Culture, "Curitiba," Google, 2022, https://artsandculture.google.com/entity/curitiba/m028mpr?hl=en; 7. City of Austin, "Imagine Austin Population and Jobs Forecast," 2022, https://data.austintexas.gov/stories/s/Imagine-Austin-Population-and-Jobs-Forecast/j5a7-yk8d/; 8. World Population Review, "Curitiba Population 2022," 2022, https://worldpopulationreview.com/world-cities/curitiba-population; 9. U.S. Census Bureau, "QuickFacts: Austin City, Texas; United States," U.S. Census Bureau, July 2021, https://www.census.gov/quickfacts/fact/table/austincitytexas/LND110210; 10. Google Arts & Culture, "Curitiba," Google, 2022, https://artsandculture.google.com/entity/curitiba/m028mpr?hl=en; 11. City of Austin, "Austin Climate Equity Plan," 2021, https://www.austintexas.gov/page/austin-climate-equity-plan; 12. ICLEI, "Curitiba, Brazil - City Statistics", https://sustainablemobility.iclei.org/ecomobility-alliance/curitiba-brazil/; 13. City of Austin, "M.A.1 - Percent Split of Modes Based on Commute to Work (Mode Share)"; 14. ICLEI, "Curitiba, Brazil - City Statistics," https://sustainablemobility.iclei.org/ecomobility-alliance/curitiba-brazil/

Determining and Applying the Relationship Between Street Tree Canopy Cover and Car Mode Share

Identification of Street and Catchment Area Preconditions for Analysis

We distinguish between two types of characteristics when identifying similar pairs of streets and similar pairs of transit catchment areas for analysis (see Exhibit 21). The first category is preconditions, which we describe as criteria that locations must have before street trees can be added to support less car use. For streets and catchment areas, the preconditions are high density of nearby employment and easy access to that employment (via biking and walking for streets or public transit for catchment areas). The study areas also provide residents access to places such as open space and parks, educational institutes, and hospitals.

The second category is control variables to hold constant across both halves of a given pair of streets or pair of catchment areas. Control variables are listed in Exhibit 21. Otherwise, street trees are unlikely to have an impact on mode share (e.g., shift to walking is impossible without sidewalks). We only use the control variables for street and catchment pair analysis (not for selection of eligible streets to extend analysis to).

Exhibit 21: Preconditions and Control Variables for Street Pair and Catchment Pair Selection

Feature	Control Variables
Preconditions: Streets (to select original pairs and additional streets to apply analysis to eligible areas across the city)	• Medium- and high-comfort bike routes (defined by the cities) • Confirmed functionally acceptable sidewalks • Within 15-minute walk to high density of jobs • Within 30-minute bike ride to high density of jobs (Curitiba)
Control variables for pair analysis: Streets (to select pairs for comparison to observe impact of canopy on mode)	• Size of street (neighborhood and 2-lane streets) • Predominant zoning type • Walkability score • Percent of households with zero cars • Median household income • Population density • Geographic location and street function within city
Preconditions: Catchment areas (to select original pairs and additional transit stops to apply analysis to eligible areas across the city)	• Public transit access (>70 bus arrivals within 0.8 kilometers of catchment area boundary per hour during evening peak period) • Within 30-minute transit ride to high density of jobs
Control variables for pair analysis: Catchment areas (to select pairs for comparison to observe impact of canopy on mode)	• Total weekday arrivals of primary bus route at studied transit stop (>50/wk) • Confirmed functionally acceptable sidewalks • Predominant zoning type • Walkability score (high) • Percent of households with zero cars • Median household income • Population density • Percent of commuters who take bus to work • Absence of shelter at stop (to isolate tree canopy impact) • Geographic location of catchment area and bus route function within city

Note: Within a given pair, the control variables match for all characteristics to best isolate the impact of tree canopy. Across pairs, we select the greatest possible difference (e.g., one pair in a low population density location and one pair in a high population density location) to develop the broadest and most representative analysis of local conditions.

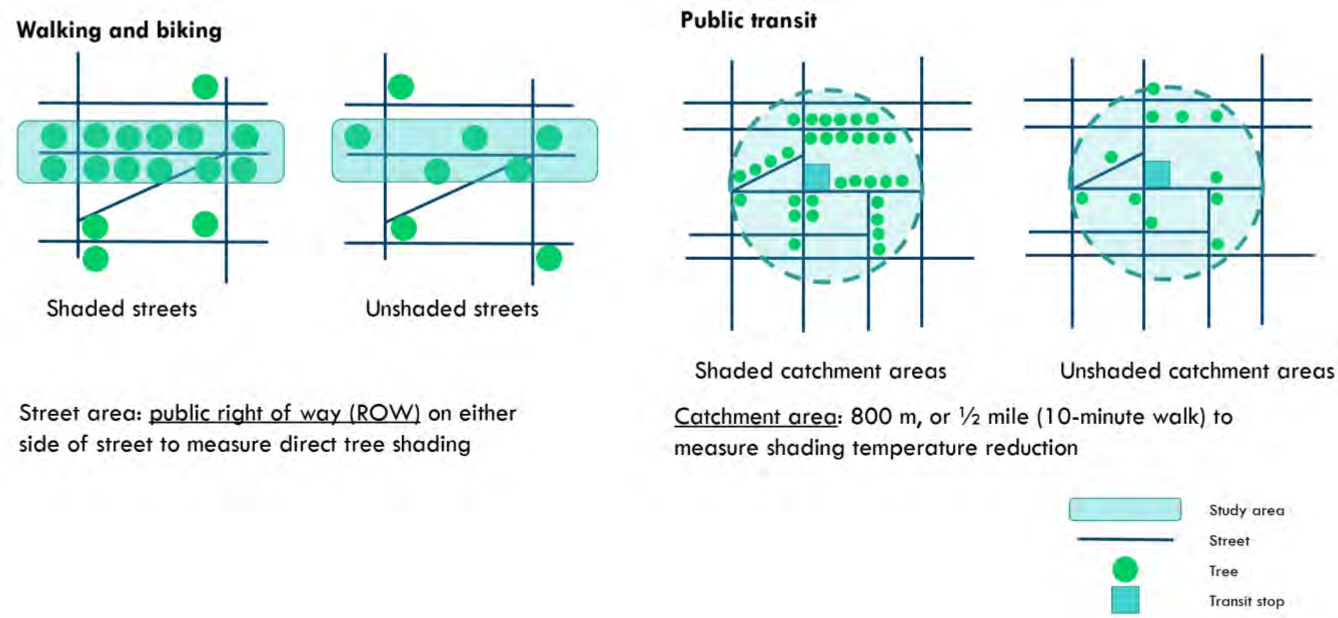
Source: RMI Analysis

When selecting pairs of streets or catchment areas, we pick two locations with the largest difference in tree cover (holding control variables constant) to best observe the relationship between shading and car use (see Exhibit 22). While 40% canopy cover is cited as the threshold for increased thermal comfort, Austin's and Curitiba's actual landscapes have few areas that meet both our conditions and 40% or more tree shading. Therefore, we study shaded areas that are almost all above 30% street tree canopy cover and under-shaded areas that are almost all below 20% canopy cover.[106] Often, the under-shaded areas are below 10% canopy cover. We study five street pairs in each city (all streets at least 900 m in length) and an additional five catchment area pairs in Austin, as shown in Exhibits 23 and 24, respectively.

We also study tree shading at the bus stop but prioritize street tree canopy in the catchment areas because transit users might need to walk 10 minutes in unshaded environments before even reaching the transit stop. The US Federal Highway

Administration's Pedestrian Safety Guide for Transit Agencies shows most people are willing to walk 800 m (a half-mile) to a transit stop.[107] Increasing tree shading at the stops themselves can provide crucial health benefits to waiting commuters and support even greater mode shift to public transit.

Exhibit 22: Visualization of Street and Catchment Area Pair Selection



Source: RMI

Determining Private Vehicle Mode Share on Selected Shaded and Unshaded Streets

In Austin and Curitiba, we observe the relationship between tree canopy cover and car mode share (the number of trips residents take by car) on pairs of otherwise-similar streets.

In Austin, we first identify streets that are close to a high density of employment — a high number of jobs available in an area — and have robust existing active transportation infrastructure. We define robust infrastructure as sidewalks that are confirmed functionally acceptable by the City of Austin and bike routes that are reported as medium-comfort (at a minimum) by Austin residents.[108] For example, a medium-comfort bike route would be a shared lane with cars on roads with low-to-moderate vehicle speeds and volumes. We use employment density from UrbanFootprint's database.[109]

We follow a similar approach to identify the five street pairs in Curitiba but use different local data sets to estimate density of employment and active transportation infrastructure.[110] Due to limited data, we only study streets with bike routes and do not incorporate sidewalk quality into the analysis. Instead, we use data on active transportation infrastructure and access to employment from the Instituto de Pesquisa Economica Aplicada and Mobilidados.[111]

Next, holding control variables constant — including median household income, zoning, population density, percent of households with zero cars, walkability, and street size (see Exhibit 21) — we select five pairs of streets with the greatest difference in tree canopy for each city.

Exhibit 23: Estimated Mode Share on 10 Streets in Austin

	Median Bike Mode Share	Median Walk Mode Share	Median Private Car Mode Share	Median Bike Trips	Median Walk Trips	Median Private Car Trips	Median Total Trips
A. Shaded	8	5	70	75	25	600	975
A. Unshaded	2	2	76	25	38	1,300	1,738
B. Shaded	5	3	69	175	100	2,888	4,275
B. Unshaded	5	2	71	200	50	2,600	3,725
C. Shaded	13	11	63	75	75	400	675
C. Unshaded	4	1	56	125	25	1,675	2,650
D. Shaded	1	1	70	75	50	4,025	5,750
D. Unshaded	3	3	79	75	100	2,325	3,025
E. Shaded	2	1	61	50	25	1,400	2,250
E. Unshaded	7	7	67	75	50	700	988

Source: RMI Analysis, UrbanFootprint, Replica

After selecting five representative street pairs across Austin, we use mode share data from Replica to estimate the percentage of users biking, walking, and driving private cars on these streets.[112] Replica estimates mode share at the individual street segment — the length of street between any adjacent intersections — providing an extremely detailed model for Austin residents' transportation patterns. For each street in the five pairs, we record the estimated number of bicyclists, pedestrians, and car drivers from each street segment and calculate the median value for all three modes across segments. We find a reduction in car mode share in streets with greater tree canopy on average, but the results are slightly variable.

As Replica data is unavailable in Curitiba, we use mode share counts from Google Street View (GSV) to estimate private vehicle share on the selected streets based on previous research demonstrating a correlation between observed mode share from GSV images and census data on household commuting patterns in Britain.[113] We selected GSV images manually and randomly along the 10 identified streets at a consistency of one observation per 150 m (500 ft) of street length.

For each GSV observation, we downloaded the 360° panorama file and conducted a manual count to observe the share of motorcycles, private cars, buses, cyclists, and pedestrians within the image. Following GSV data collection, we calculate an average private car mode share for each selected street, outlined in Exhibit 24 below.

Exhibit 24: Estimated Private Car Mode Share for 10 Streets in Curitiba

	Average Private Car Mode Share
A. Shaded	31%
A. Unshaded	39%
B. Shaded	43%
B. Unshaded	43%
C. Shaded	52%
C. Unshaded	55%
D. Shaded	77%
D. Unshaded	71%
E. Shaded	50%
E. Unshaded	82%

Source: RMI Analysis, UrbanFootprint, Replica

Determining Transit Ridership in Selected Shaded and Unshaded Catchment Areas

In Austin, we also study the effect of increased canopy cover between pairs of transit catchment areas (supporting residents going to and from transit stops). The approach differs slightly from the street pair analysis in that we study access to employment within a 30-minute transit ride (not via biking and walking) and only study transit routes with at least a medium frequency of bus arrivals per day (80–230), as defined by UrbanFootprint. When selecting pairs, we ensure the two catchment areas in each pair are on comparable bus routes, for example, both the stops in the pair are located on bus routes that go north-south in the city through downtown. As with the street pairs, we select catchment pairs with the greatest difference in street tree canopy, holding all control variables constant.

Exhibit 25: Estimated Shading and Mode Share in 10 Catchment Areas in Austin

	Tree Canopy of Catchment Area	Tree Canopy at Stop	Total Boardings Over 10-Month Study Period in 2019
A. Shaded	39%	5%	1,093
A. Unshaded	7%	0%	267
B. Shaded	50%	1%	421
B. Unshaded	21%	0%	1,349
C. Shaded	33%	20%	1,212
C. Unshaded	26%	15%	474
D. Shaded	44%	10%	844
D. Unshaded	10%	5%	232
E. Shaded	37%	21%	848
E. Unshaded	24%	33%	1,037

Source: RMI Analysis, UrbanFootprint, Replica

RMI

We first need to observe increased bus boardings for the catchment area pairs. We use a database of Austin transit stops prepared by the University of Texas to observe bus boardings in the studied catchment areas over a 10-month study period in 2019.[114] Considering the number of boardings can significantly differ even between adjacent bus stops, to reduce variability and better identify trends, we average the tree cover of the catchment area and the stop, and the number of boardings at the nearest stop on the same bus route that still meets all the pair's control variables.

Summary of Selected Streets and Catchment Areas

After ascertaining the reduction in car use from shaded streets and shaded catchment areas, we apply it to all under-shaded streets (in both cities) and under-shaded catchment areas (in Austin) by increasing their tree canopy cover to the significant 40% threshold for thermal comfort. We only study increased tree canopy on the under-shaded streets and catchment areas that meet the respective preconditions outlined in Exhibit 21. We consider these under-shaded transit catchment areas and under-shaded streets "primed" for mode shift, with the addition of street trees complementing the existing infrastructure and increasing the potential mode shift. Austin has 1,765 transit stops and 150 streets (290 km) and Curitiba has 45 streets (160 km) that meet these preconditions. For reference, the streets we use for the pair analysis are at least 900 m in length, and all the under-shaded streets are at least 300 m (and frequently much longer). We model fewer streets in Curitiba because of less data availability to determine locations that meet the preconditions; thus, Curitiba's VKT and emission reductions are likely greater than modeled.

Estimating Daily Trip Reduction from Shaded Streets and Catchment Areas

Estimating Daily Private Vehicle Trips from Reduction in Private Vehicle Mode Share on Shaded Streets (in Austin and Curitiba)

To estimate the difference in private car mode share between shaded and unshaded streets, we calculate a weighted average based on street length for shaded and unshaded streets separately, providing a combined private car mode share figure for shaded streets in addition to unshaded streets.

We then calculate the delta between unshaded and shaded private vehicle mode share to estimate the private vehicle mode share percentage reduction due to shaded streets. To translate mode share reduction into a reduction of vehicle kilometers traveled, we consult citywide average annual daily traffic count (AADT) data for the number of cars on an unshaded street in a given day. We then calculate AADT for shaded streets using the mode share reduction from shaded streets previously calculated. We estimate the number of cars on shaded and unshaded streets with the following equation:

Unshaded streets = AADT

*Shaded streets = AADT * (average shaded car mode share % / average unshaded car mode share %)*

AADT data for Austin is obtained from the Texas Department of Transportation 2018 AADT data set.[115] For Curitiba, we estimate AADT by taking daily VKT from Google Environmental Insights Explorer and total road length from an analysis of the city's OpenStreetMap to estimate a citywide AADT figure.[116] These calculations provide an estimate of private cars on shaded and unshaded streets per day. Taking the delta between the number of daily cars on unshaded and shaded streets provides an estimate of how many cars are avoided daily on shaded streets.

Estimating VKT Reduction from Increase in Bus Boardings on Shaded Transit Catchment Areas (in Austin)

Due to limited data availability in Curitiba, we only analyze the transit stops and catchment areas in Austin. To determine VKT reduction from shaded catchment areas, we calculate the delta between the average number of bus boardings on our selected shaded transit catchment areas and our selected unshaded transit catchment areas. This calculation yields an estimated number of car trips avoided as a result of shaded catchment areas. We then multiply this difference by two to account for both travel directions in a day (out and back) and arrive at avoided car trips each day.

To translate trips into a VKT reduction, we multiply the number of avoided trips by the average commute length in Austin from US census data.[117] This value represents the VKT reduction from a single shaded catchment area in Austin.

Scaling up VKT Reduction to the City Level

Estimating Citywide VKT Reduction Potential from Under-Shaded Streets (in Austin and Curitiba)

To convert daily reduced trips from shaded streets to VKT savings and expand these savings to all under-shaded streets in the city that meet our street preconditions outlined in Exhibit 26, we calculate the total km of road that meet street characteristics and have under 30% tree canopy cover.

To calculate the reduction in VKT by increasing tree canopy cover to 40% on all "primed" under-shaded areas, we use the following equations:

*Total VKT on shaded streets citywide = km of applicable road * number of cars on shaded streets*

*Total VKT on unshaded streets citywide = km of applicable road * number of cars on unshaded streets*

The difference between these two equations yields the scaled-up daily VKT reduction from shaded streets in both cities. We then convert daily VKT to annual VKT by multiplying the output by 365 days in a year. To account for future car ownership growth through 2050, we calculate the annual growth rate for Austin's and Curitiba's metropolitan areas and multiply each city's annual VKT reduction by their respective annual population growth projections through 2050.[118]

Estimating Citywide VKT Reduction Potential from Under-Shaded Catchment Areas (in Austin)

To scale up to the avoided VKT from increasing tree canopy cover to 40% in all primed catchment areas in Austin, we apply the VKT reduction from a single shaded catchment area to all unshaded transit catchment areas within Austin that meet the preconditions for mode shift in Exhibit 21, using UrbanFootprint and a database of Austin transit stops.[119]

Estimating Avoided Transportation Emissions and Vehicle Fuel and Electricity Consumption

We assume all trees along streets and within catchment areas planted in 2022 provide at least 40% tree canopy cover beginning in 2035.

Projected Scenarios for Electric Vehicle Adoption and Power Grid Decarbonization

When estimating emissions, fuel savings, and electricity savings out to 2050, we employ two scenarios to account for a range of future policy directions: business-as-usual (BAU) and sustainable.

BAU: Assumes no additional policy changes that would increase electric vehicle (EV) adoption and decrease carbon intensity of the grid in both cities.

- Austin EV Adoption Projection: Based on EV car stock projections in the United States with no policy interventions. Gradual increase in EV car stock, minor reduction in gasoline and hybrid vehicles.[120]
- Austin Grid Projection: RMI analysis based on Rhodes and Deetjen, 2021, assuming increased load and reduced emissions.[121]
- Curitiba EV Adoption Projection: Based on fleet market study and projections for Brazil with no policy interventions. Assumes small, consistent increase in EV stock.[122]
- Curitiba Grid Projection: International Energy Agency (IEA) BAU projection for electricity generation by source.[123]

Sustainable scenario: Assumes more aggressive policy changes that would increase EV adoption and decrease carbon intensity of the grid in both cities.

- Austin EV Adoption Projection: Assumes 100% new car sales are electric by 2050.[124]
- Austin Grid Projection: Texas grid emissions intensity aligned with 1.5ºC grid decarbonization scenario.[125]
- Curitiba EV Adoption Projection: Uses the same growth rate as Austin for EV adoption due to limited data availability.[126]
- Curitiba Grid Projection: IEA Sustainable Development Scenario projection for electricity generation by source, including assumptions around increased renewable energy.[127]

Annual Transportation Emissions Reduction

We calculate the emissions savings of internal combustion engine (ICE) vehicles from reduced on-road combustion and EVs from reduced emissions from the power grid. For both vehicle types, we use the two projections of total car stock each year through 2050, mentioned in the above. To calculate the annual emission reduction from ICE vehicles and EVs, we use the following equation:

*GHG emissions reduction = (Annual VKT reduction estimate * ICE car stock % * grams of CO_2e/km) + (Annual VKT reduction estimate * EV car stock % * grams of CO_2e/km)*

We assume ICE vehicles emit 8,887 g of CO_2/gallon from tailpipe carbon dioxide emissions based on US Environmental Protection Agency data and assume ICE vehicle improvements (resulting in more km per gallon) from US Energy Information Administration energy policy projections.[128] We assume an EV requires 0.00016 MWh of energy per km traveled from US Department of Energy estimates (based on a 2020 Tesla Model 3).[129] To estimate the amount of CO_2e/km, we multiply 0.00016 MWh/km by the annual marginal emissions factor for the respective city.

Annual Electricity Consumption Reduction (from Reduced VKT with EVs)

To estimate reduced electricity demand from decreased EV VKT, we isolate the VKT reduction of the EV stock and apply the estimated efficiency of an EV (stated above) via the following equation:

*Electrical consumption reduction = Annual VKT reduction estimate * EV car stock % * 0.00016 MWh/km*

Annual Fuel Consumption Reduction (from Reduced VKT with ICE Vehicles)

To estimate reduced gasoline consumption from decreased ICE vehicle VKT, we follow the same approach as for EVs and use the following equation:

*Fuel consumption reduction = (Annual VKT reduction estimate * ICE car stock %) / annual projected kilometers per gallon*

We use projected fuel efficiency of gasoline cars from the US Energy Information Agency.[130]

Estimating Household Transportation Savings, Health Benefits, and Cost of Increasing Street Tree Canopy to 40% in Under-Shaded Areas

Household Transportation Savings (Mode Shift from Car to Cycling or Walking)

To determine household transportation savings for residents switching one car round trip each day to cycling and walking, we use the following equation:

*Household transportation savings from shaded streets = Average daily commute distance * 2 * cost per VKT * 365 days*

To obtain the average commute distances in each city, we use values from the US Census Bureau for Austin and use an estimate from commuter travel patterns and surveys for Curitiba.[131] We then double the average commute distance to account for a round trip. In Austin, we derive cost per VKT using the Center for Neighborhood Technology's housing and transportation costs analysis (H&T Index) data for annual transportation costs per household and average annual household VKT.[132] Using these two values, we calculate transportation costs per VKT:

Transportation costs per VKT = Total annual household transportation costs / annual household VKT

In Curitiba, we use average household transportation costs from the Brazilian Institute of Geography and Statistics.[133] We calculate the total annual household VKT by dividing citywide VKT from Google Environmental Insights Explorer (EIE) and the Brazilian Institute of Geography and Statistics by the total number of households.[134] Using these two values, we calculate transportation costs per VKT using the above equation. For both cities, we multiply the transportation costs per VKT by 365 days per year to develop an annual estimate for household transportation savings.

Household Transportation Savings (Mode Shift from Car to Public Transit)

To determine household transportation savings for residents switching one car round trip each day to public transit (only in Austin), we use the following equation:

*Household transportation savings from shaded transit catchment areas = (average commute distance * 2 * cost per VKT * 365) – (transit cost per trip * 2 * 365)*

We calculate the transit cost per trip using the H&T Index for Austin[135] and divide the annual transit costs by the number of annual transit trips to get the transit cost per trip. We use the US Census Bureau value to obtain the average transit commute distance.[136]

Health Benefits

We conservatively calculate health benefits from avoided mortality and disabling injury due to reduced vehicle collisions with pedestrians, avoided mortality due to less local air pollution, and avoided mortality due to greater physical activity by applying the existing methodology to our VKT reductions in Austin and Curitiba.[137] Reduced vehicle collisions with pedestrians and reduced local air pollution apply to shaded streets and shaded transit catchment areas — both are related to decreasing vehicle traffic — while greater physical activity only applies to more walking and biking on shaded streets. We do not study the increased physical activity from the first and last parts of transit commutes in shaded catchment areas, implying the health benefits are likely even greater.

To determine reduced fatality and injury costs from fewer vehicle collisions with pedestrians, we use empirical values from Cambridge Systematics, Inc. for the frequency of fatalities and injuries caused by motor vehicles per million VKT (0.013 and 0.195, respectively).[138] We multiply these values by our annual VKT reduction from shaded streets and catchment areas and then by the financial value of statistical lives and injuries. We use the US Department of Transportation's value of a statistical life ($9.6 million) and the US Federal Transit Administration's value of a statistical pedestrian injury from motor vehicles ($490,000).[139]

We calculate the healthcare benefits from lives saved due to reduced air pollution for five different pollutants: NO_x, particulate matter (PM) 2.5, SO_2, volatile organic compounds, and NH_3. We use an existing methodology from Harvard University and Tsinghua University combining the impact of all five pollutants into a value of $0.03 in pollutant-related health impacts for every km traveled by a light-duty vehicle in large metro areas.[140] The study assumes 422 g of CO_2 equivalent emitted by light-duty vehicles per mile (262 g per km), and we use our earlier projections for improved ICE vehicle engine efficiency to not overestimate the avoided pollutants through 2050 and, therefore, the healthcare benefits. Once we match the annual pollutant-related health costs to the projected gasoline engine efficiency through 2050, we multiply each year's pollutant-related cost per VKT from private cars by the avoided VKT each year from shaded streets and catchment areas.

For all the health benefits, we replicate the same strategy in Austin and in Curitiba but use each city's respective reduction in VKT from increased street tree canopy cover.

Finally, for shaded streets, we calculate health benefits from lives saved due to greater physical activity such as walking and biking. We use Cambridge Systematics, Inc.'s work, assuming the reduction in VKT is a 1:1 ratio with an increase in person km traveled. For example, a person driving to and from work would travel the same distance on their bike or by walking.[141] We also conservatively use the existing methodology's low estimate for annual deaths prevented per million VKT from increased walking (0.55) and increased biking (0.18). Finally, we multiply a reduction in residents' deaths (from improved physical health due to less driving) by the value of a statistical life ($9.6 million).[142]

Planting and Maintenance Costs of Street Trees

We calculate the VKT reduction from increasing tree canopy cover to 40% on all the primed under-shaded streets in both cities and the primed under-shaded catchment areas in Austin.

Following the guidance in Austin's Great Streets Development Program, we assume street trees are planted every 6.7 m (22 ft) to achieve 40% canopy cover along a given street and again assume trees reach 40% canopy cover by 2035.[143]

To determine the number of additional trees required to meet 40% tree cover on the primed streets, we calculate the average tree canopy along all 45 streets in Curitiba using Google satellite imagery to determine if they are above or below 30% canopy cover currently. For all streets we identify as under-shaded (but still close to jobs and with biking and walking infrastructure), we calculate their total length (160 km) and estimate the number of trees required to reach 40% canopy cover (16,770 street trees) using the same 6.7 m of spacing as in Austin.[144] In Austin, we use more granular data from Google EIE to determine the average tree canopy cover along the 150 streets and calculate the number of trees required to achieve 40% canopy cover along the entire 290 km (9,300 trees).[145]

For the Austin transit catchment areas, we find 1,765 bus stops and their surrounding half-mile-radius catchment areas that meet our preconditions to support mode shift, including relatively frequent transit service and proximity to a high density of jobs. We use Google EIE's tree canopy cover for Austin to estimate the street tree canopy cover of all catchment areas in five groupings: 0%–10%, 10%–20%, 20%–30%, 30%–40%, and over 40%. We group catchment areas into regions based on similar levels of canopy cover. As Google EIE estimates canopy cover down to the individual tree scale, we can easily and accurately distinguish which areas have adequate/inadequate canopy cover (see Exhibit 26).

Exhibit 26: Determining Number of New Trees Needed to Reach 40% Canopy Cover

Catchment area canopy grouping	Number of transit stops	Total street length (m)	Total trees required for 40% canopy	Percent of canopy cover goal achieved	Number of new trees needed
0% – 10%	251	334,463	49,881	13%	43,645
10% – 20%	626	834,158	124,403	38%	77,752
20% – 30%	184	245,184	36,566	63%	13,712
30% – 40%	255	339,793	50,675	88%	6,334
>40%	449	1,963,028	89,229		

Note: We did not calculate new trees needed in areas with >40% canopy cover, because we assume these areas already successfully support mode shift.
Number of Transit Stops: *Number of transit stops in Austin that meet preconditions per canopy area grouping.*
Total Street Length: *Total length of street across all catchment areas in a grouping; accounts for overlapping catchment areas.*
Total Trees Required for 40% Canopy: *Total street length / 6.7m, assuming trees planted every 6.7m.*
% of Canopy Cover Goal Achieved: *Derived by dividing mid-point in catchment area tree canopy cover by 40%.*
Number of New Trees Needed: *Estimated number of trees needed to bring the current canopy cover to 40%.*

Source: RMI Analysis

We use an area-based approach to determine the number of trees needed to reach consistent 40% canopy cover in catchment areas in Austin. Because many bus stops are much closer together than 800 m (one half-mile) and, therefore, have overlapping catchment areas, we want to ensure we do not overcount the number of trees required. First, we identify all regions of Austin that are near employment and have frequent transit service but are below 40% canopy cover. We calculate the total length of streets within all these under-shaded regions and divide by the number of stops in those regions to get an estimate of the average total street length within a catchment area (avoiding overlapping and double-counting). As shown in Exhibit 31, we then determine the number of transit stops located in areas with different levels of canopy cover and calculate the number of trees required for each group of catchment areas to reach a consistent 40% canopy along all their under-shaded street lengths.

We estimate 141,450 trees are required for Austin's 1,765 catchment areas and again assume all trees are planted in 2022. For both cities, we assume a cost of $36.51 to plant one tree and a mortality rate of 3% each year, requiring a constant number of trees to be planted each year (at the same cost of $36.51 per tree) to maintain the high canopy cover.[146] For both cities, we also assume an annual maintenance cost of $3.65 per tree, recognizing that planting and maintenance costs can increase due to local site constraints, outreach programs, and more.

Limitations of the Modeling

Our analysis does not attempt to identify a statistical correlation between tree canopy and car mode share given the small number of study sites. Further research with a much larger data set can continue investigating the connection between increased street tree canopy and reduced private car use. However, our approach can be replicated in other cities. EV adoption scenarios and grid decarbonization forecasts introduce potential uncertainty to emissions, power consumption, and gasoline consumption results, but the two scenarios we evaluate present an indicative range of outputs.

Features We Do Not Model

Street trees are most effective as part of a broad urban planning strategy to enhance the safety, comfort, and efficiency of transit and active transportation. Cities can reduce emissions and improve residents' quality of life by creating more compact, destination-rich environments with smart growth strategies such as housing reform and infill development, mixed-use transit corridors, creation of 15-minute neighborhoods, and avoided highway expansion.[147] We exclude urban cooling measures such as cool pavements (reflective street surfaces), street-adjacent parks, or citywide tree canopy, as well as awnings, vegetated trellises, and other shading structures along streets and at transit stops.[148] These features can be especially useful for locations where street trees are not feasible or before they provide sufficient shade. Finally, many socioeconomic, cultural, and behavioral factors influence choice of transportation mode or ability to change modes, and we do not model these.

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