Draft Research Report

Benefits and Costs of Decarbonizing Latin America and the Caribbean

Technical Appendices

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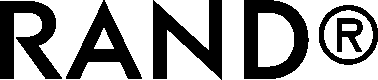
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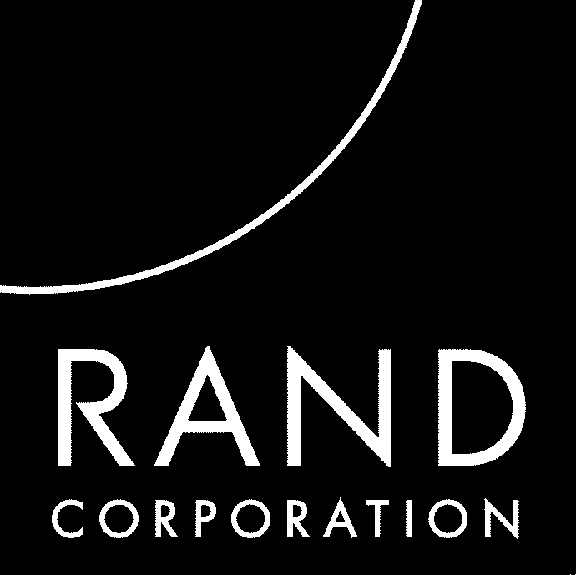
RR-A2847-1

December 2023

Prepared for the Inter-American Development Bank

Not Cleared for Public Release

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# About This Research Report

This volume contains the technical appendices to the report, *The Benefits and Costs of Reaching Net-Zero Emissions in Latin America and the Caribbean*.”

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# 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.

Diagram

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Note: Arrows indicate data flows between submodules in SiSePuede.

Figure 1. 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 (CH4, CO2, N2O), 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 (CO2e) emissions of each sector.

s.t

where

* is the estimated CO2e SiSePuede emissions in sector *s* at time *t*;
* is the historical series (we used climate watch data for this study, but other sources can also be used); and
* vector 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 2. 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.

Diagram

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Figure 3. Agriculture, Forestry, and Land Use (AFOLU) calibration.

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Figure 4. 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.

A white sheet with many small squares

Description automatically generated with medium confidence

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 matrix[[1]](#footnote-2) 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>.

# 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 sources |
| 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). We estimate $20/ha. |
| 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 Non-technical 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. | | |

### Transforming livestock

Livestock emissions can be reduced through transformations to enteric fermentation, manure management, and overall sector productivity. Many practices can contribute to these reductions but overlap or vary in regional applicability. For enteric fermentation and silvopasture, we describe strategies from the EPA (2019) and McKinsey (2020) that are non-duplicative, are shown to have significant applicability in LAC, and target emissions directly rather than as a co-benefit of increased productivity.

Table A.6 shows transformations to reduce emissions from livestock. Table A.7 shows the technical costs and benefits of these transformations. We have not identified sector-specific non-technical costs and benefits.

Table A.6 Livestock’s transformations

|  |  |  |
| --- | --- | --- |
| Transformation | Description | Implementation |
| Reducing enteric fermentation | Certain feed additives, such as propionate precursors, can inhibit enteric fermentation (EPA, 2019; McKinsey, 2020). In addition, genetics play a meaningful role in enteric fermentation, and animals can be selected for lower emissions (McKinsey, 2020). | 80% of ruminants receive enteric fermentation interventions |
| Managing manure | Manure can be managed through several pathways, including anaerobic digesters, lagoons, spreading on fields, and composting. The biogas from digesters can be captured and converted to energy (EPA, 2019; Frank et al., 2018). | 95% of manure is managed with a combination of anaerobic digestion, daily spread, dry lot, and composting, and 90% of biogas at anerobic digestion facilities is captured |
| Silvopasture | An agroforestry practice that integrates forestry, livestock, and forage crops to increase the livestock’s productivity while simultaneously sequestering carbon in trees. | 30% of pasture grazeland is converted to silvopasture |
| Improving livestock productivity | This encompasses many sector-wide improvements that increase productivity, including better feed conversion, animal health, and grazing practices. | Discussed in the section “Crosscutting Supply and Demand Changes” |
|  |  |  |

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.  Pagiola et al. (2007), for example, provide a range of costs for silvopasture, from $180 to $400/ha, which would be distributed across multiple years. They also estimate that silvopasture can increase stocking rates by 25% for cattle and reduce animal mortality. |

## 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

|  |  |  |
| --- | --- | --- |
| **Benefit or cost** | **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.

Table B.2 Forestry transformations

|  |  |  |
| --- | --- | --- |
| Transformation | Description | Implementation |
| Rehabilitating degraded land | Returns some fraction of grassland and cropland to secondary forest. | At maximum implementation, 20% of grassland and cropland is reforested by 2050. |
| Slowing or ending deforestation | The deforestation rate is slowed, or deforestation is ended. | At maximum implementation, deforestation is halted in 2030. |

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 (by 2050)** |
| *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 hydrogen. | 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. |
| N2O abatement in the chemicals industry (adipic and nitric acid production) | This transformation reduces nitrous oxide N2O process emissions from the chemicals industry by destroying the N2O. Applicable abatement measures include ammonia burner (avoid N2O formation), thermal decomposition, or catalytic decomposition (N2O removal). | Ninety percent of N2O 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 CO2 is key to reducing emissions from hard-to-abate sectors, particularly where production of CO2 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-CO2 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** **(LAC 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. |
| *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 | Value  (LAC 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 | Fuel costs are estimated for coal, oil, nuclear, naturals gas, coal and biomass using different datasets, including British Petroleum’s (BP’s) Statistical Review of World Energy (Dudley, 2019), and data from the World Nuclear Association (2023). | |
|  | 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 | Production of oil and natural gas can result in significant fugitive emissions of CH4, which has a higher global warming potential than CO2 (Gordon et al., 2023). This transformation replaces venting of fugitive emissions with flaring, which combusts CH4 into CO2 and lowers GWP (EPA, 2019). | Eighty percent of vented emissions are flared. |
| 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

|  |  |  |
| --- | --- | --- |
| **Transformation** | **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 Non-technical 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 projection** |
| 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

|  |  |  |
| --- | --- | --- |
| **Transformation** | **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). | 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 |  | 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). |
| Mode shift local and regional passenger travel |  |

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  (Transit cost is weighted assuming 75% bus, 25% rail) | 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 | Open defecation (OD) or basic latrines without wastewater treatment, corresponding to the lowest two rungs of the Joint Monitoring Program (JMP) sanitation ladder (unimproved and limited sanitation). | | |
| 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 baseline projection** |
| 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) | $6.5/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. |
| Improved sanitation (rural) | $68.1/capita/year |
| Safely managed sanitation (rural) | $102.1/capita/year |
| Unimproved sanitation (urban) | $6.5/capita/year |
| Improved sanitation (urban) | $34.1/capita/year |
| Safely managed sanitation  (urban, sanitation only) | $66.2/capita/year |
| *Industrial and domestic urban wastewater treatment* | | |
| No treatment | $[0.02, **0.06**, 0.30]/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. |
|  |  |
| Primary | $[0.24, 0**.64**, 3.10]/m3 |
| Secondary (aerobic) | $[0.40, **0.80**, 3.27]/m3 |
| Secondary (anaerobic) | $[0.40, **0.80**, 3.27]/m3 |
| Tertiary (aerobic) | $[0.80, **1.60**, 6.54]/m3 |
| Tertiary (anaerobic) | $[0.80, **1.60**, 6.54]/m3 |
| 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 | 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. |
| composting | 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 baseline projection** |
| 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]](#footnote-3) 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. |
|  | |  |  |

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 source** |
| 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.    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). |
| 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) |
|  | | |

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.12 Solid waste management’s non-GHG benefits

|  |  |  |
| --- | --- | --- |
| Benefit category | Benefit value or valuation method | Data source |
| 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 |  |

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1. SiSePuede treats the land-use transition matrix as a row-stochastic Markov chain. [↑](#footnote-ref-2)
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).  
     
    [↑](#footnote-ref-3)