The Benefits and Costs of Reaching Net Zero Emissions in Latin America and the Caribbean

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Foreword

At COP28, countries are expected to announce emission reduction plans that are more ambitious—in terms of long-term targets, sectoral composition, or implementation means. This timely new report may help countries' efforts to do so. Rather than reiterating the important messages from the IPCC about the world's capacity to reach net-zero emissions and limit warming to 1.5°C, this work brings a pragmatic and compelling approach to analyze practical policy and technology options at the country level.

The goal of SiSePuede is to facilitate discussions with various national and subnational decision makers by expressing emissions reductions in terms of tangible actions in their sectors and metrics they readily understand. It also provides robust estimates of the so-called "co-benefits" of these transformations across society.

As an actor and observer of long-term climate strategies, the 2050 Pathways Platform is frequently challenged to explain the relevance of its work. How can a long-term vision for 2050 or 2060, with all its inherent uncertainties, usefully inform decisions today? One way to meet this challenge is to acknowledge major uncertainties and test the robustness of options for reducing emissions while advancing development goals against unpredictable changes ahead. That is exactly the approach taken in this report.

By bringing results to life at the sectoral level in metrics decision makers use—such as tons of clinker for cement makers, ecosystem services values for forestry authorities, or costs for electricity utilities—this approach can help make countries' net-zero strategies fully palatable to those who must implement them.

As many nations beyond Latin America and the Caribbean have yet to design robust long-term climate strategies, I hope that this innovative approach will spread more broadly. The advances presented here matter significantly if we are to transition our economies and societies rapidly to a net-zero emissions future in a way that is equitable, resilient, and leaves no one behind.

Richard Baron
Executive Director
2050 Pathways Platform

Countries across Latin America and the Caribbean are charting their paths toward net-zero emissions and climate-resilient development. This report offers insights into how governments can accelerate climate progress while advancing broader economic and social goals.

Climate change poses grave threats, and we need to respond to these threats. At the same time, the global technological revolution toward renewable energy, electromobility, and sustainable land use presents new opportunities for sustainable economic growth and better lives. Several countries have embarked on transformational journeys, evidenced by implementing long-term and cross-sectoral strategies aligned with the Paris Agreement. Other countries are beginning to identify and implement sector reforms that point the way forward.

The work presented in this report shows that transitioning to net-zero emissions in Latin America and the Caribbean will confer substantial economic benefits, including cheaper energy, enhanced productivity, and improved public health. In this sense, it confirms what country studies have found before; but this study estimates for the first time the size of the economic benefits—which could be as high as 2.7 trillion dollars of net benefits between now and 2050.

Beyond the numbers, the study offers a comprehensive, rigorous, and transparent framework for assessing decarbonization options. The work presented here follows the highest technical standards. It reflects the results of extensive consultation with experts across the Inter-American Development Bank (IDB) Group, our partners at the French Development Agency (AFD), and the 2050 Pathways Platform. The open source modeling platform arising from this work enables stakeholders to evaluate the costs, benefits, and uncertainties linked to development choices.

The participatory processes and modeling used in this study mimic what countries can and should do to plan decarbonization in a way that responds to local priorities and capabilities. This report points to the benefits of climate action and beginning the process of green technological transformation. The study confirms the pivotal role in reaching net-zero emissions of renewable energy, electrification of energy uses, particularly in transport, and integrated management of food production and biodiversity.

Transformation will not be easy—it will require alignment of finance, leadership, and governance to manage complex winner and loser consequences. Governments must develop and communicate clear visions, systematically diagnose and address barriers to change, and align financing to deliver critical investments.

As climate impacts intensify and the global green transformation accelerates, time is of the essence. Realizing a just, equitable, and prosperous net-zero future is achievable, but countries must act rapidly and judiciously. As the largest source of climate and development financing for Latin America and the Caribbean, the IDB Group can help plan and change policies with knowledge and technical assistance while providing finance for the critical investments needed to drive transformation in countries.

Graham Watkins
Chief of the Climate Change Division
Inter-American Development Bank

About This Research Report

Droughts, floods, wildfires, and other climate-related catastrophes are unfolding around the globe and upending lives, wiping out economies, and leaving in their wake destruction many hoped would be decades away. It is not too late, however, to stave off the worst climate effects. Limiting temperature increases to 1.5-2°C above pre-industrial levels consistent with the Paris Agreement requires reaching net-zero greenhouse gas emissions by about 2050. This, in turn, requires transformations in every sector of the economy. Fortunately, many transformations that would help achieve climate targets often come with enormous economic and development benefits that directly align with the goals of ministries and sectors that will implement them.

This report follows in the footsteps of studies in Chile, Costa Rica, Colombia, the Dominican Republic, and Peru (Benavides et al., 2021; Groves et al., 2020; Arguello et al., 2022; Quirós-Tortos et al., 2023; Quirós-Tortos et al., 2021) that connect development and decarbonization goals by identifying and quantifying the social, economic, and environmental costs and benefits of actions that would help countries reach net zero. This work introduces SiSePuede, a toolkit for developing and assessing transformations, and uses it to develop robust decarbonization strategies for all Latin America and the Caribbean while also diving into implications for each sector and select countries.

This work is the result of collaboration between the RAND Corporation, Tecnólogico de Monterrey, the IDB, and the 2050 Pathways Platform. Funding was provided by the IDB and the European Climate Foundation. The contents of this work reflect the authors' analyses and do not necessarily represent the views and opinions of the funding organizations.

Here, we endeavor to demystify the idea of reaching net-zero and to connect climate change to the goals and concerns of many people across the economy who would enact and be affected by much-needed changes. We hope this report will be of interest to climate, finance, transverse, and line ministries and private sector leaders throughout Latin America, the Caribbean, and beyond; resonating with international finance organizations and other nongovernmental organizations (NGOs) helping to bring about these changes; and beckoning to climate policy makers around the globe.

About RAND Social and Economic Well-Being

RAND Social and Economic Well-Being is a division of the RAND Corporation that seeks to improve the health and social and economic well-being of populations and communities throughout the world. This research was conducted in the Community Health and Environmental Policy Program within RAND Social and Economic Well-Being. The program focuses on such topics as infrastructure, science and technology, industrial policy, community design, community health promotion, migration and population dynamics, transportation, energy, and climate and the environment, as well as other policy concerns influenced by the natural and built environment, technology, and community organizations and institutions that affect well-being. For more information, email chep@rand.org.

About Tecnólogico de Monterrey

Tecnológico de Monterrey is the largest private university in Mexico, with 31 campuses in 25 cities. It is a private, nonprofit, independent institution with no political or religious affiliations. Since 2018, the Quacquarelli Symonds World University Rankings has recognized Tecnológico de Monterrey as the best private university in Mexico, and in 2021 among the top 30 private universities worldwide. Its work is supported by civil associations of leaders from all over Mexico who are committed to quality in higher education. Research programs include strategic partnerships with the Massachusetts Institute of Technology, Femsa Biotechnology Center, the Water Center for Latin America and the Caribbean (financed by the IDB and the Femsa Foundation), the Motorola Research and Development Center on Home & Networks Mobility, the Center for Advanced Design at the Guadalajara Campus, and the School of Government and Public Transformation Energy Knowledge Networks funded by Mexico's National Science and Technology Council (Conacyt). For more information, email edmundo.molina@tec.mx.

About the Inter-American Development Bank

IDB is a leading source of long-term financing for economic, social, and institutional projects in Latin America and the Caribbean. Besides loans, grants, and guarantees, the IDB conducts cutting-edge research to offer innovative and sustainable solutions to the region's most pressing challenges. Founded in 1959 to help accelerate progress in its developing member countries, IDB works every day to improve lives. The opinions expressed in this publication are the authors' and do not necessarily reflect the views of IDB, its board of directors, or the countries they represent.

About the 2050 Pathways Platform

The 2050 Pathways Platform is a multistakeholder initiative launched in 2016 by the United Nations Climate Change Conference (COP21) Climate Change Ambassador for France Laurence Tubiana, one of the architects of the Paris Agreement. It was established at the request of countries who wanted a collective space to exchange best practices for the elaboration of long-term low emissions development strategies, one of the key elements of the Paris Agreement. In addition to its 38 country members, the Platform brings together a network of bilateral and multilateral donors, international and national think tanks, and climate policy experts interested in long-term planning in response to the climate challenge.

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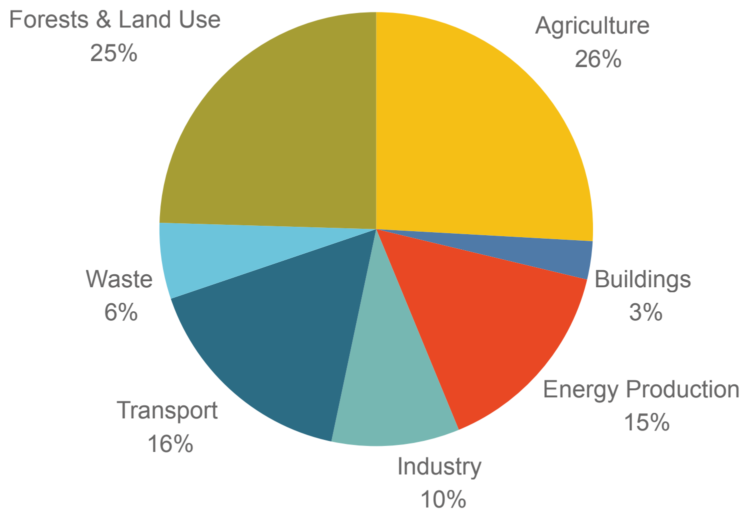
Executive Summary

Climate change poses a grave threat to sustainable development in Latin America and the Caribbean (Talbot-Wright and Vogt-Schilb, 2023). Its effects include more frequent and intense natural disasters, sea-level rise, changes in local weather patterns, and loss of vital ecosystem services. The impacts for humans are vast, including threats to food and water security, disruption of infrastructure, increased human morbidity and mortality, and lower labor productivity, household income, fiscal balances, and tourism revenues. Moreover, climate change disproportionately affects poor and underrepresented people, creating a vicious cycle. It can spur migration, both within and across national boundaries. The vulnerability of urban populations and small island states is of particular concern. While adaptation is essential and urgent, it is proving inadequate in the face of unchecked climate change (Parmesan et al., 2022).

Global warming will continue to worsen as the world emits greenhouse gases (GHGs). Limiting the temperature increase between 1.5 and 2°C above pre-industrial levels, the Paris Agreement's overarching goal requires reaching net-zero emissions of GHGs by around 2050 (Paris Agreement to the United Nations Framework Convention on Climate Change, 2015). This ambitious goal requires massive, on-the-ground changes in every sector and country (IDB and DDPLAC, 2019; Fazekas et al., 2022). Meeting both resilience and decarbonization goals requires realigning the equivalent of 7 to 19% of gross domestic product (GDP) with climate change goals every year (Galindo Paliza et al., 2022).

A key question is how much Latin American and Caribbean countries should do to reduce emissions. Emissions in the region averaged 4 gigatons of carbon dioxide equivalent (GtCO2e) per year from 2015 to 2020 (Climate Watch Historical GHG Emissions, 2022). Figure ES.1 shows the breakdown of emissions in the region by economic sector. Agriculture, forests, and other land uses account for 50% of emissions, which reflect the large role agriculture plays in the region, which is a net exporter of agricultural products, as well as the rapid deforestation that has accompanied the expansion of agriculture in general and conversion of forests to grazeland in particular (Climate Watch Historical GHG Emissions, 2022; Hernández-Blanco et al., 2020, Zalles et al., 2021). Electricity and energy production, on the other hand, contribute much less to emissions in large part because of the region's significant reliance on hydropower, though growing reliance on natural gas for electricity is an important driver of emissions (Marinkovic, 2023; Vogt-Schilb, 2023). This contrasts with the rest of the world, in which agriculture, forests, and other land uses account for 15% of emissions and electricity and energy production account for 40% (Climate Watch Historical GHG Emissions. 2022).



Source: Climate Watch, World Resources Institute (2023).

Figure ES.1 Emissions by sector in Latin America and the Caribbean (2015-2020).

The region's emissions represent less than 10% of total global emissions of 47.5 Gt CO2e (Climate Watch Historical GHG Emissions. 2022). Many therefore propose that most emission reductions should happen in developed countries, which already have benefited from fossil-fueled economies and whose emissions are far larger. Poorer countries, meanwhile, should be given room to develop as they see fit, perhaps polluting in the process (Vogt-Schilb, 2023).

Traditional development patterns around the world, however, including in Latin American and the Caribbean, have been far from optimal. There is increasing evidence that development and decarbonization can be more aligned than conflicting (Fazekas et al., 2022). As just one example, economic growth in the region has led to the fastest increase in car ownership in the world (SLOCAT 2021). While this has brought economic opportunity and high living standards to millions, it also poses huge costs from accidents, road congestion, and air pollution (Calatayud et al., 2021; Chen et al., 2019; Husaini et al., 2022). Policies and investments promoting non-motorized transport and transit, higher vehicle occupancy, increased vehicle efficiency, and electrified vehicles could improve quality of life and promote growth while also reducing emissions. As another example, many in the region lack access to safe water and sanitation. Achieving universal safe water and sanitation is not only a key Sustainable Development Goal (SDG) but the collection, safe management, treatment, and energy recovery of waste and wastewater is key to reducing emissions (Rani et al., 2022; de Foy et al., 2023).

In addition, the cost of low-carbon technology such as solar and wind has plummeted (IEA, 2023). Technologies that run on electricity, such as electric vehicles or heat pumps, often are cheaper to operate and maintain than their fossil fuel-based counterparts, even while financing high upfront costs remains a challenge (Rissman, 2022; AAA, 2019; Burke et al. 2022). In some sectors, decarbonization is becoming the fastest way to reduce costs and improve services.

Indeed, prior country-level research has found that reaching net-zero emissions could result in net benefits of approximately $41 billion in Costa Rica, $7 billion in Chile, $330 billion in Colombia, and $140 billion in Peru (Groves et al., 2020; Benavides et al., 2021; Arguello et al., 2022; Quirós-Tortos et al., 2021). Regional studies have suggested that net-zero efforts can increase GDP in Latin American and the Caribbean by 1% by 2030 (Vogt-Schilb, 2021) while creating millions of green jobs (Saget et al., 2020).

Even if reducing emissions contributes to development, it is easy for decarbonization plans to feel disconnected from the goals, knowledge, and context of ordinary citizens and decisionmakers who must implement them. Governments' ministries of environment are typically responsible for designing climate strategies. But the actions described in these plans must be implemented by the private sector; by government agencies in other ministries such as transport, energy, agriculture, industry, and finance; and by various levels of government—from national to municipal (Rakes et al., 2023; Vera et al., 2023). These actors may be sympathetic to climate change, but they have other priorities—such as growth and productivity, labor, and sector-specific concerns such as congestion, health care costs, and food security—and little knowledge of what net-zero emissions mean for them and how to reach these goals. To be motivated and able to act, farmers, transit authorities, or factory operators, who speak in terms of heads of cattle, numbers of buses, and tons of cement, need to know what specific transformations in their sector are needed from them to make progress towards net zero, and what their costs and benefits from those transformations would be.

Purpose and Approach

In this study, we explore options for Latin America and the Caribbean to robustly meet two goals: reaching net-zero emissions in alignment with Paris Agreement targets and providing net social, economic, and environmental benefits to the people who would walk that path.

We have developed SiSePuede (SImulation of SEctoral Pathways and Uncertainty Exploration for DEcarbonization), a toolbox for designing development strategies and analyzing amid uncertainty their emissions, costs, benefits, and alignment with development goals and Paris Agreement targets. We have used SiSePuede to assess decarbonization strategies in Latin America and the Caribbean under uncertainty. We calibrated SiSePuede with data from 18 countries that are IDB borrowing members: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, and Uruguay.

SiSePuede models emissions in six integrated economic sectors based on the Intergovernmental Panel on Climate Change (IPCC) methodology (IPCC, 2006; 2019): agriculture, industry, buildings, transport, waste, and electricity and fuel production. SiSePuede's process of modeling emission reductions can be understood through the ASIF framework, originally designed for the transport sector (Schipper and Marie-Lilliu, 1999). ASIF stands for Activity, mode Share, emissions Intensity, and emissions intensity of Fuel. First, levels of activity (e.g., demand for food, transport, buildings, industrial output, and energy) are based on underlying GDP and population drivers. Then, each activity is apportioned to a production mode (e.g., the fraction of residential heat demand met by natural gas furnaces, wood-burning stoves, or heat pumps). Each mode is associated with a specific emission intensity shaped by efficiency and fuel sources. The variables that drive emissions are calibrated against publicly available datasets on economic activity, energy consumption, and emissions from sources such as IDB, World Bank, International Monetary Fund (IMF), International Energy Agency (IEA), and United Nations Food and Agriculture Organization (UN FAO). SiSePuede is a free and open source model, available on GitHub at https://github.com/jcsyme/sisepuede and https://hub.docker.com/r/jsyme816/sisepuede, documented at https://sisepuede.readthedocs.io.

Given the many deep uncertainties that influence emissions, costs, and benefits, we couple SiSePuede with Robust Decision Making (RDM), a method for managing deep uncertainties (Lempert, Popper, and Bankes, 2003; Groves and Lempert, 2007; Kalra et al., 2015; Lempert, et al., 2013). RDM is an iterative, stakeholder-supported process for conducting exhaustive "what-if" analyses. Using RDM's vulnerability-analysis techniques, we evaluate strategies under an array of future conditions and assumptions to understand the potential range of outcomes and conditions that lead strategies to meet (or fail to meet) decarbonization and economic goals. This method previously has been used in Latin America and the Caribbean to inform decarbonization planning (Groves et al., 2020, 2022; Quirós-Tortós et al., 2021, 2023; Benavides et al., 2021; Arguello et al., 2022) and resilient water and transport planning (Kalra et al., 2015; Groves et al., 2021; Molina-Perez et al., 2019; Olaya et al., 2020).

Consistent with RDM's process, our experimental design was informed by the input of IDB sector experts. We engaged them at the start of our research in a first round of sector-specific workshops in which they provided guidance on transformations for achieving decarbonization, those transformations' costs and benefits, uncertainties that would shape outcomes, and data and models available to inform our analysis. After our preliminary analysis, we then held sector-specific workshops to solicit revisions to our experimental design and review data and outcomes. We revised our final analysis based on this expert feedback.

Traditional Development Results in High Emissions

A Traditional Development trajectory for the region serves as a backdrop against which other decarbonization actions (called transformations) are compared. Traditional Development reflects a future mostly unconcerned with decarbonization and consistent with historical development trajectories—for instance, car ownership increases with GDP per capita. This scenario also includes an increase in energy efficiency and productivity through improved technology, and a modest increase in using renewables for electricity production. Under a Traditional Development trajectory, we estimate emissions in the region would increase by 70% from 4.1 GtCO2e in 2020 (Climate Watch Historical GHG Emissions, 2022) to 6.9 by 2050 (see Figure ES.2).

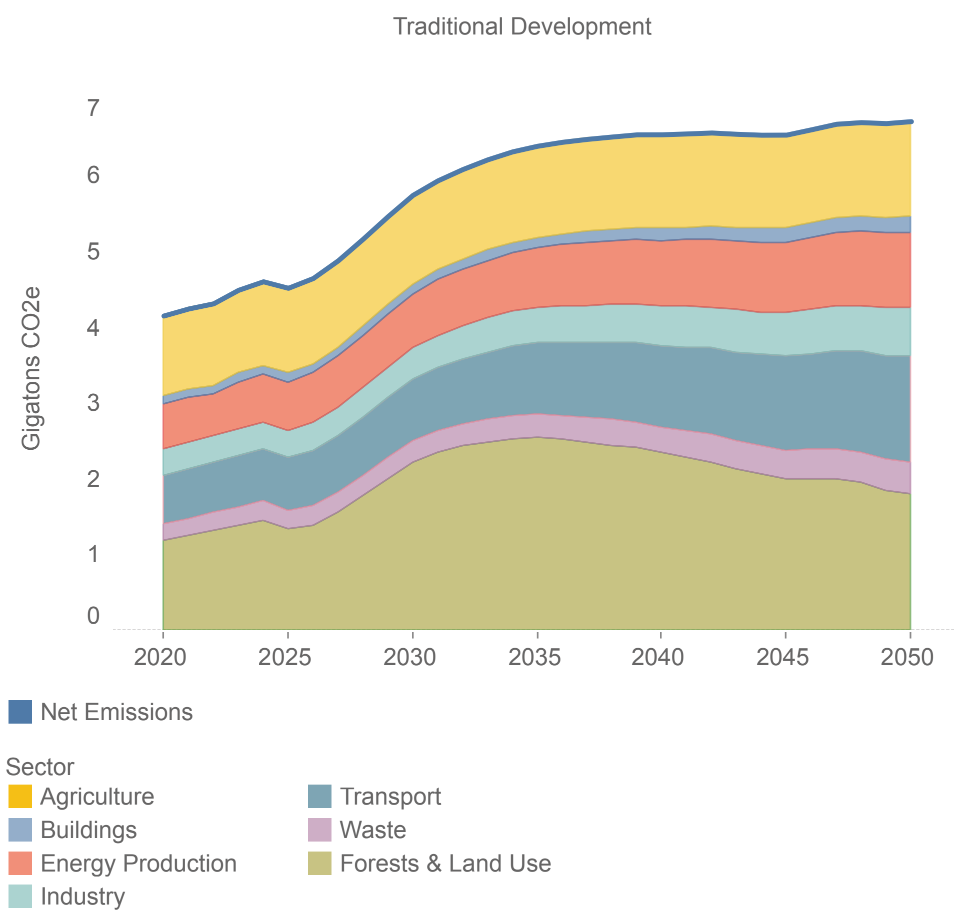


Figure ES.2 Emissions under Traditional Development.

Importantly, Traditional Development is not and should not be interpreted as a projection of how Latin America and the Caribbean currently are developing or likely to develop soon. In important ways, it is consistent with current trends in the region, such as a reliance on natural gas to offset drought-induced hydropower shortages (Climate Watch Historical GHG Emissions, 2022). However, there are many efforts to decarbonize by moving the region away from such a traditional development trajectory (Iyer et al., 2017; IDB and DDPLAC, 2019). At least 10 countries in the region have set net-zero targets, most of them for 2050.

Against the traditional development backdrop, we define more than 50 different transformations across the economy (Table ES.1). Emissions can be reduced by curtailing activity—for instance, reducing travel demand by encouraging work from home or reducing total food production by decreasing waste and losses. Transformations also can affect the carbon intensity of sector activity, such as improving road vehicles' and appliances' energy efficiency or adapting agriculture practices to increase yields. Structural changes also can be made, such as by producing electricity from renewable sources rather than fossil fuels, using public transport instead of cars, and producing foods that have a lower carbon intensity and land requirements per unit of nutrition. Finally, shifts can be made from dirtier to cleaner sources of energy—for instance, by producing electricity with solar instead of natural gas, and by using electricity instead of fossil fuels in road vehicles and to produce heat in buildings and industry.

Table ES.1 Consolidated list of transformations by sector

Sector	Transformations
Agriculture, forests, and other land use	• Reduce excess fertilizer use • Expand conservation agriculture • Improve rice management • Accelerate productivity • Use gains in productivity to conserve land • Reduce enteric fermentation • Expand silvopasture • Manure management • Reduce supply chain losses • Halt deforestation • Induce afforestation with a shift in agricultural production and consumption
Industry	• Shift from virgin to recycled inputs • Substitute clinker in cement • Increase energy efficiency • Increase efficiency of materials use • Fuel shift low-temperature heat to heat pumps • Fuel shift high-temperature heat to electricity and hydrogen • Reduce fluorinated (F) -gases • Abate nitrous oxide (N2O) in chemical production • Use carbon capture and storage (CCS) for steel, cement, chemicals, and plastics

Buildings	• Increase appliances' energy efficiency • Increase building shell efficiency • Fuel switch heat to heat pumps
Transport	• Increase transportation energy efficiency • Fuel switch medium- and heavy-duty road transport • Electrify rail • Fuel switch maritime • Mode shift freight • Electrify light-duty road transport • Increase occupancy for private vehicles • Mode shift local passenger travel to transit and non-motorized • Mode shift regional passenger travel to bus and rail
Energy production	• Reduce transmission losses • Produce electricity with renewables • Produce hydrogen with renewables • Flare vented fugitive emissions • Fix leaks of fugitive emissions
Waste	• Universal safe sanitation • Full wastewater treatment • Expand solid waste collection and end open dumping/burning • Divert waste to recyclables • Energy recovery from wastewater treatment • Increasing capture and use of biogas in digesters and landfills • Reduce consumer food waste • Divert organic material to composting or digesters

Reaching Net Zero Is Feasible and Beneficial

We first analyze the region's decarbonization and economic potential. We find that when all transformations are implemented to maximum effect, which we call an All Actions strategy, the region could achieve net-zero emissions as soon as 2040 under nominal assumptions (see Figure ES.3). (This development strategy is probably overly ambitious, and thus we consider less drastic, more realistic scenarios next). All Actions means simultaneously minimizing emissions from each economic sector (industry, transport, waste, buildings, and energy production), and making changes that enable massive afforestation to offset residual emissions, such as increasing livestock productivity, protecting forests, and shifting agricultural patterns.

Figures ES.4 shows the costs and benefits of All Actions relative to Traditional Development between 2025 and 2050—all our figures are given in 2019 US dollars, and future flows are discounted using a 7% discount rate. Under nominal assumptions, taking all actions can create $2.7 trillion in total net benefits for Latin America and the Caribbean. The main benefits are fuel savings ($900 billion), avoided pollution ($500 billion), and other health, safety, and productivity gains ($1 trillion); these more than compensate the significant additional investment needs ($1.3 trillion). But even when only considering financial costs and benefits to sectors (and excluding hard-to-value and largely public benefits of avoided pollution, ecosystem services, and gains in health, safety, and productivity), we find net benefits of $700 billion.

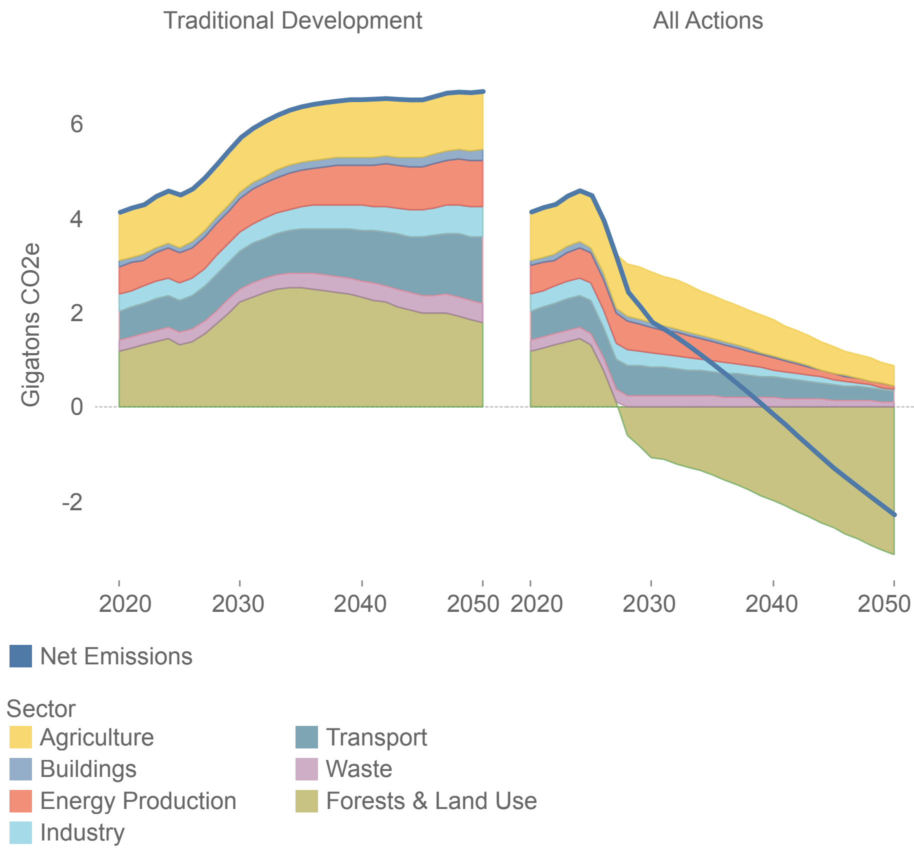


Figure ES.3 Emissions under Traditional Development and All Actions.

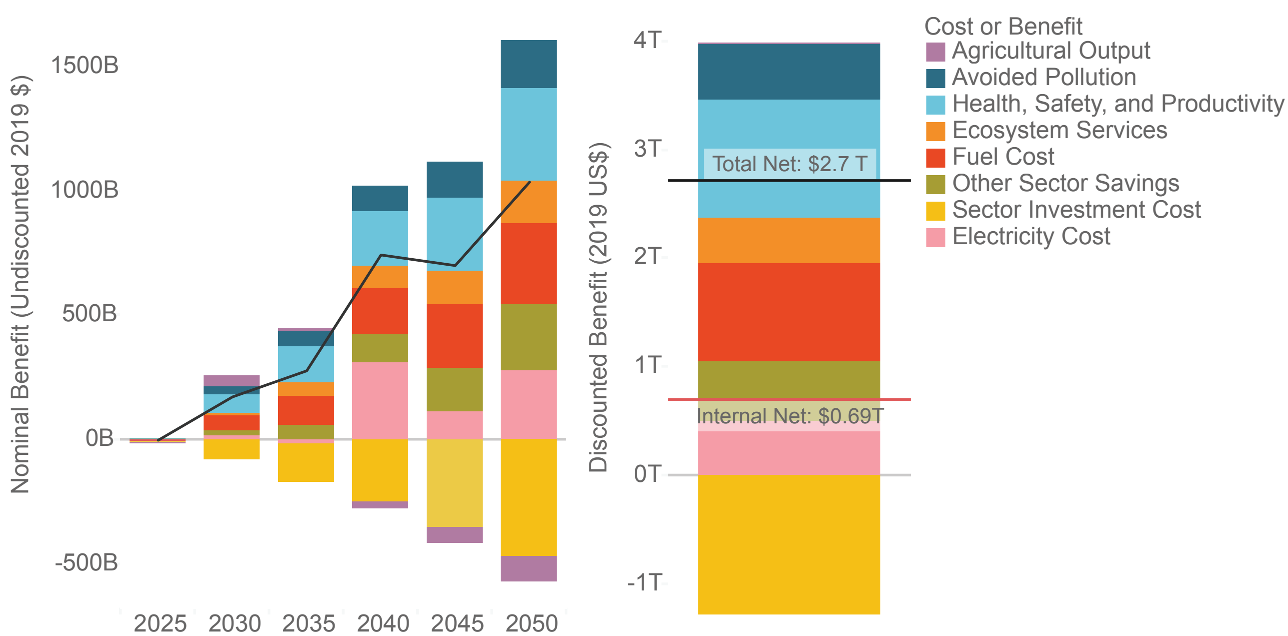


Figure ES.4 Nominal (left) and discounted net benefits (right) from taking All Actions

Key to these benefits is that taking All Actions combines the many necessary structural changes with efficiency gains throughout the economy. For instance, emissions from the electricity sector could be eliminated by switching from fossil fuels to renewables, but this approach on its own poses a high cost in a future where electricity demand increases from fuel switching to electricity and hydrogen across the economy. By coupling this structural change with increasing energy efficiency, the sector can reduce emissions by 95% at a net benefit compared to a traditional development scenario. Similarly, costly investments in using carbon capture and storage (CCS) to abate industrial process emissions can be lessened when industrial outputs such as steel and cement are used more efficiently, thereby reducing the need for production in the first place. In buildings, savings in electricity from efficiency interventions outpace the additional need for more electricity because of fuel switching.

A Robust Decarbonization Strategy Has Three Critical Actions

Our All Actions strategy serves as an upper bound on what the overall region could gain if it aggressively implemented changes to decarbonize. But doing everything everywhere all at once may not be feasible or necessary. In practice, countries' decarbonization strategies, including their Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs), will involve transformations at different implementation levels based on the impacts, costs, benefits, technological availability, political feasibility, and other barriers and drivers of those actions.

To inform those conversations, we assessed which actions are most important to reaching net zero. We generate approximately 1,000 decarbonization strategies that implement every transformation in Table ES.1 to different degrees and analyzed the outcome of each strategy in terms of emissions, costs, and benefits under uncertainty.

Consistently with previous findings at the global scale (IPCC, 2023), we find that while there are thousands of different paths to net zero, three changes are critical:

1. Produce electricity (and, to a lesser extent, hydrogen) from renewable energy sources. Fuel shifts throughout the economy abate emissions only to the extent that electricity and hydrogen—the main replacement fuels—are produced with renewables and not fossil fuels. So, cleaning the grid and producing green hydrogen are critical to decarbonization.
2. Use electricity (and to a lesser extent, hydrogen) instead of fossil fuels to power transport. Transport is one of the hardest to abate sectors, given the many diffuse sources of emissions, growing demands for private vehicle travel, and built infrastructure that entrenches travel patterns by road. Our analysis points to fuel shifts in transport as a key, as it reduces emissions even if shifts in mode and activity turned out to be constrained.
3. Return the land to a carbon sink. This is necessary to offset any residual emissions from the rest of the economy. It involves protecting forests and enabling afforestation through a combination of increasing agricultural productivity and shifting agricultural production and consumption from higher to lower-carbon foods, which are often healthier.

These three actions must be coupled with other, potentially more modest changes across the economy, such as increasingly building energy efficiency, shifting to heat pumps, using materials more efficiently, and destroying potent fluorinated (F)-gases.

Implementing these key changes also results in net benefits under nearly all future conditions we examined. Figure ES.5 shows the net benefit from 2025-2050 (horizontal axis) and net 2050 emissions (vertical axis) of 1,000 variants of decarbonization strategies with the three critical actions implemented and evaluated across a wide range of uncertain conditions (each mark on the plot represents a different variant of this strategy under different conditions). They are categorized by whether they meet, miss, or overshoot net-zero emissions by 2050, and whether they pose net costs or benefits. We find a median benefit of $1 trillion across all the deeply uncertain conditions we explored, net of substantial technical investments which range from $0.5 to $1.5 trillion. Here too, the largest consistent benefits are in the form of fuel cost savings, health, productivity, safety benefits, and ecosystem services.

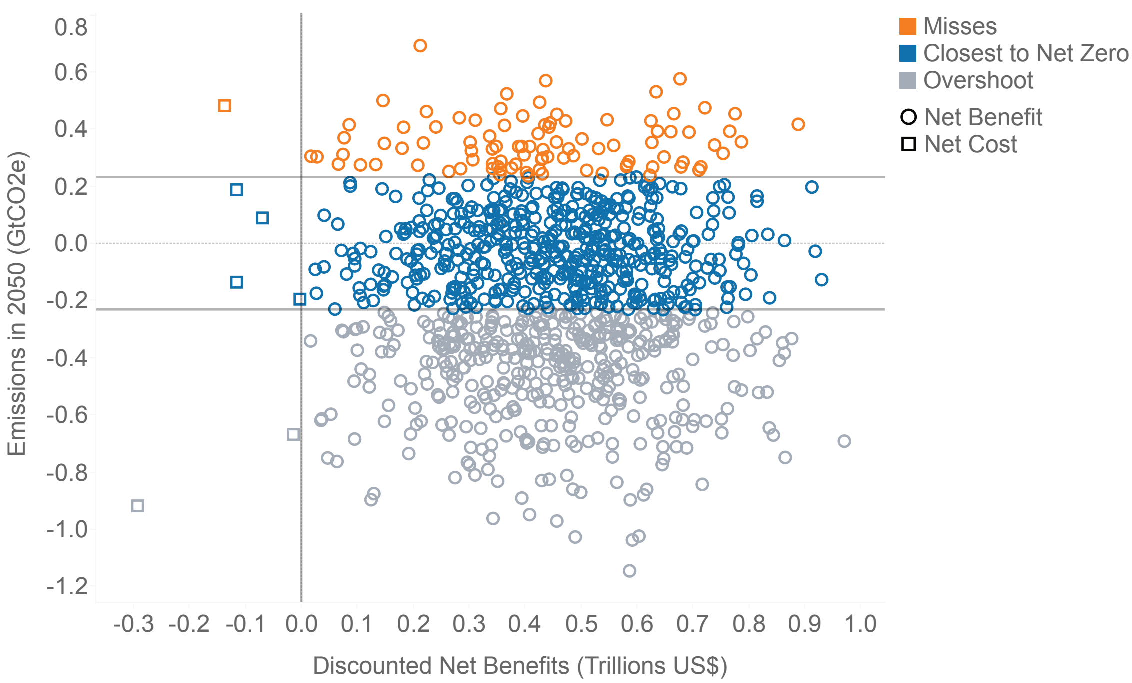


Figure ES.5 Net benefits and net 2050 emissions of critical action strategies under uncertainty.

Strategies with the aforementioned features still can be vulnerable to missing net zero when the sequestration and offsets provided by forests are reduced, because of reduced livestock productivity and lower forest sequestration rates—stressors that may be exacerbated by climate change (Gatti et al. 2021, Rojas-Downing et al., 2017). Reduced livestock productivity increases the amount of land needed for raising livestock, thereby increasing pressures to deforest. Reduced sequestration means that even more areas must be reserved to protect existing forests and return grazeland to secondary forests. Hedging against these risks requires maximizing cattle productivity and more intense efforts to end deforestation and enable afforestation. Measures such as silvopastures may help on all fronts.

Low-Carbon Development Strategies Are Development Enhancing

Our analysis suggests that Latin America and the Caribbean can transition to a net-zero economy while enjoying better development, with potential gains to social, economic, and environmental outcomes. It is therefore logical to ask why these transformations are not occurring at a pace that these results might warrant.

There are a host of regulatory, fiscal, information, and other barriers that stand in the way of changes that would lead to better development (Fazekas et al., 2022). For example, the widespread subsidies associated with fossil fuels (International Monetary Fund, 2021) entrench the use of fossil fuels in transport and energy production, even when renewables are the more cost-effective alternative. Even the built environment can pose barriers to change: urban sprawl enabled by historical emphasis on road travel and an absence of bike lanes and walking paths can make it difficult to then shift development toward walking, biking, transit, and other sustainable modes—even for those who would be ready to take them (Mouratidis et al., 2019).

Compounding the challenge is that the costs and benefits of transformations are borne by different people, and many of the largest costs are internalized but many of the benefits remain external to market forces. For instance, many of the health, safety, productivity, and environmental benefits are diffuse and would improve many people's lives, whereas the technical costs and benefits are experienced more acutely by sector actors. The timing of costs and benefits also poses a barrier: sector costs are often up-front capital investments, whereas sector benefits are enjoyed over time in the form of operational, maintenance, and fuel savings.

This points to the significance of government interventions to redistribute benefits through society, fiscal and industrial policies, tariff structure, and social policy. For instance, governments could internalize some of the social benefits of reduced congestion and air pollution by adjusting taxes on fuel and vehicle ownership or reforming fossil fuel subsidies while reinforcing cash transfers or subsidizing adoption of clean technology (e.g., Victor-Gallardo et al., 2022, Missbach et al., 2023). In Latin America and the Caribbean, where half of emissions come from agriculture and deforestation, ensuring a just transition will be critical. Decarbonization cannot come at the cost of slowing efforts to reduce rural poverty or ensuring food security for all. Our analysis suggests that this sector's advancement will make decarbonization efforts more robust.

These barriers and opportunities crucially depend on a nation's resources and local economic and political conditions, and so do development priorities. Therefore, each country will have to build its own vision of a low-emission future that begins the development outcomes it needs most; diagnose the barriers that prevent it from securing a future with a healthier population, healthier environment, and stronger economy; and make its own plans to enable a just transition to net-zero emissions. For example, Brazil is the largest country in the region and hosts the most rainforest of any country in the world. It has significant potential to reduce emissions, compared to the Traditional Development strategy, by safeguarding existing forests and promoting afforestation. Brazil also enjoys a relatively clean electricity grid, thanks to enormous amounts of hydropower. In that sense, Brazil's situation is somewhat similar to the regional averages we show here. In contrast, as an island nation with 0.5% of Brazil's land area, the Dominican Republic has much less sequestering potential and a different mix of emissions sources, where industrial processes and electricity production play a larger role. In the full report, we show that trying to indiscriminately apply regional findings at the country level would be inadequate.

In designing country-specific climate-friendly development strategies, it will be essential to involve active participation from the private sector, civil society, and relevant government agencies. By engaging early in the process, each stakeholder's insights, expertise, and concerns can shape the plan, buttress support for it, and facilitate its implementation toward a highly developed and low-carbon future.

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1 CHAPTER

Introduction

CHAPTER ONE
Introduction

Climate change poses a grave threat to sustainable development in Latin America and the Caribbean (Talbot-Wright and Vogt-Schilb, 2023). Its effects include more frequent and intense natural disasters, sea-level rise, changes in local weather patterns, and loss of vital ecosystem services. The impacts for humans are vast, including threats to food and water security, disruption of infrastructure, increased human morbidity and mortality, and lower labor productivity, household income, fiscal balances, and tourism revenues. Moreover, climate change disproportionately affects poor and underrepresented people, creating a vicious cycle. It can spur migration, both within and across national boundaries. Urban populations' and small island states' vulnerability is of particular concern. While adaptation is essential and urgent, it already is proving inadequate in the face of unchecked climate change (Parmesan et al., 2022).

Global warming will only get worse as the world emits GHGs. Limiting the temperature increase between 1.5 and 2°C above pre-industrial levels, the overarching goal of the Paris Agreement, requires reaching net-zero GHG emissions by around 2050 (Paris Agreement to the United Nations Framework Convention on Climate Change, 2015). Net zero means reducing emissions as much as possible and using offsets, such as reforestation, as a last resort to compensate for emissions that are too difficult or expensive to abate.

These are ambitious goals. Mitigating climate change requires massive, on-the-ground changes in every sector and country (IDB, 2019; Fazekas et al., 2022). Meeting both resilience and decarbonization goals requires realigning the equivalent of 7 to 19% of GDP with climate change goals every year (Galindo Paliza et al., 2022). While this is not a net cost, as much of the effort involves redirecting existing domestic private finance from traditional investments or technologies to lower-emitting alternatives (e.g., diesel to electric buses), it illustrates the required effort's magnitude and depth (Fazekas et al., 2022).

Cooperating to Mitigate Climate Change

To organize such action, the Paris Agreement requires countries to submit NDCs periodically and strive to formulate and communicate LTSs. At COP26, in Decision 1/CMA.4, signatories of the Paris Agreement also noted the importance of aligning NDCs that have shorter time frames with LTSs to facilitate a just transition toward a net-zero economy by around midcentury (UNFCCC, 2023a). Yet global commitments and policies remain far short of Paris targets. Current policies would result in warming of between 2.6 and 2.9°C and NDCs would limit that to only 2.4° (Climate Action Tracker, 2022c). Only six countries globally have net-zero targets that are rated "acceptable" by Climate Action Tracker in terms of transparent, comprehensive, and robust design.

This situation holds true in Latin America and the Caribbean. Of the 33 countries in the region that are party to the Paris Agreement, at least 10 have pledged to reach net-zero emissions by 2050 or sooner (Climate Watch Data, 2023). However, the region's NDCs would reduce emissions only by about one-third compared to today's emissions levels, well short of what is needed to put them on track toward net-zero emissions by 2050 (Cárdenas and Orozco, 2022; Binsted et al., 2020). What is more, only eight countries have prepared LTSs that could inform NDC updates, and of these, only three—Costa Rica, Chile, and Colombia—are rated "acceptable" with respect to a net-zero goal by Net-Zero Tracker (2023). Of these, Costa Rica's LTS translated the 2050 net-zero goal into a framework with more than 70 targets for immediate delivery, which attracted US$1.4 billion in policy-based loans from international funders (Jaramillo et al., 2023). Costa Rica is not representative of the whole region, unfortunately, as most countries lack a public policy strategy to inform immediate action that is consistent with reaching the targets of their NDCs (Jarmillo and Saavedra, 2021).

A key question is whether Latin American and Caribbean countries should do more to reduce emissions. Under the Paris Agreement, parties are expected to act according to the principle of Common but Differentiated Responsibilities and Respective Capabilities (CBDRRC). After all, most GHGs in the atmosphere are emitted from outside the region. For instance, economic development has been fueled chiefly by coal, gasoline, diesel, and natural gas. The richer a country is, the more likely its citizens are to own cars, the more miles per year they travel, the larger homes they live in, and the more food they consume. Thus, many have proposed that most emission reductions should happen in developed countries, leaving room for less-developed countries to follow traditional development paths, perhaps polluting in the process (Vogt-Schilb, 2023).

An opportunity for more sustainable growth?

Emission reductions are not necessarily antinomic with economic growth. Development patterns around the world, including in Latin American and Caribbean, have been far from optimal. For instance, recent economic growth in the region has led to the fastest growth in car ownership in the world (SLOCAT 2021). This has brought economic opportunity and high living standards to millions. But it also poses major costs to the region, including loss of lives and health costs related to accidents, road congestion, and air pollution (Calatayud et al., 2021; Chen et al., 2019; Husaini et al., 2022). In Rio de Janeiro and Sao Paulo, for instance, congestion cost 8% of the metropolitan regions' GDPs, and 2% of Brazil's GDP overall, in 2014 (FIRJAN, 2015). The region also has more than 100 million residents living in areas with air pollution levels exceeding World Health Organization (WHO) guidelines (Riojas-Rodríguez et al., 2016). With policies and investments promoting a transition to non-motorized transport and transit, higher vehicle occupancy, increased vehicle efficiency, and electrified vehicles, countries in the region might be able to continue improving living standards while also avoiding locking themselves in a high-carbon development trajectory.

Similarly, current food production and consumption patterns in Latin America and the Caribbean come with substantial public health and environmental costs. Approximately 43 million people in the region are undernourished and 133 million people cannot afford a healthy diet because the region has the highest level of income inequality in the world, a situation made worse by the recent global pandemic (Salazar and Muñoz, 2018; FAO, IFAD, UNICEF, WFP and WHO. 2023). At the same time, obesity rates are high and growing, driven by poor diets low in fruits and vegetables (Popkin & Reardon, 2018; Guthold et al., 2018). In South America, diets high in red meat, the food group most negatively associated with non-communicable diseases (Popkin and Reardon, 2018), have been linked to premature deaths of more than 60,000 people in 2018 (Hartinger et al., 2023). And conversion to pastures is the largest driver of deforestation, threatening $15 trillion in forest services (Climate Watch, 2022; Hernández-Blanco et al., 2020). A shift In production and consumption toward healthier foods, coupled with better agriculture practices, might help avoid more than 500,000 premature deaths and provide $100 billion to $2 trillion in health benefits by 2050 (Springmann et al., 2016), while reducing emissions through forest preservation, afforestation, avoiding enteric fermentation, and reduced manure emissions.

Often the best way to close development gaps also results in emission reductions. Achieving universal safe water and sanitation is not only a key Sustainable Development Goal (SDG) but the collection, safe management, treatment, and energy recovery of waste and wastewater is key to reducing GHG emissions (Rani et al., 2022; de Foy et al., 2023).

Finally, there is growing evidence that emission reductions can be cost beneficial, even in developing countries (Fazekas et al., 2022). One reason is that the cost of key technology has plummeted. The best examples are solar panels and wind turbines, which cost less than 10% and 30%, respectively, of what they cost in 2009 (IRENA, 2022). They are now the cheapest available option for energy production, while they were the most expensive option when European, North American, and Asian countries built the bulk of their coal power plants (IEA, 2023). As such, investments in renewable electricity production offer significant financial benefits in the form of fuel savings. Moreover, technologies that run on electricity, such as electric vehicles or heat pumps, often are cheaper to operate and maintain than their fossil fuel-based counterparts, even while financing high upfront costs remains a challenge (Rissman, 2022; AAA, 2019; Burke et al. 2022).

Indeed, prior country-level research has found that reaching net-zero emissions could result in net benefits of approximately $41 billion in Costa Rica, $7 billion in Chile, $330 billion in Colombia, and $140 billion in Peru (Groves et al., 2020; Benavides et al., 2021; Arguello et al., 2022; Quirós-Tortos et al., 2021). Regional studies have suggested that net-zero efforts can increase GDP in Latin America and the Caribbean by 1% by 2030 (Vogt-Schilb, 2021) while creating millions of green jobs (Saget et al., 2020).

Decarbonization planning is complex, and many countries lack capacity

Even if reducing emissions could contribute to development, it is easy for decarbonization plans to feel disconnected from the goals, knowledge, and context of ordinary citizens and decisionmakers who must implement them (Calfucoy et al., 2022). Governments' ministries of environment are typically responsible for designing climate strategies. However, the actions described in these plans need to be implemented by the private sector, by government agencies in other ministries—such as transport, energy, agriculture, industry, and finance (Fazekas et al., 2022)—and by various levels of government, from national to municipal (Rakes et al., 2023; Vera et al., 2023). These actors may be sympathetic to climate change, but they have other priorities—including growth and productivity, labor, and sector-specific concerns such as congestion, healthcare costs, and food security—and little knowledge of what net-zero emissions mean for them and how to reach these goals.

Indeed, much existing decarbonization research and plan making is not directly usable by these actors. Many analyses describe mitigation measures in terms of their costs per ton of carbon dioxide equivalent (CO2e) avoided (e.g., Cárdenas and Orozco, 2022; Hof et al., 2017; Johnson et al., 2009). A focus on emission reductions and their marginal cost may make sense to climate change economists, but this is not the language of farmers, transit authorities, or factory operators, who speak in terms of heads of cattle, numbers of buses, and tons of cement. To be motivated and able to act, these leaders need to know what specific transformations they must enact in their sector to make progress toward net zero. These should be expressed tangibly and actionably, such as producing electricity with 50% solar and wind power by 2030; shifting 70% of local transport to transit, walking, or biking by 2040; or reforesting 1,000,000 hectares of degraded pasture by 2050 (Fay et al., 2015; Waisman et al., 2019). In turn, this can provide concrete information to ministries of finance to plan public budgets, clarify public investment priorities, assess impacts and required adjustments on fiscal policy (Solano-Rodríguez et al., 2021; Victor-Gallardo et al, 2022), and manage debt to support delivery across sectors in addition to relevant macroeconomic indicators such as jobs, GDP, and trade balance dynamics in the transition (Orozco and Jaramillo, 2021; Delgado et al., 2021).

Developing plans that reach net zero and align with stakeholders' and citizens' knowledge, concerns, and priorities is analytically challenging. Integrated, multisectoral emissions models are complex and costly to develop and can be time-consuming and difficult to use. The data needed to produce credible estimates is vast and heterogeneous and, particularly for countries in the region, huge data gaps exist in essential sectors. Conditions also are changing rapidly, requiring sophisticated analytical methods for managing deep uncertainties. Many countries face capacity challenges to create robust decarbonization and development plans (World Bank, 2022). This partly may explain why only 15% of the least-developed countries have submitted LTSs, compared to more than 80% of the Organisation for Economic Co-operation and Development (OECD) countries (Climate Watch LTS Explorer, 2020).

In addition, active participation during the LTS formulation stage for those who will need to implement is essential to inform analysis and increase buy-in; policymakers often do not buy into plans that they had no role in developing (Niet et al., 2021; Calfucoy et al., 2022). By engaging early in the process, their insights, expertise, and concerns can shape the plan and ease its delivery. This approach requires the use of flexible processes and tools to ensure that stakeholder'' viewpoints genuinely are considered and integrated into the analysis. This type of expertise often is challenging to set up.

Recognizing the need for support, many organizations have launched initiatives to enable decarbonization planning. At IDB, the Latin American Deep Decarbonization Pathways project sought to create both analytical capabilities and a community of practice around decarbonization planning (Bataille et al., 2020; IDB, 2019). This program launched decarbonization analyses for Argentina, Colombia, Costa Rica, Ecuador, Mexico, and Peru. At the World Bank, the Country Climate and Development Reports seek to help governments, sector leaders, and stakeholders assess and prioritize climate actions, particularly those that also can advance development goals (World Bank, 2022). The 2050 Pathways Platform, a government and multistakeholder initiative, also seeks to support LTS development and provide financial and technical assistance to support governments in formulating LTS tailored to country priorities (The 2050 Pathways Platform, 2023). Other international initiatives to support LTS development include the AFD 2050 Facility (AFD, 2023); the German International Climate Initiative (IKI, 2023); the Global Environment Facility's Net-Zero Nature-Positive Accelerator (GEF, 2023); and the Nationally Determined Contributions Partnership (NDCP, 2023).

One lesson from LTS development is that models can serve a whole-of-government and society conversation, help build consensus, find synergies between decarbonization and development goals, and make any net-zero strategy more actionable. Modeling in universities or think tanks done at the country level also can be one way to convene relevant actors into the process and alleviate the workload of government leads. Finally, modeling work can be used to facilitate coordination among diverse international development partners, making the provision of support more effective (Jaramillo et al., 2023).

Our Goals

Keeping these factors in mind, we seek to contribute to improving countries' understanding of decarbonization strategies that are aligned with the social, economic, environmental, and development needs of the people who will implement them and experience their effects. Building on prior work done in Chile, Costa Rica, Colombia, the Dominican Republic, and Peru (Benavides et al., 2021; Groves et al., 2020; Arguello et al., 2022; Quirós-Tortos et al., 2023; Quirós-Tortos et al., 2021), we advance these goals for Latin America and the Caribbean through three areas of work.

Develop a global analytical toolkit for more accessible decarbonization planning

We begin by introducing SiSePuede (sImulation of sEctoral Pathways and Uncertainty Exploration for dEcarbonization), a toolbox for designing bottom-up mitigation strategies and analyzing amid uncertainty their emissions, costs, benefits, and alignment with NDCs, SDGs, and Paris Agreement targets.

SiSePuede models emissions in six economic sectors based on IPCC methodology (IPCC, 2006; IPCC, 2019): agriculture, industry, buildings, transport, waste, and electricity and fuel production. SiSePuede's process of modeling emissions can be understood through the ASIF framework, originally designed for the transport sector (Schipper and Marie-Lilliu, 1999). ASIF stands for Activity, mode Share, emissions Intensity, and emissions intensity of Fuel. First, levels of activity (e.g., demand for food, transport, buildings, industrial output, and energy) are based on underlying drivers of GDP and population. Then, each activity is apportioned to a production mode (e.g., the fraction of residential heat demand met by natural gas furnaces, wood-burning stoves, or heat pumps). Each mode is associated with a specific energy intensity met by a fuel mix with specific emissions intensities. The variables that drive emissions are calibrated against publicly available datasets on economic activity, energy consumption, and emissions from sources such as the IDB, World Bank, IMF, IEA, FAO. These sectors also are integrated, e.g., an increase in capture of landfill biogas reduces demand for extracting fossil gas; the reduction of losses in the agricultural supply chain reduces waste in the waste stream; and a switch from using cement to wood in buildings changes deforestation rates. SiSePuede is available on GitHub at https://github.com/jcsyme/sisepuede and https://hub.docker.com/r/jsyme816/sisepuede documented at https://sisepuede.readthedocs.io.

Develop and evaluate emissions, costs, and benefits of bottom-up transformations

Next, we use SiSePuede to assess decarbonization strategies for the 18 countries in Latin America and the Caribbean (see Figure 1.1). These are the subset of the 26 member countries of the IDB for which we subjectively determine that existing data and imputations of missing data would allow us to calibrate the model. For these countries, emissions are approximately 4.1 GtCO2e net of land-use changes and sequestration.

A "Traditional Development" trajectory for the region serves as a backdrop against which other decarbonization options—called transformations—are compared. Traditional Development reflects a future largely unconcerned with decarbonization and consistent with historical development trajectories. It includes a growing demand for goods and services overall; and, consistent with past trends associated with a growth in gross domestic product (GDP) per capita, there is an increase in consumption of beef and private automobile ownership. While there is a modest background improvement in energy intensity (IEA, IRENA, UNSD, World Bank, WHO, 2023) and some transition to renewables (IRENA 2018), there is also significant continued reliance on fossil fuels throughout the economy.

Against this backdrop, we define over 50 different transformations across the economy (see Table 2.3 in Section 2). Consistent with the ASIF framework, initially emissions can be diminished by reducing activity—for instance, reducing travel demand by encouraging work from home or reducing total food production by reducing waste and losses. Second, transformations can affect sector activity's energy intensity, such as improving road vehicles' or appliances' energy efficiency or adapting agriculture practices to increase yields. Third, structural changes can be made, producing electricity from renewable sources rather than fossil fuels, using public transport instead of individual cars, and producing foods that have a lower carbon and land footprint per unit of nutrient. Finally, shifts can be made from higher to cleaner energy sources—for instance, by producing electricity with solar instead of gas, and using electricity rather than fossil fuels in road vehicles and to produce heat in buildings and industry (Fazekas et al., 2022).

In addition to this typology of emission reductions, a common question is whether consumers or producers should be held responsible for reducing emissions. This distinction might be misleading, in the sense that both consumers and producers are responsive to infrastructure investments, regulatory choices, and price signals shaped by the government (Fazekas et al., 2022). But it does matter because it shapes how the government communicates with people and firms about decarbonization and how decarbonization is perceived.

We categorize emission-reduction options into three mutually exclusive categories that reflect different approaches to decarbonization. Transformations that are "Incremental Improvements" make marginal gains upon current practices, without making significant structural changes. This includes, for example, increasing vehicles' energy efficiency, increasing livestock-carrying capacities, and expanding basic waste and wastewater management. Many of these transformations affect the intensity factor in the ASIF framework.

Other transformations fall into the banner of "Supply-Side Solutions" and can involve significant structural changes to production, such as pursuing nearly emissions-free electricity, switching to industrial processes such as hydrogen-based steel production, and transitioning transport to electricity. These changes are typically made by producers and not under the meaningful control of consumers; often they are not even directly observable to consumers. Many of these transformations align with structure and fuel factors.

A third category of transformations involves "Changing Consumption" and includes transformations that are observable by and often involve participation from consumers. Examples include using transit instead of personal auto for travel or changing food production and consumption patterns to reduce the relative importance of high-carbon-footprint foods and increase the importance of low-carbon foods. Many of these transformations affect activity and structure factors. To be clear, these divisions are untidy and subjective: many transformations fall across categories, and the real world will embrace complex combinations of transformations across the divisions.

We use these transformations individually and in combinations to see how different actions could affect emissions and development outcomes in Latin America and the Caribbean and reach net zero. We quantify development outcomes using estimates found in the literature of their costs and benefits. This includes technical costs or benefits that actors generally experience within a sector and also generally are internal to markets, such as the cost to the agricultural sector of capturing biogas from livestock, the cost of increasing energy efficiency in industry, or the cost of investments in the electricity sector for new capacity to keep up with growing demand. We also include non-technical costs or benefits that are paramount to aligning decarbonization with development goals, such as health benefits of avoided automobile crashes and air pollution, the value of conserving biodiversity, or the time saved thanks to less congestion (Fazekas et al., 2022). Many of these benefits accrue to those other than sector actors and/or may be external to the market. We exclude the social cost of carbon (Nordhaus, 2017) as one of the benefits of decarbonization, for two reasons. First, decarbonization is a goal per se, aimed at avoiding climate change's impacts. We consider net-zero emissions as a goal that individual governments can set for themselves, not to be offset against other costs and benefits. Second, we seek to understand how strategies to decarbonize can yield costs and benefits to development, outside of their climate effects. This of course means we are undercounting the value of decarbonization to development, e.g., as the cost to produce food in Latin America and the Caribbean will be higher in a world with more climate extremes, and the loss of infrastructure will be massive (Talbot-Wright and Vogt-Schilb, 2023).

Achieving these transformations will require implementing a wide range of policies and regulations. For example, to favor modal shifts in transport, governments may opt to subsidize private mass transit operators, to invest in transit infrastructure, to restrict passenger car use through parking or congestion charges, and so on. Given that many measures will lead to winners and losers, governments will need to adequately manage the transition to mitigate the potential negative impacts, to effect a more just transition. The policies that need to be enacted to carry out the transformations and to appropriately manage their impacts fall outside of the scope of this study.

We also purposely do not evaluate countries' NDCs and LTSs in this study. While NDCs and LTSs include many of the transformations we discuss, it is well documented that they fall far short of Paris targets (Cárdenas and Orozco, 2022; Binsted et al., 2020). Rather than evaluate existing NDCs and LTS's here, we hope to inform future iterations of those policies with an analysis that goes beyond the transformations they already consider, including some that are seldom discussed, such as shifts in food production and consumption. Chapter 6 details how we could do so using SiSePuede and our findings.

Figure 1.1 Map of countries included in this analysis.

Identify and quantify robust decarbonization strategies that meet net-zero goals and provide net socioeconomic benefits

Last, we look at these transformations' costs, benefits, and effect on emissions over the next 25 years. Such prospects are deeply uncertain and will be shaped by factors we can imagine but not predict—e.g., changing costs of green hydrogen production or the sequestration capacity of forests in an ever-warming planet—as well as factors that may take us by surprise, such as the recent global pandemic. The challenge of assessing effects is further exacerbated by pervasive data gaps and rapidly changing socioeconomic conditions, particularly for developing countries which by their nature are undergoing rapid change.

Deep uncertainty raises key questions: What combination of transformations, at what intensities, most assuredly reach net zero and net benefits? And what actions or uncertainties most threaten these goals? Guided by decision making under deep uncertainty (DMDU) methods (Marchau et al., 2019), we evaluate transformations under thousands of combinations of assumptions about the future. From the results, we can identify which transformations are essential for meeting net-zero emissions, and what combination of transformations most robustly reaches net zero by 2050 while also consistently providing net benefits. These insights can help countries develop and further tailor NDCs, LTSs, and other climate and development plans. They also can help international development partners prioritize their investments and policy dialogue in Latin America and the Caribbean.

Organization of This Report and Accompanying Material

The remainder of this report documents our approach and findings. Chapter 2 describes our approach, including the model, data, methodology, and experimental design. Chapter 3 explores the emissions, costs, and benefits of transformations in various categories for Latin America and the Caribbean, in aggregate and then for individual sectors. Chapter 4 expands the analysis to chart a robust decarbonization path for the region amid deep uncertainty. Chapter 5 highlights different implications of a regional strategy in select individual countries. Chapter 6 concludes with a review of major findings, implications for decarbonization, and next steps.

In addition to this report, our work is documented in a separate volume with technical appendices that describe SiSePuede and the modeling, data, transformations, and costs and benefits in each sector. As mentioned previously, SiSePuede and the data accompanying it are publicly available to download at https://github.com/jcsyme/sisepuede an https://hub.docker.com/r/jsyme816/sisepuede, documented at https://sisepuede.readthedocs.io.

2 CHAPTER

Approach to Assessing Emissions, Costs, and Benefits

CHAPTER TWO

Approach to Assessing Emissions, Costs, and Benefits

In this study, we have developed and used the SiSePuede analytical framework to identify strategies by which Latin America and the Caribbean can reach net-zero emissions, and the costs and benefits of those strategies. Given the many deep uncertainties that influence emissions, costs, and benefits, we couple SiSePuede with Robust Decision Making (RDM), a method for managing deep uncertainties (Lempert, Popper, and Bankes, 2003; Groves and Lempert, 2007; Kalra et al., 2015; Lempert et al., 2013). RDM is an iterative, stakeholder-supported process for conducting exhaustive "what-if" analyses. Using RDM's vulnerability analysis techniques, we evaluate strategies under an array of future conditions and assumptions to understand the potential range of outcomes and conditions that lead strategies to meet or fail to meet decarbonization and economic goals. This methodology has had success in Latin America not only for decarbonization planning (Groves et al., 2020; Quirós-Tortós et al., 2021, Benavides et al., 2021; Arguello et al., 2022), but also for resilient water and transport planning in the face of climate uncertainties (Kalra et al., 2015; Groves et al., 2021; Molina-Perez et al., 2019; Olaya et al., 2020), and global sustainability policies (Lempert et al., 2003; Molina-Perez et al., 2020).

Consistent with RDM's process, our experimental design was informed by the input of IDB's sector experts. We engaged them at the start of our research in a first round of sector-specific workshops in which they provided guidance on transformations for achieving decarbonization, costs and benefit of those transformations, uncertainties that would shape outcomes, and data and models available to inform our analysis. After our preliminary analysis, we then held sector-specific workshops to solicit revisions to our experimental design and review data and outcomes. We revised our final analysis based on this expert feedback.

Design of Experiments

We first used SiSePuede to evaluate emissions in a Traditional Development trajectory in which Latin America and the Caribbean's future development is an extrapolation of its past development trajectory. It is consistent with traditional global development of the 19th and 20th centuries, which pursued rapid and often unsustainable economic growth while also increasing quality of life (Commoner, 2013). This includes the following trends:

- increasing demand for goods and services associated with increasing population and economic growth;
- more production and consumption of red meat and shifts in transport toward more personal automobile travel associated with increasing wealth;
- continued deforestation needed to create greater space for crops and livestock;
- background increases in energy efficiency from technological improvements; and
- a modest increase in renewable energy, but with significant continued reliance on fossil fuels to produce electricity and for energy throughout the economy.

Importantly, Traditional Development is not and should not be interpreted as a projection of how Latin America and the Caribbean is developing or likely to develop in the future. In important ways, it is consistent with current regional trends. For instance, in its country-level assessment of Brazil, Climate Action Tracker notes, “Brazil is laser-focused on boosting the use of fossil gas in the power supply to combat hydropower shortages caused by droughts in 2021, despite the far more promising performance of other renewable energy technologies in the country, such as wind and solar” [emphasis added] (Climate Action Tracker, 2022a). It makes sense that countries globally continue to follow traditional development patterns, as there are many barriers that prevent rapid shifts toward net-zero prosperity, especially in developing countries (Fazekas et al., 2022). However, new efforts to decarbonize also are underway that shift the region away from such a traditional development trajectory (Iyer et al., 2017; IDB, 2019).

The Traditional Development trajectory is instead meant as counterfactual backdrop against which to assess and compare the effects of over 50 different transformations throughout the economy that could reduce emissions, some of which are being undertaken already or have been pledged. For each transformation, we simulated emissions effects, costs, and benefits. We arrange these transformations into three categories, each representing a different approach to development and decarbonization as discussed in the introduction. Table 2.2 lists these transformations and their inclusion in each of the categories.

We then use SiSePuede to analyze how far a maximum implementation of these categories of transformations can take us toward net zero under a set of nominal assumptions, and what kinds of costs and benefits result. This helps answer questions such as, “How much could we decarbonize through efficiency gains alone, without changing the production structure or consumption patterns?” and “What are the costs and benefits of changing food production and consumption as part of a decarbonization strategy?” We also assess all transformations in an “All Actions” strategy to understand how maximum effort can reach net-zero emissions in 2050.

In practice, countries’ decarbonization strategies, including their NDCs and LTSs, will involve transformations at diverse levels of implementation based on the impacts, costs, benefits, technological availability, political feasibility, and other barriers and drivers of those actions. Our next set of experiments answer the question, “What transformations are the most important drivers toward net zero?” We use Latin Hypercube Sampling to generate about 1,000 decarbonization strategies statistically that implement each transformation to different degrees, from almost no implementation to a maximum level. We evaluate each of these strategies under nominal assumptions about exogenous uncertainties, and we used regression analysis to identify the largest drivers and a minimum level of implementation necessary to approach net zero.

Our final set of experiments answer the questions, "What combination of transformations, at what implementation intensities, most assuredly reach net zero and net benefits amid deep uncertainty? And what uncertainties most undermine the ability to reach net zero?"

We used the prior experiment's result to increase the number of trajectories that might reach net zero under uncertainty to allow sufficient data for scenario discovery. That is, we generated another 1,000 decarbonization strategies, this time requiring the minimum level of implementation for critical transformations. We also generated 1,000 futures, each representing a unique combination of assumptions about deeply uncertain emissions drivers, transformation effects, and costs and benefits. In each future, we simulated one of the 1,000 decarbonization strategies and compared it to the performance of Traditional Development in that same future to calculate costs and benefits. Using scenario-discovery techniques, we identified conditions under which strategies are vulnerable to either not meeting net-zero goals, net benefit goals, or both. We identified strategies that robustly achieve both goals.

Table 2.1 provides an overview of the experimental design's key elements: the strategies, emission and development metrics, uncertainties, and modeling framework. The remainder of this section expands upon each of these design elements.

The SiSePuede Analytical Framework

SiSePuede is a bottom-up greenhouse gas emissions, cost, and benefit simulation model. As noted in the introduction, SiSePuede estimates the emissions that occur in each sector based on economic and population drivers of demand and energy and non-energy emissions that result from meeting those demands. Our implementation is consistent with and informed by the IPCC guidance on greenhouse gas inventories (IPCC 2006; 2019). SiSePuede is implemented at the national level, so region-wide results are the aggregation of outcomes in each of the 18 countries listed in Table 2.2. In Chapter 5, we present detailed results for three individual countries, which illustrate local differences from aggregate findings.

Table 2.1 Overview of experimental design

Metrics	Strategies
• Greenhouse gas (GHG) emissions' 100-year global warming potential (GWP) • Technical costs or savings ○ Capital costs ○ Non-fuel operations and maintenance ○ Fuel costs ○ Other sector input costs ○ Change in sector value add ○ Consumer costs • Non-technical costs or savings ○ Air, soil, and water quality ○ Ecosystem services ○ Transport congestion and crashes ○ Human health and productivity	• Traditional development • Transformations in Table 2.1 at maximum implementation evaluated in four groups: 1. Incremental Improvements 2. Supply-Side Solutions 3. Changing Consumption 4. All Actions (all the above) • 1,000 statistically generated strategies that involve all transformations in Table 2.1, but at varying levels of implementation • 1,000 statistically generated variants of a "Critical Actions" strategy that involve critical transformations at high levels of implementation and other transformations at modest levels of implementation
Uncertainties	**Modeling Framework**
• Driver uncertainties ○ Demand for output or services in each sector ○ Demand for beef, private vehicle travel, and other consumption associated with increasing wealth ○ Productivity or efficiency gains ○ Fuel costs ○ Sequestration and emissions associated with land uses and land-use change • Uncertainties in transformations' effect on emissions ○ Effectiveness of enteric fermentation interventions in reducing emissions	SiSePuede Analytical Framework
• Cost and benefits of transformations ○ Technical costs ○ Degree or value of non-technical benefits	

Table 2.2 List of and key statistics from 2020 for countries included in the study

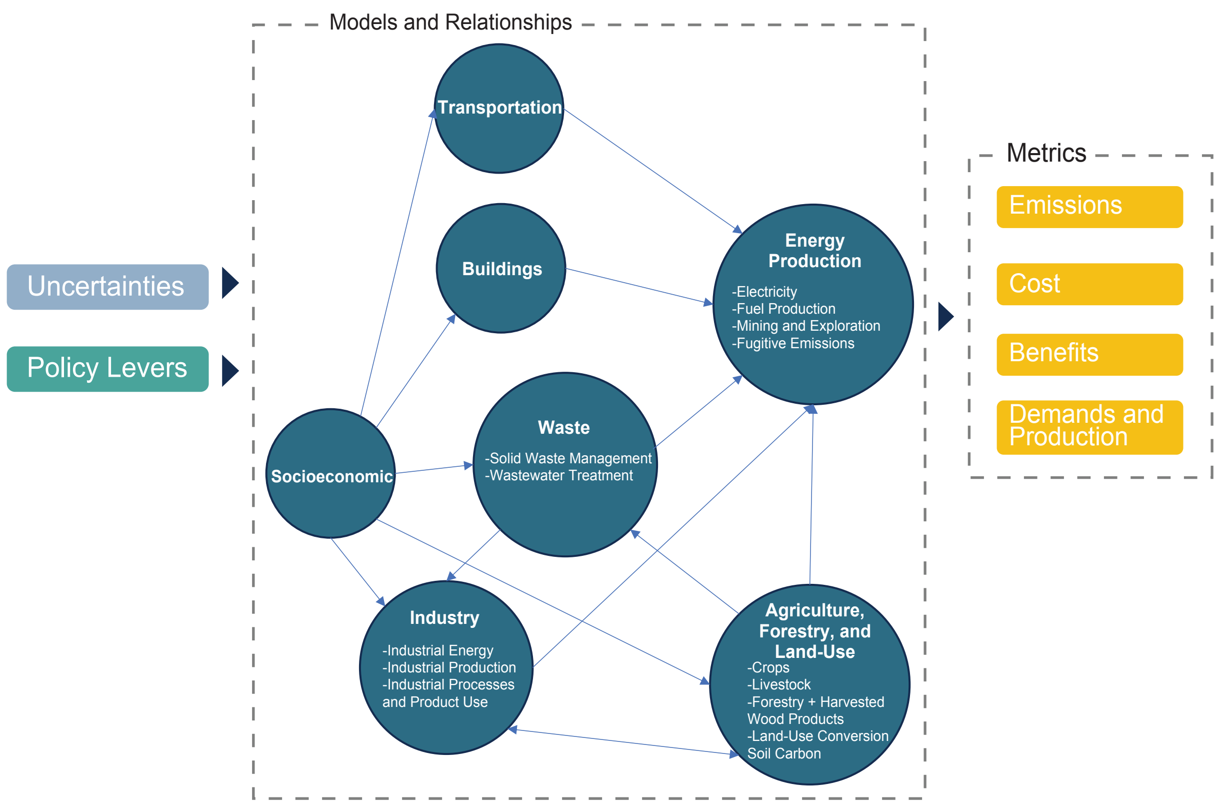
Country	Total emissions		Total emissions, excluding land-use change		Population		GDP in current US$	
	(MtCO2e)	(% of total)	(MtCO2e)	(% of total)	(millions)	(% of total)	(billions)	(% of total)
Brazil	1,469.64	41.8	1,064.71	38.4	213	36.1	1,476	34.7
Mexico	609.07	17.3	592.32	21.4	126	21.4	1,091	25.6
Argentina	394.76	11.2	361.43	13.0	45	7.6	386	9.1
Colombia	270.31	7.7	187	6.7	51	8.6	270	6.3
Peru	179.78	5.1	89.87	3.2	33	5.6	202	4.7
Bolivia	131.43	3.7	55.2	2.0	12	2.0	37	0.9
Paraguay	97.29	2.8	50.78	1.8	7	1.2	35	0.8
Ecuador	94.19	2.7	68.06	2.5	18	3.1	99	2.3
Chile	49.69	1.4	106.72	3.8	19	3.2	254	6.0
Nicaragua	38.15	1.1	18.45	0.7	7	1.2	13	0.3
Guatemala	36.78	1.0	33.17	1.2	17	2.9	78	1.8
Dominican Republic	35.5	1.0	37.05	1.3	11	1.9	79	1.9
Uruguay	34.28	1.0	35.99	1.3	3	0.5	54	1.3
Honduras	27.67	0.8	21.15	0.8	10	1.7	24	0.6
Panama	21.46	0.6	17.23	0.6	4	0.7	57	1.3
El Salvador	12.15	0.3	11.06	0.4	6	1.0	25	0.6
Jamaica	7.58	0.2	7.43	0.3	3	0.5	14	0.3
Costa Rica	7.08	0.2	14.41	0.5	5	0.8	62	1.5
Total	*3,516*		*2,772*		590		*4,256*	

Notes: Emissions data taken from www.climatewatchdata.org and economic data taken from https://data.worldbank.org/. GDP stands for gross domestic product; MtCO2e stands for metric tons of carbon dioxide equivalent.

SiSePuede approach to emissions, costs, and benefits accounting

SiSePuede accounts for emissions by gas in each of the four key IPCC emission sectors: Agriculture, Forestry, and Other Land Use (AFOLU); Waste Management (Circular Economy); Energy; and Industrial Processes and Product Use (IPPU) as described in the technical appendices. For the purposes of our policy-focused audience, however, we remap these subsectors into policy-relevant sectors: Agriculture, Forestry, and Land Use; Transport; Buildings; Industry (including emissions from both energy and processes); Waste; and Energy Production. SiSePuede also has a fifth Socioeconomic subsector to coordinate shared drivers among the other sectors. SiSePuede integrates these sectors by passing key outputs from one subsector to another. For example, livestock manure management creates opportunities for replacing synthetic fertilizers with manure in croplands and pastures; increasing recycling modifies industrial production to reduce demands for virgin materials; and fuel switching in energy subsectors leads to changes in fuel production, including for electricity and hydrogen. Figure 2.1 describes how each of these policy sectors interconnect.

Figure 2.1. Conceptual SiSePuede modeling framework.



For all transformations included in SiSePuede, capital and operational costs, as well as monetized socioeconomic benefits are specified. Baseline social, environmental, and economic costs and benefits factors are based on estimates found in the literature. However, the framework is built to enable uncertainty exploration over these baseline factors. Additionally, to make the analysis more relevant to a wider set of stakeholders (e.g., ministry of transport or energy departments), factors for costs and benefits are estimated in the natural units in which they are incurred (e.g., cost of clinker substitution per ton of cement produced, cost of managing enteric emissions per head of cattle, and ecosystem services gained or lost per hectare of forest) rather than in costs per unit of GHG emitted or abated. Thus, costs and benefits of transformations depend on their level of implementation and deployment across time.

SiSePuede contrasts with and complements other modeling approaches

SiSePuede has several advantages over other modeling frameworks to answer the questions posed in this analysis. First, SiSePuede is designed to assess transformations at the subsector level, addressing the need of modeling actions to reflect tangible goals for sectoral actors while quantifying the system-wide effects, including the social costs and benefits of those actions. Second, SiSePuede is based on IPCC inventory guidelines and emission codes, meaning that it is well suited for comparison to NDCs and other publicly available emissions accounts (including FAO, Climate Watch [CAIT], IEA, and UN Framework Convention on Climate Change [FCCC]). Third, SiSePuede is built on a scalable, open-source platform and driven by simple numerical calculations, facilitating a robust exploration of strategies for specific country contexts by enabling substantive exploration over uncertainties (drivers, transformations, and costs and benefits factors) at highly refined levels (i.e., all sectors and all greenhouse gases). Fourth, SiSePuede simulates the impact of over 50 sectoral transformations that stakeholders can adjust in terms of how quickly and intensively these transformations are implemented in each sector and country and combine them into different portfolios. For all transformations, SiSePuede models required implementation costs and associated economy-wide benefits. Finally, SiSePuede uses hundreds of data points[1] retrieved from public databases (i.e., FAO, World Bank, and OECD) to capture nations' and transformations' characteristics. This data captures both formal and informal sectors. Then each nation is calibrated to historical data from 2015-2020 and rescaled to match its registered emissions inventory in international databases, such as Climate Watch, or as registered in its national archives. Because of data availability 2020 is used as the initial year is simulations. This does not require a special treatment of COVID19 impacts. These elements allow SiSePuede to reflect the set of resources, restrictions, and options that different countries have to meet their mitigation goals.

[1] There were 300 variables estimated and retrieved for the AFOLU sector, 73 for Circular Economy, 528 for Energy, 206 for Industrial Processes and Produce Use (IPPU), and 13 for the socioeconomic module. Metadata and processing protocols for this database can be found at https://github.com/milocortes/sisepuede_data.

SiSePuede's sectoral transformation-centered approach to modeling emissions contrasts with other common modeling techniques. For example, some integrated assessment models (IAMs) are used to model biophysical emissions processes as driven by anthropogenic activity, and some include biophysical feedbacks. In accordance with IPCC inventory guidelines, SiSePuede bases emissions on emission factors that respond to drivers, though certain phenomena—such as methane emissions from anaerobic decomposition in solid waste landfills, which is modeled using a first-order decay model—include biophysical treatments. Biophysical feedbacks—such as impacts of climate change on hydropower production or crop yield factors—are treated as uncertain factors that can be explored within reasonable expected ranges.

The relative numerical simplicity of calculations in SiSePuede and integrated uncertainty frameworks allows extensive exploration over uncertainties at highly refined levels, facilitating a robust exploration of strategies. SiSePuede endogenizes uncertainty exploration through Latin Hypercube Sampling across exogenous uncertainties and intervention effects, a robust data management system, and scalable computational architecture.

SiSePuede also differs significantly from general and partial equilibrium models (GEMs and PEMs). Equilibrium models, which endogenize economic outcomes such as prices based on factors of production, are another class of models paired with emission factors to estimate how changes in economic activity may drive changes in emissions. However, while GEMs advantageously endogenize demands and prices, they can be difficult to calibrate and solve, especially when exploring large parameter and variable spaces, such as supplies and demands for a refined range of products and services across an entire economy. While SiSePuede does not endogenize prices and quantities through equilibria, it does facilitate exploration over combinations of prices and behaviors that then can be used to identify policy-relevant scenarios across a range of potential futures.

These differences aside, outputs of IAMs or other global modeling exercises (e.g., GCAM, MESSAGE-GLOBIOM, and REMIND-MAgPIE) are comparable to ours. Some of their outputs also can be used as inputs to SiSePuede. For example, GDP, population, and emission trajectories from these modeling exercises can be used in SiSePuede as inputs or as calibration targets, which may be useful in developing a more granular understanding of emission pathways estimated through IAMs.

Appendix A describes SiSePuede in more detail.

SiSePuede's limitations

SiSePuede and the data that were used in this analysis have some important limitations. First, as noted, SiSePuede does not endogenize market signals and economic feedback loops that could affect costs, benefits, and demands. For example, as renewables are adopted more widely, the price of fossil fuels might decline. This would increase demand for fossil fuels and decrease the cost savings associated with switching to renewables.

As another example, SiSePuede simulates the impact of domestic shifts toward healthier diets with less red meat. The resulting impact on household food expenditures is valued based on exogenous food prices, even though a decrease in demand for red meat would endogenously decrease red meat prices and alter that estimate. These feedbacks are not included in the analysis. However, outputs from SiSePuede can be used in specialized economic models to account for such impacts, as well as other macroeconomic impacts such as labor effects and tax revenues.

Second, SiSePuede does not contain inter-region mass balances for goods that are imported and exported (e.g., manufacturing products, crops, and/or livestock) and energy (e.g., trade in electricity and fuels).

Third, our transformations do not distinguish between informal and formal aspects of sectors (e.g., buildings or waste management) and do not differentiate results geographically within a country. Decarbonization strategies at the country, sector, and subnational level will need to include these details.

Fourth, data used to run SiSePuede were derived entirely from public and open sources. Data for many countries were limited in these datasets, and many imputations were used to generate estimates for countries that had no available data. In particular, country-level data for land-use transition matrices were unavailable. To fill this gap, exogenous land-use transitions were developed using an optimization model that explored potential matrices that align with land-use prevalence data found in FAO data. Future iterations could improve on this approach by integrating satellite data.

Strategies and Transformations

Table 2.3 summarizes the transformations evaluated in the study by sector, subsector (if applicable) and category. For each transformation, we have identified an emissions effect, costs, and benefits per unit of implementation, and a maximum level of implementation by 2050 based on our review of the literature. These are detailed in the technical appendices. Many, if not most, of these transformations are complex to implement, requiring new or different technology, regulatory and infrastructure changes, financing, shifts in public perception and acceptance, and a host of other public and private efforts. Our intent here is not to oversimplify or gloss over the implementation complexities, but to analyze the potential emissions, costs, and benefits of undertaking a particular transformation.

Table 2.3 Transformations in Incremental Improvements, Supply-Side Solutions, and Changing Consumption categories

Sector	Subsector	Incremental improvements	Supply-Side Solutions	Changing Consumption
Agriculture, forests, and other land use	Crops	• Reduce excess fertilizer use • Expand conservation agriculture • Improve rice management		
	Livestock		• Reduce enteric fermentation • Expand silvopasture • Manure management	
	Forests and land use			• Halt deforestation
	Cross-cutting	• Accelerate productivity • Use gains in productivity to conserve land	• Reduce supply chain losses	• Induce afforestation with a shift in agricultural production and consumption
Industry	Cross-cutting	• Shift from virgin to recycled inputs • Substitute clinker in cement conserve land	• Increase efficiency of materials use	
	Industrial energy		• Fuel shift low-temperature heat to heat pumps • Fuel shift high-temperature heat to electricity and hydrogen	
	Other abatement		• Reduce F-gases • Abate N2O in chemical production • CCS for steel, cement, chemicals, and plastics	
Buildings		• Increase energy efficiency of appliances • Increase building shell efficiency	• Fuel switch heat to heat pumps	

Transport	Fuels and vehicles	• Increase transportation energy efficiency	• Fuel switch medium- and heavy-duty road transport • Electrify rail • Fuel switch maritime	• Electrify light-duty road transport
	Mode shifting and occupancy		• Mode shift freight	• Increase occupancy for private vehicles • Mode shift local passenger travel to transit and non-motorized • Mode shift regional passenger travel to bus and rail
Energy production		• Reduce transmission losses	• Produce electricity with renewables • Produce hydrogen with renewables • Fix leaks of fugitive emissions • Flare (instead of venting) fugitive emissions that cannot be captured	• Halt deforestation
Waste	Sanitation and wastewater	• Universal safe sanitation • Treat wastewater	• Recover energy from wastewater treatment	
	Solid waste management	• Expand waste collection and end open dumping/burning • Divert waste to recyclables	• Increasing capture and use of biogas in digesters and landfills	• Reduce consumer food waste • Divert organic material to composting or digesters

Emissions, Cost, and Benefit Metrics

We evaluate the performance of all strategies in three general dimensions:

1. GHG emissions at 100-year Global Warming Potential (GWP) consistent with the Paris Agreement (Paris Agreement to the United Nations Framework Convention on Climate Change, 2015). GHG emissions include a wide range of gases, e.g., CO2 emissions from electricity production, N2O from cement production, methane (CH4) from enteric fermentation, and F-gases from chemicals production.
2. Technical costs or benefits, which generally are experienced by actors within a sector and also are generally internal to markets. These include capital, operational, maintenance, and fuel-related expenditures and savings, as well as changes in value added in different sectors or subsectors.
3. Non-technical costs or benefits that are essential to economic development and human welfare, but generally accrue to non-sector actors and/or may be entirely external to the market.

Table 2.4 presents a summary of the costs and benefits of transformations across different sectors. Appendices A-G provide additional detail on each of these performance metrics, costs, and benefits.

Exogenous Uncertainties

Many transformations' effects, costs, and benefits are deeply uncertain. To address uncertainty, the strategies' performances were evaluated under 1,000 different futures to identify conditions in which they may fail to meet either economic or emissions goals. Each future was generated with a combination of three types of uncertainties:

1. Emission driver uncertainties, which control demand for goods and services and technical or environmental factors that determine the emissions intensity of producing these goods and services. Examples include demand for beef in consumers' diets, demand for transportation, waste production, productivity improvements in agriculture, and sequestration capacity of different forest types.
2. Transformation effect uncertainties, which determine sectorial transformations' effectiveness in reducing emissions. Examples of these uncertainties include the effect that conservation agriculture and rice management have on emissions reductions in the agricultural sector, the effect that enteric fermentation management has on reducing emissions from livestock, or the extent to which the investments in public transport would lead people to shift to transit away from private vehicles.
3. Transformation costs uncertainties include factors that determine the cost and benefits of different transformations such as fuel costs, renewable energy production costs, human health and pollution externalities' economic value, and ecosystem services' value.

Table 2.5 describes in detail the factors included in each group. A key concern for policymakers will be how and how effectively different transformations can be implemented. For this study's aims of understanding transformation effects, however, we treat the level of implementation of each transformation as a policy lever rather than an exogenous uncertainty.

We discount future costs and benefits using a fixed 7% discount rate, a rate that is at the higher bound of the range of values of midcentury evaluation of climate policy portfolios (Emmerling, et al., 2019). We do not explore over the discount rate in uncertainty experiments because, in this study, the discount rate does not have an ordinal impact on results, as transformations' implementation and timing are specified exogenously. Thus, the discount rate would affect the magnitude of costs and benefits but would not change the our findings' arc. In other studies where climate policy response is modeled as an optimal response to damages induced by climate change, the discount rate's magnitude impacts policies' timing and intensity over time. While there is debate among climate specialists regarding the discount rate's appropriate value (e.g., Sterner, 2008; Nordhaus, 2007), studies show that in the context of deep uncertainty, other parameters such as the rate of technological change and climate sensitivity are significantly more impactful in mitigation trajectories (Molina-Perez, 2016).

Table 2.4 Transformation costs and benefits by sector

Sector	Technical Costs and Benefits	Non-Technical Costs and benefits
Agriculture, forests, and other land use	• Investment cost of transformations • Value of agricultural inputs, such as fuel and fertilizer • Value of agricultural outputs (crops and livestock produced) • Technical cost of reforestation	• Nitrate leaching and runoff from fertilizer • Soil health benefits of conservation agriculture • Ecosystem services of forests • Human health and productivity of better diets • Household grocery costs from improved
Industry	• Investment cost of transformations • Maintenance savings of transformations, e.g., from lower maintenance of heat pumps • Value of industrial inputs, such as fuel • Value of industrial outputs	• Air quality changes from industrial energy and production
Buildings	• Investment cost of transformations • Maintenance savings of transformations, e.g., from lower maintenance of heat pumps • Value of building inputs, such as fuel	• We did not assess non-technical benefits and costs in buildings such as indoor air
Transport	• Investment cost of transformations • System cost of transportation service provisioning • Maintenance savings, e.g., from lower maintenance of electric vehicles • Value of transport inputs, such as fuel	• Health impacts of changing air quality • Health and productivity impacts of avoided crashes • Productivity impacts from congestion
Energy production	• Capital and operating expenditures of electricity production • Cost of fuels used to produce electricity and other fuel production • Investment cost of other transformations	• Health benefit of avoided air pollution
Waste	• Technical costs of transformations • Value of energy recovery	• Health impacts of universal safe sanitation • Health and environmental impacts of ending open dumping • Water quality impacts of wastewater treatment

Table 2.5. Uncertainties

Sector	Emissions driver uncertainties	Transformation effect uncertainties	Transformation cost uncertainties
Cross-cutting			• Fuel costs • Renewables • Fossil fuels • Hydrogen • Renewable electricity production costs (battery and production) • Value of human health externalities • Value of environmental pollution externalities • Value of industrial outputs
Agriculture, forests, and other land use	• Annual change in crop and livestock productivity • Overall demand for agricultural products • Demand for beef in diets as a function of wealth, which drives deforestation • Emissions and sequestration from different land use • Emission of land-use conversion	• Effect of conservation agriculture and rice management • Effect of enteric fermentation interventions productivity of better diets • Household grocery costs from improved diets	• Cost of transformations • Benefit of transformations • Value of ecosystem services
Transport	• Demand for transport • Demand for car/air travel		• Cost of transport by mode
Industry	• Demand for industrial output	• Availability of clinker substitutes	• Cost of efficiency improvements • Cost of clinker substitutes
Buildings	• Demand for heating/cooling		• Cost of efficiency improvements
Electricity and energy production	• Productivity of hydropower		• Transmission cost • Cost of abating fugitive emissions
Waste	• Waste production		• Cost of sanitation and waste infrastructure

3

CHAPTER

Understanding the Effects of Transformations on Decarbonization and Development

CHAPTER THREE

Understanding the Effects of Transformations on Decarbonization and Development

In this chapter, we analyze the region's decarbonization and economic potential. We evaluate the emissions, costs, and benefits of different categories of transformations relative to a traditional development trajectory. The analysis uses nominal values for each uncertain variable and assumes each transformation is implemented to its maximum potential level. Chapter 4 explores the effects of transformations under uncertainty and with varying levels of implementation.

Emissions Under a Traditional Development Trajectory

Under a Traditional Development trajectory, one that is unconcerned with decarbonization, we estimate emissions would increase in Latin American and the Caribbean by 70% from 4.1 GtCO2e in 2020 to 6.9 GtCO2e by 2050 (see Figure 3.1). This increase is driven by projected population and GDP growth, which results in more activity overall and a shift in the structure of that activity associated with increasing wealth. This includes, for example, a shift toward more travel in private automobiles and more production and consumption of beef, with associated deforestation for grazeland. These trends are counteracted by increases in energy efficiency and productivity through improved technology, and a modest increase in the use of renewables for electricity production.

Exploring Transformations' Emissions, Costs, and Benefits

Against the backdrop of traditional development, we evaluate the emissions and economic effect of transformations, some of which are already underway in the region. We first examine the effects of maximally implementing each transformation category—Incremental Improvements, Supply-Side Solutions, and Changing Consumptions—and then of maximally implementing all transformations simultaneously. This helps explore these questions: How far can incremental improvements alone take the region toward its decarbonization and development goals? Are structural changes to the economy necessary to reach net zero? How do these approaches' costs and benefits compare? What are the effects of maximally implementing all actions? These results use nominal assumptions for all exogenous uncertainties.

Four figures illustrate our findings. Figure 3.2 shows the emission trajectory under each category of transformations alongside the emissions under Traditional Development (shown alone in Figure 3.1). Emissions are disaggregated by sector and net CO2e emissions are indicated by a solid blue line. Values less than zero indicate negative emissions, i.e., sequestration and offsets. Figure 3.3 shows land use by type under each category over time. The trends in this figure help explain some of the emissions results, as preservation of primary forests and expansion of secondary forests plays a pivotal role in the region's emissions and development.

Figures 3.4 and 3.5 show the costs and benefits of each of the four categories of transformations relative to Traditional Development over the period of 2025-2050 in 2019 US dollars. Figure 3.4 shows the nominal undiscounted benefits in 5-year increments, while Figure 3.5 shows these benefits' net present value using a 7% discount rate.

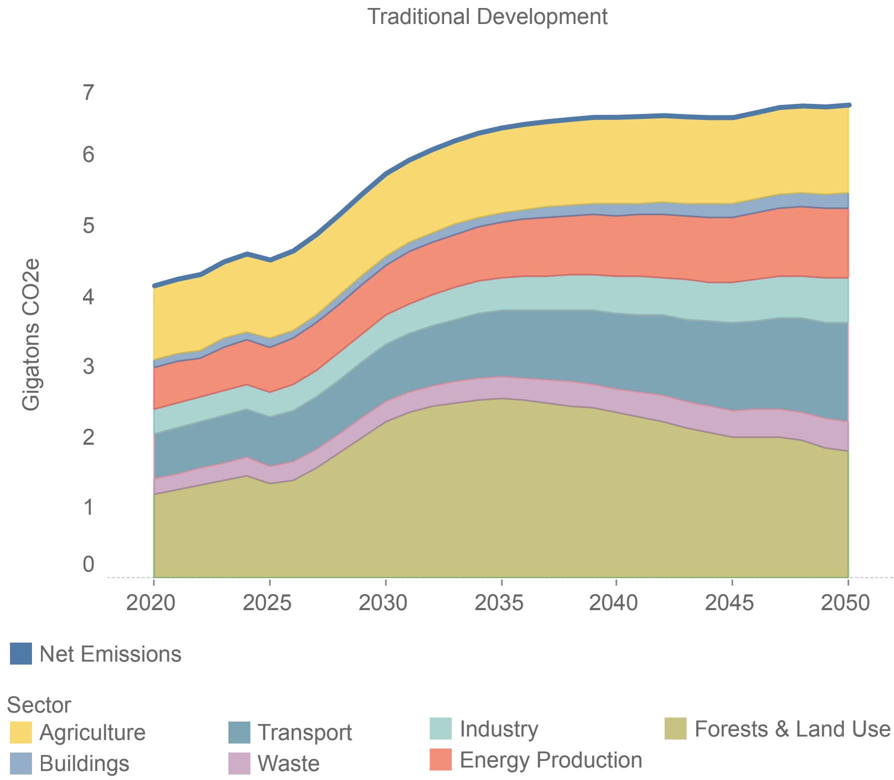


Figure 3.1 Emissions under Traditional Development.

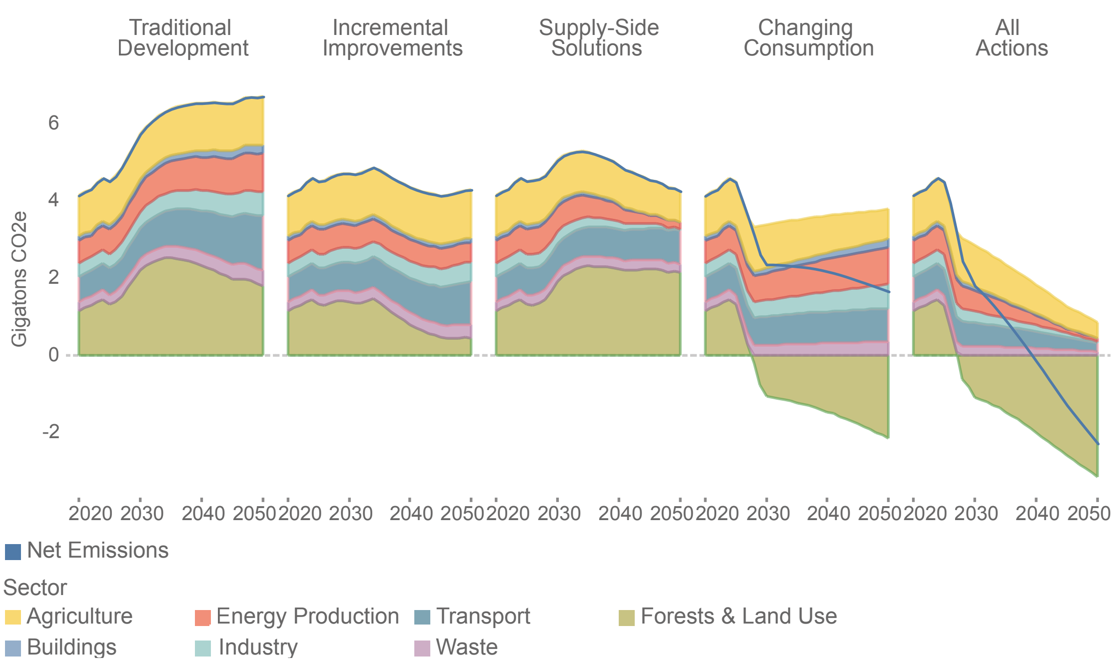


Figure 3.2 Emissions under maximum implementation of transformations by category.

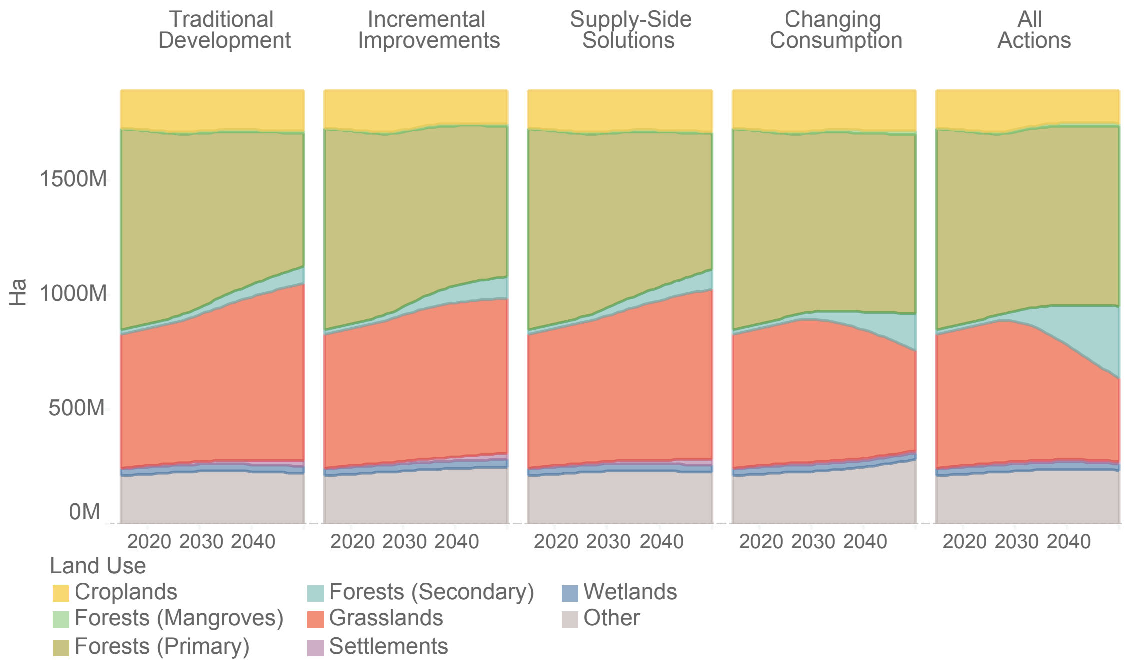
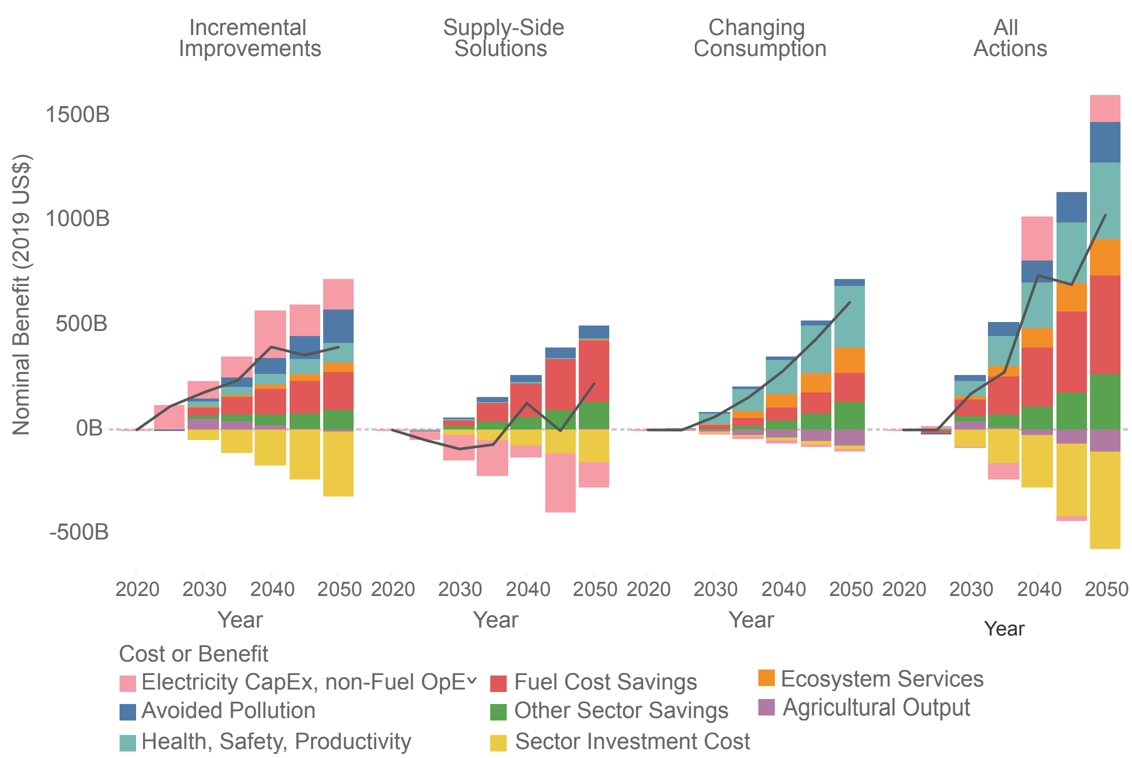
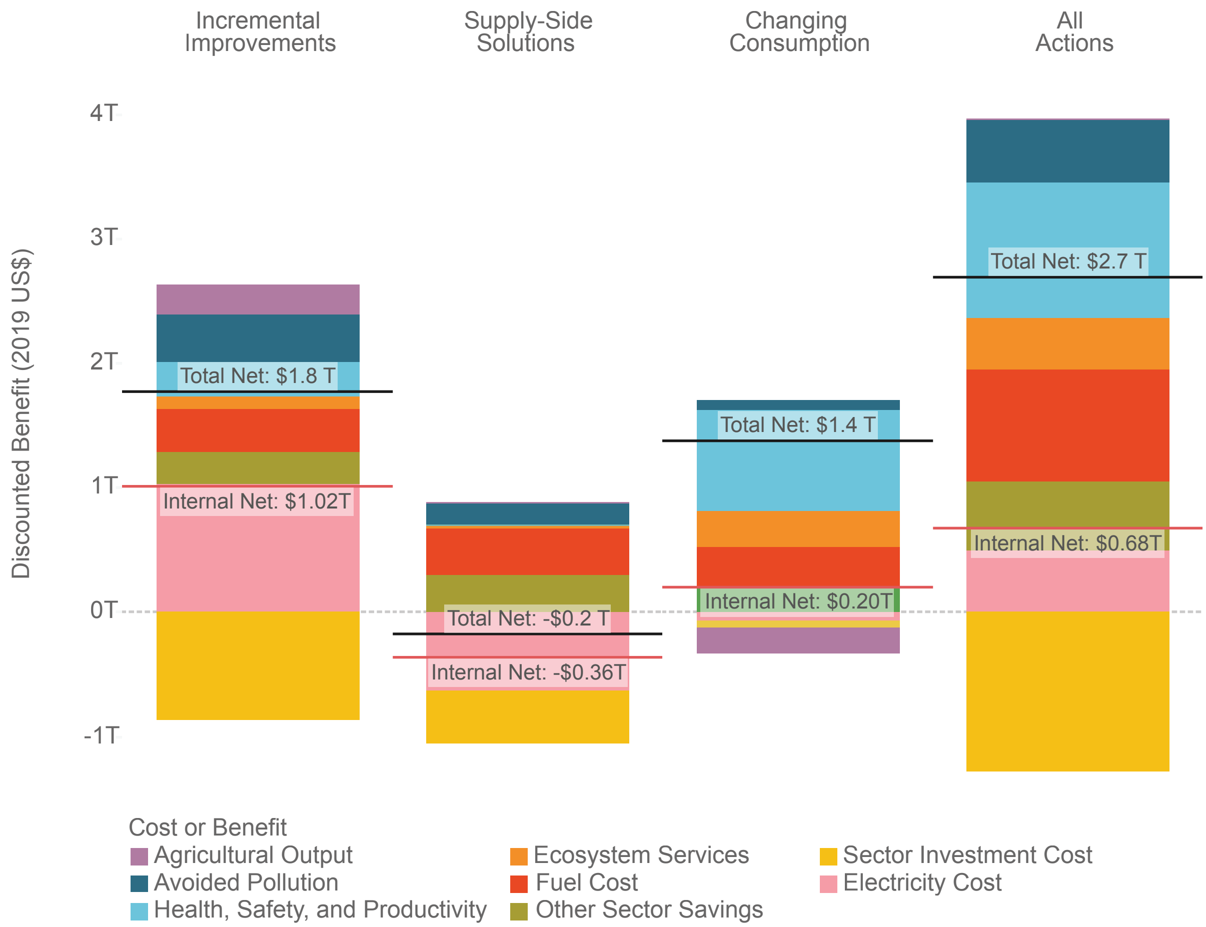


Figure 3.3 Land use in hectares (ha) under maximum implementation of transformations by category.



Note: This figure shows annual benefits in 5-year time slices in each category of transformations, compared to a future under Traditional Development. These benefits are undiscounted, and negative benefits imply costs. The black line shows the net benefit across all categories.

Figure 3.4 Nominal costs and benefits under maximum implementation of transformations by category.



Note: This figure shows the present value of costs and benefits in each category of transformations, compared to a future under Traditional Development. These benefits are discounted at 7%, and negative values imply costs. The black line shows the net value of all costs and benefits; the labeled red lines show the net value of costs and benefits that are incurred by sector actors and excluding hard-to-value (and largely external) costs and benefits of health, safety, and productivity; avoided pollution; and ecosystem services.

Figure 3.5 Discounted costs and benefits under maximum implementation of transformations by category.

Maximizing Incremental Improvements

Maximum implementation of transformations in Incremental Improvements reduces emissions in 2050 by 36% to 4.5 GtCO2e. The gains from maximizing efficiency and productivity meaningfully reduce emissions in every sector, including in agriculture, where productivity gains reduce land-use needs, which are directed toward slowing deforestation and increasing secondary forests. However, the reductions are not enough, and significant residual emissions remain in all sectors. Simultaneously, continued (albeit slower) deforestation (see Figure 3.3) means that the land-use and forestry sector continues to be a net emitter and not the sink the region needs it to be to offset those residual emissions (Dumas et al., 2022).

While far from reaching net zero, Incremental Improvements offers significant net benefits across the region's economies of approximately $1.8 trillion, net of the technical investment costs in energy efficiency, agricultural productivity and efficiency, and basic civic infrastructure (sanitation, waste management, and wastewater treatment). Two effects are at play. First, an increase in agricultural productivity results in more agricultural output in the near term than under Traditional Development, while also slowing deforestation and providing ecosystem service benefits (see Figure 3.4). Second, the energy-efficiency gains result in significant savings in avoided energy costs throughout the economy. Increases in energy efficiency means Latin America and the Caribbean can spend less on new and expensive electricity-production capacity than it would otherwise. The avoided energy production and consumption have subsequent benefits in terms of cleaner air. Investments in sanitation and waste management reduce pollution and offer benefits to human health, safety, and productivity.

Maximizing Supply-Side Solutions

Maximizing transformations in Supply-Side Solutions reduces emissions to 4.4 Gt CO2e by 2050, a 36% reduction compared to 2050. (That Supply-Side Solutions and Incremental Improvements lead to similar reduction in emissions is an unintended coincidence because they have entirely different transformations). These reductions are the combined effect of switching to electricity and hydrogen throughout the economy and simultaneously producing electricity and hydrogen almost entirely with renewables. In addition, industrial emissions reductions are achieved by capturing process emissions in select industries and destroying particularly potent F-gases and N2O. Despite these gains, agriculture and land-use changes remain major emitters as their emissions are not primarily driven by energy use, but by biological processes of livestock and crop production and the deforestation they induce. These emissions only partly can be abated with technological solutions to enteric fermentation and livestock manure management.

On their own, transformations in Supply-Side Solutions pose a net cost. Whereas Incremental Improvements reduce the cost of electricity production by reducing overall demand through efficiency measures, Supply-Side Solutions require more electricity production because of fuel switching across the economy and making major investments to produce renewable electricity and hydrogen. This requires added capacity, storage, transmission, and other investments. Fuel switching also involves significant investment costs that are only partly recovered by other sector savings.

Supply-Side Solutions also offer smaller social and environmental co-benefits than transformations in Incremental Improvements. Many transformations—such as destroying F-gases and N2O in industry and reducing enteric fermentation—have no social and environmental co-benefits outside of emissions reductions.

Maximizing Changes in Consumption

Transformations in Changing Consumption achieve greater reductions through a few key strategies. Changes to food production and consumption and changes to transport consumption combine with a slowing of deforestation to reduce emissions to 1.9 GtCO2e by 2050. This is a reduction of 73% compared to Traditional Development. Even more importantly, halting deforestation and shifting production and consumption from beef to crops makes room for secondary afforestation, converting forests and land use from significant net emitters to net sequesters. This is essential to offset residual emissions and reach net zero. However, this transformations category does little to abate emissions in other sectors, and thus the residual emissions are far too high to be offset by improvements in forests and land use.

These transformations offer significant net benefits, primarily from social and environmental benefits, such as $75 billion in avoided pollution costs from improving transport and waste management; $800 billion in other avoided health, safety, and productivity costs, including household savings from healthier diets and avoided food waste and avoided congestion and crash costs from changes to transport; and $290 billion in ecosystem services from preserved primary forests and new secondary forests.

Savings in fuel costs and other technical costs, primarily from transforming transportation, lead to additional benefits. In this strategy, mode shifting passenger transport yields significant economic savings, because it often costs less to transport people via transit than by private auto (Jakob, 2006), although the costs are differently borne by the private and public sectors.

The transformations also pose some costs—in terms of electricity production to meet higher electricity demands ($60 billion); the foregone cost of agricultural output ($185 billion); and the technical investment costs of, for example, electrifying transport ($70 billion), but total costs are far less than total benefits.

The overarching conclusion is that, while each of these categories of transformations can achieve significant reductions, even at maximum implementation, none approach net-zero because each one focuses transformations on only part of the ASIF framework. Instead, a whole-economy approach that transforms activities, structure, and intensity is necessary to achieve net-zero emissions.

Maximizing All Actions

The All Actions trajectory implements all transformations to achieve a whole-economy approach to decarbonization and provides a sense of the emissions reduction and economic potential in the region. Net zero is achieved in 2040 when all transformations are implemented to maximum effect. This simultaneously minimizes emissions from each economic sector (industry, transport, waste, buildings, and energy production) and makes changes to livestock production and land use to halt deforestation and accelerate reforestation sufficiently to offset any residual emissions from all sectors. Despite the substantial political, financing, logistics, regulatory, and other important barriers, this suggests that reaching net zero by 2050 may remain within reach in Latin America and the Caribbean. At $2.7 trillion, All Actions' net benefits are also much higher than any of the three categories alone, suggesting that not only is a whole-economy approach better for emissions, it also is better for development. Figure 3.6 shows the net 2050 emissions and benefits for each transformation category.

For instance, emissions from the electricity sector can be eliminated by only switching to renewables, as under Supply-Side Solutions, but this approach comes at a high cost for the sector (see the pink bars in Figure 3.5). By simultaneously increasing energy efficiency (as in Incremental Improvements) and switching to renewables (as in Supply-Side Solutions), All Actions shows that the sector can reduce emissions by 95% at a net benefit compared to a traditional development scenario—even as total demand for electricity increases from fuel switching to electricity across the economy.

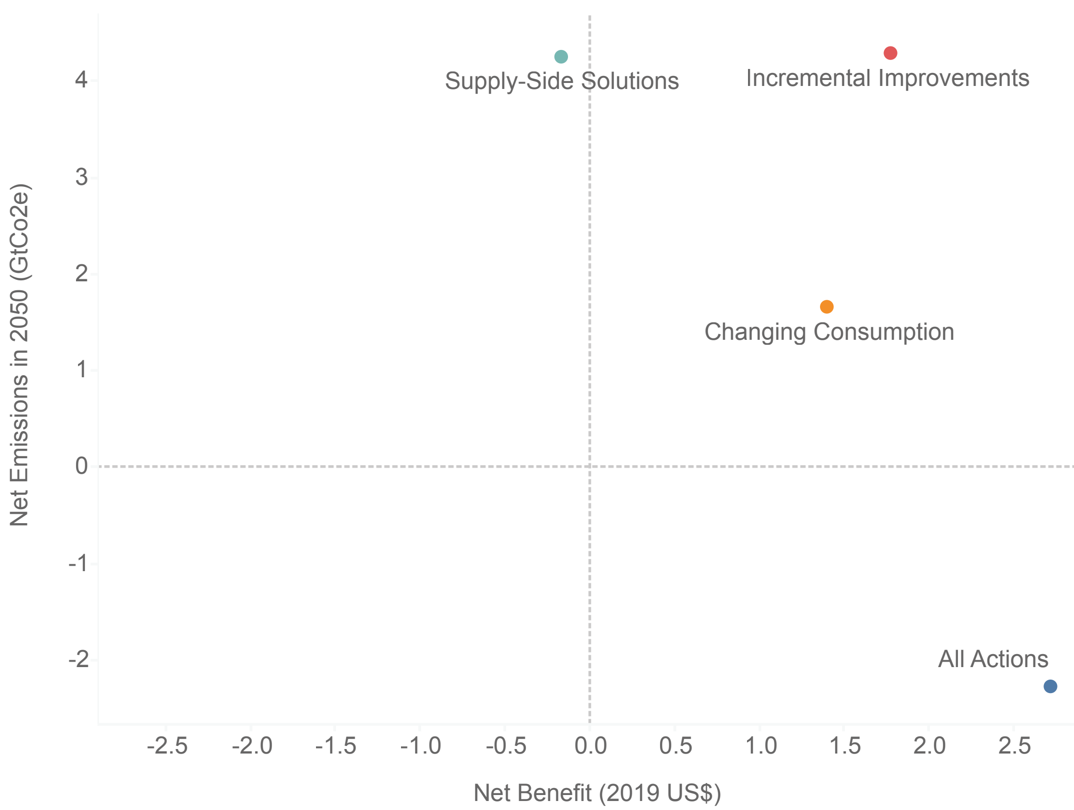


Figure 3.6 Net benefits vs. net 2050 emissions under maximum implementation of transformations by category.

Similarly, All Actions also reaches net-zero emissions without affecting the total value of agricultural output (purple bars in Figure 3.5). Under incremental improvements, the increase in agricultural productivity induces an increase in agricultural output value, primarily from crops. (The increase in livestock productivity partly is redirected to slow deforestation.) This slows land-use conversion but does not return forests and land use to net sequesterers. In contrast, Changing Consumption sees major reductions in agricultural emissions primarily from foregone livestock production, but this is accompanied by a significant loss in agricultural value. When combined, the value of increasing crop output offsets the foregone livestock output's value, with no net effect. This finding confirms the relevance of a decarbonization strategy focused on dramatically increasing livestock yields, moderating beef-demand growth, and ensuring that the land saved is directed toward land sparing and ecosystem restoration (Searchinger et al., 2019; Dumas et al., 2022). It also suggests that decarbonizing agriculture warrants attention to shifting sector activity and that a key issue for governments is managing distributional effects of decarbonization actions rather than managing an overall loss of value in the sector.

These phenomena merit a more detailed look at sector effects. Figure 3.7 compares emissions produced in each sector in 2020 under Traditional Development and All Actions, with Agriculture separated from Forests and Other Land Use. Note that electricity and fuel production emissions are accounted for in the Energy Production sector. The largest changes (-4.9 GtCO2e) occur in Forests and Land Use, where halting deforestation and expanding secondary forests turn the sector from the region's largest emitter to an even larger sink. In the other sectors, the largest absolute reductions come from the other three largest emitting sectors: transport (-1.2 GtCO2e), agriculture (-0.8 GtCO2e), and industry (-0.6 GtCO2e). As a percentage, however, the largest reductions come from buildings (100%) and industry (94%) as they switch to electricity and green hydrogen, and from energy production (96%), where electricity and hydrogen are produced almost entirely with renewables.

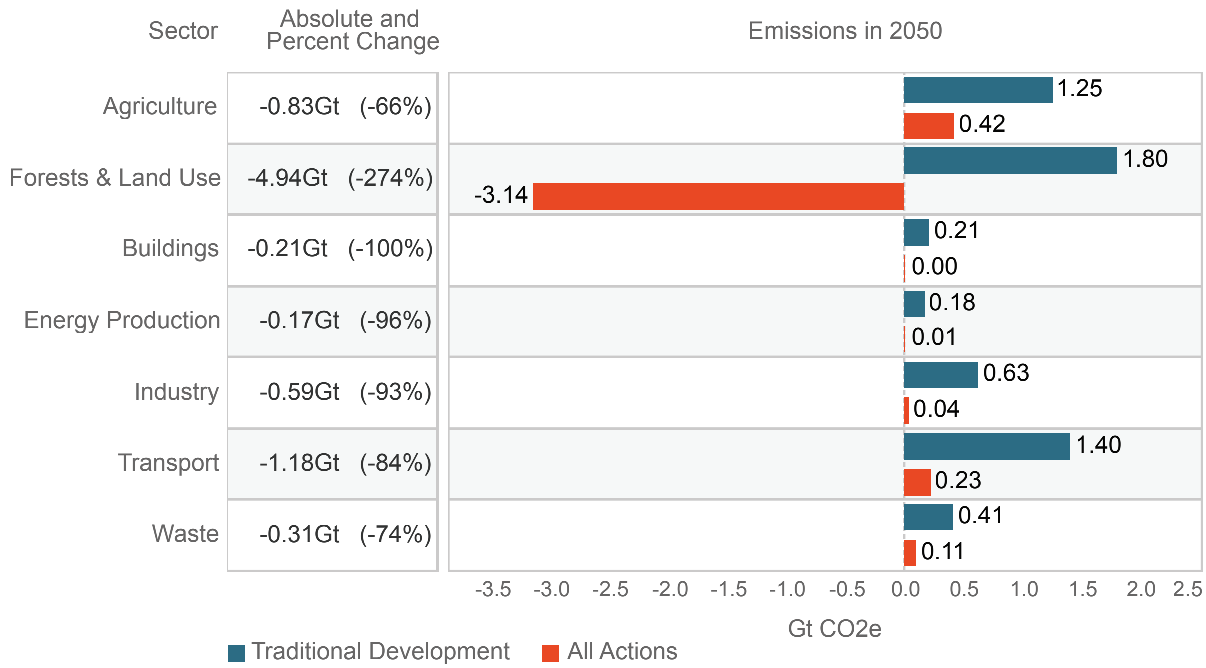


Figure 3.7 Emissions by sector in 2050 under Traditional Development and All Actions.

Figure 3.8 shows the net benefits by sector under All Actions, relative to Traditional Development. Here, we reallocate the costs and benefits of electricity and energy production to energy-consuming sectors to reflect more accurately the costs and benefits those sectors will face. The largest gains are in transport, where electrification and adoption of transit lead to significant fuel cost savings ($775 billion), transport system savings ($215 billion), safety and congestion benefits ($200 billion), and avoided air pollution benefits ($150 billion). The costs are, by comparison, modest: $100 billion in technical investments, such as electrification of vehicles, and $70 billion in electricity expenditures.

Net benefits are large in Agriculture Forests, and Land Use as well: more than $900 billion, which includes the benefits of people shifting to healthier patterns of food consumption and ecosystem services of forests. Other sectors have more modest but still significant benefits: $150 billion in buildings, primarily from energy savings in electricity, $215 billion in industry, and $180 billion in waste.

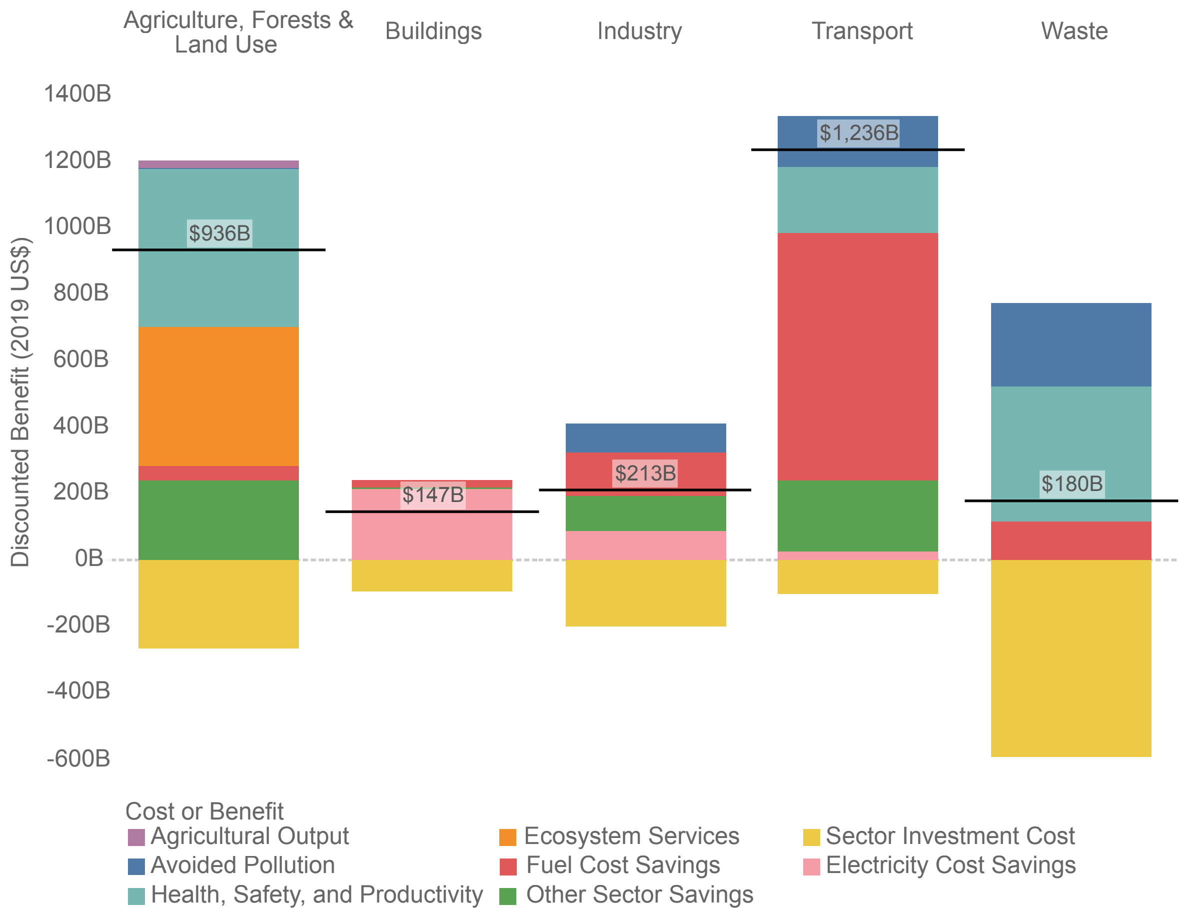


Figure 3.8 Net benefits by sector under All Actions.

Note that costs and benefits associated with a particular sector do not mean those costs and benefits will accrue to actors in that sector. As one example, a change in the types of foods people consume will have significant consequences for farmers, ranchers, and others in the agricultural sector, but the health benefits will accrue to the healthcare system and to households. Other benefits such as forest ecosystem services are generally external and experienced diffusely throughout society.

Sector Snapshots

In the remainder of this chapter, we discuss how to transform each sector, identify who might need to be mobilized to achieve decarbonization and development goals, and explore the extent to which the costs and benefits of those transformations might motivate or hinder change. To this end, this chapter uses sector-level results to address the following questions:

- What kinds of transformations drive the largest changes in emissions in each sector and yield the largest net benefits?
- Which transformations are in the hands of sector actors, and which are driven by those outside the sector?
- What are the net benefits of transformations?
- What are the costs and benefits that accrue to the actors within each sector, what are other internal costs and benefits experienced by other actors in the economy, and which costs and benefits are largely external?

The answers are complex, as transformations made in one sector have emissions, costs, and benefits in other sectors. For example, the emissions from concrete production are attributed to industry, and industry actors largely undertake transformations, such to concrete production by fuel switching, using CCS to capture process emissions, and substituting clinker. However, the costs of these transformations mostly are passed on to consumers of concrete in the building and transport sectors, who may then be incentivized to use concrete more efficiently, which in turn could reduce the extent to which industry needs to transform how it produces concrete.

These issues parallel the long-running complexities around producer versus consumer carbon accounting at the national and international levels (Davis and Caldeira, 2010; Bastianoni et al., 2004; Jakob et al., 2021), and the need for governments to take the lead in setting the right incentives though public investments, market design, capacity building, and price signals (Fazekas et al., 2022). In the following sections, we discuss emissions, costs, and benefits in the sector in which they are accrued, except for electricity and fuels which we describe in the "Energy Production" section and then pass on to each sector that consumes energy.

Energy production

Under nominal assumptions, taking All Actions reduces emissions from electricity and fuel productions from 1 $GtCO_2e$ to 0.1 $GtCO_2e$ in 2050. Emissions reductions are achieved by switching to renewable electricity and hydrogen production and abating fugitive emissions, while other sectors simultaneously increase their energy efficiency and reduce their use of fossil fuels. This yields a net benefit of $500 billion, almost all of which is from electricity and fuel cost savings to the economy.

The energy production sector includes emissions from electricity generation, fuel mining and extraction, fuel processing and refinement, and fugitive emissions from these activities. Most energy is used domestically in the region, but some countries are significant exporters (Solano-Rodríguez et al, 2019; Welsby et al., 2021). As Figure 3.9 shows, under Traditional Development, emissions from energy production in 2020 are approximately 0.6 GtCO2e and rise to approximately 1 GtCO2e with population and GDP growth. Most of these emissions are from electricity production.

The transformations in Incremental Improvements include energy-efficiency improvements throughout the economy. In the energy production sector, the key transformation is reducing technical electricity transmission losses to OECD levels compared to much higher levels in the region today (Jiménez et al., 2014). Together, these transformations reduce emissions by 50% in 2050, to 0.6 GtCO2e, and significantly reduce capital and operating costs in the electricity sector and fuel costs (Figure 3.10).

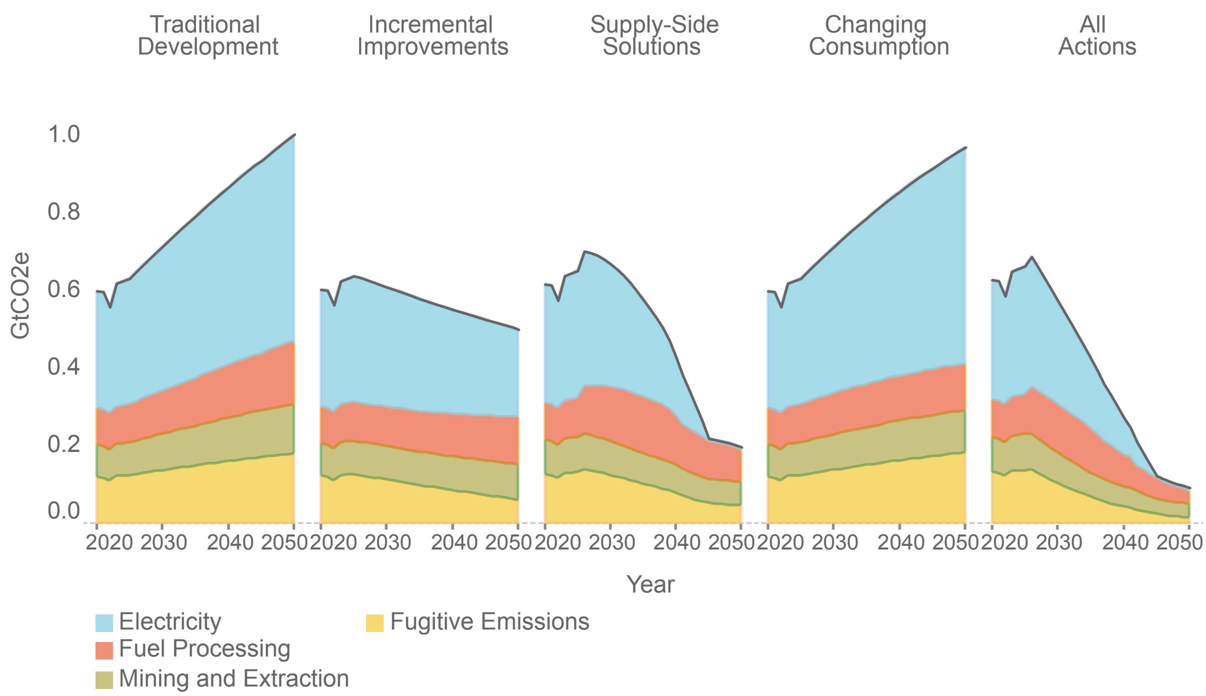


Figure 3.9 Emissions from energy production by transformation category.

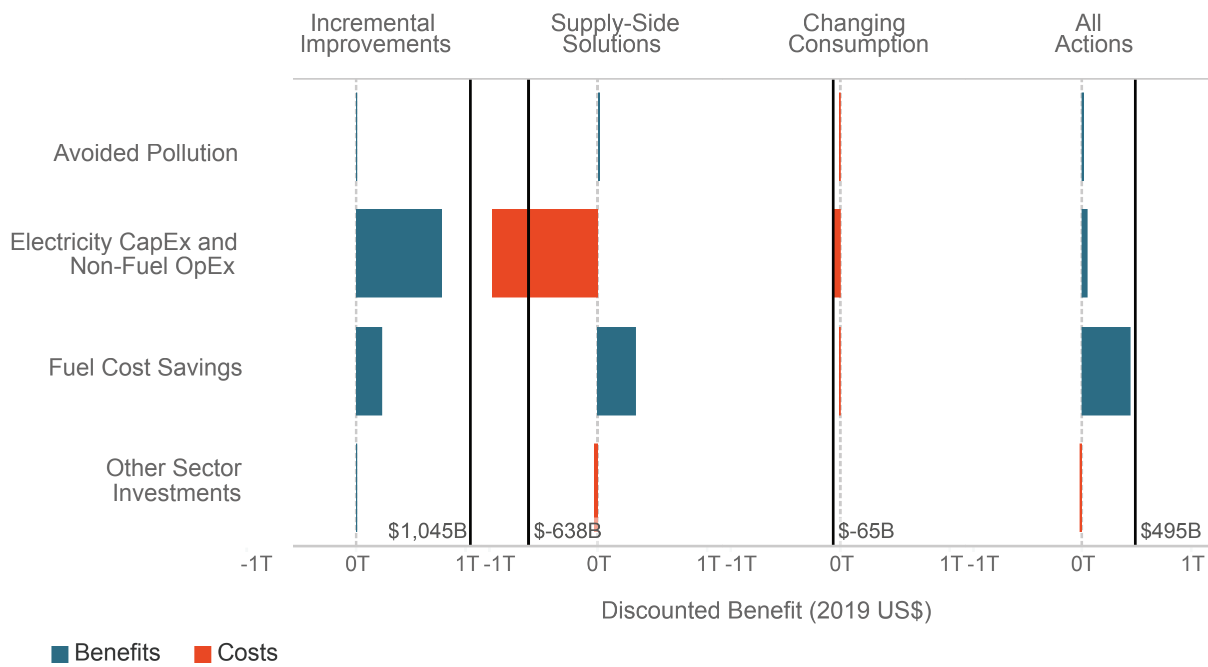


Figure 3.10 Costs and benefits in energy production by transformation category.

Transformations under Supply-Side Solutions primarily involve transitioning electricity production away from fossil fuels to renewables (solar, wind, and geothermal), as Figure 3.9 shows, while producing hydrogen through electrolysis using renewables. (We exclude expansion of large hydropower given the climate pressures faced in the region, as well as concerns about environmental justice, biodiversity, and other issues that make hydropower expansion difficult in practice. We exclude expansion of nuclear power plants for similar reasons.) Simultaneously, other sectors progressively are switching from fossil fuels to electricity and hydrogen, increasing production demands. These shifts are expensive (Figure 3.10), costing a net of $640 billion. This comes from the large costs in electricity capital and operating expenditures (capex and opex) required to reach 95% of renewable production in the electricity mix, which are only partly offset by fuel-cost savings. Other sector investment costs and benefits are negligible by comparison. Importantly, decarbonizing the electricity sector reduces emissions from other sectors as they shift energy use to electricity (Audoly et al., 2018).

Changing Consumption has modest implications for the sector, stemming from greater demand for electricity from private vehicles' electrification. This added demand poses $65 billion in costs to the sector. (The savings in transport fuel costs from fuel switching are discussed in the transport section).

All Actions abates emissions in this sector to 0.1 GtCo2e by 2050. While the reductions relative to Supply-Side Solutions are modest, the cost implications are significant. Economy-wide efforts to reduce energy consumption mean that transitioning to a fully renewable grid and green hydrogen have no net capital or non-fuel operating costs over Traditional Development, while providing significant fuel savings. These findings are consistent with those from previous research (McCollum et al., 2018). The net benefit is $500 billion, almost entirely in the form of fuel savings in the sector. As in other sectors, the often-high cost of fuel switching can be offset meaningfully with simultaneous and cost-effective energy-efficiency efforts.

Because this sector produces energy for other sectors' use, the costs and benefits will be passed through to those consuming sectors. Therefore, in the remaining sector snapshots, we distribute these costs and benefits to the sectors that consume energy, based on their level of consumption.

Agriculture, forests, and other land use

Under nominal assumptions, taking All Actions reduces emissions from agriculture, forests, and land use in 2050 from a net positive of 3 GtCO2e to a net negative of -2.6 GTCO2e, primarily from a combination of halting deforestation and, over time, shifting agricultural patterns, which frees land to increase the cultivation of secondary forest. This yields a net benefit to the region's economies of $940 billion, primarily from health benefits, household savings, and ecosystem services from forests. This also includes a cost to the agricultural sector of $200 billion from a combination of expensive technical interventions such as mitigating enteric fermentation and supply-side food losses.

Agriculture, forest, and land use are entwined in Latin America and the Caribbean, as the need for pastures and cropland drives rapid deforestation (Armenteras et al., 2017; Zalles et al., 2021; Dumas et al, 2022). Domestic demands and exports for the region's agricultural products have grown as populations and wealth increase, both in the region and in key export markets such as China (OECD and FAO, 2022).

This sector is a major source of emissions in the region. Figure 3.11 shows the emissions in this sector, which come from producing crops (including soil disturbances and application of fertilizers and other amendments), livestock (principally from enteric fermentation and manure), and converting land from forests to pasture or cropland. Note that energy used in agriculture is included in industry (e.g., for food processing) and in transport (e.g., for vehicles).

Importantly, while afforestation is needed to sequester residual emissions that cannot be abated in other sectors, forest and land-use changes together are currently a net emitter, given that deforestation and climate-induced tree mortality outpace remaining forests' sequestration (Gatti et al., 2021).

Many transformations to this sector increase agricultural productivity or decrease demand for agricultural products (mainly beef), creating a gap between what can be produced and anticipated levels of demand. Over time, this excess in production capacity is used to slow forests' conversion into cropland or pastureland, and to return cropland and pasture that is not needed for production back into secondary forest. This differs from historical development patterns in which gains in productivity have been directed toward increasing agricultural output to meet growing demand for agricultural products domestically and abroad, without fully valuing the primary or secondary forest ecosystem services. This work makes these tradeoffs explicit, consistent with previous research (Searchinger et al., 2019).

Figure 3.12 shows ecosystem services and other costs and benefits, compared to a future under Traditional Development. Other costs and benefits are the value of agricultural output; health, safety, and productivity benefits; avoided pollution; other sector savings in the form of reduced labor and other inputs; and sector investment costs.

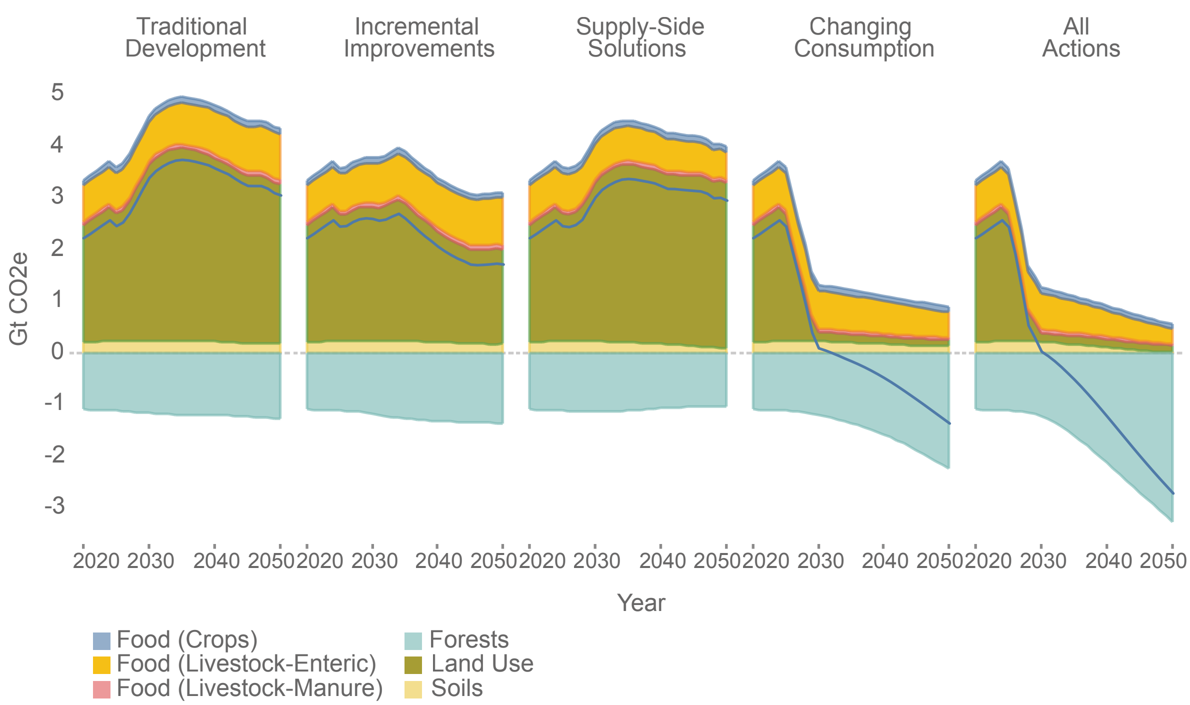


Figure 3.11 Emissions produced by agriculture, forests, and land use by transformation category.

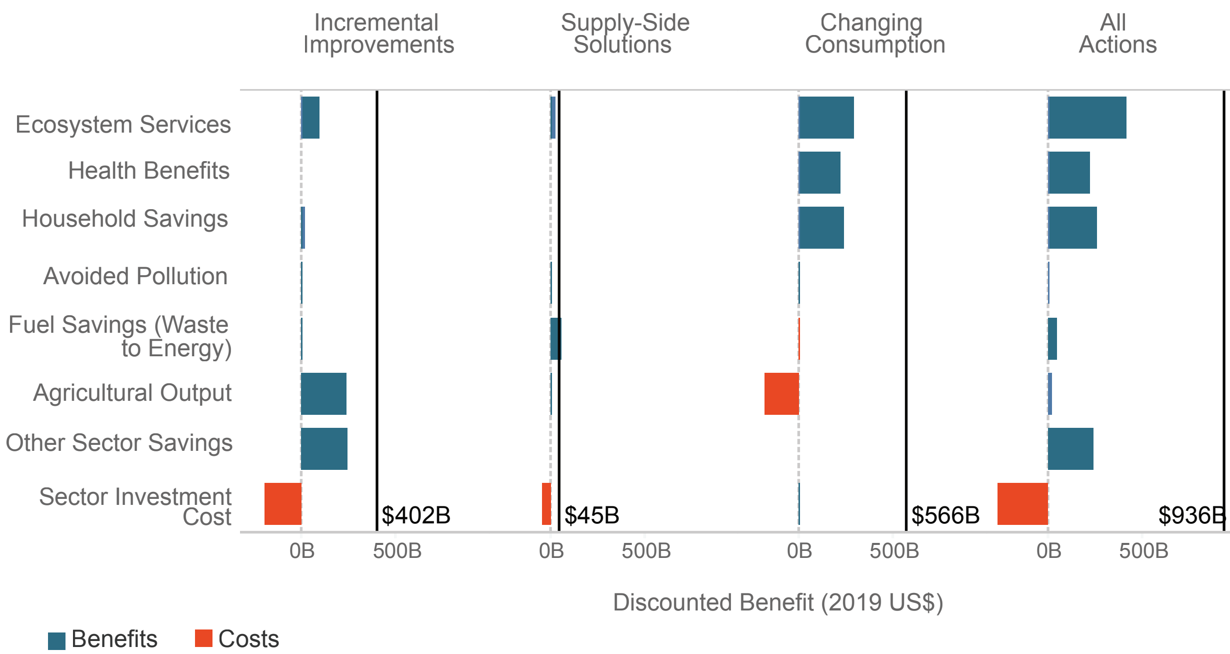


Figure 3.12 Costs and benefits of agriculture, forest, and land-use transformations by transformation category.

Under Incremental Improvements, gains in crop and livestock productivity are accelerated, fertilizer is used more effectively, conservation agriculture is practiced over larger areas, and rice management practices are improved. These changes offer meaningful reductions in emissions as deforestation is slowed, but the effects are neither enough to mitigate agriculture and livestock emissions nor to turn forests from net emitters to net sequesters. This strategy offers more than half a trillion dollars in economy-wide savings, as reducing supply-chain waste and increasing productivity leads to more agricultural output than under Traditional Development, while also slowing deforestation over time. The strategy also offers other savings, in terms of avoided labor and other inputs from conservation agriculture and rice management, and higher values of land that have better soil health. The result is that Incremental Improvements yield significant net benefits to the sector alone ($280 billion) and the economy overall ($400 billion).

Supply-Side Solutions involve several transformations that change how livestock are raised: reducing enteric fermentation through interventions such as vaccination and livestock diet change (EPA, 2019), using better manure-management methods with biogas recovery and use, and expanding silvopasture, which can increase land's carrying capacity while also reforesting pastures. It also involves technical interventions to reduce food loss in the agricultural supply chain, which reduces the amount of food that needs to be grown.

Supply-Side Solutions mitigates emissions less than Incremental Improvements and has modest costs on both industry and the economy overall. Significant residual emissions remain large because land use is mostly unchanged and emissions from enteric fermentation are difficult and expensive to abate—interventions reduce methane emissions on average by less than 25% (Arndt et al., 2022, Beauchemin et al., 2020), although some specific interventions report higher effectiveness (Vijn et al., 2020).

Changing Consumption involves eventually halting deforestation and shifting patterns of food production and consumption away from beef and toward healthier food alternatives, based on Springmann et al. (2016). This transformation halves regional consumption of meat and reduces sugar consumption while increasing fruit, vegetable, and plant protein intake. Recent research suggests that a large share of the dietary and environmental benefits of shifting foods could be attained with minor adjustments, such as substituting chicken for beef in mixed dishes, but making no other dietary changes (Grummon et al., 2023). These transformations dramatically reduce emissions by eliminating land-use conversion emissions, a necessary step to returning the forests of Latin America and the Caribbean into the net carbon sink needed to offset residual emissions, consistent with findings by Dumas et al. (2022). Simultaneously, the shrinking production and consumption of beef returns grazeland and crops used as feed, such as soybean, to secondary forests, which adds to the annual sequestration capacity. These changes have a larger effect on emissions in the region than any others in our analysis.

Halting deforestation and changing patterns of food production and consumption have enormous social and environmental benefits. Given the region's high rates and costs of obesity (Popkin and Reardon, 2018), a shift to healthier diets, compared to a Traditional Development diet that increases red meat consumption per capita by 2050, offers more than $200 billion dollars in health savings benefits alone over this period, even when the per capita health benefits are valued modestly. Much of these benefits will be recouped by the healthcare sector in avoided healthcare costs. Savings in grocery bills result in a separate benefit of approximately $240 billion, given the generally higher price of meat compared to other food choices (Springmann et al., 2016; Springmann et al., 2017).

Ecosystem services are a significant benefit, but monetizing their value is difficult and particularly fraught for services that are highly subjective and hard to value—such as the value of biodiversity or spiritual and cultural value of forests (Taye et al., 2021). Taye et al., for example, find that the value of tropical rainforests found in the literature can range from under $100 per hectare (ha) to well over $10,000/ha, and a median value of all services provided by tropical forests is approximately $1,600/ha. We find that the total value of ecosystem services is large: a present value of $300 billion, even when we use conservative per-hectare values of $500/ha and $300/ha for primary and secondary forests, respectively (Taye et al, 2021; Costanza et al., 2014). The changes pose a cost to the agricultural sector, which forgoes $185 billion in agricultural output, primarily in the form of foregone beef production. Further research should investigate means to manage a rural transition in the region.

Taking All Actions results in further sequestration as increased productivity, wider use of silvopasture, and changing food production together halt the loss of primary forest and increase secondary forests. Notably, the economic value added from increased agricultural output from productivity gains is more than the economic value foregone from the decline in domestic demand for meat. These transformations in combination also have enormous social and environmental benefits. The public health and household savings of changing diets combined are half a trillion dollars, and ecosystem service benefits increase to $415 billion dollars. Industry, however, faces a technical cost of $265 billion. The result is a net profit of approximately $930 billion.

Buildings

Under nominal assumptions, taking All Actions reduces building emissions (including electricity production for use in buildings) in 2050 from 500 MtCO2e to less than 5 MtCO2e. This essentially eliminates building emissions by increasing energy efficiency and fuel switching to electricity, while the electricity sector simultaneously switches to renewables. These transformations have a net benefit of approximately $150 billion—primarily from fuel and electricity cost savings over time.

As Figure 3.13 shows, under Traditional Development, Latin America and the Caribbean industrial emissions grow with population and GDP growth, from approximately 0.3 GtCO2e in 2020 to 0.5 GtCO2e 2050. This includes emissions from using fossil fuels in buildings, and the emissions associated with buildings' electricity consumption. It does not include embodied emissions associated with building materials, which are included in industry.

Transformations in Incremental Improvements that reduce emissions include using energy more efficiently within buildings and improving building shells to require less heating and cooling. These actions cut building emissions by over half (see Figure 3.13). Furthermore, as Figure 3.14 shows, incremental improvements in building energy efficiency have significant net benefits of $700 billion: the cost of achieving energy efficiency can be offset entirely by the direct electricity and fuel-cost savings from lower consumption, and savings in energy production from the energy sector. We do not put a monetary value on better comfort levels, better indoor air quality from shifting away from traditional biomass or biofuels, or mental health benefits from reducing indoor noise thanks to better-insulated buildings.

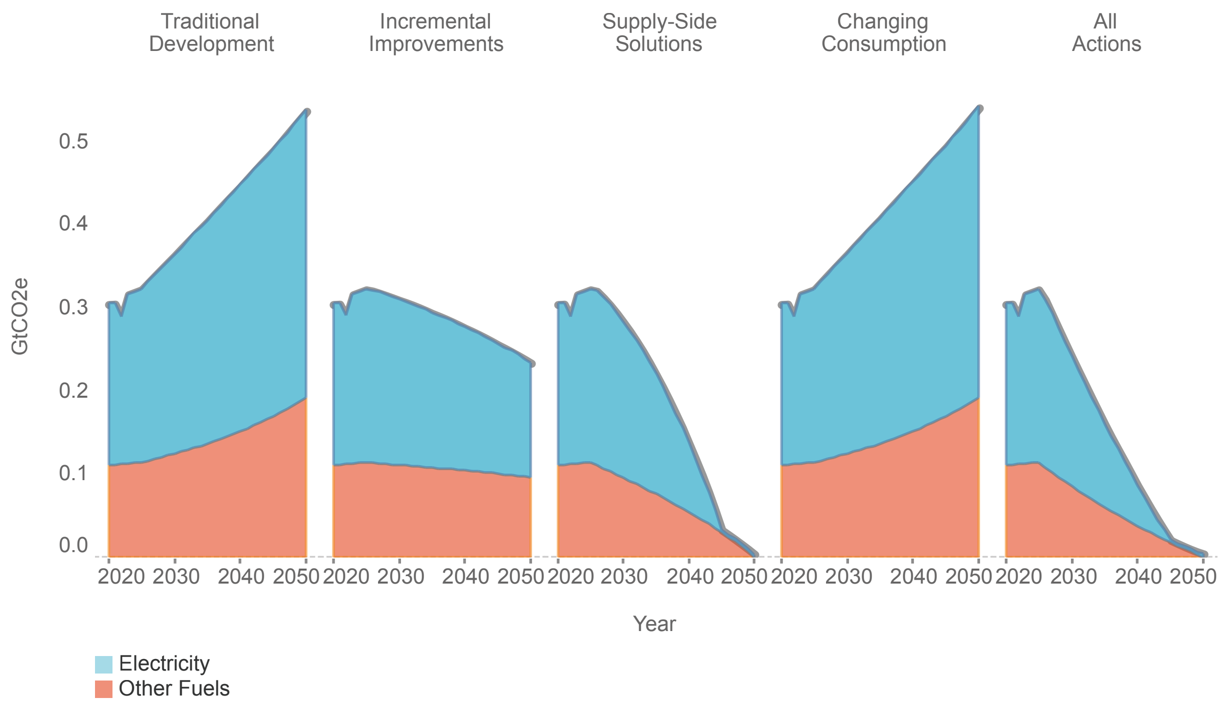


Figure 3.13 Emissions produced by buildings by transformation category.

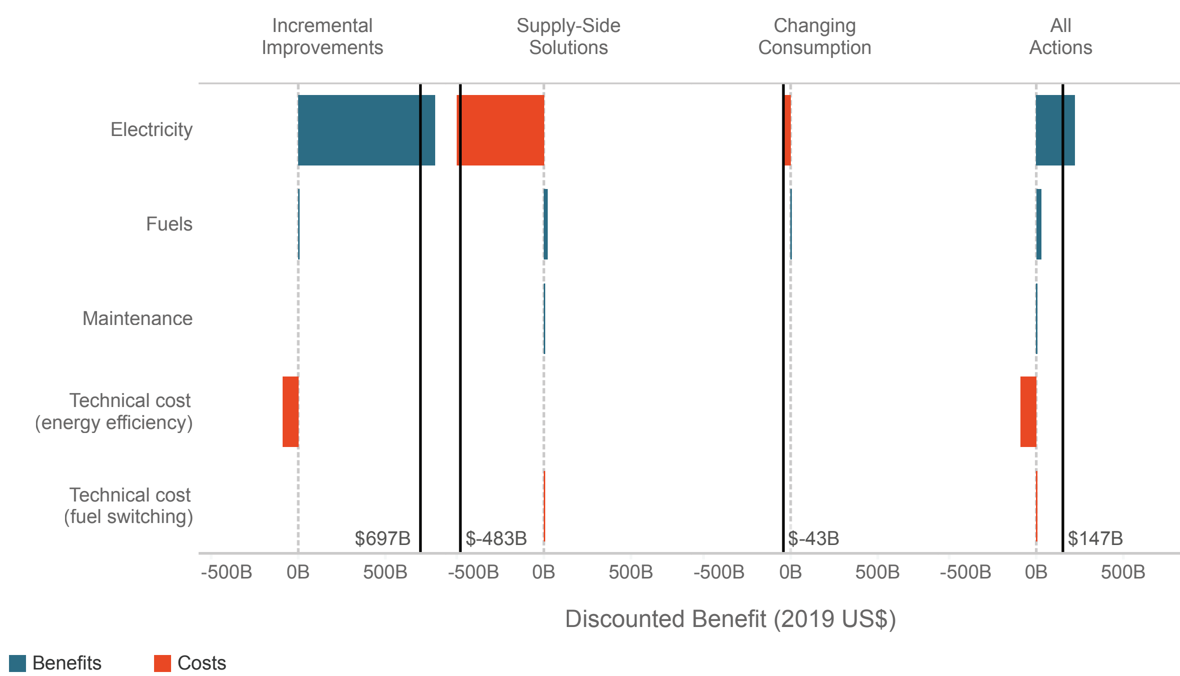


Figure 3.14 Costs and benefits of building transformations by transformation category.

However, fully abating building emissions requires adopting some transformations contained in Supply-Side Solutions. These transformations include fuel switching buildings' heat energy from fossil fuels to electricity, primarily via heat pumps (and not electrical resistance heating), while simultaneously switching electricity production to renewables in the Energy Production subsector (Audoly et al., 2018). This essentially eliminates building emissions, but the costs of higher electricity consumption and increased costs in producing that electricity result in a net cost of approximately $480 billion.

All Actions couples energy-efficiency gains with fully switching to electricity, resulting in an almost complete abatement of emissions and net benefits of $150 billion. This net benefit occurs because the savings in electricity from efficiency interventions outpace the additional need for more electricity resulting from fuel switching and are combined with passthrough savings in the energy sector.

Industry

Under nominal assumptions, taking All Actions reduces industrial emissions (including from electricity production for use in industry) in 2050 from almost 400 MtCO2e to 40MtCO2e, a reduction of 90%, from actions including materials efficiency and substitution, energy efficiency and fuel switching, and capturing or destroying remaining emissions. These transformations offer a net benefit of $213 billion from fuel, electricity, and output savings and avoided pollution, which offset the costs of $200 billion for efficiency, CCS, and other technical changes.

As Figure 3.15 shows, the industrial sector was responsible for approximately 0.4 GtCO2e of emissions in Latin America and the Caribbean in 2020. This includes emissions from the consumption of energy; the processes used to make industrial products; and the use of products, such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) in aerosols and refrigerants, which can have hundreds to thousands of times the warming potential of CO2. It also includes emissions from the production of electricity used in industry. Under Traditional Development, these emissions rise with population and GDP growth to 680 MtCO2e by 2050.

Emissions produced in the sector can be reduced through several transformations. With transformations in Incremental Improvements, transformations include increasing industrial energy efficiency and substituting waste materials for virgin materials, particularly in the substitution of fly ash or other industrial byproducts for clinker in cement. Figure 3.16 shows that improvements in energy and product-use efficiency can yield net benefits of approximately $160 billion: the cost of achieving efficiency can be offset by the fuel cost savings, on top of which are the benefits of avoided air pollution. Nearly all these benefits will accrue to the industrial sector, which may pass on benefits to sectors that use industrial products.

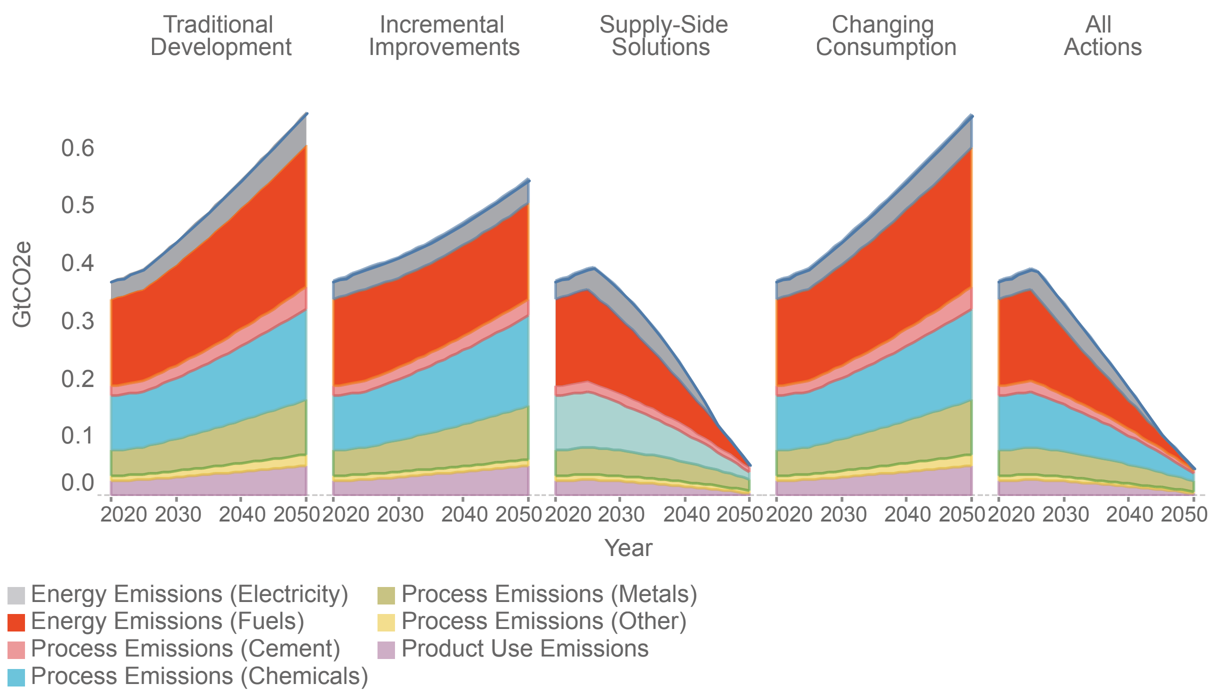


Figure 3.15 Emissions produced by industry by transformation category.

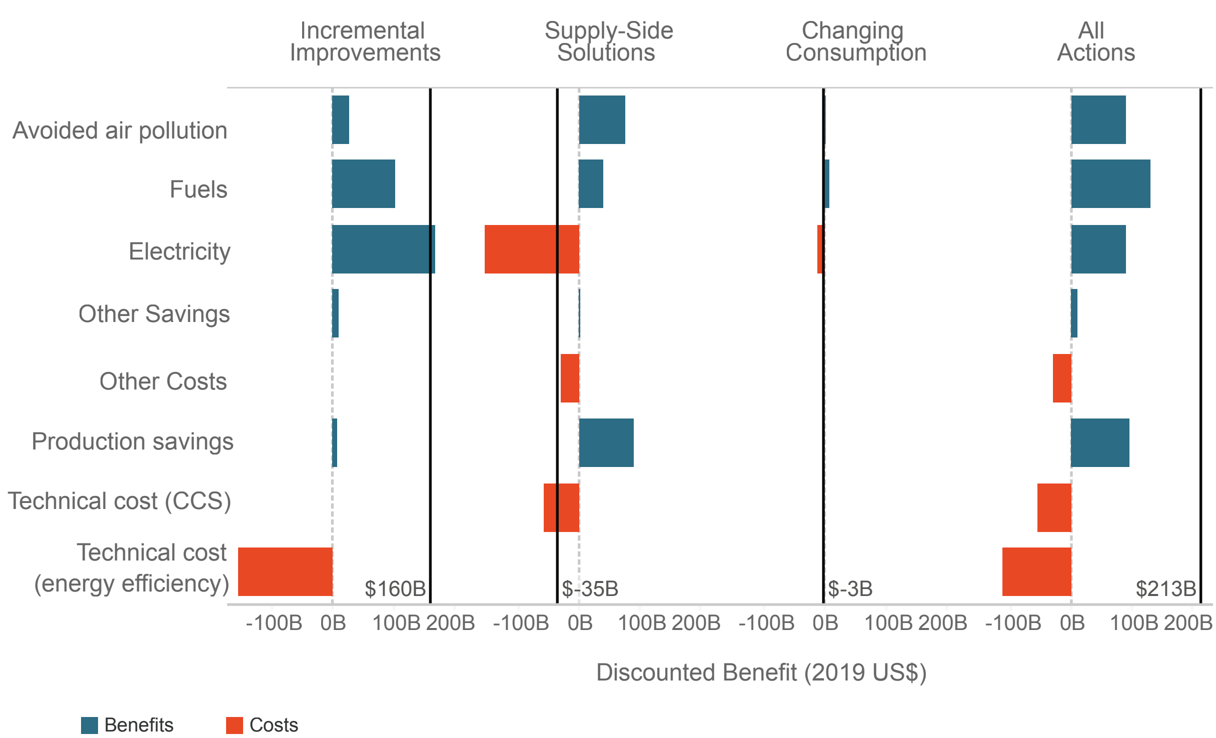


Figure 3.16 Costs and benefits of industry transformations by transformation category.

Under Supply-Side Solutions, transformations induce more significant changes to production, including fuel switching, from fossil fuels to electricity and hydrogen; capturing and using CO2 emissions from key industrial processes and energy use (CCS); destroying or otherwise abating N2O and F-Gases; and using industrial products more efficiently. Changes in Supply-Side Solutions are made alongside a shift in energy production to electricity and hydrogen produced with renewables.

This package of transformations reduces industrial emissions in 2050 by almost 90%. These transformations come at substantial cost to the sector. The cost of producing electricity and green hydrogen to meet industrial demands results in a net cost of $155 billion, which is only partly offset by direct fuel savings of $40 billion. Adopting carbon capture and sequestration poses another significant cost of $60 billion. More efficient use of industrial materials, on the other hand, leads to $90 billion in avoided production costs and $75 billion in avoided air pollution.

The All Actions strategy also reduces emissions to 40 MtCO2e, a reduction of 90% compared to Traditional Development. It reduces the technical costs of transforming industry by combining fuel switching and other high-cost changes with cost-effective energy-efficiency transformations that reduce the extent to which those more expensive transformations must be applied. This full industry transformation achieves decarbonization goals at a lower cost to the economy. Most of these transformations involve changes in industrial production, and their technical costs and benefits will be experienced within the industrial sector. One key exception is industrial materials' efficient use. This largely will be driven by how efficiently industrial products such as cement and steel are used in other sectors—mainly transport and buildings—and the direct costs and benefits of increasing material efficiency would accrue to those sectors.

Transport

Under nominal assumptions, taking All Actions reduces emissions from transport from 1.3 GtCO2e to 0.2 GtCO2e by increasing energy efficiency, expanding the use of electricity and hydrogen in all surface modes, and expanding the use of transit for passenger transport. These transformations yield a net benefit of more than $1.2 trillion—the largest sector benefits—by combining fuel cost savings (net hydrogen costs), transport system cost savings, and broader benefits of reduced air pollution, congestion, and crashes that eclipse the investment costs of $95 billion in energy efficiency and fuel switching.

Transport includes passenger and freight movement by various modes. These include air, rail, light-, medium-, and heavy-dusty vehicles, maritime, motorcycles, and walking and biking. Figure 3.17 shows transport emissions by mode (walking and biking have no emissions and are excluded, and electricity emissions are included separately as they are passed through from the energy production sector). Under Traditional Development, emissions double from 0.64 GtCO2e in 2020 to 1.3 GtCO2e by 2050, driven by GDP and population growth and a mode shift toward more travel by personal vehicle associated with increased wealth (Dargay and Gately, 2007).

Under Incremental Improvements, an increase in energy efficiency reduces emissions by 25% to 1 GtCO2e, with net benefits of $270 billion (Figure 3.18) from fuel savings and associated avoided air pollution benefits. However, these reductions fall far short of the abatement required to reach net-zero emissions.

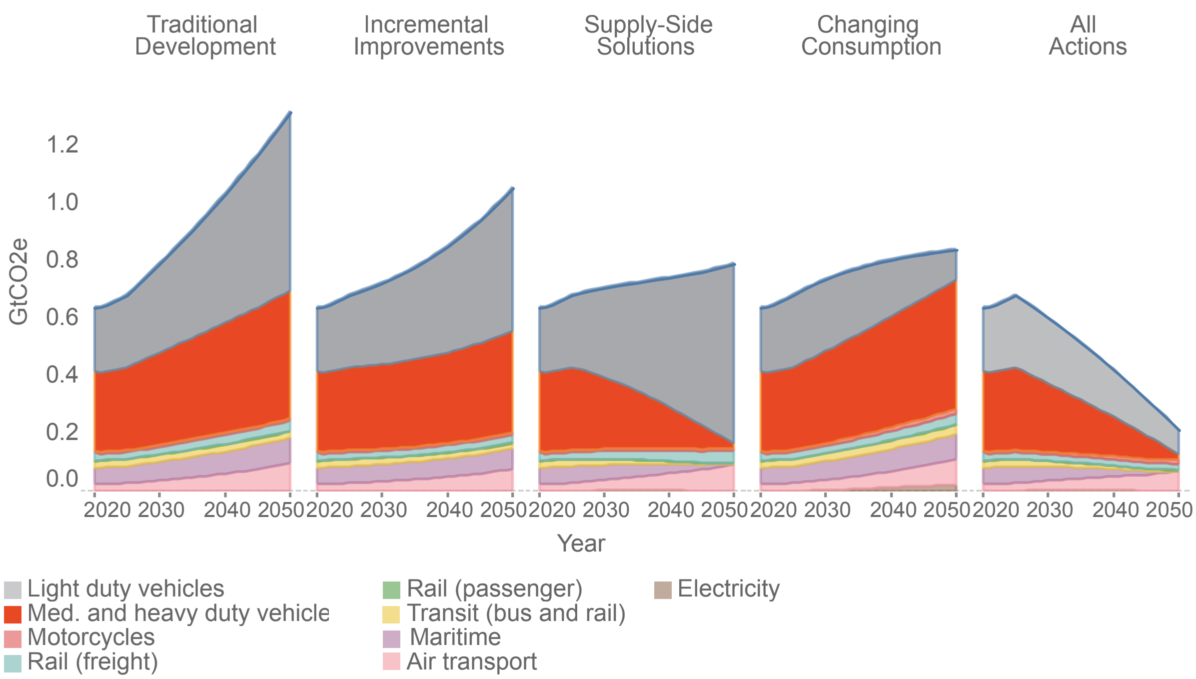


Figure 3.17 Emissions by transport mode by transformation category.

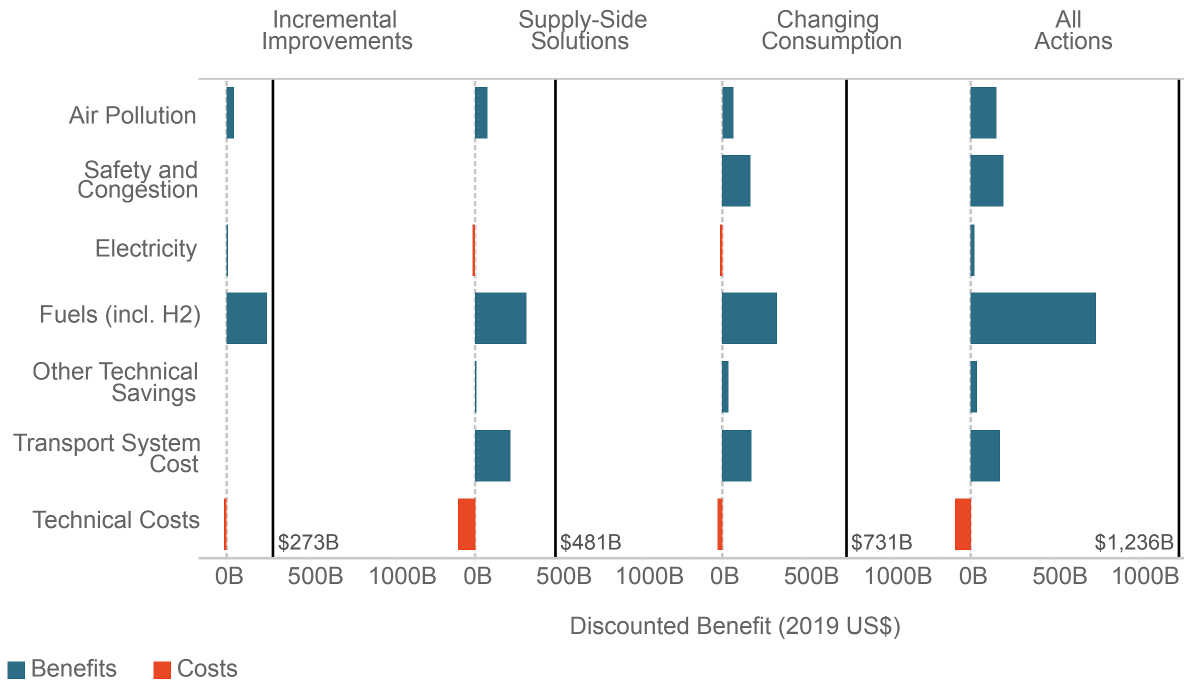


Figure 3.18 Costs and benefits of transforming transport by transformation category.

Under Supply-Side Solutions, transport is transformed through fuel switching away from diesel and gasoline to electricity and hydrogen across all freight modes and public passenger modes, as Figure 3.17 shows. This reduces emissions by 40%. These transformations cost the sector $100 billion in investment costs, but the resulting fuel cost savings, avoided air pollution, and system cost savings lead to a net benefit of $480 billion. (To elaborate, we define system costs as the public and private cost of transporting people and goods by different modes, including infrastructure requirements but excluding fuel to avoid double counting. Based on the literature and data described in the technical appendices, air and private auto tend to be the most expensive per passenger or freight kilometer, while transit and rail are much less expensive, so mode switching offers systemwide savings. This, of course, depends upon what kinds of transit are provided and how. We explore these assumptions and others in our uncertainty analysis.)

Transformations in Changing Consumption focus on changes in transport activity and mode, and involve increasing occupancy for private vehicles; mode shifting local transport to transit, walking, and biking; mode shifting regional passenger travel to bus and rail; and electrifying light-duty vehicles. This strategy decreases emissions by 35% to 0.85 GtCO2e and incurs costs of $25 billion, mostly stemming from light-duty vehicles' electrification. However, the broader benefits, particularly from adopting transit, result in a net benefit of $730 billion from both technical savings such as avoided fuel costs, vehicle maintenance costs, and system costs, and broader benefits of avoided air pollution, crashes, and time wasted in congestion and valued based on productivity. The healthcare sector and employers have much to gain from transport transformations that increase social productivity and health.

Taking All Actions results in a reduction in transport emissions of 85% to 0.2 GtCO2e. The significant and potentially hard to abate residual emissions in this sector may require offsets elsewhere. These changes together yield the largest benefits of any sector of more than $1.2 trillion dollars, from a combination of fuel savings, transport system costs, and avoided air pollution, congestion, and crash costs that dramatically outweigh the investment costs of fuel switching, energy efficiency, and other technical investments. However, these transformations will impose quite different costs on various actors. In particular, a move to transit may pose significant costs to public transport authorities, even as it reduces consumer costs of private vehicle ownership and operation costs.

Waste

Under nominal assumptions, taking All Actions reduces emissions from waste from 0.4 GtCO2e to 0.1 GtCO2e by achieving universal safe sanitation, wastewater treatment, and solid waste management; reducing consumer food waste; and by capturing biogas from waste facilities. These transformations yield a net benefit of $180 billion. Universal waste management and water treatment are expensive, but not only are such actions essential for basic development, they yield significant net benefits in terms of health and avoided pollution.

The waste sector covers liquid and solid waste management, including sanitation and sewage, wastewater treatment, solid waste collection, and solid waste management through landfilling, recycling, composting, and other waste management streams. As Figure 3.19 shows, under Traditional Development, emissions from this sector grow from 0.23 GtCO2e in 2020 to 0.41 GtCO2e with population and economic growth.

Incremental Improvements achieves universal safe sanitation by 2030, consistent with the UN's Development Program SDGs (WHO, 2021), as well as treating all wastewater and ending unmanaged solid waste streams. It also expands recycling. These changes reduce emissions by 20% (Figure 3.19) but are expensive (Figure 3.20), costing $385 billion in civic infrastructure and operations. The health benefits associated with safe sanitation (Hutton & Varughese, 2016) and avoided pollution associated with open dumping (Wilson et al., 2015) outweigh the costs. The result is a $160 billion net benefit.

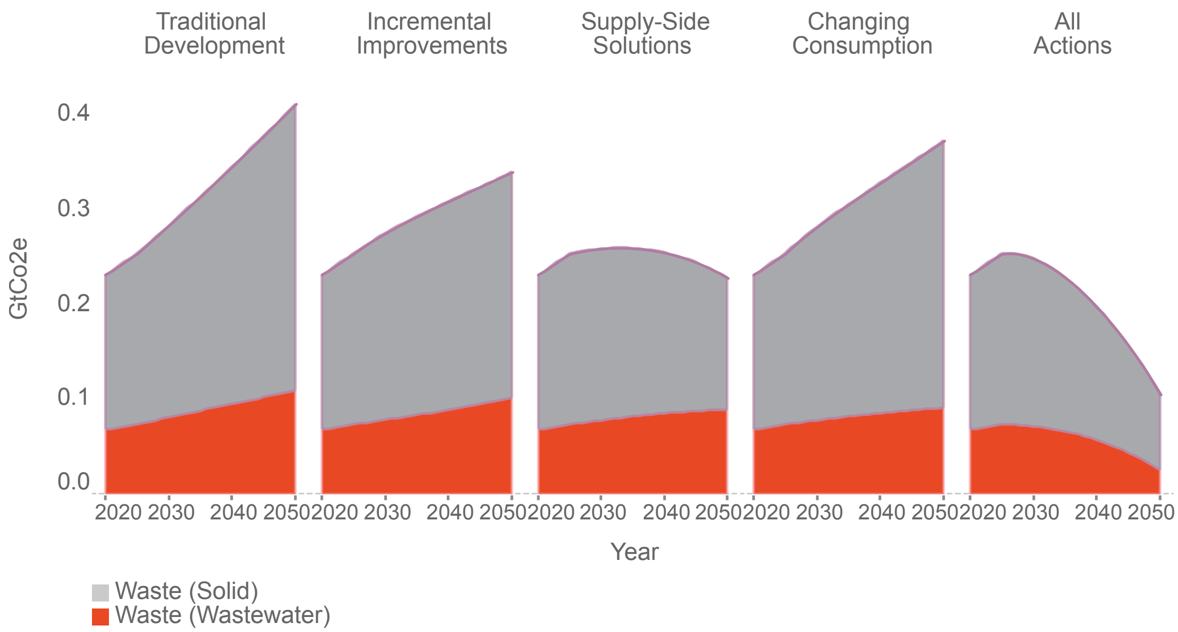


Figure 3.19 Emissions produced by waste by transformation category.

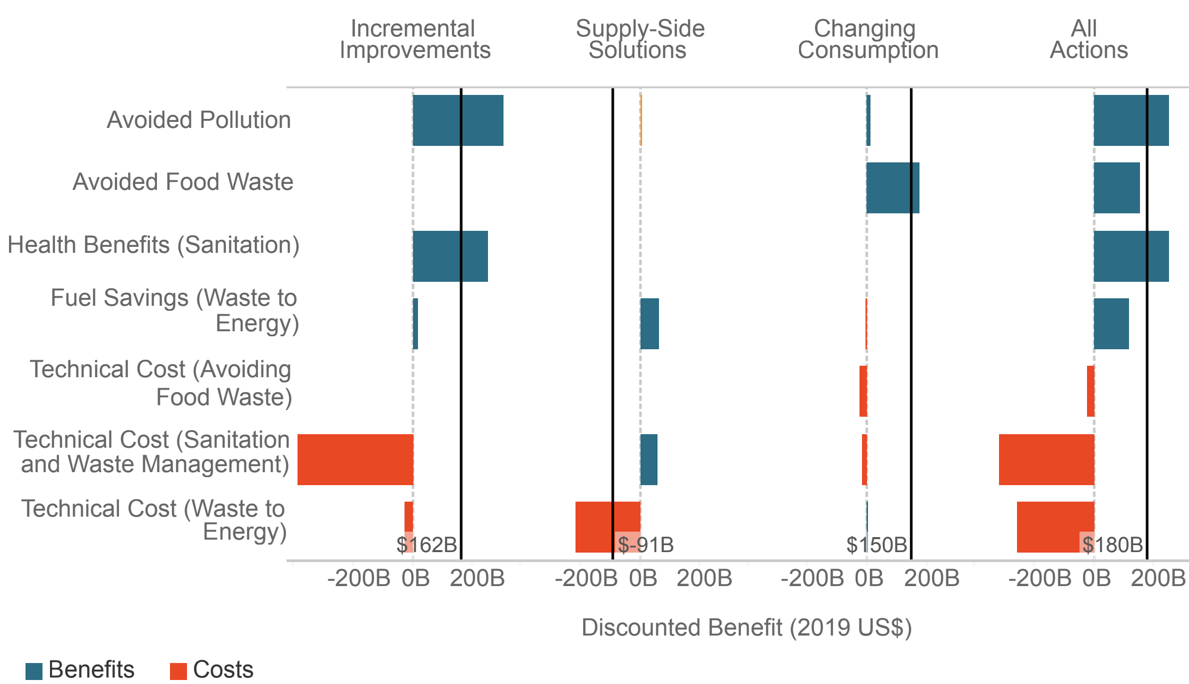


Figure 3.20 Costs and benefits of transforming the waste sector by transformation category.

Supply-Side Solutions involve increased energy recovery from pre-existing wastewater treatment and waste management facilities, reducing sector emissions to 0.22 GtCO2e by 2050. This strategy does not expand sanitation, waste management, or water treatment systems, as these are included in Incremental Improvements. Waste-to-energy recovery on its own poses a net cost of $90 billion, as waste recovery's cost may not be outweighed by the recovery energy's economic value (IEA, 2020).

Changing Consumption involves changes to consumer behavior that reduce food waste and divert organic food waste to composters and digesters. On their own, these transformations reduce emissions by about 10% to 0.37 GtCO2e. While the emissions effects are modest, the benefits to consumers are significant, saving $150 billion in avoided food waste costs. Benefits also include avoided waste management costs.

All Actions combines these transformations to reduce emissions by 75% to 0.1 GtCO2e. In combination, these actions have net benefits of $180 billion dollars—with $600 billion in technical costs outweighed by $780 billion in health and pollution savings and avoided fuel and food production costs. Most importantly, many of these transformations are an essential part of development.

4

CHAPTER

A Robust Path to Net Zero in Latin America and the Caribbean

CHAPTER FOUR

A Robust Path to Net Zero in Latin America and the Caribbean

Countries' decarbonization strategies, including their NDCs and LTSs, will involve transformations across the economy. Whether they reach net-zero emissions, and at what costs and benefits, will be shaped by many deeply uncertain factors related to underlying social and economic drivers, transformations' effects on emissions, and the costs and benefits of different actions.

In this chapter, we hope to help countries in Latin America and the Caribbean chart a robust path to decarbonization that reaches net-zero emissions and provides net economic benefits, despite these uncertainties. To that end, we first identify the region's key ingredients for decarbonization strategies, asking what transformations are critical to reach net zero?

We next ask questions to formulate a strategy that robustly meets net-zero targets in the face of deep uncertainty.

- Do strategies organized around critical transformations reach net-zero emissions under uncertainty?
- What exogenous conditions most threaten net-zero goals?
- What is a robust strategy for reaching net-zero emissions in the region?

With such a strategy, we can assess the costs and benefits of decarbonizing Latin America and the Caribbean, by understanding the following:

- What are the range of costs and benefits of reaching net zero with this strategy?
- What conditions might cause decarbonization to pose net costs?
- To whom do costs and benefits accrue?

Key Ingredients of Decarbonization Strategies for the Region

As Chapter 2 describes, we developed 1,000 decarbonization strategies that implement all transformations simultaneously but to different degrees, ranging from no (0%) to maximum (100%) implementation. (Maximum implementation differs for each transformation and is defined in the technical appendices). Of these simulations, we omit 17 that failed to complete successfully. Figure 4.1 shows the emissions of the remaining 983 as blue trajectories, alongside the five trajectories discussed in Chapter 3.

Results show that doing some of everything can reduce emissions at least as well as doing a few key transformations in Incremental Improvements or Supply-Side Solutions to maximum effect. However, fewer than 1% of these strategies reach net zero by 2050. Clearly, some transformations are more important than others.

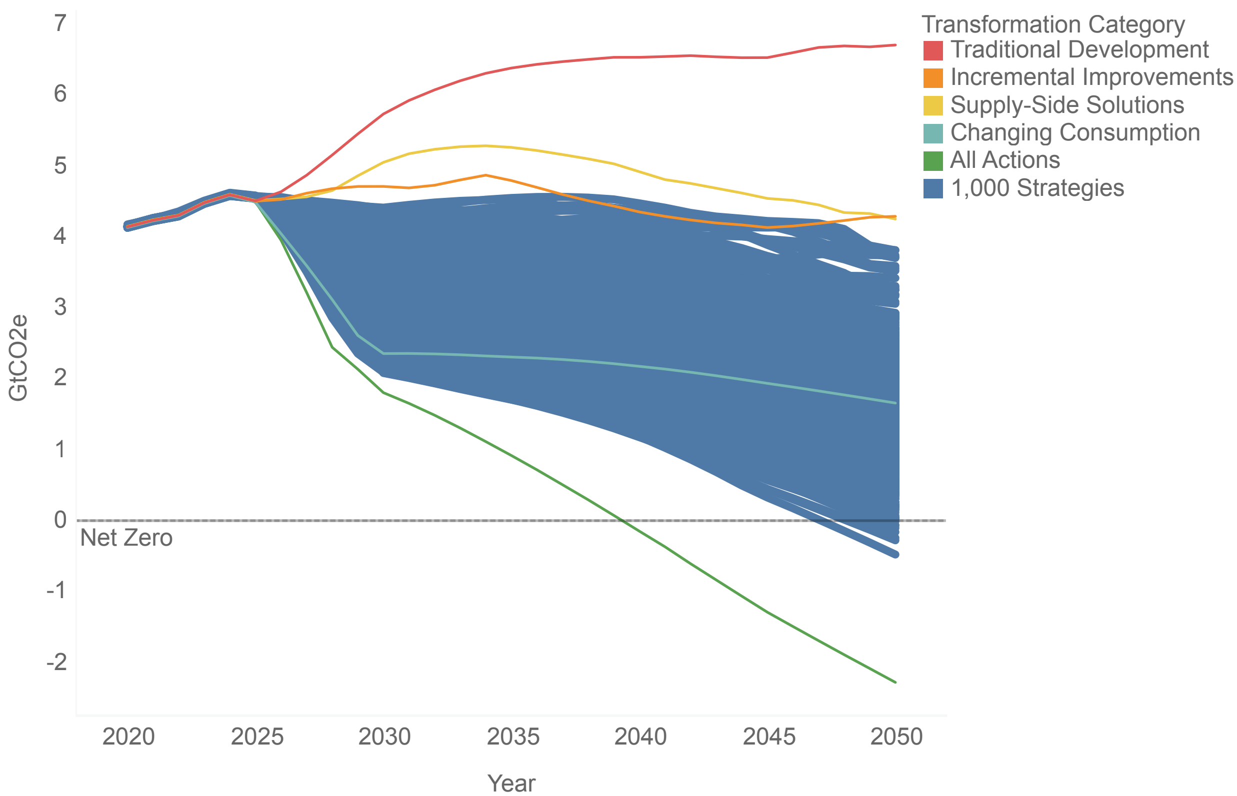


Figure 4.1 Emissions trajectories of 1,000 decarbonization strategies.

Regression and clustering analyses reveal that, of the 50+ individual transformations, four are the primary drivers of decarbonization: ending deforestation, shifting food production and consumption patterns, producing electricity and hydrogen with renewables, and electrifying transport. Table 4.1 details these transformations and their levels of implementation, with further elaborations in the appendices.

Table 4.1 Critical transformations and explanation of implementation levels

Critical Transformation	Description	Explanation of implementation levels
Ending deforestation	The average annual rate of deforestation of the region is approximately 2.6 million hectares (ha) per year (ECLAC, 2021). This transformation sets a limit on the number of hectares that can be deforested each year. This limit is phased in over five years between 2025 and 2030.	At maximum implementation, deforestation after 2030 is limited to less than 10,000 ha/year, effectively ending deforestation. A 70% level of implementation, for example, sets the cap at 780,000 ha/year (30% of 2.6 million).
Shifting food production and consumption patterns	This transformation reduces beef production in the region and adjusts regional diets accordingly, increasing the intake of fruits, vegetables, legumes, and other more healthful options. These shifts make room for afforestation and reduce emissions from enteric fermentation and manure.	At maximum implementation, production of meat is reduced in 2050 by reducing 50% of domestic demand for meat, compared to consumption under Traditional Development, with corresponding increases in intake of other fruits, vegetables, and legumes. A 70% implementation, for example, corresponds to reducing production by 35% of domestic demand by 2050.
Producing renewable energy	This transformation increases the fraction of electricity (and hydrogen) produced with solar, wind, and geothermal energy, using storage as necessary. Given climate stressors and socio-political barriers, this transformation does not include increases in hydropower or nuclear power. CCS for power plants is not included, given the much higher cost compared to renewables and technological immaturity.	At maximum implementation, by 2050 95% of electricity and 100% of hydrogen is produced with renewables as coal, gas, and other fossil fuel plants are phased out. At 70% implementation, for example, 66% of power and 70% of hydrogen is produced with renewables.
Fuel shifting in transport	This transformation shifts all transport toward electricity and hydrogen.	At maximum implementation, by 2050, 70% of light-duty vehicle transport is electric; 70% of heavy-duty and maritime transport is electric; the remaining 30% is powered by hydrogen; and 25% of rail is electrified. At 70% implementation, for example, those figures shift from 70% to 49%; 30% to 21%; and from 25% to 17.5%.

Figures 4.2 and 4.3 illustrate this finding. Figure 4.2 shows the net emissions in 2050 (vertical axis) against a simple average level of implementation across these four critical transformations (horizontal axis). Each dot represents one of the 1,000 strategies simulated. The average level of implementation of these four transformations explains 75% of a strategy's emissions trajectory; the dozens of other transformations account for only about 25% of the emissions outcome. Furthermore, the few strategies that reach net zero all implement critical transformations to at least 70% of their maximum level.

Figure 4.3 shows the importance of these critical transformations by classifying strategies that have "high" or "low" implementations of each of the four critical transformations, where "high" corresponds to an implementation of at least 50%. It shows that 90% of strategies that have high implementation of all four critical transformations reach net zero (lower right box). The percentage reaching net zero drops precipitously to 40% if even one of the four critical transformations is implemented at a low level. (Here, 40% is the average number of strategies reaching net zero across the 4 boxes with only three critical transformations implemented to a high degree, shown on the bottom and right edges with individual percentages of 52%, 56%, 17%, and 38%).

To be clear, high implementation of these four transformations is necessary for reaching net zero, but insufficient on its own. Transformations must occur throughout the economy in every sector, from using materials and energy efficiently to adopting CCS in certain industries to shifting to public transit and non-motorized transport. However, the extent to which other transformations are implemented to reach net zero can vary and be tailored—more efficient use of steel and cement, for example, may allow for lower CCS rates in steel and cement production. These tradeoffs can be governed by considerations of cost, financing, equity, infrastructure, technological feasibility, and other factors.

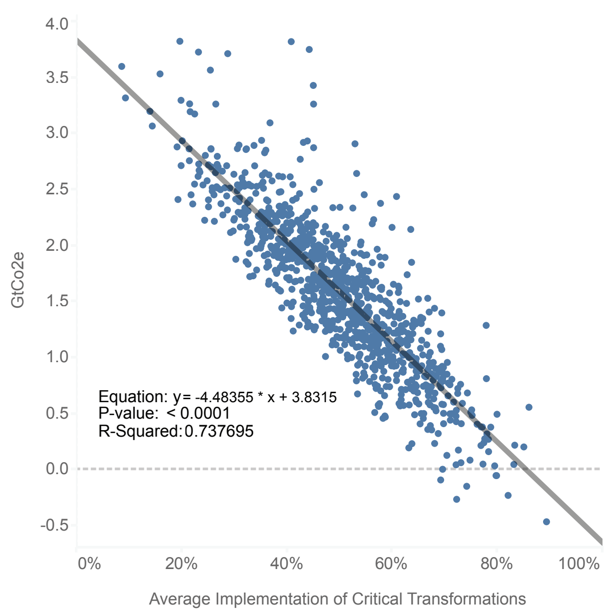


Figure 4.2. Emissions in 2050 vs. implementation of four critical transformations.

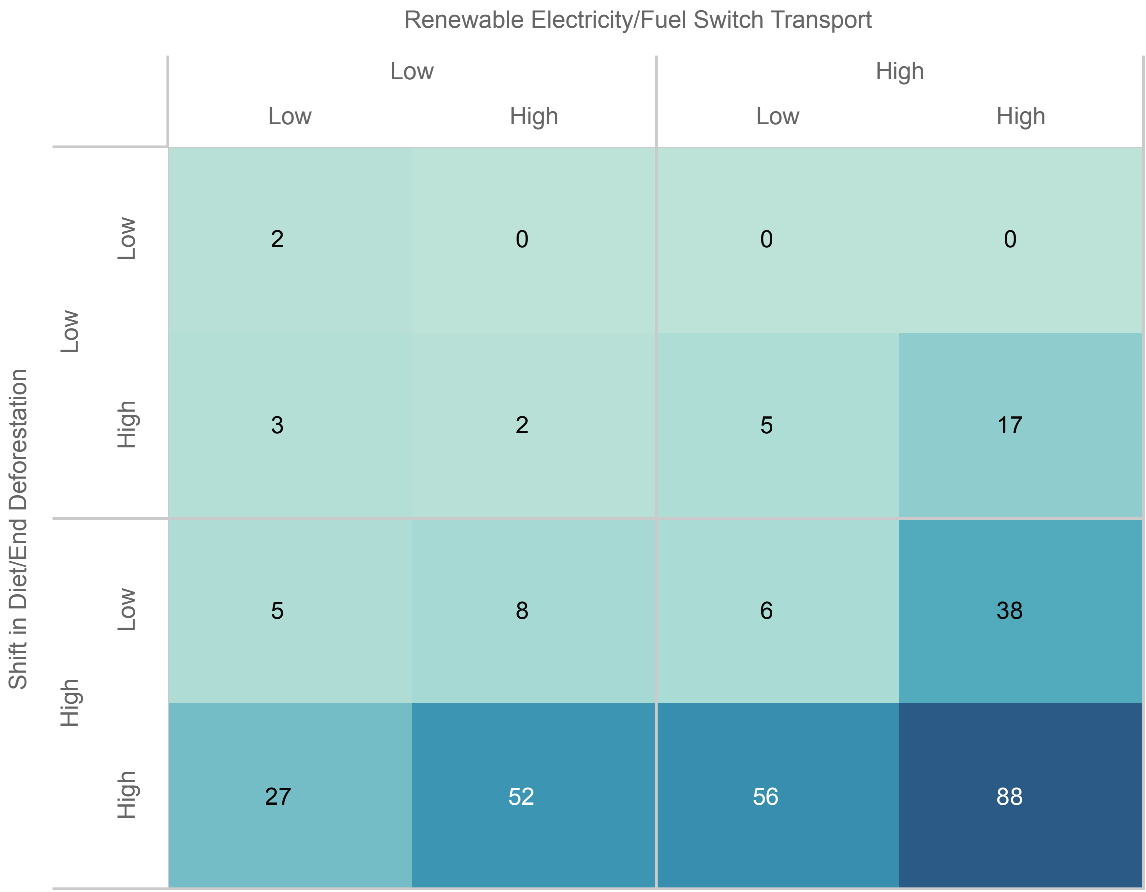


Figure 4.3 Percent of strategies reaching net zero via intensity of critical transformations.

Robustly Meeting Net-Zero Targets Amid Deep Uncertainty

Having identified four critical transformations, our next steps help formulate a strategy that meets net-zero targets in the face of deep uncertainty. We examine the how different levels of implementation of critical transformations and other transformations reach or fail to reach net zero amid uncertainty, what exogenous uncertainties best explain a failure to reach net zero, and what a robust strategy might look like for the region.

Do critical transformations robustly reach net-zero emissions under uncertainty?

We use the label "Critical Actions" to describe a strategy that has high implementation of the four critical transformations previously identified, and some implementation of all other transformations. Here, we examine how Critical Actions perform in terms of emissions, costs, and benefits, when we introduce the many deep uncertainties that challenge decarbonization planning. As described in Chapter 2, we generate 1,000 variants of Critical Actions, where the four critical transformations are implemented from 50% to 100%, and all other transformations are implemented between 25% and 100%. We evaluate Critical Actions against Traditional Development under 1,000 different futures representing uncertainty around factors that affect emissions, costs, and benefits (Table 2.4). Of these, we omit 16 simulations that failed to complete successfully.

Figure 4.4 shows the emissions trajectories of the remaining 984 Critical Action variants and Traditional Development in different future conditions. The results show that the range of emissions under Traditional Development is quite large, ranging from a future in which emissions are stabilized versus increasing manyfold, depending on assumptions about future growth, elasticities of demand, and other emissions drivers. However, Critical Actions consistently drive emissions close to net zero, with emissions in 2050 ranging from 2 to -2 GtCO2e, depending upon the future.

We classify Critical Action variants into three groups distinguished by how closely they reach net zero emissions in 2050. Forty-five percent of Critical Actions variants reach net zero at approximately 2050 (in blue; emissions in 2050 range from 0.5 and–- 0.5 GtCO2e). Another 13% reach net zero sooner than 2050. These "overshoots" have emissions in 2050 of less than -0.5GtCO2e. Finally, 42% of Critical Action variants miss net zero, with 2050 emissions higher than 0.5 GtCO2e.

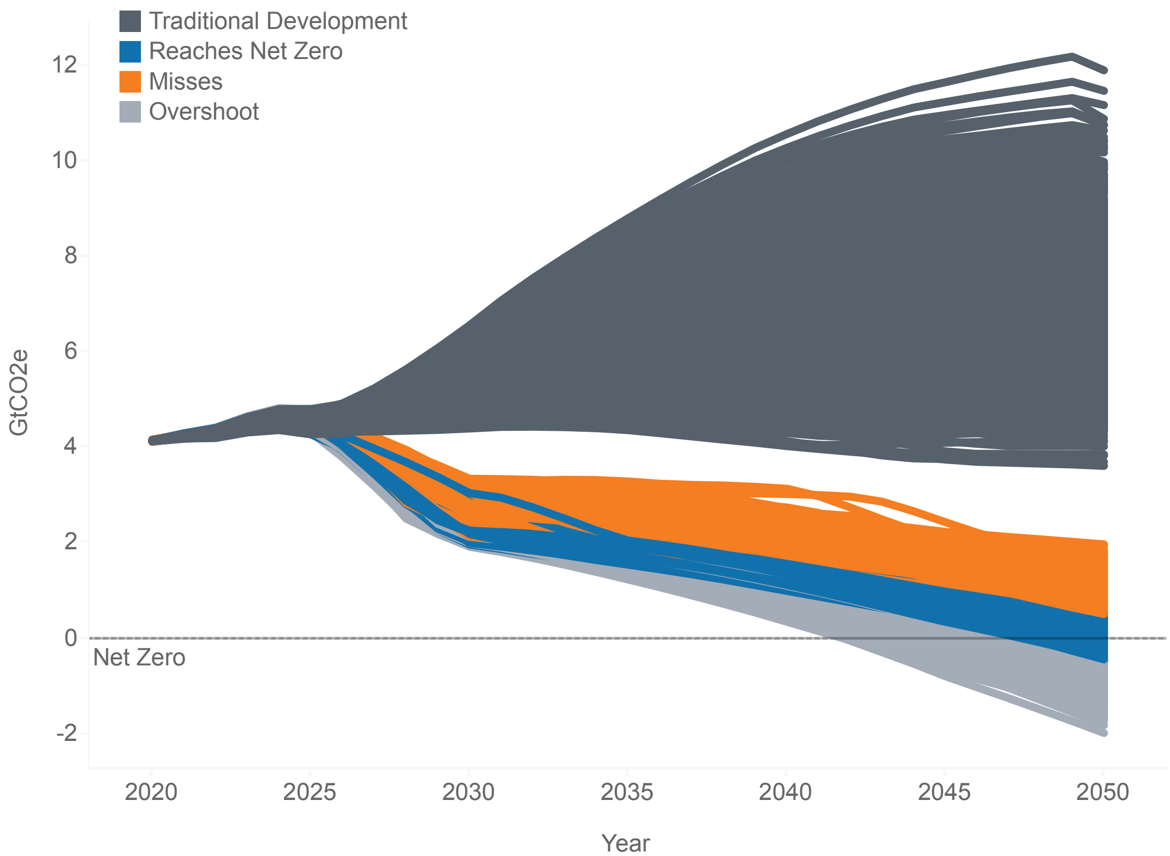


Figure 4.4 Emissions trajectories of 1,000 Critical Actions variants amid uncertainty.

What combination of conditions most threaten net-zero goals?

We use RDM's scenario discovery techniques to describe specific combinations of transformations and exogenous conditions that lead Critical Actions trajectories to reach or miss net zero. Figure 4.5 shows the Critical Actions variants. Consistent with Figure 4.4., by 2050 the trajectories that reach net zero are blue; the ones that miss net zero are orange, and the ones that overshoot net zero are gray.

We find two opposing forces at work. The first is the extent to which critical actions of halting deforestation and shifting food production patterns are taken by 2050. Figure 4.4 shows this as an average implementation level of these transformations on the vertical axis. Implementing these transformations at higher levels means that more forest land remains available to sequester and offset residual emissions in other sectors, making it more likely that net zero is achieved.

The second is the extent to which the exogenous uncertainties of livestock productivity and forest sequestration rates shape forests' abilities to expand and offset emissions. Figure 4.5 shows this on the horizontal axis as an average change in rates of livestock productivity (head per hectare) and rates of sequestration (CO2 per hectare) relative to nominal assumptions. As productivity declines, a larger forest area is required to meet any demand for beef, adding to deforestation. As sequestration rates decline, each hectare of forest is less effective at serving as an emissions sink.

Whether net zero is achieved depends on these forces' relative balance. As we move closer to Figure 4.5's top-right corner, lower deforestation rates, lower beef consumption, and higher productivity of pastures and forests lead to higher likelihoods of reaching net zero by or before 2050.

Figure 4.5 Conditions driving emissions of Critical Action variants under uncertainty.

What strategy robustly reaches net-zero goals?

RDM's scenario-discovery techniques can help summarize information in these results and identify areas of vulnerability and robustness. Figure 4.6 replicates Figure 4.5 and highlights two regions of interest. On the left is a vulnerable region where 90% of trajectories fail to reach net zero. In this region, the stressors of reduced productivity and sequestration rates are not compensated for with higher levels of implementation to end deforestation and shift production and consumption of meat.

On the right in Figure 4.6 is a region of robustness. It shows that sufficiently implementing transformations of ending deforestation and shifting production and consumption of meat provides robustness against these stressors. There are 270 trajectories that have implementation of these two critical transformations at 80% or higher (the shaded area in the figure). In these trajectories, production and consumption of meat is reduced by 40% and deforestation is slowed by 2030 to 780,000 ha/year. Roughly 85% of these trajectories reach or overshoot net zero by 2050, regardless of the change in productivity and sequestration rates explored.

This analysis suggests that livestock productivity and forest sequestration rates may be difficult headwinds against which to navigate to net-zero emissions, but that strong efforts to halt deforestation and shift food production and consumption patterns to lower emitting foods, coupled with transitions to renewable energy and fuel shifts in transport, can provide a robust path to net zero.

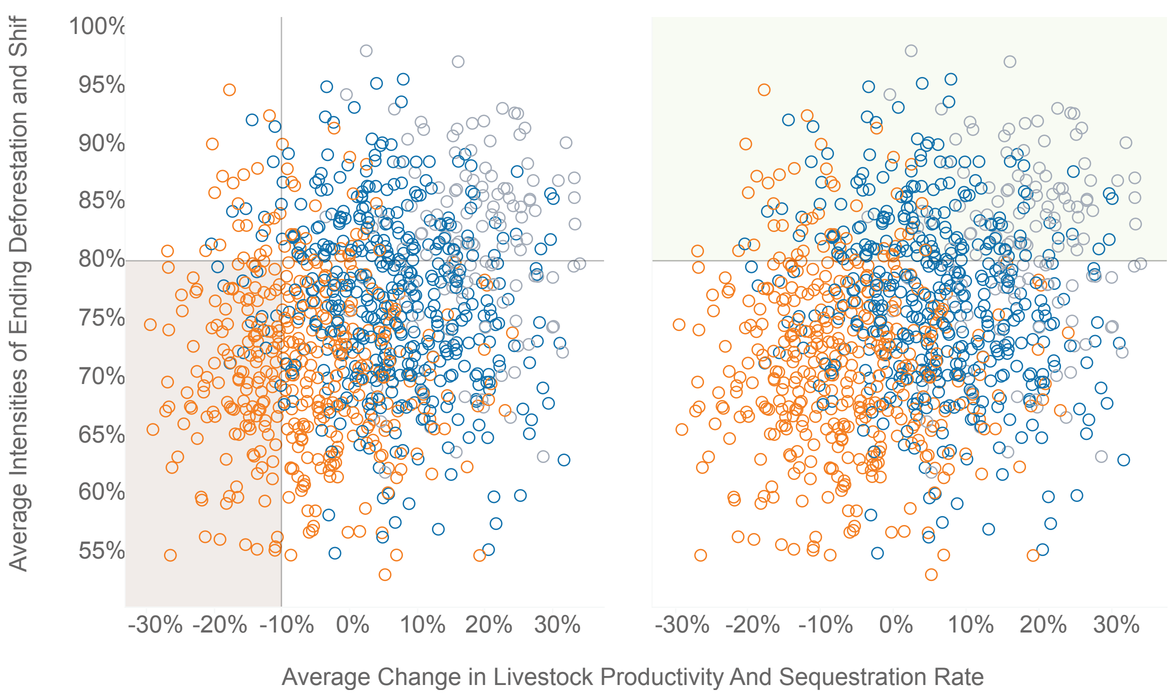


Figure 4.6 Vulnerable conditions (left) and robust levels of implementation (right) of Critical Actions.

Costs and Benefits of Decarbonizing Latin America and the Caribbean

We next examine the macroeconomic implications of decarbonizing the region. We assess the range of costs and benefits that might result from implementing Critical Action strategies, the conditions that might result in net costs to the region, and to whom those costs and benefits accrue.

What are the range of costs and benefits of reaching net zero with this strategy?

Figure 4.7 shows the discounted net benefits (horizontal axis) against net emissions in 2050 (vertical axis) for each of the previous section's Critical Actions trajectories. Marks are shaded based on whether they reach, overshoot, or miss net zero by 2050. In addition, marks are represented by circles when net benefits are positive (to the right of the reference line at 0) and by squares when net benefits are negative (i.e., strategies pose a net cost).

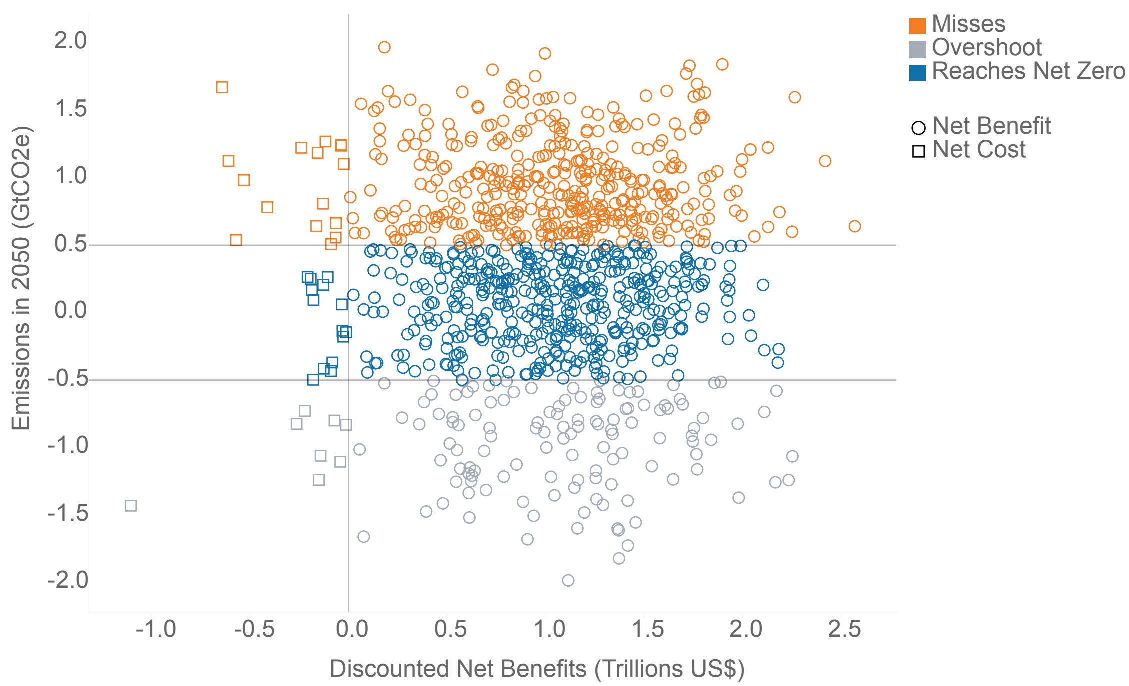


Figure 4.7 Net benefits and net 2050 emissions of Critical Action variants under uncertainty.

Figure 4.7 shows first that 96% of Critical Actions trajectories result in positive net benefits, and the median net benefit across all trajectories is $1 trillion with a maximum of $2.5 trillion. This level of benefits has no relationship to the emissions reductions achieved (a simple regression between emissions and benefits has an R-squared value of 10-5 and a p-value of 0.8). This suggests that Critical Actions are not only robustly beneficial compared to a future with Traditional Actions, but that overshooting net zero is not associated with lower net benefits.

What conditions might cause decarbonization to pose net costs?

There are only 38 trajectories of 984 in which Critical Actions variants pose net costs. Our analysis of these trajectories reveals no specific, summarizable set of drivers of high cost. Each one presents a unique combination of exogenous emissions drivers, transformation effects, and cost uncertainties. This is similar to the findings in Groves et al. (2020), which analyzed the costs and benefits of Costa Rica's decarbonization plan and found few net cost futures, and the conditions that led to them were difficult to summarize.

To whom do costs and benefits accrue?

Figure 4.8 describes the range of benefits across these results by category of costs and benefits used in Chapter 3. Several categories of benefits are positive across all futures: health safety and productivity; avoided pollution; ecosystem services; and fuel costs. This is consistent with the fact that Critical Actions strategies reduce fossil fuel dependency and increase forestation, with corresponding benefits in those categories. The benefits in terms of sector investment are, by definition, negative across all futures, as this category captures capital and other investments' costs.

The benefits in the other categories vary by future. The electricity sector can experience net costs if capital costs, particularly for transmission and system upgrades, are extremely high and not offset by maintenance and fuel-cost savings. In agriculture, the net impact of implementing the Critical Actions on output is typically positive, but can be negative in some futures, if livestock's foregone value is not outpaced by increased output in crops. The other sector savings or costs include avoiding industrial activity because of more efficient material use, maintenance savings from electrification, and the system costs of transport by mode. Whether these lead to net costs or net benefits depends on how far related transformations are implemented, and the exogenous values of costs and benefits per unit of implementation.

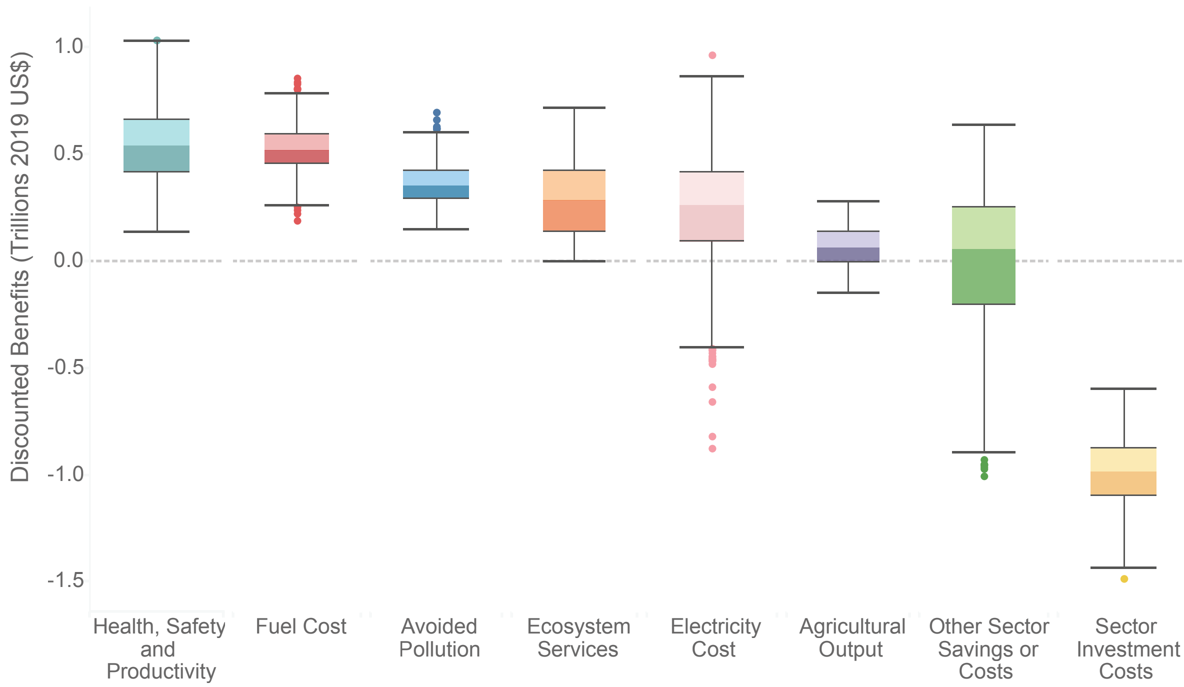


Figure 4.8 Major categories of costs and benefits under uncertainty.

Figure 4.8 classifies benefits into those that are incurred by actors in our key sectors—agriculture, buildings, industry, transport, and energy production sectors (right box plot), and benefits that are external to those sectors (left box plot), including avoided pollution; other health, safety, and productivity benefits; and ecosystem services. These benefits tend to accrue to the public and the healthcare system.

Figure 4.9 shows that while external benefits are large and positive in all scenarios, internal benefits vary. In some futures, actors can enjoy positive internal benefits, particularly when energy cost savings recoup technical investments. But many futures pose net technical costs to sector actors. While the external benefits almost always outweigh these costs, and typically by a large margin (see Figure 4.8), the cost to sector actors may prohibit climate action, regardless of the broader benefits that might accrue to a nation.

This points to the significance of government interventions to redistribute benefits through society, through fiscal policy, tariff structure, and social policy. For instance, governments could internalize some of the social benefits of reduced congestion and air pollution by adjusting taxes on fuel and vehicle ownership (e.g., Victor-Gallardo et al., 2022) or reforming fossil fuel subsidies while reinforcing cash transfers or subsidizing adoption of clean technology (Missbach et al., 2024).

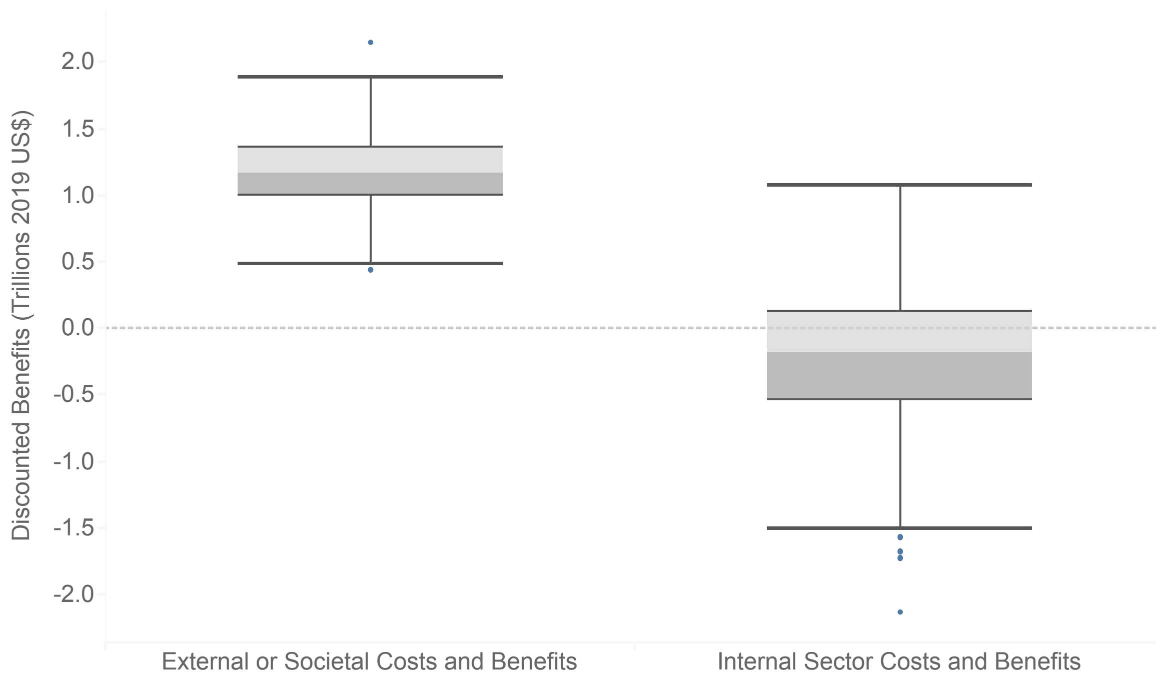


Figure 4.9 Internal and external costs and benefits.

5

CHAPTER

Country Snapshots

CHAPTER FIVE
Country Snapshots

This chapter explores how the regional strategies from Chapters 3 and 4 have different outcomes and implications for individual countries based on their underlying socioeconomic, geographic, development, and other differences.

We illustrate results in three countries: Brazil, the Dominican Republic, and Mexico. For each country we provide a summary of its NDC, focusing on their mitigation targets and their stated actions for achieving these targets. Also, if available, we discuss their LTS objectives. We then summarize the country-level results of the five strategies analyzed in Chapter 3, and then of the Core Actions strategy described in Chapter 4.

These differences reiterate that while some common actions are critical to reach net zero, the specific implementation levels of these and other actions across the economy will depend on local conditions, and their success will be challenged by different uncertainties and conditions. Overall, decarbonization planning cannot be a copy-paste exercise; it should be based on national deliberation and tailored for local priorities and challenges.

Brazil

Brazil, the largest economy in Latin America, faces various economic, political, and environmental challenges in the context of climate change. Economically, Brazil depends on industries such as agriculture, mining, and energy production, which contribute significantly to GHG emissions and environmental degradation. Brazil has made progress in addressing climate change through commitments under the Paris Agreement and implementing national policies to reduce the Amazon's deforestation. However, political challenges and competing interests pose barriers to effective enforcement and regulation (Gallo and Albrecht, 2019).

Environmentally, Brazil is home to the Amazon, the world's largest tropical rainforest. The Amazon plays a critical role in global climate regulation, storing about 25% of the world's above-ground biomass carbon, 64% of which is in Brazil (Fawcett et al., 2023). Deforestation, illegal logging, and land encroachment pose significant threats to the region's biodiversity and its ability to meet its GHG emissions targets (Cardil et al, 2020). Adaptation efforts require sustainable land-use practices, conservation measures, and increased resilience in vulnerable communities (Niemeyer and Vale, 2022; Di Gregorio et al, 2016). Brazil's unique position as a global environmental steward and major emitter of GHGs highlights the need for comprehensive strategies that integrate economic development, political will, and environmental protection to address the complex challenges of mitigating and adapting to climate change (Gallo and Albrecht, 2019).

In 2020, Brazi''s total emissions stood at 1.45 GtCO2eq, accounting for 2.92% of global emissions, marking a decline of 28% compared to 2005. Brazil's NDC targets the major sectors contributing to its emissions. The main drivers of emissions identified in the NDC's business-as-usual (BAU) scenario include agriculture, energy, land-use change and forestry, waste, and industrial processes. Agriculture alone accounted for 35.3% of emissions, followed by energy at 29.9% and land-use change and forestry at 27.5%. By 2025, Brazil commits to reducing emissions by 37% compared to 2005 levels, while aiming for a substantial GHG emission reduction of 50% by 2030. Furthermore, Brazil envisions achieving a long-term objective of carbon neutrality by 2050 (UNFCCC, 2022a). However, Climate Action Tracker's overall rating of Brazil's climate policies and commitments currently is deemed insufficient, requiring substantial improvements to meet its 2030 NDC target (Climate Action Tracker, 2022a).

To mitigate emissions, Brazil has implemented various actions across key sectors. In agriculture and forestry, the country provides incentives to reduce deforestation, enhances afforestation and reforestation efforts, promotes sustainable agricultural practices, sets sustainability standards for biomass use, and encourages reducing CO_2, CH_4, and N_2O emissions from agricultural activities. In the electricity and heat sector, Brazil has established a support scheme for renewables, focusing on highly efficient power plant infrastructure, investing in grid infrastructure development, exploring non-renewable low-carbon alternatives, and encouraging electricity storage. In transport, the country promotes energy-efficient heavy- and light-duty vehicles, encourages a switch to low-emissions land transportation, and aims to shift the modal share, among others. The industry sector receives support for energy efficiency in production, material efficiency, establishing performance and equipment standards, incentives to reduce methane emissions from fuel exploration and production, landfill methane reduction, and a support scheme for CCS and fuel-switching initiatives. Lastly, in buildings, Brazil focuses on implementing performance and equipment standards, while providing support for highly efficient appliances (Bezerra et al, 2021; Silvero et al, 2019). Brazil has not yet submitted an LTS that could further outline its plans for achieving carbon neutrality and sustainability in the coming decades.

Our findings for Brazil track closely with regional findings, given that Brazil constitutes 40% of the region's emissions. Figure 5.1 shows results of our Chapter 3 analysis for Brazil. It shows that, under initial conditions, the Agriculture and Forest and Other Land Use sector accounts for the country's largest share of emissions. None of the three individual categories of transformation analyzed in this report (Incremental Improvements, Supply-Side Solutions, and Changing Consumption) reach net zero, though Changing Consumption comes close as it returns massive amounts of land to secondary forests that can offset emissions in the rest of the economy. However, taking All Actions achieves the 2050 carbon-neutrality objective, suggesting that actions from across these categories can enable Brazil to reach its targets.

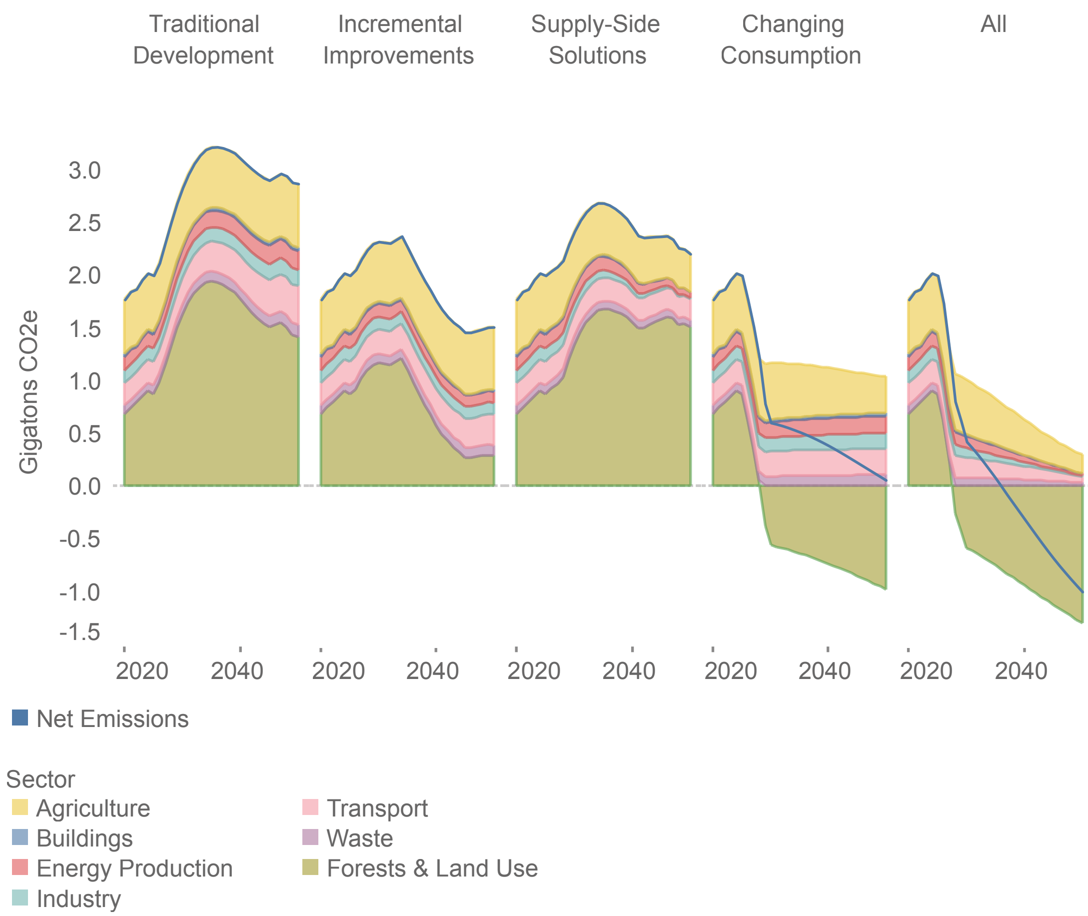


Figure 5.1 Emissions under maximum implementation of transformations by category, Brazil.

We find that Brazil would benefit from implementing the sectoral transformations analyzed in this report. As Figure 5.2 shows, all categories of transformations yield positive net benefits for Brazil under nominal assumptions. The biggest benefits will be generated in the avoided pollution, health, safety and productivity, and other sectors' savings categories. Implementing All Actions would require US$709 billion (1.92% of today's GDP per year) in sector-specific investments, yielding $1 trillion in net benefits.

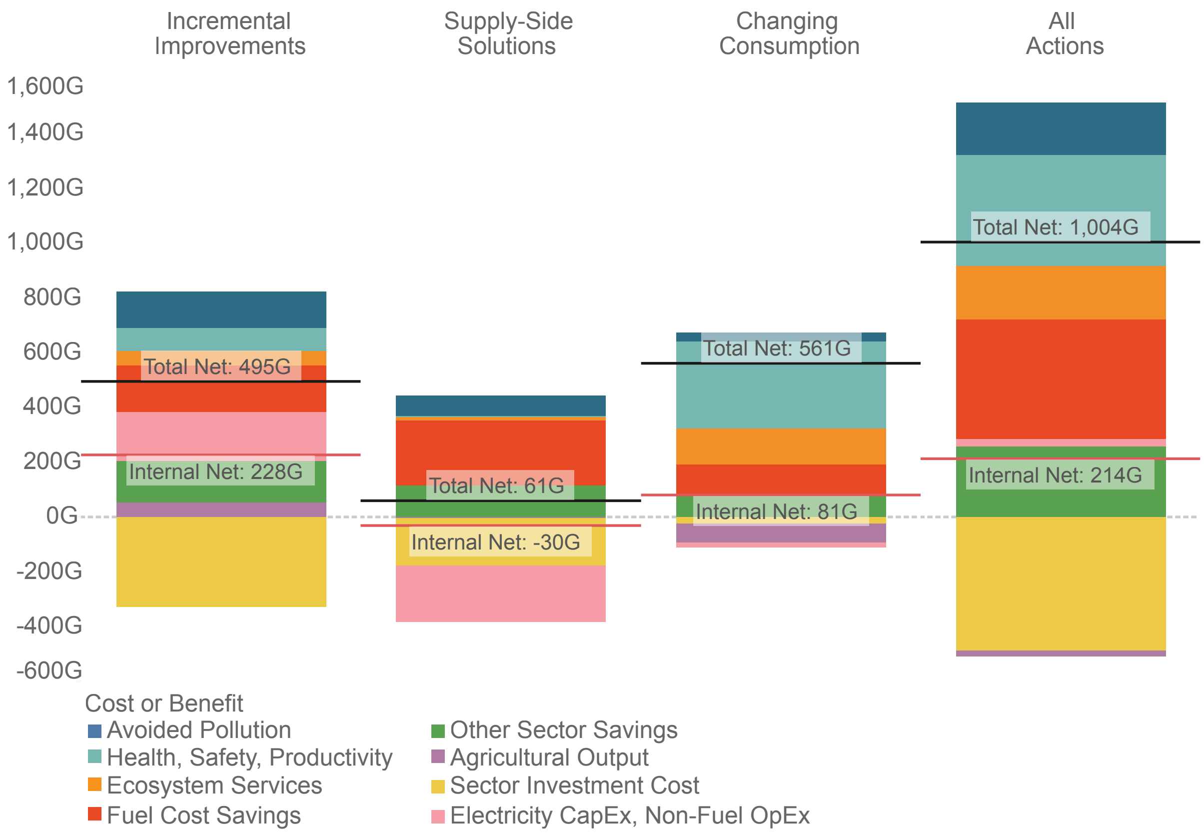


Figure 5.2 Discounted costs and benefits under maximum Implementation of transformations by category, Brazil.

Figures 5.3 and 5.4 present results under uncertainty for Brazil and provide country-level versions of our Chapter 4 analysis. Figure 5.3 shows the emissions over time and under uncertainty of 1,000 variants of the Critical Actions strategy described in Chapter 4: shifting food-production patterns, altering deforestation, decarbonizing electricity production, and electrifying transport. Approximately 90% of these variants reach or overshoot net-zero emissions by 2050, with only 10% of trajectories falling short of this target. Figure 5.4 shows this strategy results in positive net benefits in nearly all variants and conditions. Here again, emission reductions benefit from efforts to boost agricultural productivity, shift diets toward foods that require less space to grow, and afforest the freed-up land.

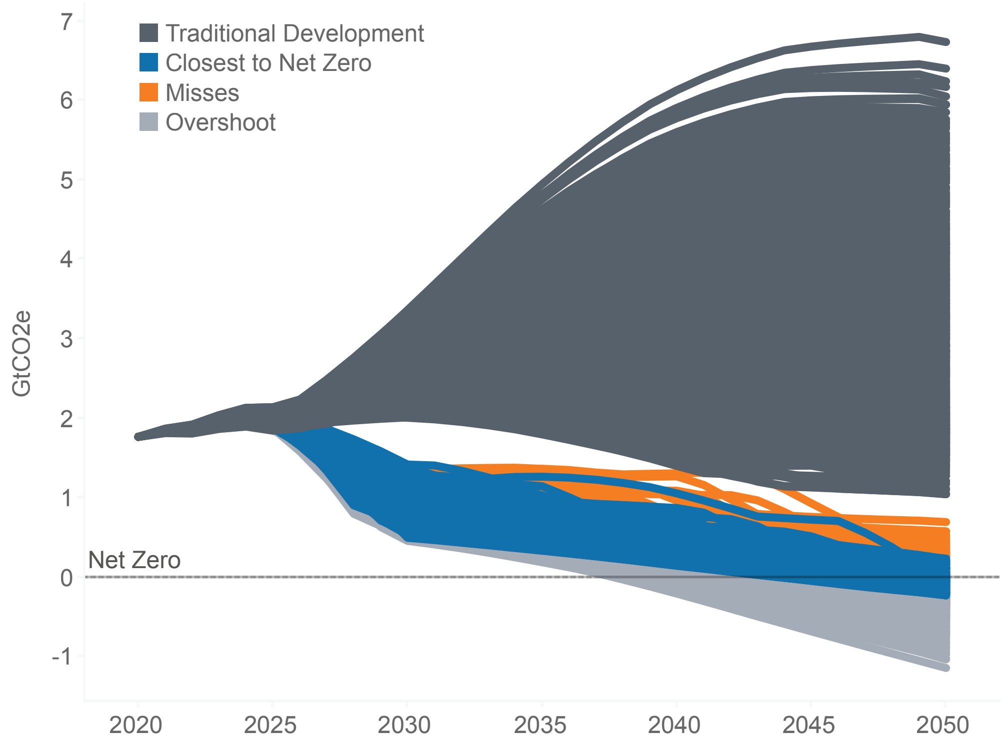


Figure 5.3 Emissions trajectories of 1,000 Critical Action variants amid uncertainty, Brazil.

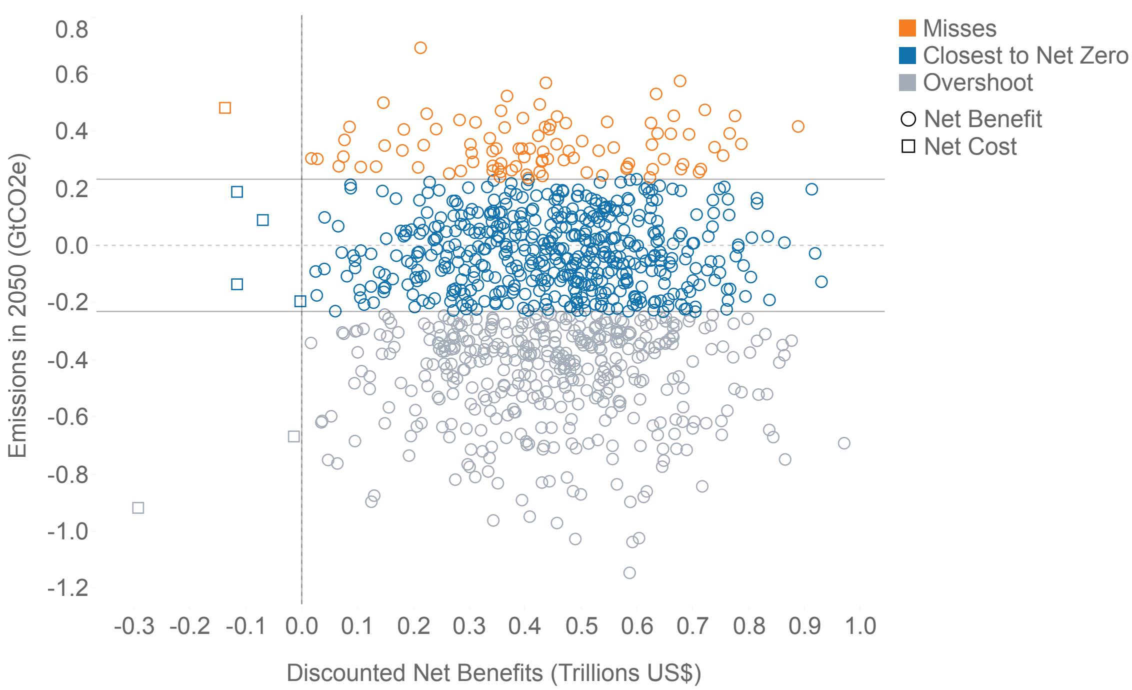


Figure 5.4 Net benefits and net 2050 emissions of Critical Action variants under uncertainty, Brazil.

Figure 5.5 identifies combinations of lever intensities and exogenous conditions that lead the Critical Actions strategy to miss net-zero emissions. In Brazil's case, these vulnerable conditions resemble the vulnerable conditions identified for the overall region because of Brazil's importance in both emissions and sequestration potential. In this respect, shifting agricultural production and consumption and halting deforestation are critical transformations for reaching net zero, and net zero is most challenged by the lower livestock productivity and lower sequestration potential of primary and secondary forests.

Figure 5.5 highlights one vulnerable region in the lower left corner where productivity and sequestration rates are lower than 20% of nominal and transformations are implemented at less than 40% of maximum. Sixty-eight percent of the trajectories in this region fail to reach net zero. This region describes 53% of the trajectories that fail to meet net-zero targets.

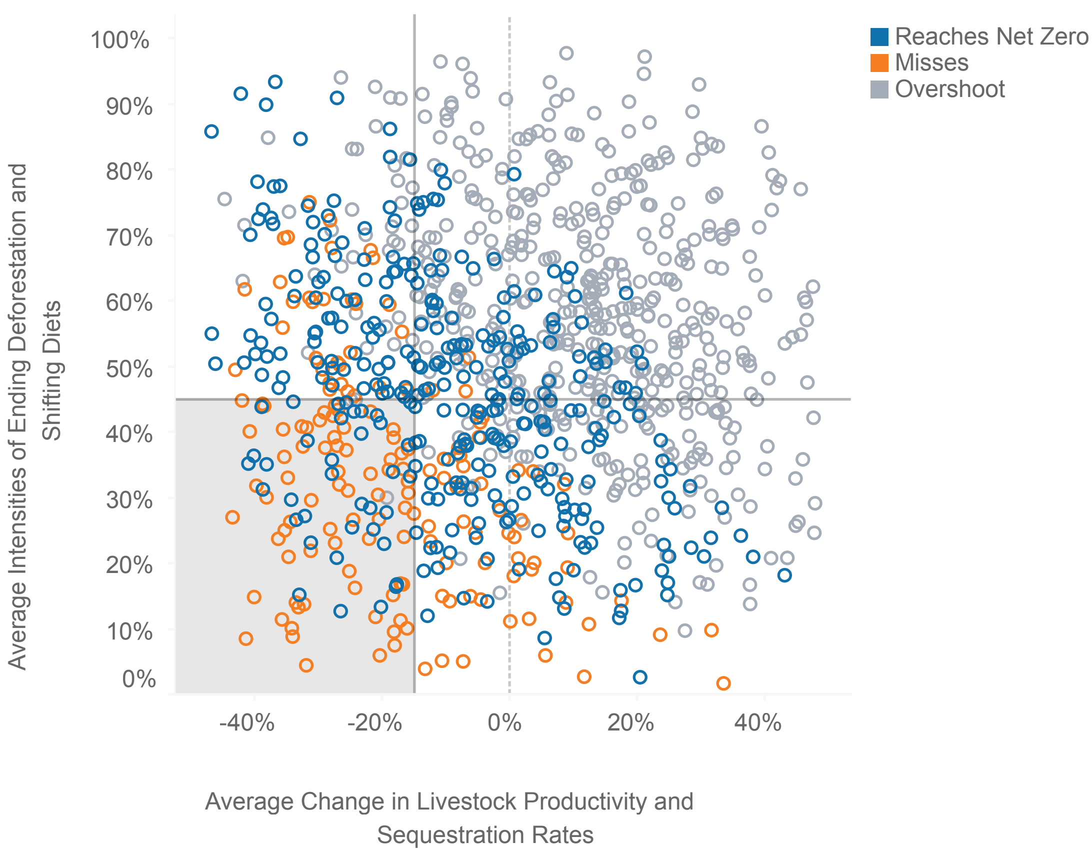


Figure 5.5 Vulnerable conditions of Critical Actions, Brazil.

Dominican Republic

The Dominican Republic economy relies on industries such as tourism, agriculture, and manufacturing, which are vulnerable to the impacts of climate change. Rising sea levels, increased storm intensity, and changing precipitation patterns pose risks to coastal infrastructure, agricultural productivity, and water resources (WHO, 2021). The Dominican Republic has demonstrated commitment to addressing climate change, with the government implementing policies and initiatives to promote renewable energy, improve environmental regulations, and enhance resilience in vulnerable areas. However, challenges related to political coordination and funding hinder comprehensive climate change strategies. Environmentally, the nation's diverse ecosystems, including coral reefs and mangroves, are threatened by climate change, leading to habitat loss, coastal erosion, and loss of biodiversity. Adaptation efforts require sustainable land and water management practices, conservation measures, and protecting natural resources (de Municipios et al, 2017).

In 2020, the country's total emissions amounted to 40 MtCO2eq, representing 0.08% of global emissions. Comparing this to the year 2000, emissions have doubled. Agriculture, Electricity, Transportation, and Industrial Processes were the main emitting sectors, contributing 26, 25, 20, and 10% respectively (Climate Watch Data, 2020a).

The Dominican Republic's updated NDC aims to achieve a reduction of 27% compared to BAU by 2030 (UNFCCC, 2022b). To meet its commitments, the Dominican Republic is implementing several actions across economic sectors, via incentivizing private investment. In the electricity and heat sector, the country has established a renewable energy target that aims to prioritize the development of grid infrastructure and electricity storage. In transport, there is support for biofuels and implementing a tax on fuel and/or emissions. However, in the agriculture and forestry, industry, and buildings sectors, no specific mitigation actions have been articulated (Climate Policy Database, 2019a). The Dominican Republic has not yet submitted an LTS to outline its comprehensive plans for achieving climate neutrality and sustainability in the long run (UNFCCC, 2023b).

Our findings for the Dominican Republic meaningfully differ from regional findings. First, Figure 5.6 shows that individual transformation categories (Incremental Improvements, Supply-Side Solutions, and Changing Consumption) can all help the country reduce emissions by at least 27% compared to Traditional Development. At the same time, it is possible to see those efforts will not be enough to achieve carbon neutrality.

None of the model development strategies achieve carbon neutrality by 2050, not even if All Actions are taken. Compared to the entire region—or Brazil described in the previous section—energy production, transport, and industry in the Dominican Republic play a much larger role in present emissions. The country also has less potential to offset emissions through afforestation. If the land-constrained island is to pursue a domestic net-zero target, more emissions reductions than what we modeled are required by 2050 in agriculture, transportation, and waste management.

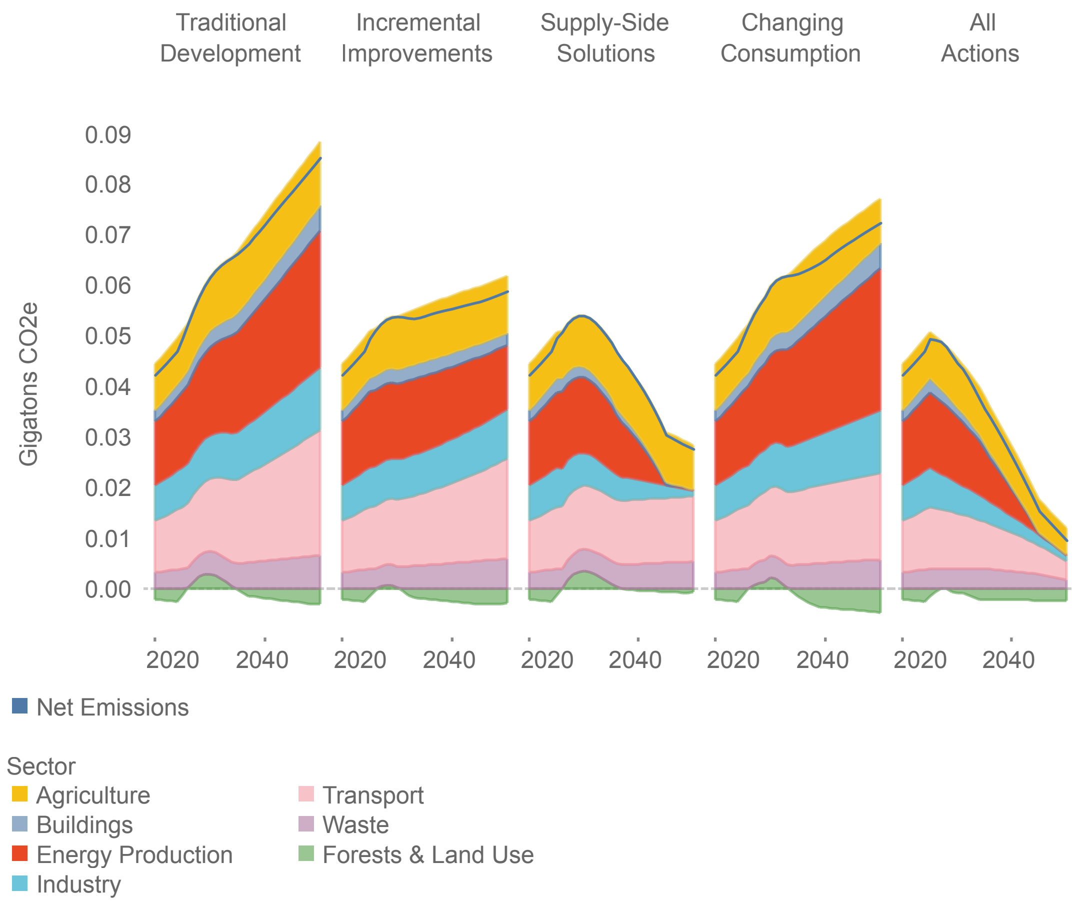


Figure 5.6 Emissions under maximum implementation of transformations by category, Dominican Republic.

For instance, our simulations show that there is room to further reduce emissions in transport. Figure 5.7 shows fuel consumption in the sector under Traditional Development and All Actions. The reductions in All Actions are a combination of reductions in energy demand resulting from higher transportation energy efficiency, increased occupancy of private vehicles, and transport mode shifts toward public transportation and non-motorized travel, and electrification of transportation and fuel switching toward hydrogen. Further reductions in emissions could be achieved if the remaining share of conventional fuels used (i.e., gasoline and diesel) is substituted by electricity or hydrogen, or if modal shift further improves. Either option might be easier to implement on the island than in the overall region.

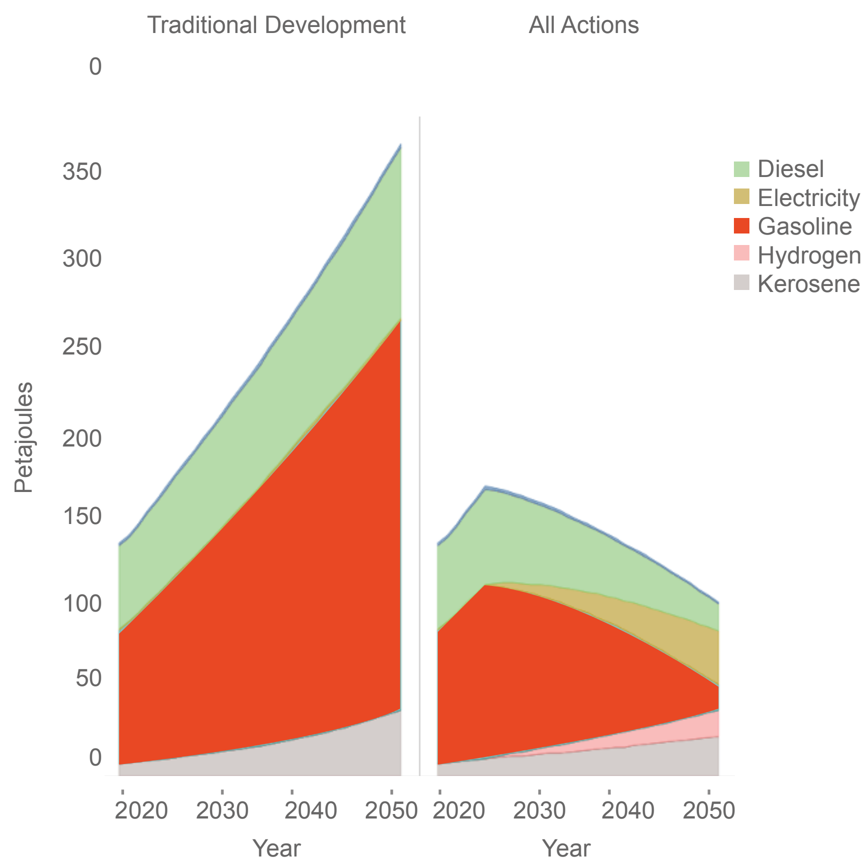


Figure 5.7 Fuel demand in transportation under selected trajectories, Dominican Republic.

Figure 5.8 displays estimated costs and benefits for the Dominican Republic for these categories. All but Supply-Side Solutions yield robust net benefits. For Supply-Side Solutions, the benefits of avoided pollution, fuel, and other sectors' savings are equivalent to the required sector investment costs. Implementing All Actions would require investing US$30 billion between 2025 and 2050 (about 1.6% of today's GDP each year) and would yield net benefits of US$59 billion.

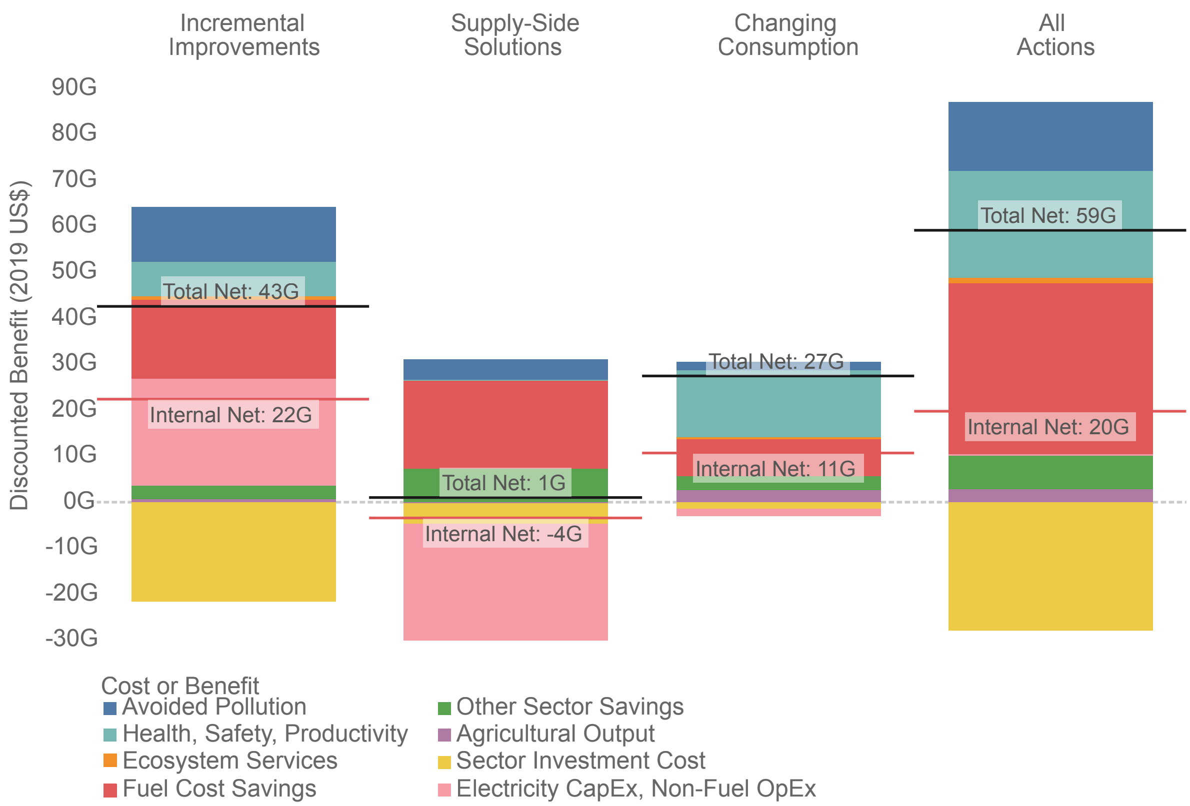


Figure 5.8 Discounted costs and benefits under maximum implementation of transformations by category, Dominican Republic.

Figure 5.9 shows emissions over time and under uncertainty of 1,000 variants of the Critical Actions strategy described in Chapter 4: shifting food-production patterns, altering deforestation, decarbonizing electricity production, and electrifying transport. No variants reach net zero, confirming that while critical actions may be important for decarbonization, a different strategy may be necessary to achieve net-zero targets. Figure 5.10 shows that efforts to decarbonize bring overwhelmingly positive economic returns, even when net zero is not achieved.

We conduct a vulnerability analysis on trajectories with emissions greater than 25 MtCO2e in 2050. (We exclude net benefits in our criteria, as so few cases have negative net benefits). Our vulnerability analysis shows that two groups of factors are at play and differ from regional findings: the increase in industrial production, buildings' energy demand, and freight demand (horizontal axis) associated with development and economic growth; and the level of action taken to counteract emissions by increasing renewable energy use and electrifying transport (vertical axis). The higher the increase in economic activity in buildings, industry, and freight, the more effort needed to fuel shift and reduce emissions in the energy supplied to those sectors.

Figure 5.11's shaded area shows the vulnerable conditions that lead strategies to fail to meet the emissions threshold:

- The increase in activity in these sectors is higher than -10% of nominal assumptions.
- The level of action is collectively less than 70% of the maximum level.

These conditions hold for 78% of all trajectories that miss emissions targets, and 90% of trajectories with these conditions miss emissions targets. In more technical terms, these conditions have a 78% density and 90% coverage.

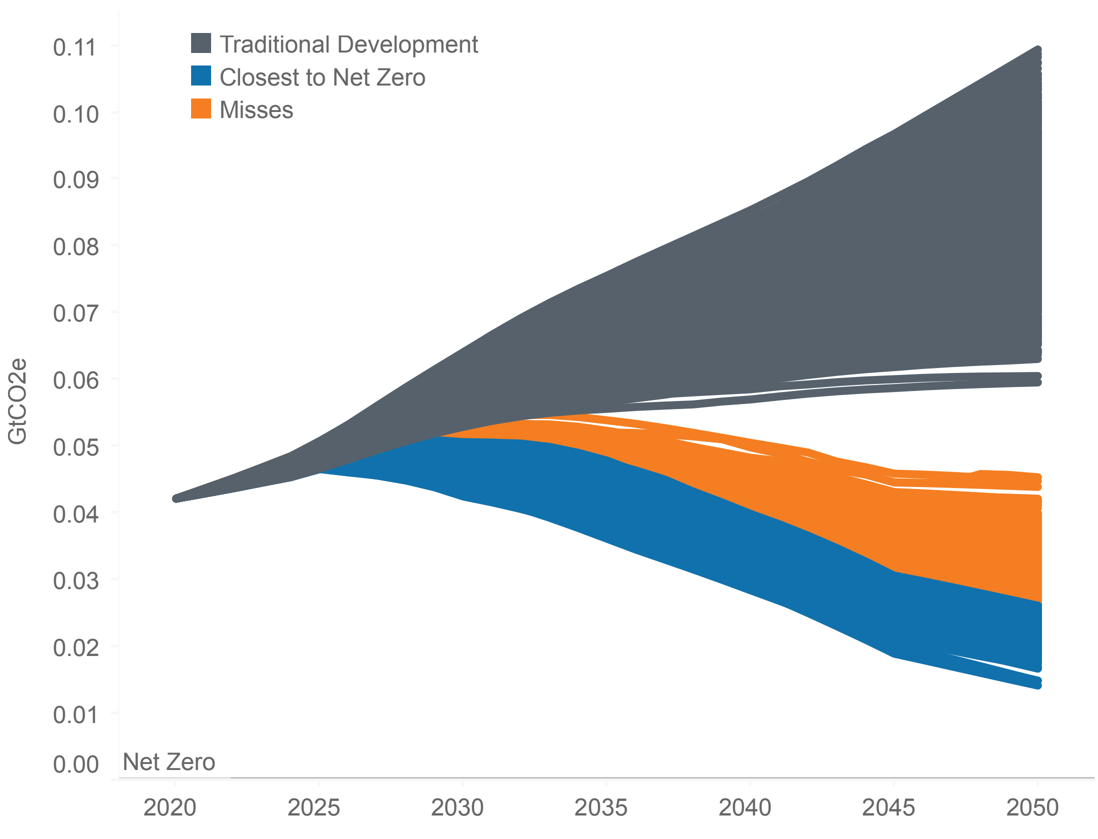


Figure 5.9 Emissions trajectories of 1,000 Critical Action variants amid uncertainty, Dominican Republic.

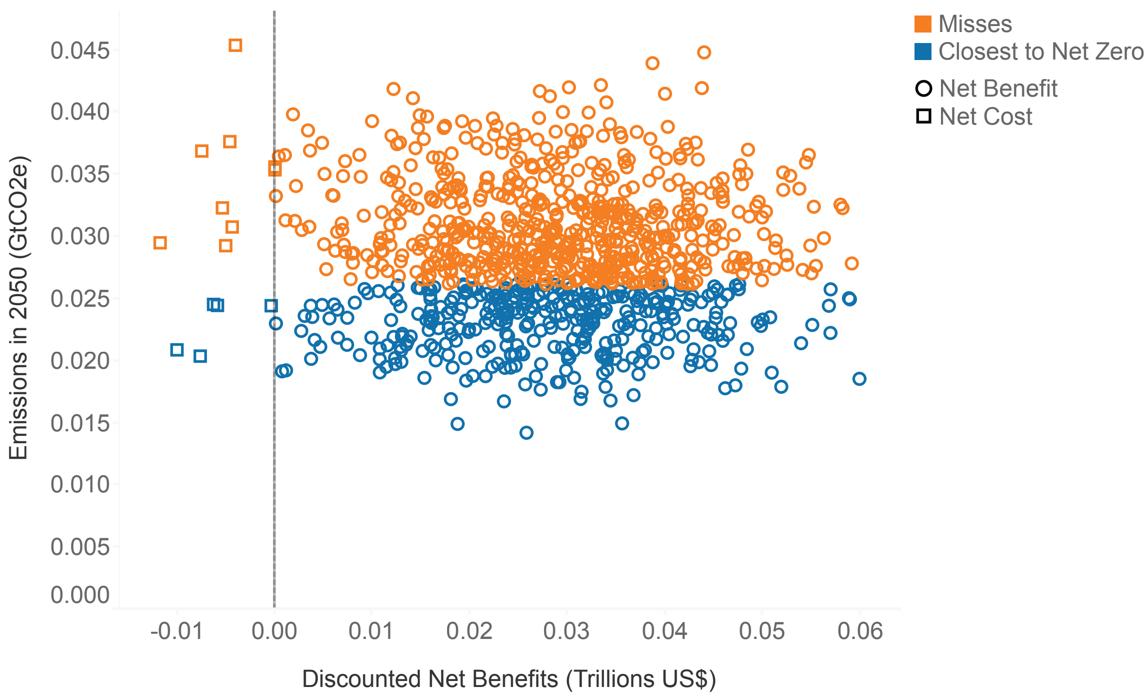


Figure 5.10 Net benefits and net 2050 emissions of Critical Action variants under uncertainty, Dominican Republic.

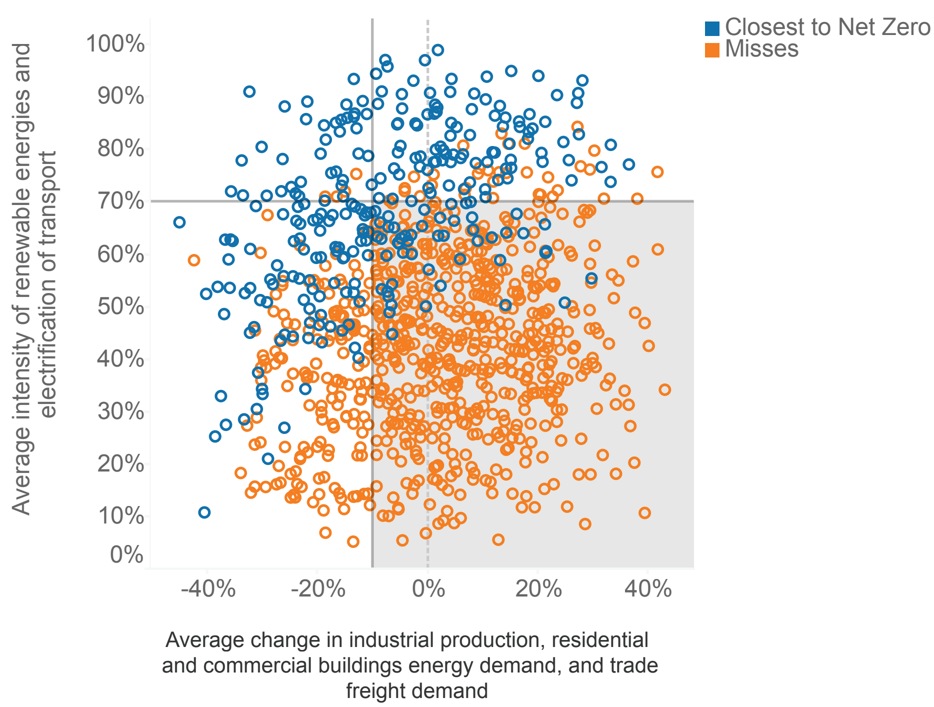


Figure 5.11 Vulnerable conditions of Critical Actions, Dominican Republic.

Mexico

Mexico's economy is tied closely to industries such as manufacturing, oil production, and tourism. Transitioning to low-carbon technologies, promoting renewable energy, and adopting sustainable practices in these sectors can contribute to emissions reduction while fostering economic growth and job creation (Raihan and Tuspekova, 2022). Mexico, in accordance with the Paris Agreement, has implemented policies to promote renewable energy, enhance energy efficiency, and reduce deforestation. However, political delays, policy inconsistencies, and inefficient implementation remain crucial challenges (Ruiz-Rivera et al, 2017).

Environmentally, Mexico's diverse ecosystems and vulnerable communities are affected by climate change impacts such as rising temperatures, water scarcity, and increased frequency of extreme weather events. Adaptation efforts have focused on ecosystem conservation, sustainable land management, and improving resilience in vulnerable areas (Escudero and Mendoza, 2021).

In 2020, Mexico's total emissions reached 670 MtCO2eq, accounting for 1.35% of global emissions. The main drivers of emissions in its NDC BAU scenario include energy, contributing 66% of emissions, followed by agriculture at 16%, waste at 8%, industrial processes at 7%, and land-use change and forestry at almost 3%. Emissions have grown by 18% compared to the baseline year of 2000.

Mexico's NDC states a commitment to reducing GHG emissions by 35% with respect to the BAU scenario and anticipates that 30% will be achieved with national resources and the remaining 5% with international cooperation. Unfortunately, Climate Action Tracker’s overall rating of Mexico's climate policies and commitments is critically insufficient. The country estimates that with current policies it will be able to meet this 35% reduction objective; however, emissions will continue to rise through 2030 (Climate Action Tracker, 2022b).

To mitigate emissions, Mexico’s NDC plans to implement several transformations across sectors. In the electricity and heat sector, the country has established a support scheme for renewables, focused on grid infrastructure development, explored non-renewable low-carbon alternatives, and it has implemented a carbon pricing scheme in industry. In agriculture and forestry, Mexico provides incentives to reduce deforestation, enhance afforestation and reforestation efforts, promotes sustainable agricultural practices, and sets sustainability standards for biomass use. Meanwhile the industry sector supports energy efficiency, incentives to reduce methane emissions from fuel exploration and production, and performance and equipment standards’ implementation. The transport sector focuses on low-emissions transportation, support for energy-efficient vehicles, implementing a tax on fuel and/or emissions, and modal share switch. In the buildings sector, Mexico plans to implement policies to incentivize highly efficient appliances, performance, and equipment standards, building codes, and highly efficient construction.

Mexico's LTS proposes to achieve a 50% reduction in emissions from 2000 levels by 2050. The strategy aligns various sectors such as land-use planning, urban development, sustainable buildings, energy, transport, waste management, and water policies. One review of this LTS identifies weaknesses, including the lack of a net-zero target and the need for more specific mitigation and adaptation actions (Climate Action Tracker, 2022b).

Our analysis complements Mexico's LTS by providing insights on how to combine transformations across the economy to achieve carbon neutrality. Figure 5.12 shows emissions in Mexico under each category of transformations. To the extent that Traditional Development reflects Mexico's NDC BAU, all individual categories of transformations would achieve the 35% emission reduction targets expressed in the NDC. However, no individual category achieves net-zero emissions on its own by 2050. If Mexico decided to reach net-zero emissions by 2050, a more comprehensive approach closer to All Actions probably would be needed.

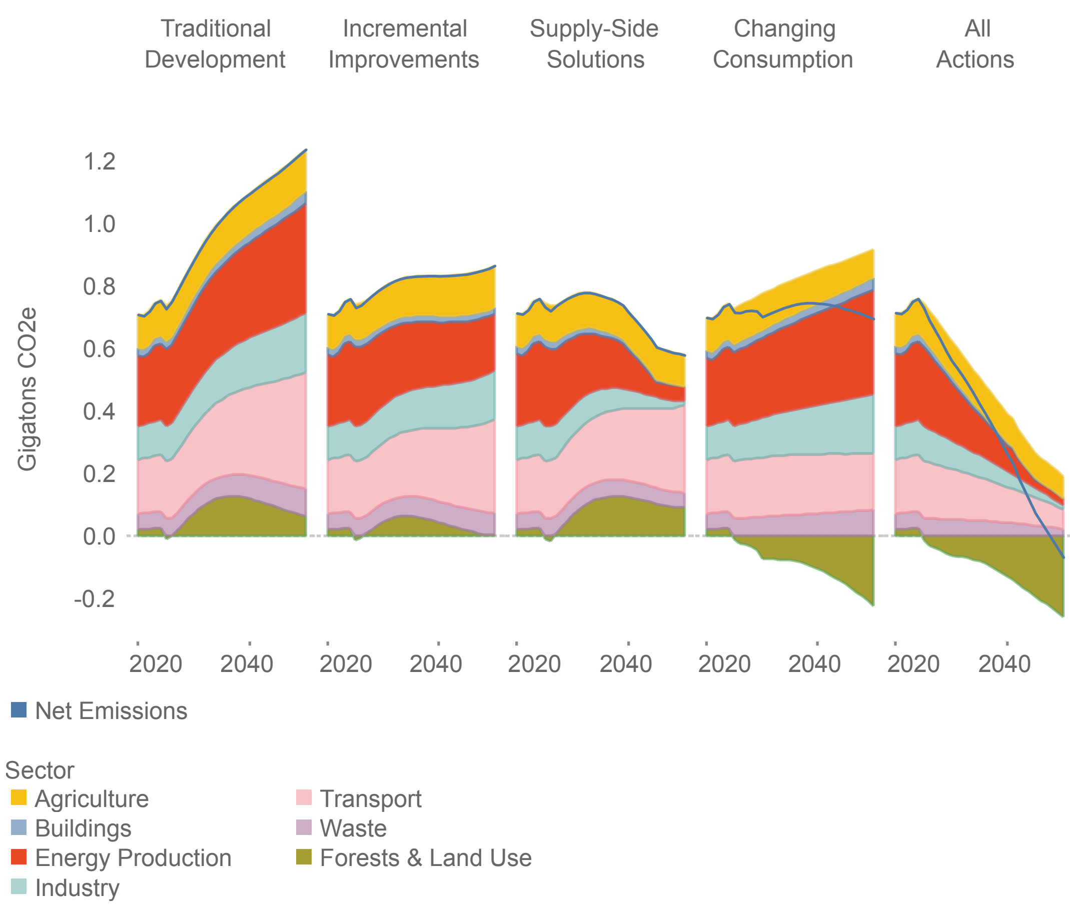


Figure 5.12 Emissions under maximum implementation of transformations by category, Mexico.

Figure 5.13 shows that all categories of transformations result in positive net benefits under nominal assumptions about uncertainties. The most significant benefits are generated in fuel costs savings and health, safety, and productivity benefits. Enabling the transformations in All Actions requires sector-specific investments on the order of US$272 billion from 2025-2050 (approximately 1% of today's GDP per year) and yields net benefits of US$659 billion.

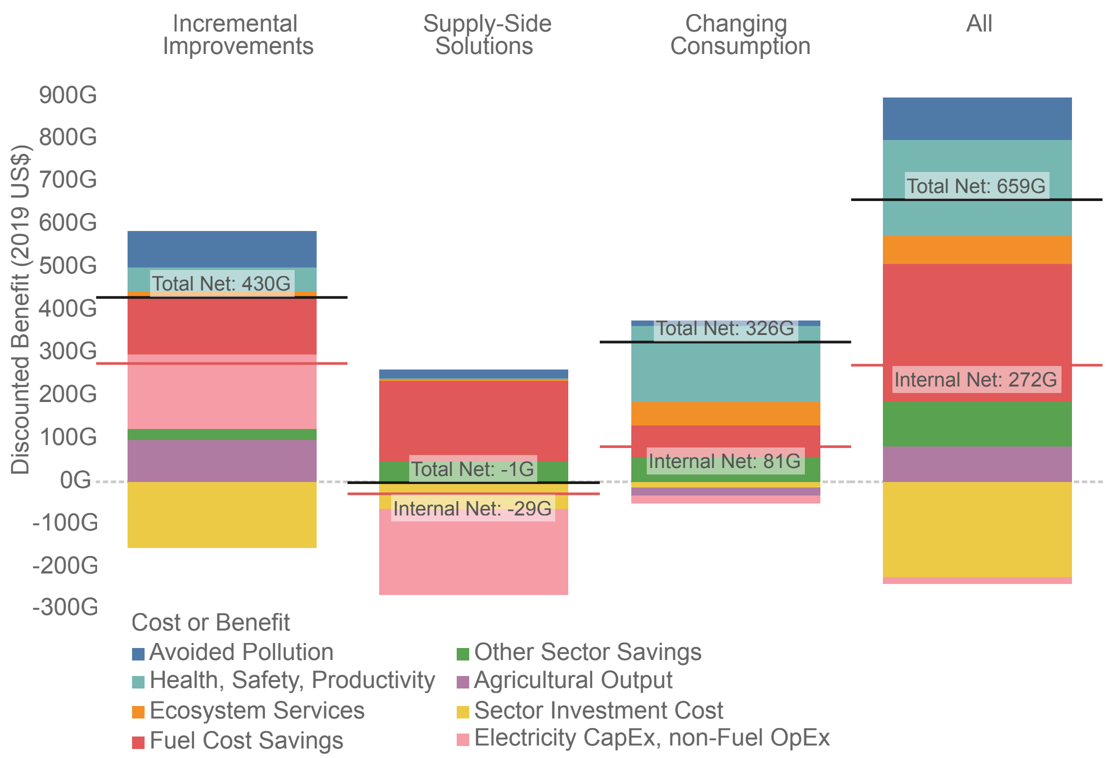


Figure 5.13 Discounted costs and benefits under maximum implementation of transformations by category, Mexico.

Figures 5.14 and 5.15 present results under uncertainty for Mexico and provide country-level versions of our Chapter 4 analysis. Figure 5.14 shows the emissions over time and under uncertainty of 1,000 variants of the Critical Actions strategy described in Chapter 4. Contrary to what happens in Brazil or the region as whole, we scarcely find strategies that robustly reach net-negative emissions.

We set a threshold of 250 MtCO2e by 2050 (down from more than 1,200 MtCo2e in the traditional development trajectory) to identify strategies that reduce emissions the most. Approximately 60% of these variants reduce emissions below the threshold, while 40% of trajectories are above it. Figure 5.15 shows that implementing the four critical actions results in net benefits in the preponderance of variants and conditions we examine.

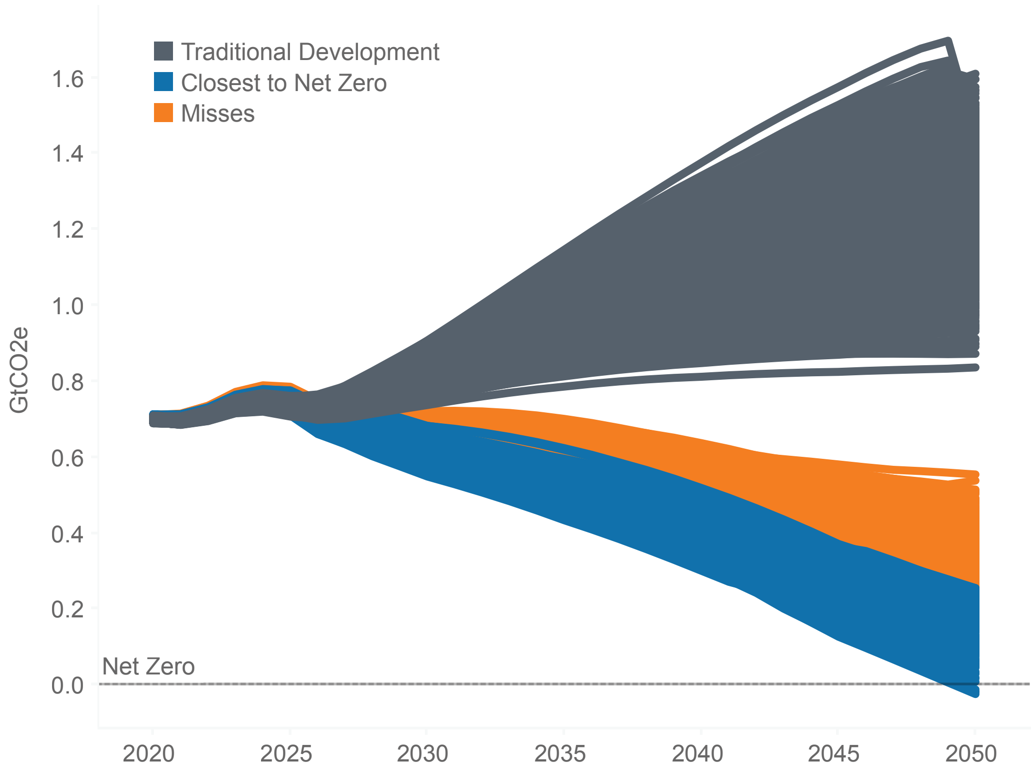


Figure 5.14 Total greenhouse gas emissions' trajectories under uncertainty across strategies, Mexico.

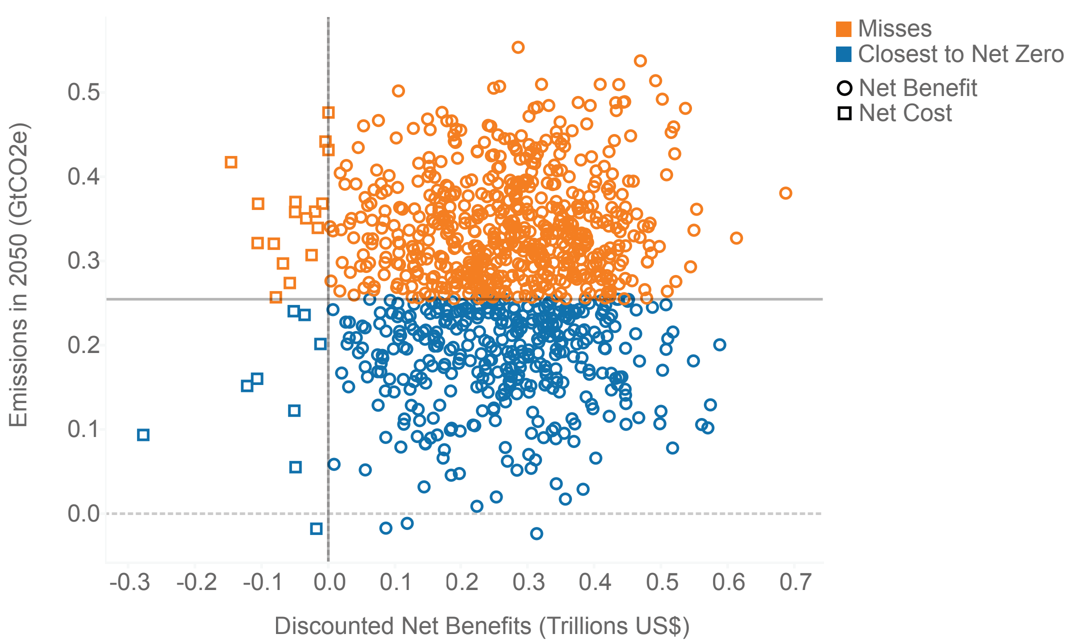


Figure 5.15 Net benefits and net 2050 emissions of Critical Action variants under uncertainty, Mexico.

Figure 5.16 identifies the combinations of conditions that lead Critical Actions to miss net-zero targets in Mexico. Here, a different set of vulnerable conditions emerges than in either the region or in other countries. For Mexico, reductions in the average change in secondary forest sequestration rates (horizontal axis) is a key threat to reaching net zero, although the signal is noisy. Worsening rates require higher intensity of specific key transformations: shifts in production and consumption of food, transitions to renewable energy, and electrifying transport are key determinants of reaching low emissions.

Figure 5.16 highlights a region in the lower left corner where even higher-than-nominal sequestration rates can threaten deep reduction targets if these transformations are implemented at low intensity. Here, 95% of the trajectories in this region fail to reach the emissions threshold, and 53% of the total trajectories that miss it are in this region.

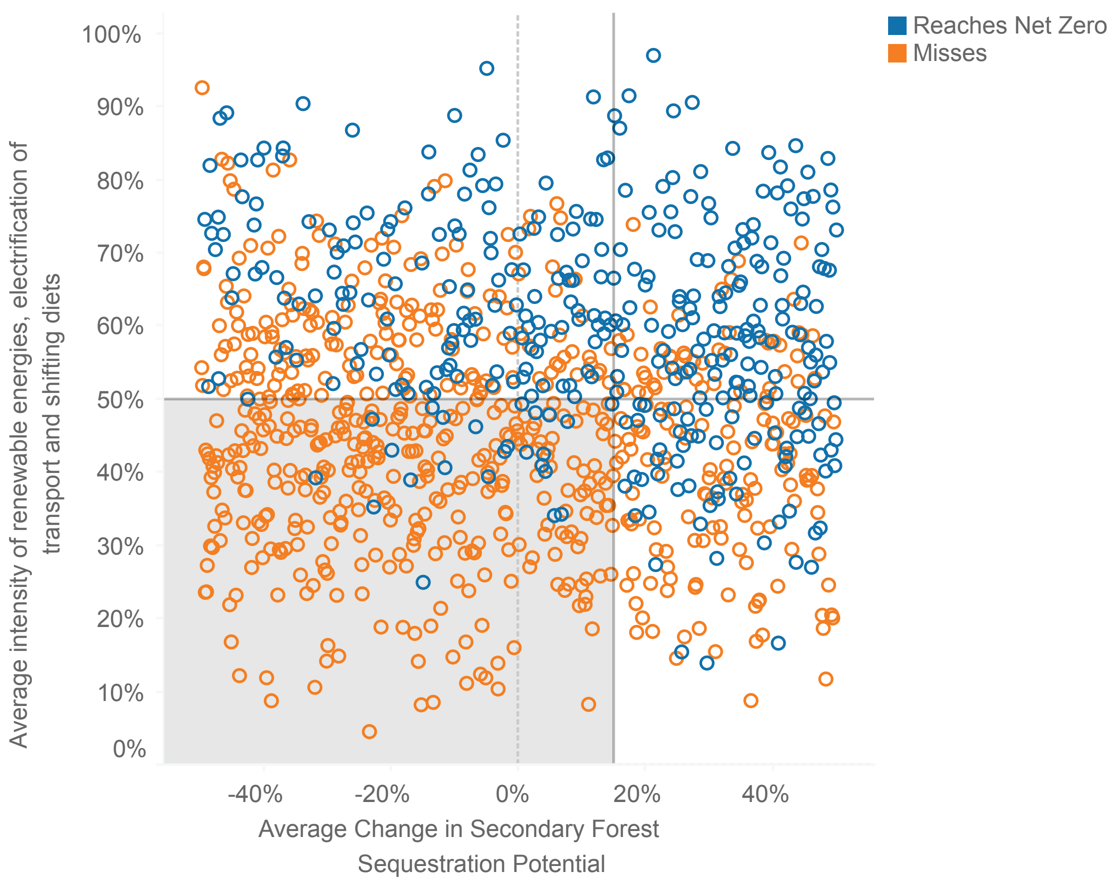


Figure 5.16 Vulnerable conditions of Critical Actions, Mexico.

6 CHAPTER

Discussion and Conclusions

CHAPTER SIX

Discussion and Conclusions

In this study, we analyzed options for Latin America and the Caribbean to robustly meet two development goals: reaching net-zero emissions in alignment with Paris Agreement targets and providing net social, economic, and environmental benefits its people. In this chapter, we review our findings and then discuss the barriers that may need to be overcome to realize those goals, and how this study can inform country-level decarbonization plans to do so. We conclude with a review of limitations that point to next steps.

Key Regional Findings

We find that reaching net-zero emissions by 2050 at the regional level is technically doable and can confer enormous benefits of up to $2.7 trillion to the region, under nominal assumptions and a strategy that takes all available decarbonization actions, compared to development that follows historical patterns.

However, doing everything everywhere all at once is not feasible or necessary. Local particularities means that each country willing to take this path would need to develop its own strategy, based on its priorities and capacity. The uncertainty that surrounds any plan for 2050 means that LTSs and NDCs will need to be updated regularly, based on consultations with stakeholders and considering the latest available data and science.

Notwithstanding these caveats, our analysis of thousands of pathways suggests that any robust regional path to net zero requires significantly implementing at least four key actions:

1. ending deforestation;
2. moderating the increase of, or even decreasing, beef production;
3. fuel shifting transport toward electricity and hydrogen; and
4. producing electricity and hydrogen with renewables.

Ending deforestation is critical to ending land-use conversion, a huge source of regional emissions. Doing so can turn the region's forests from a net source of emissions to a net sink. However, the sink must be large enough to offset residual emissions from the rest of the economy. For this, afforestation is necessary and occurs by shifting food production away from land-intensive foods, particularly beef, and toward other foods.

Transport is one of the region's fastest-increasing sources of emissions, given growing demands for private vehicle travel. Our analysis points to fuel shifts in transport as a key, as it reduces emissions even if shifts in mode and activity were constrained. Fuel shifts in transport and in any other sector abate emissions only to the extent that electricity and hydrogen—the main replacement fuels—are produced with renewables and not fossil fuels. So, cleaning the grid and producing green hydrogen are the fourth critical action in a region-wide decarbonization strategy. A recent study from the IEA suggests the world is pivoting toward electric vehicles and renewables, and the key question is now whether these changes will go fast enough and far enough in the coming years (2023).

To reach net zero, these four actions must be coupled with other changes across the economy, such as increasing building energy efficiency, shifting to heat pumps and public transit, using materials more efficiently, and destroying potent F-gases. Each such transformation has a modest but important impact on regional emissions and may be more or less critical to reducing emissions or unlocking socioeconomic benefits in individual countries.

A regional strategy with these features is still vulnerable to missing net zero when the area of forest needed to offset residual emissions is less than what is available. This can in a future with low livestock productivity and lower forest sequestration rates. Lower livestock productivity increases the amount of area needed for raising livestock, thereby increasing pressures to deforest. Reduced sequestration means that even more existing forests must be protected and more grazeland and feed crops need to be returned to secondary forests. Hedging against these risks requires more intense efforts to end deforestation and reduce livestock production.

Importantly, climate change exacerbates these stressors. Aside from the negative impact of human-induced deforestation, studies show that more intense dry seasons already are placing stress on Amazonian ecosystems and may limit their ability to store carbon (Gatti et al. 2021). Increasing heat stress, declining water availability, pathogens, and declining food availability are among the many potential stressors climate change places on livestock productivity (Rojas-Downing et al., 2017). However, livestock productivity is both an exogenous stressor and an endogenous action. Many techniques that farmers in the region use today are not state-of-the-art, so switching to new agricultural practices that generate higher yields can produce more food on less land. There are also high rates of food losses in the supply chain and food waste at the retail and consumer level, and reducing those losses and wastes would reduce the quantity that needs to be produced on field in the first place. Collectively, these actions reduce the need for more land and preserve the value of forest ecosystem services as a co-benefit (Searchinger et al., 2019; Dumas et al, 2022), while also better meeting the population's dietary and health needs.

Finally, robust decarbonization can confer net benefits of up to \$2 trillion to the region (discounted at 7%), with a median net benefit of \$1 trillion across all the deeply uncertain conditions we explored. These benefits are net of substantial technical investments, which range from \$0.5 to \$1.5 trillion depending upon the future. The largest consistent benefits are in the form of fuel-cost savings; health, productivity, and safety benefits; and ecosystem services.

Barriers to Change

Our analysis suggests that Latin America and the Caribbean can transition to a net-zero economy while enjoying better development, with tremendous gains to social, economic, and environmental outcomes. Given this, it is logical to ask why these transformations are not occurring at a pace that these results might warrant.

A host of regulatory, fiscal, information, and other barriers stand in the way of changes that would lead to better development (Fazekas et al., 2022). For example, the widespread subsidies associated with fossil fuels (International Monetary Fund, 2021) entrench the use of fossil fuels in transport and energy production, even when renewables are the more cost-effective alternative. Poor government oversight and enforcement of existing laws and regulations can weaken protections already in place for forests and create land grabs that accelerate deforestation, yielding near-term gains at the expense of long-term sustainability (Carrero et al., 2022). Even the built environment can pose barriers to change: urban sprawl enabled by historical emphasis on road travel and an absence of bike lanes and walking paths can make it difficult to shift development toward walking, biking, transit, and other sustainable modes (Mouratidis et al., 2019).

Compounding the challenge is that the costs and benefits of transformations are borne differently by various people or actors, and many of the largest costs are internalized while many of the benefits remain external to market forces. As one example, a shift in food production and consumption from livestock to crops, with attendant dietary improvements, could offer massive and widespread benefits in terms of productivity, nutritional benefits and health cost savings, and potentially grocery savings (Springmann et al., 2016). However, it would present costs to the livestock sector in terms of foregone output, which can generate resistance from powerful industries (Merrigan et al., 2015) and challenge poverty reduction efforts in rural areas. Meanwhile the benefits of healthier diets accrue to households and to the healthcare system over the long term. As another example, the costs of expanding transit generally fall to public transit authorities who face a host of budgetary and regulatory constraints. The benefits of transit, in contrast, are reaped not only by transit users, but the general population that may benefit from greater mobility, lower congestion, safer roads, and cleaner air. In sum, costs are often distinct, measurable, and acutely felt by certain groups, while the benefits are diffuse, hard to measure, and broadly experienced by a much larger group.

Timing is another issue. While a transition to net-zero progressively departs, in terms of emissions, from a traditional development trend, changing course often requires large initial investments driven by a long-term vision (Vogt-Schilb et al., 2018). For some transformations, countries may rely on international capital. Many governments in the region, for instance, have designed power generation and public transport markets that let foreign compagnies invest in solar panels, windmills, or electric buses at no or little upfront cost for the countries, being funded instead over time by rate payers. Our research does not investigate such programs' large-scale feasibility, nor their macroeconomic impact.

Developing Long-Term Decarbonization Plans for Individual Countries

Our research shows that Latin America and the Caribbean can reach net-zero emissions in 2050 at a net benefit, and that four key actions form decarbonization strategies' backbone. However, our work also shows that one size does not fit all. Countries differ in many ways, such as whether they produce substantial amounts of fossil fuels and cattle, whether they have room for massive reforestation, and how their built environment shapes efforts to decarbonize transport. This shapes the extent to which regionally important actions make sense nationally.

Each country will have to build its own vision of a low-emission future, make its own plans on how to get there, and diagnose the barriers preventing their countries from capitalizing on a future with a healthier population, healthier environment, and stronger economy. Like a picture coming into focus, the cost and benefit implications of decarbonization will also become clearer at the national level. For instance, while the regional strategy to decarbonize transport leans heavily on fuel shifting, a country with high urban density and a walkable environment might find mode shifting transport and reducing transport demand to be a cheaper and more beneficial alternative.

Countries face a common set of challenges in decarbonization planning (Calfucoy et al., 2022). Their successful long-term decarbonization planning shares some characteristics (Climate Action Tracker, 2019; IDB, 2019; World Bank, 2023; Jaramillo et al., 2023):

- Plans should integrate and jointly address decarbonization and development goals.
- All stakeholders from across the government and private sector should be consulted in framing those goals and in articulating actions, constraints, and uncertainties and providing inputs in the form of data, models, and analytical tools.
- Actions should be described in terms that are meaningful and actionable for those who must implement them.
- Actions should be evaluated in terms of not only their emissions effects, but also their macroeconomic effects, including costs and benefits to sector actors and to society overall.
- The assessments should include all sectors and all greenhouse gases and make transparent and scientifically grounded assessments of how they will be reduced.
- Planning should make uncertainty explicit, identify how plans may be vulnerable to assumptions or changing conditions, and identify actions to make them more robust.

Our approach in this study facilitates decarbonization planning and processes with these characteristics. As Chapter 2 describes, SiSePuede is a toolbox for developing and evaluating decarbonization strategies, and it is embedded in a Robust Decision Making methodology, which provides an interactive stakeholder engagement process, an approach for developing large ensembles of futures to account for uncertainty, and techniques for analyzing hundreds of scenarios to identify and mitigate key vulnerabilities of different strategies.

SiSePuede can be run for any country or region in the world. It integrates and is calibrated against publicly available global datasets from the IEA, IMF, FAO, World Bank, OECD, IDB, and others. Where data are missing or erroneous, SiSePuede imputes data points based on information from countries similar in size, geography, level of development, climate, and other relevant factors. SiSePuede is also open source, scalable, non-proprietary, and publicly available.

Initial country-level analyses such as those shown in this study can be generated quickly and used as a concrete starting place for LTS discussions with the full suite of stakeholders from sector and transverse government actors and the private sector. They can recommend transformations, uncertainties, and metrics designed for country conditions, goals, and constraints. Then analyses can be tailored and iterated upon with country-specific data and models held by national agencies, academics, and others.

Active participation during the LTS formulation stage from those who will need to implement change is essential to inform analysis and increase buy-in: policymakers often do not buy into plans that they had no role in developing (Niet et al., 2021). By engaging early in the process, their insights, expertise, and concerns can shape the plan and ease its delivery. SiSePuede and RDM together provide a flexible process and tools to ensure that stakeholders' priorities and viewpoints are integrated into the analysis, increasing national ownership of resulting plans.

Next Steps

This study has several limitations that also point the way to the next steps. Our analysis focuses primarily on mainstream decarbonization actions. However, various promising innovations merit inclusion in future analyses, such as producing zero emissions steel with hydrogen-based direct reduction iron (Wang et al., 2021) or using wind propulsion for large-scale maritime operations (Chou et al., 2021).

There are also important questions to be answered regarding equity, jobs, and environmental justice. While much research shows that actions to reduce emissions in Latin America and the Caribbean also could create jobs, the flow of job creation and loss in different sectors is an important metric for assessing distributional impacts of a decarbonization strategy, and for facilitating plan support and success (Saget et al., 2020; Feng et al., 2023; Alfonso et al., 2023).

While our study answers many questions about decarbonization strategies for Latin America and the Caribbean, it also raises new questions. Smart climate financing will be important for enabling the many technical changes required, even when those changes confer savings in the longer term. A future use of SiSePuede is to examine the effects of decarbonization on tax expenditures and revenues: How quickly will energy savings reduce fossil fuel subsidies? What could replace gasoline and diesel taxes once car fleets go electric? Which economic activities stand to decline and what could replace them? How will lower health costs reflect in increased productivity, economic activity, and profit taxes? SiSePuede can help shed light on these questions, which will no doubt be important to finance ministries as their countries embark on paths to decarbonize.

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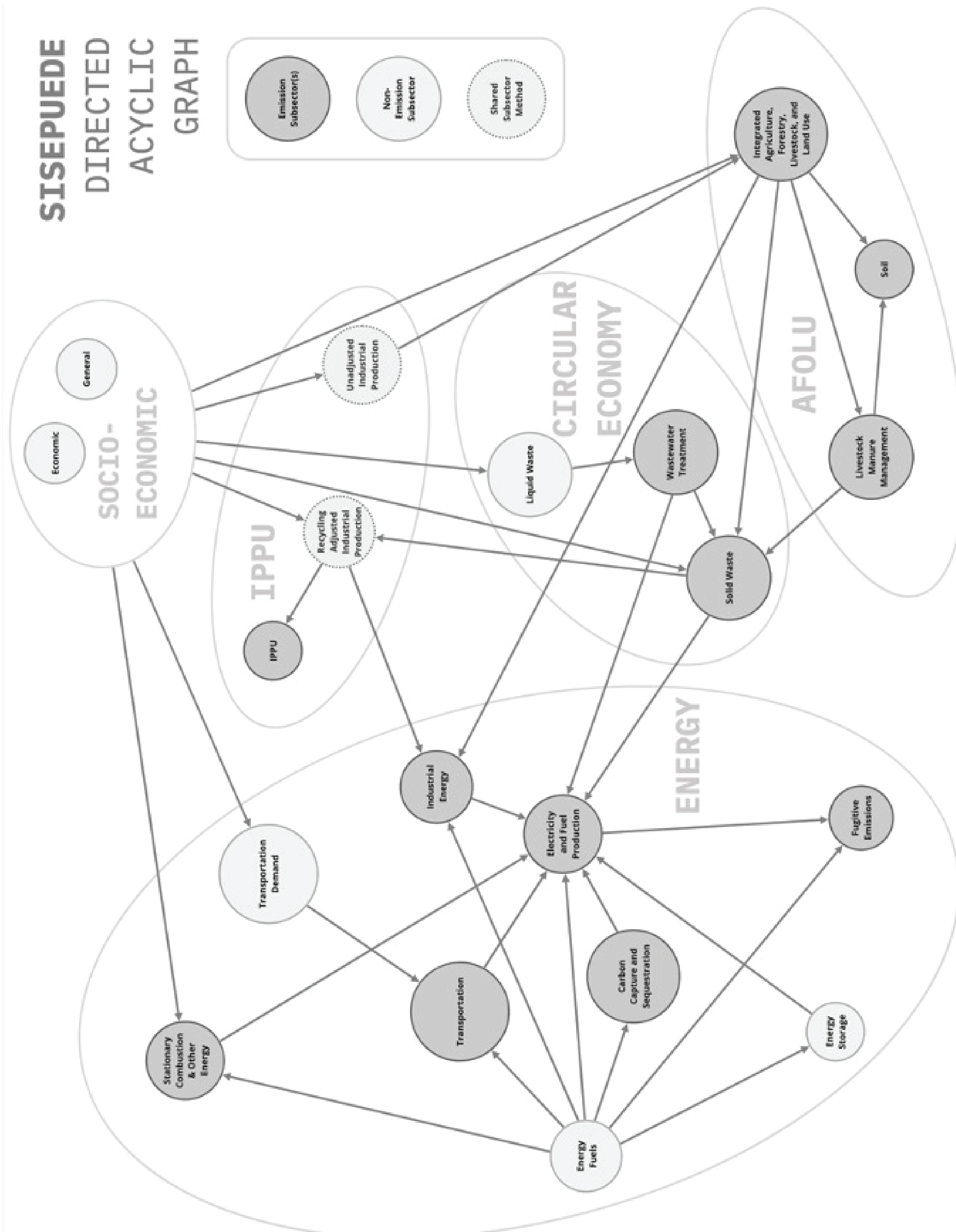
The Benefits and Costs of
Reaching Net Zero Emissions in
Latin America and the Caribbean

Technical Appendices

SiSePuede Analytical Framework

SiSePuede is an open source, robust modeling framework for emission accounting based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006) and subsequent 2019 Revision (Buendia et al., 2019). The framework, which is written in Python and Julia, includes several analytical components used to facilitate exploratory modeling of sectoral transformations and their effects on demands and emissions, including an integrated multisector emissions model; an uncertainty quantification system based on Latin Hypercube sampling; and scalable database generation and scenario management.

The SiSePuede integrated emission model includes four emission accounting sectors—Agriculture, Forestry, and Land Use (AFOLU), Circular Economy (waste management), Energy, and Industrial Processes and Product Use (IPPU)—in addition to a shared driver sector, the Socioeconomic sector. Each sector is divided into multiple accounting subsectors, which include refined emissions that correspond to different IPCC emission accounting codes.



Note: Arrows indicate data flows between submodules in SiSePuede.

Figure TA1. Technical modeling framework for SiSePuede.

AFOLU models six subsectors: agriculture, forestry, land use, livestock, livestock manure management, and soil. These six sectors are based on volume 4 of the IPCC guidance for national greenhouse gas (GHG) inventories and include extensive treatment of key emission phenomena, including crop residues and burning, forest sequestration, land-use conversion and use, enteric fermentation, manure management, fertilizer application, and soil carbon sequestration in mineral and organic soils. The land-use subsector models land-use transitions directly as a discrete Markov chain, allowing for a detailed accounting of emissions stemming from land-use conversion. Furthermore, it includes a novel mechanism, known as the land-use reallocation factor, to model land-use changes that occur in response to changing demands for livestock and crops and reconcile these demands with exogenous expectations about land-use changes. Demands for crops and livestock production generally are based on historical production, imports, and exports and are responsive to changes in trade and gross domestic product (GDP), GDP/capita, and population.

Circular Economy includes three subsectors: liquid waste, solid waste, and wastewater treatment. These three sectors are derived from volume 5 of the IPCC guidance for national greenhouse gas inventories and include detailed emissions estimates from wastewater treatment and management pathways, solid waste treatment pathways (including a first-order decay model of landfilled waste), and recycling, which then gets passed to the industrial production model to estimate changes for producing virgin materials. Waste generation primarily is driven by per-person generation factors, which are responsive to changes in GDP, GDP/capita, and population and other sectors, including livestock manure management and supply-chain loss in agriculture.

Energy includes nine model subsectors, six of which are emission subsectors: carbon capture and sequestration, energy fuels, energy storage, energy technology (fuel production, including electricity), fugitive emissions, industrial energy, stationary combustion and other energy, transportation, and transportation demands. These sectors include estimates of energy demands, emissions from fuel combustion, and fuel consumption using information from other sectors as input, including GDP, industrial production, number of households, and more. All energy demands for fuel production–including electricity, petroleum refinement, coal mining, natural gas production and processing, and hydrogen production–are passed to a least-cost optimization model developed in Julia NEMO (SEI, 2023) to estimate emissions from energy and fuel production.

IPPU is based on volume 3 of the IPCC Guidance for National Greenhouse Gas (GHG) Inventories. The IPPU sector includes estimates of emissions from a range of gases released during industrial production, including a by-gas accounting of several fluorinated compounds (including HFCs, PFCs, and other FCs) derived from other bottom-up estimates in the literature. Industrial production primarily is driven by domestic demands and trade and is responsive to changes in GDP, GDP/capita, and recycling (for applicable industries). In the SiSePuede Directed Acyclic Graph (DAG), industrial production functions are stored in IPPU and accessed in both Circular Economy and AFOLU.

Finally, the Socioeconomic sector includes two subsectors: general and economy. These two subsectors are used to manage exogenously defined drivers that are shared across emission models, such as GDP and population. The Socioeconomic subsector includes some simple calculations–such as GDP/capita, the number of households, and various rates of growth in drivers—but does not account for any emissions.

SiSePuede accounts for gas-specific emissions across several greenhouse gases, including methane, carbon dioxide, nitrous oxide (CH_4, CO_2, N_2O), and numerous PFCs, HFCs, and other fluorinated compounds. Accounting can be set to reflect different global warming potentials (GWP), including 20-, 100-, and 500- year GWPs.

SiSePuede Calibration

Figure 2 describes the calibration process for SiSePuede and how this interrelates with simulation runs. In the first step, two sets of input parameters are defined: a) parameters that have observed historical data and b) parameters that need to be estimated through calibration. For the latter, historical emissions are the response of interest used in the calibration process. The calibration process searches for a set of calibrated parameters that minimize the error between the model-simulated emissions and observed emissions. This process occurs separately for each sector.

A minimization problem is defined where the objective function to be minimized is the mean square error between the simulated and observed series of carbon dioxide equivalent (CO_2e) emissions of each sector.

$$\min \frac{1}{T}\sum_{t}^{T}\left(CO_2\text{e emissions}_{s,t} - CO_2\text{e }\widehat{\text{emissions}}_{s,t}\right)^2$$

$$\text{s.t}$$

$$x_1,\ x_2, \ldots, x_n \in (0, c), \quad where\ c \in \mathrm{R}$$

where

- $CO_2\text{e }\widehat{\text{emissions}}_{s,t}$ is the estimated CO_2e SiSePuede emissions in sector s at time t;
- $CO_2\text{e emissions}_{s,t}$ is the historical series (we used climate watch data for this study, but other sources can also be used); and

vector x_1, x_2, …, x_n is a set of scaling factors that multiply a set of input variables to be calibrated. These calibrated parameters include factors for which we do not have data or for which we require a more reliable baseline.

Once a calibrated set of input parameters is estimated for historical conditions, this set is then projected in the future varying as two groups of parameters: a) parameters that describe how transformations will evolve over time and b) parameters that describe how exogenous trends will evolve in the future. Then this database is used as an input database for SiSePuede. For each input database, a SiSePuede simulation run will result in projected emissions, benefits, and costs over time.

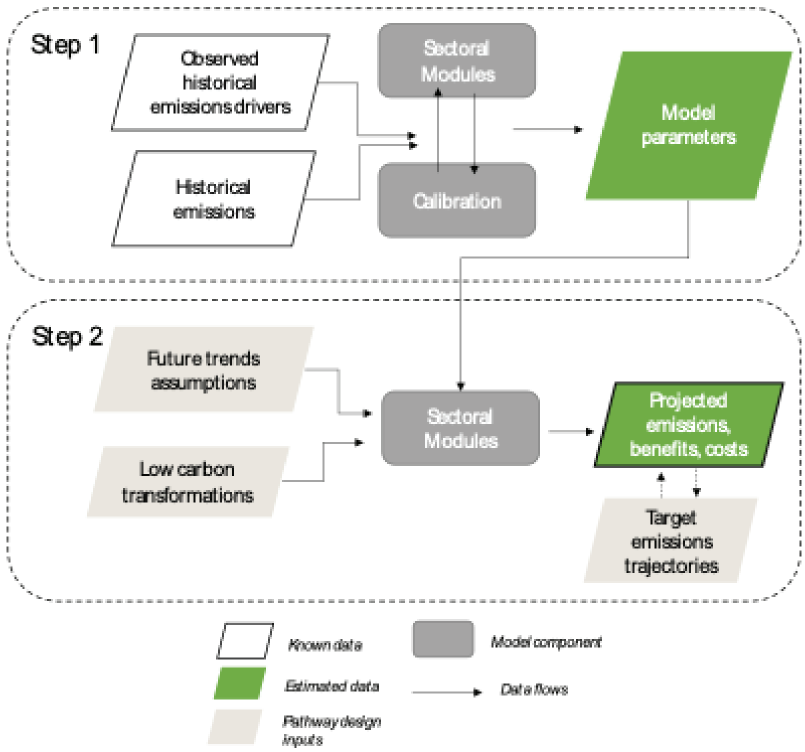


Figure TA2. Calibration workflow.

The minimization problem is solved using two bio-inspired algorithms:

- Genetic binary (Sadri et al., 2006); and
- Particle Swarm Optimization (PSO) (Wang et al., 2018).

Genetic algorithms balance exploitation and exploration. This balance is achieved by the individuals of the population's selection mechanism based on their aptitude and the genetic crossover operator. The PSO algorithm engages a group of individuals (particles) from different points in the search space, each guided by the collective action's natural life principles to find an optimal solution.

SiSePuede calibration occurs via cross-validation such that the process is repeated randomly selecting subsets of the variation in the response of interest (i.e., sectorial emissions). Figures 3 and 4 exemplify the calibration performance for all countries considered in this study across two sectors: AFOLU and Liquid Waste. The dark blue line indicates known historical data of the response of interest (i.e., sector emissions), while the light-blue lines display simulated results for different instances of cross validation. As these figures show, a successful calibration process is on which different calibration instances revolve around the historical time series of the response of interest.

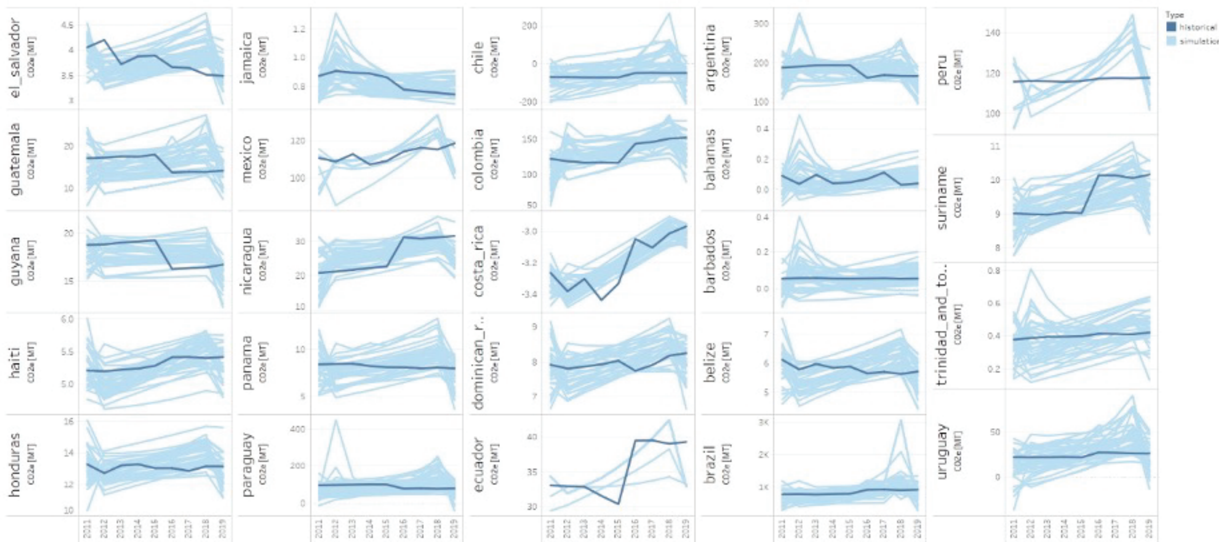


Figure TA3. Agriculture, Forestry, and Land Use (AFOLU) calibration.

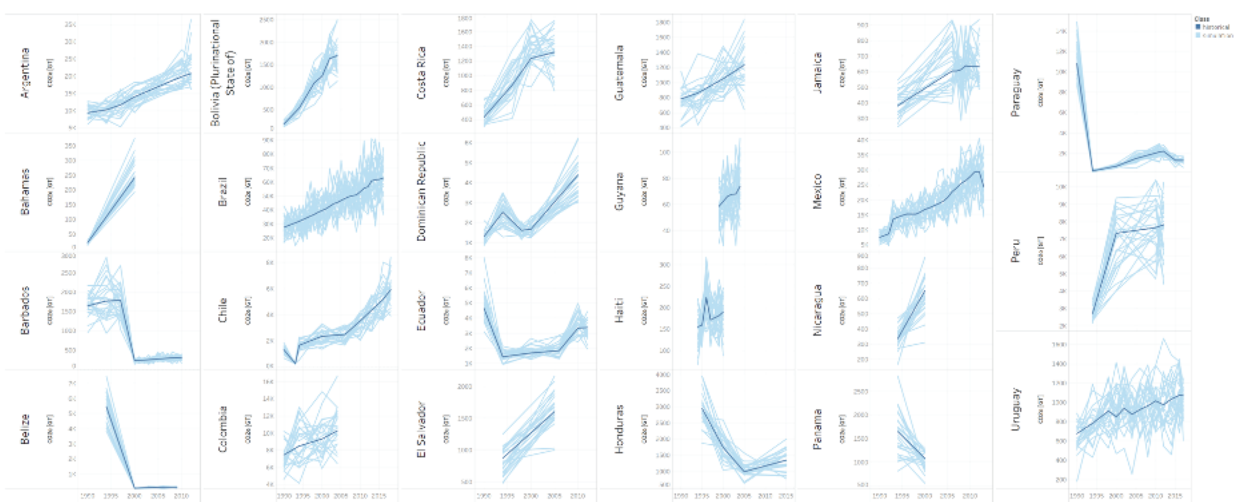


Figure TA4. Liquid waste calibration.

Each instance of cross-validation is associated with a specific database of input parameters, such that, after cross-validation, for each calibration parameter, point-estimates that aggregate the behavior across the cross-validation set can be estimated. Figure 5 shows this exercise for a subset of calibration parameters. Note that since this process is carried out for each country used in the simulation, it is possible to estimate and compare mean and variance variation across countries.

Once simulations are executed, it is possible to run the model using the mean values of cross-validation as input parameters to the model. However, because using the mean value of cross-validation will result in an initial condition different to the one observed—for example, in the last available data point of historical data—it is possible to rescale the simulation data such that the simulation's intertemporal variation reflects the initial conditions of a particular emissions trajectory more accurately.

Nation	Avg. Avgmass Lvst Animal Buffalo Kg	Variance of Avgmass Lvst Animal Buffalo Kg	Avg. Avgmass Lvst Animal Cattle Dairy Kg	Variance of Avgmass Lvst Animal Cattle Dairy Kg	Avg. Avgmass Lvst Animal Cattle Nondairy Kg	Variance of Avgmass Lvst Animal Cattle Nondairy Kg	Avg. Avgmass Lvst Animal Chickens Kg	Variance of Avgmass Lvst Animal Chickens Kg	Avg. Avgmass Lvst Animal Goats Kg	Variance of Avgmass Lvst Animal Goats Kg	Avg. Avgmass Lvst Animal Mules Kg	Variance of Avgmass Lvst Animal Mules Kg
argentina	1.023	0.008	1.023	0.008	1.023	0.008	1.023	0.008	1.023	0.008	1.023	0.008
bahamas	0.970	0.002	0.970	0.002	0.970	0.002	0.970	0.002	0.970	0.002	0.970	0.002
barbados	1.071	0.001	1.071	0.001	1.071	0.001	1.071	0.001	1.071	0.001	1.071	0.001
belize	0.978	0.001	0.978	0.001	0.978	0.001	0.978	0.001	0.978	0.001	0.978	0.001
bolivia	0.957	0.002	0.957	0.002	0.957	0.002	0.957	0.002	0.957	0.002	0.957	0.002
brazil	1.009	0.005	1.009	0.005	1.009	0.005	1.009	0.005	1.009	0.005	1.009	0.005
chile	0.991	0.007	0.991	0.007	0.991	0.007	0.991	0.007	0.991	0.007	0.991	0.007
colombia	1.006	0.002	1.006	0.002	1.006	0.002	1.006	0.002	1.006	0.002	1.006	0.002
costa_rica	1.014	0.004	1.014	0.004	1.014	0.004	1.014	0.004	1.014	0.004	1.014	0.004
dominican_republic	1.012	0.005	1.012	0.005	1.012	0.005	1.012	0.005	1.012	0.005	1.012	0.005
ecuador	0.960	0.004	0.960	0.004	0.960	0.004	0.960	0.004	0.960	0.004	0.960	0.004
el_salvador	1.017	0.003	1.017	0.003	1.017	0.003	1.017	0.003	1.017	0.003	1.017	0.003
guatemala	1.084	0.006	1.084	0.006	1.084	0.006	1.084	0.006	1.084	0.006	1.084	0.006
guyana	0.973	0.002	0.973	0.002	0.973	0.002	0.973	0.002	0.973	0.002	0.973	0.002
haiti	1.010	0.003	1.010	0.003	1.010	0.003	1.010	0.003	1.010	0.003	1.010	0.003
honduras	1.041	0.004	1.041	0.004	1.041	0.004	1.041	0.004	1.041	0.004	1.041	0.004
jamaica	1.035	0.003	1.035	0.003	1.035	0.003	1.035	0.003	1.035	0.003	1.035	0.003
mexico	0.999	0.005	0.999	0.005	0.999	0.005	0.999	0.005	0.999	0.005	0.999	0.005
nicaragua	1.028	0.001	1.028	0.001	1.028	0.001	1.028	0.001	1.028	0.001	1.028	0.001
panama	0.996	0.006	0.996	0.006	0.996	0.006	0.996	0.006	0.996	0.006	0.996	0.006
paraguay	0.961	0.002	0.961	0.002	0.961	0.002	0.961	0.002	0.961	0.002	0.961	0.002
peru	1.011	0.007	1.011	0.007	1.011	0.007	1.011	0.007	1.011	0.007	1.011	0.007
suriname	0.980	0.003	0.980	0.003	0.980	0.003	0.980	0.003	0.980	0.003	0.980	0.003
trinidad_and_tobago	1.028	0.006	1.028	0.006	1.028	0.006	1.028	0.006	1.028	0.006	1.028	0.006
uruguay	0.993	0.003	0.993	0.003	0.993	0.003	0.993	0.003	0.993	0.003	0.993	0.003
venezuela	0.982	0.007	0.982	0.007	0.982	0.007	0.982	0.007	0.982	0.007	0.982	0.007

Nation	Avg. Avgmass Lvst Animal Horses Kg	Variance of Avgmass Lvst Animal Horses Kg	Avg. Ef Agrc Biomass Fruits Tonne Co2 Ha	Variance of Ef Agrc Biomass Fruits Tonne Co2 Ha	Avg. Ef Agrc Biomass Burning N2O	Variance of Ef Agrc Biomass Burning N2O	Avg. Ef Agrc Biomass Bevs And Spices Tonne Co2 Ha	Avg. Ef Agrc Anaerobicdom Rice Kg Ch4 Ha	Variance of Ef Agrc Anaerobicdom Rice Kg Ch4 Ha	Avg. Avgmass Lvst Animal Sheep Kg	Avg. Avgmass Lvst Animal Pigs Kg
argentina	1.023	0.008	0.985	0.011	0.944	0.018	0.967	1.012	0.025	1.023	1.023
bahamas	0.970	0.002	1.120	0.003	1.036	0.013	0.976	1.379	0.060	0.970	0.970
barbados	1.071	0.001	0.928	0.008	1.015	0.024	0.952	1.054	0.074	1.071	1.071
belize	0.978	0.001	1.003	0.007	1.024	0.011	0.948	0.913	0.038	0.978	0.978
bolivia	0.957	0.002	0.944	0.009	0.982	0.011	1.012	1.058	0.058	0.957	0.957
brazil	1.009	0.005	1.017	0.022	1.107	0.004	0.974	1.024	0.142	1.009	1.009
chile	0.991	0.007	0.981	0.025	1.047	0.019	0.934	1.088	0.097	0.991	0.991
colombia	1.006	0.002	0.968	0.016	0.980	0.007	0.968	1.110	0.117	1.006	1.006
costa_rica	1.014	0.004	1.011	0.009	0.861	0.017	0.843	1.106	0.089	1.014	1.014
dominican_republic	1.012	0.005	1.010	0.015	0.890	0.008	1.080	1.620	0.008	1.012	1.012
ecuador	0.960	0.004	1.001	0.013	1.043	0.007	1.101	1.040	0.059	0.960	0.960
el_salvador	1.017	0.003	1.020	0.034	1.084	0.007	0.982	1.096	0.090	1.017	1.017
guatemala	1.084	0.006	0.988	0.013	0.927	0.017	0.946	1.028	0.069	1.084	1.084
guyana	0.973	0.002	1.046	0.022	1.038	0.014	0.930	1.297	0.174	0.973	0.973
haiti	1.010	0.003	1.036	0.014	1.055	0.019	0.974	1.201	0.018	1.010	1.010
honduras	1.041	0.004	1.002	0.006	0.961	0.013	0.926	1.346	0.164	1.041	1.041
jamaica	1.035	0.003	1.008	0.015	1.039	0.008	1.017	1.037	0.039	1.035	1.035
mexico	0.999	0.005	0.953	0.016	1.095	0.016	1.062	1.210	0.114	0.999	0.999
nicaragua	1.028	0.001	0.933	0.009	1.042	0.012	0.966	1.057	0.109	1.028	1.028
panama	0.996	0.006	1.000	0.019	1.018	0.026	1.048	1.006	0.066	0.996	0.996
paraguay	0.961	0.002	0.989	0.015	1.004	0.029	0.968	1.130	0.099	0.961	0.961
peru	1.011	0.007	1.053	0.023	0.931	0.016	1.045	1.071	0.111	1.011	1.011
suriname	0.980	0.003	0.990	0.017	1.126	0.009	0.983	1.217	0.131	0.980	0.980
trinidad_and_tobago	1.028	0.006	0.999	0.004	0.997	0.007	1.018	1.020	0.068	1.028	1.028
uruguay	0.993	0.003	0.936	0.017	0.877	0.001	1.034	1.244	0.080	0.993	0.993
venezuela	0.982	0.007	1.003	0.008	0.972	0.028	1.012	1.208	0.154	0.982	0.982

Figure 5. Point estimate and standard deviation of estimated parameters.

Contrast with Other Modeling Approaches

SiSePuede takes a unique, sectoral transformation-centered approach to modeling emissions, contrasting with other common modeling techniques. For example, integrated assessment models (IAMs) are used to model biophysical emissions processes as driven by anthropogenic activity, and some include biophysical feedback. In accordance with IPCC inventory guidelines, SiSePuede bases emissions on emission factors that respond to drivers, though certain phenomena—such as methane emissions from anaerobic decomposition in solid waste landfills, which are modeled using a first-order decay model—include biophysical treatments. Biophysical feedback such as impacts of climate change on hydropower production or crop yield factors are treated as uncertain factors that can be explored within reasonable expected ranges.

Given their computational requirements, IAMs require significant computational power for evaluating portfolios of specific policy transformations and sectoral actions because they are often massive and chaotic, requiring extensive time and computational power to assess a single scenario. The relative numerical simplicity of calculations in SiSePuede and the integrated uncertainty framework allow extensive exploration over uncertainties at highly refined levels, facilitating a robust exploration of strategies. SiSePuede endogenizes uncertainty exploration through Latin Hypercube sampling across exogenous uncertainties and intervention effects, a robust data management system, and scalable computational architecture.

SiSePuede also differs significantly from general- and partial-equilibrium models (PEMs and GEMs). Equilibrium models, which endogenize economic outcomes based on exogenous factors such as prices, are another class of models paired with emission factors to estimate how changes in economic activity may drive emissions changes. However, while GEMs advantageously endogenize demands, they can be extremely difficult to calibrate and solve, especially when exploring large parameter and variable spaces, such as supplies and demands for a refined range of products and services across an entire economy. While SiSePuede does not endogenize supplies and demands through market-clearing conditions, it does facilitate exploration over combinations of prices and behaviors that then can be used to identify policy-relevant scenarios across a range of potential futures.

SiSePuede relies on some key assumptions to deal with potential conflicts that may arise from the use of exogenous variable specifications. Most notably, consider the interaction between agriculture and livestock demands and land use. Demand for crops and animal products are modeled endogenously as a combination of historical demand, import fractions, exogenous exports, red meat consumption behavior, changes to productivity, and elasticities to GDP and GDP/capita (used as an endogenous proxy for average income). Land-use transition probabilities also are defined exogenously in the model, representing expectations for region's future land use. Because cattle and cropland drive extensive shifts in land use, these two trajectories can come into conflict if left unresolved.

To reconcile differences in exogenous specifications of demands for land use, SiSePuede introduces a novel parameter referred to as the land-use reallocation factor. The land-use reallocation factor represents the fraction of land needed (or not needed) for crop and livestock production that is adjusted to ensure land use meets demands. In the initial state, demands for crop and livestock production are combined with land-use prevalence to determine a baseline carrying capacity for grazing livestock. As livestock stock demands change, baseline carrying capacities—which can be scaled up or down to represent changes to productivity—are used to estimate land-use requirements needed to fulfill these domestic production demands. If demands for crops or livestock increase, then more land is required. Alternatively, if livestock demands decrease or carrying capacities increase, more land may be available for restoration or reforestation, critical components of decarbonization pathways.

The land-use reallocation factor determines the fraction of land-use deficit, or how much is needed less how much is specified, that is reallocated away from exogenous transition trajectories to meet demands for grazeland. Using this value, columns on the land-use transition matrix1 are scaled accordingly to ensure transitions into grazeland meet demands. If the factor is 0, then no land use is reallocated away from exogenous land-use transition trajectories, and all livestock demands that exceed carrying capacity are used to adjust exports, while deficits are met with new imports. If the factor is set to 1, then transition probabilities are scaled to ensure that pastures and croplands will meet production demands precisely. Any value in-between is the fraction of land that is moved away from exogenous specification through column scaling, representing a mix between the two approaches.

Accessing SiSePuede

The complete documentation for SiSePuede—including the installation instructions, detailed mathematical specifications, variable information, and schema—are available at https://sisepuede.readthedocs.io. SiSePuede is written in Python and Julia. NemoMod was developed by Stockholm Environmental Institute and is available under the Apache 2.0 License from https://github.com/sei-international/NemoMod.jl. Python and Julia model code are available for use under the GNU Public License at https://github.com/jcsyme/sisepuede, and a precompiled Docker image can be used to run the latest version of the model, available at https://hub.docker.com/r/jsyme816/sisepuede.

[1] SiSePuede treats the land-use transition matrix as a row-stochastic Markov chain.

Appendix A. Agriculture

The agricultural sector consists of crop and livestock production. The demand for crops and livestock is driven by population and GDP growth. Crops and livestock are distinguished by type according to FAO categories. We discuss crop and livestock production separately.

Crops

Crop historical data and projections

Emissions in crops are produced by the release of soil carbon in tillage, fertilizer applications and crop liming, crop burning, organic material's decomposition, and methane emissions from paddy rice fields. Fossil fuels burned by on-farm equipment are accounted for in industrial energy, where demands for energy are driven by agriculture and livestock production. Agriculture emissions are a product of the data in Table A.1.

Table A.1 Data and methods

Data	Method for historical data	Method for projections
Quantity of agricultural demand per agricultural category per country	Production volumes are estimated using the United Nations Food and Agriculture Organization (FAO) Production database (FAO, 2023c) Exports and import volumes are estimated using the FAO Trade database (FAO, 2023d)	We use the US Department of Agriculture (USDA) Commodity and Food Elasticities Database for estimating crop demand income elasticities by country. We combine these elasticities with gross domestic product (GDP) per capita projections to estimate baseline demand.
Yield (land area and fertilizer and other inputs needed per unit of crop output)	Yields and area harvested figures are estimated using FAO Production database (FAO, 2023c) Fertilizer use is estimated based on data from the International Fertilizer Association (IFA, 2023)	Yields are projected to grow 1.6% per year from 2020 to 2050. Areas and volumes of production, exports, and imports are determined endogenously in the simulation.
Emissions intensity (emissions per ton of crop produced)	Fertilizer use emission factors based on Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories, Table 11.1, volume 4 (IPPC, 2019)	Factors are assumed to remain constant under baseline conditions (i.e., no transformations).
Total emissions	Historical sector emissions are used in the calibration process. Emissions data for calibration are obtained from Climate Watch (2022)	Production of different crops and technologies and practices used in agriculture determine emissions levels.

Note: To map SiSePuede crops categories to FAO crops categories, we developed data crosswalks that allow us to aggregate statistical information from FAO to be used as input in SiSePuede.

Transforming crops

While many individual practices can address emissions from crop production, we broadly group practices into three transformations: improving the use of fertilizers, expanding conservation agriculture, and improving rice management, consistent with strategies from the Environmental Protection Agency or EPA (2019) and McKinsey (2019 & 2020) that are non-duplicative and have significant applicability in Latin America and the Carribean (LAC). The fourth, discussed in the section "Crosscutting Changes in Agriculture" is to increase overall sector productivity, in ways that do not specifically target emissions.

Table A.2 shows transformations to reduce emissions from crops. Table A.3 shows the technical costs and benefits of these transformations, and Table A.4 shows the sector-specific non-technical costs and benefits. The costs and benefits of transforming agriculture on energy and waste management are valued endogenously in those sectors.

Table A.2 Crop transformations

Transformation	Description	Implementation (by 2050)
Reduce excess fertilizer use	Use of fertilizer in agriculture is the primary source of anthropogenic nitrous oxide (N2O) emissions (Tian et al., 2020). Global overuse and misapplication of N2O is a significant and avoidable contributor to these emissions (McKinsey et al., 2020). This strategy targets applying excess nitrogen (i.e., the amount of fertilizer that can be reduced without affecting yield), which is highest in countries such as China and India that subsidize fertilizer use but is also significant in Latin America (West et al., 2017). Table X.2 specifies per-hectare nitrogen (N) input that is not taken up by harvested crops, of which 10-30% could be avoided without an impact on yield.	Any fertilizer historically applied beyond the benefits it yields is avoided.

Expand conservation agriculture	Conservation agriculture is the term given to agricultural practices that seek to preserve soil and ecosystem health. FAO describes three inter-related practices: minimum tilling, maintaining permanent soil cover, and diversifying plant species (FAO, 2022). While Latin America is already a leader in no-till practices (McKinsey et al., 2020; Kassam et al., 2019; Sperow, 2020), there is room for improving these practices' extent and scope, particularly given the poor quality of some current efforts (Kassam, 2019).	High-quality conservation agricultural practices are expanded to 80% of crop land on which grains and staples are grown, excluding rice (which is addressed in the next transformation).
Improve rice management	Many practices can reduce emissions associated with growing rice, including improved water management, fertilizer practices, tillage practices, rice variety choices, residue management, and seeding practices (McKinsey et al., 2020; Chirinda et al., 2018).	All rice growing is transitioned to these improved practices.
Improve sector productivity	This encompasses many sector-wide improvements that increase productivity.	This is described in the section "Crosscutting Agriculture Changes."

Notes: West et al. (2017) estimate the excess N per hectare (ha) per country globally (measured as the difference between rates of nutrient input versus nutrient removal from plant harvesting). They estimate that 10-30% could be removed without impact on yield. Data are available for download at ; accessed May 25, 2022).

Table A.3 Crop transformations' technical costs

Transformation	**Technical costs (Labor cost average in 2019 USD)** (Negative values indicate avoided costs, i.e., savings)	Notes and data
Reduce excess fertilizer use	-$200/ton of fertilizer	West (2017), Good and Beatty (2011). We calculate the cost of eliminating excess N as the avoided cost of fertilizer using the minimum, average, and maximum costs per ton of urea over the past five years available for download, accessed June 17, 2023.
Expand conservation agriculture	-$20/ha under conservation agriculture	Savings from avoided fuel and labor expenditures make this transformation a technical cost savings. Crop-specific estimates include savings of $232/ha for soy and $84/ha for maize (SHP, EDF, and Isom [2021]), and general savings estimated at $23/ha (Frank et al., 2018).
Improve rice management	-$30/ha under improved rice management	McKinsey (2020) describes various rice-management practices and techniques that can yield significant carbon reductions, all at negative technical cost. Chirinda et al.'s (2018) metanalysis of rice management describes impacts on greenhouse gases (GHGs) and yields in Latin America for a variety of these practices, and we use that data to inform the ranges. Chakraborty et al. (2017, Supplementary Table S8) describes the difference in costs for these practices globally, which we adapt here, adjusting in dollar values from 2017 to 2019.

Table A.4 Benefits and costs of transforming agriculture

Benefit or cost	Value (LAC average in 2019 USD) (Positive indicates benefits)	Notes and data sources
Avoided nitrate leaching and runoff	$60/ton of fertilizer avoided	Good and Beatty (2011, Box 2 and Table 4) estimate the total environmental cost of nitrate leaching and runoff to be 44% of the total cost of excess fertilizer applied, of which 70% of is attributed to nitrate leaching and runoff. The value of avoided nitrate leaching and runoff is estimated at 30% of the per-ton cost of fertilizer in the prior table.
Improved soil health	$350/ha	Telles et al. (2018) estimate the difference in agricultural land values in Brazil in 2006 under different tillage practices. They find that on average, hectares of no-till are over $700 more valuable per acre than those under conventional tillage practices, which can serve as a proxy for the benefits of healthier soils from conservation tillage. Recognizing that agricultural land values vary greatly by country and that the causal direction of the relationship between value of land and tillage practice may be complex, we use a conservative estimate of the difference to value the benefits of this practice.

Note: LAC stands for Latin America and the Caribbean.

Livestock

Livestock historical data and projections

Emissions in livestock are produced by enteric fermentation (for ruminants), manure, and converting land to pasture, which we discuss in the land use and forests sector. Livestock emissions are a product of the data in Table A.5.

Table A.5 Data and methods

Data	Method For historical data	Method for projections
Initial livestock head count	Live animals head count is estimated using UN FAO Production database (FAO, 2023c) Export and import volumes are estimated using FAO Trade database (FAO, 2023d)	We estimate livestock demand's elasticity to GDP per capita based on data from Komarek et al. (2021). We combine these elasticities with GDP per capita projections to estimate baseline demand.
Dry matter consumption	Daily dry matter consumption is taken from Holechek (1988)	Dry matter consumption is assumed constant through the simulation. However, areas and volumes of production, exports, and imports are determined endogenously in the simulation.
Emissions intensity	Enteric fermentation factors' values are taken from IPCC Guidelines for National Greenhouse Gas Inventories, Tables 10.10-10.11, volume 4, chapter 10 (IPPC, 2019) Livestock manure management fractions are taken from IPCC Guidelines for National Greenhouse Gas Inventories, Table 10A.6, volume 4, chapter 10 (IPPC, 2019)	Factors are assumed to remain constant under baseline conditions (i.e., no transformations).
Total emissions	Historical sector emissions are used in the calibration process. Emissions data for calibration are obtained from Climate Watch (2022)	Meat demand, along with the technologies and practices used for production, determine emission levels in the future.

Notes: Export data contain records on processed animal products. We developed a crosswalk to convert these export statistics to equivalent animal head counts. Daily dry matter consumption is used to allocate grassland to grazing animals and estimate carrying capacity under the assumption that livestock's distribution across grazelands is uniform, grasslands are homogenous, and there is no mixed grazing. Climate Watch data aggregate crops and livestock into one single sector named "agriculture." We approximate livestock emissions using CH4 totals produced by Climate Watch.

Table A.7 Livestock transformations' technical costs

Transformation	Cost	Source
Reducing enteric fermentation	$40/head	The cost of reduced enteric fermentation is taken as the range of costs in Table 5-59 in EPA (2019) for fermentation inhibitors, and the nominal value is the average of that range. McKinsey (2020) reports breed change as a no-cost transformation. The costs of enteric fermentation inhibitors are converted from 2010 to 2019 dollars and adjusted to LAC values.
Managing manure	$10/TLU	Frank et al. (2018) suggest global costs of digesters from $8-$38/ Tropical livestock units (TLU). We use an average for digesters and then adjust to account for the fact that much of the manure in this transformation is handled by lower-cost methods such as spreading on fields.
Silvopasture	$45/ha/year	We conservatively estimate silvopasture's cost as the same as the cost of restoring degraded land, although this may be a higher cost than is seen in the literature.

Crosscutting Agriculture Supply-and-Demand Transformations

Several transformations shape the underlying supply, demand, and productivity of the agricultural system and can have significant impacts on emissions. They include shifting consumer diets to reduce meat consumption, reducing food losses and waste, improving productivity, and changing agricultural land-use policy.

Table A.8 shows these transformations, and Table A.9 shows their technical costs and benefits. Table A.10 shows the sector-specific non-technical costs and benefits. The costs and benefits of these transformations on land use are described in the land use and forestry sector.

Table A.8 Crosscutting transformations

Transformation	Description	Implementation (by 2050)
Improving diets	Latin America has high rates of obesity and poor nutrition, with attendant social health costs (Popkin and Reardon, 2018). This transformation transitions the population in aggregate to a healthier and more sustainable diet consistent with the vegetarian diet described in Table S.7 in Springmann et al. (2016).	By 2040, overall dietary consumption has shifted in a manner that—in aggregate—is consistent with 40% of the population adopting a vegetarian diet, although the distribution of dietary change across the population will vary. Some will forego meat, others will reduce their consumption, and still others who have inadequate access to protein will increase it.
Reducing food losses and waste in the supply chain	Food waste and loss is a massive economic cost to LAC and globally (Hanson et al., 2022; Flanagan et al., 2019). As of 2020, an average of 12% of food produced on the farm in LAC is lost before it reaches retailers (FAO, undated). This is approximately 171 kg per capita (UNEP, 2018). This strategy reduces food waste throughout the agriculture supply chain, from the farm through production, processing, handling and storage, and distribution and marketing. (Post-market waste by consumers is handled in the waste sector.)	The maximum implementation of this transformation involves halving food losses in the supply chain, consistent with Hanson et al.'s (20220) recommendations.
Improving agricultural and livestock productivity	Latin America is not yet at the frontier of agricultural productivity. This transformation accelerates total factor productivity in Latin America to Organization for Economic Co-operation and Development (OECD) levels.	Agricultural productivity will grow 1.6% per year throughout 2050
Redirecting gains in productivity to land conservation	As agricultural or livestock productivity increases, or domestic demand decreases, domestic production can be reduced and land returned to native conditions.	All gains in productivity or decreases in waste or demand are used to reduce production (rather than export more).

Table A.9 Crosscutting transformations' technical costs

Transformation	**Technical costs (LAC average in 2019 USD)** (Negative values indicate avoided costs, i.e., savings)	**Notes and data sources**
Reducing supply chain losses and waste	$400/ton of food waste avoided	Costs are based on the average per-ton costs of methods of reducing producer-side food waste in the United States, weighted by their effect size ($700 in 2016), based on data found in the appendix of ReFED (2016), adjusted to LAC. We expect this is an overestimate of costs, given that Latin America's food industry is generally less well developed than the United States, and gains may be available at a lower cost.
	-$500/ton of food waste avoided	Food waste occurs across food types, and without specific information on the types of food that are wasted and the recovery potential in the supply chain, we use the average cost of food across all product types. We reduce this value given that the food that is recovered from waste may be of lower value than food that is not wasted.
Increasing crop or livestock productivity	Varies by country	This is deeply uncertain. As an initial estimate, we use the average annual investment in agriculture and livestock research and development (R&D) in OECD countries, as a fraction of GDP (roughly 0.02%). We use that fraction for OECD countries in LAC; for others, we increase that fraction by 20% to account for less-developed economies.
Change in sector value add	Price per ton varies by type of product	The value per ton of crops and livestock varies by type and is based on producer prices from FAOStat's food producer prices dataset (FAO, undated), with TLU values (FAO, 2023) and average production efficiencies for livestock (Williams and Anderson, 2020).

Table A.10 Crosscutting agricultural transformations' non-technical benefits and costs

Value	Value (LAC average in 2019 USD) (Positive indicates benefits)	Notes and data sources
Household grocery costs from improved diets	$385 per person per year transitioned to a better diet	The annual cost of food in the improved diet described by Springmann et al., (2016) is less than the existing average diet, with food prices in LAC based on Springmann et al. (2017) and adjusted to 2019 dollars.
Health benefits of better diets	$1,750/per person per year transitioned to a better diet	The health benefits of a dietary change is calculated based on the aggregate annual health benefits defined in Springmann et al. (2016) for LAC in 2050. The costs are deeply uncertain: a direct-costs approach estimates costs of $100B in LAC; a value-of-statistical-life approach estimates costs of approximately $2.5 trillion (see Figures S.12 and S.13) divided by the population in LAC projected by the World Bank for 2050 (approximately 750 million). We use an average, but explore the full range, from $350/person to $3,500/person.

Appendix B. Forests and Land Use

Forest emissions include CO2 sequestration in biomass in primary and secondary forests, as well as harvested wood products, CH4 from mangrove ecosystems, and CO2 from forest fires. Land-use emissions include CO2 emissions derived from converting forest land to other types of land. Land-use changes are specified using a transition matrix for all land-use types and modeled in response to changing demands for livestock and crops. Forestry is divided into primary forest, secondary forests, and mangroves. These categories reflect an aggregation of forestry types into emission-relevant categories. Land-use types include croplands, grasslands, settlements, wetlands, forests-mangroves, forests-primary, and forests-secondary.

Land-Use Historical Data and Projections

Forest and land-use emissions are a product of the data in Table B.1. Model parameters are calibrated to match model's emissions estimates in the Land Use and Forestry sector available at Climate Watch (2022), combined with forestland sequestration estimates available at the UN FAO Emissions database (FAO, 2023g). The set of calibrated parameters is comprised of transition probabilities for different land-use transitions. Estimated baseline values are modulated to reflect specific national contexts.

Table B.1 Data and methods

Data	Method for historical data	Method for projections
Land-use conversion emission factor	Emissions factors are derived from biomass stock factors found in IPCC Guidelines for National Greenhouse Gas Inventories, volume 4, Tables 4.12 and 6.4 (IPPC, 2019).	Emission factors are assumed to be constant.
Initial land-use area proportion	Proportions of different land-use types are estimated using the UN FAO Land Use database (FAO, 2023e) and Land Cover database (FAO, 2023f).	Changes in land-use area are determined endogenously in the model as a function of expected transition probabilities, agriculture production, meat demand and deforestation rates.
Land-use climate fractions	Land-use types by Köppen Climate Classification are derived from KGClim 1 km data 1987-2013 averages (Cui et al., 2021). These fractions are combined with climate-dependent default IPCC factors across AFOLU to determine country-level average factors, including emissions from soil mineral carbon, forest sequestration, and biomass emissions from land-use conversion.	Country climate classification fractions are assumed to be constant.
Soil organic carbon stocks	Soil organic carbon stock estimates are based on SoilGrids 1 km 0-30 cm global gridded organic carbon stock data (Poggio et al., 2021).	Average per unit carbon stocks are assumed to be constant.
Land-use transition probability	Estimated using FAO's Land Use database (FAO, 2023e), Land Cover database (FAO, 2023f), and Emissions database (FAO, 2023g). FAO items are mapped into SiSePuede items; transition probabilities are estimated based on observed land-use changes and forest regeneration rates.	Baseline projection assumes expansion of crops and grasslands and a reduction in primary and secondary forest.
Forest fire emission factor	Factors are based on IPCC Guidelines for National Greenhouse Gas Inventories, volume 4, chapter 2, Table 2.4 (IPPC, 2019).	Factors are assumed to be constant.

Forest sequestration factor	Forest sequestration factors are based by combining IPCC forest-type biomass factors (Table 4.12, IPCC, 2019) with country-level overlays of Köppen Climate Classification (Cui et al., 2021) and land-use type (FAO, 2014) to country-specific factors by forest type.	Sequestration factors are assumed to be constant at baseline.
Total emissions	Historical sector emissions are used in the calibration process. Emissions data for calibration are obtained from Climate Watch (2022). Sequestered emissions in forestland are estimated using FAO's Emissions database (FAO, 2023g).	Total emissions are calculated based on the amount of secondary and primary forest sequestering emissions, and conversion emissions resulting from converting primary and secondary forests into other land uses.

Forests and Land-Use Transformations

Table B.2 shows transformations to reduce emissions from forests and land use. It includes rehabilitation of degraded land and stopping deforestation. Table B.2 shows the technical costs and benefits of these transformations.

The value of ecosystem services is deeply uncertain. We use a single value for all forests to avoid false precision and use nominal values within the range of ecosystem services found in the literature (Taye et al., 2021, Table 3; Costanza et al., 2014, Table S.1).

Table B.3 Forestry transformations' emissions, costs, and benefits

Transformation	Emissions	Benefits	Cost	Source
Rehabilitating degraded land	Endogenously calculated	Ecosystem services of forests valued in Table B.2	$45 / hectare / year to turn grassland or cropland to secondary forest	Fargione et al. (2021), estimate a range of per-hectare costs of reforestation across the United States. We use the average for the US ($1,262/ha) and adjust to LAC, amortizing this cost over 15 years.
Slowing or ending deforestation	Endogenously calculated	Ecosystem services of forests valued in Table B.2	Foregone annual agricultural or livestock revenue (endogenously calculated based on the productivity per acre)	See above table.

Appendix C. Industry

Industry includes production of cement, chemical products, construction and demolition, electronics, glass, metals, and other products and product uses. The emissions from this sector depend upon the quantity of product demanded, the emissions associated with industrial processes to create that product, the amount of energy needed to enable those processes, and the sources of energy used. Correspondingly, emissions reductions can be achieved by reducing the amount of product created, using lower-emitting input materials and processes, increasing the processes' energy efficiency, and using cleaner energy sources.

Industry Historical Data and Projections

Industrial emissions are specific to each industry, but in general are a product of the data in Table C.1.

Table C.1 Data and methods

Data	Method for historical data	Method for projections
Quantity of industrial output per industry per country	Estimated using Atlas of Economic Complexity (Harvard, 2023) and global production statistics for individual products and activities estimated by Statista Search Department (2023). Our method uses exports and imports to estimate shares of global production for individual countries. Then these rates are used to allocate global production individually for each nation (see notes).	Using historical data, we calculate an elasticity of industrial output per GDP per capita and apply that to a baseline projection of the GDP and population. The estimated elasticity is bounded and trends linearly toward 1 by 2050.
Energy intensity (energy demand per unit of industrial output)	Energy intensities are estimated using data from the International Energy Agency (IEA) (2018).	Projected values for energy demand are estimated using a multilinear regression model that uses urban and rural population shares, and GDP as predictors of future demand. Then projected values of production are divided by the estimated energy demand per sector.
Energy consumed by energy source	Fractions of energy consumed by sector are estimated using data from IEA (2018).	Fractions of energy by source are assumed to remain fixed over time within each industry.
Emissions intensity (emissions per unit of energy, by fuel)	Historical emissions intensity is calibrated between energy consumption data (previous line) and the emissions per fuel type used in each industry (last line).	Energy emissions intensities are assumed to remain unchanged in a baseline future.
Process intensity (emissions per unit of industrial output)	CO2, CH4, and N2O emissions, as well as those from fluorinated gases (F-gases: HFCs, PFCs, SF6, NF3) per industrial sector are estimated using Minx et al.'s (2021) database. This database is part of the Earth System Science Data project.	Process emissions intensities are assumed to remain unchanged at a baseline future.
Total emissions	Historical sector emissions are used in a calibration process. Emissions data for calibration is obtained from Climate Watch (2022).	Total emissions are calculated based on the energy and process intensities, and the quantities of energy consumed, or output produced, respectively.

Notes: To calculate the industrial output's quantity, we combine information on exports and imports in shares of exports and imports as a percent of GDP, and global total production of different sectors in tonnage. Using exports and imports, we estimate total local production, assuming the following: National Production = National Demand + Exports – Imports. National demand is estimated based on shares of exports and imports as a percentage of GDP. Once national production totals are estimated, national shares of the total monetary value of production with respect to global production are estimated. Then this share is used globally to distribute the global estimate in tonnage for individual countries. Industry parameters are calibrated to match the model's emissions estimates in an industrial process with emissions data for this sector available at Climate Watch (2022). The set of calibrated parameters comprises emission-intensity factors of F-gases and fugitive emissions factors for different industrial processes. Estimated baseline values are modulated to reflect specific national contexts.

Transforming Industry

Table C.2 shows transformations to reduce emissions from industry, which include changes to industrial processes and industrial energy. Some transformations are specific to certain industries (e.g., substituting clinker in cement production) while others apply across industries (e.g., replacing virgin materials with recycled materials). Table C.3 details these transformations' technical costs and benefits, and Table C.4 outlines the industry-specific non-technical costs and benefits. The costs and benefits of transforming industry on energy, waste management, and so forth are valued endogenously in those sectors.

Table C.2 Transformations to industry

Transformation	Description	Implementation
Improve material use		
Reducing demand through material efficiency, longevity, and reuse (cement and steel)	Smarter designs can reduce the amount of steel and cement in a product; products and buildings are designed and built to last longer; products that are no longer used are reallocated for other purposes or recycled (Allwood, 2013).	The demand for steel (metals) and cement is reduced by 30% compared to the demand for those materials under traditional development (see the table's notes).
Shifting from virgin material to recycled material (all recyclable materials)	An increase in the use of recycled materials can provide industrial inputs that have lower GHGs than virgin production of those same materials.	The amount of recycled material available is determined endogenously in the waste management sector and used as a substitute for virgin materials.
Clinker substitution (cement)	Clinker can be replaced partially by other inputs, such as fly ash and blast furnace slag, which are byproducts of other industrial and energy processes.	The amount of clinker in cement is reduced by 50% for all cement produced (see the table's notes).
Improve industrial energy use		
Improve existing processes' energy efficiency	Energy efficiency of existing industrial processes can be improved through better management and process control (e.g., kiln system improvement and heat loss reduction in cement and steel plants) and newer technologies.	Industrial energy intensity is reduced by 30% compared to intensity under traditional development.
Electrify low-temperature industrial heat	Low-temperature heat accounts for half of all industrial heat demands. This transformation transitions that heat-to-heat pumps, which run on electricity and can be several times more efficient at providing heat than fossil fuels (Rissman, 2022).	Heat pumps are used to meet 95% of low-temperature industrial heating demands.
Transition medium and high-temperature industrial heat to electricity and hydrogen	Medium- and high-temperature heat accounts for half of all industrial heat demands, primarily in metals, cement, and chemicals (Rissman, 2022). This transformation switches that heat to electricity and hydrogen1	Electricity and hydrogen equally replace fossil fuels to meet 95% of medium- and high-temperature industrial heating demands.

Other GHG abatement		
F-gas reduction (all industries that emit F-gases)	This transformation includes various actions to reduce F-gas emissions across multiple industries and products—for example, substitutions with less-harmful chemicals, destruction of byproducts, and gas recovery (Sovacool et al., 2021).	F-gas per unit of output is reduced by 85% from industrial processes and product use.
N_2O abatement in the chemicals industry (adipic and nitric acid production)	This transformation reduces nitrous oxide N_2O process emissions from the chemicals industry by destroying the N_2O. Applicable abatement measures include ammonia burner (avoid N_2O formation), thermal decomposition, or catalytic decomposition (N_2O removal).	Ninety percent of N_2O emissions from all nitric and adipic acid facilities are abated.
Carbon capture and storage (CCS) for steel, cement, chemicals, and plastics	The capture and storage, sequestration, or use of CO_2 is key to reducing emissions from hard-to-abate sectors, particularly where production of CO_2 is an inherent part of an industrial process (Paltsey et al., 2021; IEA, 2020b).	CCS is implemented for 80% of the steel, cement, chemicals, and plastics with a 90% capture rate.

Notes: Regarding materials efficiency, the Energy Policy Solutions Simulator () suggests that material efficiency could reduce cement demand by 70% and steel demand by 65% if sales reached a steady state. We have taken a more conservative estimate of the potential as a 30% reduction in demand for these materials compared to baseline, given that demand will increase in LAC as GDP rises and to avoid double counting the impact of recycling as a transformation in Circular Economy.
Regarding F-gas, the EPA's non-CO_2 Greenhouse Gas Data Tool suggests that by 2050, 85% of the emissions from F-gases could be abated. The EPA estimates a net increase in demand for these gases, whereas here it is per unit of demand, making the transformation described here more conservative.
Regarding clinker substitution, the amount of cement that can be replaced depends upon the replacement material. We estimate a potential replacement of 50%, given the range described by Atunes et al. (2021). Such replacement could be possible for all cement, given that reuse of fly ash, one of the most widely used substitutes, remains highly underutilized (Herath et al., 2020).

Table C.3 Industry transformations' technical costs

Transformation	**Technical costs (Labor cost average in 2019 USD)** (Negative values indicate avoided costs, i.e., savings)	Notes and data sources
Improve material use		
Reducing demand through material efficiency, longevity, and reuse (cement and steel)	$85/ton cement avoided $370/ton steel avoided	Efficiency in materials presents a savings equivalent to the cost of material use or production that is avoided, less the cost of efforts to implement efficiency and longevity measures. Here, we assume 90% of the cost of materials is realized as savings, with 10% used to achieve reductions. Steel's cost in LAC is estimated at $410/ton (ITA, undated, adjusted from US prices in January 2019 of $800/ton) and the cost of cement is estimated at $94/ton (Sindicato Nacional da Indústria do Cimento, 2022)
Clinker substitution (cement)	$47/ton of clinker substitution	Leming et al. (2017) estimate that a ton of fly ash costs roughly one-third of a ton of cement, although more fly ash may be needed to replace an equivalent amount of clinker to achieve the same physical properties. We estimate therefore that each ton of substitution results in 50% savings in cement costs, which was approximately $94/ton in LAC in 2019 (Sindicato Nacional da Indústria do Cimento, 2022).
Improve industrial processes and energy use		
Improve energy efficiency of existing processes	$10/GJ	Talaei et al. (2019, Table 4) and Talaei et al. (2020, Table 6) estimate the capital cost of increasing energy efficiency of the existing Canadian cement and steel industries, respectively. Average costs across interventions in both industries are CAD$18/gigajoule (GJ) for cement in and CAD$44/GJ for steel.
Electrify low-temperature industrial heat	$5/megawatt hour of thermal heat (MWhth) capital cost $0.90/MWhth non-fuel operations and maintenance	Rissman (2022) estimates that heat pumps have a levelized capital cost of $8/MW of thermal heat demand compared to other technologies (although this cost premium is rapidly shrinking), and a $1.50 savings in non-fuel operating expenditure (opex) in the US in 2022 dollars. (No discount rate is documented in this report, and we use levelized costs as presented.)

Transition medium and high-temperature industrial heat to electricity and hydrogen	\$15/MWhth capital cost \$0.90/MWhth non-fuel operations and maintenance	In the absence of other data, we estimate the costs to be triple that of low-temperature heat and equivalent maintenance savings.
Clinker substitution (cement)	\$47/ton of clinker substitution	Leming et al. (2017) estimate that a ton of fly ash costs roughly one-third of a ton of cement, although more fly ash may be needed to replace an equivalent amount of clinker to achieve the same physical properties. We estimate therefore that each ton of substitution results in 50% savings in cement costs, which was approximately \$94/ton in LAC in 2019 (Sindicato Nacional da Indústria do Cimento, 2022).
Other GHG abatement		
F-gas reduction (all industries that emit F-Gases)	\$63/tCO2e	The EPA (2019, undated) estimates that approximately 85% abatement of F-gases in Brazil, Argentina, and Venezuela (the three largest emitters in LAC) occur at a cost of less than \$100 per tons of carbon dioxide equivalent (tCO2e) by 2050, in 2010 dollars. We use a weighted average to account for abatement that can occur at no cost and adjust to LAC in 2019 dollars.
N2O abatement in chemicals industry (adipic and nitric acid production)	\$13/tCO2e	We use EPA data (2019, Table 5-10) to estimate an undiscounted abatement cost of \$38/ton of adipic acid and \$3/ton of nitric acid approximated (in the US in 2010 dollars). We use an average of these costs and adjust to LAC 2019 USD.
CCS for steel, cement, and other industries	\$40/ton CO2 (cement) \$50/ton CO2 (steel) \$100/ton CO2 (chemicals)	The IEA (2020b) estimates that CCS globally adds \$30-50/ton cement, \$50/ton of steel, and \$100/ton of chemicals.

Table C.4. Non-technical benefits and costs of transforming industry

Benefit or cost	**Technical costs (Labor cost average in 2019 USD)** (Positive values indicate benefits and savings)	Notes and data sources
Avoided health effects from local air pollution from concrete production, excluding industrial energy pollution	$45/ton cement	Miller et al., (2020, Figure 2) estimate cement externalities of $80-90/ton in Latin America in 2015 dollars, of which at least 75% stem from local air pollution's health effects. Of this, at least 70% is from process-based (i.e., non-energy) emissions.
Avoided health impacts from local air pollution from industrial on-site energy	$2.47/GJ coal $0.12/GJ natural gas $2.47/GJ coke (a coal-based fuel) $0.31/l diesel $0.039/l gasoline $3.05/GJ biomass	We use IMF's fossil-fuel subsidies database (2021) to calculate the avoided air pollution costs of industrial fuel consumption. This database provides costs specific to industry's use of coal and natural gas. We use average values across LAC. We use coal costs for coke, and use costs shown in transport for diesel and gasoline. For biomass, we use average pollution costs across other fuel types.

Appendix D. Energy Production

The electricity and fuel production sector assesses the demands and emissions associated with both primary and secondary energy, and the costs of transforming them. The electricity sector is modeled differently from other sectors using NemoMod, an energy framework developed by the Stockholm Environmental Institute (Veysey et al., 2023). NemoMod takes as input varous drivers and data, including demands, residual generation capacities, capacity and availability factors, capital and operating costs, emission factors, and a series of constraints and generates a least-cost pathway to meet demand contingent on constraints.

Electricity and Fuel Production Historical Data and Projections

Electricity and fuel production emissions are a product of the data in Table D.1. Under Traditional Development, the electricity sector simulates a least-cost future that resembles today's electricity production portfolio. That is, we constrain NemoMod to find a solution subject to the following constraints:

• Fossil fuels will continue to comprise at least the same fraction of electricity generation in the future as they do today.

• No nuclear, hydropower, or biomass generation capacity can be added.

For emissions, electricity and fuel-production parameters are calibrated to match emissions estimates in the electricity sector available at Climate Watch (2022). The set of calibrated parameters comprises technologies' and fuels' efficiency factors.

Table D.1 Data and methods

Data	Method for historical data	Method for projection under nominal future conditions
Electricity and fuel demand from each sector (energy/fuel/sector)	Demands are endogenously modeled in each sector as described, based on sector activity, energy intensity, sector-specific fuel mix, and other factors. The demand for electricity in fuel production and for fuels in electricity production are included here, based on the Energy Information Administration (EIA) World Energy Balance (2022).	
Electricity production costs by technology	Capital expenditure (capex) is based on IEA estimates (EIA, 2022). Non-fuel opex is assumed to be a fraction of capex, based on proportions to levelized cost of electricity (LCOE) per different technologies using IEA estimates (IEA, 2020c).	The cost of renewable energy production is expected to decline on average by 50% by 2050 but vary by technology. The cost of fossil fuels' energy production remains unchanged.
Fuel costs	Demands are endogenously modeled in each sector as described, based on sector activity, energy intensity, sector-specific fuel mix, and other factors. The demand for electricity in fuel production and for fuels in electricity production are included here, based on the Energy Information Administration (EIA) World Energy Balance (2022).	
	Installed and residual capacities are estimated using the World Resources Institute (WRI) Global Database of Power Plants (Byers, 2018) and scaled to match installed capacity totals to scale capacities from the UN Energy Statistics Database (United Nations Statistics Division, 2023) in each country to avoid undercounting available capacity. Minimum shares of production are estimated using IEA monthly electric statistics (2022a). Transmission losses by country are estimated using World Bank Data API (World Bank, 2023) Constant average capacity factors for electricity production for different technologies are estimated using data from the US EIA (EIA, 2015)	NemoMod calculates the least-cost method of meeting future electricity demand subject to two constraints: continued use of fossil fuels; and no new nuclear, hydropower, or biomass capacity
Emissions intensity (emissions per unit of energy, by fuel)	Historical emissions intensities of fossil fuels are based on factors found in volume 2, Table 2.2 of the IPCC Guidance for National Greenhouse Gas Inventories (IPCC, 2006) and calibrated between energy consumption data (previous line) and the emissions per fuel type used in each industry (last line). Fuel demands are determined by imports, energy intensity of different industrial activities, and share of fuel type used in different industrial sectors. These shares are estimated using IEA (2022b).	Energy emissions intensities are assumed to remain unchanged in a baseline future.

Emissions (MTCO2e)	Historical sector emissions are used in the calibration process. Emissions data for calibration is obtained from Climate Watch (2022). Emissions also include fugitive emissions.	Total emissions are calculated based on emissions intensities and the quantities of energy consumed (by fuel).

Transforming Energy and Fuel Production

We implement three transformations in electricity described in Table D.2. We currently do not transform primary fuel production. Tables D.3 and D.4 show the technical and non-technical costs and benefits.

Table D.2 Transformations to energy and fuel production

Transformation	Description	Implementation
Transition to a renewable grid	A renewable grid phases out fossil fuels and meets demand with renewable energy coupled with storage.	This transition constrains NemoMod to produce electricity with 95% renewables, which are limited to solar (≥ 15%), wind (≥ 15%), and geothermal (≥10%), along with a variety of storage technologies. No new nuclear, hydropower, or biomass generation capacity can be added.
Produce green hydrogen	Green hydrogen is generally produced by electrolysis powered by renewable energy, instead of more typical methods of steam methane reformation or gasification.	All hydrogen is produced through electrolysis.
Reduce transmission losses	Electricity grids experience technical and non-technical losses in transmission and distribution from infrastructure and demand characteristics (Jiménez et al., 2014). This transformation mitigates technical losses through upgrades and improvements to the grid, such as replacing transformers and power lines, installing smart grids, and managing reactive power (IEA, 2020).	Investments in transmission infrastructure reduce half of excess losses currently experienced in each country, where excess is defined as losses greater than the 4% experienced in OECD (World Bank, 2023).
Flaring fugitive emissions	Energy efficiency of existing industrial processes can be improved through better management and process control (e.g., kiln system improvement and heat loss reduction in cement and steel plants) and newer technologies.	Industrial energy intensity is reduced by 30% compared to intensity under traditional development.
Minimizing leaks of fugitive emissions	This transformation uses a variety of technology to identify and repair leaks of fugitive emissions (EPA, 2019).	Eighty percent of leaked fugitive emissions are repaired.

Table D.3 Energy and fuel production transformations' technical costs

Transportation	**Technical costs (LAC average in 2019 USD)** (Negative values indicate avoided costs, i.e., savings)	Notes and data sources
Transition to a renewable grid	Capex, non-fuel opex, and fuels are calculated endogenously $2.70/MWh of new transmission	NemoMod calculates the least-cost pathway to a renewable grid, including capital, operations and maintenance, and fuel costs. According to the National Renewable Energy Laboratory (Gorman et al., 2019), the levelized cost of new transmission in the US ranges from $1/MWh to $10/MWh. We use an average of $5/MWh and convert to LAC.
Produce green hydrogen	Endogenously calculated in NemoMod based on increased demand for renewable electricity to produce hydrogen.	
Reduce transmission losses	Varies by country	The Inter-American Development Bank (Brichettei et al., 2021) estimates the cost between 2020 and 2030 of upgrading each country's grid to meet Sustainable Development Goals (SDGs) to 2030. We use a simple annual average as an approximation of the annual cost of upgrades in each country that would yield reductions in transmission losses.
Minimize fugitive emissions leaks	$20/tCO2e	Studies suggest that fugitive emissions could be abated for less than $14/tCO2e in the US oil and gas industry through various technologies (ICF International, 2014, Figures A-4 and A-5). We use a conservative estimate, given variations in discount rates, assumptions about methane prices, and so on.
Flare fugitive emissions	$2/tCO2e	We assume flaring will be one-tenth the cost of fixing leaks.

Table D.4 Benefits and costs of transforming energy

Benefit or cost	Value (LAC average in 2019 USD) (Positive indicate benefits)	Notes and data sources
Health benefit of avoided air pollution	\$2.77/GJ coal \$0.99/GJ natural gas \$1.43/GJ oil	We use IMF's fossil-fuel subsidies database (2021) to calculate the avoided air pollution costs of electricity generated by renewables versus coal, natural gas, and oil. (Costs are averaged across LAC, and the average cost of coal and natural gas is used for oil).

Appendix E. Buildings

This sector includes energy consumed by residential, commercial, and municipal buildings, and other stationery combustion not captured elsewhere. The emissions from this sector depend upon the building stock and population, and the demands for heating, cooling, and other appliances in the building, and the source of energy used. Residential building stock is estimated as a function of population and occupancy rate, which is elastic to GDP per capita. Emissions reductions can be achieved by reducing the amount of energy required in buildings, increasing their energy efficiency, and using cleaner energy sources.

Buildings Baseline Data and Projections

Building emissions are a product of the data in Table E.1. Model parameters are calibrated to match model's emissions estimates in the Buildings sector available at Climate Watch (2022). The set of calibrated parameters comprises efficiency factors of different fuels. Estimated baseline values are modulated to reflect specific national contexts.

Table E.1 Data and methods for historical and baseline projection results

Data	Method for historical data	Method for baseline
Demand for heat energy	Heat demand is estimated using IEA's World Energy Balance Highlights (2021).	Using historical data, we currently calculate an elasticity of heat demand per GDP per capita and apply that to a baseline projection of GDP and population.
Demand for appliance energy, including cooling	Energy demand is estimated using IEA's World Energy Balance Highlights (2021). The number of households per country is estimated using World Bank's population time series and the Helgi Library Global Socioeconomic Indicators Database (2023)	Using historical data, we calculate an elasticity of appliance energy demand per GDP per capita and apply that to a baseline projection of GDP and population.
Energy consumed by energy source	Historical energy consumption data for buildings is available from IEA (2021). Efficiency factors are estimated using IEA's World Energy Balance (2018)	Fractions of energy by source are assumed to remain fixed over time.
Emissions intensity (emissions per unit of energy, by fuel)	Historical emissions intensity is calibrated between energy consumption data (previous line) and the emissions per fuel type (last line).	Energy emissions intensities are assumed to remain unchanged in a baseline future.
Total emissions	Historical sector emissions are used in the calibration process. Emissions data for calibration are obtained from Climate Watch (2022)	Total emissions are calculated based on the quantities of energy consumed and each source's emissions intensities.

Transforming Buildings

Table E.2 shows transformations to reduce emissions from buildings and includes changes to energy efficiency and fuel shifting to heat pumps for heat. Table E.3 shows these transformations' technical costs and benefits. We do not assess non-technical costs or benefits associated with buildings.

Table E.2 Transformations to buildings

Transformation	Description	Implementation
Improve building and appliance efficiency	Significant improvements are possible in the building shells and appliances, e.g., through better insulationand energy management. This is applicable both to new buildings and retrofits to existing buildings.	In this transformation, energy demands decline by 50% per capita relative to today.
Transition heating to heat pumps	This transformation switches heating to heat pumps, which run on electricity and are several times more efficient at providing heat than fossil fuels (Rissman, 2022).	By 2050, 95% of heat demand is met by heat pumps.

Table E.3 Building transformations' technical costs

Tranformation	**Technical costs (LAC average in 2019 USD)** (Negative values indicate avoided costs, i.e., savings)	Notes and data sources
Improve building and appliance efficiency	\$0.02/kWh saved	Perry et al. (2019, p. 17) estimate the costs in 2018 dollars of reducing building energy demands through a variety of energy-efficiency measures in the US (for purposes of comparing them to the costs of installing solar photovoltaic). We adjust the average cost effectiveness of \$0.04/kWh saved for LAC.
Transition heating to heat pumps	\$5/MWhth capital cost, reaching cost parity in 10 years \$0.90/MWhth non-fuel operations and maintenance	We use the same cost data as for low-temperature heat pumps used in industrial energy. Rissman (2022) estimates that heat pumps have a levelized capital cost of \$8/MW of thermal heat demand compared to other technologies, but that this cost premium is shrinking rapidly, with a \$1.50 savings in non-fuel opex in the US in 2022 dollars. (No discount rate is documented in this report, and we use levelized costs as presented).

Appendix F. Transport

Transportation consists of different categories (or modes) of transportation used to satisfy various demands, and emissions from mobile combustion of fuels are highly dependent on the technologies (e.g., types of vehicles) that use the fuels. Therefore, emission factors for mobile combustion of fuels are contained in the Transportation rather than Energy Fuels subsector.

Modeling Transportation Emissions

Transportation emissions are a product of the data in Table F.1. Model parameters are calibrated to match model's emissions estimates in transportation available at Climate Watch (2022).

Table F.1 Data and methods

Data	Method for historical data	Method for projections
Demand for travel	Demand for travel is specified by categories: aviation, heavy duty road, heavy freight rail, heavy passenger rail, human powered, light duty road, public heavy road, regional road, powered bikes, and water borne. Travel demand for public and private transportation is determined using the OECD (2023a) passenger transport database and Oak Ridge National Laboratory (2023). Freight travel demand is determined using the OECD (2023b) Freight Transport database. Shares of transportation across different forms of travel are estimated using data from the US, with adjustments to reflect Latin American conditions. Occupancy rates in private transportation are estimated using the European Environment Agency (2023) Occupancy Rates of Passenger Vehicles database. Freight capacity for different transportation modes is estimated using statistics from the Association of American Railroads (2023) statistics and the US Department of Transportation, Federal Highway Administration (2023), Tables 3-4.	Future demand for travel is projected using elasticities of freight travel and passenger-kilometer demand with respect to GDP per capita. It is assumed at baseline (i.e., no transformations) that as countries develop their mode, shares of transport will converge to those of the US.
Fuel mix	Fuel mix is the share of fuel type consumption (e.g., diesel, hydrogen, natural gas, gasoline, and biofuels) by transportation mode (e.g., public and private aviation, bikes, public and private car transportation, heavy freight and heavy regional, rail freight, passenger, and water-borne) using data mostly the US Department of Energy (2022) and Palocz-Andresen (2012).	

Fuel efficiency	Fuel efficiencies for fuels (diesel, hydrogen, natural gas, gasoline, and biofuels) is estimated for public and private transportation, and for heavy freight and heavy regional transportation using data from various sources, including Huo et al., (2012), Ou et al., (2013), Brynolf et al. (2014, p. 90), Delgado et al. (2017, p. 38), Talaiekhozani et al. (2017), Ančić et al. (2018), Chen and Melaina, (2019), To et al. (2020), Liu et al., (2021), Popovich et al. (2021), and Ravigne and Da Costa (2021). Fuel mix is the share of fuel type consumption (e.g., diesel, hydrogen, natural gas, gasoline, and biofuels) by transportation mode (e.g., public and private aviation, bikes, public and private car transportation, heavy freight and heavy regional, rail freight, passenger, and water-borne) using data mostly the US Department of Energy (2022) and Palocz-Andresen (2012).	For road heavyfreight hydrogen efficiency (km per liter), the fuel economy improvement rate is set at 1 % from 2020 to 2050 for fuel cells (Ou et al., 2013; Chen and Melaina, 2019). For road heavyregional diesel efficiency (km per liter), projected values take a long-term 30.64-L(diesel)/100-km estimate (Delgado et al., 2017, p. 38). Railroad efficiencies for freight are estimated using means from Talaiekhozani et al. (2017) and Popovich et al. (2021) as 14.8 L/km (diesel) and 74.8 kWh/km (electric). Passenger railroad efficiencies are estimated as 3.2 L/km (diesel) and 16.2 kWh/km (electric) using Talaiekhozani et al. (2017). For road light biofuel, diesel, gasoline, and hydrogen efficiency (km per liter), projected values adopt the mature technology values (Dincer et al. 2015). Mature technology values are the projected value for 2035. Between 2020-2035, the values are interpolated. For 2035-2050, the values remain the same.
Mobile combustion emission factor	Factors are based on IPCC Guidelines for National Greenhouse Gas Inventories, volume 4, chapter 3, Tables 3.2.2 (IPPC, 2019)	Factors are assumed to be constant
Total emissions	Historical sector emissions are used in the calibration process. Emissions data for calibration are obtained from Climate Watch (2022).	Total emissions are calculated based on the amount of secondary and primary forest-sequestering emissions, and conversion emissions resulting from converting primary and secondary forests into other land uses.

Note: For countries not included in the OECD and IEA databases, a statistical imputation model was trained using observations of countries in the database. This model uses GDP and urban and rural population shares of countries to estimate imputed values.

Defining transportation transformations

Tables F.2, F.3, and F.4 describe the transformations modeled to reduced emissions in the Transportation sector, as well as the corresponding technical cost and benefits that result from implementing these transformations. The levels of implementation broadly are derived from recent studies of decarbonizing transport in the region (Papaioannou and Windisch, 2022; Paternina Blanco et al., 2022).

Table F.2 Transportation transformations

Transformation	Description	Implementation
Transformations to fuels and vehicles		
Electrify light-duty road transport	Private transportation from internal combustion light-duty vehicles (LDVs) is prevalent in high- and medium-income economies. At a fixed size, electric and partial electric vehicles are more efficient than traditional internal combustion engines and generally are powered by electric grids, shifting emissions to electricity production. Thus, they can be powered by renewable energy.	70% of LDVs are electric by 2050
Fuel switch medium- and heavy-duty road transport	Similar to light-duty transport, medium- and heavy-duty vehicles (MDVs and HDVs) can be powered by alternative fuels such as electricity and hydrogen, both of which are more efficient than fossil fuels and have zero emissions. Then emissions from these fuels are shifted to fuel production.	By 2050, 70% of medium-duty road transport is powered by electricity and 30% by hydrogen
Electrify rail	Electric rail is not uncommon in passenger rail, including advanced, high-speed rail. Increasing its prevalence in passenger and freight rail offsets emissions largely generated by burning diesel.	An additional 25% of rail transport is electrified by 2050, compared to 2025
Fuel switch maritime	Maritime shipping accounts for approximately 3% of emissions globally. Shifting to fuels such as hydrogen in large freight ships and electricity in smaller passenger and local vehicles shifts emissions to fuel production, which can be generated using clean sources such as renewable energy and hydrogen electrolysis.	By 2050, 70% of maritime transport is powered by hydrogen and 30% is powered by electricity
Increase transportation energy efficiency	Private vehicles can become more efficient. Increasing the efficiency of vehicles, independent of fuels, reduces the need for energy to satisfy a fixed demand.	By 2050, vehicle energy efficiency increases by 25% over the nominal gains in efficiency in a traditional development future.

Mode shifting and occupancy		
Increase occupancy for private vehicles	An increase in vehicle occupancy can achieve the same level of mobility in passenger kilometers while reducing the number of vehicle kilometers traveled.	By 2050, there is a 25% increase in occupancy of private vehicles over current rates, consistent with Grubler et al. (2018).
Mode shift local passenger vehicles to others	These transformations shift passenger travel from high-emissions-intensity modes (e.g., private auto) to lower-intensity modes (e.g., bus). Consistent with Vergara et al., (2019), we exclude mode shifts to rail given the sparse rail network in Latin America and the lack of data on expanding the network to accommodate mode shifts.	A total of 30% of passenger travel (passenger-kilometer or pkm) in private vehicles shifts to other modes; 5% of passenger travel shifts to non-motorized modes; 10% shifts to powered bikes and motorcycles; and 15% shifts to transit. This is broadly consistent with trends described by Papaioannou and Windisch (2022).
Mode shift regional passenger travel		A total of 10% of aviation passenger travel and 20% of private vehicle travel (pkms) shifts to bus.

Source: https://www.iea.org/articles/changes-in-transport-behaviour-during-the-covid-19-crisis

Table F.3 Transforming transportation's technical costs and benefits

Transformation	Technical costs (LAC average in 2019)	Notes and data sources
Electrify LDVs	$0.039/vehicle-kilometer (vkm) in capital cost, declining over time $0.012/vkm in maintenance cost (i.e., savings)	These costs reflect the marginal capital and maintenance costs of EVs versus internal combustion engine (ICE) LDVs per km. In the US, light-duty EVs are estimated to have $12,000 of higher up-front cost (Baik et al., 2019) than traditional LDVs and have $949/year lower maintenance costs (AAA, 2019) than their ICE counterparts. We approximate that charging infrastructure may involve an additional $1,000 in capital costs per EV, consistent with data from the US on the costs (Purnazeri, 2022) and deployment of charging stations (Evadoption, 2021). The per-km capital cost shown in the table assumes vehicles are driven 15,000 km/year (Ecola et al., 2008, Ecola et al, 2012, Ecola et al., 2014) and have a 12-year lifespan, consistent with data on vehicle lifetimes in the US (BTS, undated). Then costs are adjusted to 2019 costs for LAC.
Fuel switch MDVs and HDVs	$0.042/vkm + $0.011/kWh in capital cost, declining over time $0.02/vkm in maintenance cost (i.e., savings)	Burke et al. (2022) provide marginal capital and maintenance costs of a variety of medium- and heavy-duty battery electric vehicles (BEVs) versus ICEs (Table 19a, p. 50), and the cost of charging infrastructure (p. 22). Using a stated 12-year lifetime, we calculate a simple average of these costs across all vehicle types. Then costs are adjusted to 2019 costs for LAC.
Electrify rail	$0.0013/metric ton per kilometer (mtkm) or pkm in capital cost $0.0002/mtkm or pkm in maintenance cost (i.e., savings)	Popovich et al. (2021) estimate the capital and maintenance costs of electrifying freight rail. In absence of other information, we assume that electrifying passenger rail will have similar costs per person-km, with a lower mass of passengers compared to freight offset by climate control, lower density, and other variables.

Fuel switch maritime	$0.0005/mtkm	Carlo et al. (2020) estimate that decarbonizing the maritime industry (using ammonia as the primary fuel) by 2050 will cost roughly $1 trillion, with 55% of that cost associated with ammonia production and storage and ship-related investments (Krantz et al, 2020). Here, 45% of the cost is associated with hydrogen production, which we account for in energy production. They also estimate a total demand of approximately 500,000-billion-tonnautical miles of demand. We use this data to approximate a cost of fuel switching per MTKM of total goods movement and apply this to LAC.
Increase energy efficiency	$0.88M/PJ, equivalent to $0.002/vkm for ICE LDVs	The National Research Council (2015) estimates the technical cost and percent fuel economy improvements for LDVs from a wide range of vehicle technologies, including power train, accessories, and vehicle mass. We estimate the average cost per improvement across all technologies and calculate a per-km cost assuming a 12-year vehicle lifetime and 15,000 km/year use. Assuming a fuel economy of 12km/l, we calculate a cost per unit of energy saved and, in the absence of other data, apply this to other modes and fuel types.
Increase occupancy for private vehicles		There are no technical costs associated with increasing private vehicle occupancy; the savings (from avoided costs of transport by auto) are calculated in the system costs.
Mode shift freight Mode shift local and regional passenger travel		The technical costs and savings of freight and passenger mode shifting are a combination of the following: the system cost for providing transport by different modes, the additional cost of expanding infrastructure associated with certain modes of the transport system (e.g., rail transport) to account for added demand; and the cost savings of avoided infrastructure expansion in modes with less demand (e.g., air transport). Quantifying these effects is deeply uncertain, highly localized, and beyond this study's scope. We note, however, that mode shifts could result in a net cost savings, given that the shifts are generally from modes that are infrastructure inefficient (e.g., personal autos) to modes that are more infrastructure efficient (e.g., transit).

Table F.4 Other benefits and costs of transforming transportation

Benefit or cost	Value	Notes and data sources
System cost of passenger transport	\$0.17/vkm for automobiles \$0.017/vkm for motorcycles \$5.20/vkm for bus \$14/vkm for passenger rail \$1067/vkm for aviation	The system cost of providing passenger transport will change as modes and demand change. We approximate this as the cost of vehicle ownership and operating costs. In the US, the capital and operating costs (excluding fuel) by mode are approximately: • \$0.31/vkm for automobiles (US DOT National Transportation Statistics, undated, Table 3-17); • \$10/vkm on for buses (averaged across bus types) and \$27/vkm (per passenger car) for passenger rail (averaged across rail types) (US FTA, 2021, Capital Expenses, Operating Expenses, and Metrics tables); • \$2,000/vkm for aviation (calculated from US Department of Transportation National Transportation Statistics' Tables 1-35, 1-40, and 3-20, assuming 10% of costs are for fuel); and • \$0.031/vkm for powered bikes, which we assume are one-tenth the cost of automobiles. Note that different modes may include infrastructure costs to different degrees – the cost of transport infrastructure is largely external to automobile owner/operating costs, whereas it is more likely to be internalized for air transport costs. We adapt these costs to Latin America.
System cost of freight transport	\$0.41/mtkm for air \$0.053/mtkm for truck \$0.014/mtkm for rail \$0.01/mtkm for water	We estimate the impact of mode shifting freight based on costs associated with freight transport in the US (\$0.86/mtkm by air; \$0.11/mtkm by truck; 0.03/mtkm by rail, and \$0.02/mtkm by water) and adjust to LAC (US Department of Transportation's National Transportation Statistics, undated, Table 3-21). We exclude fuel costs, assuming they account for 10% of the reported revenue cost. Note that different modes may include infrastructure costs to different degrees – the cost of transport infrastructure is largely external to automobile owner/operating costs, whereas it is more likely to be internalized for air transport costs.
Health benefit of avoided air pollution	\$0.039/l gasoline and biofuels \$0.31/l diesel	We use IMF's fossil fuel subsidies database (2021) to estimate the avoided air pollution costs of fossil fuels used for road transport, averaged across LAC.

Avoided external crashes and congestion	Crash costs $0.33/l gasoline and biofuels $0.17/l diesel $0.008/kwh electricity Congestion costs $0.19/l gasoline and biofuels $0.17/l diesel $0.005/kwh electricity	We use IMF's fossil-fuel subsidies database (2021) to estimate the avoided congestion and crash cost on roads. These costs are provided per liter of fuel and reflect external costs. We use average costs across LAC and calculate total crash costs assuming external crash costs are 75% of the total (Parry et al., 2014). We assume gasoline externalities apply to biofuels and we apply costs to EVs by calculating the cost per unit of energy, adjusting for approximately 4× higher energy efficiency of EVs.

Appendix G. Waste

The waste sector consists of solid and liquid waste from domestic and industrial sources. The emissions from this sector depend upon the quantity of waste produced, the composition of that waste, and the pathways by which that waste is handled. Correspondingly, emissions reductions can be achieved by reducing the amount of waste produced, altering the waste's composition to have lower emissions potential, improving waste-treatment methods, and returning some portion of the waste stream back into the economy in the form of reused or recycled inputs.

Wastewater

Wastewater is produced by industrial and domestic sources. For industrial sources, wastewater management is defined by various levels of treatment, as Table G.1 describes. These treatments are consistent with the systems and discharge pathways described in the wastewater chapters of the IPCC's 2006 IPCC Guidelines for National Greenhouse Gas Inventories and the subsequent 2019 Refinement (Eggleston et al., 2006; Zhongming et al., 2019).

For domestic users, wastewater management consists of sanitation and wastewater treatment. The World Health Organization and United Nations Children's Fund (WHO/UNICEF) Joint Monitoring Program (JMP) for Water Supply, Sanitation, and Hygiene describes a sanitation ladder with five rungs—from (1) open defecation (OD) to (2) unimproved, (3) limited, (4) basic, and (5) safely managed sanitation. Sustainable Development Goal (SDG) 6.2.1a seeks universal access to safely managed sanitation (WHO, 2021), but that means different pathways for urban and rural users, as Table G.2 shows.

In urban settings, safely managed sanitation generally involves sewers that collect household wastewater for subsequent centralized treatment using one of the categories of treatment options described in Table G.1. In rural settings, collection is generally cost prohibitive, so safely managed sanitation includes on-site treatment, e.g., in septic tanks with fecal sludge management. For this study, we have bundled rungs 1 and 2 into an "unimproved" sanitation category and rungs 3 and 4 into an "improved" sanitation category.

Table G.1 Wastewater treatment systems for industrial and domestic urban wastewater

Treatment system	Description
No treatment	Wastewater is not treated and is discharged into the environment.
Primary treatment	Wastewater first is submitted to preliminary treatment to remove grit, rags, and large solids (e.g., wood or plastic) followed by primary treatment.
Secondary treatment	Wastewater is treated at a wastewater treatment plant and includes preliminary, primary, and secondary treatment.
Tertiary treatment (aerobic)	Wastewater is treated at an aerobic wastewater treatment plant and includes preliminary, primary, secondary, and tertiary treatment. Sludge is diverted further and managed as solid waste in the solid waste model.
Tertiary treatment (anaerobic)	Wastewater is treated at an anaerobic wastewater treatment plant and includes preliminary, primary, secondary, and tertiary treatment.

Table G.2 Domestic sanitation systems

Sanitation system	Rural	Urban
Unimproved sanitation	Private transportation from internal combustion light-duty vehicles (LDVs) is prevalent in high- and medium-income economies. At a fixed size, electric and partial electric vehicles are more efficient than traditional internal combustion engines and generally are powered by electric grids, shifting emissions to electricity production. Thus, they can be powered by renewable energy.	
Improved sanitation	On-site treatment in basic septic tanks or improved latrines, corresponding to the middle two rungs of the JMP sanitation ladder (improved and basic sanitation).	On-site treatment in basic septic tanks or sewered collection without subsequent wastewater treatment, corresponding to the middle two rungs of the JMP sanitation ladder (improved and basic sanitation).
Safely managed sanitation	Septic tanks or improved latrines with fecal sludge management (FSM), consistent with the definition of “safely managed sanitation” used by the JMP.	Sewered collection with subsequent centralized treatment at a wastewater treatment facility (see Table B.1), consistent with the definition of “safely managed sanitation” used by the JMP.

Wastewater historical data and projections

Domestic wastewater is generated per capita and grows with GDP, while industrial wastewater is driven by industrial goods' production. Then wastewater is allocated to various wastewater management options. The GHG emissions associated with each wastewater option are calculated using emissions factors consistent with the methodology in the 2006 and 2019 IPCC guidelines for national GHG inventories on which the wastewater model is based. Wastewater is estimated to increase under baseline conditions because of projected population and industrial activity increases. Table G.3 lists data sources we used to project wastewater emissions.

Table G.3. Data and methods for historical and baseline projection results

Data	Method for historical data	Method for projections
Production of wastewater	Wastewater volumes are estimated using FAO AQUASTAT (2019) database.	Wastewater production volumes are projected in the future using GDP per capita to project volumes of wastewater produced.
Fraction of wastewater treated by each pathway	Wastewater volumes across different pathways are estimated using the HydroWASTE (2023) database.	At baseline (i.e., no transformations), shares of treatment across pathways are assumed to remain constant. These shares are modified when transformations are activated in the simulation.
Emissions intensity (emissions per unit of wastewater, by pathway)	The N2O Wastewater Treatment Emission Factor is based on IPCC Guidelines for National Greenhouse Gas Inventories, Tables 6.8A and 6.10C (IPPC, 2019). The Wastewater Treatment Methane Correction Factor is based on IPCC Guidelines for National Greenhouse Gas Inventories, Table 6.3 (IPPC, 2019).	Emission factors are assumed constant in projections.
Total emissions	Historical sector emissions are used in the calibration process. Emissions data for calibration are obtained from Climate Watch (2022).	

Notes: For countries not included in the FAO AQUASTAT and HydroWASTE databases, a statistical imputation model was trained using observations of countries in the database. This model uses GDP, urban, and rural population shares of countries to estimate imputed values. A data crosswalk between SiSePuede categories and FAO AQUASTAT and HydroWASTE categories was used to map data inputs.

Transforming wastewater

Defining wastewater transformations

Table G.4 shows transformations to reduce wastewater GHGs. The most aggressive transformation of wastewater management involves reaching universal safe sanitation and tertiary treatment of all wastewater by 2030, consistent with SDGs.

Table G.4. Transformations to wastewater

Transformation	Description	Implementation
Expand access to safe sanitation	This transformation expands access to safely managed sanitation for both rural and urban populations consistent with the goals in SDG 6.2.1a.	In this transformation, all people are moved to safely managed sanitation pathways by 2030. All rural residents have access to upgraded septic tanks and all urban residents have sewerage with treatment.
Treat all wastewater	This transformation treats all industrial and domestic wastewater to at least secondary treatment levels.	By 2030, 100% of wastewater is treated in the following ways. Rural areas: 100% septic tanks Industrial wastewater: 80% tertiary anaerobic treatment, 20% secondary treatment (10% anaerobic, which can be captured), and 10% aerobic) Urban: 30% tertiary aerobic, 30% tertiary anaerobic (which can be captured), 20% secondary aerobic, and 20% secondary anaerobic
Capture biogas	This transformation captures biogas from wastewater-treatment facilities for use in the energy sector.	85% of biogas will be captured by 2050.

Cost of wastewater transformations

The costs of improving wastewater management are calculated as the difference in technical costs for providing service under a baseline future and an alternative future with better wastewater management. Table G.5 shows each system's technical costs.

Table G.5 Wastewater management's technical costs

Wastewater management system	Technical costs (LAC average in 2019 USD)	Notes and data sources
Domestic rural and urban sanitation		
Unimproved sanitation (rural) Improved sanitation (rural) Safely managed sanitation (rural) Unimproved sanitation (urban) Improved sanitation (urban) Safely managed sanitation (urban, sanitation only)	\$6.5/capita/year \$68.1/capita/year \$102.1/capita/year \$6.5/capita/year \$34.1/capita/year \$66.2/capita/year	Domestic sanitation and wastewater treatment costs are based on Tables D.1 and E.1 in Hutton & Varughese (2016), Table A.4.1 in Brichetti et al. (2021), Table 1 in Dodane et al. (2012), and Daudey (2018). Average wastewater produced in LAC is based on Table 4 in Jones et al. (2021). We assume industrial wastewater treatment costs the same as domestic wastewater treatment per quantity of treated water. The full cost of safely managed sanitation in urban settings is the cost of the sanitation system (per capita) and the cost of treating the collected wastewater (per m³) using one of the wastewater treatment systems.
Industrial and domestic urban wastewater treatment		
No treatment *Primary* *Secondary (aerobic)* *Secondary (anaerobic)* *Tertiary (aerobic)* *Tertiary (anaerobic)*	\$[0.02, **0.06**, 0.30]/m³ \$[0.24, **0.64**, 3.10]/m³ \$[0.40, **0.80**, 3.27]/m³ \$[0.40, **0.80**, 3.27]/m³ \$[0.80, **1.60**, 6.54]/m³ \$[0.80, **1.60**, 6.54]/m³	Domestic sanitation and wastewater treatment costs are based on Tables D.1 and E.1 in Hutton & Varughese (2016), Table A.4.1 in Brichetti et al. (2021), Table 1 in Dodane et al. (2012), and Daudey (2018). Average wastewater produced in LAC is based on Table 4 in Jones et al. (2021). Here, the costs are given for each treatment option in isolation. So, wastewater that receives tertiary treatment will also receive primary and secondary treatment and incur those costs. We assume industrial wastewater treatment costs the same as domestic wastewater treatment per quantity of treated water. The cost of no treatment is the cost of collecting industrial wastewater and dumping it untreated into waterways. We estimated it as one-tenth the cost of sewerage (i.e., safely managed urban sanitation) on a per cubic meter basis.
Biogas capture	\$17/million British thermal units (MBtu) of biogas	IEA (2020f) provides a global average cost of biogas capture at wastewater treatment facilities of \$10.30/MBTU in capex and \$4.30/MBTU in opex, which we convert to 2019 dollars in LAC.

The non-GHG co-benefits of better wastewater management largely involve avoiding social and environmental costs from poor wastewater management practices, listed in Table G.6. The first group of benefits are associated with improving household sanitation services, consistent with SDG 6.2.1a, the proportion of the population using safely managed sanitation services. For this study, we quantify the benefits of moving households from unimproved and basic sanitation to safely managed sanitation. Benefits of this transformation include seeking less healthcare, avoiding productive time losses from disease, reducing premature mortality, and time savings (Hutton, 2013).

The second group of benefits are associated with treating wastewater, consistent with SDG 6.3.1, the proportion of wastewater safely treated. These benefits are avoiding health, environmental, and productivity costs associated with contaminated water. For this study, we quantify the benefits of wastewater treatment by the amounts of key contaminants for chemical oxygen demand (COD), biological oxygen demand (BOD), N, and phosphorous (P) removed by each wastewater treatment system and applying shadow prices to those quantities as Table G.5 shows (Hernández-Sancho et al., 2010; 2015). This does not include the benefits of removing other contaminants (Hernández-Sancho et al., 2015).

The other benefit is the value of methane captured and reused for energy (addressed in the energy sector).

Table G.6 Non-technical benefits and costs of transforming wastewater

Benefit	Value	Data source
Improvements in health and productivity from better household sanitation	$200/year/person transitioned to safe sanitation	The per capita benefits were calculated by dividing the total annual benefit of transitioning from unimproved to improved sanitation in LAC (Table 9) by the total population receiving improved sanitation interventions in LAC (Table 1) in Hutton (2012), adjusted from 2010 to 2019 dollars. The sanitation ladder in Hutton (2012) calculates the benefits of moving from unimproved to improved sanitation, but where the latter term could be extended to include (i.e., safely managed) sanitation options of septic tanks and sewerage with wastewater treatment without affecting the value of benefits. We therefore assume that the benefits roughly apply to transitions from unimproved to safely managed sanitation and improved to safely managed sanitation.
Health, environment, and productivity benefits of improved water quality from more and better wastewater treatment	$51/kg P $20/kg N $0.13/kg of chemical oxygen demand (COD) $0.06/kg of biological oxygen demand (BOD)	Several studies (Hernández-Sancho et al. (2010, 2015) and Antalová and Haluš (2020) calculate the value of BOD, COD, N, and phosphorous (P) removed from wastewater effluent. We use average values and adjust to LAC in 2019.
Value of CH4 captured and used for energy	Endogenously valued in the energy sector model	

Solid Waste

Modeling solid waste

Solid waste is generated by consumption. Growth in domestic consumption is driven by GDP per capita, while growth in industrial consumption is driven by production (represented by value added). Solid waste streams are disaggregated by subtype—such as wood, paper, or food—and can be managed in several pathways (see Table G.7), consistent with the systems and discharge pathways described in the waste chapters IPCC's 2006 Guidelines for National Greenhouse Gas Inventories and the subsequent 2019 refinement. Emissions are calculated using specific emissions factors for each waste stream subtype managed in each system, consistent with the methodology and factors in the IPCC Guidelines.

Table G.7 Solid waste management systems

Solid waste management	Category	Description
Open dump	Unmanaged	Unmanaged discharge of solid waste (e.g., into above-ground piles, holes in the ground, or dumping into natural features such as ravines)
Open burning	Unmanaged	Unmanaged combustion of waste (e.g., in open air or open dumps, where emissions are directly released into the air)
Landfilling, with methane capture and flaring or reuse composting	Managed landfill	Solid waste collected and deposited in managed sites. This category includes different levels of methane and capture and flaring or reuse, the latter of which is an input into the energy sector.
	Managed biological treatment	Diverting organic matter for biological treatment, where degradable organic carbon largely is converted to CO2.
Anaerobic biogas	Managed biological treatment	Diverting organic matter to anaerobic biogas facilities, which expedites the natural decomposition of organic material without oxygen to generate CH4, which can be recovered for energy and is an input into the energy sector.
Recycling	Diversion	Diverting paper, plastics, and other waste materials to reuse in industrial processes.

Projecting solid waste emissions

Solid waste is estimated to increase under baseline conditions because of projected population and industrial activity increases. Table G.8 lists data sources we used to project solid waste emissions in addition to the 2006 and 2019 IPCC guidelines for national GHG inventories on which the solid waste model is based. A new dataset, the Hub Waste and Circular Economy from the Inter-American Development Bank (https://hubresiduoscirculares.org/en/) , may be useful in future updates, but was not available in time for the current analysis.

Table G.8 Data and methods for historical and baseline projection results

Data	Method for historical data	Method for projections
Production of solid waste	Waste production rates per inhabitant; volumes of waste and recycling rates of waste are obtained from World Bank's What a Waste database (2023).	Solid waste production volumes are projected in the future using GDP per capita
Treatment pathways for solid waste	Treatment pathways for different solid waste types are estimated using World Bank's What a Waste database (2023).	At baseline (i.e., no transformations) shares of treatment across pathways are assumed to remain constant. These shares are modified when transformations are activated in the simulation.
Emissions intensity (emissions per unit of wastewater, by pathway)		Emission factors are assumed constant in projections.
Total emissions	Historical sector emissions are used in the calibration process. Emissions data for calibration are obtained from Climate Watch (2022).	

Notes: For countries not included in the World Bank database, a statistical imputation model was trained using observations of countries in the database. This model uses GDP, urban, and rural population shares of countries to estimate imputed values. A data crosswalk between SiSePuede categories and World Bank's categories was used to be able to map data inputs.

Transforming solid waste

Defining solid waste transformations

Table G.9 shows transformations for reducing solid waste GHGs. They include reducing how much solid waste is produced; reducing emissions from waste management vehicles (included in the transportation sector); diverting recyclable and organic material; and improving methane management at landfills.

The most aggressive solid waste management transformation entails ending unmanaged waste disposal (i.e., open dumping and open burning) by 2030 and then by 2050; diverting 100% of organic waste to biological treatments; diverting 100% of recyclable materials to recycling facilities; and capturing and achieving 85% methane recovery and reuse in landfills. We define less aggressive transformations as the fraction of these targets reached by the specified year and, in the case of unmanaged solid waste disposal, we extrapolate the rate of change out to the year 2050.

Table G.9 Transformations affecting solid waste

Transformation	Description	Implementation
Reducing how much waste is produced	Households' food waste and other waste is reduced. Domestic demand for food also decreases as a result and affects agricultural production and exports in the AFOLU sector.	The maximum implementation of waste reduction involves reducing consumers' food waste by 50% by 2030 and by 75% by 2050,[2] and reducing other waste by 10% by 2030 and 25% by 2050. Lower implementation levels yield smaller reductions in these time frames.
Increasing waste collection	Increasing the amount of solid waste that is collected and safely managed, with the aim of ending open dumping and open burning	The maximum implementation of this transformation involves collecting 100% of waste (i.e., ending open dumping and open burning) by 2030. Lower implementation levels yield less collection by 2030.
Diverting more recyclables	Increasing the fraction of recyclable material that is diverted from the waste stream, recycled, and used in IPPU where it offsets producing virgin materials.	The maximum implementation involves diverting 100% of recyclable materials by 2050. Lower levels of implementation involve less diversion by 2050.
Diverting more organic waste	Increasing the fraction of organic material that is diverted from the traditional waste stream to managed biological treatment.	The maximum implementation involves diverting 100% of organic waste by 2050. Lower levels of implementation have less diversion by 2050.
Improving landfills gas capture and flaring or reuse	Increasing the fraction of methane captured and flaring or reuse. Captured energy is input into the energy sector.	The most aggressive implementation involves capturing and achieving 85% methane recovery and reuse in landfills. Lower implementation levels yield less capture by 2050.

[2] This transformation targets household food waste, which we estimate as 62 kg per capita per year in Latin America (233 kg per capita per year in total waste [FAO, 2016], 27% of which occurs in the consumption phase [UNEP 2018]). This is consistent with individual city or regional case studies, which report 34-95 kg of food waste per capita per year at the household level (UNEP, 2019).

These transformations are consistent with the United Nations Environmental Program (UNEP's) Latin America Waste Outlook (Table 6.8, 2015), which identifies several global solid waste management goals and describes how they relate to SDGs:

- Ensure access for all to adequate, safe, and affordable solid waste collection services.
- Eliminate uncontrolled dumping and open burning.
- Ensure the sustainable and environmentally sound management of all waste, particularly hazardous wastes.
- Substantially reduce waste generation through prevention and the 3Rs (reduce, reuse, and recycle), thereby creating green jobs.
- Halve global per capita food waste at the retail and consumer levels and reduce food losses in the supply chain.

Costs of solid waste transformations

The cost of waste minimization is calculated per ton of waste avoided (see Table G.10 for costs on different types of waste). Table G.10 also shows transformations to reduce solid waste GHGs. These transformations include reducing how much solid waste is produced; reducing emissions from waste management vehicles (included in the transportation sector); diverting recyclable and organic material; and improving methane management at landfills.

The most aggressive transformation of solid waste management involves ending unmanaged waste disposal (i.e., open dumping and open burning) by 2030 and then by 2050; additionally diverting 100% of organic waste to biological treatments; diverting 100% of recyclable materials to recycling facilities; and capturing and achieving 85% methane recovery and reuse in landfills. We define less aggressive transformations as the fraction of these targets reached by the specified year and, in the case of unmanaged solid waste disposal, extrapolate the rate of change out to the year 2050. Table G.11 shows each system's technical costs.

Table G.10 Waste reduction's technical costs

Waste Reduction	Annualized technical costs	Data sources and notes
Retail and consumer food Waste reduction	$100/ton of food waste avoided	**Costs are based on the average per-ton costs of consumer-facing actions to reduce food waste in the US found in the appendix of ReFED (2016), adjusted to LAC.**

Table G.11 Solid waste management's technical costs

Waste management	Technical costs	Data sources
Collection	$86/ton of waste	World Bank (2012) provides costs for collecting and managing waste for countries of different income groups. We use a LAC average to average costs between lower-middle and upper-middle income countries. We assume 70% of recycled and open dumped waste in LAC is collected, and 100% of waste in other management systems is collected.
Management	$10/ton—open dumping $57/ton—managed landfill $61/ton—composting $86/ton—anaerobic biogas $72/ton—recycling $70/ton—incineration	
Energy recovery	$170/ton waste feedstock (incineration) $500/ton of gas recovered (landfills, anaerobic digesters)	For management without energy recovery, we use average costs across the lower-middle and upper-middle income tiers. The recycling cost includes the cost of separation and materials recovery. The processing and manufacturing costs are included in the value of recyclables (discussed in benefits) and estimated from the EPA's documentation of paper recycling costs (EPA, 2019). Cost for energy recovery is based on IEA estimates (2020f).

Note: The technical costs and baseline service coverage in our study broadly align with the findings in Correal et al. (2023), which provides comprehensive data on municipal solid waste generation, collection, and final destination in LAC countries, as well as an assessment of the resource gap needed to fulfill SDGs related to the region's solid waste management by 2030.

Benefits of solid waste transformations

The GHG benefits from improving solid waste management are calculated endogenously in the model based on the amount of waste produced and fraction of waste handled by each management system in a baseline versus alternative future. Avoided emissions are valued by the social cost of carbon. Emissions benefits of using recycled materials instead of virgin materials are calculated in the IPPU sector, emissions benefits of lower food production requirements from avoided reduced food waste are calculated in the AFOLU sector, and emissions benefits of methane capture and use are calculated in the energy sector.

The non-GHG benefits of better solid waste management involve expenditure savings from reduced waste, avoided social and environmental externalities of poor solid waste management practices, and the value of byproducts from better solid waste management, including recyclable materials, compost, sludge (valued in the wastewater sector), and energy (valued in the energy sector). These benefits are listed in Table G.12.

Table G.11 Solid waste management's technical costs

Benefit category	Technical costs	Data sources
Value of waste avoided	$700/ton of food waste avoided	Food waste occurs across food types, and without specific information on the types of food that are wasted and have recovery potential in the supply chain, we use the average price of food across all product types.
Reduced environmental and health impacts from open dumps to managed systems	$115/ton of unmanaged waste transitioned to managed pathways	Wilson et al. (2015) suggest a "conservative" cost of $20-50/capita/year from unmanaged waste and describe an average waste of 220 kg/capita/year among the poorest. We calculate costs assuming $20/capita and 0.22 ton/capita, adjusted from 2015 to 2019 dollars.
Value of CH4 captured in landfills and used for energy	Endogenously assessed in the energy model	

Benefits of solid waste transformations

The GHG benefits from improving solid waste management are calculated endogenously in the model based on the amount of waste produced and fraction of waste handled by each management system in a baseline versus alternative future. Avoided emissions are valued by the social cost of carbon. Emissions benefits of using recycled materials instead of virgin materials are calculated in the IPPU sector, emissions benefits of lower food production requirements from avoided reduced food waste are calculated in the AFOLU sector, and emissions benefits of methane capture and use are calculated in the energy sector.

The non-GHG benefits of better solid waste management involve expenditure savings from reduced waste, avoided social and environmental externalities of poor solid waste management practices, and the value of byproducts from better solid waste management, including recyclable materials, compost, sludge (valued in the wastewater sector), and energy (valued in the energy sector). These benefits are listed in Table G.12.

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Are development and decarbonization conflicting or complementary goals? In this report, we explore how Latin America and the Caribbean can improve socioeconomic and development outcomes while also reaching net-zero greenhouse gas emissions by 2050. Specifically, we introduce SiSePuede, an open source decarbonization modeling toolkit that evaluates decarbonization actions' costs, benefits, and emissions reductions across the economy. We find that maximizing actions could achieve net-zero emissions in the region before 2050 and net $2.7 trillion in benefits compared to more traditional development. Benefits include massive fuel cost savings; avoided costs from reduced air pollution, congestion, and car crashes; and the value of ecosystem services from forests. Although there are many paths to net-zero emissions, three actions are critical: producing electricity with renewables, electrifying transport, and protecting and restoring forests by halting deforestation and shifting food-production patterns. Economy-wide strategies that implement these actions at scale can reduce emissions dramatically and net enormous benefits to the region even amid deep uncertainties, with a median of $1 trillion in net benefits across all scenarios. These benefits are unevenly distributed across sectors and actors, and across time, so realizing them and ensuring a just transition to net zero requires governments to overcome important financing, regulatory, infrastructure, and other barriers. Each country must tailor its own strategy to address development and emissions goals based on local priorities, capabilities, resources, and technical capacity. SiSePuede provides a robust analytical foundation to support these efforts.

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