The Benefits and Costs of Decarbonizing Costa Rica’s Economy

Appendixes

DAVID G. GROVES, JAMES SYME, EDMUNDO MOLINA-PEREZ, CARLOS CALVO HERNANDEZ (RAND CORPORATION)
LUIS F. VÍCTOR-GALLARDO, GUIDO GODÍNEZ-ZAMORA, JAIRO QUIRÓS-TORTÓS (UNIVERSITY OF COSTA RICA)
FELIPE DE LEÓN, ANDREA MEZA MURILLO (MINISTRY OF ENVIRONMENT AND ENERGY, CLIMATE CHANGE DIRECTORATE)
VALENTINA SAAVEDRA GÓMEZ, ADRIEN VOGT-SCHILB (INTER-AMERICAN DEVELOPMENT BANK)
Preface

## Contents

Preface ............................................................................................................................................ iii  
Figures ............................................................................................................................................. v  
Tables ............................................................................................................................................. vi  
Abbreviations ................................................................................................................................ vii  
Appendix A. Modeling Details and Sector Benefit and Cost Factors ............................................ 1  
  Transport Sector (Lines 1–3) .................................................................................................................... 1  
  Electricity Sector (Line 4) ........................................................................................................................ 4  
  Buildings Sector (Line 5) .......................................................................................................................... 6  
  Industry Sector (Line 6) ............................................................................................................................ 9  
  Waste Sector (Line 7) .............................................................................................................................. 14  
  Agricultural Sector (Line 8) .................................................................................................................... 18  
  Livestock Sector (Line 9) ........................................................................................................................ 21  
  Forestry Sector (Line 10) ........................................................................................................................ 24  
  Appendix A References .......................................................................................................................... 29  
Appendix B. Developing Socioeconomic Scenarios .................................................................... 36  
  Appendix B References .......................................................................................................................... 36  
Appendix C. Transportation Vulnerability Analysis Details ........................................................ 38  
  Transport Sector Analysis ....................................................................................................................... 38  
  Risk of High Transport Emissions ......................................................................................................... 38  
  Risk of Low Net Benefits from Transportation Decarbonization ......................................................... 39  
  Appendix C References .......................................................................................................................... 40  
Appendix D. Stakeholder Organizations ...................................................................................... 41
Figures

Figure A.1. Interactive Visualization of Key Transport Assumptions and Sources ....................... 2
Figure A.2. Interactive Visualization of Key Electricity Sector Assumptions and Sources .......... 5
Figure A.3. Interactive Visualization of Key Buildings Sector Assumptions and Sources .......... 8
Figure A.4. Interactive Visualization of Key Industry Sector Assumptions and Sources .......... 12
Figure A.5. Schematic of Waste Model .................................................................................. 15
Figure A.6. Interactive Visualization of Key Industry Sector Assumptions and Sources .......... 16
Figure A.7. Interactive Visualization of Key Agriculture Sector Assumptions and Sources ....... 20
Figure A.8. Proportions of Emissions by Different Animal Types in 2018 ................................. 22
Figure A.9. Interactive Visualization of Key Livestock Sector Assumptions and Sources ......... 23
Figure A.10. Interactive Visualization of Projected Land Use Changes from 2015 to 2050 for Without Decarbonization and with NDP Conditions .................................................................. 26
Figure A.11. Interactive Visualization of Key Forestry Sector Assumptions and Sources .......... 27
Figure B.1. Schematic for the Integration of the IEEM and Costa Rica Emissions Model ......... 37
Tables

Table A.1. Benefit Factors for the Transport Sector ................................................................. 3
Table A.2. Benefit Factors for the Electricity Sector .............................................................. 5
Table A.3. Electricity Sector Cost Factors ............................................................................. 6
Table A.4. Benefit Factors for the Buildings Sector ............................................................... 9
Table A.5. Building Sector Cost Factors ............................................................................... 9
Table A.6. Benefit Factors for the Industrial Sector ............................................................. 13
Table A.7. Costs Factors for the Industrial Sector ................................................................. 14
Table A.8. Benefit factors for the Waste Sector ................................................................. 17
Table A.9. Waste Sector Cost Factors .................................................................................. 18
Table A.10. Benefit Factors for the Agriculture Sector ...................................................... 21
Table A.11. Costs Factors for the Agriculture Sector .......................................................... 21
Table A.12. Benefit Factors for Livestock Sector ................................................................. 24
Table A.13. Costs Factors for Livestock Sector ................................................................ 24
Table A.14. Benefit Factors for the Forestry Sector ............................................................. 28
Table A.15. Costs Factors for the Forestry Sector ................................................................. 29
Table C.1. Scenario Discovery Analysis for Risk of High Transport Emissions .......... 39
Table C.2. Scenario Discovery Results for Risk of Low Net Benefits from Transportation

Decarbonization .................................................................................................................. 40
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2e</td>
<td>carbon dioxide equivalent</td>
</tr>
<tr>
<td>CR-IDPM</td>
<td>Costa Rica Integrated Decarbonization Pathways Model</td>
</tr>
<tr>
<td>GDP</td>
<td>gross domestic product</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gas</td>
</tr>
<tr>
<td>GJ</td>
<td>gigajoule</td>
</tr>
<tr>
<td>Gpkm</td>
<td>billions of passenger kilometers (gigapassenger kilometer)</td>
</tr>
<tr>
<td>Gtkm</td>
<td>grosse tonne kilometer</td>
</tr>
<tr>
<td>ICE</td>
<td>Instituto Costarricense de Electricidad</td>
</tr>
<tr>
<td>IEEM</td>
<td>Plataforma de Modelación Económico-Ambiental Integrada (Integrated Economic-Environmental Modeling)</td>
</tr>
<tr>
<td>IRENA</td>
<td>International Renewable Energy Agency</td>
</tr>
<tr>
<td>kWh</td>
<td>kilowatt hour</td>
</tr>
<tr>
<td>MtCO2e</td>
<td>megatons carbon dioxide equivalent</td>
</tr>
<tr>
<td>NDP</td>
<td>Costa Rica’s National Decarbonization Plan</td>
</tr>
<tr>
<td>OSeMOSYS-CR</td>
<td>Open Source energy Modelling System—Costa Rica</td>
</tr>
<tr>
<td>PJ</td>
<td>petajoule</td>
</tr>
<tr>
<td>PRIM</td>
<td>Patient Rule Induction Method</td>
</tr>
<tr>
<td>RDM</td>
<td>Robust Decision Making</td>
</tr>
<tr>
<td>vkm</td>
<td>vehicle kilometer</td>
</tr>
</tbody>
</table>
Appendix A. Modeling Details and Sector Benefit and Cost Factors

This appendix provides additional details about the models developed to estimate Costa Rica greenhouse gas (GHG) emissions and the benefits and costs of implementing the National Decarbonization Plan.

Transport Sector (Lines 1–3)

The transport sector is modeled using an open-source energy system modeling platform—OSeMOSYS-CR\textsuperscript{1}—which was configured to represent the Costa Rican electricity and transport sector by University of Costa Rica researchers. As part of this effort, we developed a set of assumptions to reflect future uncertainties. To integrate this model into the CR-IDPM framework, previously independent estimates of electricity demand by non-transport sectors were replaced by links to the other sector models. We also included variations in demand for transport that are consistent with three economic projections from the Costa Rica IEEM.

Projecting Transport Emissions, Benefits, and Costs

Because of the level of sophistication of the OSeMOSYS-CR model, there are many assumptions used to estimate future transportation emissions under “without decarbonization” conditions. Key assumptions include those about

\begin{itemize}
  \item the cost of fuels\textsuperscript{2}
  \item infrastructure costs for electrification, fuel changes, and modal changes
  \item technological costs
  \item elasticities of demand for different modes of transport
  \item new technology adoption rates.
\end{itemize}

To model the effects of the NDP on transportation emissions, we defined factors that affect the growth of the following parameters:

\begin{itemize}
  \item growth of electric public transport
  \item growth of hydrogen public transport
  \item growth of electric private transport
  \item growth of electric light freight
\end{itemize}

\textsuperscript{1} Details of the OSeMOSYS-CR model are in Electric Power and Energy Research Laboratory (EPERLab), 2020.

\textsuperscript{2} All costs in the main report and these appendixes are in U.S. dollars.
- growth of electric heavy freight
- growth of hydrogen heavy freight
- growth of share of public transport use
- growth of share of non-motorized transport.

Figure A.1 shows the baseline key assumptions driving estimates of GHG emissions with and without the NDP for the public transport sector. Go to the URL in the figure notes to view the interactive visualizations for all three transportation subsectors, and to see estimates of associated emissions.

Figure A.1. Interactive Visualization of Key Transport Assumptions and Sources

NOTES: This is a screenshot of Groves et al., “Evaluation of the Benefits and Costs of Decarbonization in Costa Rica,” 2020. Go to https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html to access this interactive tool. BAU denotes baseline assumptions of the “without decarbonization” estimate; NDP denotes the “with implementation of the NDP” estimate.

3 In the main report, we use the terms “without decarbonization” and “with implementation of the NDP” to denote our two estimates. In the interactive tool we developed (“Evaluation of the Benefits and Costs of Decarbonization in Costa Rica,” 2020), the “without decarbonization” estimate is labeled “BAU” (for “baseline assumptions”), and the “with implementation of the NDP” estimate is labeled “NDP.”
Quantifying Benefits

Transportation benefits include

- reduced social cost of carbon emissions, which reflect country-specific climate impacts
- reduced health impacts from pollution
- reduced medical costs from accidents
- improved productivity from reduced congestion.

### Table A.1. Benefit Factors for the Transport Sector

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced climate change impacts from emissions (reduced social cost of carbon)</td>
<td>Social cost of GHG emissions estimated for Costa Rica</td>
<td>[$0.36, $0.61, $1.04] per ton CO2e</td>
<td>Ricke et al., 2018a, 2018b.</td>
</tr>
<tr>
<td>Health savings from reduced emissions</td>
<td>Cost per ton of pollutant per quantify of fuel consumed</td>
<td>$0.0263 per liter (gasoline)</td>
<td>Coady et al., 2019, p. 39.</td>
</tr>
<tr>
<td></td>
<td>$0.3141 per liter (diesel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduced medical costs from accidents</td>
<td>Death costs (CD) $738,130 and cost of an injury (CI) $179,260 from technical reports provided by the government of Costa Rica, adjusting for (1) numbers of deaths and injuries per vehicle type and (2) the entire country (CD and CI are for the Great Metropolitan Area)</td>
<td>$56.19 million per Gpkm (private vehicles)</td>
<td>COSEVI, 2017.</td>
</tr>
<tr>
<td></td>
<td>$1.27 million per Gpkm (public transport vehicles)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$555.55 million per Gpkm (motorcycles)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improved productivity from reduced congestion</td>
<td>Congestion caused per vkm, per vehicle type</td>
<td>$0.046 per vkm (light vehicles and motorcycles)</td>
<td>Ministerio de Ambiente y Energía, Ministerio de Vivienda y Asentamientos Humanos, and Ministerio de Planificación Nacional y Política Económica, 2017.</td>
</tr>
<tr>
<td></td>
<td>$0.09 per vkm (heavy vehicles)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

Estimating Costs

The OSeMOSYS-CR model estimates costs for the transport sector through a large set of cost parameters reflecting up-front investment costs and maintenance costs. A complementary detailed cost analysis (Haro et al., 2019) provides estimates that are based on a different methodology yet similar results.
Electricity Sector (Line 4)

The electricity sector in Costa Rica is currently almost completely renewable, due to high levels of installed hydropower and some geothermal, wind, and solar development. The NDP includes actions to achieve and ensure 100 percent renewable capacity to support electrification of transport and industry. The electricity sector is modeled using the same open-source energy system modeling platform—OSeMOSYS—that was configured to represent the Costa Rican electricity and transport sector by University of Costa Rica researchers. Electricity demand is estimated independently for the building, industrial, and agricultural sectors outside of the OSeMOSYS-CR model. Historical and projected baseline assumption electricity demands were generated using data from Gallardo (2018). These demand estimates are passed to the OSeMOSYS-CR model, which also estimates electricity demand from the transport sector. OSeMOSYS-CR then determines how the electricity demand is satisfied by renewable and carbon-based electricity generation sources, and estimates any corresponding GHG emissions.

*Projecting Electricity Sector Emissions*

The OSeMOSYS-CR model includes estimates for the amount of renewable electricity generation capacity and GHG emissions factors to represent Costa Rica’s existing nonrenewable electricity generating facilities.

OSeMOSYS-CR includes assumptions about additional renewable capacity that would be developed as part of the NDP to ensure that the electricity sector is 100 percent renewable through 2050. Figure A.2 shows the baseline key assumptions driving estimates of GHG emissions with and without the NDP for the electricity sector. Go to the URL in the figure notes to view the interactive visualization.
Figure A.2. Interactive Visualization of Key Electricity Sector Assumptions and Sources

NOTES: This is a screenshot of Groves et al., “Evaluation of the Benefits and Costs of Decarbonization in Costa Rica,” 2020. Go to https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html to access this interactive tool. BAU denotes the “without decarbonization” estimate; NDP denotes the “with implementation of the NDP” estimate. GW = gigawatts.

Quantifying Benefits

There are a variety of benefits from maintaining the very high level of renewables in the electricity sector, including avoiding the need to import expensive fuels and emissions-related impacts. For this analysis, we quantify benefits related to reducing the social cost of carbon emissions and reducing health impacts from avoiding the use of nonrenewable electricity generating sources. Benefits to electricity users from switching to low-cost electricity are accounted for within the electricity-using sectors. For all sectors, we also combine the change in GHG emissions with and without the NDP and with a cost of carbon factor derived from the literature. The nominal value is $0.608 per ton carbon dioxide equivalent (CO2e).

Table A.2. Benefit Factors for the Electricity Sector

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced climate change impacts from emissions (reduced social cost of carbon)</td>
<td>Social cost of GHG emissions estimated for Costa Rica</td>
<td>[$0.36, $0.61, $1.04] per ton CO2e</td>
<td>Ricke et al., 2018a, 2018b.</td>
</tr>
<tr>
<td>Health savings from reduced emissions</td>
<td>Cost per ton of pollutant per quantify of fuel consumed</td>
<td>$0.0263 per liter (gasoline) $0.3141 per liter (diesel)</td>
<td>Coady et al., 2019, p. 39.</td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.
**Estimating Costs**

The OSeMOSYS-CR model estimates costs for the electricity sector through a set of cost parameters reflecting up-front investment costs and maintenance costs.

<table>
<thead>
<tr>
<th>Description</th>
<th>Factor</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs to increase transmission or distribution</td>
<td>Cost per PJ (historic average based on Instituto Costarricense de</td>
<td>$29.23 million per PJ</td>
<td>ICE, 2017.</td>
</tr>
<tr>
<td>capacity per unit energy</td>
<td>Electricity [ICE] data). The cost for transmission and distribution is assumed equal as a reference, although the literature suggests distribution expansions have higher costs.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costs of additional power plant capacity</td>
<td>Cost per added PJ production capacity in 2020 (or 2050). For solar and wind, the cost trajectories are taken from IRENA (2017, 2019), as well as an additional cost of storage per unit of capacity. The remaining plant types are overnight costs from the TIMES-CR model (DecisionWare Group LLC, 2017), which used ICE data.</td>
<td>$2,463.28 million per PJ (biomass)</td>
<td>ICE Data and International Renewable Energy Agency (IRENA) projections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1,269.78 million per PJ (diesel)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$4,650.33 million per PJ (fuel oil)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$7,828.28 million per PJ (geothermal)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$8,241.97 million per PJ (hydro dam)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$4,385.15 million per PJ (hydro run of river)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1,900 (1,553.5) million per PJ (solar)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$2,500 (2,153) million per PJ (wind)</td>
<td></td>
</tr>
<tr>
<td>NOTE: Costs inside parentheses are costs for 2050.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Buildings Sector (Line 5)**

The building sector model estimates GHG emissions from residential and commercial buildings. Emissions from residential buildings are calculated by combining estimates of the number of households with estimates of per household energy use rates, percentage of energy use met by electricity, and per-household carbon factors for non-electricity energy use. Stationary emissions from commercial buildings are calculated by combining estimates of commercial economic activity with estimates of energy use rates, percentage of
energy use met by electricity, and per-dollar value-added carbon factors for non-electricity energy use.

**Projecting Building Emissions**

The basic equation used to estimate future emissions from buildings is:

\[ E_t = A_t d_t (1 - \lambda_t) f_t \]

where:

- \( E \) = emissions [MtCO2e]
- \( A \) = number of households; value of commercial output [millions of $]
- \( d \) = energy demand per activity by sector [PJ per hour or PJ per million $]
- \( f \) = stationary emissions factor (e.g., from cooking [MtCO2e/PJ])
- \( \lambda \) = fraction of energy in from electricity \([0 \leq \lambda \leq 1]\)
- \( t \) = time slice.

Estimates of the number of houses in the future are developed using a historical relationship between the number of households, gross domestic product (GDP), and population. We combine the population projection from the IEEM (very modestly scaled to match the World Bank [2017] population estimate) with GDP projections from the IEEM and the historical relationship to estimate future numbers of houses. Future commercial economic activity is estimated by applying sector-based growth rates from the IEEM to recent World Bank value added estimates.

Energy demand from households and commercial activity is partitioned between the portion met by electricity and the portion met by on-site fossil-fuels, such as natural gas. Electricity demand is passed to the electricity sector model (OSeMOSYS-CR) and stationary emissions associated with non-electricity energy demand is modeled through emissions factors. Emissions from commercial buildings are calculated by combining estimates of commercial economic activity from the IEEM with estimates of energy use rates, percentage of energy use met by electricity, and carbon factors for non-electricity energy use.

Figure A.3 shows the baseline key assumptions driving estimates of GHG emissions with and without the NDP. Go to the URL in the figure notes to view the interactive visualizations, which include estimates of emissions and ranges for the inputs.
NOTES: This is a screenshot of Groves et al., “Evaluation of the Benefits and Costs of Decarbonization in Costa Rica,” 2020. Go to https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html to access this interactive tool. BAU denotes the “without decarbonization” estimate; NDP denotes the “with implementation of the NDP” estimate.

Quantifying Benefits

Benefits to reducing GHGs in the building sector include those related to reducing the social cost of GHG emissions and cost savings related to switching from natural gas and propane to lower-cost electricity. The parameters used for these benefits calculations are summarized in Table A.4.
Table A.4. Benefit Factors for the Buildings Sector

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced climate change impacts from emissions (reduced social cost of carbon)</td>
<td>Social cost of GHG emissions estimated for Costa Rica</td>
<td>[$0.36, $0.61, $1.04] per ton CO2e</td>
<td>Ricke et al., 2018a, 2018b.</td>
</tr>
<tr>
<td>Energy cost savings to building operators from switching to low-cost electricity (residential and commercial buildings)</td>
<td>Difference in energy costs between electricity and non-electricity sources</td>
<td><strong>Electricity</strong>: (2018) $0.14 per kWh; (2050, without decarbonization) $0.06, $0.08, $0.12 per kWh; (2050, with NDP) [$0.03, $0.05, $0.08] per kWh</td>
<td>Electricity costs are calculated by OSeMOSYS-CR. Non-electricity energy prices are proxied by propane and butane cost projections from RECOPE’s “Precios Históricos” (RECOPE, undated).</td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

Cost estimates for the buildings sector decarbonization actions are based on a single per household cost estimate for improving efficiency and electrification of households, and cost per commercial value added for improving efficiency and electrification of commercial buildings. Both of these factors are highly uncertain.

Table A.5. Building Sector Cost Factors

<table>
<thead>
<tr>
<th>Cost</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs for improving efficiency and electrification of households</td>
<td>Cost per household</td>
<td>[$400, $575, $850] per household</td>
<td>Baseline value based on estimate for increasing household efficiency, increased by about 3 times to account for electrification: Institute for Electric Efficiency, 2011, Table 2, p. 14. Range: author judgment.</td>
</tr>
<tr>
<td>Costs for improving efficiency and electrification of commercial buildings</td>
<td>Cost per commercial value added in 2020</td>
<td>[0.1%, 0.5%, 1.5%] value added in 2020</td>
<td>No source available, so we used a wide range with baseline assumption of 0.5 percent.</td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

Industry Sector (Line 6)

The industrial sector model estimates GHG emissions from energy used as inputs into the industrial sector (electricity and non-electricity), emissions released from industrial processes (e.g., CO2 releases from cement manufacturing), and emissions from the use of industrial materials, such as refrigerants and electronics. Recycled raw materials, such as glass and metals, are assumed to replace the production of virgin materials. The emissions savings from recycling...
versus virgin production of materials are captured in the waste sector, as a negative emissions associated with the recycled waste. This representation of the “circular economy” ensures that emissions savings are not double counted.

*Projecting Industrial Emissions*

Energy input emissions are projected by combining estimates of industrial, manufacturing, and mining activity (in terms of economic value added) from the IEEM with estimates of the energy demand per value added, the percentage of energy that is provided by sources other than electricity, and a GHG emissions factor for non-electricity energy use. Emissions associated with electricity use are captured in the electricity sector.

Process emissions are estimated for the four major emitting activities—the manufacture of cement, glass, lime, and carbide. Recent production estimates of cement are derived from the U.S. Geological Survey (undated). Cement emissions factors are calibrated to Costa Rica industrial conditions by dividing recent emissions estimates from the BUR by the production estimates. Glass, lime, and carbide emissions factors are estimated by dividing recent emissions from the BUR by 2015 manufacturing (glass and carbide) or construction and mining (lime) value added estimates from the World Bank (2020). Forward projections of production (for cement) and value added (for glass, lime, and carbide) are based on outputs from the IEEM.

Use emissions include those related to the use of chemicals and equipment across the industrial sector. We model emissions from the use of refrigeration and air conditioning, sodium carbonate, oil and lubricants, aerosols, electronic equipment, paraffin waxes, and fire suppression chemicals. Use of these chemicals and equipment are projected to increase proportionally as industrial value added estimates from the IEEM. These estimates are combined with GHG emissions factors that are estimated by dividing recent use emissions estimates from the BUR by recent industrial value added estimates.

The basic set of equations used to estimate future industrial emissions is:

\[ E_t = I_t + U_t + P^\text{other}_t + P^\text{cement}_t \]

Where:

\[ I_t = A_t d_t (1 - \lambda_t) f_t, \]

\[ U_t = A_t r_t, \]

\[ P^\text{other}_t = \sum_i A_{it} r_{it}, \]

and
\[ p_{cement}^t = A_{cement,t} p_t m_t, \]

where

- \( E \) = emissions [MtCO2e]
- \( A \) = value of industrial production (from IEEM—\( Ai \) is value added by industry) [million $]
- \( I \) = emissions from industrial energy use [MtCO2e]
- \( P_{other} \) = process emissions for non-cement industries [MtCO2e]
- \( P_{cement} \) = process emissions for cement [MtCO2e]
- \( U \) = emissions from industrial product use (refrigerants, electronics, hydrofluorocarbons, oil and lubricants, etc.) [MtCO2e]
- \( d \) = energy demand per activity [PJ per million $]
- \( f \) = industrial energy emissions factor per energy demand [MtCO2e per PJ]
- \( m \) = production emissions factor for cement [MtCO2e/Kt cement produced]
- \( p \) = cement production per activity [Kt cement produced per million $]
- \( r \) = process emissions factor for industry \( i \) [MtCO2e per million $]
- \( \lambda \) = fraction of energy in from electricity \([0 \leq \lambda \leq 1]\)
- \( i \) = industry [\( i = \text{glass production, lime, carbide} \)]
- \( t \) = time slice.

We model process emissions by combining estimates of future production with carbon emission factors. Estimates of future production are derived from estimates of future production value from the IEEM for cement, glass, and lime. We model emissions from energy inputs into the industrial sector (electricity and non-electricity) by estimating the total energy requirements, the share of energy met by electricity, and non-electricity carbon emission factors. Lastly, we model emissions from the use of industrial products, such as lubricants and refrigerants, by combining industrial production value estimates with emissions per economic value factors.

Figure A.4 shows the key assumptions driving estimates of GHG emissions with and without the NDP. Go to the URL in the figure notes to view the interactive visualizations, which include estimates of emissions and ranges for the inputs.
NOTES: This is a screenshot of Groves et al., “Evaluation of the Benefits and Costs of Decarbonization in Costa Rica,” 2020. Go to https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html to access this interactive tool. BAU denotes the “without decarbonization” estimate; NDP denotes the “with implementation of the NDP” estimate.

Quantifying Benefits

Benefits to reducing GHGs by the industrial sector include those related to reducing the social cost of GHG emissions, health savings from reduced pollutants from the use and combustion of fossil fuels, and cost savings from switching to lower cost electricity.
Table A.6. Benefit Factors for the Industrial Sector

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced climate change impacts from emissions (reduced social cost of carbon)</td>
<td>Social cost of GHG emissions estimated for Costa Rica</td>
<td>[$0.36, $0.61, $1.04] per ton CO2e</td>
<td>Ricke et al., 2018a, 2018b.</td>
</tr>
<tr>
<td>Health savings from reduced emissions</td>
<td>Cost per ton of pollutant per quantity of fuel consumed</td>
<td>$0.0263 per liter (gasoline)</td>
<td>Ministerio de Ambiente y Energía, Ministerio de Vivienda y Asentamientos Humanos, and Ministerio de Planificación Nacional y Política Económica, 2017.</td>
</tr>
</tbody>
</table>
| Cost savings to industrial producers from switching to low-cost electricity | Difference in energy costs between electricity and non-electricity sources | **Electricity**: (2018) $0.14 per kWh; (2050, without decarbonization) $0.06, $0.08, $0.12 per kWh; (2050, with NDP) [$0.03, $0.05, $0.08] per kWh  
**LPG**: (2018) $13.4 million per PJ; (2050) [$10.1, $20.3, $30.1] million per PJ | Electricity costs are calculated by OSeMOSYS-CR.  
Non-electricity energy prices are proxied by propane and butane costs projections from RECOPE’s “Precios Históricos” (RECOPE, undated). |
| Industrial productivity improvement due to process and energy efficiency | Percentage value increase as a function of percent of GHG emissions reduced | [10%; 33%; 45%]  
Example: 33% indicates that for every 10% GHG emission reduction, there would be a 3.3% value improvement | No source available, so used a wide range with baseline assumption of 33%. Informed by Wang et al. (2020), Rissman et al. (2020), and Talaei et al. (2019). |
| Cost savings from processing recycled glass and metal in lieu of virgin production | Accounted for in the waste sector                                      |                                                                   |                                                                        |

**Estimating Costs**

Costs for implementing the NDP plan industrial actions are approximated by those required to reduce emissions from cement—the largest source of emissions.
### Table A.7. Costs Factors for the Industrial Sector

<table>
<thead>
<tr>
<th>Cost</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of reducing industrial product use emissions</td>
<td>Percentage of industrial value</td>
<td>[0.3%, 0.5%, 1.5%] of industrial value at full implementation (2050)</td>
<td>No source available, so we used a wide range with baseline assumption of 0.5 percent.</td>
</tr>
<tr>
<td>Cost of increasing energy efficiency</td>
<td>Cost of energy efficiency often expressed in terms of $ per saved energy.</td>
<td>[$3, $5, $10] per GJ</td>
<td>United Nations Industrial Development Organization (2014) shows a cost curve for industrial energy efficiency from China. The range of actions are between close to $0 to $9 per GJ saved.</td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

### Waste Sector (Line 7)

GHG emissions savings from the waste sector can be achieved by reducing emissions that are emitted by solid and liquid waste as they decompose and/or are treated. They can also be achieved by introducing back into the economy raw materials that otherwise would need to be obtained from virgin sources through GHG emitting processes. We model both these pathways using a well-established methodology described in the *Guidelines for National Greenhouse Gas Inventories* (Intergovernmental Panel on Climate Change, 2006). The model considers:

- solid waste generated on a per capita basis
- liquid domestic and industrial waste generated on a per capita basis
- solid industrial waste generated on a per output basis
- net GHG emissions factors that account for the avoided emissions from virgin materials replaced by recycled or composted content.

The amount of waste generated from the residential sector is proportional to population, and the amount of waste generated from the industrial sector is proportional to industrial production estimates from the IEEM. Solid waste streams are disaggregated by subtype—wood, paper, food, etc.—that is burned, landfilled, recycled, composted, or unaccounted for, each with their own equations that govern emissions. Liquid waste can be discharged into the environment or sent to formal treatment facilities, sewers without treatment, latrines, or septic tanks. Each of these end states are associated with distinct methane correction factors in liquid waste equations. In
recycling equations, some solid waste types (such as aluminum) are associated with negative net emission factors that represent a reduction in emissions from virgin production.

Figure A.5 shows a basic schematic of the model’s calculations.

**Figure A.5. Schematic of Waste Model**

![Schematic of Waste Model](image)

SOURCE: Based on IPCC, 2006.
NOTES: CH4 = methane, N2O = nitrous oxide.

**Projecting Waste Sector Emission**

Emissions are estimated to increase under “without decarbonization” conditions due to projected population and industrial activity increases. Emissions reductions as part of the NDP result from the following interventions: increased recycling and composting, increased centralized sewerage and treatment of sewage in urban areas, increased secure sanitation in rural areas, increased disposal of non-recycled waste in landfills, and increased methane capture at landfills. Historical liquid and solid waste streams and per capita waste factors are based on Solera et al. (2015), and additional baseline recycling stream estimates were guided by Canelo (2018) and Ben-Haddej et al. (2010). Methane correction factors for streams of liquid wastewater and solid waste disposal are taken from Solera et al. (2015) and IPCC (2019) Volume 5, Chapter 6. Net emissions factors for recycled materials are obtained from Turner, Williams, and Kemp (2015).

Figure A.6 shows the key assumptions driving estimates of GHG emissions with and without the NDP. Go to the URL in the figure notes to view the interactive visualizations, which include estimates of emissions and ranges for the inputs.
Quantifying Benefits

Benefits to reducing GHGs by the waste sector include those related to reducing the social cost of GHG emissions, health and aesthetic benefits from reducing untreated wastewater pollutants from use and combustion of fossil fuels, and the value of recycled solid waste and treated wastewater.

To estimate the benefit of recycling waste, we assume a percentage of newly recycled waste that has value (currently 50 percent) and then multiply by an uncertain value factor. Estimates for the value of treating wastewater are based on a willingness-to-pay study of households in Uruguay (Dixon, 2012). The specific value of recycled water is unknown, so we consider a wide range of plausible values based on the price charged for treated water in Costa Rica.
### Table A.8. Benefit Factors for the Waste Sector

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced climate change impacts from emissions (reduced social cost of carbon)</td>
<td>Social cost of GHG emissions estimated for Costa Rica</td>
<td>[$0.36, $0.61, $1.04] per ton CO2e</td>
<td>Ricke et al., 2018a, 2018b.</td>
</tr>
<tr>
<td>Value of recycled glass</td>
<td>Value of recycled or composted material</td>
<td>[$268, $447, $626] per ton of recycled material</td>
<td>Mean imputed from Montero (2009), with assumed bottle weight of 190g (Gyekye, 2014) and ±40% range.</td>
</tr>
<tr>
<td>Value of recycled metal</td>
<td>Value of recycled or composted material</td>
<td>[$1,463, $2,490, $3,517] per ton of recycled material</td>
<td>Imputed from Lobo et al. (2016) value of exported scrap material.</td>
</tr>
<tr>
<td>Value of recycled paper</td>
<td>Value of recycled or composted material</td>
<td>[$72, $132, $193] per ton of recycled material</td>
<td></td>
</tr>
<tr>
<td>Value of recycled plastic</td>
<td>Value of recycled or composted material</td>
<td>[$452, $489, $525] per ton of recycled material</td>
<td></td>
</tr>
<tr>
<td>Value to residents of sewage service</td>
<td>Household value of sewage hookup. Use willingness-to-pay survey from study of households in Uruguay.</td>
<td>[$150, $270, $320] per year per household</td>
<td>Baseline assumption value from Dixon (2012). Range from author judgment.</td>
</tr>
<tr>
<td>Value to environment from collecting and treating sewage instead of informal disposal</td>
<td>Estimate of environmental benefits to community from additional household connection.</td>
<td>[$10, $29, $40] per year per household</td>
<td>Baseline assumption value from Dixon (2012). Range from author judgment.</td>
</tr>
<tr>
<td>Value of recycled water for other uses (i.e., circular economy)</td>
<td>Value of treated wastewater</td>
<td>[$100, $200, $300] per thousand cubic meters</td>
<td>Very conservative estimate of potential value of treated wastewater. Retail rates for treated water supplies varies between $550 and $2,130 per thousand cubic meters for regular domestic use (Autoridad Reguladora de los Servicios Públicos [ARESEP], 2020)</td>
</tr>
</tbody>
</table>

**NOTE:** Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

### Estimating Costs

Costs for reducing GHG emissions in the waste sector primarily comes from those required to increase the collection of waste, increase recycling and composting, increased treatment of sewage, and capture of methane from landfills. We assume a cost of recycling waste that is equivalent to the value of recycled waste estimated above for the baseline assumptions. The
uncertainty analysis then explores variability around this estimate. The cost of recycling waste is derived from the literature.

Table A.9. Waste Sector Cost Factors

<table>
<thead>
<tr>
<th>Cost</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs to increase collection of waste</td>
<td>Unit cost of increasing collection of waste</td>
<td>[$45, $72, $100] per ton of collected waste</td>
<td>“World Bank: Costa Rica’s Waste Generation Expected to Double by 2025,” 2012.</td>
</tr>
<tr>
<td>Costs to increase recycling and composting as fraction of value</td>
<td>Costs of recycling and composting as fraction of value</td>
<td>[0.9, 1, 1.5]</td>
<td>Cost is assumed as a fraction of calculated value.</td>
</tr>
<tr>
<td>Costs to increase treatment of sewage in urban areas</td>
<td>Unit costs of increasing treatment in urban areas with sewers</td>
<td>[$830, $1,063, $1,354] per household</td>
<td>AyA, 2016. Values were imputed so that undiscounted aggregate costs would be equivalent to investment totals from the PNIS.</td>
</tr>
<tr>
<td>Costs to increase urban sewer connections</td>
<td>Unit costs of expanding sewer network and connection in urban areas</td>
<td>[$1,088, $6,906, $10,181] per household</td>
<td></td>
</tr>
<tr>
<td>Costs to increase secure sanitation in rural areas</td>
<td>Unit costs of converting latrines and other types to septic tanks for rural populations</td>
<td>[$172, $366, $503] per household</td>
<td></td>
</tr>
<tr>
<td>Costs to rehabilitate existing sewer networks and treatment facilities</td>
<td>Aggregate cost (spread over 26 years—2020 to 2045)</td>
<td>[$2,055, $2,569, $3,083] million</td>
<td>Lower bound from Stege and Michelson, 2008.</td>
</tr>
<tr>
<td>Cost to increase methane capture from landfills</td>
<td>Cost per ton of methane captured from landfills</td>
<td>[$12, $60, $91] per ton of methane</td>
<td>Upper bound from U.S. Environmental Protection Agency, 2020</td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

Agricultural Sector (Line 8)

The agricultural sector model estimates GHG emissions associated with the land and crop processes (e.g., soil emissions, net crop emissions, fertilizer application, and burning of waste) and non-electricity energy inputs, such as fuel for agricultural equipment. Emissions associated with electricity use are captured in the electricity sector.

Emissions from the agricultural sector are disaggregated by the following major crops:

- coffee
- fruits
- palm oil
- pineapple
• rice
• sugarcane
• vegetables
• bananas

and an “other” category to represent all other crops.

Crop process emissions are assumed to be proportional to the area of land used for cultivation and crop-specific emissions factors. Current emissions factors are derived using current land use estimates from Quirós-Tortós (2020) and crop-specific emissions estimates from the BUR. Changes in land use in the future are informed by the IEEM. Emissions from energy use for agricultural activities are calculated to be proportional to the sum of crop and livestock value added, which is projected by the IEEM.

The primary equation for the agriculture model is:

\[ E_t = \sum_{s} (A_{s,t} \times F_{s,t}) \]

where:

• \( E \) = emissions
• \( A \) = area by crop cultivation
• \( F \) = emission factor
• \( s \) = type of crop
• \( t \) = time.

**Projecting Agricultural Emissions**

Agricultural emissions are estimated to increase under “without decarbonization” conditions because of projected increases in land used to cultivate crops and the intensity of crop production, represented by the economic value of the production. Emissions reductions as part of the NDP result from reducing GHG emissions from crop cultivation processes, planting trees, and reducing the required energy input to produce crops. These reductions are represented in the model through changes in the emissions per unit area of crops (carbon intensity of crop production) and changes in the energy requirements per crop value.

Figure A.7 shows the key assumptions driving estimates of GHG emissions with and without the NDP. Go to the URL in the figure notes to view the interactive visualizations, which include estimates of emissions and ranges for the inputs.
Quantifying Benefits

For all crops, we combine the change in GHG emissions with and without the NDP and with a cost of carbon factor derived from the literature. The nominal value is $0.608 per ton CO2e. For each crop, the sector model estimates the economic value of the crop for and the corresponding emissions due to its cultivation with and without the NDP. The literature suggests that improving practices to reduce emissions also can increase yields and thus economic value. To represent this benefit we use an uncertain parameter that specifies the elasticity of economic value increase to emissions reduction. For example, a 0.33 value for this parameter indicates that every 10 percent of GHG emissions reduction leads to a 3.3 percent value increase.
Table A.10. Benefit Factors for the Agricultural Sector

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced climate change impacts from emissions (reduced social cost of</td>
<td>Social cost of GHG emissions estimated for Costa Rica</td>
<td>[$0.36, $0.61, $1.04] per ton CO2e</td>
<td>Ricke et al., 2018a, 2018b.</td>
</tr>
<tr>
<td>change)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased crop yields due to agricultural improvements to reduce</td>
<td>Percentage value increase as a function of percentage of GHG emissions</td>
<td>[10%, 33%, 45%]</td>
<td>Author’s judgment, informed by Karlsson et al. (2020) and Verspecht et al. (2012)</td>
</tr>
<tr>
<td>emissions</td>
<td>reduced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost savings from switching to low-cost electricity</td>
<td>Difference in energy costs between electricity and non-electricity</td>
<td><strong>Electricity:</strong> (2018) $0.14 per kWh; (2050,</td>
<td>Electricity costs are calculated by OSeMOSYS-CR.</td>
</tr>
<tr>
<td></td>
<td>sources</td>
<td>without decarbonization) $0.06, $0.08, $0.12 per kWh; (2050, with NDP) $0.03, $0.05, $0.08 per kWh</td>
<td>Non-electricity energy prices are proxied by propane and butane costs projections from RECOPE’s Precios Históricos (RECOPE, undated).</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>LPG:</strong> (2018) $13.4 million per PJ; (2050) $[10.1,$20.3,$30.1] million per PJ</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

Estimating Costs

We estimate the costs of agricultural sector decarbonization actions by cost factors specific to coffee farms and all other crops.

Table A.11. Costs Factors for the Agriculture Sector

<table>
<thead>
<tr>
<th>Cost</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of implemented GHG emissions programs for coffee farms</td>
<td>Cost of program implementation per farm</td>
<td>[$13,000; $22,000; $30,000] per farm</td>
<td>Nationally Appropriate Mitigation Actions, Café de Costa Rica, undated, p. 6 (total cost per productivity level). Increased by about three times to be conservative. Range: author judgment.</td>
</tr>
<tr>
<td></td>
<td>Applied to 20,000 farms (approximate number in Costa Rica)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of programs to reduce GHG emissions for other crops</td>
<td>Cost of program implementation per ton of GHG emissions reduced</td>
<td>[$30, $60, $100] per ton CO2e</td>
<td>Gillingham and Stock, 2018, p. 59, Table 2.</td>
</tr>
<tr>
<td></td>
<td>(Range from source expanded by authors.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.
Livestock Sector (Line 9)

The livestock sector model estimates GHG emissions from the raising of ten major animal types:

- Meat cattle
- Milk cattle
- Dual-purpose cattle
- Goats
- Horses
- Mules
- Pigs
- Poultry
- Sheep
- Water buffalo.

The GHG emissions for each type of animal is based on per animal emissions rates, which is composed of separate emission factors for enteric fermentation and manure. As seen in Figure A.8, the vast majority of current (year 2018) emissions come from cattle and horses.

Figure A.8. Proportions of Emissions by Different Animal Types in 2018

Projected Livestock Emissions

Livestock emissions are estimated to increase under “without decarbonization” conditions as the sizes of herds increase. Projections of future herd sizes are based on growth rates of herd size estimated by the IEEM. Emissions reductions as part of the NDP result from reducing GHG emissions related to enteric fermentation and manure management. These are represented in the
model using percentage reduction factors for GHG emissions from enteric fermentation and
manure.

Figure A.9 shows the key assumptions driving estimates of GHG emissions with and without
the NDP. The vast majority of GHG emissions derive from cattle, thus we show only model
values for cattle. Go to the URL in the figure notes to view the interactive visualizations, which
include estimates of emissions and ranges for the inputs.

**Figure A.9. Interactive Visualization of Key Livestock Sector Assumptions and Sources**

![Livestock Parameters](image)

<table>
<thead>
<tr>
<th>Driver (Units)</th>
<th>BAU</th>
<th>NDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Livestock Value Added (USD billions)</td>
<td>1.23</td>
<td>3.46</td>
</tr>
<tr>
<td>Dual Purpose Cattle (animals)</td>
<td>627K</td>
<td>1,211K</td>
</tr>
<tr>
<td>Goats (animals)</td>
<td>25,082</td>
<td>49,069</td>
</tr>
<tr>
<td>Horses (animals)</td>
<td>1,126K</td>
<td>2,252K</td>
</tr>
<tr>
<td>Meat Cattle (animals)</td>
<td>563K</td>
<td>1,120K</td>
</tr>
<tr>
<td>Milk Cattle (animals)</td>
<td>393K</td>
<td>783K</td>
</tr>
<tr>
<td>Mules (animals)</td>
<td>5,273</td>
<td>9,636</td>
</tr>
<tr>
<td>Pigs (animals)</td>
<td>462,282</td>
<td>852,158</td>
</tr>
<tr>
<td>Poultry (animals)</td>
<td>24,109,000</td>
<td>46,092,063</td>
</tr>
<tr>
<td>Sheep (animals)</td>
<td>2,890</td>
<td>5,201</td>
</tr>
<tr>
<td>Water Buffalo (animals)</td>
<td>4,313</td>
<td>7,760</td>
</tr>
<tr>
<td>% Reduction in carbon intensity of enteric fermentation (%)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>% Reduction in carbon intensity of manure (%)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

NOTES: This is a screenshot of Groves et al., “Evaluation of the Benefits and Costs of Decarbonization in Costa Rica,” 2020. Go to https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html to access this interactive tool. BAU denotes the “without decarbonization” estimate; NDP denotes the “with implementation of the NDP” estimate.

**Quantifying Benefits**

Benefits from decarbonizing the livestock sector are related to reducing climate impacts on
Costa Rica, as represented by a Costa Rica cost of carbon factor, and improving the value of
pastureland through improved livestock management practices, including planting trees.
Specifically, we combine estimates of changes in GHG emissions between “without
decarbonization” and “with implementation of the NDP” conditions for range animals (cows,
goats, horses, mules, sheep, and water buffalo), using a benefit factor derived from the literature.
Table A.12. Benefit Factors for Livestock Sector

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced climate change impacts from emissions (reduced social cost of carbon)</td>
<td>Social cost of GHG emissions estimated for Costa Rica</td>
<td>[$0.36, $0.61, $1.04] per ton CO2e</td>
<td>Ricke et al., 2018a, 2018b.</td>
</tr>
<tr>
<td>Value of improved soil health and productivity from improved livestock management</td>
<td>Increased value of pasture land per GHG emissions reduction</td>
<td>[$1, $2.46, $3.5] per ton CO2e</td>
<td>Henderson et al., 2017; Arango et al., 2020.</td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

Estimating Costs

Cost of livestock sector GHG reduction is based on an estimated unit cost for reducing emissions in pasture land from the literature.

Table A.13. Costs Factors for Livestock Sector

<table>
<thead>
<tr>
<th>Cost</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of programs to reduce GHG emissions from cattle</td>
<td>Cost of program implementation per ton of GHG emissions reduced. Includes feed alternatives and diet supplements, implementation of efficiency programs, reducing stocking rate, and increasing biological control.</td>
<td>[$50, $71, $100] per ton CO2e</td>
<td>Gillingham and Stock, 2018, p. 59, Table 2. Range: author judgment.</td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

Forestry Sector (Line 10)

Existing forests (including mangroves) sequester carbon dioxide. Conversion of forested lands to other land types emits carbon dioxide into the atmosphere. The forestry model estimates GHG emissions associated with these two components: (1) emissions related to conversion of forests to other land types and (2) net emissions (primarily sequestration) from existing forests (including mangroves).

Separate GHG emission factors are used to represent net sequestration by the following land use categories:

- primary and secondary forest of the following types (wet, moist, dry, mangrove, and palm)
- grasslands
- cropland
• wetlands
• settlements
• other.

The primary equations for the forestry sector model are:

\[ E_t = \sum_{s \in S} A_{st} X_{st} + \sum_{s \in S_c} \sum_{f \in S_F} A'_{f, st} C_{fs} \]

such that:

\[ L = \sum_{s \in S} A_{st} \]

where:

• \( E \) = emissions [MtCO2e]
• \( A \) = area by type of land use \( s \) [hectares]
• \( A' \) = area of forest type \( f \) converted by type of land use \( s \) [hectares]
• \( C \) = emission factor for conversion of forest to another type of land use, \( s \) [MtCO2e per hectare]
• \( L \) = estimated total area, assumed to be 5,113,939.5 ha (Quirós-Tortós, 2020) [hectares]
• \( X \) = existing coverage emission factor (forested lands have a negative emission factor) [MtCO2e per hectare]
• \( S \) = all land use types
• \( S_f \) = all forested land use types (\( S_f = \{ \text{wet primary, wet secondary, moist primary, moist secondary, dry primary, dry secondary, mangroves primary, mangroves secondary, palm primary, palm secondary} \})
• \( S_c \) = all land use types with conversion emission factor (\( S_c = \{ \text{cropland, grassland} \})
• \( s \) = land use type
• \( t \) = time.

Conversion emissions are calculated for the forested land classes to cropland and grassland. Estimates of existence emissions for cropland are treated in the agricultural sector.

Projected land use for the “without decarbonization” cases are derived from transition probability matrices developed by Quirós-Tortós (2020). We started by calculating the patterns of change from 2010 to 2015 and applying these changes forward through 2050. We made minor adjustments so that change in agricultural lands would be consistent with projections from the IEEM. For the NDP conditions, we reduced the amount of primary forest deforestation from current rates to zero by 2050. Other options for increasing forested area could also be explored, including increasing secondary forests even more than they are projected to increase under
“without decarbonization” conditions. Note that planting trees in agricultural areas (for example, coffee farms) is a strategy for reducing net emissions in the agricultural sector. Agricultural lands with increased trees are still classified as agricultural in this study. Figure A.10 shows the area for each land class for 2015 and 2050 for the “without decarbonization” and “with implementation of the NDP” conditions. Go to the URL in the figure notes to access this interactive visualization.

**Figure A.10. Interactive Visualization of Projected Land Use Changes from 2015 to 2050 for Without Decarbonization and with NDP Conditions**

---

**NOTES:** This is a screenshot of Groves et al., “Evaluation of the Benefits and Costs of Decarbonization in Costa Rica,” 2020. Go to https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html to access this interactive tool. BAU denotes the “without decarbonization” estimate; NDP denotes the “with implementation of the NDP” estimate.

**Projecting Forestry Net Emissions**

Net land use emissions are estimated to be increasingly negative under “without decarbonization” conditions because of an anticipated continued reduction in deforestation. Net emissions with the implementation of NDP are projected to become further negative as deforestation of primary forest is reduced and investments are made in increasing the GHG sequestration potential of existing forests.
Figure A.11 shows the key assumptions driving estimates of GHG emissions with and without the NDP. Go to the URL in the figure notes to view the interactive visualizations, which include estimates of emissions and ranges for the inputs.

**Figure A.11. Interactive Visualization of Key Forestry Sector Assumptions and Sources**

NOTES: This is a screenshot of Groves et al., “Evaluation of the Benefits and Costs of Decarbonization in Costa Rica,” 2020. Go to https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html to access this interactive tool. BAU denotes the “without decarbonization” estimate; NDP denotes the “with implementation of the NDP” estimate.

**Quantifying Benefits**

There are a variety of benefits associated with increasing net sequestration through improving forest extent and heath. For this study we quantify the benefits from reducing the social cost of carbon emissions, increasing the value of biodiversity, and increasing climate resilience.

For all sectors, we combine the change in GHG emissions with and without and with a cost of carbon factor derived from the literature. The nominal value is $0.608 per ton CO2e.
A comprehensive assessment of ecosystem service values for forests and mangroves in Costa Rica provides estimates of per area and year ecosystem service benefits (Proyecto Humedales de SINAC-PNUD-GEF, 2017). Benefits include those related to

- services (hydro energy, food, genetic material, medicines, wood, firewood and charcoal, forage food, other raw materials, and freshwater)
- regulation (water and flow, water quality, biologic control, climate, erosion, resilience, pollination)
- cultural (tourism and cultural resources)
- additional services (protection of biodiversity, hatcheries, soil fertility).

For benefits due to preservation of forested area as part of NDP implementation, we combine changes in wet, dry, and mangrove forests with and without the NDP with the ecosystem service benefit factors to estimate the ecosystem service benefits of the NDP.

There may be an additional ecosystem service benefit from investments to increase sequestration from existing forests. We estimate this very uncertain benefit using a benefit elasticity factor. For each percentage increase in sequestration, we assume a proportional increase in ecosystem services. For example, a factor value of 0.33 would indicate that a 15 percent increase in sequestration would lead to a 5 percent increase in ecosystem services.

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced climate change impacts from emissions (reduced social cost of carbon)</td>
<td>Social cost of GHG emissions estimated for Costa Rica</td>
<td>[$0.36, $0.61, $1.04] per ton CO2e</td>
<td>Ricke et al., 2018a, 2018b.</td>
</tr>
</tbody>
</table>
| Value of increased ecosystem services due to forest preservation | Estimates of the value of ecosystem services by type of forest         | **Primary Wet Forest**: [$15,000, $25,000, $30,000] per hectare per year  
**Primary Dry Forest**: [$30, $49, $60] per hectare per year  
**Primary Mangrove Forest**: [$10,000, $25,000, $30,000] per hectare per year 
**Secondary Forests**: 50% of primary (author’s judgment) | Proyecto Humedales de SINAC-PNUD-GEF, 2017: Tropical/rainforests (Table 4.1), Dry forest (Table 4.2), Mangroves (Table 4.3). |
| Value of increased ecosystem services due to improved management | Estimate of the relative increase in ecosystem service value (per parameter above) per percentage increase in CO2 sequestration | [0, 33%, 50%]  
Example: 33% indicates that for every 10% increase in sequestration, ecosystem services would increase by 3.3% | Author judgment. |

NOTE: Ranges are indicated in brackets, with the "Baseline Assumption" bolded.
**Estimating Costs**

We estimate the opportunity costs from reducing deforestation and the cost of increasing carbon sequestration from existing forests.

We consider the value of timber that is not harvested, the lost potential value of agriculture, and lost potential value of raising livestock. We assume a simple unit value of timber derived from recent land sales advertisements. An alternative approach of using the value of payments for conservation easements would lead to significantly lower costs (Porras et al., 2013). The opportunity cost from not cultivating the land is derived endogenously from the model, using the difference in land area for agriculture and grasslands and the value of agriculture and grazing. A simple elasticity factor is assumed to estimate the proportion of grassland that would have been used for grazing.

**Table A.15. Costs Factors for the Forestry Sector**

<table>
<thead>
<tr>
<th>Cost</th>
<th>Factor</th>
<th>Baseline Assumption and Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of timber not harvested</td>
<td>Value of timber ($ per hectare)</td>
<td>[$16,000; $21,100, $33,000] per hectare</td>
<td>Rough estimate based on authors’ review of land solicitations. Estimate is conservative, in that using the value of forest conservation easements would be significantly lower—$640 to $800 per hectare (using 2013 figures) (Porras et al., 2013).</td>
</tr>
<tr>
<td>Opportunity cost of forgone agriculture</td>
<td>Endogenous calculation based on agricultural land area differences between the NDP and “without decarbonization” condition and value of agriculture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opportunity cost of forgone livestock</td>
<td>Endogenous calculation based on livestock differences between the NDP and “without decarbonization” conditions times an elasticity factor and value of agriculture</td>
<td>[25%, 50%, 75%]</td>
<td>Author’s judgment.</td>
</tr>
<tr>
<td>Cost of increasing carbon sequestration from existing forests</td>
<td>Unit cost of increasing sequestration</td>
<td>[$50, $80, $120] per ton CO2e</td>
<td>Busch et al., 2019.</td>
</tr>
</tbody>
</table>

NOTE: Ranges are indicated in brackets, with the “Baseline Assumption” bolded.

**Appendix A References**

Arango, Jacobo, Alejandro Ruden, Deissy Martinez-Baron, Ana María Loboguerrero, Alexandre Berndt, Mauricio Chacón, Carlos Felipe Torres, Walter Oyhantcabel, Carlos A. Gomez, Patricia Ricci, Juan Ku-Vera, Stefan Burkart, Jon M. Moorby, and Ngonidzashe Chirinda,


https://thecostaricanews.com/costa-rica-recycles-only-6-6-of-its-daily-residues/


EPERLab—See Electric Power and Energy Research Laboratory.


ICE—See Instituto Costarricense de Electricidad.
https://www.edisonfoundation.net/-/media/Files/IEI/publications/IEE_BenefitsofSmartMeters_Final.ashx

As of October 8, 2020:
https://www.grupoice.com/wps/wcm/connect/32e304c0-bff9-4436-ace0-33e13a85d3da/Plan+de+Expansi%C3%B3n+de+Transmisi%C3%B3n+2017-2027.pdf?MOD=AJPERES&CVID=m1s2MEe

Intergovernmental Panel on Climate Change, *Guidelines for National Greenhouse Gas Inventories*, 2006. As of October 7, 2020:


IPCC—See Intergovernmental Panel on Climate Change.


Nationally Appropriate Mitigation Actions, Café de Costa Rica, NAMA Facility Administración de Finca, undated. As of October 8, 2020: https://www.namacafe.org/sites/default/files/content/bloque3_administracion_de_finca.pdf


Appendix B. Developing Socioeconomic Scenarios

The Integrated Economic-Environmental Modeling (IEEM) Platform is a future-looking computable general equilibrium framework that enables the analysis of the impact of public policy and investment on indicators such as GDP, income and employment, but also on wealth and natural capital (Banerjee et al., 2016). For this study, we used the IEEM modeling framework to generate a set of growth scenarios for the Costa Rican economy that then were integrated into the modeling architecture of the NDP cost-benefit study. This integration allows for a more detailed understanding of how different growth paths impact the NDP cost-benefit ratio in the ten proposed lines of action.

Figure B.1 schematically describes the approach followed for integrating both models. Each of the blocks represents a component of IEEM and the proposed information flows between the different models. The first two blocks refer to the Social Accounting Matrix and IEEM calibration parameters to generate the long-term growth paths (i.e., 2 percent, 3.5 percent, 4 percent). The third block aggregates the results of each of the simulated growth trajectories into sectors reflecting the ten lines of action of the NDP. Finally, the fourth module is an integrated module that translates the results of the IEEM under each of the growth trajectories into inputs for the NDP cost-benefit model.

Appendix B References

Figure B.1. Schematic for the Integration of the IEEM and Costa Rica Emissions Model
Appendix C. Transportation Vulnerability Analysis Details

Transport Sector Analysis

For this analysis, we classified simulation outcomes in two risk groups (1) high emissions cases and (2) low net benefits cases. Then we implemented scenario discovery cluster-finding algorithms that parse the simulation database to provide a concise description of the uncertainty conditions that lead to these risks. In scenario discovery, we used three statistical measures to describe the suitability of a decision relevant cluster. Coverage is the percentage of total vulnerable futures that are represented by the cluster. Density is the percentage of futures within the cluster that are vulnerable. Interpretability is the ease by which the uncertainty conditions that defined the cluster can be communicated to policy audiences (e.g., decisionmakers, relevant stakeholders). Generally, the fewer dimensions used by the cluster, the easier its interpretation. We implemented scenario discovery combining two algorithms. First, we used the C5.0 classification algorithm for dimensionality reduction (Quinlan, 1993; Hornik et al., 2007), a recursive algorithm that uses data splits to build a model in the form of a tree structure. Second, we used the algorithm PRIM (Patient Rule Induction Method) (Friedman and Fisher, 1999), a non-parametric bump hunting classification algorithm, to quantitatively describe vulnerability conditions of the NDP. In particular, we used PRIM in the context of the scenario discovery method developed by Bryant and Lempert (2010).

Risk of High Transport Emissions

First, we used scenario discovery to understand the high emissions futures. These are futures in which transport emissions are above 0.57 MtCO2e. Table C.1 summarizes the results. Each row describes one of the scenario boxes identified with scenario discovery. For each vulnerability condition, we provide a detailed description of the boundary conditions, as well as the corresponding coverage and density statistics that describe to which extent these scenario boxes adequately capture the vulnerability conditions of this target.

The results presented in Table C.1 display a policy relevant pattern of variation across economic the different scenario boxes. We find three vulnerability conditions. The first vulnerability condition, “Low adoption of alternative fuel vehicles,” describes 40 percent of the vulnerability cases related to high GHG emissions. Two drivers predict 73 percent of the vulnerable cases: the share of electric private transport in 2050 and the share of hydrogen vehicles in public transport. The second vulnerability, “Cheap and efficient conventional vehicles under high economic growth,” describes an additional 20 percent of the vulnerable cases. The rate of economic growth, the cost ratio of electric and hybrid vehicles to conventional vehicles, and the fuel efficiency of conventional vehicles predict 72 percent of the vulnerable
cases of this condition. The third vulnerability, “Low electrification of private and freight transport under moderate growth,” explains an additional 16 percent of the vulnerable cases. The three drivers found in Vulnerability 2 in combination with the share of electric light freight in 2050 predict 61 percent of the vulnerable cases.

Table C.1. Scenario Discovery Analysis for Risk of High Transport Emissions

<table>
<thead>
<tr>
<th>Economic Scenario</th>
<th>Drivers of Vulnerability</th>
<th>Density</th>
<th>Coverage</th>
</tr>
</thead>
</table>
| Vulnerability 1: “Low adoption of alternative fueled vehicles” | • Share of electric private transport in 2050 < 90%  
• Share of electric and hydrogen vehicles in public transport < 82% | 73% | 40% |
| Vulnerability 2: “Cheap and efficient conventional vehicles under high economic growth” | • High-growth scenario  
• Cost ratio of electric and hybrid vehicles to conventional fuel vehicles > 101%  
• Fuel efficiency of diesel, gasoline, and Lpg vehicles > 60% | 72% | 20% |
| Vulnerability 3: “Low electrification of private and freight transport under moderate economic growth” | • Base growth scenario  
• Cost ratio of electric and hybrid vehicles to Conventional fuel vehicles > 98%  
• Share of electric light freight < 92% | 61% | 16% |

Risk of Low Net Benefits from Transportation Decarbonization

Next, we used scenario discovery to understand the low net benefits futures. These are cases in which the net benefits are relatively low relative to what would occur under the baseline assumptions. We set the thresholds as net benefits that are less than $13.1 billion (the first quantile of the distribution of net benefits). Table C.2 summarizes the results. Each row describes one of the scenario boxes identified with scenario discovery. For each vulnerability condition a detailed description of the boundary conditions is provided, as well as the corresponding coverage and density statistics that describe to which extent these scenario boxes adequately capture the vulnerability conditions of this target. Two vulnerability conditions are identified: Vulnerability 1 “high costs alternative vehicles under low economic growth” and Vulnerability 2 “low use of public transportation, high demand for freight and expensive electric vehicles.”
Table C.2. Scenario Discovery Results for Risk of Low Net Benefits from Transportation Decarbonization

<table>
<thead>
<tr>
<th>Scenario Box</th>
<th>Drivers of Vulnerability</th>
<th>Density</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vulnerability 1: “High-cost alternative vehicles under low economic growth”</td>
<td>• Low-growth scenario</td>
<td>52%</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>• Cost ratio of electric and hybrid vehicles to conventional fuel vehicles &gt; 91%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vulnerability 2: “Low use of public transportation, high demand for freight, and expensive electric vehicles”</td>
<td>• Cost ratio of electric and hybrid vehicles to conventional fuel vehicles &gt; 123%</td>
<td>56%</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td>• Occupancy rates of SUVs, sedans, and minivans &lt; 133%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Growth in public transport use &lt; 18%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Light freight demand &gt; 10.14 Gtkm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Appendix C References


For this study, we engaged stakeholders multiple times. The following list identifies the agencies or organizations that participated in one or more stakeholder workshop:

- 5C
- Acciona Energía
- ACOPE: Asociación Costarricense de Productores de Energía
- ACEPESA: Asociación Centroamericana para la economía, salud y el ambiente
- AED: Alianza Empresarial para el Desarrollo (Business Alliance for Development)
- AFD: Agencia Francesa de Desarrollo (French Development Agency)
- Aliarse: Amigos of Costa Rica
- BCCR: Banco Central de Costa Rica
- Camara Nacional de Productores de Leche
- CANABUS: Cámara Nacional de Autobuseros (National Chamber of Buses)
- CATIE: Centro Agronómico Tropical de Investigación y Enseñanza
- CCAFS: CGIAR Research Program on Climate Change, Agriculture, and Food Security
- CENIGA: National Geoenvironmental Information Center
- CICR: Cámara de Industrias de Costa Rica (Chamber of Industries)
- COMEX: Ministerio de Comercio Exterior (Ministry of Foreign Trade)
- Coopesantos: La Cooperativa de Electrificación Rural Los Santos
- CORFOGA: Corporación Ganadera
- CPSU: Centro Para la Sostenibilidad Urbana
- CTP: Consejo de Transporte Público (Public Transport Council)
- DCC: Dirección Cambio Climático
- DIGECA: Dirección de Gestión de Calidad Ambiental
- DINARAC: Dirección Nacional de Resolución Alterna de Conflictos
- DPRSA: Departamento de Regulacion de los Programas e la Salud Y Ambiente (a department of the Ministry of Health)
- EBI Costa Rica: Empresas Berthier EBI de Costa Rica S.A.
- EGP: Enel Green Power
- Fortech
- Fundecooperación Para el Desarrollo Sostenible
- GBCCR: Consejo de Construcción Verde de Costa Rica
- Geocycle
- GIZ: a German Development Agency
- Green Building Council – CR
- IDB: Inter-American Development Bank
- ICAFE: Instituto del Café de Costa Rica
- ICE: Instituto Costarricense de Electricidad
- IMN: Instituto Meteorológico Nacional
- INA: Instituto Nacional de Aprendizaje
- Laica
- MAG: Ministerio de Agricultura y Ganadería
- MEIC: Ministerio de Economía, Industria y Comercio
- Metalub: private company
- MINAE-DIGECA: Ministerio de Ambiente y Energía-Dirección de Gestión de Calidad Ambiental (Directorate of Environmental Quality Management)
- MOPT: Ministerio de Obras Públicas y Transportes
- ONF: Oficina Nacional Forestal
- Pedal Movilidad Sostenible (Sustainable Mobility Pedal)
- RECOPE: Costa Rican Petroleum Refinery S.A.
- Red de Juventudes y Cambio Climático (Youth Network and Climate Change)
- SEPSE: Secretariat of Planning of the Energy Subsector
- SINAC: National System of Conservation Areas
- South Pole: Consultancy
- TEC: Tecnológico de Costa Rica
- UCR: University of Costa Rica
- UNDP: United Nations Development Programme
- VAM: Viceministerio de Aguas y Mares
- Viceministerio de Energía