THE BENEFITS AND COSTS OF DECARBONIZING COSTA RICA'S ECONOMY

Informing the implementation of Costa Rica's National Decarbonization Plan under uncertainty

David G. Groves, James Syme, Edmundo Molina-Perez, Carlos Calvo, Luis Víctor-Gallardo, Guido Godinez-Zamora, Jairo Quirós-Tortós, Felipe De León, Andrea Meza Murillo, Valentina Saavedra Gómez, Adrien Vogt-Schilb

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This study built on a collaboration between the University of Costa Rica's Electric Power and Energy Research Laboratory (EPERLab), the RAND Corporation, the Costa Rica Climate Change Directorate, and the Inter-American Development Bank (IDB)

Foreword

The health and economic crises reveal the limitations of current growth systems. Our unbalanced relationship with the environment exposes us to zoonotic pandemics such as COVID-19. Meanwhile, the deficit of social development means that the same households that face the greatest economic difficulties also suffer the most from environmental crises like the pandemic. Today in Costa Rica and beyond, the priority is to stop the pandemic, alleviate its social impact, and reactivate the engines of the economy.

We cannot go back to the old normal. This crisis has provided a glimpse of what the impacts of the climate crisis will bring if we do not change the development paradigm. We must move towards a sustainable recovery that creates jobs and fosters growth, but also increases inclusiveness and resilience, reduces greenhouse gas emissions, and protects our ecosystems.

The green, blue, and orange economy is the path out of this crisis. Environmental sustainability can bring social and economic benefits. The study you are holding shows that implementing the National Decarbonization Plan will bring USD 41 billion in net benefits to the Costa Rican economy between 2020 and 2050. Rural territories could benefit the most. Improving agricultural yields and the ecosystem services provided by forests, such as support to tourism, have immense value. They are worth far more than the investments needed to reduce emissions from agriculture and livestock and the opportunity cost of land dedicated to forests instead of crops or grazelands.

The benefits of decarbonization in cities also outweigh the costs. Energy savings, reduced accidents, and improved competitiveness linked to less traffic congestion and lowering the economic health impacts of air pollution easily offset the initially higher costs of switching to electric vehicles and building infrastructure to modernize public transport. Efficiency gains in industry and the economic value of recycled materials are other benefits of decarbonization. The National Decarbonization Plan is not an economic sacrifice for Costa Rica. On the contrary, well executed, it can be beneficial for everyone.

Costa Rica's history shows that green growth is possible. Thirty years of conserving ecosystems and restoration efforts clearly show this. Beyond reversing deforestation and drastically reducing its emissions, the country managed to create new business models for farmers with high-quality crops in premium niches and to make Costa Rica the ecotourism destination it has become. Going forward, the transition towards an economy with net-zero emissions has to be led by the productive sectors, companies and civil society, with the support of the government. Our work with the Inter-American Development Bank offers lessons on how to facilitate the participatory design of carbon-neutral development strategies. We started by building models with the University of Costa Rica that allowed us to quantify the visions of the different sectors in a common framework, taking advantage of the experience of RAND Corporation analysts—chosen among the best internationally. This effort makes it easier for

public policies to benefit both from academic science and from the knowledge that actors in each sector bring to the table.

This cost-benefit analysis was informed by information provided by actors from the energy, transportation, buildings, industry, waste, agriculture and livestock, and forestry sectors. Without letting the pandemic get in the way, they used virtual workshops to discuss the development objectives, beyond reducing emissions, that the Plan must include. Thanks to them, our teams have been able to quantify the effects that the Plan can create on issues such as air pollution and congestion in cities, ecosystem services provided by natural systems, productivity of agricultural systems, and fossil fuel imports.

The year 2020 has presented us with major challenges, and the years to come will be complex and difficult to navigate. Decarbonization offers an opportunity to think of a more prosperous, sustainable, and cleaner future in greater harmony with nature. But this future cannot be imposed from above: It must be built by each worker, community, company, and government entity. The work presented here contributes ideas and examples of how governments and international donors can facilitate this process.

Carlos Alvarado Quesada
President of the Republic of Costa Rica

Andrea Meza Murillo
Minister of Environment and Energy
of Costa Rica

Preface

Costa Rica is one of the few countries with an absolute and unconditional reduction target for greenhouse gas (GHG) emissions. The National Decarbonization Plan (NDP; *Descarbonicemos Costa Rica Compromiso País 2018–2050* in Spanish), published in 2019 by the government of Costa Rica (*Costa Rica Gobierno del Bicentenario 2018–2022* in Spanish), sets the goal of becoming carbon-neutral by 2050, with Costa Rica's local emissions being equivalent to the local sequestration provided by forests and other carbon sinks. The NDP proposes a set of actions organized around ten "lines" that represent the main economic and infrastructure sectors of Costa Rica's economy. Reducing emissions across all sectors will require up-front investments, but these investments are consistent with Costa Rica's economic development strategy and will provide significant benefits to society. This report is intended to inform Costa Rican policymakers and other stakeholders about the benefits and costs of the NDP, relevant trade-offs in its implementation, and opportunities for making it a more robust plan.

In this study, we estimated the benefits and costs of the NDP under uncertainty to help Costa Rica refine and implement its decarbonization plan. The study built on a collaboration between the University of Costa Rica's Electric Power and Energy Research Laboratory (EPERLab), the RAND Corporation, the Costa Rica Climate Change Directorate, and the Inter-American Development Bank (IDB). It was funded by the Inter-American Development Bank's (IDB)'s French Climate Fund (RG-T3193) and Sustainable Energy and Climate Change Initiative (RG-T2713). This work is based on, and extends, a study funded by the IDB's Economic and Sector Work Program (RG-K1447) in 2019 that evaluated the benefits and costs of the decarbonization of just the transport sector, which will be published in an academic journal.

The model developed for this study will be further improved in future projects by including detailed models of the land and water sector currently being developed by the University of Costa Rica and used to support Costa Rica's update to its Nationally Determined Contribution (NDC). This study is part of a series of economic analyses of the NDP that the IDB is performing. Other forthcoming studies include an analysis of options to align Costa Rica's fiscal strategy with the decarbonization objectives, an evaluation of options to fund a scaled-up payment for ecosystem services, and the design of an investment program to implement the decarbonization plan. Lastly, this study provides an example that is valuable for other countries and development institutions interested in analyzing decarbonization strategies.

About RAND Social and Economic Well-Being

RAND Social and Economic Well-Being is a division of the RAND Corporation that seeks to actively improve the health and social and economic well-being of populations and communi-

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

About University of Costa Rica EPERLab

The Electric Power and Energy Research Laboratory (EPERLab) of the School of Electrical Engineering at the University of Costa Rica develops planning tools related to the nexus between climate, land, energy, and water, and executes cutting-edge research related to their linkage with society. It seeks to provide practical and innovative solutions to academic and non-academic sectors bringing multi- and trans-disciplinary teams working together and creating alliances with public and private sectors to create and provide robust and rigorous knowledge to different audiences. Since its foundation in 2013, EPERLab has collaborated with government ministries providing technical support in the design of policies. For more information, email eperlab.eie@ucr.ac.cr.

About Costa Rica's Climate Change Directorate

The Climate Change Directorate of Costa Rica is an office of the Ministry for Energy and the Environment (Ministerio de Ambiente y Energía) responsible for the articulation of public policy on climate change in the country. Since its creation in 2010, it has worked with civil society, the private sector, academia, and other parts of the public sector to decarbonize Costa Rica's economy and increase the resiliency of its social and economic sector.

About the Inter-American Development Bank

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

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Summary

Costa Rica has taken a leadership role in global decarbonization through its ambitious National Decarbonization Plan (NDP), which aims to achieve net-zero greenhouse gas (GHG) emissions by 2050 (Government of Costa Rica, 2019b). Indeed, virtually all countries in the world have ratified the Paris Agreement, with the overall goal to stabilize the increase in global temperature at well below 2°C, and as close to 1.5°C as possible (United Nations, 2015). This ambitious goal requires countries to make plans to reach net-zero emissions of carbon dioxide (CO2) by 2050 and to drastically reduce emissions of other GHGs before the end of the century (Inter-American Development Bank [IDB] and Deep Decarbonization Pathways for Latin America and the Caribbean, 2019). Reducing emissions of CO2 is particularly important, as it is the main GHG and has a long lifetime: Once emitted, CO2 can stay in the atmosphere for centuries (Intergovernmental Panel on Climate Change, 2018).

The NDP lays out broad sector targets and actions to decarbonize across ten lines of action.[1] At the heart of this strategy are

1. taking further advantage of the significant natural resources available to Costa Rica, specifically its renewable hydro, solar, and wind resources, which can potentially provide clean electricity to all sectors of the economy
2. improving efficiency and access to public transportation
3. preserving and enhancing the carbon sequestration capabilities of Costa Rica's rich forest resources
4. improving processes to reduce energy use and carbon intensity in buildings, industry, agriculture, and livestock
5. collecting, treating, and reusing liquid and solid waste.

To facilitate these changes, the NDP lays out a wide range of policy and institutional reforms.

A bit more than a year after the NDP was published, the COVID-19 pandemic hit, imposing harsh socioeconomic impacts on Costa Rican households and business. The immediate priority for the Costa Rican government is stopping the health crisis, attending its social impacts, and restarting the economy. The good news is that there are opportunities to recover in a way that addresses many of the pre-COVID-19 social, environmental, political, and economic challenges in Costa Rica. Many of the strategies for decarbonization, if implemented well and soon, could address socioeconomic inequities (Saget, Vogt-Schilb, and Luu, 2020). For example, improving mobility through an upgraded public transportation system, improv-

[1] In Costa Rica, decarbonization and net-zero emissions means that all GHG emissions (not just CO2) do not exceed the natural sequestration from forests.

ing health and environmental conditions through the reduction in use of polluting fossil fuels or untreated wastewater, and increasing employment in rural areas through decarbonization efforts in the land-use sector can increase the sustainability and equity of Costa Rica's economy. More than ever, it is imperative to better understand the benefits and costs associated with decarbonization in order to ensure its alignment with critically needed economic recovery and development.

In this study, we applied a novel methodology for planning under deep uncertainty to evaluate whether the implementation of the NDP makes economic sense for Costa Rica beyond meeting its international commitments—meaning that the benefits exceed the costs for the country. If this is the case, then the NDP is worthy of collective action.

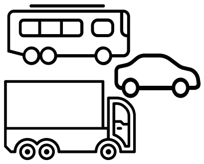
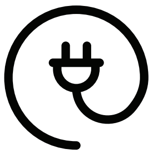
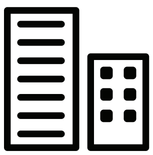
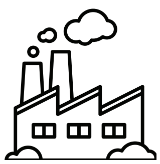
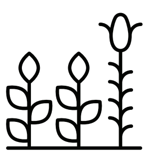
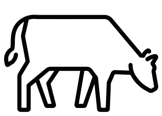
To design the analysis, we consulted with national stakeholders representing more than 50 of Costa Rica's government agencies, industries, and nongovernmental organizations to understand better how decarbonization interacts with sectoral development objectives. We built a new sector-integrated quantitative model that jointly considers the transport, electricity, buildings, industry, waste, agriculture, livestock, and forest sectors to estimate GHG emissions under conditions with no decarbonization efforts and with the implementation of the NDP.

The modeling framework estimates the benefits that would accrue to Costa Rica as a nation and the associated costs of implementing the NDP. We did not look in detail at which costs and benefits accrue to a particular household, income group, firm, or government agency; instead, we focused on the aggregate impact. We also did not assess what specific policy instruments or institutional changes would be required to implement the NDP; instead, we assessed directly the impact of the sectoral transformation listed in the NDP (see Table S.1). For instance, the NDP contemplates that mobility in the future should rely more on public transport and that buses should run on electricity or other zero-carbon technologies. We did not assume or predict anything with respect to business models for electric buses or impacts on rates paid by passengers. We do show that Costa Rica as a nation can benefit from energy savings and fewer congestion and accidents if it implements these changes. This justifies the importance of pursuing these targets and highlights the relevance of designing business models that would lead to the uptake of zero-emissions buses while sharing economic benefits between bus companies, users, and the government.

To account for uncertainty, we used Robust Decision Making (RDM; Lempert, Popper, and Bankes, 2003; Groves and Lempert, 2007; Lempert, 2019), which guides the evaluation and analysis of thousands of plausible futures to explore the risks and opportunities associated with decarbonization. As part of this process, we developed and used an interactive tool to support discussions with national stakeholders over assumptions and findings with stakeholders.[2]

[2] Groves et al., "Evaluation of the Benefits and Costs of Decarbonization in Costa Rica," 2020. This interactive tool can be accessed at https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html.

Table S.1
Representative Decarbonization Actions in Costa Rica's National Decarbonization Plan

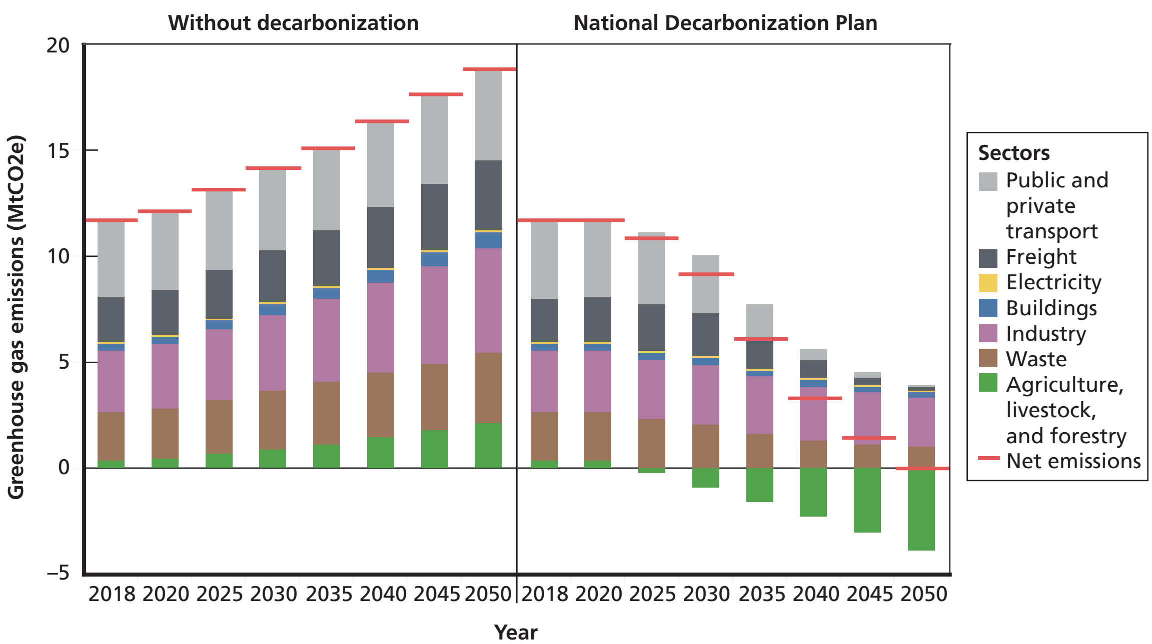
	Public, private, and freight transportation	• Electrification of public and private fleet • Conversion of freight transport away from diesel • Increased reliance on public transportation and ride sharing over private vehicles • Deployment of electric train for passengers in the Greater Metropolitan Area • Stabilized motorcycle fleet by 2025, and plan to decarbonize • Infrastructure for electricity charging and hydrogen refueling • Electric trains for freight and passengers
	Electricity system	• Reach and maintain 100% renewable electricity generation • Upgrade transmission and distribution systems to support electrification of the economy
	Buildings	• Electrification and increased energy efficiency • Adoption of low emissions building technologies and practices
	Industry	• Process improvements to reduce energy use • Electrification of processes • Process improvements to reduce emissions • Increased efficiency of use and reduction in emissions from industrial products
	Waste management	• Increase recycling and composting • Complete sanitation and sewer system coverage
	Agriculture	• Reduce emissions through improved agricultural practices
	Livestock	• Reduce emissions through improved rangeland and manure management
	Forestry	• Maintain and increase forests • Restore and protect coastal and rural areas

Benefits and Costs of Decarbonization Under Baseline Assumptions

Our analysis suggests that, under baseline assumptions, implementing the NDP would lead to net-zero GHG emissions by 2050 and provide about $41 billion of net benefits across the economy from 2020 to 2050, discounted back to 2015 at a rate of 5 percent per year.[3] It would save or otherwise provide $78 billion in benefits, and it would cost about $37 billion. There is significant uncertainty around these estimates, but the analysis shows that under the vast majority of plausible assumptions about the future, the NDP would achieve or nearly achieve its emissions reduction goals and do so at a net economic benefit.

Without a concerted focus and investment in decarbonization, net GHG emissions from Costa Rica could increase from about 12 megatons of carbon dioxide equivalent (MtCO2e) today to almost 19 MtCO2e by 2050. Bending this trajectory downward in order to reach net-zero emissions by 2050 will require a substantial transformation in how the economy is powered and how natural resources are used and preserved. By design, if Costa Rica successfully implements its NDP, zero net emissions would be achieved by 2050 (Figure S.1). Under baseline assumptions, the largest reductions in net emissions would occur in the transport sector, which would see a 7.4 MtCO2e reduction by 2050. Significant reduction would also occur in the agricultural, livestock, and forestry sectors: a total of 6 MtCO2e. Reductions in buildings, industry, and waste account for an additional reduction of 5.4 MtCO2e.

Figure S.1
Costa Rican Greenhouse Gas Emissions, by Sector, over Time, Without Decarbonization (left) and with the Implementation of the National Decarbonization Plan (right) Under Baseline Assumptions



NOTE: Emissions from the electricity sector are negligible in Costa Rica under baseline assumptions.

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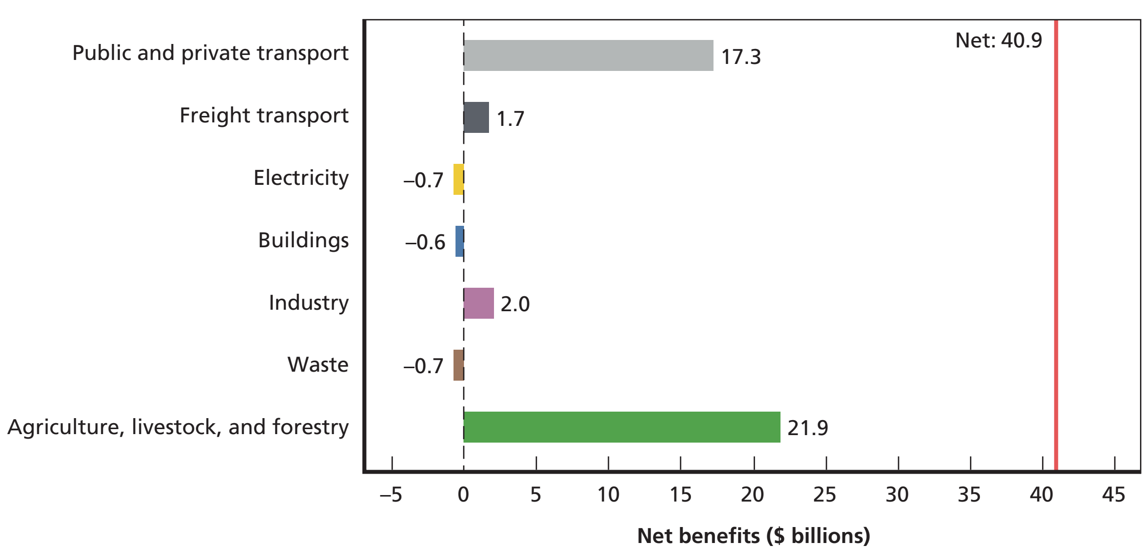
[3] All costs are reported in U.S. dollars. Five percent per year is the discount rate suggested by the Central Bank of Costa Rica and consistent with guidance from Coppola, Fernholz, and Glenday (2014). If net benefits were discounted back to 2020 at 5 percent per year, then they would be $52.2 billion; if they were discounted back to 2020 at 10 percent per year, then they would be $20.0 billion.

Under baseline assumptions, fully implementing all lines of action in the NDP would lead to about $41 billion in net benefits (Figure S.2). The greatest benefits are due to actions affecting transport, agriculture, livestock, and forestry net emissions. In the agriculture, livestock, and forestry sectors, ecosystem services provided by forests, such as renewable forestry products, water and soil benefits, support for tourism and cultural heritage, and improved yields are worth much more than the investments required to decarbonize and the forgone value of land dedicated to forests—providing discounted net benefits of about $22 billion. The public and private transport sectors together with the freight sector would provide $19 billion in net benefits under baseline assumptions, since the economic benefits from energy savings, fewer accidents, time saved from reduced congestion, and the reduced negative impacts of air pollution on health more than compensate for the initially higher up-front costs of switching to electric vehicles and building infrastructure for public transport (Godínez-Zamora et al., 2020).

Efficiency gains in industry, and the economic value of recycled materials and treated wastewater, result in a small net benefit for the industry and waste sectors: $1.3 billion together. Figure S.2 shows modest net costs for the electricity and buildings lines of actions. However, the benefits of cheaper electricity are accounted for under the transport, industry, and buildings sectors.

Most of the costs and benefits of the plan are related to the private sector. For instance, most of the cost of implementing the transport lines of action relate to investments required by motorists to purchase electric vehicles (authors' calculations), and the same motorists are the ones who will benefit from lower energy and maintenance costs over time. Note, however, that we focused on the costs and benefits of the decarbonization plan at the national level. The distribution of costs and benefits of the plan over economic actors and over time, and in particular the NDP's fiscal cost, can be drastically altered by the choice of policy instruments to implement it. For instance, if the government subsidizes electric vehicles to incentivize their

Figure S.2
Discounted Net Benefits from Implementing the National Decarbonization Plan Under Baseline Assumptions, by Sector



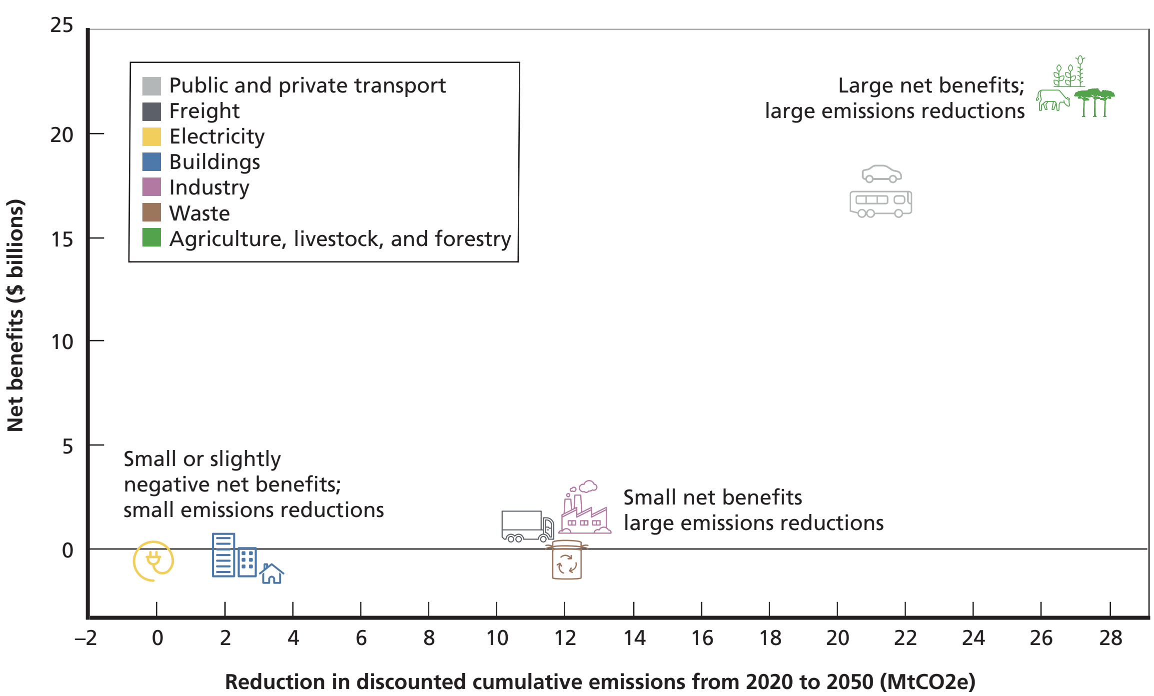
adoption, this would shift some of the cost from motorists to taxpayers. If the government took external debt to fund such a rebate, this could shift costs from today's taxpayers toward future taxpayers. The same applies to costs associated with decarbonization of buildings and waste. We did not analyze these distributional issues in this study.

When looking at emissions and net benefits together, we see that a few lines of action lead to large emissions reductions and significant net benefits—agriculture, forestry, livestock, and private and public transport (Figure S.3). In these sectors, historical development, while leading to significant economic benefits, has also led to unintentional economic impacts. For example, congestion, traffic accidents, and health effects from vehicular pollution currently lead to significant costs to society (about $5 billion per year; authors' calculations). The decarbonization strategies for the transport sector both would reduce emissions and reduce these transportation-imposed economic costs. Similarly, land use development in Costa Rica (and all other countries) has reduced valuable ecosystem services. Improvements in land-use activities that reduce emissions and increase sequestration, such as improved forest management or better manure management, also can restore many of these lost ecosystem services.

There is a large potential to reduce GHG emissions in the freight transport, industry, and waste sectors, and the benefits are of similar scale to the costs. For example, there are significant benefits due to improved economic efficiency and the reuse of solid and liquid waste, but the investments needed to achieve these benefits are also large.

Lastly, the decarbonization actions in the electricity and buildings sectors would lead to much lower emissions reductions and modest net costs. This is due to the low level of emissions currently associated with these sectors and, for the case of electricity, our accounting for most of the benefits of renewable electricity in the transport sector.

Figure S.3
Discounted Net Benefits Versus Discounted Reductions in Emissions from 2020 to 2050, by Sector



Maximizing the Benefits of Decarbonization Under Uncertainty

Estimating the costs and benefits of a 30-year program of economic transformation is fraught with uncertainty. There is uncertainty about how the Costa Rican people and economy will grow and change over the coming decades. There is uncertainty about the availability and costs of new technologies required to decarbonize. There is uncertainty about the health and function of Costa Rica's rich forest resources, which play a key role in CO2 sequestration. There is also uncertainty in how effective the NDP will be in driving the changes needed to decarbonize.

We explored emissions and the net benefits of the NDP across a wide range of different assumptions about the future. Specifically, we repeated our emissions and benefit and cost calculations for 3,003 plausible futures, reflecting different assumptions over 300 uncertainties, summarized in Table S.2, and 47 additional factors used to estimate the individual benefits and costs of the NDP. Some of these uncertainties affect the underlying socioeconomic and technological conditions that drive emissions—*driver uncertainties*—and some affect the effectiveness of decarbonization actions—*decarbonization uncertainties*.

We find that, for the vast majority of cases, the NDP would lead to low net emissions, and do so with positive net benefits (Figure S.4).

Table S.3 summarizes the distribution of emissions reductions, benefits, costs, and net benefits across the plausible futures. These distributions should not be interpreted probabilistically; instead, they are suggestive of the plausible range of outcomes for each line of action.

To understand what the calculated ranges of emissions and net benefits mean to Costa Rica decarbonization efforts, we identify the conditions that lead to high emissions or low net benefits.

In the transport sector, our analysis highlights the risk of unchecked growth of fossil-fuel-based transportation. Missing NDP targets for fleet electrification, uptake of other zero-carbon technologies, and modal shift away from private cars would mean booming carbon emissions and worsening the economic impact of productive time lost in congestion, air pollution, and accidents. This is especially true in the scenarios with the highest growth in business-as-usual economic activity and resulting high transportation demand growth. It is thus crucial that the government develops policies to support public transport, cycling, walking, and zero-carbon technologies for private, public, and freight transport. This is particularly important if the evolution of technology costs alone does not provide sufficient incentive for users and firms to make the switch.

Similarly, our analysis highlights the importance of reducing emissions from livestock and industrial processes, particularly if future economic growth translates into high levels of activity in these sectors. Lastly, the success of the NDP emissions reduction rests on assumptions about the decarbonization potential of forests. If the carbon released from clearing forests is greater than we assess now, then the NDP actions, as we model them, may not lead to sufficient sequestration to reach zero-net emissions by 2050.

The good news is that virtually all the plausible futures explored in this study would lead to large net benefits, although there is considerable uncertainty. Some of this uncertainty can be reduced through improved data and modeling, some which is currently being undertaken. Developing more-refined estimates of the various cost and benefit factors would significantly reduce the uncertainty estimated in this analysis. Some uncertain factors, however, cannot be resolved now and will need to be monitored. In general, sectors such as transportation and for-

Table S.2
Key Uncertainties Evaluated in this Study

Sector	Driver Uncertainties	Decarbonization Uncertainties
All	• Economic growth rate	
Transport	• Demand for transport (linked to economic growth) • Cost of fuels • Infrastructure costs for electrification, fuel changes, and modal changes • Technological costs • Elasticities of demand for different modes of transport • New technology adoption rates	• Growth of electric and hydrogen public transport • Growth of electric private and freight transport • Growth of hydrogen heavy freight • Growth of share of non-motorized transport and public transport use
Electricity	• Cost of new renewables	• Development of new renewables to meet increasing demand
Buildings	• Population • Household occupancy rates • Commercial economic activity	• Household energy use • Percentage of household electrification • Energy use per amount of economic activity • Percentage of commercial electrification
Industry	• Cement and other industrial production • Decarbonization rates of cement and other industrial products • Industrial value added	• Decarbonization rates of cement and other industrial products (both a driver and decarbonization uncertainty) • Energy demand per value • Efficiency of non-electrical energy use • Increase in electrification of industrial activity
Waste	• Population • Industrial activity • Waste per capita and value of industrial production	• Share of waste that is recycled and composted • Percentage of sewage treated • Methane captured in landfills
Agriculture, livestock, and forestry	• Agriculture and livestock value added • Change in area used for cultivation and grazing	• Energy efficiency in agriculture and livestock • Amount of electrification of agriculture and livestock activities • Change in carbon intensity of agricultural production • Change in carbon emissions from animals and manure • Deforestation rates • Change in carbon sequestration by wet, moist, dry, palm, and mangrove forests

estry are expected to contribute large net benefits. If key assumptions in these estimations do not hold, adjustments to ensure high net benefits may be required. For example, if ecosystem benefits from improved forestry practices are lower than expected, then seeking more benefits from other related sectors, such as the agriculture or livestock sectors, may be an important hedge.

Figure S.4
Discounted Net Benefits and 2050 Greenhouse Gas Emissions Across Range of Plausible Futures, Classified by Achievement of Net Benefits and Low Emissions

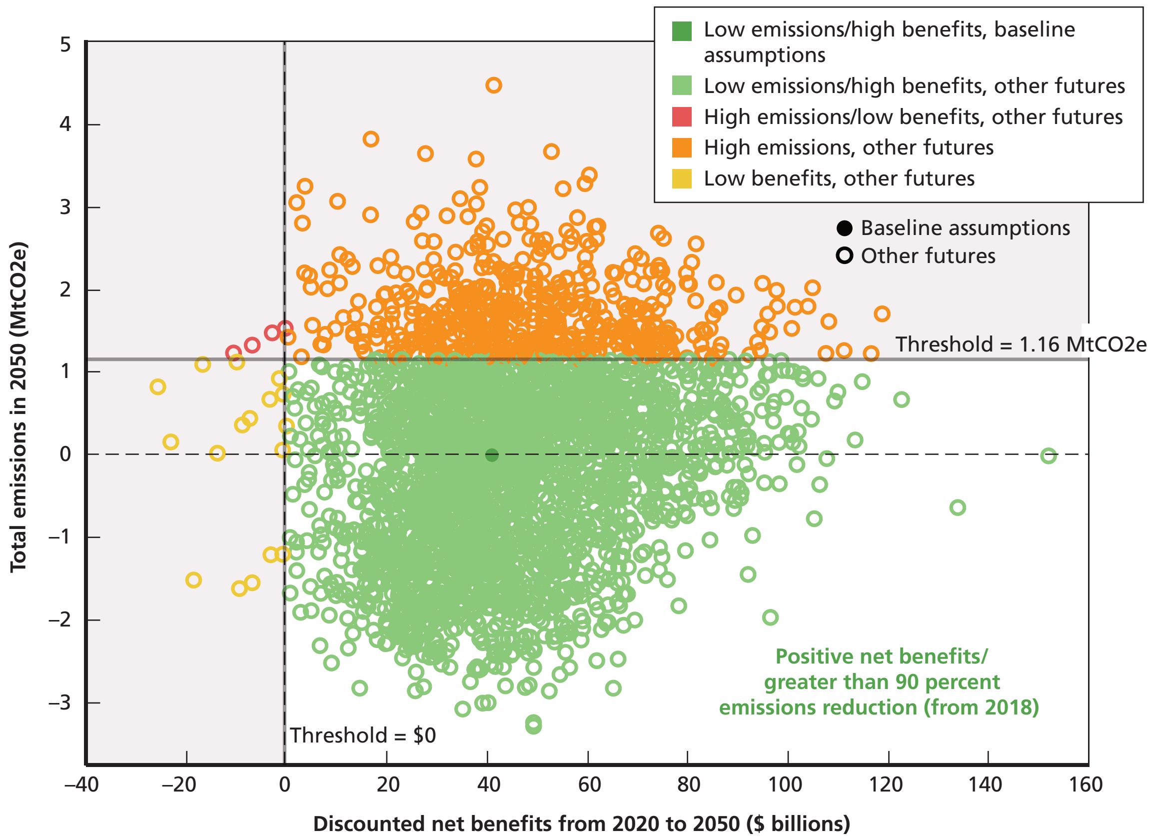


Table S.3
Changes in Emissions, Benefits, Costs, and Net Benefits from Implementation of the National Decarbonization Plan, by Line of Action and Total (lowest 25 percent value, base assumption value, highest 25 percent value)

Sector	Change in Emissions by 2050 Due to Implementation of the NDP (MtCO2e)	Benefits ($ billion)	Costs ($ billion)	Net Benefits ($ billion)
Transport	–9.4, –7.4, –4.9	32.2, 42.9, 51.6	6.7, 23.9, 18.9	15.5, 19.0, 42.2
Electricity	0.0, 0.0, 0.0	0.0, 0.0, 0.0	1.8, 0.7, 3.5	–3.5, –0.7, –1.8
Buildings	–0.6, –0.5, –0.4	1.4, 1.8, 2.0	1.9, 4.9, 4.8	–3.1, –0.6, –0.2
Industry	–3.0, –2.6, –1.8	3.3, 4.2, 5.1	2.1, 2.1, 3.4	0.6, 2.0, 2.2
Waste	–2.5, –2.3, –2.0	3.0, 3.5, 3.8	3.9, 4.2, 4.9	–1.4, –0.7, –0.6
Agriculture, livestock, and forestry	–6.2, –6.0, –5.6	19.3, 25.2, 25.3	3.2, 3.3, 4.0	15.9, 21.9, 21.6
Total	**–21.2, –18.8, –15.5**	**62.6, 77.7, 84.5**	**20.8, 36.8, 36.4**	**29.8, 40.9, 56.8**

NOTE: These results do not imply the probabilities of change in emission, benefits, costs, and net benefits. Instead, they describe the distribution of results across a wide scan of assumptions about future conditions.

Advancing Decarbonization in Costa Rica and Globally

The findings from this study can play an important role in ensuring that the implementation of the NDP is robust—meaning that it will achieve its goals in the uncertain future. Our analysis confirms which lines of action are most critical to the success of the NDP—transport and forestry—and we identify some key conditions necessary to achieve close to zero net emissions at a large net economic benefit. This study's findings can be helpful in building support for the NDP by demonstrating that reducing emissions can also lead to significant net benefits to Costa Ricans. This can help garner support for the necessary up-front investment and regulatory changes. We also developed a new modeling framework that is supporting stakeholder engagements as Costa Rica updates its Nationally Determined Contribution (NDC) under the Paris Agreement, scheduled to be completed by December 2020. There are important limitations to this work that could be usefully improved upon in the coming months and years. While the model of the transportation and electricity sector is quite advanced, the models developed to represent the other sectors are coarse and should be improved.

Lastly, this work fits into a larger research and policy agenda informing decarbonization globally. It shows the value of approaching policy analysis in a way that (1) is participatory and leverages domestic knowledge and analytical capability, (2) translates the lofty net-zero-emissions-by-2050 goal into specific actions at the sector level and over time, (3) considers socioeconomic costs and benefits further than the impact of sectoral actions on GHG emissions, and (4) accounts for uncertainty through the evaluation of futures. This study offers ideas and models that are valuable for other countries interested in decarbonization, and that can inspire development partners globally.

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We greatly appreciate the use of the Plataforma de Modelación Económico-Ambiental Integrada (Integrated Economic-Environmental Modeling [IEEM]; a general equilibrium model of the Costa Rican economy) by the Central Bank of Costa Rica, through a partnership with Onil Banerjee of the Inter-American Development Bank. Many stakeholders participated in three sets of workshops and provided written feedback to review information. In particular we would like to thank the following informal reviewers (in alphabetical order): Javier Abarca Jiménez, Francisco Alpízar, Onil Banerjee, Mauricio Bayona Pulido, Giulia Carcasci, Ana Rita Chacon Araya, Magda Carolina Correal Sarmiento, Andrea Denzinger, Xiomara González Hernández, Priscilla Gutierrez, Stephane Hallegatte, Marcela Jaramillo Gil, Sylvia Larrea, Diana Madrigal Barquero, Rebeca Madrigal, Juan Manuel Murguia, Johnny Montenegro Ballestero, Silvia Ortiz Stradtmann, Rodrigo Palma, Andres Pica Tellez, Juan Alfredo Rihm Silva, Cristian Salas Parra, Juliana Salles Almeida, and Rosa Vasquez.

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Abbreviations

BUR	Costa Rica II Informe Bienal De Actualización
CO2	carbon dioxide
CO2e	carbon dioxide equivalent
COVID-19	coronavirus disease 2019
CR-IDPM	Costa Rica Integrated Decarbonization Pathways Model
EPERLab	Electric Power and Energy Research Laboratory
GHG	greenhouse gas
Gtkm	grosse tonne kilometer
ICE	Instituto Costarricense de Electricidad
IDB	Inter-American Development Bank
IEEM	Plataforma de Modelación Económico-Ambiental Integrada (Integrated Economic-Environmental Modeling)
kWh	kilowatt-hour
LHS	Latin hypercube sampling
LPG	liquefied petroleum gas
MtCO2e	megatons carbon dioxide equivalent
NDC	Nationally Determined Contribution
NDP	Costa Rica's National Decarbonization Plan
OSeMOSYS-CR	Open Source energy Modelling System—Costa Rica
PJ	petajoules
PNSAR	Política Nacional de Saneamiento en Aguas Residuales (National Wastewater Sanitation Plan)
PRIM	Patient Rule Induction Method
RDM	Robust Decision Making

CHAPTER ONE

Costa Rica's Ambitious Plan to Decarbonize by 2050

Costa Rica has taken a leadership role in global decarbonization through its ambitious National Decarbonization Plan (NDP; Government of Costa Rica, 2019b). Indeed, virtually all countries in the world have ratified the Paris Agreement, with the overall goal to stabilize the increase in global temperature at well below 2°C, and as close to 1.5°C as possible (United Nations, 2015). This ambitious goal requires reaching net-zero emissions of carbon dioxide (CO2) by 2050, and drastically reducing emissions of other greenhouse gases (GHGs) before the end of the century.[1] CO2 plays a special role because it is the atmosphere's main GHG and has a long lifetime: Once emitted, it can stay in the atmosphere for centuries (Intergovernmental Panel on Climate Change, 2018).

Reaching net-zero CO2 emissions means both reducing sources of emissions, such as the combustion of fossil fuels, and increasing carbon sinks, by, for example, expanding forests, since trees capture carbon from the atmosphere as they grow. The salient message of climate research is that as long as the global economy releases more CO2 into the atmosphere than it removes through carbon sinks, the climate will continue to warm (Intergovernmental Panel on Climate Change, 2018).

Country and sector experts within the international scientific community have shown that getting to net-zero carbon emissions by 2050 is technically feasible and can be beneficial with respect to other development goals, including the creation of 15 million net jobs in Latin America and the Caribbean by 2030 (Saget, Vogt-Schilb, and Luu, 2020). There are also numerous other benefits that would accrue to Costa Rica in response to decarbonization efforts, including health benefits from reduced pollution, fuel cost savings from electrification (Godínez-Zamora et al., 2020), and ecosystem services from preserved and enhanced forests. Nonetheless, there are challenges on the road to a net-zero carbon emissions economy, including planning, regulatory, and political economy barriers. Decarbonization plans have a key role to play in helping line ministries identify and lift these barriers in consultation with key stakeholders from the public and private sectors (Inter-American Development Bank and Deep Decarbonization Pathways for Latin America and the Caribbean, 2019; Cavallo, Powell, and Serebrisky, 2020).

The Costa Rica NDP lays out broad sector targets and actions to decarbonize across ten lines of action. At the heart of these strategies are

[1] *Net-zero emissions* in this context means that GHG emissions do not exceed sequestration of CO2 by forests.

1. taking further advantage of the significant natural resources available to Costa Rica, specifically its renewable hydro, solar, and wind resources, which can potentially provide clean electricity to all sectors of the economy
2. improving efficiency and access to public transportation
3. preserving and enhancing the carbon sequestration capabilities of Costa Rica's rich forest resources
4. improving processes to reduce the energy and carbon intensity of industry, agriculture, and livestock
5. collecting, treating, and reusing liquid and solid waste.

To facilitate these changes, the NDP lays out a wide-range of policy reforms. Table 1.1 lists some of the specific actions considered in the NDP across all the sectors included in this study.

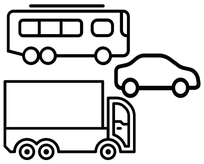
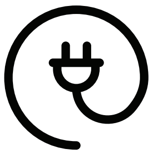
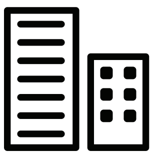
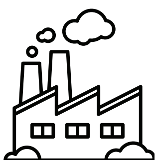
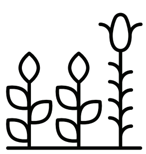
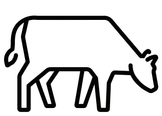
For each sector, the NDP presents a long-term vision of the ideal future to reach net-zero emissions by 2050. It then uses a back-casting approach to define mid-term (2023–2030) targets for sectoral transformation. Lastly, it uses this as the basis to describe policy options and updates needed to unlock the transformation.

As Costa Rica focuses on a sustainable post-COVID-19 recovery and moves toward defining specific actions, including investments and policy changes to implement the NDP, understanding what is required now and how Costa Rica will benefit in the coming decades is of paramount importance. There are many benefits to decarbonization beyond meeting international commitments and avoiding the climate change impacts that otherwise would occur (Karlsson, Alfredsson, and Westling, 2020). Understanding the balance of these benefits and costs can help Costa Rica implement a successful decarbonization strategy and make the case, as appropriate, for up-front investments. Tracing out how the implementation of decarbonization strategies in the near term can have a compounding impact by 2050 can also help ensure that today's investments are consistent with decarbonization objectives and do not "lock in" technologies or practices that have long lifetimes and are large emitters of carbon (Binsted et al., 2019; González-Mahecha et al., 2019).

To evaluate the benefits and costs of the NDP, we developed a sector-integrated model of GHG emissions from the present through 2050 for all major sectors of the Costa Rican economy. The integration of individual sector models is critical, as decarbonization in some sectors affects other sectors (Bataille et al., 2020). For example, electrification of the transportation sector increases total electricity demand. While this potentially requires additional investment in renewable energy capacity—this effect is low in most cases in Costa Rica—electrification also lowers electricity rates. Lower rates then benefit all sectors that use electricity. Another important interaction is among the agriculture, livestock, and forestry sectors. While there is a potential to reduce agriculture and livestock activities through preservation and expansion of forested areas, other approaches, such as planting trees in grazing lands or agricultural fields, blur the boundaries between forests, agricultural areas, and livestock to the benefit of all three sectors (Government of Costa Rica, 2019b).

The integrated model was developed as part of an active collaboration of university researchers, government officials, and international experts in policy analysis. Over time, this model can be improved to yield more-refined estimates of emissions and of the benefits and costs of decarbonization. Co-constructing data, models, and analytic approaches leads to results that are relevant to Costa Rica decisionmaking and builds ownership and capacity that

Table 1.1
Representative Decarbonization Actions in Costa Rica's National Decarbonization Plan

	Public, private, and freight transportation	• Electrification of public and private fleet • Conversion of freight transport away from diesel • Increased reliance on public transportation and ride sharing over private vehicles • Deployment of electric train for passengers in the Greater Metropolitan Area • Stabilized motorcycle fleet by 2025, and plan to decarbonize • Infrastructure for electricity charging and hydrogen refueling • Electric trains for freight and passengers
	Electricity system	• Reach and maintain 100% renewable electricity generation • Upgrade transmission and distribution systems to support electrification of the economy
	Buildings	• Electrification and increased energy efficiency • Adoption of low emissions building technologies and practices
	Industry	• Process improvements to reduce energy use • Electrification of processes • Process improvements to reduce emissions • Increased efficiency of use and reduction in emissions from industrial products
	Waste management	• Increase recycling and composting • Complete sanitation and sewer system coverage
	Agriculture	• Reduce emissions through improved agricultural practices
	Livestock	• Reduce emissions through improved rangeland and manure management
	Forestry	• Maintain and increase forests • Restore and protect coastal and rural areas

can ensure that the quest for decarbonization continues to be informed by the best available information and analysis.

In this report, we use the sector-integrated model to estimate GHG emissions under conditions with no decarbonization efforts and with the implementation of the NDP, and then we identify some of the benefits that would accrue to Costa Ricans and roughly estimate the costs. Estimating the benefits and costs of a 30-year program of economic transformation, however, is fraught with uncertainty. There is uncertainty about how the Costa Rican people and economy will grow and change over the coming decades. There is uncertainty about the availability and costs of new technologies required to decarbonize. There is uncertainty about the health and function of Costa Rica's rich forest resources, which play a key role in GHG sequestration. And how all of this uncertainty will affect implementation of a decarbonization plan is not knowable.

To assess the impact of such uncertainty, we explore a wide range of plausible futures in which the NDP will be implemented. This means evaluating thousands of different assumptions about the drivers of emissions and decarbonization, as well as factors that describe how benefits and cost could accrue. We use methods for Decision Making Under Deep Uncertainty (Marchau et al., 2019) to guide our analysis of how the NDP would play out under these many plausible futures. In particular, we use Robust Decision Making (RDM; Lempert, Popper, and Bankes, 2003; Groves and Lempert, 2007; Lempert, 2019) to understand the future conditions that would lead to successful and less-than-successful outcomes. This can then inform how to implement the NDP in a manner that ensures its success.

Chapter Two of this report describes the analytic framework and briefly describes how sectors and the NDP lines of action are modeled. Chapter Three presents estimates of GHG emissions and the benefits and costs of Costa Rican decarbonization analysis under a single set of baseline assumptions. Chapter Four shows the results of the uncertainty analysis and describes several key risks that the current NDP faces in ensuring net-zero emissions by 2050 and providing net benefits to Costa Rica. Chapter Five concludes by highlighting lessons learned from this analysis and how they can inform implementation of the NDP and the revision of Costa Rica's Nationally Determined Contribution (NDC).

A separate volume, available at www.rand.org/t/RRA633-1, contains the following appendixes:

- Appendix A. Modeling Details and Sector Benefit and Cost Factors
- Appendix B. Developing Socioeconomic Scenarios
- Appendix C. Transportation Vulnerability Analysis Details
- Appendix D. Stakeholders Organizations.

CHAPTER TWO

Approach for Analyzing the Benefits and Costs of Costa Rica's Decarbonization Plan Under Uncertainty

Overview of Approach

In this study, we developed models for estimating the benefits and costs of implementing Costa Rica's NDP under many different assumptions about the future. Using a method for Decision Making Under Deep Uncertainty (Marchau et al., 2019) called Robust Decision Making (RDM; Lempert, Popper, and Bankes, 2003; Groves and Lempert, 2007; Lempert, 2019), we evaluated the many benefits and costs of decarbonizing Costa Rica's economy under uncertainty. RDM has been applied to natural resources planning problems for years (Groves et al., 2008; Groves et al., 2015; Groves et al., 2019; Molina-Prez et al., 2019) and has been used to explore global sustainability policies in the academic context (Lempert et al., 2006; Lempert, 2019). This study represents its first use explicitly to evaluate a national decarbonization strategy.

We first created two estimates of Costa Rican GHG emissions through 2050 under a single set of assumptions. The first assumed no concerted effort to decarbonize. We call this first estimate "without decarbonization." We then estimated how emissions would change under one possible approach for implementing the NDP (called "with implementation of the National Decarbonization Plan"). Next, we roughly estimated the monetary benefits and costs to provide a high-level assessment of the net benefits of decarbonization to Costa Rica.

We then created thousands of *futures*, each an independent set of assumptions about how drivers of emissions, benefits, and costs might evolve in the future. We again evaluated how Costa Rican GHG emissions would evolve without decarbonization and with the implementation of the NDP, this time for each future. Lastly, we used RDM techniques to identify key vulnerabilities to the NDP and identify ways to ensure robust implementation.

Learning from Stakeholders

Throughout the study, we met with Costa Rica stakeholders and representatives of various sectors to provide input regarding key concerns around decarbonization, inform the scoping of the technical analysis, and review results. Stakeholder organizations consulted are listed in Appendix D. Specifically, we engaged stakeholders through the following activities:

- **Scoping workshops with stakeholders from the transport sector (February 2019) and additional sectors (July 2019).** In this first set of workshops, we first met with

representatives from the transport sector and then the other sectors to present the study purpose and approach. We gathered participants' insights about the important performance metrics, including benefits and costs, decarbonization actions to represent in the study, key uncertainties that could affect the success of the NDP, and available data and models. This workshop followed a methodology for scoping a long-term policy analysis introduced by Lempert, Popper, and Bankes (2003). In this approach, a semi-structured stakeholder discussion identifies key policy objectives as metrics, available decisions or policy levers, potential future uncertainties, and available data and relationships that can be used to relate policy actions and uncertain factors into outcomes.
- **Analysis review workshops—February 2020.** In this second set of workshops, we presented preliminary analysis of GHG emissions across the sectors with and without the implementation of the NDP, as well as the approach underway for quantifying benefits and estimating costs.
- **Interactive remote review of modeling assumptions—June 2020.** Select stakeholders were provided a link to an interactive visualization that contained information about the key assumptions for each sector represented by the NDP.[1] Written feedback was returned to us and considered as the final analysis was prepared.

Modeling Future GHG Emissions, Benefits, and Costs

We have developed a new modeling framework to support the iterative evaluation of the NDP under uncertainty and estimate its benefits and costs. This framework combines previously developed models of transportation and energy sectors (Godínez-Zamora et al., 2020) with new aggregated models of other sectors that do not have more detailed models available. These models are based on recent socioeconomic and emissions data, projections of the drivers of GHG emissions and emissions factors, and other benefit and cost factors. (Chapter Three lists the costs and benefits considered for each sector.) The framework is designed to incorporate new, more detailed models of emissions, benefits, and costs.[2]

The Costa Rica Integrated Decarbonization Pathways Model (CR-IDPM) evaluates GHG emissions and the benefits and costs of implementing the NDP across different sectors and plausible futures. In general, GHG emissions are estimated based on projections of activities or quantities of emitters/sinks (vehicles, buildings, quantities of waste, land, industrial processes) times emissions rates per activity or quantity. For some sectors, emissions rates depend on the technology used for the activities or some other disaggregation (e.g., electric vehicles versus gasoline cars, or waste that is composted versus that which is landfilled). Different trajectories of activities, share of the use of technologies, and emissions rates lead to different emissions projections. Economic benefits due to additional jobs are not accounted for in this study, but could be significant.

For the transportation and electricity sectors (lines 1–4), the CR-IDPM incorporates the detailed Open Source energy Modelling System—Costa Rica (OSeMOSYS-CR) model, developed and maintained by the Electric Power and Energy Research Laboratory

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1 Groves et al., "Evaluation of the Benefits and Costs of Decarbonization in Costa Rica," 2020. The interactive tool can be accessed at https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html.

2 All costs are reported in U.S. dollars.

(EPERLab) at the University of Costa Rica (EPERLab, 2020; Godínez-Zamora et al., 2020). OSeMOSYS-CR also includes fixed estimates of energy consumption from buildings (line 5) and industry (line 6), but variation in these estimates were modeled outside OSeMOSYS-CR, as described below. OSeMOSYS-CR estimates emissions from the transportation and energy sectors based on demands for transport, specifications of the technologies and fuels used to meet those demands, emissions factors, and energy demands from other sectors. For the other sectors—buildings (line 5), industry (line 6), waste (line 7), agriculture (line 8), livestock (line 9), and forestry (line 10)—CR-IDPM includes Python-based models that project emissions, benefits, and costs based on specified activities, applications of technologies or methods, and emissions rates.

We use a general equilibrium model of the Costa Rican economy—Plataforma de Modelación Económico-Ambiental Integrada (Integrated Economic-Environmental Modeling [IEEM])—to derive three scenarios of underlying economic activity through 2050 (Banerjee and Cicowiez, 2020 and 2019; Banerjee et al., 2019).[3] The IEEM is configured to develop three projections of economic growth—2, 3.5, and 4 percent per year—that are consistent with the underlying economic structure of the Costa Rican economy, as captured by its social accounting matrix. Trade patterns are modeled in IEEM assuming that the corresponding services are required in fixed proportions in the value chain. World prices of the products Costa Rica trades with the rest of the world are treated as exogenous parameters. The IEEM then produces estimates of transportation demand, industrial production, agricultural production, and livestock production for each economic scenario (Appendix B). Figure 2.1 provides a schematic of the CR-IDPM.

We calibrated the model factors so that the 2015 sectoral GHG emissions matched the 2015 GHG emissions inventory from the *Costa Rica II Informe Bienal De Actualización* (Government of Costa Rica, 2019a), also known as the BUR. We then developed independent estimates of how key drivers of GHG emissions could change in the future under "without decarbonization" conditions. We then evaluated emissions through 2050 across all sectors of the economy for thousands of plausible futures reflecting uncertainty.

We calculated the benefits of decarbonization by combining results of the emissions calculations along with additional factors derived from the literature. For example, the health benefits of reducing GHG emissions in the industrial sector are estimated by multiplying changes in GHG emissions by industrial processes by an estimated factor of how much potential economic benefit would be achieved through the reduction in pollution in Costa Rica. This approach has been taken in other Costa Rican assessments of the benefits of pollution reduction, for example, Alpizar, Piaggio, and Pacay (2017). While these estimates, based on aggregate benefit factors, are coarse and highly uncertain, they provide a rough-order-of-magnitude estimate that can be compared across sectors and to costs.

For all sectors, we include the benefits that Costa Rica's emissions reductions have on reducing climate change effects in Costa Rica, such as warming and increased tropical storms. This is done by combining the change in emissions under implementation of the NDP with the social cost of carbon estimates for Costa Rica (Ricke et al., 2018). Note that these benefits

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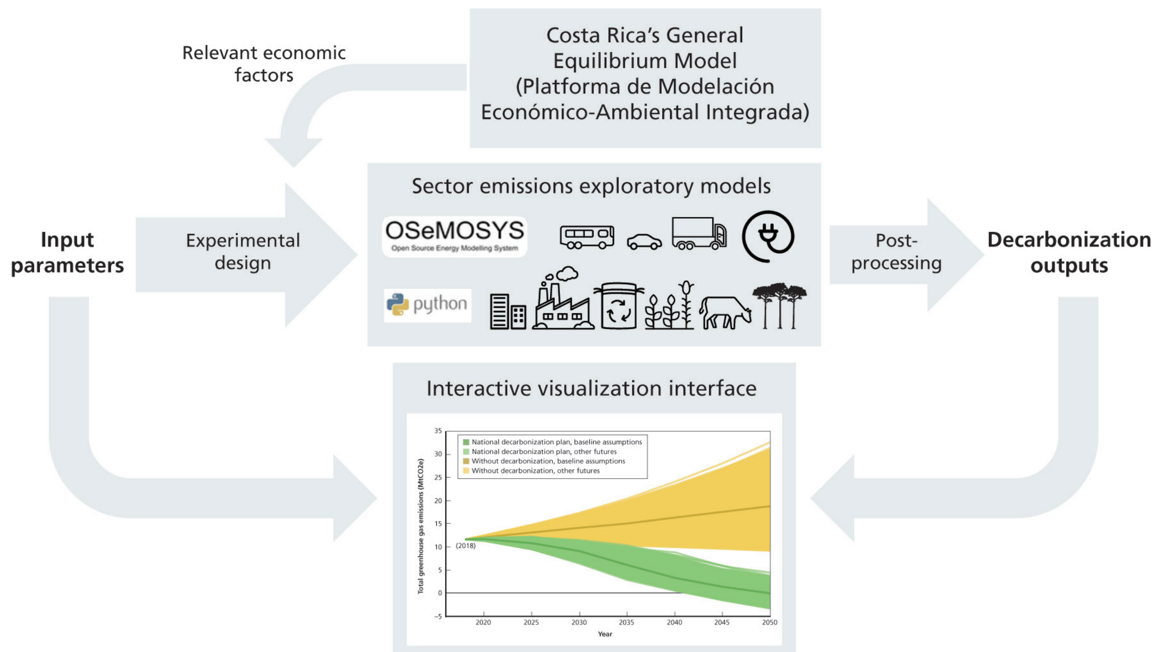
[3] The IEEM was provided to the study team by the Central Bank of Costa Rica, through a partnership with Onil Banerjee of the Inter-American Development Bank.

Figure 2.1
Modeling Schematic for the Costa Rica Integrated Decarbonization Pathways Model



are a very small fraction of all the climate change reduction benefits that would accrue if all countries reduced emissions per the 1.5°C global emissions target.[4]

Costs of implementing the decarbonization actions are estimated by using values from the literature of the per unit cost (either of production or GHGs) of reducing carbon emissions. For the transport sector, the model uses more detailed costs developed by University of Costa Rica researchers to track capital costs, fixed annual costs, and variable annual costs for the technologies used under the "without decarbonization" and "with implementation of the NDP" conditions (EPERLab, 2020; Godínez-Zamora et al., 2020). For the other sectors, costs are estimated using several different approaches detailed below. In some cases, the academic literature provides cost estimates as a function of GHG emissions reductions by a specific sector activity. In other cases, we draw estimates from Costa Rican sources that are related more directly to the actions proposed in the NDP. As with the benefits, these estimates are coarse and highly uncertain.

[4] The question of how to monetize the reductions of greenhouse gases emissions is complex. From a global perspective, the main economic benefit of decarbonization is to stop the climate crisis, which will otherwise have devastating impacts on economic and social development (Hallegatte et al., 2015). The parties to the Paris Agreement have agreed that maintaining the global temperature increase to 1.5°–2°C is the appropriate way to contain the costs of climate change on economic development. The international advice is to value GHG emissions reductions using carbon prices consistent with the decarbonization targets that the governments have set—which is often estimated to be around $50 per ton of CO2 in U.S. dollars (USD) in 2020 (Fay et al., 2015; Stiglitz and Stern 2017; Kaufman et al., 2020). Here, we take a more conservative approach. Since this study seeks to highlight the cost and benefits of implementing the NDP for Costa Rica, the carbon price that we used, below $1/tCO2, reflects an estimate of the benefits of avoiding climate change impacts only in Costa Rica (Ricke et al., 2018). Even while Costa Rica is exposed to many climate change impacts, such as more intense tropical storms and sea level rise, it is a small part of the global economy, therefore this value is very small and our estimates of avoided climate impacts to Costa Rica is negligible with respect to other benefits. At the end, our approach shows that decarbonizing Costa Rica has many economic benefits, even if we effectively set aside the climate change benefit.

How COVID-19 Might Affect Costa Rica's Decarbonization Efforts

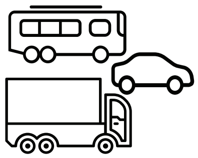
The analysis presented here was designed and developed in large part before the COVID-19 pandemic hit, in February 2019. The socioeconomic impacts of the pandemic and the decarbonization agenda can interact in various ways; however, we do not think the pandemic affects our results dramatically. First, decarbonization is best understood as a back-casting exercise: It starts from the vision of a decarbonized economy by 2050, and works backward to identify sectoral pathways to be met in 2030 or 2035 to put the economy on track toward the long-term goal (Fay et al., 2015; Waisman et al., 2019). While the impacts of the pandemic on economic activity over the next few years matter dramatically for households, businesses, and public policy, they do not change significantly the economic relevance of choosing a carbon-neutral future as opposed to a carbon-intensive future for 2050—the focus of this study.

Second, the pandemic may affect the preference of Costa Rican consumers and businesses in ways that facilitate or prevent decarbonization. For instance telework may become more frequent, but consumers may become more averse to using crowded public transport and rely more on private transport. Although the uncertainty analysis presented below was set up before the pandemics, it is wide enough to encompass these cases.

Finally, some decarbonization actions can play a key role in short-term economic reactivation and job-creation efforts (Hepburn et al., 2019). Investments in public transport infrastructure or public spending to facilitate reforestation, for instance, have been found to be effective at creating jobs (Garrett-Peltier, 2017; Saget, Vogt-Schilb, and Luu, 2020). Investment in public infrastructure and public work programs can also have multiplier effects in a depressed economy. On the other hand, the fiscal and financial markets impacts of the pandemic could hamper the ability of Latin American governments to perform such investments, depending on the response of the international community (Izquierdo et al., 2020). Despite their relevance for public policy, the present analysis does not attempt to quantify these short-term financial, fiscal, and labor issues. This effort focuses on quantifying the mid- and long-term impacts of implementing the decarbonization plan on the economic well-being of Costa Rica and on GHG emissions.

We refer to the assumptions underlying these emissions, benefits, and costs projections as **baseline assumptions**. Chapter Three presents results from the model assuming the single set of baseline assumptions. We provide this single baseline estimate to convey how emissions, benefits, and costs could evolve for each sector. This estimate should not be interpreted as the most likely outcome, but rather one that is plausible given known information today. To reflect uncertainty about future drivers and the achievement of decarbonization actions, we developed a range of estimates for the model factors and created a large set of **plausible futures**, as described below. These futures should not be assumed to be equally likely. However, comparing the modeling results across these futures can provide a reasonable representation of how Costa Rica's GHG emissions evolve without and with the NDP. Chapter Four provides emissions, benefits, and cost results under the wide range of futures. Chapter Five describes how Costa Rica can use this information to inform the implementation of the NDP and the update of Costa Rica's NDCs.

The next subsections in this chapter provide a brief description of how each sector is modeled, the key drivers of emissions, the NDP strategies and their modeling, and which benefits and costs are accounted for. Appendix A provides overviews for the models and parameters used to estimate GHG emissions, benefits, and costs for each sector.



Transport Sector

The transport sector is modeled using an open-source energy system modeling platform—OSeMOSYS-CR—that was configured to represent the Costa Rican energy and transport sector by University of Costa Rica researchers (EPERLab, 2020; Godínez-Zamora et al., 2020). This model evaluates demands for different modes of transportation (e.g., private or public), the fleet of vehicles with different fuels and fuel efficiencies, and the corresponding emissions. OSeMOSYS-CR uses estimates of freight demand from the IEEM to calculate the different kinds of truck fleets and fuels used to meet this demand. The model also includes the possible implementation of the electric freight train from Limon to Sarapiquí and the implementation of the electric train for passengers in the Greater Metropolitan Area. This model does not represent geographic traffic flow patterns; it relies instead on factors that describe average distance traveled over time for various vehicle classes at the national level. We consulted a range of stakeholders from the transport sector, who are listed in Appendix D.

The key drivers of transport emissions can be summarized by the following items:

- demand for transportation and elasticities of demand for different modes of transport
- demand for freight transport
- adoption rates of new technologies, such as electric cars
- vehicle kilometers traveled by buses, private vehicles, and different types of trucks
- fuel use by vehicles
- cost of fuels
- infrastructure costs for electrification, fuel changes, and modal changes
- costs of technologies.

Table 2.1 summarizes the key NDP actions for the transport sector and how these actions are represented in the model.

The OSeMOSYS-CR model evaluates several key benefits of decarbonization in the transport sector:

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

The OSeMOSYS-CR model estimates financial benefits and costs for the transport sector through a large set of cost parameters reflecting up-front investment costs and changes in operations and maintenance costs. Additional benefits are estimated by combining benefit factors derived from other studies with modeled changes in total distance traveled by different

Table 2.1
Transport Sector National Decarbonization Plan Actions and Model Implementation

Decarbonization Plan Actions	Model Implementation
Electrification of public fleet	• Increase electric vehicle imports (and corresponding decrease in imports of fossil fuel vehicles)
Increased reliance on public transportation over private vehicles	• Increase in public transport use (and a corresponding decrease in private transport use)
Increase of non-motorized trips	• Reduction of passenger demand • Investments on infrastructure to enable active mobility, such as the electric train
Electrification of private fleet	• Increase electric vehicle imports (and corresponding decrease in imports of fossil fuel vehicles)
Stabilized motorcycle fleet by 2025, and plan to decarbonize	• Limit growth of motorcycle adoption compared to trends • Increase the penetration of electric motorcycles
Increased ride sharing	• Increase occupancy rates of private vehicles
Extensive electric recharge network and/or hydrogen charging stations	• Price of electric light duty vehicles including charge-at-home cost • Additional cost of the distribution system for private vehicle charging • Investments in charging infrastructure for heavy duty vehicles proportional to the level of electrification
Freight transport from diesel to liquefied petroleum gas (LPG)	• Target 20 percent LPG for freight in 2030 • LPG is included as an option for freight transport and competes with electricity and hydrogen technologies for years after 2030
Reduced emissions from freight transport	• Penetration of electric and hydrogen freight vehicles • Introduction of battery electric and fuel-cell hydrogen heavy duty trucks (semi-trucks) after 2030
Limon's Electric Freight Train	• Investment in rail infrastructure and rolling stock
Improved freight logistics	• Reduction of freight transport demand in ton-kilometers

vehicle types. For example, implementation of the NDP would lead to reduced accidents as the distance that private vehicles travel lessens in response to greater use of public transportation. Table 2.2 summarizes the benefits and costs represented in the analysis. Appendix A provides details and numerical values.

Table 2.2
Transport Sector Benefits and Costs of Decarbonization Modeled in This Study

Benefits of Decarbonization	Costs of Decarbonization
• Operations and maintenance costs savings due to alternative fuel vehicles and reduced private transport • Reduced medical costs from accidents • Improved productivity from reduced congestion • Health savings from reduced emissions • Reduced climate change impacts from emissions (reduced social cost of carbon)	• Change in capital costs of new equipment and infrastructure, including energy storage (such as batteries) • Change in waste streams due to switching from conventional to alternative vehicles is captured implicitly in the waste sector

Electricity Sector

The electricity sector in Costa Rica is currently almost completely renewable, based on 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 model used for the transport sector: OSeMOSYS-CR. Note that this model does not resolve the geographical components of the electricity network. Instead, it relies on assumptions about capacities to deliver electricity to the defined demands in the model. We consulted with a range of stakeholders from the electricity sector, who are listed in Appendix D.

Electricity demand is estimated for the buildings (residential and commercial), industrial, and agricultural sectors using the corresponding sector models described below. These demand estimates are passed to the OSeMOSYS-CR model, which also estimates electricity demand from the transport sector. OSeMOSYS then determines how much electricity can be satisfied by renewable sources, reflecting a range of plausible climate change effects, and carbon-based electricity generation sources. It then estimates the GHG emissions from the carbon-based electricity generation sources. The representation of the electricity sector through 2034 is consistent with recent generation expansion plan modeling by Costa Rica's public electricity and telecommunications company—Instituto Costarricense de Electricidad (ICE). Table 2.3 summarizes the key NDP actions for the electricity sector and how these actions are represented in the model. Appendix A provides details and numerical values.

The primary objective of the decarbonization actions for the electricity sector is to support broad-based electrification of the Costa Rican economy using competitively priced, carbon-free, renewable sources. In addition to supporting emissions reductions through electrification, the other main benefit of electrification is the energy cost savings in the sectors in which additional electricity is used. The OSeMOSYS-CR model estimates the required additional renewable energy sources (and associated investment costs), and the GHG emissions savings and fuel cost savings from using these sources instead of existing fossil-fuel based sources, and generating electricity by non-renewable sources and the costs. The benefits and costs of decarbonization actions in the electricity sector are summarized in Table 2.4. Appendix A provides details and numerical values.

Table 2.3
Electricity Sector Decarbonization Plan Actions and Model Implementation

Decarbonization Plan Actions	Model Implementation
• Maintain near 100% renewable supplies • Increased capacity to support electrification of transport and industry	• Implement additional investments in wind and solar capacity when demand requires

Table 2.4
Electricity Sector Benefits and Costs of Decarbonization Modeled in This Study

Benefits of Decarbonization	Costs of Decarbonization
• Reduced fuel costs for electricity generation • Reduced climate change impacts from emissions (reduced social cost of carbon)	• Change in capital costs of new equipment and infrastructure

Buildings Sector

The buildings 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 carbon factors for non-electricity energy use. Because of the lack of available data, the building sector model does not track commercial building inventory, thus we use economic activity as a proxy for the number of commercial buildings. Commercial building emissions 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. Calculated electricity demands for the buildings sector are passed to OSeMOSYS-CR to estimate total electricity demands. We consulted a range of stakeholders from the buildings sector, who are listed in Appendix D. Table 2.5 summarizes the key NDP actions for the buildings sector and how these actions are represented in the model.

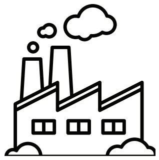
The primary benefits from decarbonization in the buildings sector is the energy cost savings due to efficiency and electrification. We estimate costs for household and building electricity retrofits and efficiency (Table 2.6).

Table 2.5
Buildings Sector National Decarbonization Plan Actions and Model Implementation

Decarbonization Plan Actions	Model Implementation
Emission reduction through electrification and energy efficiency	• Reduced household energy use • Increased share of electricity use (and corresponding decrease in use of fossil fuels)
Adoption of low emissions building technologies and practices	*Not included in the study.*
Increased use of wood and natural building materials	

Table 2.6
Buildings Sector Benefits and Costs of Decarbonization Modeled in This Study

Benefits of Decarbonization	Costs of Decarbonization
• Cost savings to building utility payers from efficiency and switching to low-cost electricity (residential and commercial buildings) • Reduced climate change impacts from emissions (reduced social cost of carbon)	• Costs for improving efficiency and electrification of households • Costs for improving efficiency and electrification for commercial buildings



Industrial Sector

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. Estimates of future industrial production are supplied by the IEEM model for the three economic scenarios, and reflect baseline assumptions about trade and the structure of the economy. A more complete analysis could consider how international price changes in key exports for Costa Rica (e.g., machinery and medical supplies) would affect industrial production and trade patterns. 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 are negative emissions associated with the recycled waste. This representation of the "circular economy" ensures that emissions savings are not double counted. Calculated electricity demands for the industrial sector are passed to OSeMOSYS-CR to estimate total electricity demands. The industry model does not represent individual firms and only focuses on the main emitting activities. We consulted representatives from a range of stakeholders from the industrial sector, who are listed in Appendix D. Table 2.7 summarizes the key NDP actions for the industrial sector and how these actions are represented in the model. Appendix A provides details and numerical values.

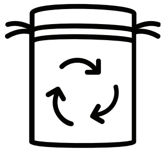
The primary benefits to industrial decarbonization include energy cost savings due to electrification and productivity improvements due to improved processes and efficiencies. We represent three major costs: those to reduce emissions from the cement manufacturing, those to improve the efficiency of use of industrial products, and those related to efficiency and electrification across all industries (Table 2.8).

Table 2.7
Industrial Sector National Decarbonization Plan Actions and Model Implementation

Decarbonization Plan Actions	Model Implementation
Process improvement to reduce energy use	• Reduction in energy use per value added by industry
Electrification of processes	• Increased share of electricity use (and corresponding decrease in use of fossil fuels)
Process improvements to reduce emissions	• Reduction in carbon intensity of industrial production (particularly cement)
Increased efficiency of use and reduction in emissions from industrial products	• Reduction in process emissions per value added by industry

Table 2.8
Industrial Sector Benefits and Costs of Decarbonization Modeled in This Study

Benefits of Decarbonization	Costs of Decarbonization
• Cost savings to industrial producers from switching to low-cost electricity • Industrial productivity improvement due to process and energy efficiency • Cost savings from processing recycled glass and metal in lieu of virgin production (accounted for in the waste sector) • Health savings from reduced emissions • Reduced climate change impacts from emissions (reduced social cost of carbon)	• Costs of reducing emissions from cement manufacturing • Costs of improving efficiency and reducing emissions from industrial products (such as refrigerants) • Costs for improving efficiency and electrification



Waste Sector

The waste sector emits GHGs through the decomposition of solid and liquid waste generated by households, commerce, and industry. Formal treatment of waste can reduce the associated emissions. We model waste sector emissions using the well-established methodology described in the Intergovernmental Panel on Climate Change's 2006 *Guidelines for National Greenhouse Gas Inventories*. 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 estimates of emissions are quite detailed but do not resolve individual communities or waste-processing facilities. During the stakeholder interactions, we consulted representatives from a range of stakeholders from the waste sector, who are listed in Appendix D. Table 2.9 summarizes the key NDP actions for the waste sector and how these actions are represented in the model.

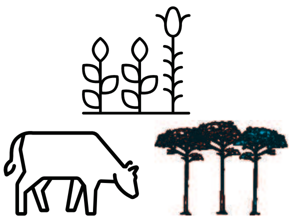
The primary benefits to decarbonization in the waste sector are represented by the value of recycled materials, connecting households to sewage service for proper treatment, reduction in some environmental impacts from untreated wastewater, and recycled water that can be used as part of a circular economy in other sectors. Costa Rica's National Wastewater Sanitation Plan (Política Nacional de Saneamiento en Aguas Residuales; PNSAR) calls for many of these same investments due to these potential benefits (AyA, 2016). We estimate the costs of collecting and processing waste for landfill disposal, composting, and recycling; capturing methane at landfills; and rehabilitating and adding sewage connections and treatment capacity (Table 2.10). We consulted representatives from a range of stakeholders from the waste sector, who are listed in Appendix D. Appendix A provides details and numerical values.

Table 2.9
Waste Sector Decarbonization Plan Actions and Model Implementation

Decarbonization Plan Actions	Model Implementation
Increase composting	• Divert food waste to composting facilities
Implement Política Nacional de Saneamiento en Aguas Residuales (PNSAR), Costa Rica's sanitation plan (AyA, MINAE, and MS, 2016); increase sewer, sanitation, and treatment system coverage (per the most recent national sanitation plan)	• Increase in domestic, commercial, and industrial waste that is collected and processed through a wastewater treatment facility, including 100% treatment of urban wastewater and secure sanitation for rural areas by 2045
Increase recycling	• Divert recyclables to material recovery facilities or at source
Increase landfilling and methane capture	• Reduce open air trash burning, increase collection of solid waste, and increase landfilling. Additionally, increase methane capture at landfills

Table 2.10
Waste Sector Benefits and Costs of Decarbonization Modeled in This Study

Benefits of Decarbonization	Costs of Decarbonization
• Commercial value of recycled waste • Value to residents of sewage service • Value to environment from collecting and treating sewage instead of informal discharge • Value of recycled water for other uses (i.e., circular economy) • Reduced climate change impacts from emissions (reduced social cost of carbon)	• Collecting solid waste • Disposing of waste in landfills • Recycling and composting waste • Adding new/rehabilitating existing urban sewage connections and rural secure sanitation • Increasing wastewater treatment • Capturing methane at landfills



Agriculture, Livestock, and Forestry Sector

GHG Emissions from the agriculture, livestock, and forestry sectors are interconnected and thus often considered together for decarbonization planning. For this effort, we model each of the three sectors separately, but reflect linkages through common land-use projections.

The agricultural and livestock sectors are modeled in a similar fashion. 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. The GHG emissions for each type of animal is based on per animal emissions rates, which are composed of separate emission factors for enteric fermentation and manure decomposition. The vast majority of current emissions come from cattle and horses—96 percent.

Emissions from the agricultural and livestock sectors are disaggregated by the crops and animal categories listed in Table 2.11. The model does not represent spatial heterogeneity across Costa Rica.

Table 2.12 summarizes the key NDP actions for the agriculture and livestock sectors and how these actions are represented in the model.

Decarbonization in agriculture and livestock can be achieved through increasing carbon sinks—for instance, by planting of trees—and reduction in emissions—through, for example, more efficient uses of fertilizer, use of different agricultural feed, and better manure management. There are many benefits to decarbonization in the agriculture and livestock sectors, as listed in Table 2.13 and Appendix A. The largest benefits include agricultural and livestock yield increases. Costs for the agricultural sector are divided between those specific to coffee

Table 2.11
Crop and Animal Type Estimates in the Agriculture and Livestock Sector Models

Crops	Animal Types
• Coffee • Fruits • Palm Oil • Pineapple • Rice • Sugarcane • Vegetables • Bananas • Other	• Meat cattle • Milk cattle • Dual-purpose cattle • Horses • Goats • Mules • Pigs • Poultry • Sheep • Water buffalo

Table 2.12
Agriculture and Livestock Sector Decarbonization Plan Actions and Model Implementation

Decarbonization Plan Actions	Model Implementation
Emissions reduction by primary agricultural chains	• Reducing carbon emissions per area of cultivated land by crop type
Achievement of low emissions and sustainability	
Use of biodigesters	• Reduction of emissions per head of herding animals
Use of low-carbon technologies for livestock	

Table 2.13
Agriculture and Livestock Sector Benefits and Costs of Decarbonization Modeled in This Study

Sector	Benefits of Decarbonization	Costs of Decarbonization
Agriculture	• Energy cost savings from electrification in the agriculture sector • Increased agricultural yields due to improved practices • Reduced climate change impacts from emissions (reduced social cost of carbon)	• Coffee farm decarbonization programs • Non-coffee decarbonization
Livestock	• Improved productivity due to improved feeding and livestock management, which can reduce the number of unproductive cattle, for example • Reduced climate change impacts from emissions (reduced social cost of carbon)	• Cost of reducing carbon emissions from livestock

farms based on existing Costa Rica programs and all other crops. Costs from the livestock sector are based on aggregate GHG emissions reductions, per academic studies. We consulted representatives from a range of stakeholders from these sectors, who are listed in Appendix D.

The forestry sector model tracks estimates of the use of all major types of land and evaluates the associated emissions sequestration from forests, mangroves, and wetlands and the emissions released or sequestered from the conversion between forested and other land types. 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
- wetlands
- settlements
- other.

Table 2.14 summarizes the key NDP actions for the forestry sector and how these actions are represented in the model.

Decarbonization in the forestry sector leads to increases in a range of ecosystem services that can be classified as follows:

- **Provision of renewable products or material:** For wet forests, the largest value comes from genetic material, hydropower, and other forest products; for mangroves, the largest value comes from food and other products.

Table 2.14
Forestry Sector National Decarbonization Plan Actions and Model Implementation

Decarbonization Plan Actions	Model Implementation
Maintenance and increase in forest cover	• Elimination of deforestation of primary forests • Increasing carbon sequestration rates from forested land types
Restoration and protection of coastal and rural areas	• Elimination of deforestation of primary mangrove forests • Increasing carbon sequestration rates from mangrove and wetland land types

- **Ecosystem management:** For wet forests, the largest value comes from erosion management, climate regulation, and water filtration and purification; for mangroves, significant value comes from preservation of biodiversity, protection from extreme events, erosion prevention, and climate regulation.
- **Cultural support:** Wet forests and mangroves provide significant tourism and recreation value.

Costs are represented by opportunity costs from not deforesting and the costs required to increase net sequestration from existing forests (Table 2.15).

Table 2.15
Forestry Sector Benefits and Costs of Decarbonization Modeled in This Study

Benefits of Decarbonization	Costs of Decarbonization
• Ecosystem services from wet, dry, and mangrove forests • Reduced climate change impacts from emissions (reduced social cost of carbon)	• Opportunity cost of forgone timber • Opportunity cost of forgone grazing • Opportunity cost of forgone agricultural production • Increasing carbon sequestration by forests

Accounting for Uncertainty About Future Emissions and Decarbonization

It is not likely that the baseline assumptions will play out exactly as anticipated today, and thus there is uncertainty about how emissions could evolve in the future without decarbonization. Uncertainty about model estimates of future emissions stems from (1) inaccurate or incomplete information about current emissions, such as the emissions rates from cows or cement manufacturing; (2) uncertainty in the evolution of emissions drivers, such as the number of livestock or amount and type of manufacturing in the future; (3) uncertainty about how processes leading to emissions could change, such as forest use and sequestration rates; (4) imprecise averaging of effects across the sectors, such as representing average household energy use rates or land use actions across the Costa Rican landscape instead of disaggregating across municipalities or regions; and (5) the specific modeling formulation used to make the estimate.

There is also uncertainty about the effectiveness of decarbonization actions. For example, the NDP establishes targets for adoption of electric vehicles, but achievement of the targets is not guaranteed. The NDP also seeks to ensure that electricity is generated using renewable sources such as hydropower, wind, and solar. The amount of available hydropower, in particular, could decline in the future because of the uncertain effects of climate change.

There is uncertainty around the cost and benefit factors used to estimate net benefits of the decarbonization plan. In many cases, Costa Rica–specific cost or benefit factors are

not available, so values derived from other regions were used. There are also benefits and costs to decarbonization that are not included in this study. For example, economic benefits from employment are not included, and there are many intangible benefits to quality-of-life improvements from the decarbonization actions that are not included. In some cases, data were not available, such as the direct costs of reducing emissions in the buildings sector, and thus had to be estimated. As a result, some benefits and costs may be under- or overestimated.

There are more than 125 uncertainties defined in the models we use to estimate emissions across all the sectors. Table 2.16 summarizes uncertainties around drivers of emissions that are independent of the implementation of the NDP—called *driver uncertainties*—and uncertainties about the implementation of the NDP—called *decarbonization uncertainties*. There are an additional 47 factors used to estimate the benefits and costs of the NDP. These factors are summarized in the sections above—Tables 2.2, 2.4, 2.6, 2.8, 2.10, 2.13, and 2.15.

To account for these uncertainties, we developed several thousand futures exploring uncertainty—each future reflects a set of assumptions about the uncertain parameters. These estimates were developed prior to the spread of COVID-19. Recent studies suggest, however, that the pandemic-related reductions are likely to be temporary (Forster et al., 2020). As such, any impact on long-term economic activities can be suitably reflected in a reasonable range of long-term average economic growth rates, as we have done in this study (see also box above). Then we used the CR-IDPM to evaluate GHG emissions and decarbonization benefits and costs for each future.

We developed the set of futures by first using the IEEM to develop three economic futures based on the following economic growth rates: 2 percent per year, 3.5 percent per year, and 4 percent per year. The baseline economic growth rate for 2021 to 2050 is based on estimates from the International Monetary Fund (2019), in which Costa Rica's gross domestic product grows to 3.5 percent for the period 2020 to 2050, and we set the lower and higher values to explore across a broader range of rates. Each future includes internally consistent estimates of emissions drivers, such as transportation demand and value added from different industries, crops, and livestock animals. We then mapped these data into specific inputs for the different sectoral models. We combined these three economic futures with baseline assumptions for all other parameters summarized in Table 2.13, and specified no implementation of the NDP. We label these Futures 1–3.

Next, we developed a 1,000-element sample across plausible ranges for the other driver uncertainties summarized in Table 2.16 and benefit and cost uncertainties described in Tables 2.2 through 2.15 to add to the baseline future. We used an approach called Latin hypercube sampling (LHS) to ensure that the resulting 1,000-element ensembles of futures efficiently sampled the full plausible ranges of uncertainties considered. The plausible ranges for each driver were established based on the literature or, when uncertainty information was not available, simply a standard percentage range around the best estimate. We combine these 1,000 futures with the three economic scenarios to define Futures 4–3003. Again, these assume no implementation of the NDP.

We then developed three experiments representing the implementation of the NDP under baseline assumptions for the three economic growth rate scenarios (experiments 3004–3006). Again, we developed a 1,000-element LHC sample, this time varying the driver uncertainties and the decarbonization uncertainties. We combined these 1,000 futures with the three economic growth rate scenarios to get an additional 3,003 experiments (Futures 3007–6006) that reflected the implementation of the NDP. Table 2.17 summarizes this experimental design.

Table 2.16
Summary of Uncertainties in the Emissions Models

Sector	Driver Uncertainties	Decarbonization Uncertainties
All	• Economic growth rate	• N/A
Transport	• Demand for transport (linked to economic growth) • Cost of fuels • Infrastructure costs for electrification, fuel changes, and modal changes • Technological costs • Elasticities of demand for different modes of transport • New technology adoption rates	• Growth of electric and hydrogen public transport • Growth of electric private and freight transport • Growth of hydrogen heavy freight • Growth of share of non-motorized transport and public transport use
Electricity	• Cost of new renewables	• Development of new renewables to meet increasing demand • Production from hydropower facilities
Buildings	• Population • Household occupancy rates • Commercial economic activity	• Household energy use • Percentage of household electrification • Energy use per amount of economic activity • Percentage of commercial electrification
Industry	• Cement and other industrial production • Decarbonization rates of cement and other industrial products • Industrial value added	• Decarbonization rates of cement and other industrial products (both a driver and decarbonization uncertainty) • Energy demand per value • Efficiency of non-electrical energy use • Increase in electrification of industrial activity
Waste	• Population • Industrial activity • Waste per capita and value of industrial production	• Share of waste that is recycled and composted • Percentage of sewage treated • Methane captured in landfills
Agriculture, livestock, and forestry	• Agriculture and livestock value added • Change in area used for cultivation and grazing	• Energy efficiency in agriculture and livestock • Amount of electrification of agriculture and livestock activities • Change in carbon intensity of agricultural production • Change in carbon emissions from animals and manure • Deforestation rates for primary forests • Change in carbon sequestration by wet, moist, dry, palm, and mangrove forests

Table 2.17
Experimental Design to Evaluate GHG Emissions, Benefits, and Costs Under Uncertainty

Futures	Economic Growth Rate	Other Driver Uncertainties	Decarbonization Uncertainties	Benefit and Cost Uncertainties
1–3	Low, baseline, high	Baseline assumptions	N/A	Baseline assumptions
4–3003	Low, baseline, high	1,000 element LHS sample	N/A	1,000-element LHS sample
3004–3006	Low, baseline, high	Baseline assumptions	Baseline assumptions	Baseline assumptions
3007–6006	Low, baseline, high	1,000-element LHS sample		

Identifying Vulnerabilities to Inform the Implementation of the National Decarbonization Plan

We evaluate the emissions, benefits, and costs of the NDP across thousands of plausible futures to first roughly estimate what the range of outcomes are. Might Costa Rica over- or undershoot its target for zero net emissions, and by how much? What range of net benefits might be achieved? Second, we seek to understand what future conditions could lead Costa Rica's decarbonization strategy to not achieve its goals. This information then informs how to implement the NDP in an adaptive way that ensures success no matter how the future unfolds. These results are presented in Chapter Four.

Using vulnerability analysis techniques from the RDM literature (Groves and Lempert, 2007; Bryant and Lempert, 2010), we define a threshold for GHG emissions, above which would indicate missing Costa Rica's decarbonization goals. Similarly, we defined another threshold for net economic benefits. The vulnerability analysis identifies key vulnerabilities, defined by the ranges of specific uncertainties that lead to poor outcomes. In Chapter Five, we discuss shaping and hedging strategies that Costa Rica could use to ensure successful implementation of the NDP.

CHAPTER THREE

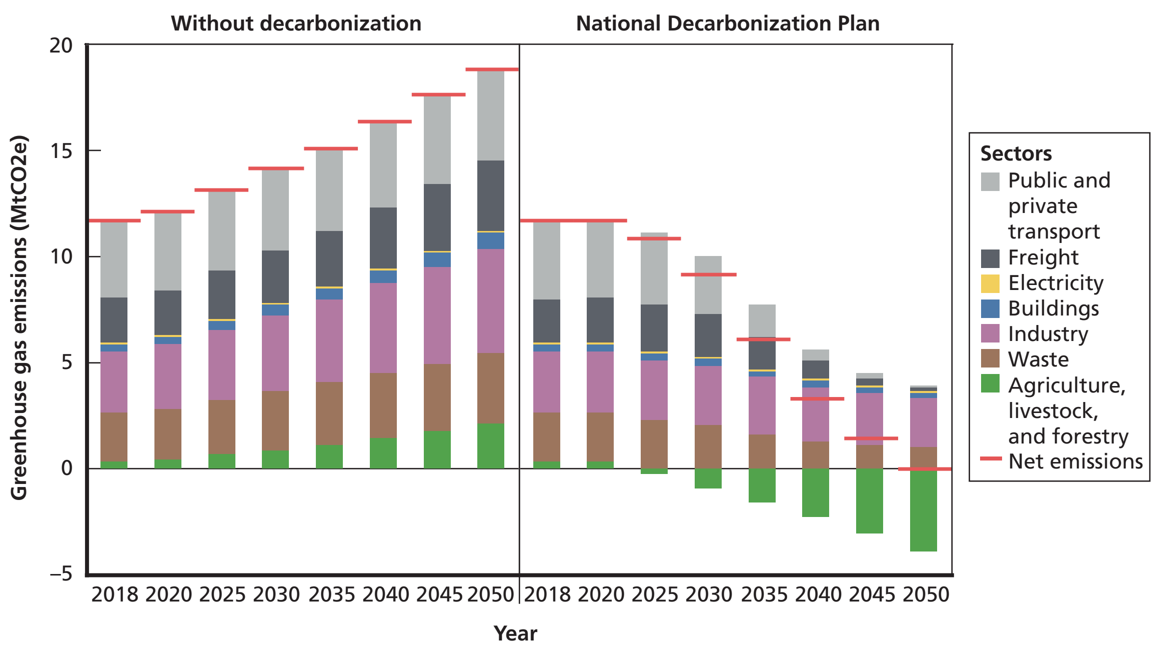
The Benefits and Costs of Costa Rica's Decarbonization Plan Under Standard Assumptions

Overall Benefits and Costs of Decarbonization to Costa Rica's Economy

If Costa Rica successfully implements its NDP, we estimate that net emissions would decline across all sectors from approximately 11.7 megatons carbon dioxide equivalent (MtCO2e) in 2018 to 0 MtCO2e in 2050, under baseline assumptions. Without implementation of the NDP, emissions would increase to 18.8 MtCO2e by 2050. Figure 3.1 shows these results disaggregated by sector. For the results presented here, we group the public and private transport sectors together, as some actions in the public sector, such as improving public transportation, lead to emissions reductions by private vehicles and benefits such as reduced congestion. We also group the agricultural, livestock, and forestry sectors together because land use changes affect all three.

The largest reductions in net emissions would occur in the transport sector: 4.2 MtCO2e reduction by the public and private transport systems and another 3.2 MtCO2e by freight

Figure 3.1
Costa Rican GHG Emissions, by Sector, over Time, Without Decarbonization (left) and with the Implementation of the National Decarbonization Plan (right) Under Baseline Assumptions



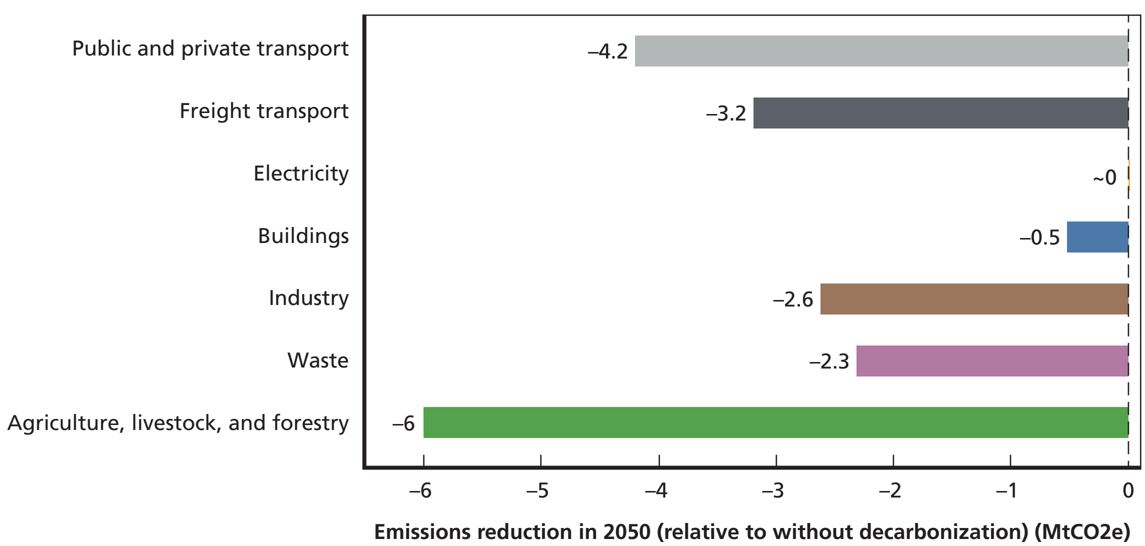
transport (Figure 3.2). Significant reduction would also occur in the agricultural, livestock, and forestry sectors: 6 MtCO2e by 2050, becoming the only net absorbing sector. Reductions in industry and waste account for an additional reduction of 4.9 MtCO2e. The current electricity system is nearly 100 percent renewable and has significant excess capacity. So, while emissions reductions are not directly coming from the electricity sector, the current renewable capacity of the electricity sector will support significant decarbonization in other sectors through electrification.

Under baseline assumptions, implementing the NDP would save or otherwise provide \$75 billion in benefits from 2020 to 2050, discounted back to 2015 at a rate of 5 percent per year. The discounted cost would be \$34 billion, yielding a net benefit of \$41 billion.[1]

Figure 3.3 shows how benefits and costs accrue over time, presented in terms of seven annual time slices. The largest class of benefits are due to cost savings from *electrification and efficiency*. This includes reduced fuel costs in the transport sector due to the adoption of electric and hydrogen vehicles. It also includes energy cost savings in the buildings and industrial sectors. The category *economic benefits* includes benefits other than lower energy costs from electrification that accrue directly to individuals and businesses, such as health savings and increased productivity. *Environmental services* include benefits from the agriculture, livestock, and forestry sector, such as providing plants for medicine, food for forest-based communities, and controlling erosion and filtering water supplies. *Circular economy* includes the benefits from recycling materials and the reuse of wastewater.

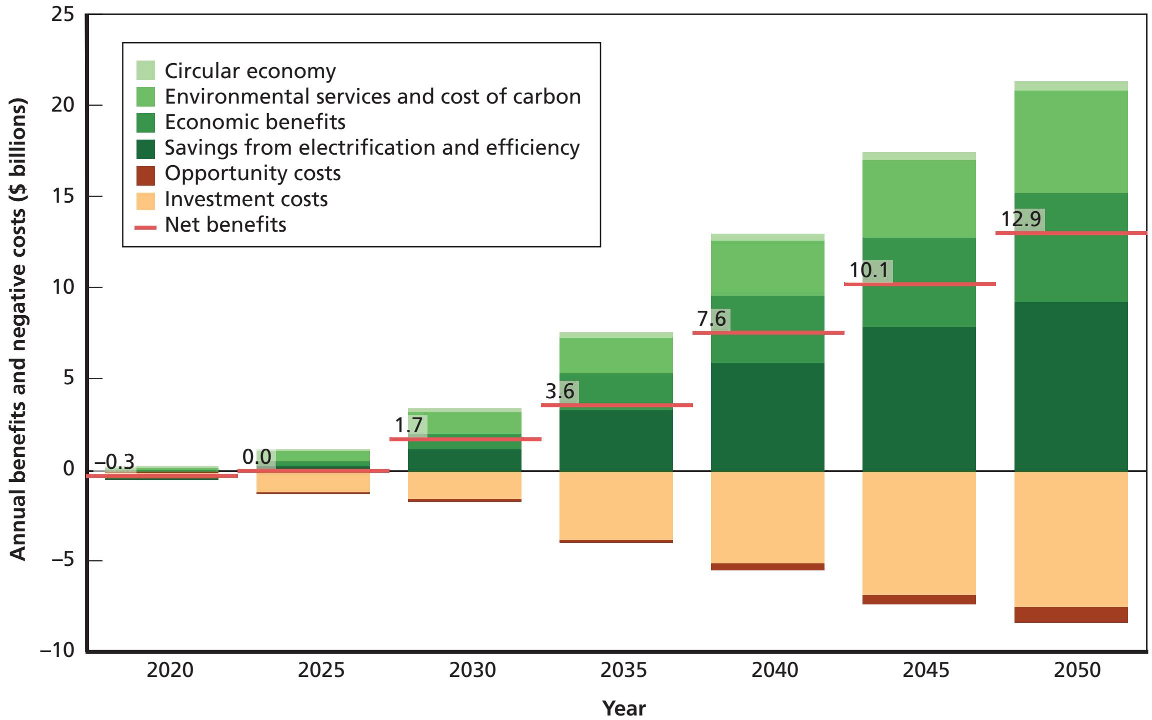
To implement the NDP, Costa Rica will incur *investment costs* and *opportunity costs*. The investment costs include switching to electric mobility, improving public transport, purchasing energy efficient equipment, and converting building energy use to electricity. Near-term

Figure 3.2
Costa Rican Reduction in 2050 Emissions, by Sector, with the Implementation of the National Decarbonization Plan Under Baseline Assumptions



[1] Five percent per year is the discount rate suggested by the Central Bank of Costa Rica and consistent with guidance from Coppola, Fernholz, and Glenday (2014). If net benefits were discounted back to 2020 at 5 percent per year, then they would be \$52.2 billion; if they were discounted back to 2020 at 10 percent per year, then they would be \$20.0 billion.

Figure 3.3
Annual Benefits and Costs of Implementing the Costa Rica Decarbonization Plan Under Baseline Assumptions, by Sector



investment costs are quickly outweighed by the benefits.[2] Opportunity costs include those related to preserving primary forests instead of using the land for timber production or agriculture and livestock.

Putting the benefits and costs together, we see the greatest net benefits in the agriculture, livestock, and forestry sectors—about $22 billion (Figure 3.4). This is followed by public and private transport, which would provide $17 billion in net benefits under baseline assumptions, while industry and waste would provide smaller net benefits ($1.4 billion together). Based on the way in which costs and benefits are accounted for across the sectors, net benefits in the electricity sector are slightly negative. However, the benefits of cheaper electricity are accounted for under the transportation, buildings, and industrial sectors. The net benefits from the buildings sector are also slightly negative under baseline assumptions. However, the estimates of benefits and costs are rough, as discussed below, and the net benefits could be slightly positive under different assumptions.

Uncertainty around the benefits and costs factors can be very high, and some benefits and costs may have been left out of the analysis. Our estimates of the costs of implementing energy efficiency in buildings, for example, are based on particularly weak evidence. In addition, even if costs listed under a given line of action exceed its benefits, the emissions reduc-

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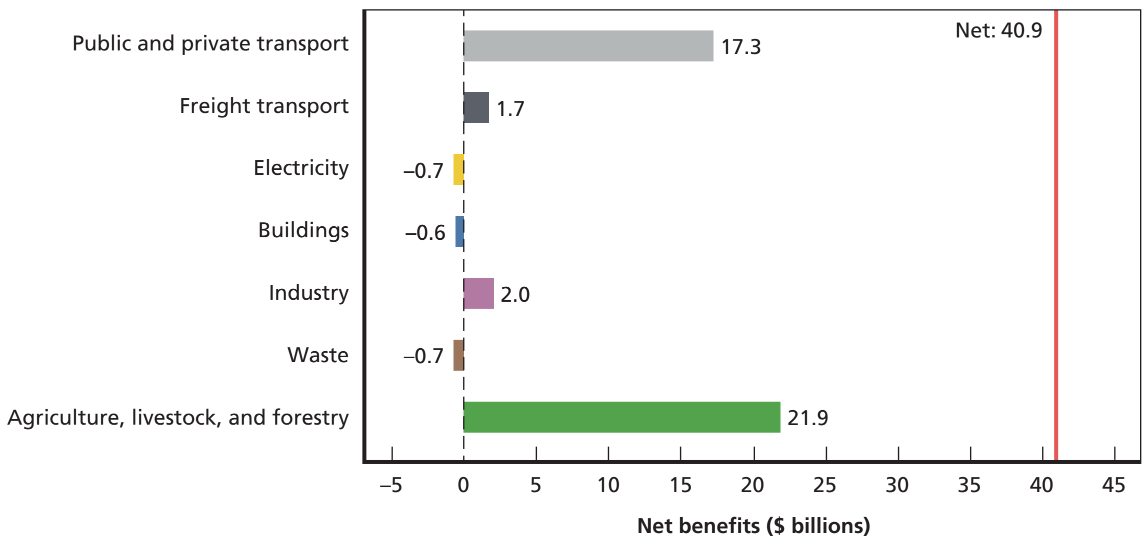
2 In an economy in which production factors are not fully used, as is perhaps the case in Costa Rica following the impacts of the pandemic, investments financed by public debt can under some conditions contribute to reactivate the economy and more than pay for themselves (Riera-Crichton, Vegh, and Vuletin, 2014; International Monetary Fund, 2019). The present study does not consider this impact: All investments are counted as net costs.

Figure 3.4
Total Discounted Net Benefits from Implementing the National Decarbonization Plan Under Baseline Assumptions, by Sector

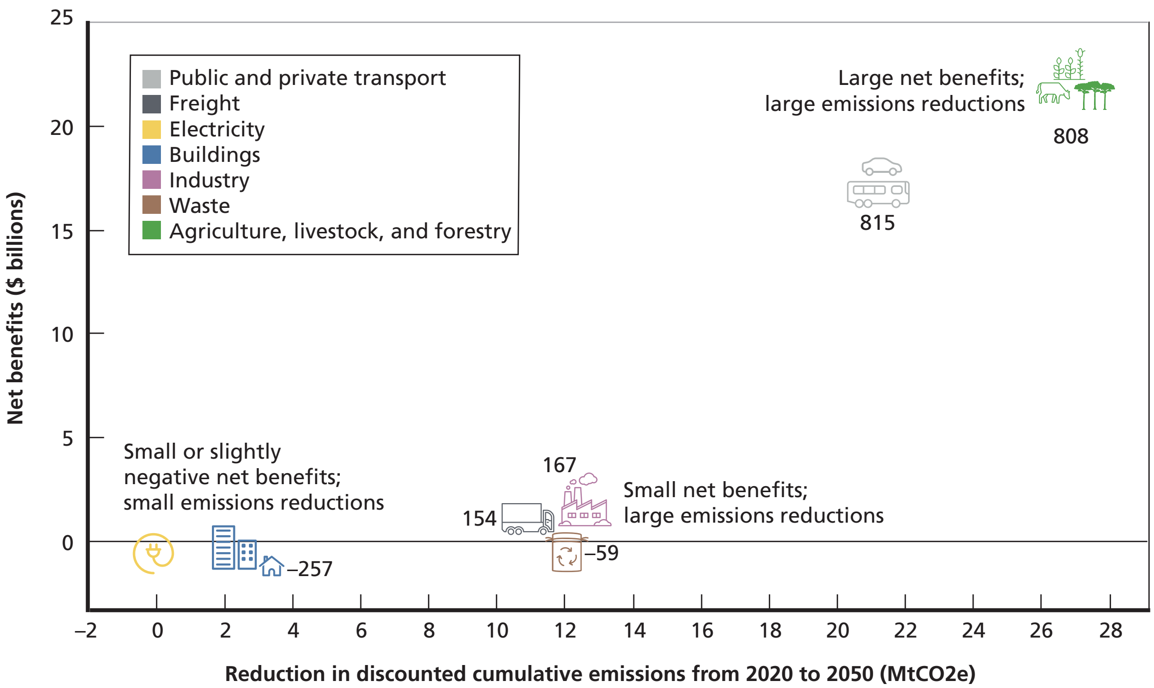


tions from this line of action may not be easily replaced by additional reductions with other actions. Costa Rica could also delay some investments until they become less expensive. Lastly, some shifts in NDP actions across the lines of actions in the NDP could reduce benefit/cost imbalances, as discussed in Chapter Five.

Importantly, costs associated with a particular line of action do not need to translate into costs for the economic actors of that sector. The distribution of costs and benefits over consumers and firms depends crucially on government policy, which is not considered here. For instance, the government can use tax policy or other mechanisms to transfer some of the gains to those who incur net costs under the NDP.

When looking at emissions and net benefits together by the sectors, we see clearly that a few sectors lead to large emissions reductions and significant net benefits: agriculture, forestry, livestock, and private and public transport (Figure 3.5). Net benefits per discounted cumulative emissions amount is also greatest for these sectors—$808 per ton CO2 equivalent (CO2e) and $815 per ton CO2e. Actions in the freight transport, industry, and waste sectors lead to large GHG emissions reductions, but lower net benefits. The unit benefit is also significantly lower than for the prior sectors. Lastly, decarbonization actions in the electricity and buildings sector would lead to much lower emissions reductions and modest net costs.

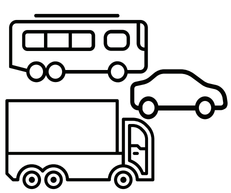
Figure 3.5
Discounted Net Benefits Versus Discounted Change in Emissions from 2020 to 2050, by Sector



NOTE: Numbers indicate the net benefits per discounted cumulative emissions ($ per ton CO2e)—no value is provided for the electricity sector due to very small emissions reductions and net benefits

Sector-by-Sector Breakdown of Emissions, Benefit, and Costs

The following subsections drill down in each sector to examine how emissions are reduced, and the individual benefits and costs that accrue over time under the baseline assumptions.



Transport Sector

Under baseline assumptions and the implementation of the NDP, transport emissions would decline from 5.7 MtCO2e in 2018 to 0.3 MtCO2e in 2050, at a discounted cost of $24 billion. These reductions would lead to $30 billion in discounted cost savings and about $13 billion in health, accidents, and congestion savings.

Implementation of the NDP would lead to emissions reductions across public, private, and freight transport (Figure 3.6). Emissions would be all but eliminated in the private transport sector, because the fleet is completely electrified. Small rates of GHG emissions would remain in 2050 from the freight and public sectors.

Decarbonization in the transport sector would lead to benefits that significantly outweigh the costs (Figure 3.7). The largest benefits would come from reduced operations and maintenance costs from a largely electrified fleet—$14.4 billion from public and private transport, $12.3 billion from freight, and an additional $3.6 billion from the transport system as a whole. The next largest benefit category are reductions in costs associated with pollution, accidents, and congestion—about $11 billion. Most benefits come from reduced accidents, accomplished through reduction in the numbers of private vehicles used and distance traveled

as mobility is shifted to public transport options, enabled by the investments in improved bus lines, the electric train, and non-motorized mobility options.

Figure 3.6
Emissions from the Transport Sector Without Decarbonization and with the Implementation of the National Decarbonization Plan

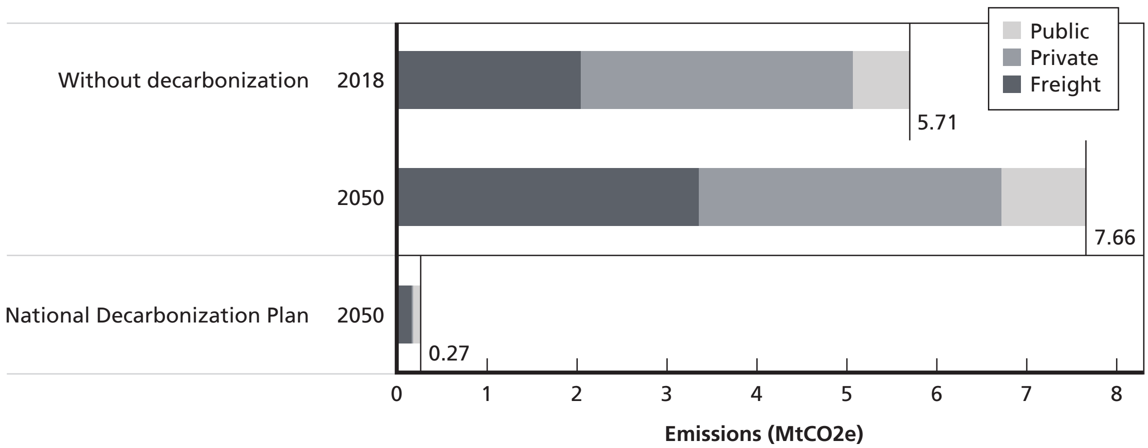
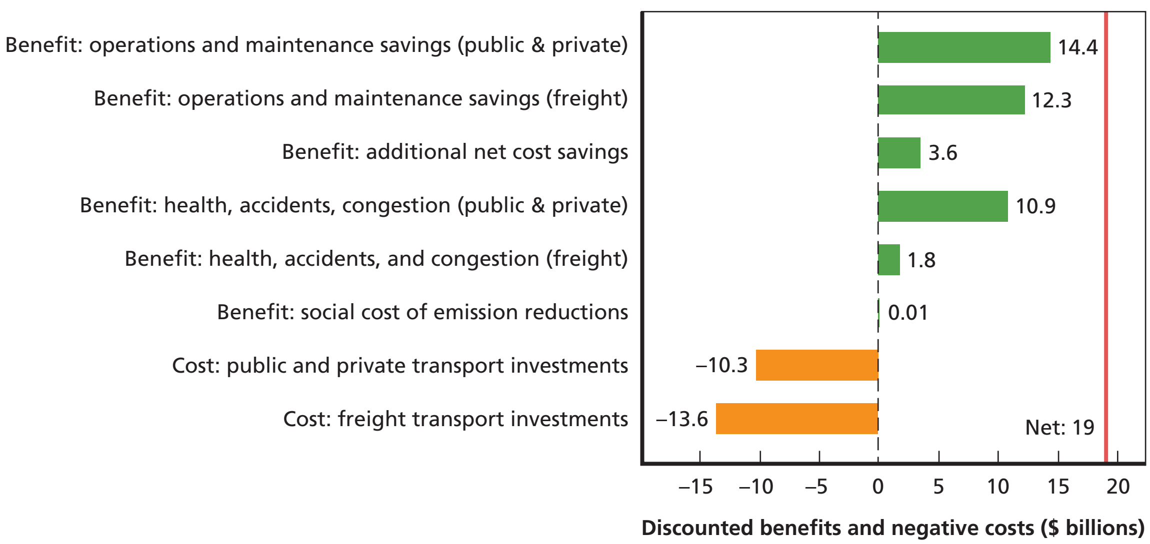
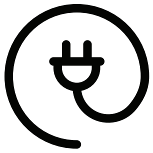


Figure 3.7
Benefits and Costs from Decarbonization in the Transport Sector Under Baseline Assumptions





Electricity Sector

Under baseline assumptions and the implementation of the NDP, emissions from the electricity sector would remain close to zero through 2050, as renewable sources continue to provide carbon-free electricity. Only modest investments of less than $1 billion through 2050 would be required to maintain the high level of renewable capacity.

The Costa Rican electricity system currently has excess renewable capacity due to a highly developed hydropower infrastructure. As Costa Rica electrifies the transport and other sectors, this excess capacity provides inexpensive replacement fuel. The difference in emissions from power generation between the "without decarbonization" and "with implementation of the NDP" are very small—less than 0.08 MtCO2e per year from 2040 to 2050. Similarly, the net costs are small because of the modest investment costs—about $700 million discounted costs from 2020 to 2050. Note that the benefit in terms of cheaper energy for transportation, buildings, and industry are accounted for under the respective lines of actions.

Implementing the NDP increases electricity consumption (Figure 3.8). In 2018, electricity use was about 31 petajoules (PJ) per year, and it increases to almost 140 PJ per year under baseline assumptions. The largest increases come from electrification of public, private, and freight transport and industry. The electricity demand by buildings remains roughly constant, as increases due to electrification are offset by increases in energy efficiency.

Increased electricity demand is met largely with existing renewable hydropower. As a result, the levelized cost of electricity declines over time faster with the implementation of the NDP than without—from 0.14 dollars per kilowatt-hour ($/kWh) to 0.05 $/kWh (Figure 3.9).

Figure 3.8
Change in Electricity Consumption by the Transport, Buildings, Industry, and Agricultural Sectors

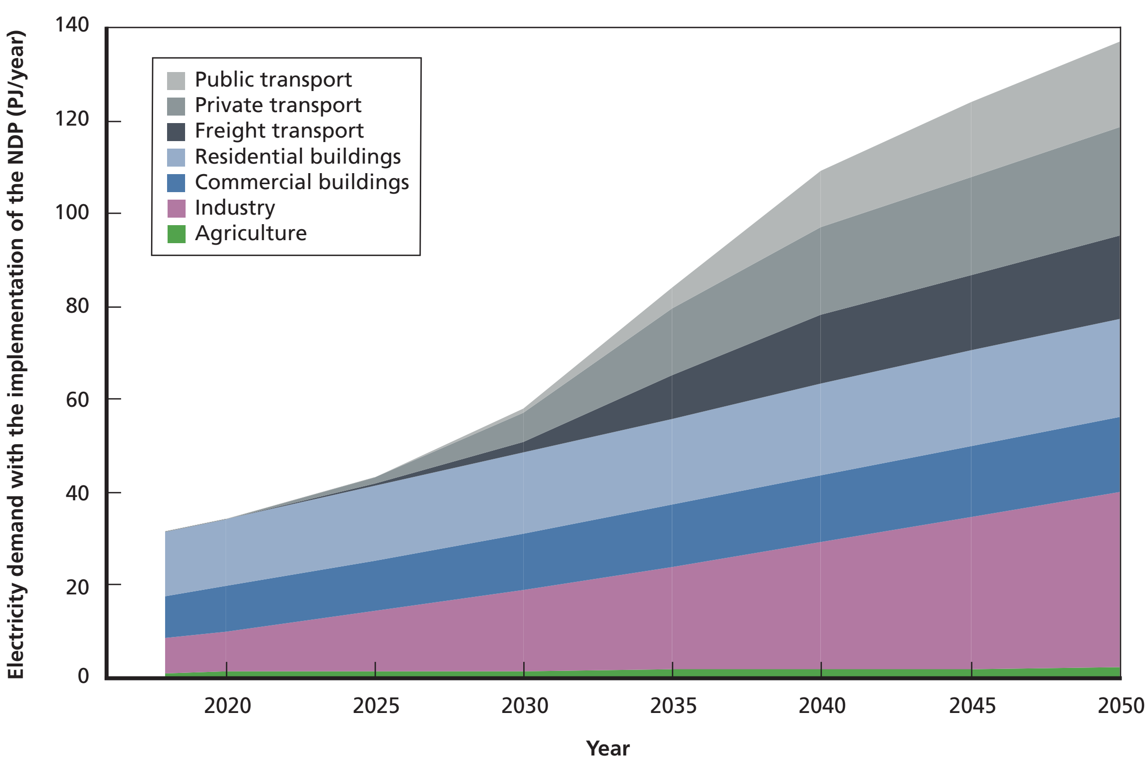
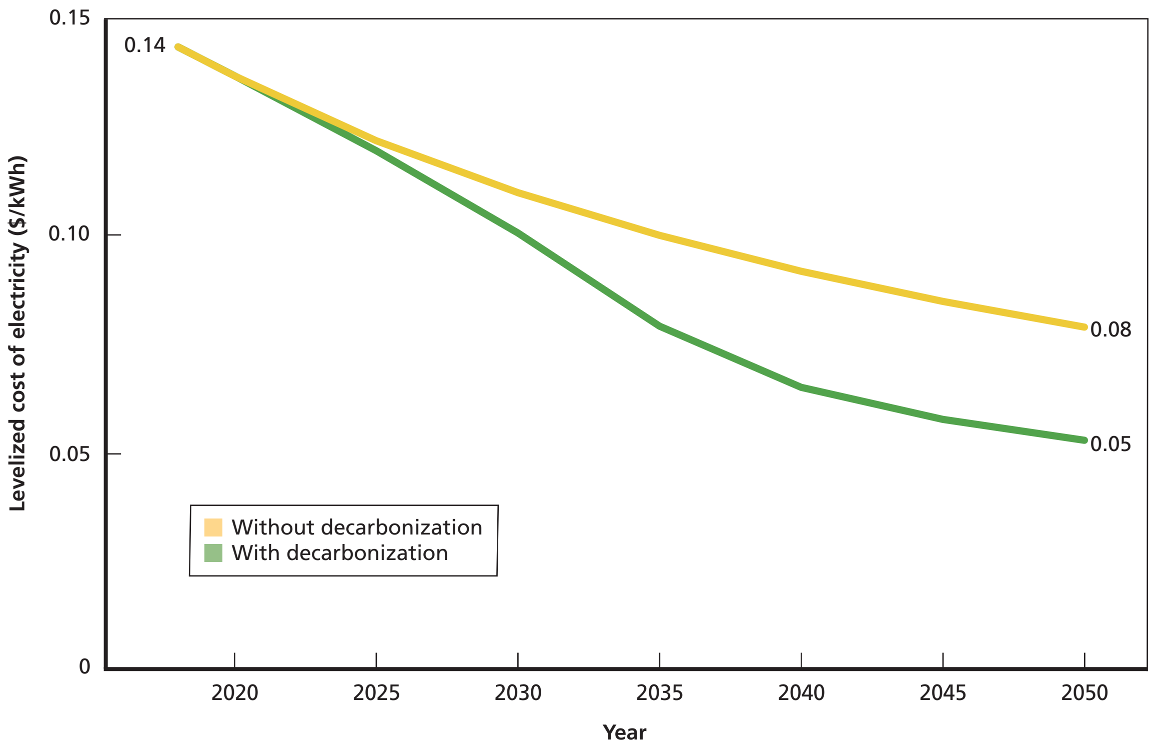
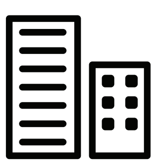


Figure 3.9
Levelized Cost of Electricity over Time Without Decarbonization and with the Implementation of the National Decarbonization Plan



By 2050, we estimate that electricity would be 38 percent less costly to generate with the implementation of the NDP and 79 percent less costly than in 2018, under baseline assumptions. This benefit is accounted for as savings from electrification under the transportation, buildings, and industry sectors. Current regulations in Costa Rica mandate that electricity is priced at its levelized costs. Our result suggests that under this arrangement, the implementation of the NDP would result in reduced electricity prices for consumers and firms.



Buildings Sector

Under baseline assumptions and the implementation of the NDP, emissions from the buildings sector would decline by about 42 percent through 2050 at a cost of about $2.4 billion through 2050. The decarbonization investments would yield about $1.8 billion in energy cost savings to residential and commercial building owners or occupants, which do not entirely offset higher investment costs in our baseline scenario.

Emissions from the buildings sector are relatively low compared to other sources—only about 0.4 MtCO2e in 2018. Under the NDP and baseline assumptions, emissions would decline to about 42 percent of what they would have been, due to reductions in both residential and commercial buildings (Figure 3.10). The rate of emissions reduction for residential and commercial buildings is similar.

Decarbonization benefits in the residential sector result primarily from energy cost savings to residential and commercial building energy customers (Figure 3.11). Costs, though difficult to estimate for the commercial sector, are considerably higher for commercial buildings

under baseline assumptions. Improved estimates for these costs, based on building inventories with detailed characteristics that are not currently available, could increase our assessment of the net benefits from the buildings sector. Alternative assumptions are explored through the uncertainty analysis described in Chapter Four.

Figure 3.10
Emissions from the Buildings Sector Without Decarbonization and with the Implementation of the National Decarbonization Plan

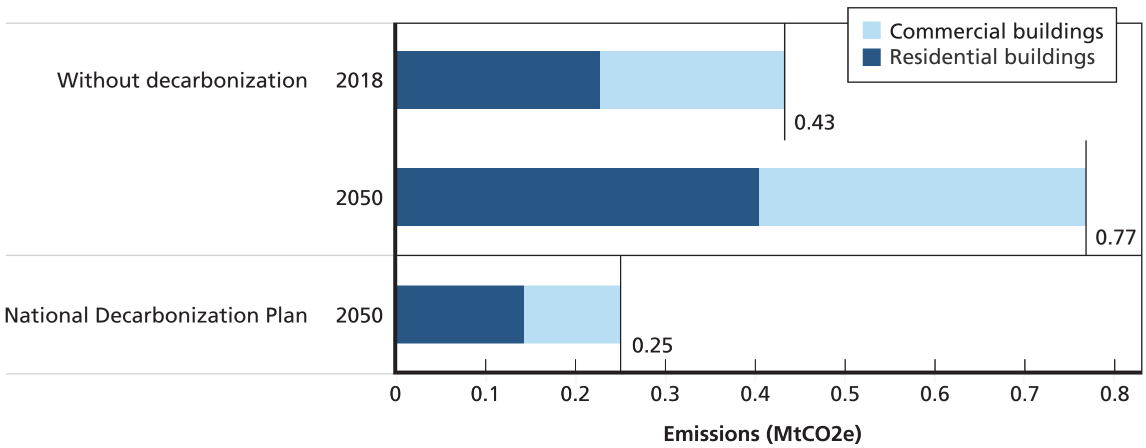
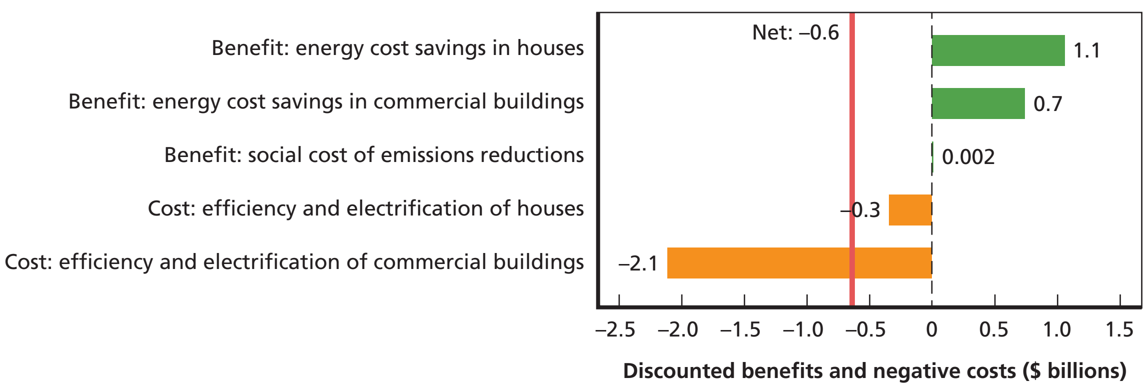
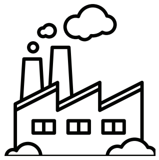


Figure 3.11
Benefits and Costs from Decarbonization in the Buildings Sector Under Baseline Assumptions





Industrial Sector

Under baseline assumptions and the implementation of the NDP, emissions from the industrial sector would decline modestly—about 21 percent, but would be less than half of the emissions without the NDP. The cost would be about $2.2 billion and yield about $4.3 billion in benefits from reduced energy costs and increased productivity.

There are three main ways in which emissions would be reduced in the industrial sector: (1) reductions in emissions associated with cement production (the largest industrial GHG emission source), (2) reduction in the emissions associated with the use of industrial products, such as refrigerants, and (3) reductions in emissions related to the energy needed to power industrial processes (Figure 3.12).

The major benefits to Costa Rica from decarbonization of the industrial sector could come from increased industrial productivity associated with the decarbonization actions. We conservatively estimate that productivity could improve at a rate of one-third that of decarbonization (e.g., a 10 percent decarbonization would lead to a 3.3 percent productivity improvement). Under this assumption, $3.6 billion in benefits would be realized in the industrial sector (Figure 3.13). Costs to the industrial sector are due primarily to reducing cement emissions—about $1.4 billion—reducing emissions from industrial products—about $0.6 billion—and increasing energy efficiency—about $200 million, under baseline assumptions. The net benefits under these baseline assumptions are $2 billion.

Figure 3.12
Emissions from the Industrial Sector Without Decarbonization and with the Implementation of the National Decarbonization Plan

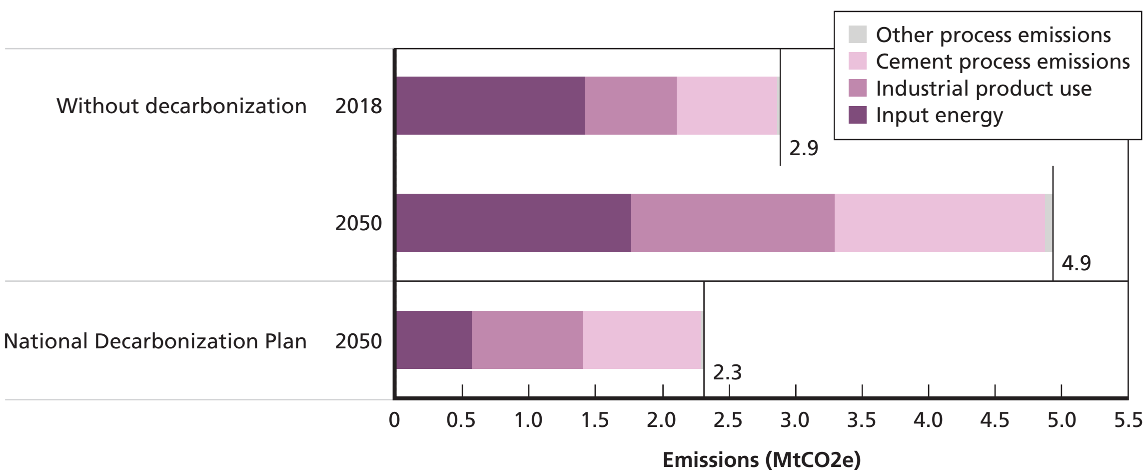
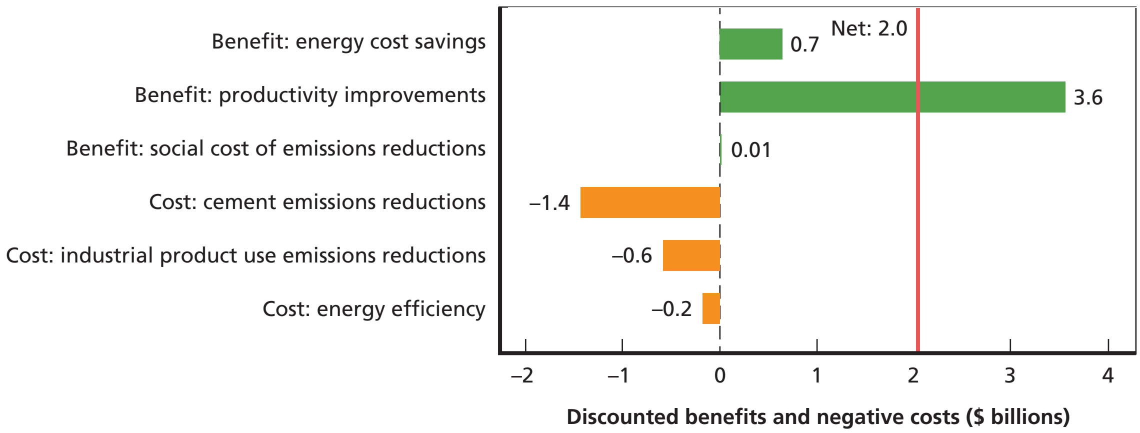


Figure 3.13
Benefits and Costs from Decarbonization in the Industrial Sector Under Baseline Assumptions



Waste Sector

Under baseline assumptions and the implementation of the NDP, emissions from the waste sector would decline significantly—about 57 percent, at a cost of about $4.4 billion. Decarbonization would provide about $3.7 billion of value through recycled materials, treated wastewater, and health and aesthetic benefits from collecting and treating most solid and liquid waste.

Decarbonization of the waste sector leads to GHG emissions reductions from a variety of sources. Currently only 14.4 percent of sewage is treated, leading to large GHG emissions as the organic material decomposes. Collection and treatment of this waste from the industrial and commercial sectors would lead to significant GHG emissions reductions (Figure 3.14). Similarly, the informal disposal of trash and landfilling of waste that otherwise could be recycled or composted would lead to almost 3.3 MtCO2e of emissions by 2050 under baseline assumptions. Implementing the collection, recycling, methane capture, and composting actions in the NDP could reduce these emissions by about 70 percent. The negative emissions associated with recycling in Figure 3.14 reflects the replacement of virgin material and elimination of the emissions needed to produce them.

There are many benefits from decarbonizing the waste sector. Consistent with the concept of the "circular economy," the value of recycled waste and treated wastewater could offset much of the costs associated with decarbonization (Figure 3.15). There are also significant environmental benefits to collecting and treating sewage. Willingness to pay assessments reveal that households without connections to centralized sewage systems value the increased hygiene and convenience of connections by over $20 per month, per household—about $440 million in aggregate (Dixon, 2012). Similar assessments reveal another $200 million to the regional environment and groundwater benefits from reducing untreated wastewater in communities. There may be additional ecosystem benefits from increasing the collection and treatment of solid and liquid waste that are not reflected in our calculations due to lack of data.

The costs to recycle waste are hard to estimate at the high level of this study. We assume in the baseline that the sum of the cost of collecting and recycling material is equal to the value of the recycled material—that more profitable materials, such as metals, will offset net costs or recycling other materials with less value, such as plastics. We explore the assumption that the

Figure 3.14
Emissions from the Waste Sector Without Decarbonization and with the Implementation of the National Decarbonization Plan under Baseline Assumptions

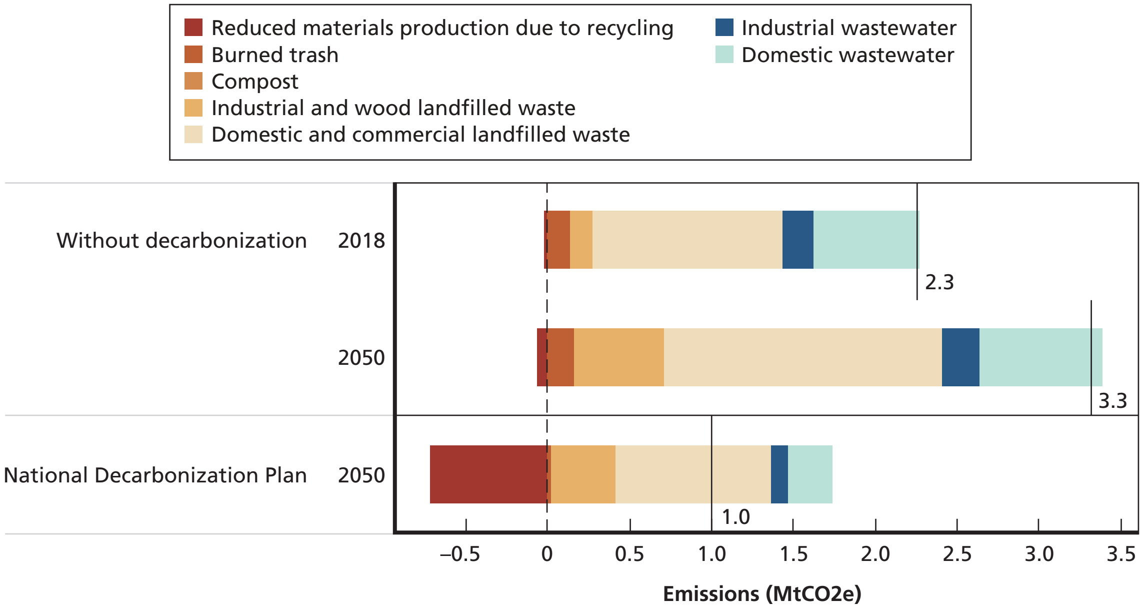
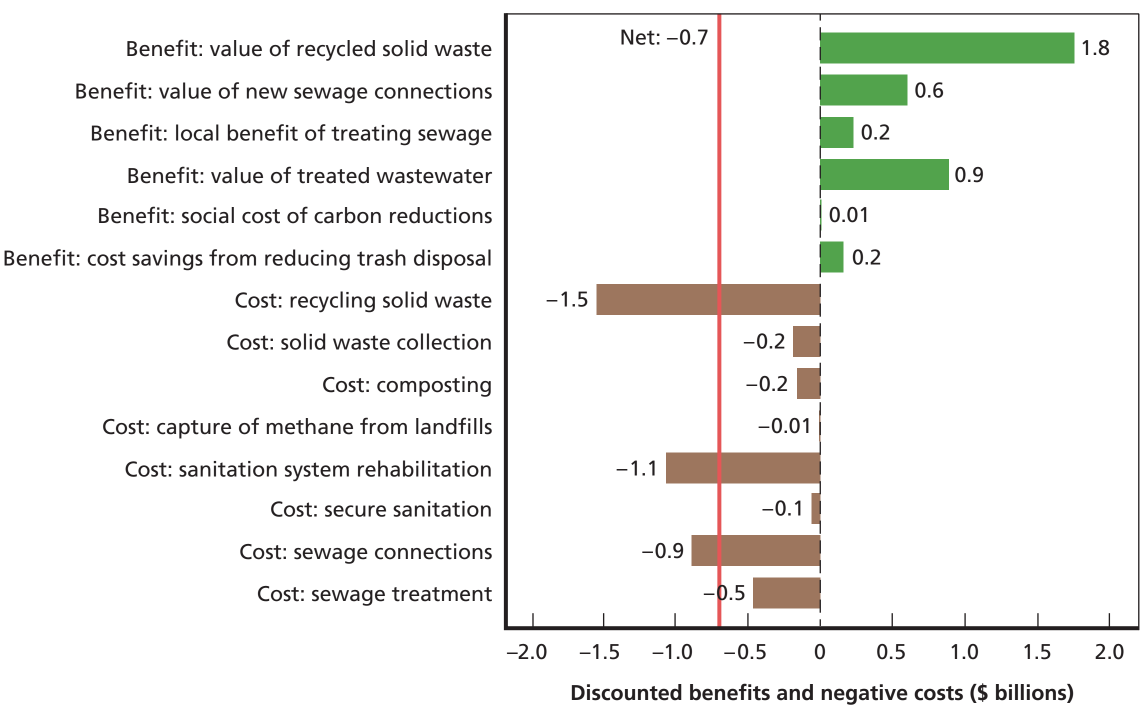


Figure 3.15
Benefits and Costs from Decarbonization in the Waste Sector Under Baseline Assumptions



costs are higher than the value in Chapter Four. The total discounted cost of the rehabilitation of the sanitation system and increasing the coverage of sewage connections and associated

treatment is high—\$2.6 billion. Lastly, costs to capture methane and convert to CO2 through burning is low and a practical approach for reducing GHG emissions.

Agricultural, Livestock, and Forestry Sector

Under baseline assumptions and the implementation of the NDP, emissions from the agriculture and livestock sector would be considerably lower than without the NDP: about 2.6 MtCO2e or 53 percent lower. Net emissions from forestry would decline even more: 3.3 MtCO2e. These emissions reductions would cost about \$3.1 billion through 2050, but would yield about \$25 billion of benefits from increased agricultural and livestock yields and additional forest ecosystem services.

The agriculture, livestock, and forestry sector collectively leads to net sequestration in Costa Rica. Agriculture and the raising of livestock contribute to modest levels of emissions relative to other sources in Costa Rica (3.1 MtCO2e in 2018, or 22 percent of emissions from the non-forestry sectors; Figure 3.16), which are mostly offset by sequestration from forests (–2.8 MtCO2e in 2018; Figure 3.17). Without decarbonization, however, emissions from agriculture and livestock would increase by almost 2 MtCO2e by 2050.

The NDP strategies call for investments in the agriculture and livestock sectors to counteract emissions increases and could lead to a reduction of 2.6 MtCO2e. The largest potential for emissions reductions come from management strategies targeted at the large cattle industry. Improving the management of manure, improving feed, and planting additional trees could lead to 2 MtCO2e reduction, relative to the "without decarbonization" condition. Improvement in agricultural processes and electrification of equipment could lead to an additional decrease of about 0.5 MtCO2e by 2050 under baseline assumptions.

The forestry sector provides tremendous opportunity for increasing carbon sequestration and offset otherwise difficult to eliminate emissions from other sectors. The NDP could

Figure 3.16
Emissions from the Agricultural and Livestock Sectors Without Decarbonization and with the Implementation of the National Decarbonization Plan

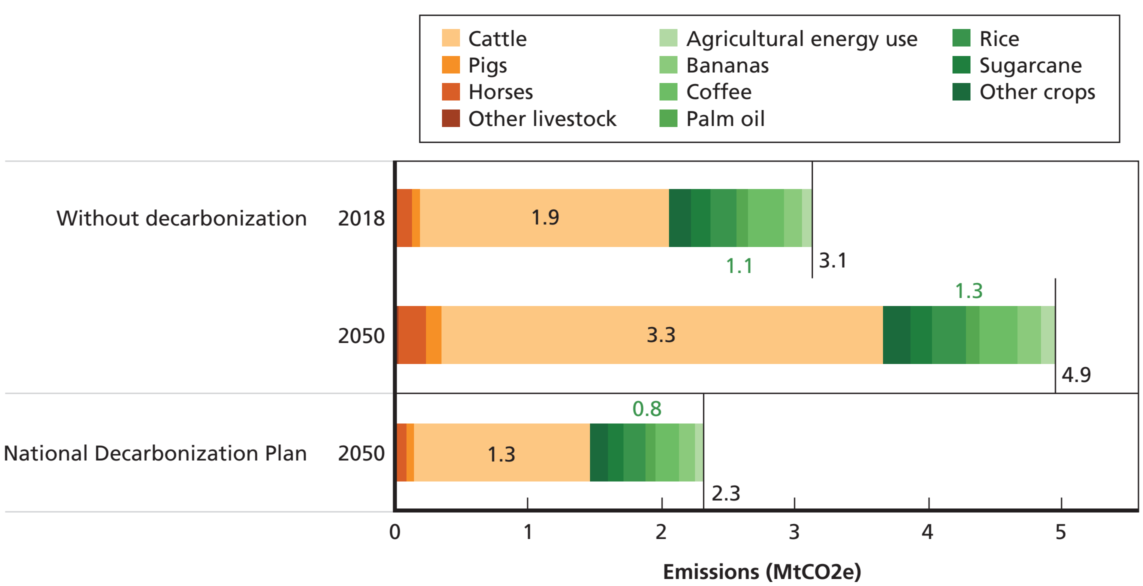
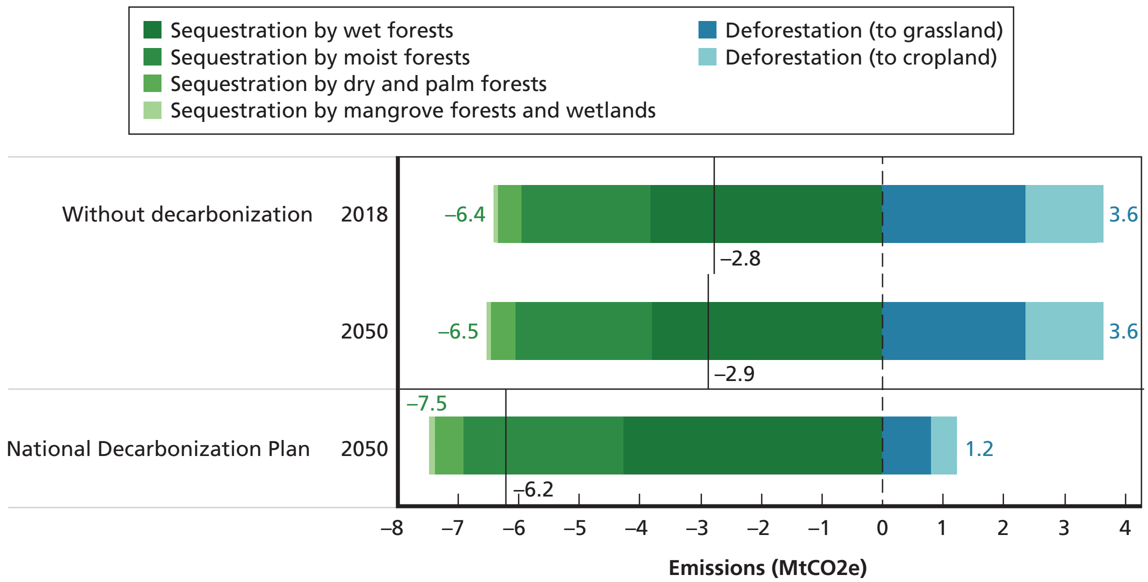


Figure 3.17
Emissions from the Forestry Sector for the Without Decarbonization and with the Implementation of the National Decarbonization Plan



reduce emissions using two main strategies: (1) preserving forests, which would eliminate the release of CO2 to the atmosphere when forests are cleared, and (2) improving management of the forest to sequester more carbon. Under our baseline assumptions, Costa Rica phases out all deforestation of primary forest and reduces net emissions by about 2.4 MtCO2e (Figure 3.17). Next, the sequestration rate of existing forested lands increases to reflect improved management and reduces net emissions by about 1 MtCO2e.

The decarbonization actions in the agriculture, livestock, and forestry sectors would lead to very large net benefits (Figure 3.18). The three largest benefit categories are (1) increased agricultural output due to improved management ($4 billion);[3] (2) increased ecosystem service benefits from not removing wet, dry, or mangrove forests ($7.2 billion), and (3) improving forest management ($13.5 billion).[4] According to our estimates, the costs would be much lower than benefits. Baseline assumptions suggest about $0.4 billion of costs for implementing agricultural improvements and $0.65 billion for improving livestock practices, based on the use of cost factors for unit reductions in GHG emissions for the agricultural and livestock sectors (Gillingham and Stock, 2018). We make an upper bound estimate of the costs of reducing deforestation by considering the opportunity costs of not removing forests. Specifically, we estimate the forgone value of timber from not removing primary forests ($0.7 billion), forgone value from livestock by grazing ($0.4 billion) and forgone value from agriculture ($1 billion). Based on estimates of the unit cost for reducing GHG emissions from tropical forests, compiled by Busch et al. (2019), we calculate the costs of increasing forest carbon sequestration to be about $0.3 billion over the 30-year period, as shown in Figure 3.18.

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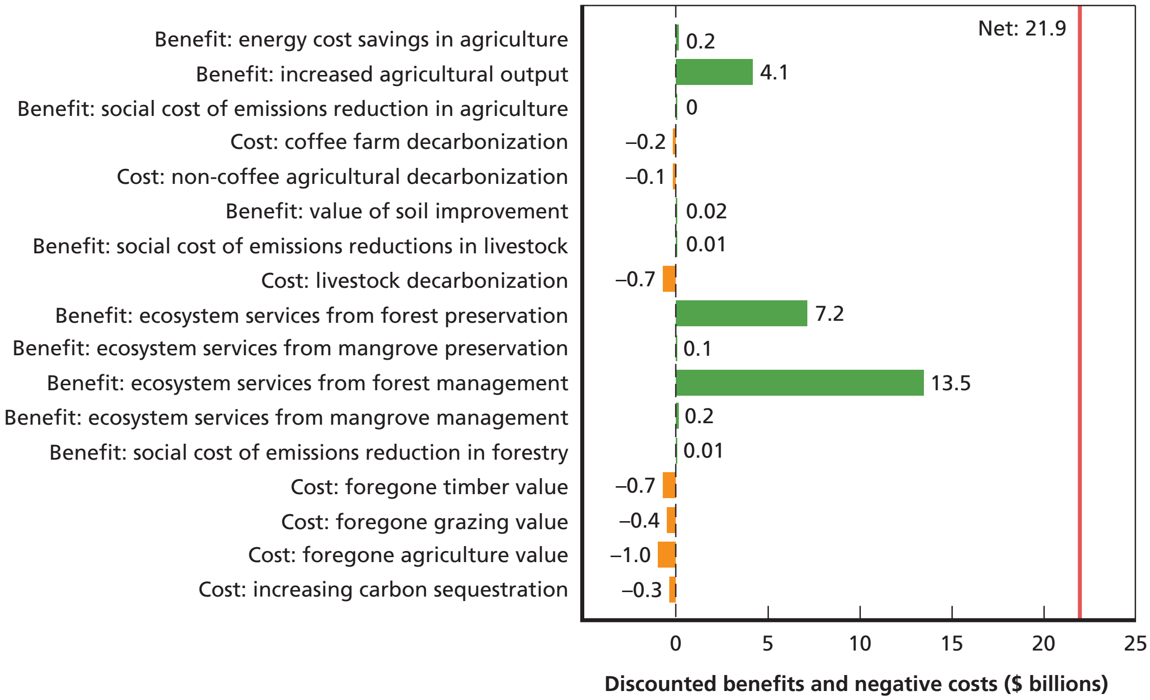
[3] See Karlsson, Alfredsson, and Westling (2020) and Verspecht et al. (2012) for a review of studies describing the agricultural benefits from climate mitigation.

[4] Proyecto Humedales de SINAC-PNUD-GEF (2017) provides estimates of the ecosystem value associated with forests, which we use to estimate benefits from preserving forests and improving their management.

Figure 3.18
Benefits and Costs from Decarbonization in the Agriculture, Livestock, and Forestry Sectors Under Baseline Assumptions



The results shown in this chapter are all based on a set of baseline assumptions. There is significant uncertainty around these assumptions, so it is important to understand whether and how these uncertainties could affect the achievement of the NDP emissions target and the net benefits of implementing the NDP. Chapter Four presents the analysis of uncertainty.

CHAPTER FOUR

How Uncertain Is the Success of Costa Rica's Decarbonization Plan?

The estimates in Chapter Three of future GHG emissions and the net benefits of implementing the Costa Rica NDP are based on a single baseline assumption for each of the 348 uncertain factors. In this chapter, we explore how sensitive this estimate is to other plausible assumptions about the future. The range of results presented here do not suggest how likely different outcomes are, but rather they

1. establish that implementing the NDP would lead to close to net-zero emissions over most plausible futures and do so while also leading to net benefits to other aspects of Costa Rica, and
2. provide information about which assumptions need to hold in order for the NDP to achieve its decarbonization goals at a large net benefit to Costa Rica.

This information helps determine whether alternative targets would be useful to develop, or how to develop adaptive targets that adjust over time in response to the outside drivers. Chapter Five elaborates on this approach.

The first section of this chapter describes how the NDP will perform across the 3,003 plausible futures described in Chapter Two, focusing on portraying the potential variability of the NDP with respect to emissions and net benefits. The second part of the chapter systematically analyzes these results to identify key vulnerability drivers and their associated thresholds.

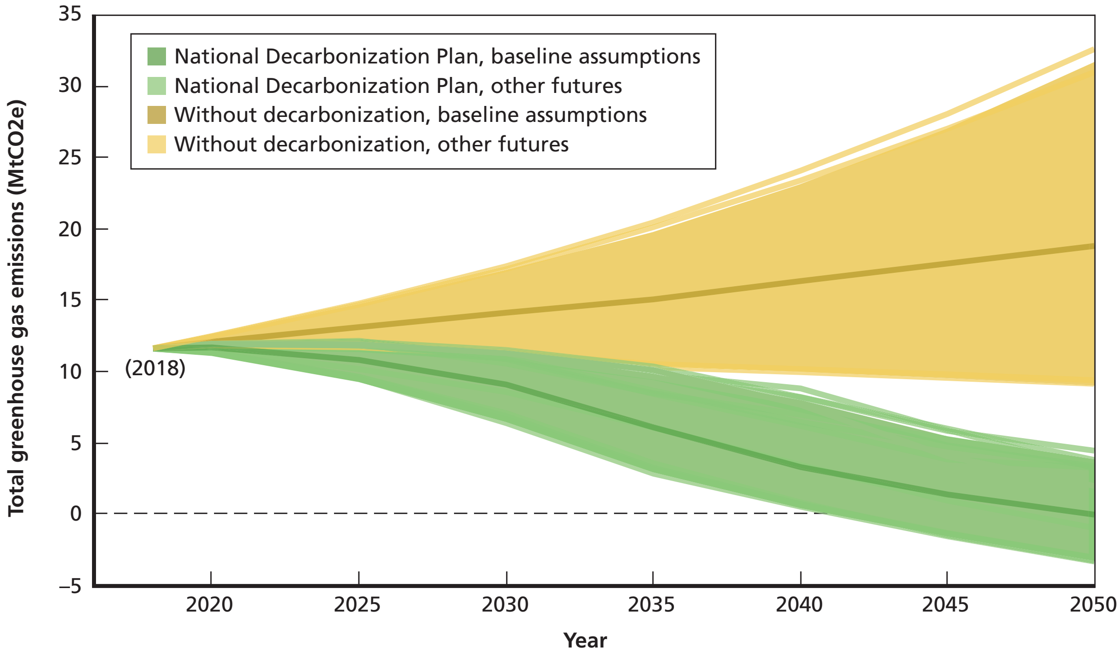
Range of Emissions and Net Benefits Across Uncertain Futures

Without implementation of the NDP, emissions would likely rise from current levels (around 12 MtCO2e) and even possibly more than double (Figure 4.1). Under some assumptions, emissions could hold steady or even decline slightly to about 9 MtCO2 in 2050. But achievement of zero net emissions would only happen with significant decarbonization efforts.

The implementation of the NDP would lead to a decline in emissions of at least 61 percent in all plausible futures, fall below 1 MtCO2e in 77 percent of futures, and lead to net negative emissions in 47 percent of futures evaluated. The uncertainty around emissions with the implementation of the NDP is lower than in cases without decarbonization, as the actions of the NDP reduce the sensitivity of emissions to socioeconomic drivers.

The implementation of the NDP would lead to significant net benefits to Costa Rica under the wide range of plausible conditions evaluated. Figure 4.2 shows the discounted costs

Figure 4.1
Projections of GHG Emissions Without Decarbonization (yellow) and with the Implementation of the National Decarbonization Plan (green) Across 3,003 Plausible Futures



along the horizontal axis and discounted net benefits along the vertical axis for each of the 3,003 plausible futures.[1] The vast majority of cases (99 percent) indicate positive net benefits (indicated by the green coloring), and some projections (1 percent) suggest net benefits higher than $100 billion. In a few cases (21 cases, less than 1 percent), costs exceed the benefits, as indicated by red coloring in Figure 4.2. We explore what could drive negative benefits below.

What Could Lead the Decarbonization Plan to Miss Its Goals?

To understand what the calculated ranges of emissions and net benefits mean to Costa Rica decarbonization efforts, we identify the assumptions that lead to high emissions or low net benefits. We do so by both inspecting the results and applying more sophisticated statistical tools.

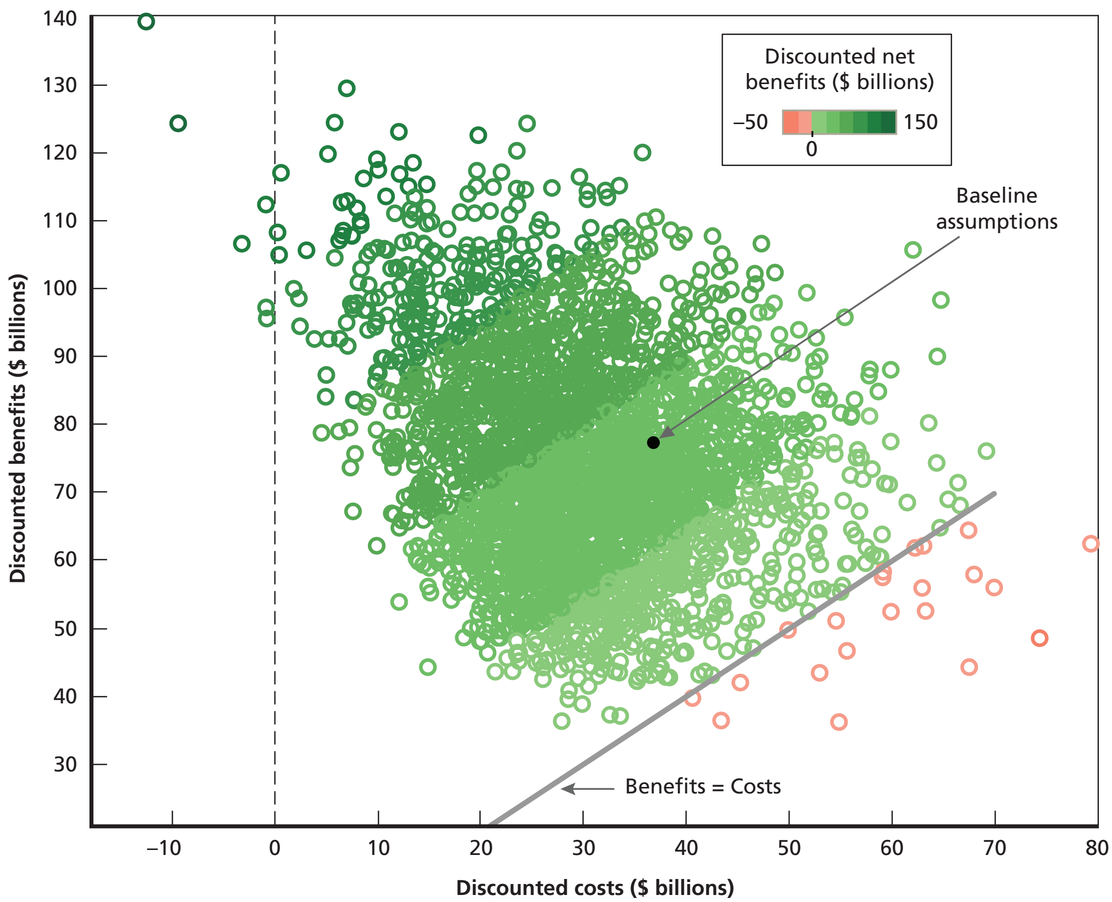
Defining Performance Thresholds

To guide this analysis, we define the outcomes that represent the unsuccessful implementation of the NDP. Specifically, we consider two conditions:

- **High GHG Emissions:** These are cases in which the NDP would reduce 2050 emissions by less than 90 percent of 2018 emission levels, as future emissions goals are often discussed with respect to current emissions. When evaluating all sectors, this threshold is

[1] We discount costs and benefits using a 5 percent discount rate. Negative costs reflect futures in which capital expenditures, which are generally higher for the NDP, are actually lower under the NDP.

Figure 4.2
Benefits and Costs from Implementing the National Decarbonization Plan Across 3,003 Plausible Futures



1.16 MtCO2e (10 percent of 11.62 MtCO2e). When evaluating the transport sector, the threshold is 0.57 MtCO2e (10 percent of 5.7 MtCO2e). When evaluating non-transport sectors, we consider a threshold that identifies the lowest 25 percent of cases, as not all sectors will need to reduce 90 percent of current emissions to reach the overall target. In each case, we use RDM techniques to characterize the uncertain conditions that would lead to high GHG emissions.

- **Low Net Benefits:** We consider two different thresholds, as each can provide important insight. We first set the threshold at zero net benefits and describe which factors drive the small number of cases in which net emissions are negative. To consider a wider set of plausible cases in which net benefits are classified as low, we set a higher threshold: the level of net emissions that demarcates the lowest 25 percent of the cases. When looking at all sectors, this threshold is $29.7 billion; when looking at the transport sector only, this threshold is $15.5 billion; when looking at the non-transport sectors, this level is $11.6 billion. As with emissions, we use RDM techniques to characterize the future uncertain conditions that would lead to low net benefits.

Figure 4.3 shows total emissions in 2050 versus discounted net benefits for each of the 3,003 futures, and it indicates which results would not achieve the NDP goals. Symbols colored red and orange are High GHG Emissions cases (18 percent of cases). Symbols colored yellow and red are Low Net Benefits cases (less than 1 percent of cases). Symbols colored green are those cases that are both below the emissions threshold and above the net benefits threshold (81 percent of cases). The estimate presented in Chapter Three is indicated by the dark green circle.

Identifying Key Drivers and Vulnerabilities

Each future projection of GHG emissions and net benefits are based on more than 300 different uncertain model factors (see Table 2.13). Scenario discovery techniques (Bryant and Lempert, 2010) help identify in which futures an outcome of interest—in this case, High GHG Emissions or Low Net Benefits—would occur. The techniques identify vulnerabilities as the ranges of a small set of uncertain parameters that lead to outcomes of interest. There are many different vulnerabilities that could be defined. Some describe many plausible futures of interest (high coverage) but also define conditions that could lead to successful outcomes (low density). Other vulnerabilities might be more highly targeted on outcomes of interest (high density), but only explain a small amount of the cases of interest (low coverage). For this analysis, we use

Figure 4.3
Discounted Net Benefits and 2050 GHG Emissions for All 3,003 Futures, Classified by Outcome Risk

several specific techniques to sort through the large set of uncertainties and identify what is most important. There are many seemingly obvious reasons why the NDP might not achieve the desired emissions reductions or do so at low net benefits. This technical analysis, however, tells us which seemingly obvious reasons actually are the ones that drive bad outcomes.

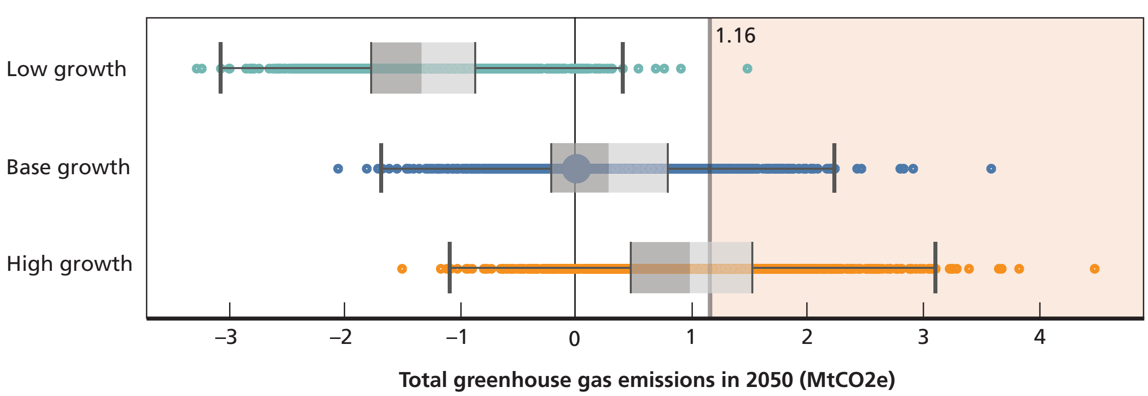
We first focus on High GHG Emissions outcomes and then look at Low Net Benefit outcomes. Since there are considerable differences in the way that each sector is modeled, we first determine which sectors are the most important drivers of uncertainty, and then define vulnerabilities within those sectors.

Drivers of High GHG Emissions

Without concerted action to decarbonize, higher economic growth leads to higher emissions. The analysis tells us which aspects of the NDP would need to be particularly effective in order to ensure sufficient decoupling between the growth of economic activities and GHG emissions with net benefits to the economy. Under Low Growth assumptions, total GHG emissions in 2050 are almost always less than the defined threshold of 1.16 MtCO2e (Figure 4.4). However, under Base Growth and High Growth assumptions, there are many cases in which emissions exceed the threshold. For High Growth, about 41 percent of the cases exceed the threshold, and for Base Growth, about 13 percent of cases exceed the threshold. These findings do not suggest that economic growth is inconsistent with decarbonization; in fact, more than half the High Growth scenarios lead to emissions lower than our threshold. The findings only suggest that higher economic growth has the *potential* to lead to higher emissions. The faster the economy grows the more important it is to decarbonize economic activities to reach zero net emissions by 2050.

The analysis identifies which sectors are driving variation in total GHG emissions. Table 4.1 shows that emissions in the transport, industry, livestock, and forestry sectors tend to be low when total emissions are low and tend to be high when total emissions are high. As such, the uncertainties in emissions from these sectors are most important to total emissions and the success of the NDP—reflecting that these sectors play a large role in both emissions

Figure 4.4
Total GHG Emissions in 2050, by Economic Growth Scenario



NOTES: Orange shading indicates results that exceed the emissions threshold. Results for baseline assumptions are indicated by the large circle. Horizontal boxes and whiskers indicate the median result and interquartile range (25th and 75th percentile results) plus the extent of an extended range of results (1.5 times the IQR range). Low, Base, and High Growth economic scenarios correspond to long-term average growth of 2 percent, 3.5 percent, and 4 percent growth per year.

Table 4.1
Sector-Specific Median GHG Emissions in 2050 for Low Total GHG Emissions and High Total GHG Emissions Cases

Sector	Median Sector Emissions for Low Total GHG Emissions (% of emissions for High Total GHG emissions)	Median Sector Emissions for High Total GHG emissions
Transportation	0.47 (65%)	0.72
Electricity	0.05 (100%)	0.05
Buildings	0.23 (82%)	0.28
Industry	2.07 (73%)	2.83
Waste	0.97 (86%)	1.13
Agriculture	0.82 (94%)	0.87
Livestock	1.31 (76%)	1.72
Forestry	–6.31 (+7% reduction)*	–5.9

NOTES: * indicates that emissions that are more negative than for the High Total GHG emissions case, and thus we report the additional reduction from the median result. Shaded sectors are those with significantly higher median sector emissions for futures that lead to high total GHG emissions.

and emission reductions. Below, we focus our vulnerability analysis on these sectors. Because of the similarity in emissions between the low and high emissions cases for the other sectors, additional vulnerability analyses do not provide insight.

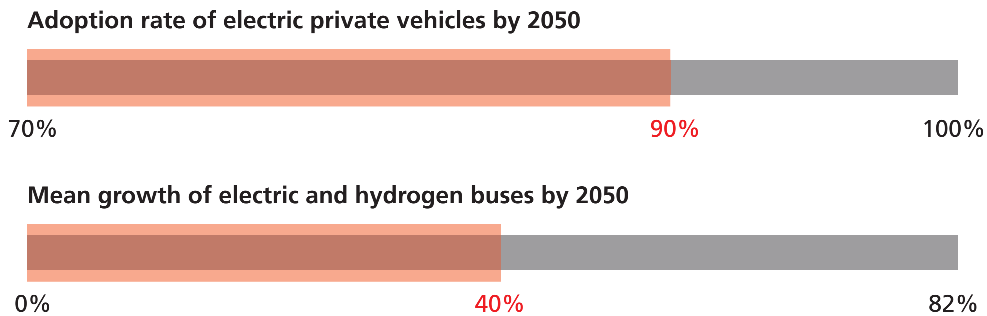
Transport Sector Emissions

In this section, we identify which assumptions are the most critical to emissions reductions in transport. We define High Transport Emissions cases as those in which emissions are greater than 10 percent of 2018 levels—0.57 MtCO2e—and then use scenario discovery to define vulnerabilities. We first identify a set of most influential uncertainties from the initial set of uncertainties using the C5.0 algorithm (Quinlan, 1993; Hornik et al., 2007). This process identifies 39 out of 135 uncertainties related to transportation emissions. Next, we use the Patient Rule Induction Method algorithm (PRIM; Lempert et al., 2006; Bryant and Lempert, 2010) to identify which of the 39 uncertainties are most critical and what combination of assumptions lead to vulnerabilities. Using this approach, PRIM identifies three vulnerabilities that together describe 76 percent of the High Transport GHG cases.

Vulnerability 1: "Low adoption of alternative fueled vehicles": This vulnerability describes futures in which adoption of electric and hydrogen vehicles is low, leading to high transport GHG emissions. The decarbonization actions in the NDP for the transport sector would facilitate the switch from conventional vehicles to different types of alternative-fueled vehicles. The analysis, however, identifies that the diffusion of two particular technologies is critical for transport GHG emissions reduction (Figure 4.5):

- **Low adoption of electric private vehicles:** The share of private electric vehicles (including taxis) falls below 90 percent by 2050 in this vulnerability. The range of variation of this driver in our analysis is between 70 and 100 percent.

Figure 4.5
Range of Uncertain Factors Defining the "Low Adoption of Alternative Fueled Vehicles" Vulnerability



- **Low conversion of busses to electricity and hydrogen:** The average growth of electric and hydrogen vehicles in public transport is less than 40 percent by 2050 in this vulnerability. The range of variation of this driver in our analysis is between 0 and 82 percent.

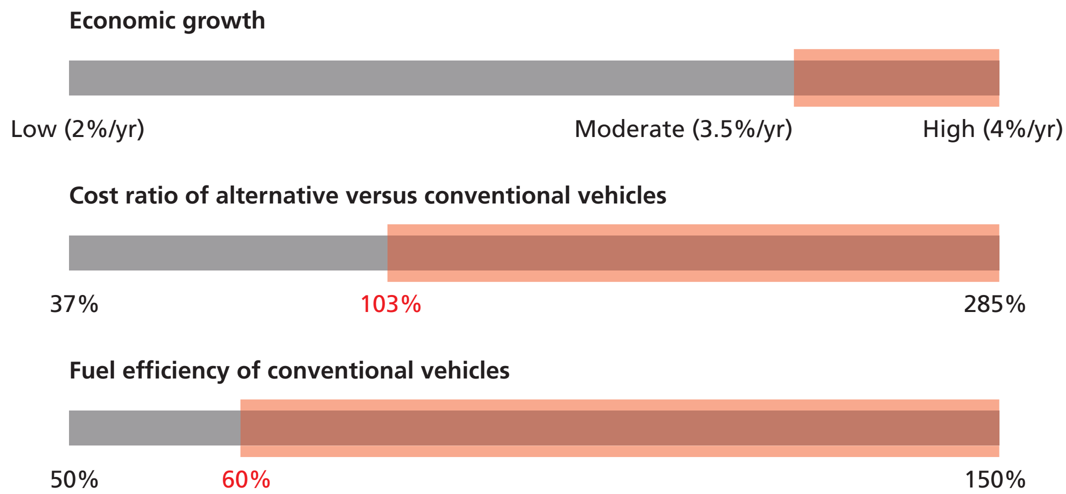
Over 70 percent of the futures that have low electric vehicle and hydrogen bus adoption also have high transport emissions (greater than the threshold of 0.57 MtCO2e), and 40 percent of the High Transport GHG Emissions cases have low electric vehicle and hydrogen bus adoption. Therefore, this particular combination of future conditions represents a key risk to the NDP's emissions goal.

Two additional vulnerabilities describe much of the remaining risk.

Vulnerability 2: "Cheap and efficient conventional vehicles under high economic growth": This vulnerability describes futures in which GDP growth is strong (averaging 4 percent per year), but decoupling of emissions and economic growth is hindered by conventional vehicles remaining cheap relative to new electric and hybrid vehicles, and the fuel efficiency of conventional vehicles is greater than expected. The availability of cheap and relatively efficient conventional vehicles slows the adoption of electric and hybrid vehicles, leading to high transport sector GHG emissions. Over 70 percent of the futures that have these characteristics are vulnerable, and these futures describe another 20 percent of the High Transport GHG Emissions cases. Specifically, the following vulnerability is defined by the following conditions (Figure 4.6):

- **High economic growth:** Economic growth is high—4 percent per year growth—in this vulnerability.
- **Relatively expensive alternative vehicles:** The relative cost of electric and hybrid vehicles to conventional vehicles is high in this vulnerability (i.e., the cost ratio of electric and hybrid vehicles to conventional vehicles is above 103 percent in 2050). The current (year 2018) ratio in the model is about 180 percent, with the alternative fuel vehicles costing on average $39,000 for buses, $47,000 for SUVs, $25,000 for sedans, and $38,000 for minivans.
- **Relatively high fuel efficiency of conventional vehicles:** The fuel efficiency of conventional vehicles increases more than expected (60 percent more efficient by 2050 with respect to current conditions—3.5 PJ per giga-vehicle kilometers) in this vulnerability.

Figure 4.6
Range of Uncertain Factors Defining the "Cheap and Efficient Conventional Vehicles with High Economic Growth" Vulnerability



Vulnerability 3: "Low electrification of private and freight transport with moderate economic growth": This vulnerability focuses on high emissions cases when economic growth is moderate—around 3.5 percent per year. Under these conditions, emissions are high when the relative costs of alternative fuel vehicles are high, as in Vulnerability 2, and adoption of electric trucks is low. Sixty-one percent of the futures that display these conditions are vulnerable, and these conditions describe another 17 percent of the High Transport GHG Emissions cases. Specifically, the following vulnerability is defined by the following conditions (Figure 4.7):[2]

- **Moderate economic growth:** Economic growth is moderate—3.5 percent per year growth—in this vulnerability.
- **Relatively expensive alternative vehicles:** The relative cost of electric and hybrid vehicles to conventional vehicles is high in this vulnerability (i.e., the cost ratio of electric and hybrid vehicles to conventional vehicles is above 98 percent in 2050). The current (year 2018) ratio in the model is about 180 percent, with the alternative fuel vehicles costing on average $39,000 for buses, $47,000 for SUVs, $25,000 for sedans, and $38,000 for minivans.
- **Low adoption of electric trucks:** The adoption of electric light freight vehicles remains below 92 percent by 2050 in this vulnerability. The range of variation of this driver in our analysis is between 50 percent and 100 percent.

Together, these three vulnerabilities describe the key risks to achieving the needed decarbonization in the transport sector. Table 4.2 summarizes these vulnerabilities, and Appendix C provides more detail on the methodology used and the specific definitions and statistics for the transport emissions vulnerabilities.

[2] This vulnerability excludes the high economic growth scenario, as most of those cases are included in Vulnerabilities 1 and 2.

Figure 4.7
Range of Uncertain Factors Defining the "Low Electrification of Private and Freight Transport with Moderate Economic Growth" Vulnerability

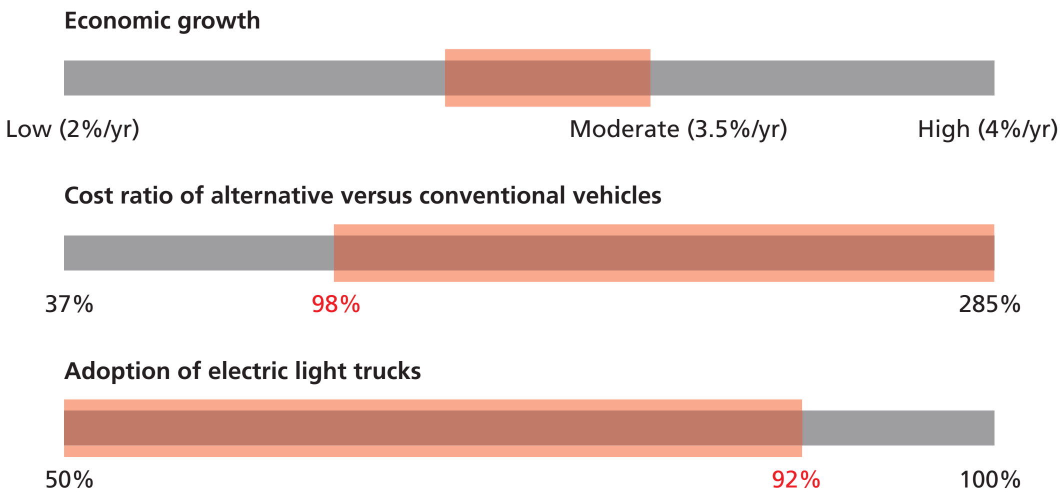


Table 4.2
Major Transport Uncertainties and Definitions of Vulnerabilities

Uncertainties Relevant to Transportation	Vulnerability 1: "Low Adoption of Alternative Fueled Vehicles"	Vulnerability 2: "Cheap and Efficient Conventional Vehicles Under High Economic Growth"	Vulnerability 3: "Low Electrification of Private and Freight Transport Under Moderate Economic Growth"
Demand for transport (linked to economic growth)	N/A	High economic growth: 4% average GDP growth	Moderate economic growth: 3.5% average GDP growth.
Technological costs	N/A	Relatively expensive electric and hybrid vehicles: cost ratio of electric and hybrid vehicles to conventional fuel vehicles above 100%	Relatively expensive electric and hybrid vehicles: cost ratio of electric and hybrid vehicles to conventional fuel vehicles above 98%
Vehicle efficiencies	N/A	Relatively high fuel efficiency of conventional vehicles: mean fuel efficiency improvements of diesel, gasoline, and LPG vehicles higher than 60%	N/A
Growth of electric private and freight transport*	Low growth in the adoption of electric private vehicles: share of electric private transport in 2050 below 90%	N/A	Low adoption of electric trucks: share of electric light freight below 92%
Growth of hydrogen heavy freight*	Low growth in the adoption of hydrogen bus fleet: share of hydrogen vehicles in public transport in 2050 below 29%	N/A	N/A

NOTE: Variables not included in the vulnerabilities include the cost of fuels, infrastructure costs for electrification, fuel changes, and modal changes; elasticities of demand for different modes of transport; growth of electric and hydrogen public transport; and growth of share of non-motorized transport and public transport use.

* = uncertainties with respect to achievement of NDP targets.

Industry, Livestock, and Forestry Emissions Vulnerabilities

We next use the PRIM algorithm to identify the important uncertainties and define the main emissions vulnerabilities for the industry, livestock, and forestry sectors.

For industry, the key emissions vulnerability is related to the ability for Costa Rica to decouple industrial activity and emissions. When industrial production is high (corresponding to the high economic growth scenario and high industrial activity), it is essential that electrification improvements are successful. When they are not, industrial emissions are higher than is consistent with zero-net emissions for Costa Rica as a whole. Table 4.3 summarizes the key uncertainties and vulnerability for the industrial sector.

For livestock, emissions are high when strategies targeted toward reducing emissions from cattle operations are not as effective as intended, unless growth in the number of animals is much lower than anticipated—consistent with the low economic growth scenario. Specifically, if efforts to reduce cattle-enteric fermentation emissions are less effective, then emissions will be high regardless of efforts decarbonizing other types of livestock or even the number of cattle in the future. Table 4.4 summarizes the key uncertainties and vulnerability for the livestock sector.

Lastly, in the forestry sector, low rates of sequestration (i.e., less negative emissions) would occur under futures in which the sequestration rates of wet forests are lower than expected or

Table 4.3
Industry Uncertainties and Definition of Key Emissions Vulnerability

Industry Uncertainties	"Low Industrial Emissions Decoupling" Vulnerability
Economic growth	High economic growth (average 4% GDP growth per year)
Industrial value added	High industrial value added (greater than $37.5 million by 2050) [uncertainty range = $35 million–$54 million]
Increase in electrification of industrial activity	Less than 70 percent electrified [uncertainty range = 47%–73%]

NOTES: This vulnerability describes 75 percent of high emissions cases, and 69 percent of the cases described have high emissions. Variables not included in the vulnerabilities include those related to the decarbonization rates of cement and other industrial products, and energy efficiency rates. The 2050 industry emissions threshold is set at 2.65 MtCO2e.

Table 4.4
Livestock Uncertainties and Definition of Key Emissions Vulnerability

Livestock Uncertainties	"Highly Emitting Cattle" Vulnerability
Economic growth	Moderate to high economic growth: on average 3.5% or higher GDP growth per year
Reduction in enteric fermentation emissions in cattle	Low reductions for: • dual purpose cattle (greater than 0.25 tonnes CO2e per animal [uncertainty range = 0.04–0.80 tonnes CO2e per animal]); • meat cattle (greater than 0.2 tonnes CO2e per animal [0.04, 0.77]); and • milk cattle (greater than 0.2 tonnes CO2e per animal [0.04, 0.77])

NOTES: Variables not included in the vulnerabilities include the decarbonization rates of enteric fermentation for non-cattle livestock, decarbonization rates for manure, and the number of animals. This vulnerability describes 91 percent of high emissions cases, and 51 percent of the cases described have high emissions. The 2050 livestock emissions threshold is set at 1.65 MtCO2e.

decline over time. This is because two key decarbonization strategies for forestry are (1) halting the deforestation of primary forests (including wet forests, which have a high sequestration rate and potential for deforestation) and (2) improving management to increase the current rate of sequestration. Table 4.5 summarizes the key uncertainty and vulnerability for the livestock sector.

Table 4.5
Forestry Uncertainties and Definitions of Key Emissions Vulnerability

Forestry Uncertainties	"Low Sequestration Rates by Wet Forests" Vulnerability
Sequestration rates of wet forests	Carbon sequestration rate for wet primary forests less than 2.7 tonnes CO2 per hectare [uncertainty range = 2.2–3.3 tonnes CO2 per hectare]

NOTES: Variables not included in the vulnerability include the rates of deforestation (separate factors between different forest types and grasslands and agricultural lands), emissions from converting forests to grassland or agricultural land, and sequestration rates from dry, moist, palm, and mangrove forests (primary and secondary forests) and sequestration rates from secondary wet forests. This vulnerability describes 91 percent of high emissions cases, and 53 percent of the cases described have high emissions. The 2050 forestry emissions threshold is set at –5.91 MtCO2e.

Drivers of Low Net Benefits

We performed a similar vulnerability analysis to understand what conditions would lead to low net benefits from the implementation of the NDP. We first examined the cases in which total NDP net benefits are negative (the red symbols on Figure 4.2). There are only a few cases (21), and they are all associated with cases in which the transport sector has low net benefits. By examining the transportation assumptions for these 21 cases, we see that negative net benefits cases occur when two adverse conditions exist simultaneously. Thus, this vulnerability describes a unique set of adverse circumstances that can affect the NDP breaking even from an economic perspective:

- High costs for several key technologies simultaneously: electric buses, freight, and rail, combined with high penetration of electric freight. This leads to high investment costs and thus contributes to low net benefits of the NDP.
- Low occupancy rates of taxis and slow development of electric bus lines. This leads to more miles driven and thus more health, accident, and congestion costs, as well as higher operations and maintenance costs for private transportation.

Importantly, if either of these conditions do not hold, then we estimate that benefits would be positive.

Next, the analysis identifies sectors that might lead to low total NDP net benefits. An examination of the distribution of sector net benefits for low NDP net benefits cases and high NDP net benefits cases reveals that the variation in transportation net benefits is much greater than that for all other sectors (not shown). For this reason, we must explore the uncertainty around net benefits from the non-transport sectors independently.

Low Net Benefits from Transport Sector Decarbonization

We use the same approach presented in the previous section to analyze vulnerability conditions associated with transportation net benefits. In this case, PRIM identifies two vulnerabilities that together describe 68 percent of the Low Transportation Net Benefits cases.

Transportation Net Benefits Vulnerability 1: "High-cost alternative vehicles under low economic growth": In this vulnerability, economic growth is low, which leads to lower emissions without decarbonization and thus less opportunity for corresponding benefits from emissions reductions. This is coupled with high costs for alternative vehicles, which pushes up the cost of decarbonization. Fifty-two percent of the cases that display these conditions are vulnerable, and this vulnerability describes 41 percent of the low net benefits cases. It is defined by the following conditions (Figure 4.8):

- **Low economic growth:** Average economic growth is low—2 percent per year—in this vulnerability.
- **Relatively expensive alternative vehicles:** The relative cost of electric and hybrid vehicles to conventional vehicles is high in this vulnerability (i.e., the cost ratio of electric and hybrid vehicles to conventional vehicles is above 91 percent in 2050). The current (year 2018) ratio in the model is about 180 percent, with the alternative fuel vehicles costing on average $39,000 for buses, $47,000 for SUVs, $25,000 for sedans, and $38,000 for minivans.

Transportation Net Benefits Vulnerability 2: "Low use of public transportation, high demand for freight, and expensive electric vehicles": In this vulnerability, Costa Ricans do not switch to using public transportation sufficiently enough, and also do not increase shared private trips, leading to higher costs for providing private transportation. High demand for freight transport leads to higher costs for electrifying that subsector. Lastly, costs of electric vehicles are higher than expected. Fifty-six percent of the cases that display these conditions are vulnerable, and this vulnerability describes 27 percent of the low net benefit cases. It is defined by the following conditions (Figure 4.9):

- **Relatively expensive alternative fuel vehicles:** In this vulnerability, alternative fueled vehicles remain relatively more expensive as compared to conventional fuel vehicles (i.e., the cost ratio of alternative fuel vehicles to conventional vehicles is above 123 percent).
- **Low occupancy rates of private vehicles:** Increases in ride sharing is low in this vulnerability—the average number of passengers in private vehicles does not increase by more than 32 percent by 2050, considering mean baseline conditions of 1.8 passengers per vehicle.

Figure 4.8
Range of Uncertain Factors Defining the "High-Cost Alternative Vehicles Under Low Economic Growth" Vulnerability

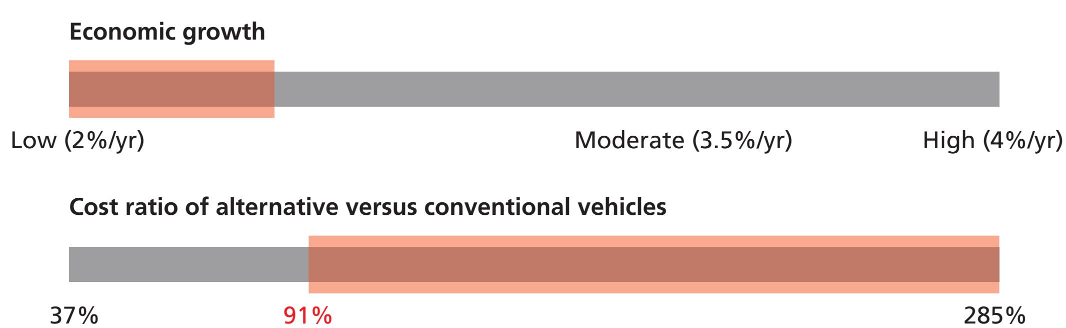
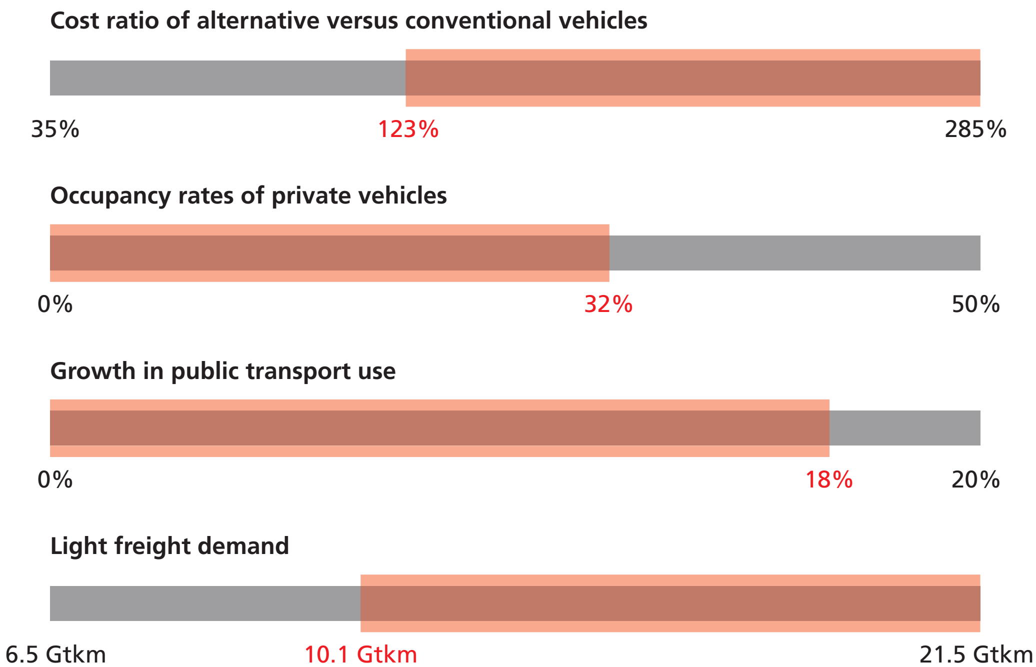


Figure 4.9
Range of Uncertain Factors Defining the "Low Use of Public Transportation, High Demand for Freight, and Expensive Electric Vehicles" Vulnerability



- **Low growth in public transport use:** Futures in which growth in public transport use remains below 18 percent by 2050.
- **High light freight demand:** Futures in which demand for light freight transportation is above 10.14 gross tonne kilometers (Gtkm; considering 12.5 percent less demand from baseline conditions).

Together, these two scenarios describe the key risks for achieving substantial positive net benefits through the NDP. Table 4.6 summarizes these vulnerabilities, and Appendix C provides more detail on the methodology used and the specific definitions and statistics.

Other Sector Net Benefits

Next, we identified which uncertain conditions would lead to low net benefits for the non-transport sectors. For this analysis, we used the PRIM algorithm to identify which variables across the seven non-transport lines of action would contribute to low non-transport net benefits—lower than $11.6 billion, the 25th percentile value for the net benefits for the non-transport sectors. We consider the following types of uncertainties:

- economic conditions per the economics growth scenarios (3 factors)
- emissions from each of the non-transportation lines of action reflecting all uncertainties described in Table 2.16 (7 factors)
- benefit factors (27 factors: total across the seven lines of action)
- cost factors (20 factors: total across the seven lines of action).

Table 4.6
Uncertainties and Definitions of Vulnerabilities for Low Transportation Net Benefits

Uncertainties Relevant to Transportation	Vulnerability 1: "High-Cost Alternative Vehicles Under Low Economic Growth"	Vulnerability 2: "Low Use of Public Transportation, High Demand for Freight, and Expensive Electric Vehicles
Demand for transport (linked to economic growth)	Low economic growth: 2% average GDP growth	High light freight demand: light freight demand higher than 10.14 Gtkm
Technological costs	Relatively expensive electric and hybrid vehicles: cost ratio of electric and hybrid vehicles to conventional fuel vehicles above 91%	Relatively expensive electric and hybrid vehicles: cost ratio of electric and hybrid vehicles to conventional fuel vehicles above 123%
Vehicle efficiencies	N/A	Low occupancy rates of private vehicles: growth in occupancy rates of SUVs, sedans, and minivans lower than 133%
Growth of share of non-motorized transport and public transport use*	N/A	Low growth in public transport use: public transport use below 18%

NOTES: Variables not included in the vulnerabilities include the cost of fuels, Infrastructure costs for electrification, fuel changes, and modal changes; elasticities of demand for different modes of transport; and growth of electric and hydrogen public transport.

Of all the uncertainties evaluated, the variation in non-transportation net benefits is largely driven by two key uncertainties. First, uncertainty around **benefits from primary wet forests' ecosystem services** (forestry line of action) is important because our model estimates large benefits accruing from preserving and improving the management of primary forest (about $20 billion across all forest types under baseline assumptions). Estimating ecosystem services benefits is also highly imprecise. Second, uncertainty around the **cost of efficiency and electrification of commercial buildings** is important because this factor leads to a large cost category (greater than $2 billion), and our estimation is also rough and thus highly uncertain. Uncertainties around other factors are dominated by these two identified factors. Recall that the net benefit from the NDP as a whole is driven primarily by transportation, as described above.

Low ecosystem services benefits or high cost of commercial efficiency and electrification alone could lead to low net benefits. However, facing both conditions together would likely lead to low net benefits for the non-transport sectors. Table 4.7 summarizes the quantitative vulnerability analyses that identified these uncertainties.

Summary of the National Decarbonization Plan Vulnerabilities

This chapter has presented analyses of the benefits and costs of the Costa Rican NDP under a wide range of plausible assumptions about the future.

First, achievement of zero net emissions would only happen with the implementation of the NDP. There are no futures in which emissions decline sufficiently without decarbonization policies and investments. The analysis confirms, though, that higher economic growth leads to higher emissions, all else being equal. This would occur even with increased decoupling of emissions and economic growth. However, the analysis also tells us which aspects of the NDP

Table 4.7
Non-Transportation Net Benefits Vulnerabilities

Vulnerability	Threshold(s) and Range(s)	Statistics
"Low value of ecosystem services for wet primary forests" vulnerability	Less than $20,000 per hectare per year: Range = [15,000–30,000 $/ha per year]	Explains 70 percent of low net benefits cases (coverage); almost 60 percent of cases are low net benefit cases (density)
"High costs for commercial efficiency improvements and electrification" vulnerability	Greater than 0.7% of commercial value: Range = [0.1%–1.5% of commercial value]	Explains 77 percent of low net benefits cases (coverage); almost 37 percent of cases are low net benefit cases (density)
"Low value of ecosystem services for wet primary forests + High costs for commercial efficiency improvements and electrification" vulnerability	• Less than $21,000 per hectare per year: Range = [15,000–30,000 $/ha per year]; • Greater than 0.7% of commercial value: Range = [0.1%–1.5% of commercial value]	Explains 59 percent of low net benefits cases (coverage); almost 73 percent of cases are low net benefit cases (density)

would need to be particularly effective in ensuring sufficient decoupling and emissions reductions with significant net benefits to the economy.

In the transport sector, our analysis suggests that Costa Rica needs to pay attention to uncertainties around both the drivers of emissions, costs, and benefits and those affecting the implementation of the NDP itself. Avoiding or managing specific conditions described below can help ensure that the NDP is more resilient against rapid technological change and current volatile economic environment.

Of the 91 uncertain drivers we considered in the analysis, we find two technological and two socioeconomic trends as the most relevant in the transport sector:

- cost of alternative fuel vehicles
- fuel efficiency of conventional fuel vehicles
- demand for light freight transport
- use of public transportation.

If the costs of alternative fuel vehicles are high or the fuel efficiency of conventional fuel vehicles is high, then uptake of alternative fuel vehicles will not be sufficiently large to lead to the necessary emissions reduction in the transport sector. In addition, conditions that would lead to low net benefits by transport actions include high costs of alternative fuel vehicles, high demand for light freight transport, and low use of public transport. These conditions lead to both higher costs to achieve the needed decarbonization and lower benefits, since there is less of a transition away from private vehicles that lead to greater externalities (i.e., accidents, pollution, and congestion).

The analysis also finds that the effectiveness of the following decarbonization actions are critical to achieving decarbonization goals and positive net benefits:

- the electrification of private transport
- the adoption of electric and hydrogen-based technologies in public transport
- the electrification of light freight.

There is an important interplay between the uncertain factors identified above and economic growth. For instance, in the case of emissions reduction, both the electrification of private transport and the use of hydrogen in public transport contribute to reduce emissions in the transport. However, under high economic growth, if alternative fuel vehicles remain expensive and the fuel efficiency of conventional vehicles improves substantially, the transition away from fossil fuels in the transport sector will become more challenging, as will Costa Rica's efforts to reduce emissions in the long term. Similarly, for the case of net benefits, we find that if alternative vehicles remain expensive and the economy is growing at a slower rate, the NDP would still lead to positive net benefits. The net benefits would be lower, though, than when economic growth is larger and there is more opportunity to reduce the transportation externalities that accompany increased demand for transportation.

For the other sectors, the NDP may not achieve zero or close to zero net emissions if the industrial and livestock emissions rates are not low enough to compensate for high economic activity. Further, the success of the NDP emissions reduction rests on assumptions around the decarbonization potential of forests. Specifically, if the sequestration of primary forests is lower than we expect, or declines over time, then the forestry sector may not increase sequestration sufficiently to achieve economy-wide net zero emissions. There is also some risk that the benefits from decarbonization will be low—specifically if the benefits from ecosystem services provided by wet primary forests are low or the costs of electrifying and increasing energy efficiency of commercial buildings are high.

CHAPTER FIVE

Advancing Decarbonization in Costa Rica

This analysis of the benefits and costs of Costa Rica's NDP suggests that achieving net zero emissions is possible and could lead to large net benefits over the next thirty years. There is significant uncertainty in this projection, but we find that under most plausible futures, this outcome would come to pass. The findings from this study are important for many aspects of Costa Rica's decarbonization efforts. First, they may help build support for implementing the NDP. Next, they provide information that can guide the implementation of the NDP. Lastly, the tools and methods from this study are being used to inform Costa Rica's updated decarbonization commitment to the international community.

Building Support for the National Decarbonization Plan

First, this study's findings may be useful in **building support** for the NDP. By demonstrating that reducing emissions also leads to benefits to Costa Ricans, this analysis helps to justify the initial expenditures. A deeper evaluation of who benefits from decarbonization would be useful in the coming years to ensure that benefits are equitably distributed across all groups and sectors. Establishing that benefits will likely exceed costs can also help attract foreign investment to help finance various aspects of the NDP, such as improving efficiency in the industrial sector. Lastly, while the costs associated with decarbonization in the near term will require the raising of funds internally and externally, these investments could also yield important short-term economic benefits as Costa Rica recovers from the COVID-19 pandemic.

Guiding the Implementation of the National Decarbonization Plan

We identified a small set of key risks to successful implementation, and these findings provide some important **guidance for the implementation of the NDP**. In particular, the analysis points to potential hedging and shaping actions (Dewar, 2002; Marchau et al., 2019). *Hedging actions*, in this context, are actions that reduce the sensitivity of the NDP to the identified uncertainties. *Shaping actions* are those that ensure particular unfavorable conditions do not occur in the first place.

Our analysis of the transport sector further validates the importance of several principles established in the NDP. First, the successful development of the public transportation system and resulting shift of mobility away from private vehicles is key to ensuring emissions reductions goals are not missed or achieved at high costs. This will require Costa Rica to be adaptive

as it deploys investments and policies to induce the shift away from private transportation and toward public transportation. This could require revisiting plans for bus routes and adjusting incentives in response to actual ridership.

Next, the analysis highlights the importance of not idly waiting for technological advancements to occur and diffuse through Costa Rica's economy. Successful implementation of the NDP will require declining prices for alternative vehicles, and the Costa Rican government should monitor these trends carefully and adjust incentives and targets to different technologies accordingly. If costs for electric cars are declining slowly, the NDP might speed up its investments in public transportation. Costa Rica may also benefit from becoming more active in the development and production of some of these technologies, taking advantage of its relatively highly educated workforce and other high technology industries ("Costa Rica: A Haven for High Tech Investment," 2017).

The analysis also highlights the importance of aggressively pursuing decarbonization in the near term. The risks and benefits of the NDP are higher if economic growth is greater, and the more quickly Costa Rica's economy grows, the more important decarbonization becomes. For example, growth in Costa Rica's industries must be accompanied by concurrent efficiency improvements and the promotion of circular economy concepts, which can naturally and profitably reduce emissions.

Lastly, the analysis highlights the tremendous decarbonization opportunities in the land-use sector. The largest and least expensive gains can be made by halting deforestation of intact primary forests in order to preserve the valuable ecosystem services. Improving forest management, as well as agricultural and livestock practices, will be critical to the success of the NDP. Costa Rica will likely need to experiment with a range of policy instruments to ensure that these improvements are sustained over the coming decades. The benefits to Costa Rica, however, are great, with large employment opportunities, productivity gains, and increased ecosystem services.

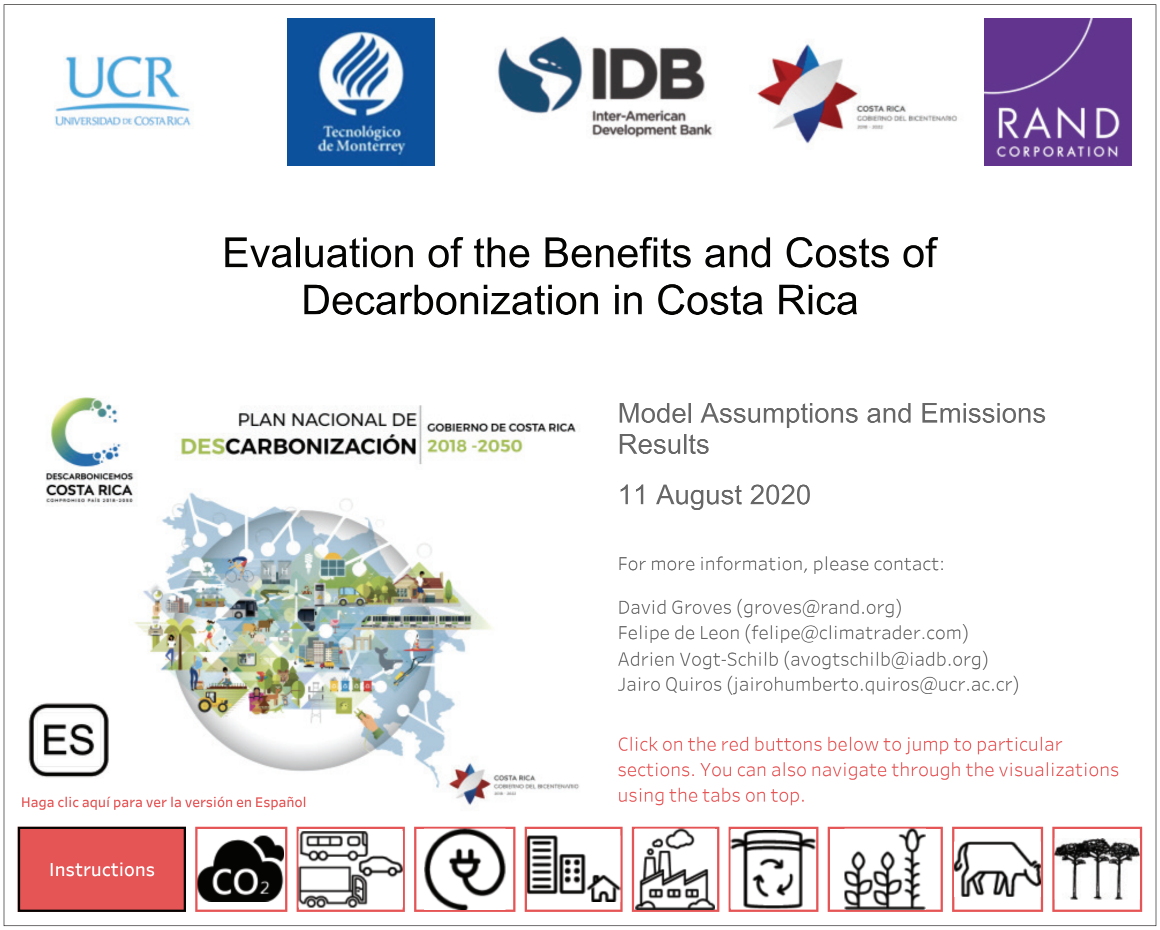
Further developing these hedging and shaping concepts could be usefully incorporated into the next update of the NDP. As the NDP develops, it should further define emissions reduction targets for each sector, but it should also indicate whether and when such targets should be revised. For example, the transition rate from conventional to alternative fueled vehicles could be connected to the relative cost of alternative vehicles. Faster cost declines of electric vehicles could trigger a faster transition, and vice versa. The targets for other sectors would then adjust to compensate, thus ensuring the achievement of net zero emissions while managing upfront costs. As another example, Costa Rica will learn through experience the actual costs of improving agricultural and forestry practices to decrease GHG emissions and increase carbon sequestration. If costs are lower than expected, then expanded decarbonization efforts in these sectors would be warranted.

Updating Costa Rica's Nationally Determined Contribution

This work also can help Costa Rica **update its Nationally Determined Contribution (NDC)** under the Paris Agreement. This update is under development, to be completed by December 2020. The models and analysis from this study are helping support stakeholder discussion about how to revise sector targets to best maximize the potential benefits—in particular, near-term employment and economic outcomes, which are so critical as Costa Rica recovers from

the COVID-19 pandemic. For example, our analysis suggests that more emissions avoidance and carbon sequestration in the land-use sectors could compensate for some potentially expensive portion of buildings and industrial decarbonization. Figure 5.1 provides a snapshot the interactive tool developed to help stakeholders provide input on key assumptions used in this study. This platform could be updated to support the NDC process.

Figure 5.1
Starting Screen of Interactive Tool for Reviewing Modeling Assumptions for This Study



SOURCE: This is a screenshot of Groves et al., "Evaluation of the Benefits and Costs of Decarbonization in Costa Rica," 2020. This interactive tool can be accessed at https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html.

Improving on the Limitations

There are **important limitations** to this work that could be usefully improved upon in the coming months and years. While the model of the transportation and electricity sector is quite advanced, the models developed to represent the other sectors are coarse and should be improved. This will require additional data, but it would also enable the representation of specific decarbonization actions and support the optimization of these actions over time as conditions evolve. The RDM methodology used for this study is designed to be iterative. As **new models are developed and integrated into the framework**, it will be straightforward

to update the simulations, analysis, and key findings in a timely way. By the end of 2020, for example, a new and more detailed land-use model will be integrated into the modeling system, and this will support a deeper look into the opportunities and risks to decarbonizing in the land use sectors.

Contributing to a Larger Policy Agenda on Decarbonization

Lastly, this work also fits into a **larger research and policy agenda informing decarbonization throughout Latin America**. Specifically, the way of approaching policy analysis that is (1) participatory, (2) accounts for uncertainty through the evaluation of futures, and (3) considers trade-offs across various performance sectors and uncertainty is being used elsewhere in Costa Rica and Latin America. The tools, data, and local capacity from this study have already been used for a targeted analysis of Costa Rica's proposed electric train to inform governmental decisions on an approximately $500 million loan for the project (Dirección de Cambio Climático). The same RDM approach as developed for this study for evaluating national decarbonization strategy is also underway in Chile, Perú, and Colombia.

References

Alpízar, Francisco, Matías Piaggio, and Eduardo Pacay, *Valoración económica de los beneficios en la salud asociados a la reducción de la contaminación del aire: El caso del Gran Área Metropolitana de Costa Rica*, United Nations Economic Commission for Latin America and the Caribbean (CEPAL), December 2017.

AyA (Instituto Costarricense de Acueductos y Alacantrillados), *Plan Nacional de Inversiones en Saneamiento, 2016–2045*, San José, Costa Rica, 2016. As of October 7, 2020: https://www.aya.go.cr/ASADAS/Documents/PLAN%20NACIONAL%20DE%20INVERSIONES%20EN%20SANEAMIENTO%202016-2045.pdf

AyA (Instituto Costarricense de Acueductos y Alacantrillados), MINAE (Ministerio de Ambiente y Energía), and Ministerio de Salud, *Política Nacional de Saneamiento en Aguas Residuales 2016–2045*, San José, Costa Rica, 2016. As of October 12, 2020: https://www.aya.go.cr/Noticias/Documents/Politica%20Nacional%20de%20Saneamiento%20en%20Aguas%20Residuales%20marzo%202017.pdf

Banerjee, Onil, and Martin Cicowiez, *The Integrated Economic-Environmental Modeling Platform (IEEM)*, IEEM Platform Technical Guides: User Guide, IDB Technical Note No. 01843, Washington, D.C.: Inter-American Development Bank, 2019.

Banerjee, Onil, and Martin Cicowiez, *The Integrated Economic-Environmental Modeling (IEEM) Platform*, IEEM Platform Technical Guides: IEEM Mathematical Statement, IDB Technical Note No. 01842, Washington, D.C.: Inter-American Development Bank, 2020.

Banerjee, Onil, Martin Cicowiez, Renato Vargas, and Mark Horridge, *Construction of an Extended Environmental and Economic Social Accounting Matrix from a Practitioner's Perspective*, IDB Technical Note No. IDB-TN-01793, Washington, D.C.: Inter-American Development Bank, 2019.

Bataille, Christopher, Henri Waisman, Yann Briand, Johannes Svensson, Adrien Vogt-Schilb, Marcela Jaramillo, Ricardo Delgado, Ricardo Arguello, Leon Clarke, Thomas Wild, Francisco Lallana, et al., "Net-Zero Deep Decarbonization Pathways in Latin America: Challenges and Opportunities," *Energy Strategy Reviews*, Vol. 30, July 2020.

Binsted, Matthew, Gokul Iyer, James Edmonds, Adrien Vogt-Schilb, Ricardo Arguello, Angela Cadena, Ricardo Delgado, Felipe Feijoo, André Lucena, Haewon McJeon, Fernando Miralles-Wilhelm, and Anjali Sharma, *Stranded Asset Implications of the Paris Agreement in Latin America and the Caribbean*, Washington, D.C.: Inter-American Development Bank, 2020.

Bryant, Benjamin P., and Robert J. Lempert, "Thinking Inside the Box: A Participatory, Computer-Assisted Approach to Scenario Discovery," *Technological Forecasting and Social Change*, Vol. 77, No. 1, January 2010, pp. 34–49.

Busch, Jonah, Jens Engelmann, Susan C. Cook-Patton, Bronson W. Griscom, Timm Kroeger, Hugh Possingham, and Priya Shyamsundar, "Potential for Low-Cost Carbon Dioxide Removal Through Tropical Reforestation," *Nature Climate Change*, Vol. 9, 2019, pp. 463–466.

Cavallo, Eduardo A., Andrew Powell, and Tomás Serebrisky, eds., *From Structures to Services: The Path to Better Infrastructure in Latin America and the Caribbean*, Washington, D.C.: Inter-American Development Bank, 2020.

Coppola, Andrea, Fernando Fernholz, and Graham Glenday, "Mexico: Estimation of the Economic Opportunity Cost of Capital for Public Investment Projects: An Empirical Analysis of the Mexican Case," policy research working paper, Washington, D.C.: World Bank, March 1, 2014.

"Costa Rica: A Haven for High Tech Investment," *The European,* July 16, 2017. As of October 7, 2020: https://the-european.eu/story-12150/costa-rica-a-haven-for-high-tech-investment.html

Dewar, James. A., *Assumption-Based Planning: A Tool for Reducing Avoidable Surprises*, RAND Studies in Policy Analysis, Charles Wolf, ed., Cambridge, UK: Cambridge University Press, 2002.

Dixon, John A., *Enhanced Cost Benefit Analysis of IDB Waste Water Treatment Projects with Special Consideration to Environmental Impacts: Lessons Learned from a Review of Four Projects*, Discussion Paper No. IDB-DP-254, Washington, D.C.: Inter-American Development Bank, 2012.

Dirección de Cambio Climático, 2020, *Análisis de costo-beneficio de la descarbonización del sector transporte y la importancia del TRP*, August 2020.

Electric Power and Energy Research Laboratory, "The OSeMOSYS–CR Model," GitHub, 2020. As of October 7, 2020:
https://osemosys-cr.readthedocs.io/en/latest/

EPERLab—*See* Electric Power and Energy Research Laboratory.

Fay, Marianne, Stephane Hallegatte, Adrien Vogt-Schilb, Julie Rozenberg, Ulf Narloch, and Thomas Kerr, *Decarbonizing Development: Three Steps to a Zero-Carbon Future*, Washington D.C.: World Bank, 2015.

Forster, Piers M., Harriet I. Forster, Mat J. Evans, Matthew J. Gidden, Chris D. Jones, Christoph A. Keller, Robin D. Lamboll, Corinne Le Quéré, Joeri Rogelj, Deborah Rosen, Carl-Friedrich Schleussner, Thomas B. Richardson, Christopher J. Smith, and Steven T. Turnock, "Current and Future Global Climate Impacts Resulting from COVID-19," *Nature Climate Change*, August 2020.

Garrett-Peltier, Heidi, "Green Versus Brown: Comparing the Employment Impacts of Energy Efficiency, Renewable Energy, and Fossil Fuels Using an Input-Output Model," *Economic Modelling*, Vol. 61, February 2017, pp. 439–447.

Gillingham, Kenneth, and James H. Stock, "The Cost of Reducing Greenhouse Gas Emissions," *Journal of Economic Perspectives*, Vol. 32, No. 4, Fall 2018, pp. 53–72.

Godínez-Zamora, Guido, Luis Victor-Gallardo, Jam Angulo-Paniagua, Eunice Ramos, Mark Howells, Will Usher, Felipe De León, Andrea Meza, and Jairo Quirós-Tortós, "Decarbonising the Transport and Energy Sectors: Technical Feasibility and Socioeconomic Impacts in Costa Rica," *Energy Strategy Reviews*, Vol. 32, November 2020.

González-Mahecha, Esperanza, Oskar Lecuyer, Michelle Hallack, Morgan Bazilian, and Adrien Vogt-Schilb, "Committed Emissions and the Risk of Stranded Assets from Power Plants in Latin America and the Caribbean," *Environmental Research Letters*, Vol. 14, No. 12, December 23, 2019.

Government of Costa Rica, *Costa Rica II Informe Bienal de Actualización ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático*, Programa de Cambio Climático, 2019a. As of October 7, 2020: http://cglobal.imn.ac.cr/index.php/publications/bur2019/

Government of Costa Rica, *Plan Nacional de Descarbonización 2018–2050*, 2019b. As of October 7, 2020: https://cambioclimatico.go.cr/wp-content/uploads/2020/01/PLAN.pdf

Groves, David G., Evan Bloom, Robert J. Lempert, Jordan R. Fischbach, Jennifer Nevills, and Brandon Goshi, "Developing Key Indicators for Adaptive Water Planning," *Journal of Water Resources Planning and Management*, Vol. 141, No. 7, July 2015.

Groves, David G., Martha Davis, Robert Wilkinson, and Robert J. Lempert, "Planning for Climate Change in the Inland Empire," *Water Resources IMPACT,* Vol. 10. No. 4, 2008, pp. 14–17.

Groves, David G., and Robert J. Lempert, "A New Analytic Method for Finding Policy-Relevant Scenarios," *Global Environmental Change*, Vol. 17, No. 1, February 2007, pp. 73–85.

Groves, David G., Edmundo Molina-Perez, Evan Bloom, and Jordan R. Fischbach, "Robust Decision Making (RDM): Application to Water Planning and Climate Policy," in Vincent A. W. J. Marchau, Warren E. Walker, Pieter J. T. M. Bloemen, and Steven W. Popper, eds., *Decision Making Under Deep Uncertainty*, New York: Springer, 2019.

Groves, David G., James Syme, Edmundo Molina-Perez, Carlos Calvo Hernandez, Luis F. Víctor-Gallardo, Guido Godinez-Zamora, Jairo Quirós-Tortós, Felipe De León, Andrea Meza Murillo, Valentina Saavedra Gómez, and Adrien Vogt-Schilb "Evaluation of the Benefits and Costs of Decarbonization in Costa Rica," Tableau Public interactive visualization, 2020. As of October 7, 2020:
https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html

Hallegatte, Stephane, Mook Bangalore, Laura Bonzanigo, Marianne Fay, Tamaro Kane, Ulf Narloch, Julie Rozenberg, David Treguer, and Adrien Vogt-Schilb, *Shock Waves: Managing the Impacts of Climate Change on Poverty*, Washington, D.C.: World Bank, 2015.

Hepburn, Cameron, Ella Adlen, John Beddington, Emily A. Carter, Sabine Fuss, Niall Mac Dowell, Jan C. Minx, Pete Smith, and Charlotte K. Williams, "The Technological and Economic Prospects for CO2 Utilization and Removal," *Nature*, Vol. 575, No. 7781, 2019, pp. 87–97.

Hornik, Kurt, Achim Zeileis, Torsten Hothorn, and Christian Buchta, "RWeka: An R Interface to Weka," R package version, 03-04, 2007. As of October 7, 2020:
https://CRAN.R-project.org/package=RWeka

Inter-American Development Bank and Deep Decarbonization Pathways for Latin America and the Caribbean, *Getting to Net-Zero Emissions: Lessons from Latin America and the Caribbean*, Washington, D.C., 2019. As of October 7, 2020:
https://publications.iadb.org/en/getting-net-zero-emissions-lessons-latin-america-and-caribbean

Intergovernmental Panel on Climate Change, *Guidelines for National Greenhouse Gas Inventories*, 2006. As of October 7, 2020:
https://www.ipcc-nggip.iges.or.jp/public/2006gl/

Intergovernmental Panel on Climate Change, "Summary for Policymakers," in *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 2018. As of October 7, 2020:
https://www.ipcc.ch/sr15/

International Monetary Fund, *World Economic Outlook, October 2019: Global Manufacturing Downturn, Rising Trade Barriers*, Washington, D.C., October 15, 2019. As of October 12, 2020:
https://www.imf.org/en/Publications/WEO/Issues/2019/10/21/World-Economic-Outlook-October-2019-Global-Manufacturing-Downturn-Rising-Trade-Barriers-48513

Izquierdo, Alejandro, Philip Keefer, Allen Blackman, Matías Busso, Eduardo Cavallo, Gregory Elacqua, Ana María Ibáñez, Julián Messina, Mauricio Moreira, Carlos Scartascini, Norbert Schady, and Tomás Serebrisky, *Emerging from the Pandemic Tunnel with Faster Growth and Greater Equity: A Strategy for a New Social Compact in Latin America and the Caribbean*, Washington, D.C.: Inter-American Development Bank, 2020.

Karlsson, Mikael, Eva Alfredsson, and Nils Westling, "Climate Policy Co-Benefits: A Review," *Climate Policy*, Vol. 20, 2020, pp. 292–316.

Kaufman, Noah, Alexander R. Barron, Wojciech Krawczyk, Peter Marsters, and Haewon McJeon, "A Near-Term to Net Zero Alternative to the Social Cost of Carbon for Setting Carbon Prices," *Nature Climate Change*, August 2020.

Lempert, Robert J., "Robust Decision Making (RDM)," in Vincent A. W. J. Marchau, Warren E. Walker, Pieter J. T. M. Bloemen, and Steven W. Popper, eds., *Decision Making Under Deep Uncertainty*, New York: Springer, 2019, pp. 23–51.

Lempert, Robert J., David G. Groves, Steven W. Popper, and Steve C. Bankes, "A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios," *Management Science*, Vol. 52, No. 4, 2006, pp. 514–528.

Lempert, Robert J., Steven W. Popper, and Steven C. Bankes, *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*, Santa Monica, Calif.: RAND Corporation, MR-1626-RPC, 2003. As of October 12, 2020:
http://www.rand.org/pubs/monograph_reports/MR1626

Marchau, Vincent A. W. J., Warren E. Walker, Pieter J. T. M. Bloemen, and Steven W. Popper, eds., *Decision Making Under Deep Uncertainty*, New York: Springer, 2019.

Molina-Perez, Edmundo, David G. Groves, Steven W. Popper, Aldo I. Ramirez, and Rodrigo Crespo-Elizondo, Developing a Robust Water Strategy for Monterrey, Mexico: *Diversification and Adaptation for Coping with Climate, Economic, and Technological Uncertainties*, Santa Monica, Calif.: RAND Corporation, RR-3017-FAMM, 2019. As of October 12, 2020:
https://www.rand.org/pubs/research_reports/RR3017.html

Proyecto Humedales de SINAC-PNUD-GEF, *Valoración de los servicios ecosistémicos que ofrecen siete de los humedales protegidos de importancia internacional en Costa Rica: Palo Verde, Caribe Noreste, Caño Negro, Gandoca Manzanillo, Maquenque, Térraba-Sierpe y Las Baulas*, SINAC/CINPE-UNA/PNUD, 2017.

Quinlan, J. Ross, *C4.5: Programs for Machine Learning*, Morgan Kaufmann Series in Machine Learning, San Mateo, Calif.: Morgan Kaufmann, 1993.

Ricke, Katharine, Laurent Drouet, Ken Caldeira, and Massimo Tavoni, "Country-Level Social Cost of Carbon," *Nature Climate Change*, Vol. 8, 2018, pp. 895–900.

Riera-Crichton, Daniel, Carlos A. Vegh, and Guillermo Vuletin, *Fiscal Multipliers in Recessions and Expansions: Does It Matter Whether Government Spending Is Increasing or Decreasing?* Washington, D.C.: World Bank, 2014.

Saget, Catherine, Adrien Vogt-Schilb, and Trang Luu, *Jobs in a Net-Zero Emissions Future in Latin America and the Caribbean*, Inter-American Development Bank and International Labour Organization, 2020.

Stiglitz, Joseph, and Nicholas Stern, *Report of the High-Level Commission on Carbon Prices*, Washington, D.C.: World Bank Group, Carbon Pricing Leadership Coalition, 2017.

United Nations, Paris Agreement, December 12, 2015. As of October 7, 2020:
https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en

Verspecht, Ann, Valerie Vandermeulen, Erik Ter Avest, and Guido Van Huylenbroeck, "Review of Trade-Offs and Co-Benefits from Greenhouse Gas Mitigation Measures in Agricultural Production," *Journal of Integrative Environmental Sciences*, Vol. 9, Suppl. 1, 2012, pp. 147–157.

Waisman, H., Chris Bataille, Harald Winkler, Frank Jotzo, Priyadarshi Shukla, Michel Colombier, Daniel Buira, Patrick Criqui, Manfred Fischedick, Mikiko Kainuma, et al., "A Pathway Design Framework for National Low Greenhouse Gas Emission Development Strategies," *Nature Climate Change*, Vol. 9, No. 4, 2019.

Appendices

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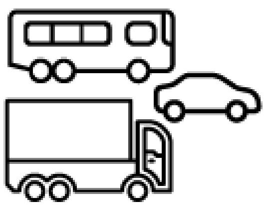
Abbreviations

CO2e	carbon dioxide equivalent
CR-IDPM	Costa Rica Integrated Decarbonization Pathways Model
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoule
Gpkm	billions of passenger kilometers (gigapassenger kilometer)
Gtkm	grosse tonne kilometer
ICE	Instituto Costarricense de Electricidad
IEEM	Plataforma de Modelación Económico-Ambiental Integrada (Integrated Economic-Environmental Modeling)
IRENA	International Renewable Energy Agency
kWh	kilowatt hour
MtCO2e	megatons carbon dioxide equivalent
NDP	Costa Rica’s National Decarbonization Plan
OSeMOSYS-CR	Open Source energy Modelling System—Costa Rica
PJ	petajoule
PRIM	Patient Rule Induction Method
RDM	Robust Decision Making
vkm	vehicle kilometer

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[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

- the cost of fuels[2]
- infrastructure costs for electrification, fuel changes, and modal changes
- technological costs
- elasticities of demand for different modes of transport
- new technology adoption rates.

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

- growth of electric public transport
- growth of hydrogen public transport
- growth of electric private transport
- growth of electric light freight

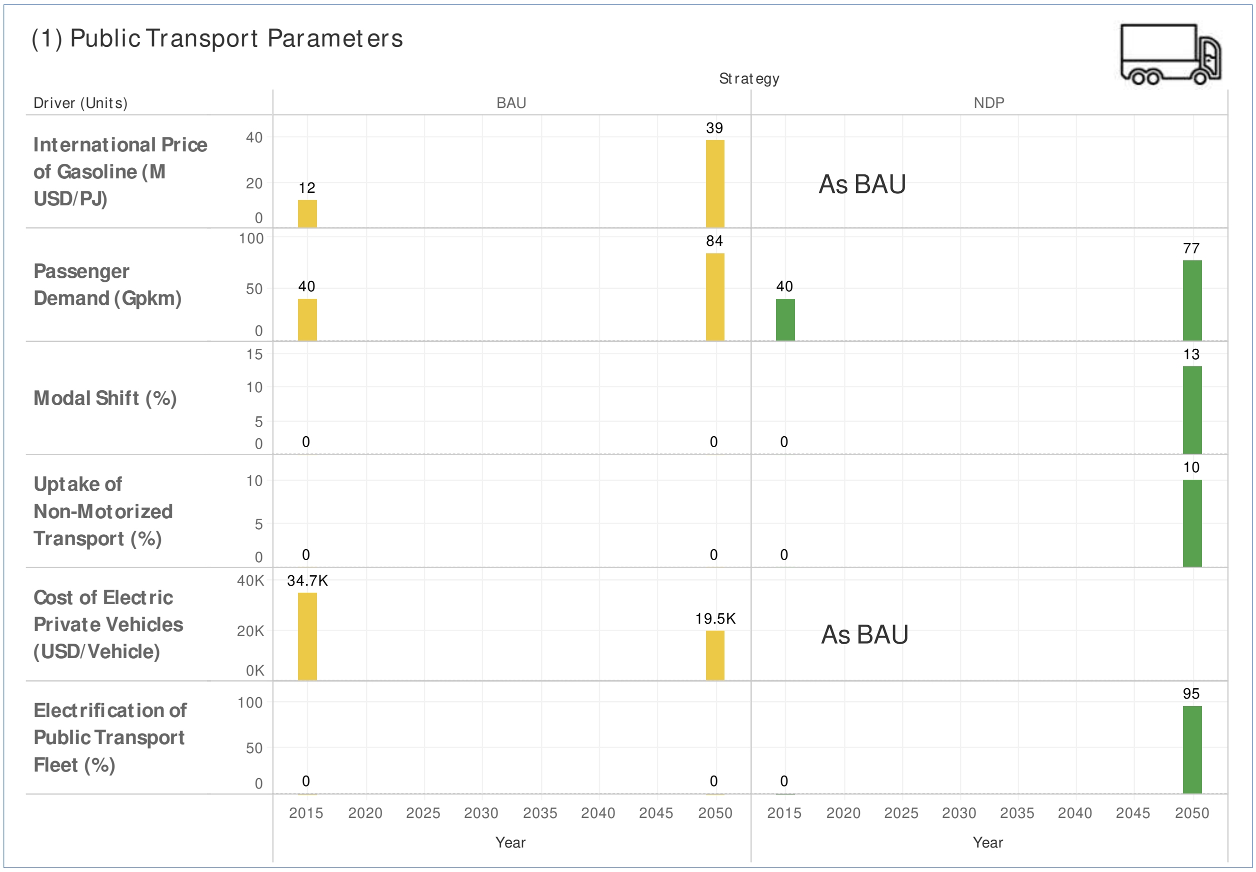
[1] Details of the OSeMOSYS-CR model are in Electric Power and Energy Research Laboratory (EPERLab), 2020.

[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.[3] 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 "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.

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[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

Benefit	Factor	Baseline Assumption and Range	Sources
Reduced climate change impacts from emissions (reduced social cost of carbon)	Social cost of GHG emissions estimated for Costa Rica	[$0.36, **$0.61**, $1.04] per ton CO2e	Ricke et al., 2018a, 2018b.
Health savings from reduced emissions	Cost per ton of pollutant per quantify of fuel consumed	$0.0263 per liter (gasoline) $0.3141 per liter (diesel)	Coady et al., 2019, p. 39.
Reduced medical costs from accidents	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)	$56.19 million per Gpkm (private vehicles) $1.27 million per Gpkm (public transport vehicles) $555.55 million per Gpkm (motorcycles)	COSEVI, 2017.
Improved productivity from reduced congestion	Congestion caused per vkm, per vehicle type	$0.046 per vkm (light vehicles and motorcycles) $0.09 per vkm (heavy vehicles)	Ministerio de Ambiente y Energía, Ministerio de Vivienda y Asentamientos Humanos, and Ministerio de Planificación Nacional y Política Económica, 2017.

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)

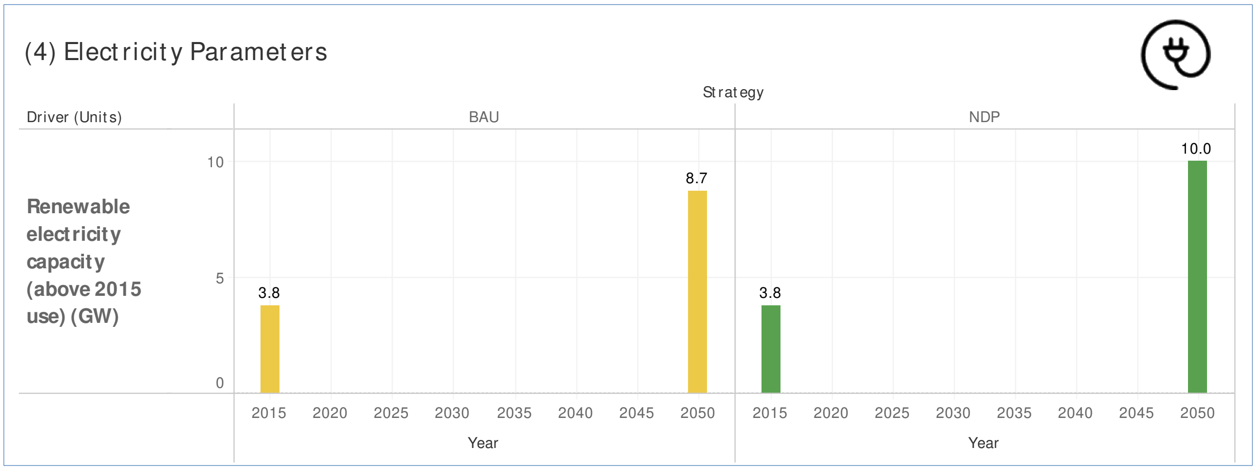
The electricity sector in Costa Rica is currently almost completely renewable, due to high levels of installed hydropower and some geothermal, wind, and solar development. The NDP includes actions to achieve and ensure 100 percent renewable capacity to support electrification of transport and industry. 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 "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

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

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 A.3. Electricity Sector Cost Factors

Description	Factor	Value	Source
Costs to increase transmission or distribution capacity per unit energy	Cost per PJ (historic average based on Instituto Costarricense de Electricidad [ICE] data). The cost for transmission and distribution is assumed equal as a reference, although the literature suggests distribution expansions have higher costs.	$29.23 million per PJ	ICE, 2017.
Costs of additional power plant capacity	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.	$2,463.28 million per PJ (biomass) $1,269.78 million per PJ (diesel) $4,650.33 million per PJ (fuel oil) $7,828.28 million per PJ (geothermal) $8,241.97 million per PJ (hydro dam) $4,385.15 million per PJ (hydro run of river) $1,900 (1,553.5) million per PJ (solar) $2,500 (2,153) million per PJ (wind)	ICE Data and International Renewable Energy Agency (IRENA) projections

NOTE: Costs inside parentheses are costs for 2050.

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:

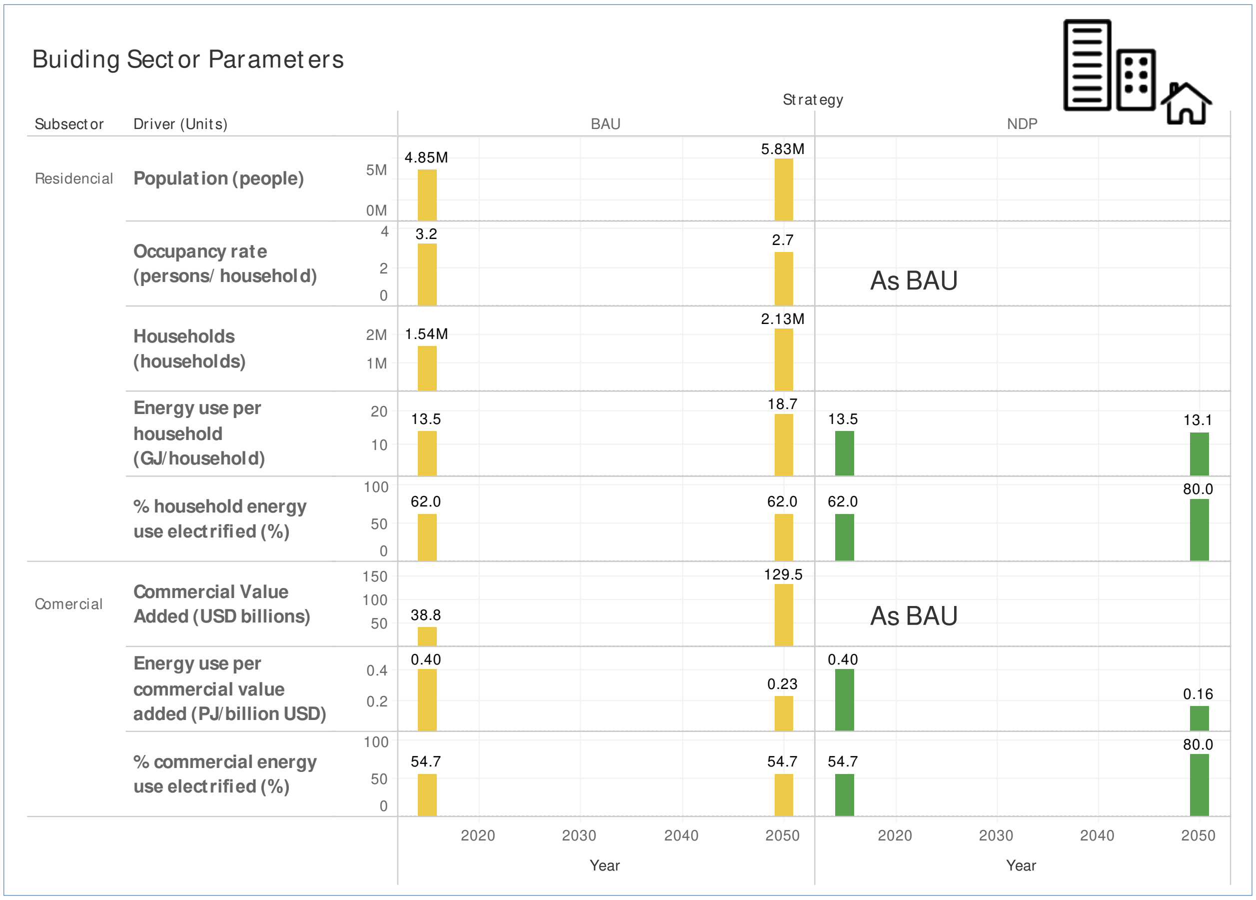
- E = emissions [$MtCO_2e$]
- A = number of households; value of commercial output [millions of $]
- d = energy demand per activity by sector [PJ per hour or PJ per million $]
- f = stationary emissions factor (e.g., from cooking [$MtCO_2e/PJ$])
- λ = fraction of energy in from electricity [$0 \leq \lambda \leq 1$]
- 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.

Figure A.3. Interactive Visualization of Key Buildings Sector Assumptions and Sources



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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

Benefit	Factor	Baseline Assumption and Range	Source
Reduced climate change impacts from emissions (reduced social cost of carbon)	Social cost of GHG emissions estimated for Costa Rica	[$0.36, **$0.61**, $1.04] per ton CO2e	Ricke et al., 2018a, 2018b.
Energy cost savings to building operators from switching to low-cost electricity (residential and commercial buildings)	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 cost projections from RECOPE's "Precios Históricos" (RECOPE, undated).

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

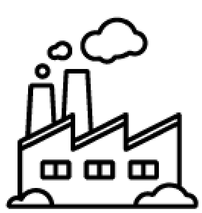
Cost estimates for the buildings sector decarbonization actions are based on a single per household cost estimate for improving efficiency and electrification of households, and cost per commercial value added for improving efficiency and electrification of commercial buildings. Both of these factors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

Table A.5. Building Sector Cost Factors

Cost	Factor	Baseline Assumption and Range	Source
Costs for improving efficiency and electrification of households	Cost per household	[$400, **$575**, $850] per household	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.
Costs for improving efficiency and electrification of commercial buildings	Cost per commercial value added in 2020	[0.1%, **0.5%**, 1.5%] value added in 2020	No source available, so we used a wide range with baseline assumption of 0.5 percent.

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:

$$E_t = I_t + U_t + P_t^{other} + P_t^{cement}$$

Where:

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

$$U_t = A_t r_t ,$$

$$P_t^{other} = \sum_i A_{it} \, r_{it} ,$$

and

$$P_t^{cement} = A_{cement,t} p_t m_t$$
,

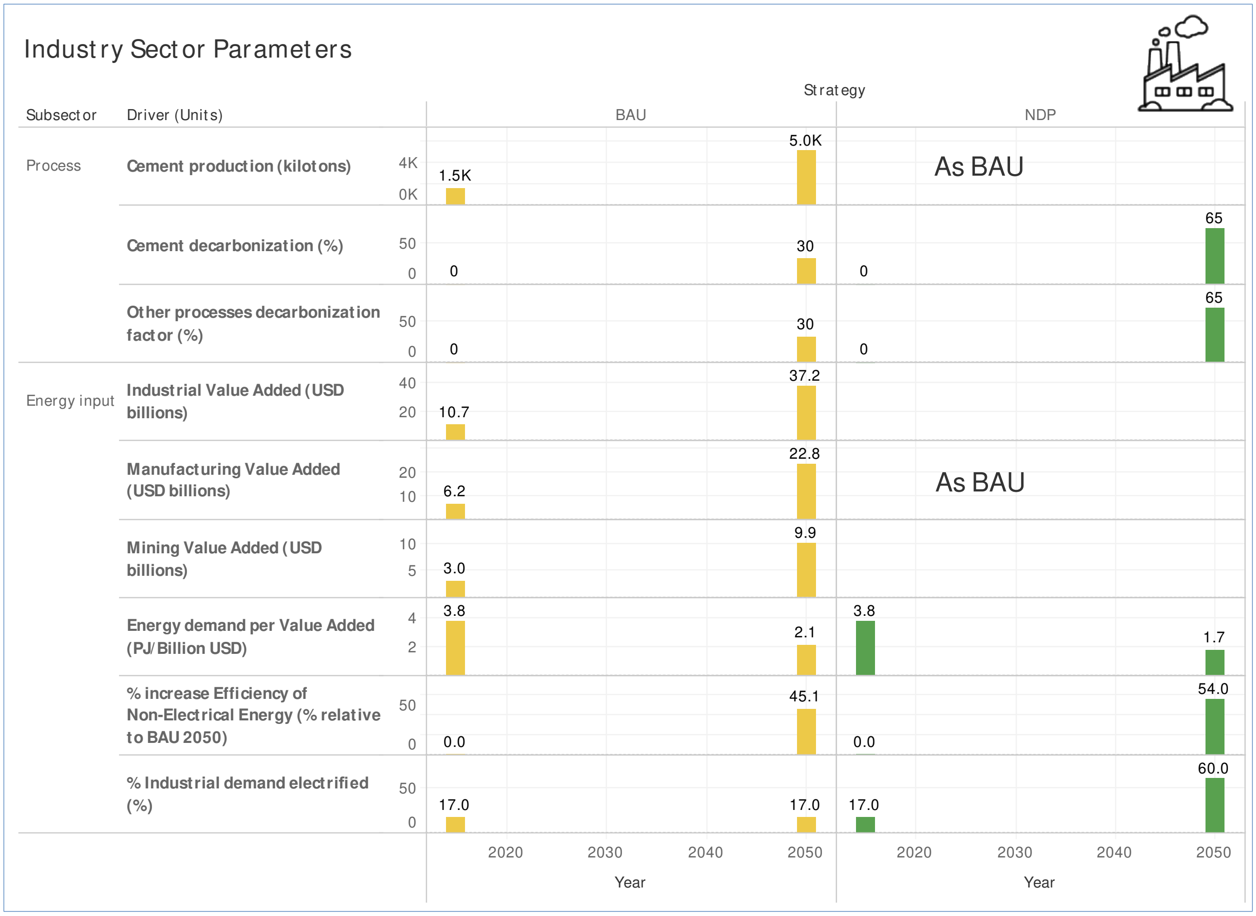
where

- E = emissions [MtCO2e]
- A = value of industrial production (from IEEM—A_i 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 $]
- λ = fraction of energy in from electricity [$0 \leq \lambda \leq 1$]
- i = industry [i = 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.

Figure A.4. Interactive Visualization of Key Industry Sector Assumptions and Sources



NOTES: This is a screenshot of "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

Benefit	Factor	Baseline Assumption and Range	Source
Reduced climate change impacts from emissions (reduced social cost of carbon)	Social cost of GHG emissions estimated for Costa Rica	[$0.36, **$0.61**, $1.04] per ton CO2e	Ricke et al., 2018a, 2018b.
Health savings from reduced emissions	Cost per ton of pollutant per quantity of fuel consumed	$0.0263 per liter (gasoline) $0.3141/ per liter (diesel)	Ministerio de Ambiente y Energía, Ministerio de Vivienda y Asentamientos Humanos, and Ministerio de Planificación Nacional y Política Económica, 2017.
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

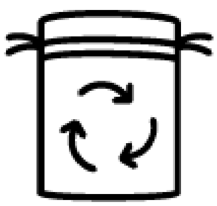
Costs for implementing the NDP plan industrial actions are approximated by those required to reduce emissions from cement—the largest source of emissions.

Table A.7. Costs Factors for the Industrial Sector

Cost	Factor	Baseline Assumption and Range	Source
Costs of reducing emissions from cement manufacturing	Additional cost to produce cement. Includes programs to increase blended materials, improve energy efficiency, heat recovery and carbon capture technologies.	[$30, **$88**, $176] per ton of cement	Cement upper bound: Fischedick et al., 2014, Chapter 10, p. 768. Cement lower bound: McKinsey & Company, 2010.
Cost of reducing industrial product use emissions	Percentage of industrial value	[0.3%, **0.5%**, 1.5%] of industrial value at full implementation (2050)	No source available, so we used a wide range with baseline assumption of 0.5 percent.
Cost of increasing energy efficiency	Cost of energy efficiency often expressed in terms of $ per saved energy.	[$3, **$5**, $10] per GJ	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.

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

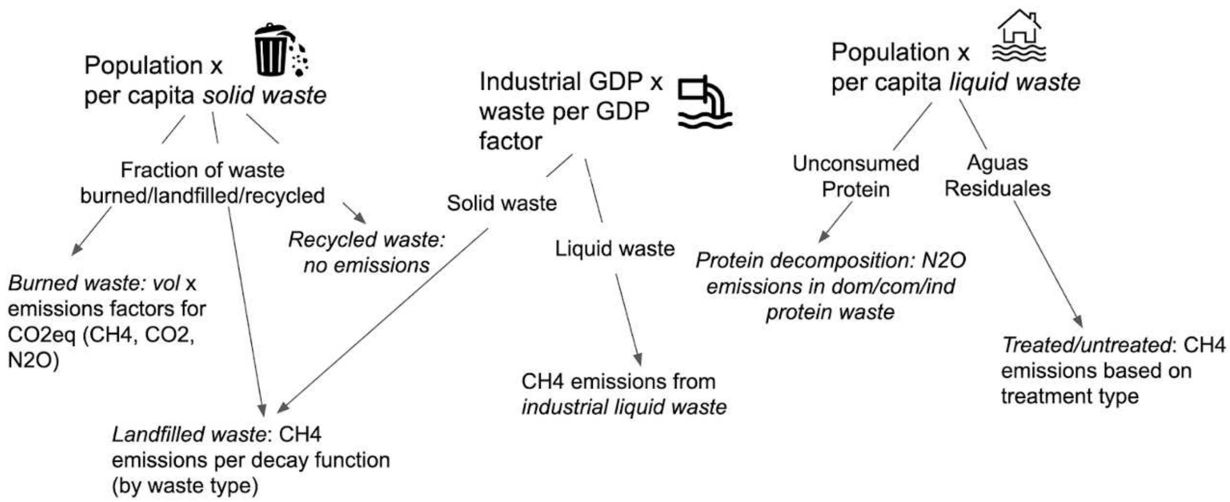
- solid waste generated on a per capita basis
- liquid domestic and industrial waste generated on a per capita basis
- solid industrial waste generated on a per output basis
- net GHG emissions factors that account for the avoided emissions from virgin materials replaced by recycled or composted content.

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



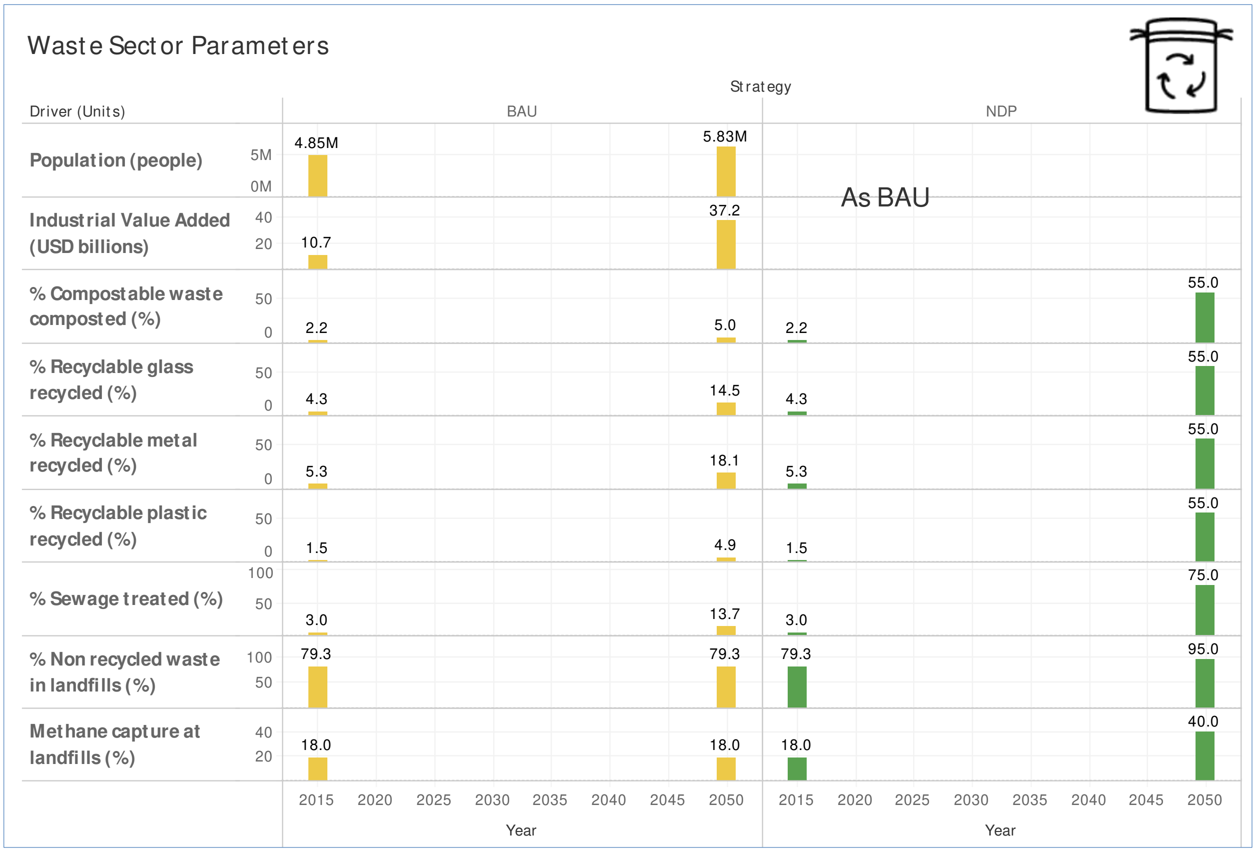
SOURCE: Based on IPCC, 2006.
NOTES: CH4 = methane, N2O = nitrous oxide.

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.

Figure A.6. Interactive Visualization of Key Industry Sector Assumptions and Sources



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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

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

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

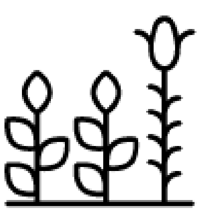
uncertainty analysis then explores variability around this estimate. The cost of recycling waste is derived from the literature.

Table A.9. Waste Sector Cost Factors

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

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:

$$E_t = \sum_s \left(A_{s,t} \times F_{s,t}\right)$$

where:

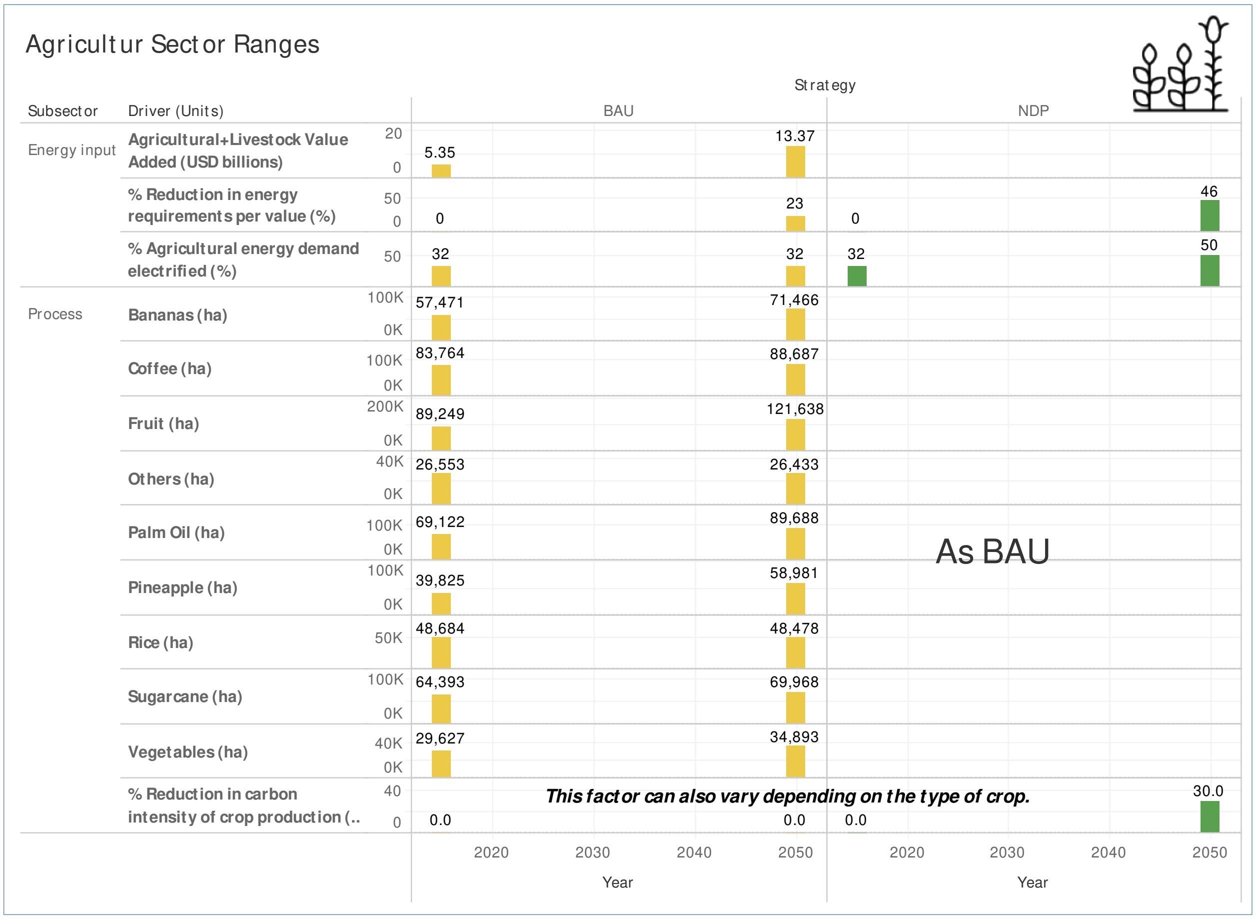
- E = emissions
- A = area by crop cultivation
- F = emission factor
- s = type of crop
- t = time.

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.

Figure A.7. Interactive Visualization of Key Agriculture Sector Assumptions and Sources



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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

Benefit	Factor	Baseline Assumption and Range	Source
Reduced climate change impacts from emissions (reduced social cost of carbon)	Social cost of GHG emissions estimated for Costa Rica	[$0.36, **$0.61**, $1.04] per ton CO2e	Ricke et al., 2018a, 2018b.
Increased crop yields due to agricultural improvements to reduce emissions	Percentage value increase as a function of percentage 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	Author's judgment, informed by Karlsson et al. (2020) and Verspecht et al. (2012)
Cost savings 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).

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

Cost	Factor	Baseline Assumption and Range	Source
Cost of implemented GHG emissions programs for coffee farms	Cost of program implementation per farm	[$13,000; **$22,000**; $30,000] per farm Applied to 20,000 farms (approximate number in Costa Rica)	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.
Cost of programs to reduce GHG emissions for other crops	Cost of program implementation per ton of GHG emissions reduced	[$30, **$60**, $100] per ton CO2e (Range from source expanded by authors.)	Gillingham and Stock, 2018, p, 59, Table 2.

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

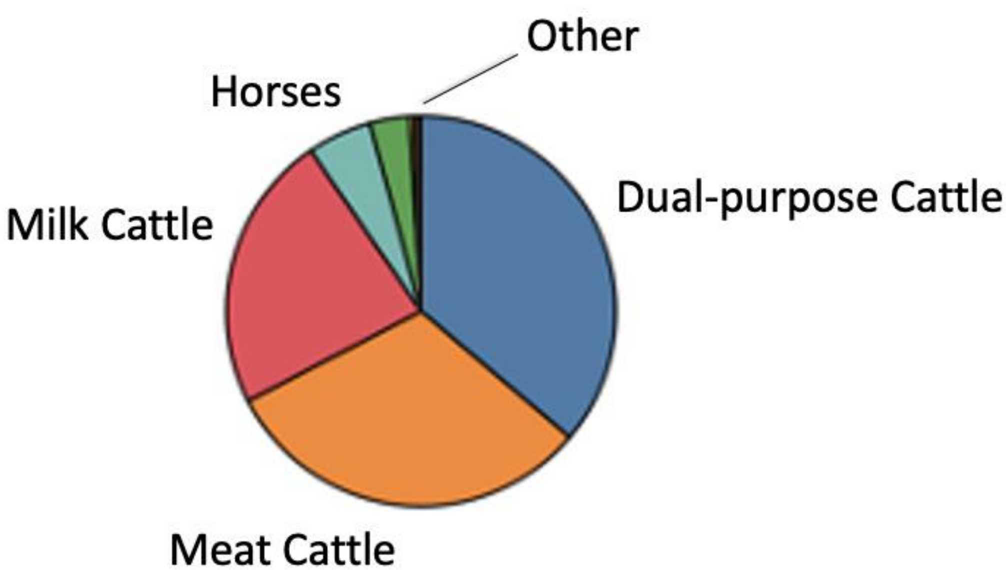
Livestock Sector (Line 9)

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



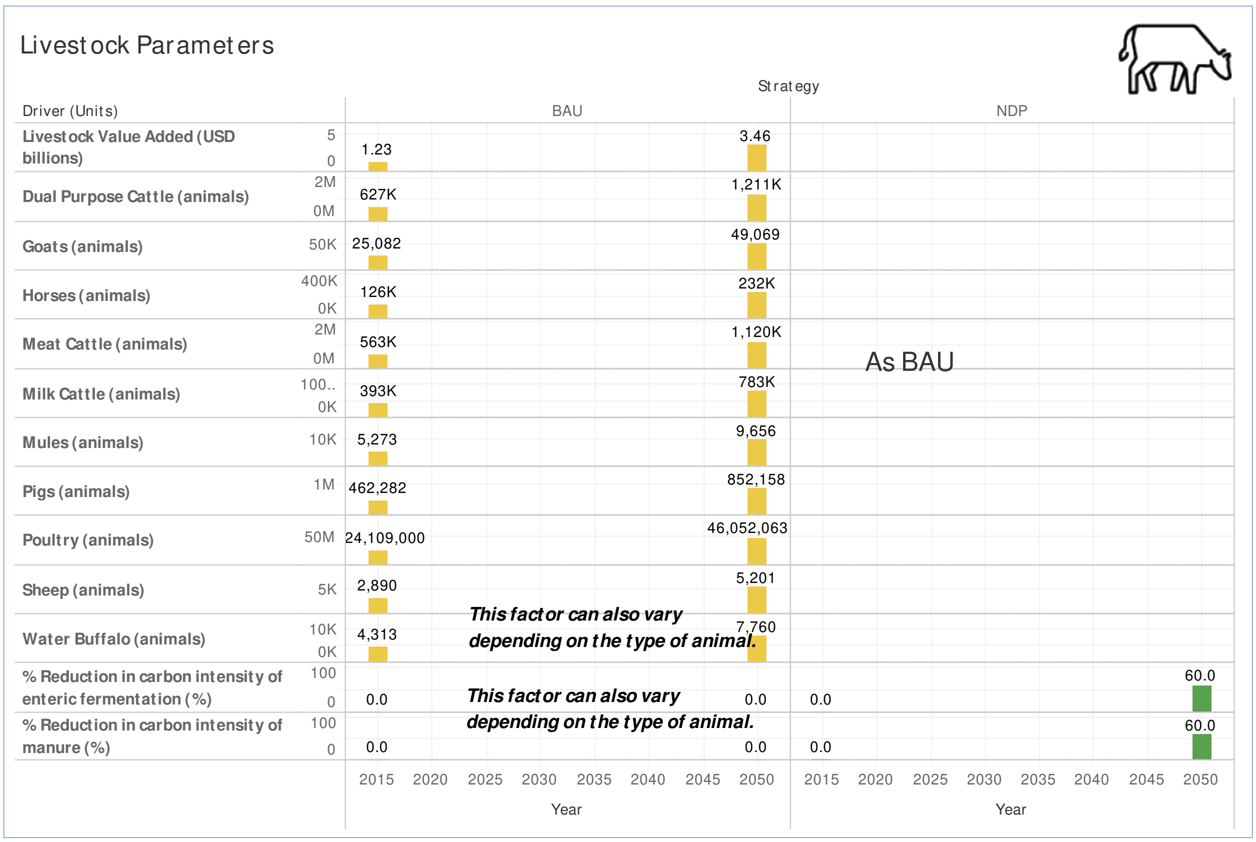
Projecting Livestock Emissions

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



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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

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

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

Estimating Costs

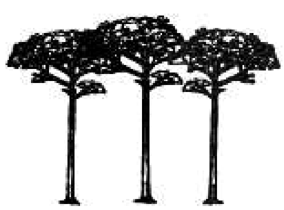
Cost of livestock sector GHG reduction is based on an estimated unit cost for reducing emissions in pasture land from the literature.

Table A.13. Costs Factors for Livestock Sector

Cost	Factor	Baseline Assumption and Range	Source
Cost of programs to reduce GHG emissions from cattle	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.	[$50, **$71**, $100] per ton CO2e	Gillingham and Stock, 2018, p. 59, Table 2. Range: author judgment.

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:

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

such that:

$$L = \sum_{s \in S} A_{st}$$

where:

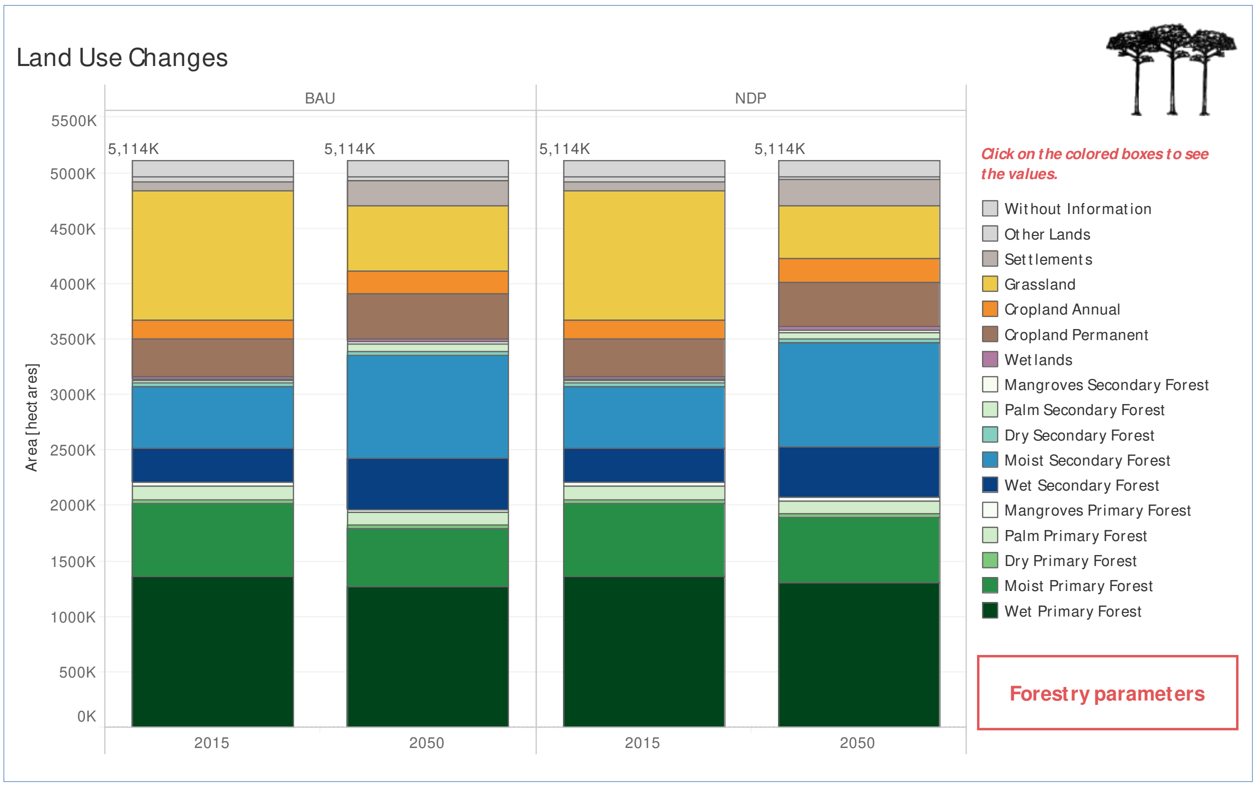
- E = emissions [MtCO2e]
- A = area by type of land use s [hectares]
- A' = area of forest type f converted by type of land use s [hectares]
- C = emission factor for conversion of forest to another type of land use, s [MtCO2e per hectare]
- L = estimated total area, assumed to be 5,113,939.5 ha (Quirós-Tortós, 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 = {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 = {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



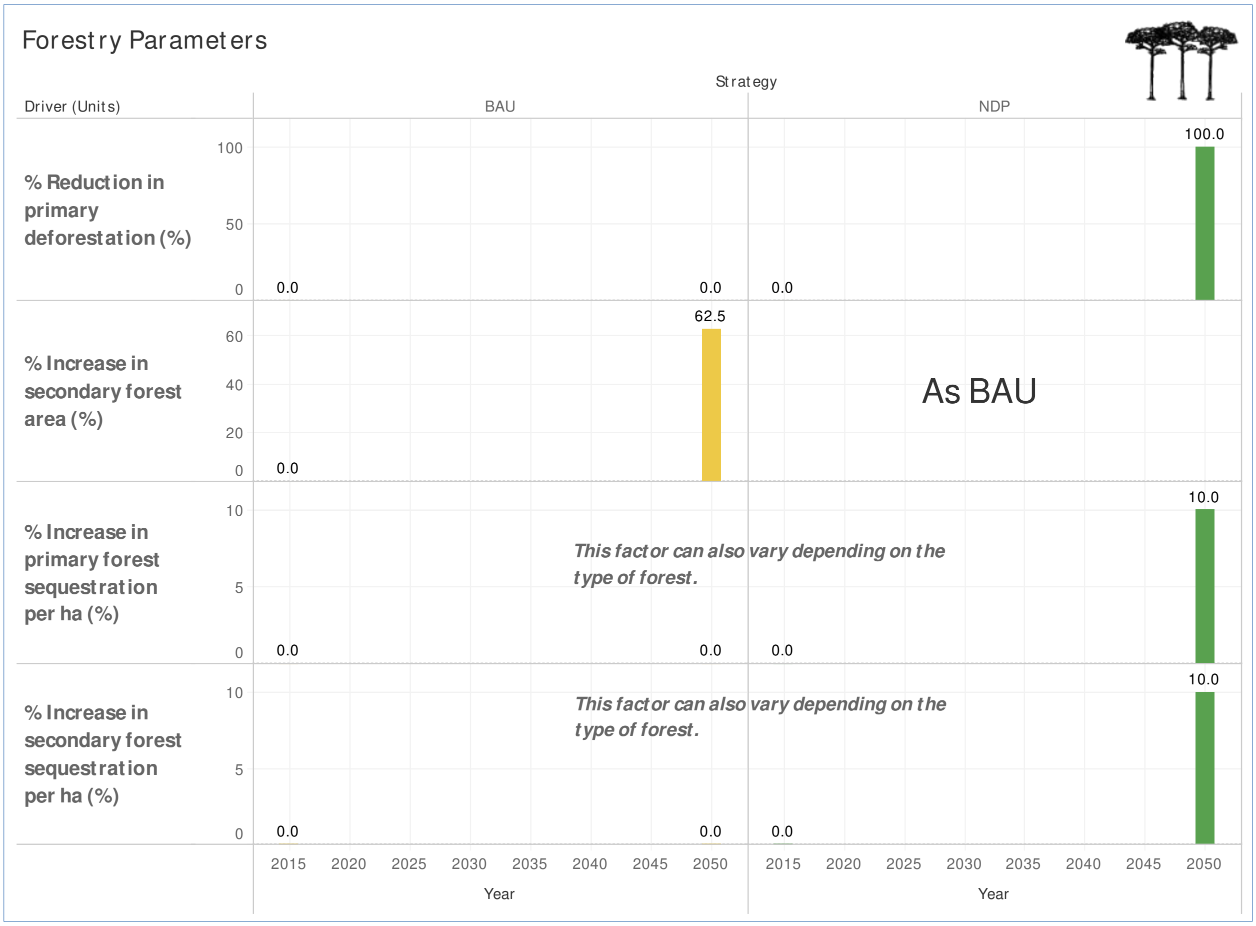
NOTES: This is a screenshot of "Evaluation of the Benefits and Costs of Decarbonization in Costa Rica," 2020. Go to https://www.rand.org/pubs/research_reports/RRA633-1/visualization.html to access this interactive tool. BAU denotes the "without decarbonization" estimate; NDP denotes the "with implementation 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 “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 A.14. Benefit Factors for the Forestry Sector

Benefit	Factor	Baseline Assumption and Range	Source
Reduced climate change impacts from emissions (reduced social cost of carbon)	Social cost of GHG emissions estimated for Costa Rica	[$0.36, **$0.61**, $1.04] per ton CO2e	Ricke et al., 2018a, 2018b.
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

Cost	Factor	Baseline Assumption and Range	Source
Value of timber not harvested	Value of timber ($ per hectare)	[$16,000; **$21,100**, $33,000] per hectare	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).
Opportunity cost of forgone agriculture	Endogenous calculation based on agricultural land area differences between the NDP and "without decarbonization" condition and value of agriculture		
Opportunity cost of forgone livestock	Endogenous calculation based on livestock differences between the NDP and "without decarbonization" conditions times an elasticity factor and value of agriculture	[25%, **50%**, 75%] Example: 50% indicates that one acre reduction in grassland due to forest preservation in the NDP condition would indicate a livestock	Author's judgment.
Cost of increasing carbon sequestration from existing forests	Unit cost of increasing sequestration	[$50, **$80**, $120] per ton CO2e Range from literature expanded by authors.	Busch et al., 2019.

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 Oyhantcabal, Carlos A. Gomez, Patricia Ricci, Juan Ku-Vera, Stefan Burkart, Jon M. Moorby, and Ngonidzashe Chirinda,

"Ambition Meets Reality: Achieving GHG Emission Reduction Targets in the Livestock Sector of Latin America," *Frontiers in Sustainable Food Systems*, May 14, 2020. As of October 18, 2020: https://www.frontiersin.org/articles/10.3389/fsufs.2020.00065/full

Autoridad Reguladora de los Servicios Públicos (ARESEP), "Tarfia Acueducto ESPH, 2020," 2020. As of October 13, 2020: https://aresep.go.cr/agua-potable/index.php?option=com_content&view=article&id=2892&catid=58

AyA (Instituto Costarricense de Acueductos y Alacantrillados), *Plan Nacional de Inversiones en Saneamiento, 2016–2045*, San José, Costa Rica, 2016. As of October 8, 2020: https://www.aya.go.cr/ASADAS/Documents/PLAN%20NACIONAL%20DE%20INVERSIONES%20EN%20SANEAMIENTO%202016-2045.pdf

Ben-Haddej, D., A. Buchenan, A. Owen, and G. Shakan, *Managing Costa Rica's Waste: Recommendations for a Municipal Solid Waste Management Plan*, Worchester, Mass.: Worchester Polytechnic Institute, 2010.

Busch, Jonah, Jens Engelmann, Susan C. Cook-Patton, Bronson W. Griscom, Timm Kroeger, Hugh Possingham, and Priya Shyamsundar, "Potential for Low-Cost Carbon Dioxide Removal Through Tropical Reforestation," *Nature Climate Change*, Vol. 9, 2019, pp. 463–466.

Canelo, Abelardo, "Costa Rica Recycles Only 6.6% of Its Daily Residues," *Costa Rica News*, May 17, 2018. As of October 8, 2020: https://thecostaricanews.com/costa-rica-recycles-only-6-6-of-its-daily-residues/

Coady, David, Ian Parry, Nghia-Piotr Le, and Baoping Shang, "Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates," International Monetary Fund Working Paper, Fiscal Affairs Department, May 2019.

COSEVI, *Anuario estadístico de accidentes de tránsito con víctimas en Costa Rica*, Technical Report, Consejo de Seguridad Vial, 2017.

DecisionWare Group LLC, *Costa Rica—Assessing Climatemitigation Pathways to Support NDC Implementation: Final Report—Assessment of Mitigation Measure to Achieve NDC Goals*, October 2017.

Dixon, John A., *Enhanced Cost Benefit Analysis of IDB Waste Water Treatment Projects with Special Consideration to Environmental Impacts: Lessons Learned from a Review of Four Projects*, Discussion Paper No. IDB-DP-254, Washington, D.C.: Inter-American Development Bank, 2012.

Electric Power and Energy Research Laboratory (EPERLab), "The OSeMOSYS–CR Model," GitHub, 2020. As of October 7, 2020: https://osemosys-cr.readthedocs.io/en/latest/

EPERLab—*See* Electric Power and Energy Research Laboratory.

Fischedick, Manfred, Joyashree Roy, Amr Abdel-Aziz, Adolf Acquaye, Julian Allwood, Jean-Paul Ceron, Yong Geng, Haroon Kheshgi, Alessandro Lanza, Daniel Perczyk, Lynn K. Price, Estela Santalla, Claudia Sheinbaum, Kanako Tanaka, Roland Clift, and Valentin Nenov, "Chapter 10: Industry," in Ottmar Edenhofer, Ramón Pichs-Madruga, Youba Sokona, Jan C. Minx, Ellie Farahani, Susanne Kadner, Kristin Seyboth, Anna Adler, Ina Baum, Steffen Brunner, Patrick Eickemeier, Benjamin Kriemann, Jussi Savolainen, Steffen Schlömer, Christoph von Stechow, and Timm Zwickel, eds., *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom, and New York: Cambridge University Press, 2014.

Gallardo, Fernando Luis Victor, *Contaminantes climáticos de corta duración en Costa Rica*. report prepared for Climate and Clean Air Coalition, Ministry of Environment and Energy (Costa Rica), Directorate of Climate Change, 2018.

Gillingham, Kenneth, and James H. Stock, "The Cost of Reducing Greenhouse Gas Emissions," *Journal of Economic Perspectives*, Vol. 32, No. 4, Fall 2018, pp. 53–72.

Gyekye, Liz, "Coca-Cola Lightweights 330ml Glass Bottle," edie News, February 18, 2014. As of October 8, 2020: https://www.edie.net/news/5/Coca-Cola-lightweights-330ml-glass-bottle/

Haro, Tapia, Daniel Ivan, Gaëtan Hinojosa, Anca Madalina Purcel, Cindy Cruz Barahona, José Pablo Murillo Corrales, and Silvia Fonseca Blanco, *30 Medidas analizadas del Plan Nacional de Descarbonización (PND) 2018–2050 de Costa Rica: Análisis y estimación de costos, procesos y necesidades de los ejes 1, 2 y 3 del PND*, 2019.

Henderson, B., A. Falcucci, A. Mottet, L. Early, B. Werner, H. Steinfeld, and P. Gerber, "Marginal Costs of Abating Greenhouse Gases in the Global Ruminant Livestock Sector," *Mitigation and Adaptation Strategies for Global Change*, Vol. 22, 2017, pp. 199–224.

ICE—*See* Instituto Costarricense de Electricidad.

Institute for Electric Efficiency, *The Costs and Benefits of Smart Meters for Residential Customers*, IEE Whitepaper, July 2011. As of October 8, 2020: https://www.edisonfoundation.net/-/media/Files/IEI/publications/IEE_BenefitsofSmartMeters_Final.ashx

Instituto Costarricense de Electricidad, *Plan de expansión de la transmisión 2017–2027*, 2017. As of October 8, 2020: https://www.grupoice.com/wps/wcm/connect/32e304c0-bff9-4436-ace0-33e13a85d3da/Plan+de+Expansi%C3%B3n+de+la+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: https://www.ipcc-nggip.iges.or.jp/public/2006gl/

Intergovernmental Panel on Climate Change, *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, 2019. As of October 8, 2020: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

International Renewable Energy Agency, *Electricity Storage and Renewables: Costs and Markets to 2030*, Abu Dhabi, 2017.

International Renewable Energy Agency, *Renewable Power Generation Costs in 2018*, Agency, Abu Dhabi, 2019.

IPCC—*See* Intergovernmental Panel on Climate Change.

IRENA—*See* International Renewable Energy Agency.

Karlsson, Mikael, Eva Alfredsson, and Nils Westling, "Climate Policy Co-Benefits: A Review," *Climate Policy*, Vol. 20, 2020, pp. 292–316.

Lobo, Susy, Maritza Marin, Victoria Rudin, and Fiorella Salas, *Analysis of the Challenges in the Development of the Recycling Value Chain in Central America*, IDB Monograph 485, Washington, D.C.: Inter-American Development Bank, 2016. As of October 8, 2020: https://publications.iadb.org/en/analysis-challenges-development-recycling-value-chain-central-america

McKinsey & Company, *Impact of the Financial Crisis on Carbon Economics: Version 2.1 of the Global Greenhouse Gas Abatement Cost Curve*, 2010. As of October 8. 2020: https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/Impact%20of%20the%20financial%20crisis%20on%20carbon%20economics%20Version%2021/Impact%20of%20the%20financial%20crisis%20on%20carbon%20economics%20Version%2021.pdf

Ministerio de Ambiente y Energía, Ministerio de Vivienda y Asentamientos Humanos, and Ministerio de Planificación Nacional y Política Económica, *Plan Integral de Movilidad Urbana Sostenible para el Área Metropolitana de San José, Costa Rica*, Technical Report, 2017. As of October 8, 2020:

https://cambioclimatico.go.cr/wp-content/uploads/2018/09/PIMUS_INFORME-EJECUTIVO.pdf

Montero, Xinia Hernández, "Centros de Acopio de Material Reciclable," Universidad Nacional Costa Rica, 2009. As of October 8, 2020: http://www.documentos.una.ac.cr/bitstream/handle/unadocs/3659/CENTROS%20DE%20ACOPIO%20DE%20MATERIAL%20RECICLABLE.pdf?sequence=1&isAllowed=y

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

Porras, Ina, David N. Barton, Adriana Chacón-Cascante, and Miriam Miranda, *Learning from 20 Years of Payments for Ecosystem Services in Costa Rica*, International Institute for Environment and Development, London, November 2013.

Proyecto Humedales de SINAC-PNUD-GEF, *Valoración de los servicios ecosistémicos que ofrecen siete de los humedales protegidos de importancia internacional en Costa Rica: Palo Verde, Caribe Noreste, Caño Negro, Gandoca-Manzanillo, Maquenque, Térraba Sierpe y Las Baulas, San José, Costa Rica*, SINAC/CINPE-UNA/PNUD, 2017.

Ricke, Katharine, Laurent Drouet, Ken Caldeira, and Massimo Tavoni, "Country-Level Social Cost of Carbon," *Nature Climate Change*, Vol. 8, 2018a, pp. 895–900.

Ricke, Katharine, Laurent Drouet, Ken Caldeira, and Massimo Tavoni, "Country-Level Social Cost of Carbon: Database Explorer," GitHub page, 2018b. As of October 8, 2020: https://country-level-scc.github.io/explorer/

Rissman, Jeffrey, Chris Bataille, Eric Masanet, Nate Aden, William R. Morrow III, Nan Zhou, Neal Elliott, Rebecca Dell, Niko Heeren, Brigitta Huckestein, et al., "Technologies and Policies to Decarbonize Global Industry: Review and Assessment of Mitigation Drivers Through 2070," *Applied Energy*, Vol. 266, 2020, p. 114848.

Quirós-Tortós, Jairo Humberto, "Development and Assessment of Decarbonization Pathways to Inform Dialogue with Costa Rica Regarding the Updating Process of Nationally Determined Contribution (NDC)," World Bank, 2020.

RECOPE (Refinadora Costarricense De Petróleo), "Precios Históricos," undated. As of October 8, 2020: https://www.recope.go.cr/productos/precios-nacionales/historicos/

Solera, Juan, Debbie Pierce, R. Espinosa, C. Julio, F. Chacón, Luis Roberto, and Federico Alice, *Proyecciones Nacionales de Costa Rica: Línea base de emisiones de gases de efecto invernadero hasta el año 2030*, SCS Global Services, 2015.

Stege, Alex, and Jim Michelsen, *Pre-Feasibility Study for Landfill Gas Recovery and Utilization at the Loma de Los Cocos Landfill Cartagena de Indias, Colombia*, prepared for the U.S. Environmental Protection Agency, Landfill Methane Outreach Program, 2008. As of October 8, 2020: https://www.globalmethane.org/Data/148_LosCocos.Pre-Feasibility.Report.Final.English.pdf

Talaei, Alireza, David Pier, Aishwarya V. Iyer, Md Ahiduzzaman, and Amit Kumar, "Assessment of Long-Term Energy Efficiency Improvement and Greenhouse Gas Emissions Mitigation Options for the Cement Industry," *Energy*, Vol. 170, 2019, pp. 1051–1066.

Turner, David A., Ian D. Williams, and Simon Kemp, "Greenhouse Gas Emission Factors for Recycling of Source-Segregated Waste Materials," *Resources, Conservation and Recycling*, Vol. 105, Part A, December 2105, pp. 186–197.

United Nations Industrial Development Organization, *Energy Efficiency Potentials in Industrial Steam Systems in China: Development of a Steam Systems Energy Efficiency Cost Curve*, 2014. As of October 8. 2020: https://www.unido.org/sites/default/files/2015-09/EE_Potentials_Steam_Systems_China__0.pdf

U.S. Environmental Protection Agency Landfill Methane Outreach Program, *LFG Project Development Handbook*, March 2020. As of October 8, 2020: https://www.epa.gov/sites/production/files/2016-11/documents/pdh_full.pdf

U.S. Geological Survey, "National Minerals Information Center: Latin America and Canada | North America, Central America, and the Caribbean," undated. As of October 8, 2020: https://www.usgs.gov/centers/nmic/latin-america-and-canada-north-america-central-america-and-caribbean#cs

Verspecht, Ann, Valerie Vandermeulen, Erik Ter Avest, et al., "Review of Trade-offs and Co-Benefits from Greenhouse Gas Mitigation Measures in Agricultural Production," *Journal of Integrative Environmental Sciences* Vol. 9, Suppl. 1, 2012, pp. 147–157.

Wang, Yun, Xiaohua Sun, Baocai Wang and Xiaoling Liu, "Energy Saving, GHG Abatement and Industrial Growth in OECD Countries: A Green Productivity Approach," *Energy*, Vol. 194, 2020.

World Bank, "World Bank Open Data," 2020. As of October 8, 2020: https://data.worldbank.org

"World Bank: Costa Rica's Waste Generation Expected to Double by 2025," *Inside Costa Rica*, June 7, 2012. As of October 8, 2020: https://www.insidecostarica.com/dailynews/2012/june/07/costarica120060706.htm

Appendix B. Developing Socioeconomic Scenarios

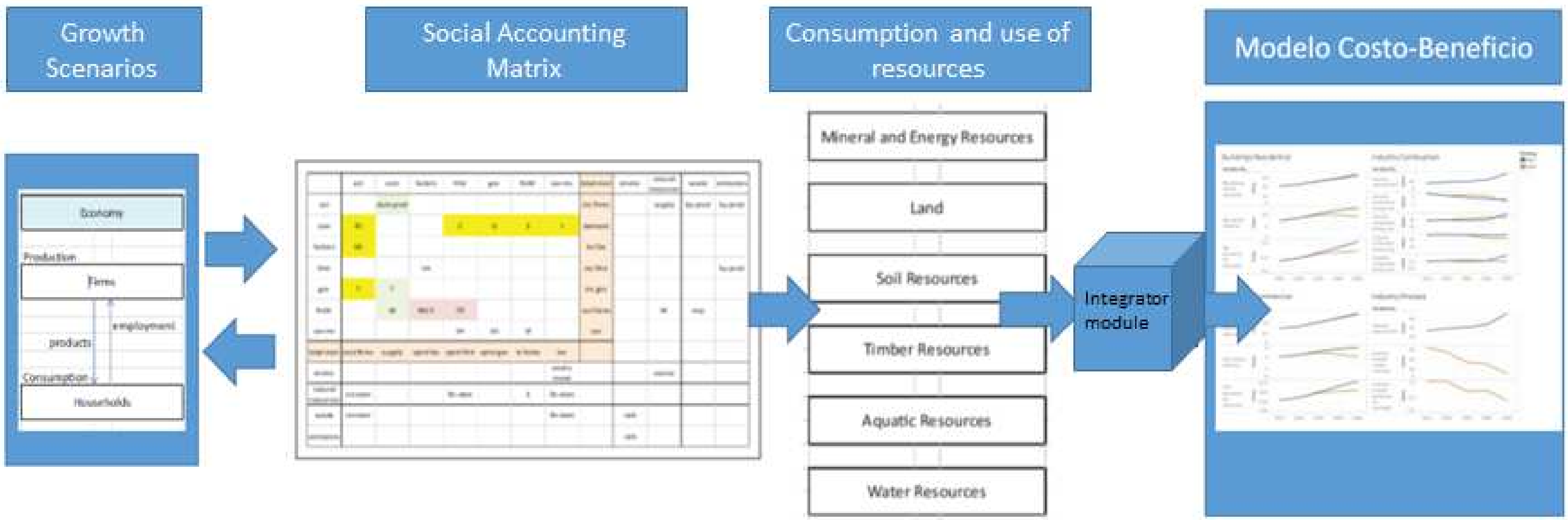
The Integrated Economic-Environmental Modeling (IEEM) Platform is a future-looking computable general equilibrium framework that enables the analysis of the impact of public policy and investment on indicators such as GDP, income and employment, but also on wealth and natural capital (Banerjee et al., 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

Banerjee, Onil, Martin Cicowiez, Mark Horridge, and Renato Vargas, "A Conceptual Framework for Integrated Economic–Environmental Modeling," *Journal of Environment and Development*, Vol. 25, No. 3, 2016, pp. 276–305.

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 $MtCO_2e$. 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

Economic Scenario	Drivers of Vulnerability	Density	Coverage
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

Scenario Box	Drivers of Vulnerability	Density	Coverage
Vulnerability 1: "High-cost alternative vehicles under low economic growth"	• Low-growth scenario • Cost ratio of electric and hybrid vehicles to conventional fuel vehicles > 91%	52%	41%
Vulnerability 2: "Low use of public transportation, high demand for freight, and expensive electric vehicles"	• Cost ratio of electric and hybrid vehicles to conventional fuel vehicles > 123% • Occupancy rates of SUVs, sedans, and minivans < 133% • Growth in public transport use < 18% • light freight demand > 10.14 Gtkm	56%	27%

Appendix C References

Bryant, Benjamin P., and Robert J. Lempert, "Thinking Inside the Box: A Participatory, Computer-Assisted Approach to Scenario Discovery," *Technological Forecasting and Social Change*, Vol. 77, No. 1, January 2010, pp. 34–49.

Friedman, Jerome H., and Nicholas I. Fisher, "Bump Hunting in High-Dimensional Data," *Statistics and Computing*, Vol. 9, 1999, pp. 123–143.

Hornik, Kurt, Achim Zeileis, Torsten Hothorn, and Christian Buchta, "RWeka: An R Interface to Weka," R package version, 03-04, 2007. As of October 7, 2020: https://CRAN.R-project.org/package=RWeka

Quinlan, J. Ross, *C4.5: Programs for Machine Learning*, Morgan Kaufmann Series in Machine Learning, San Mateo, Calif.: Morgan Kaufmann, 1993.

Appendix D. Stakeholder Organizations

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 Economia, 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

Given the socioeconomic impacts of the COVID-19 pandemic, global leaders are seeking solutions to re-activate their economies while preserving the climate and mitigating the risk of future environmental crises. Costa Ricas National Decarbonization Plan sets the ambitious goal to become carbon neutral by 2050 and lays out a series of actions that government officials, sectoral stakeholders, and more generally Costa Rican citizens would need to implement throughout the economy to decarbonize. The extent to which the implementation of the decarbonization plan can be part of an effort to restart the economy post covid depends on the costs and socioeconomic benefits it entails.

In this study, we developed an integrated model that estimates the benefits and costs of implementing the decarbonization plan in all major sectors, informed by consultations with numerous government agencies, industries and non-governmental organizations. In our central scenario, decarbonization brings $41 billion in net benefits to Costa Rica between 2020 and 2050, using a 5 percent discount rate. In the land use sector, reducing emissions would lead to increased agricultural and livestock productivity, and increasing carbon sequestration by forests would lead to greater ecosystem services, such as renewable forestry products, water and soil benefits, and support for tourism and cultural heritage. In the transportation sector, the economic benefits from energy savings, fewer accidents, time saved from reduced congestion, and the reduced negative impacts of air pollution on health more than compensate for the initially higher upfront costs of switching to electric vehicles and building infrastructure for zero-emissions public transport. Energy savings in buildings, efficiency gains in industry, and the economic value of recycled materials and treated water complete our estimates.

Recognizing uncertainty about the future, we evaluate thousands of different plausible futures in order to understand the range of possible decarbonization pathways and net benefits for the Costa Rican economy. Under all but 22 of the more than 3,000 plausible futures considered, implementation of the decarbonization plan would lead to economic benefits that exceed the costs. Our results highlight the importance of modal shift and zero-carbon technologies in the transport sector, increasing carbon sequestration in the forestry sector, and emission reductions in livestock and industrial processes, to achieve net-zero emissions. This work has helped build tools and capacity for evaluating decarbonization strategies, which will be used to support the update of Costa Ricas Nationally Determined Contributions -- its commitment to the international community under the Paris Agreement. Our approach can be replicated in other countries interested in analyzing the economic implications of pathways towards carbon-free prosperity.

COSTA RICA GOBIERNO DEL BICENTENARIO 2018 - 2022
DESCARBONICEMOS COSTA RICA COMPROMISO PAÍS 2018-2050
MINAE Ministerio de Ambiente y Energía
DCC DIRECCION DE CAMBIO CLIMATICO
IDB Inter-American Development Bank
RAND CORPORATION
UCR UNIVERSIDAD DE COSTA RICA