Cost-Benefit Analysis of Options to Achieve Net-Zero Emissions in Colombia

Summary for decision-makers

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Universidad de los Andes

cods
CENTRO DE LOS OBJETIVOS DE DESARROLLO SOSTENIBLE PARA AMÉRICA LATINA

IDB
Inter-American Development Bank

Technical Note

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Descarbonização

Keywords: Carbon Neutrality; Costs; Economic Benefits; Externalities; Mitigation; Colombia; AFOLU; Transportation; Waste; Energy.

Resumen

Este documento presenta un escenario de transformaciones sectoriales que permitiría a Colombia alcanzar la carbono neutralidad en 2050 y cuantifica los costos asociados y los beneficios económicos derivados de implementar estas transformaciones. Las alternativas presentadas no pretenden ser prescriptivas, reconociendo que existen múltiples opciones disponibles para lograr las metas climáticas definidas por el país. La contribución más relevante de este análisis tiene que ver con estimar el nivel de cambios requeridos y los costos y beneficios asociados.

Se evaluaron los siguientes sectores: agricultura, energía, transporte y gestión de residuos. Se identificó que los primeros tres sectores logran beneficios netos al implementar trayectorias de descarbonización si no solo se contabilizan los costos de implementación sino también los ahorros asociados a, por ejemplo, menores costos operativos, mayor productividad, ahorros en daños a la salud o costos evitados del cambio climático en la economía. El análisis de costo-beneficio se realizó utilizando tres niveles diferentes de la tasa de descuento, y en todos los casos, la neutralidad de carbono se alcanza con beneficios económicos netos (superando los costos asociados).

Palabras clave: AFOLU, beneficios económicos, carbono neutralidad, Colombia, costos, energía, externalidades, mitigación, transporte, residuos.

Abstract

This document presents a scenario of sectoral transformations that would allow Colombia to achieve carbon neutrality in 2050 and quantifies the associated costs and economic benefits derived from implementing these transformations. The alternatives presented are not intended to be prescriptive, recognizing that there are multiple options available to achieve the climate goals defined by the country. The most relevant contribution of this analysis has to do with estimating the level of changes required and the associated costs and benefits.

The following sectors were assessed: agriculture, energy, transportation, and waste management. It was identified that the first three sectors achieve net benefits by implementing decarbonization trajectories if not only the implementation costs are accounted for but also the savings associated with, for example, lower operating costs, higher productivity, savings in damage to health or avoided costs because of climate change on the economy. The cost-benefit analysis was performed using three different levels of the discount rate, and in all the cases, carbon neutrality is reached with net economic benefits (exceeding the associated costs).

Keywords: AFOLU, economic benefits, carbon neutrality, Colombia, costs, energy, externalities, mitigation, transportation, waste.

General results

The analysis reported in this document presents a scenario of sectoral transformations that would allow the country to achieve carbon neutrality by the year 2050 and quantifies both the associated costs and the economic benefits derived from the implementation of those transformations. The alternatives presented are not intended to be prescriptive, since there are multiple options available to achieve the climate goals defined by the country. The most relevant contribution of this analysis has to do with the estimation of the level of changes required and the associated costs and benefits.

The following sectors were assessed: agriculture, energy, transportation, and waste management. It was identified that the first three sectors achieve net benefits by implementing decarbonization trajectories if not only the implementation costs are accounted for, but also the savings associated with, for example, lower operating costs, higher productivity, savings in damage to health or avoided costs because of climate change on the economy. For the assessment of the latter, two levels of damage caused by climate change to the economy were selected based on literature, having in mind that the authors are not aware of a valuation of this impact calculated locally for Colombia. The first level is the social cost of carbon (SCC) in a world with insufficient climate action, which means that, due to the greater accumulation of greenhouse gases (GHG) in the atmosphere, the damage from emitting carbon is higher (US$13.7 per ton of CO_2e) than in the second case, where it is assumed that, thanks to more decisive climate action, the damages caused by climate change are lower (US$ 3.16 per ton of CO_2e). The discount rates used are: 6.4 %, which is the rate used to value the benefits of updating the nationally determined contribution (NDC) in Colombia (Government of Colombia, 2020); 3.1 %, which corresponds to the rate proposed by the National Planning Department (NPD) for the valuation of environmental projects (Hernández et al., 2018), and 9.0%, which is the rate used to value public projects in Colombia, also calculated by the NPD (Piraquive et al., 2018)[1].

The results of the analysis indicate that the trajectories leading to sectoral "carbon neutrality" require investments and costs that are lower than the economic savings and benefits that could be obtained. The only sector where the mitigation scenario is more expensive than the reference scenario is the waste management sector. For the agriculture, energy, and transportation sectors, the mitigation scenarios assessed including social benefits result in net savings.

In the agriculture sector, mitigation options were identified that would allow a reduction of 154 million tons of CO_2e in 2050 and would

1 The cited documents are Government of Colombia (2020). An Update of Colombia's Nationally Determined Contribution (NDC). Hernández, G., Piraquive, G., & Matamoros, M. (2018). An estimate of the discount rate for environmental projects (Archives of Economics). Piraquive, G., Matamoros, M., Cespedes, E., & Rodríguez, J. (2018). An update of the rate of return on capital in Colombia under the Harberger methodology (Economy Files).

yield a benefit of around 35 to 105 thousand million dollars (depending on the discount rate used), including the benefits of greater crop productivity and the avoided damages from reduced GHG emissions.

In the energy sector, excluding transportation, the savings in the operation of the energy system were estimated to be between 0.15 and 47 thousand million dollars, varying with the discount rate used. If the social cost of carbon (SCC) is considered, the net benefits amount to between 6.1 and 71.0 thousand million dollars (varying with the discount rate and the comparison scenario). It is important to note that, although the total system cost is lower in the mitigation scenario, the marginal cost of mitigation reaches 488 dollars per ton of CO_2e. This implies that, although low-carbon scenarios have a net benefit for society, attention must be paid to the fact that costs and benefits are distributed among each agent differently.

The transportation mitigation portfolio leads to a reduction of 106 Mt CO_2e in 2050, a 99% reduction in emissions compared to the baseline in 2050 and generates savings between 133 and 574 thousand million dollars between 2020 and 2050, depending on the discount rate used for the assessment (9.0%; 6.4% or 3.1%). These savings refer to investment, operation, maintenance, and energy consumption costs. Additionally, health co-benefits from increasing physical activity, reducing congestion, reducing accidents, improving air quality, and reducing noise generate an additional value of between 58 and 69 thousand million dollars over the same period.

Finally, a reduction of 14 Mt CO_2e is achieved in the waste sector, 83% of the GHG emissions that would occur in the baseline in 2050. The assessment of the cost-effectiveness of the mitigation scenario revealed abatement costs between 8.36 and 18.5 USD/t CO_2e (depending on the discount rate). When including the co-benefits from the sale of recycled materials and fertilizers, potential electricity production, and job creation from the implementation of new practices, waste management technologies, and the SCC in the assessment, the abatement cost becomes even lower than 4 USD/t CO_2e, increasing its economic viability in a context of emissions mitigation.

Overall, for the four sectors assessed, the measures generate economic benefits of 183 thousand million in 2015 dollars, using a discount rate of 9%, 336.1 thousand million when a rate of 6.4% is used, and 747 thousand million when the discount rate is 3.1%. These values are substantial and represent 57%, 105%, and 233% of the 2019 GDP. In broad terms, this is equivalent to a profit earning, on average, of 3.75% per year during the implementation period of the measures.

From a sectoral point of view, the assessed mitigation trajectory indicates that, except for the Agriculture, Forestry, and Other Land Use (AFOLU) sector, no sector would achieve carbon neutrality by 2050. Achieving this common goal requires the AFOLU sector to generate increasingly negative emissions from 2041 onwards so that these compensate for the residual emissions of the other sectors. Therefore, early, and sustained advance in mitigation in this sector is essential for the decarbonization of the country.

This means that low-carbon development for Colombia is desirable from the economic perspective and produces positive net economic benefits, although the costs and benefits are assumed and perceived by the different agents involved.

I. Agriculture and forestry sector

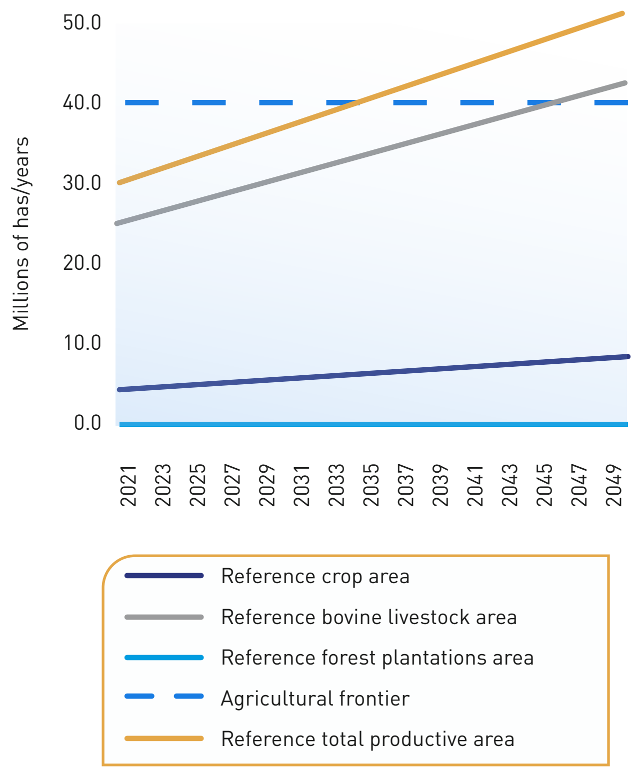
By estimating the size of the demand for agricultural products on the basis of apparent consumption (domestic production, plus imports, minus exports), it is projected that between 2020 and 2050, the domestic demand will multiply 1.9 times. Considering that part of this demand is satisfied by imports and that part of the domestic production is destined for the international market, it is expected that domestic agricultural production will increase 92% in these years, that is, the equivalent of an average annual growth rate of 2.3%.

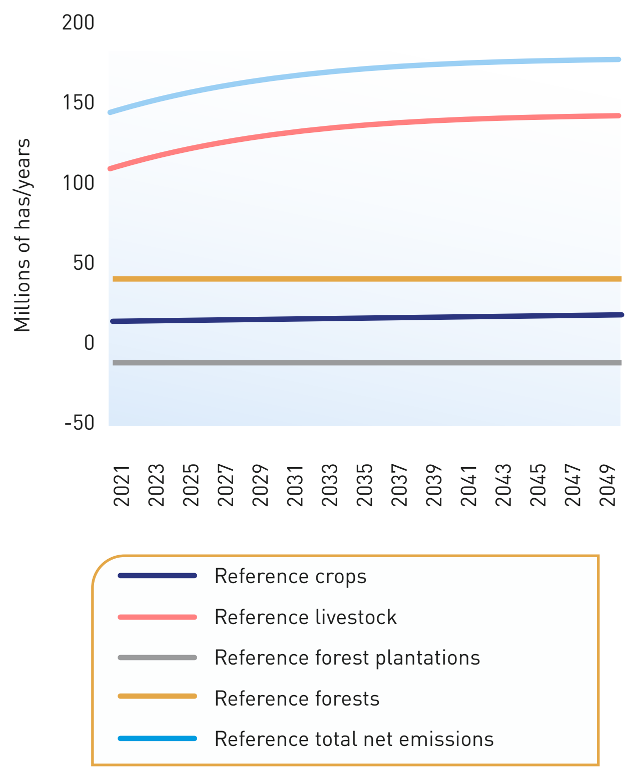
If the productivity of the sector were to remain constant, satisfying the demand for domestic production would imply an increase in the productive use of land to approximately double the area used in 2020, reaching a total of 51.6 million hectares, of which 43.1 million would be used for livestock production (essentially cattle) and 8.2 million for all crops. The country has approximately 59.1 million hectares of forests and 40 million hectares in the agricultural frontier (the area identified by the State as available for productive agricultural use). Therefore, under the described conditions, the demand for national production in 2050 would imply using the 40 million hectares within the agricultural frontier, plus 11.6 million hectares of deforested forest transformed to productive use. An unsustainable situation from an environmental, climatic, and natural capital use perspective.

On the other hand, if the GHG emissions of the sector are calculated based on the values used in the Second Biennial Update Report and on the evolution of production resulting from the above analysis, by 2050 the emissions would increase to 179.4 million tons of CO_2 equivalent, approximately, at 33% above the level estimated for 2015. Considering that agriculture is one of the sectors that does not have technologies capable of completely eliminating GHG emissions, the goal of reaching carbon neutrality in the sector by 2050 can only be achieved by making full use of technologies that allow reducing emissions and compensate the remnant with activities that generate net carbon absorption (deforestation control, restoration of forests and other ecological sinks, commercial forestry plantations and carbon sequestration in the soil).

The left panel of Figure 1 shows the projected behavior of land use, and the right panel illustrates the projected behavior of net CO_{2eq} emissions. The difference between the value of the area within the agricultural frontier and the total demand for land for productive uses (the sum of the areas used for crops, cattle ranching, and forestry plantations) becomes approximately zero in 2034, which means that the development of productive activities would have to take place in newly deforested areas until reaching in 2050, the 11.6 million hectares of deforestation mentioned above. On the other hand, the right panel shows that, including the effect of changes in land use, the greatest contribution to emissions in the sector comes from livestock activities (particularly cattle farming).

Figure 1. *Land use and net emissions in the reference scenario*





SOURCE: OWN CALCULATIONS OF THE STUDY USING THE DDPLAC MODEL

MITIGATION MEASURES.

The mitigation measures considered to achieve carbon neutrality can be summarized as follows: (i) sustainable crop intensification; (**ii**) sustainable intensification of cattle ranching; (**iii**) commercial reforestation; (**iv**) decrease in demand for beef; and (**v**) forest preservation.

Sustainable crop intensification aims to increase productivity and the use of production technologies that reduce emissions. The first contributes to reducing the demand for land for productive uses, relieving pressure on the agricultural frontier and the change in land use of forest areas, thus making it possible to allocate larger areas for the development of restoration projects and commercial forest plantations. The second contributes to the reduction of N_2O emissions (associated with the use of fertilizers) and the fixation of carbon in the soil while increasing productivity.

Sustainable livestock intensification seeks to increase productivity and reduce emissions. The means to achieve these goals are varied and include the optimization of the grazing intensity, the periodic use of legumes in pastures (increasing animal feed and contributing to carbon fixation in the soil), the use of more energy-dense foods (which help to reduce enteric fermentation) and the improvement in the management of grazing. These practices increase the number of animals per hectare and the percentage of animals in the herd that effectively go to the market, thereby decreasing the growth in demand by land for the activity and the number of animals needed to meet the demand for milk and meat.

The purpose of commercial reforestation is to promote this economic activity under conditions that allow maintaining the desired levels of carbon absorption in the biomass, which is achieved through a balance between the commercial use of the wood (which prevents the cut trees from absorbing more carbon) and newly planted areas that make up for the lost absorption capacity.

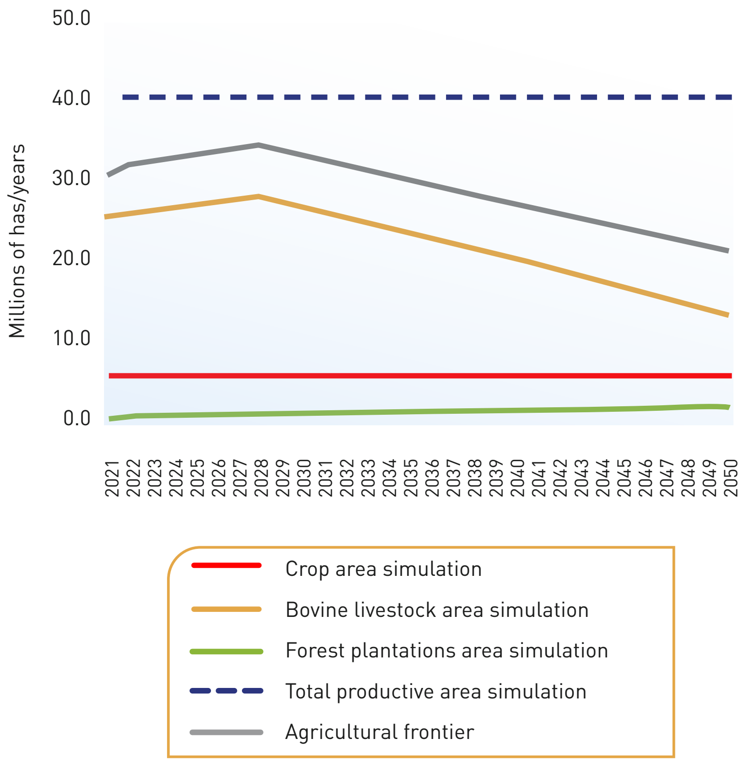
The decrease in the demand for beef seeks to reduce the number of animals needed to satisfy the demand and is based on the idea that it is possible to promote a consumption pattern more responsible with climate change, without compromising the nutritional needs of the population. This can be achieved with changes in the behavior of high-income consumers and, especially, in that of the new generations, which are already showing a trend in this direction.

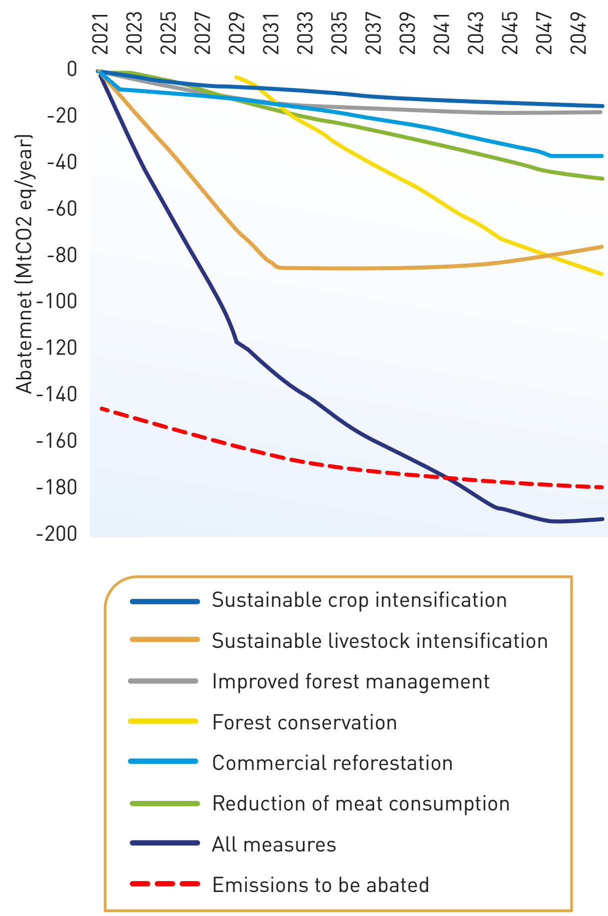
Finally, the conservation measure is a set of measures that includes improved management of natural forests to minimize biomass extraction, reforestation for forest conservation, and restoration, the latter developed in the areas freed by crop and livestock. This would also allow, in addition (although it is not an element considered in this study), to establish a basis for the development of income-generating activities related to sustainable tourism, and the supply of inputs for the cosmetics, pharmaceutical, and food industries.

These measures, applied to all productive activities (crops and livestock), to two million hectares in commercial forestry plantations, with a reduction equivalent to 14% in the number of head of livestock as a consequence of the reduction in consumption and with approximately 30 million hectares (including the avoided deforestation) associated with preservation measures, would lead to emissions neutrality in the sector in 2041 and to generate negative emissions from there, increasing the level of net absorption to reach 14.1 million tons of CO_{2eq} in 2050, compensating for the remaining emissions in other sectors to reach carbon neutrality for the country.

Figure 2 shows in the left panel the behavior of land use associated with the measures described above, while the right panel shows the behavior of net emissions by subsector. As can be seen in the left panel, the total area used for productive activities would increase to 21 million hectares, which would leave a remaining 19 million hectares within the agricultural frontier where conservation activities can be developed. On the other hand, the right panel shows the important contribution that sustainable intensification of cattle ranching, and forest conservation make to mitigation.

Figure 2. Land use and net emissions in the mitigation scenario.





Source: Own calculations of the study using the DDPLAC model

VALUATION OF THE MEASURES.

For the valuation of the measures it is assumed, as a general rule, that the benefits are given by the following components: (i) the valuation of avoided emissions, calculated as the difference between the emissions of the reference scenario and those of the mitigation scenario, using as a price the social cost of carbon (SCC), and (ii) the difference in production costs between the reference scenario and the mitigation scenario for the total of the activity considered. For some cases, particularly that of forestry plantations, the difference in income generated by the activity without mitigation measures was also considered for the valuation of the benefits. The cost-benefit analysis of the mitigation measures yields positive values, using different discount rates, which indicates the economic convenience of such measures. The analyses were performed using different discount rates: 3.1%, 6.4%, and 9.0%.

Taking the rate of 6.4% as a reference, the conservation measures generate a positive net present value of 19,600 million 2015 dollars, the sustainable crop intensification measures one of 9,400 million, the sustainable livestock intensification measures 16,900 million, forestry plantations 8,500 million, and the reduction in meat consumption 1,000 million. Together the AFOLU sector measures generate a net present value of 55,400 million 2015 dollars.

In all cases, except for crop intensification, the net private benefit of the measures is positive. Similarly, in all measures, there is a social benefit derived from the mitigation. Therefore, the implementation of the mitigation measures generates a double dividend: economic benefits directly appropriable at the private level and social benefits derived from the valuation of the mitigation. As long as the outcome of the mitigation effort can be monetized and at least partially appropriated at the private level (e.g., through the operation of a carbon market), all measures would be incentive compatible at the private level.

Nevertheless, it is important to note that for most of the measures the greatest benefits are achieved slowly over time, while the investment costs must be assumed in a short period. Therefore, this generates an unfavorable financial situation that requires the implementation of mechanisms that make viable the development of the projects necessary to implement the measures.

Key messages

The main results of the study can be summarized as follows:

i) From a technical point of view, the technologies available to the sector make its decarbonization feasible by 2050.

ii) Although the measures vary in terms of their mitigation capacity, there is no single measure that can lead the sector to total decarbonization. Achieving this goal requires the integrated implementation of all the measures considered.

iii) Sustainable crop and livestock intensification make sense as a mitigation technology, but, additionally, they are essential for the viable use of negative emission technologies (reforestation, commercial plantations, and restoration) as it creates a favorable land use balance for such technologies.

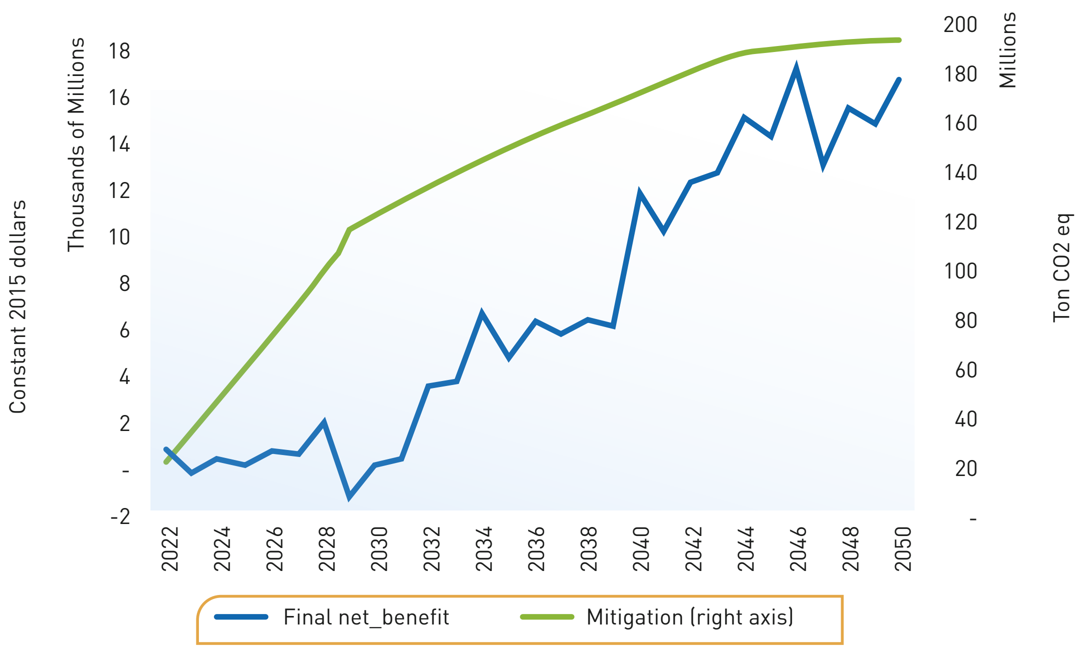
iv) The decarbonization of the sector implies a great effort in every sense and requires early progress of the necessary actions. The available technologies can help to achieve decarbonization, but their implementation takes time. Agriculture is site-specific, which means that technologies must be adapted and then adopted. International experience shows that the rate of adoption of these technologies has been very slow and there is no reason to expect that the rate of adoption in Colombia would be particularly high.

v) There are positive economic incentives for the implementation of the measures, whether they are valued from a social or private point of view.

vi) However, most measures generate relatively long periods of negative cash flows, which represents a major challenge for their implementation. In addition, some of the investments are substantial, considering the profile of the users, which means that appropriate measures must be taken to prevent them from becoming insurmountable entry barriers (thus generating inequity).

Figure 3 and Table *1* present a summary of the net economic flows and the mitigation achieved by the implementation of the different measures assessed in the AFOLU sector.

Figure 3. *Net benefit flows and emission mitigation from the mitigation measures (2022-2050).*



Source: Simulation model for DDPLAC2.

Table 1*. Cost and benefit flows and level of emission abatement achieved in the assessed mitigation portfolio.*

Years	2022	2030	2040	2050
Reference cost [thousands of millions of dollars].	27.54	20.19	27.20	28.31
Measures cost [thousands of millions of dollars].	28.37	23.74	25.03	23.02
Reference income [thousands of millions of dollars].	0.06	0.23	0.46	0.25
Measures income [thousands of millions of dollars].	0.14	1.94	7.87	9.20
Reference benefit [thousands of millions of dollars].	0.06	0.22	0.44	0.24
Measures benefit [thousands of millions of dollars].	0.11	-0.88	4.98	8.21
Social benefit [thousands of millions of dollars].	1.63	2.13	2.39	2.50
Net benefit measures [thousands of millions of dollars].	0.86	0.29	11.98	16.74
Mitigation [tons of CO2eq].	22.18	124.11	172.23	193.52

Source: Own design.

II. Energy sector

The energy sector includes primary energy production, transformation, and final consumption of all sectors, except for the transportation sector, which was analyzed as a separate one.

Energy demands were estimated using growth drivers that, when possible, are consistent with those used in the NDC update. The main drivers are population growth, and aggregate and sectoral GDP growth. The model used minimizes the total cost of satisfying the useful energy demands considering technical, environmental, and policy restrictions. Therefore, although the demands to be satisfied are the same in all modeled scenarios, fuel consumption varies according to the restrictions and requirements of each scenario.

The useful energy demands were modeled for the following sectors: residential buildings (both urban and rural); commercial buildings (including institutional and public); industrial, differentiated into six sub-sectors; and agriculture, mining, and other consumption. Similarly, oil refineries and power generation plants were modeled, and the demands for energy carriers produced in these centers are calculated endogenously. Thus, the changes in the final demand technologies are reflected in the changes in the technologies and the demands of the transformation centers.

Mitigation measures.

During the modeling process, it was identified that, in a scenario built under the energy system cost minimization logic, a greater reduction in emissions would be achieved at a lower cost than in the reference scenario of the updated Colombian NDC. That is, following the emissions route of the updated NDC reference scenario is not a least-cost solution. This outcome reflects that the improvements in energy efficiency, the electrification of some end uses, and the reduction of investment costs of some technologies that are still under development (such as renewable electricity generation, hydrogen production, and electricity storage technologies) can lead to economic savings while generating lower emissions compared to the technologies used today. Based on this, three different scenarios were built:

1. Reference Scenario: This scenario is used to facilitate comparison with the NDC reference scenario. It is important to note that the level of emissions achieved in a cost-minimization scenario to 2050 is lower than the NDC reference scenario. For this reason, a restriction was imposed to "force" the model to deliver at a minimum what was emitted in the approximation to the NDC reference scenario.

2. **Least-Cost Scenario:** this scenario does not consider any restriction on emissions. The selection of technologies and fuels is based solely on the criterion of cost minimization and considers the possibilities of technological evolution over time.

3. **Mitigation Scenario:** a maximum level of emissions was defined in a path that

starts from the 2015 level and reaches 8.5 million tons of CO_2e, equivalent to the decarbonization of more than 90% (compared with 2015 level), which is consistent with the scenarios modeled in the framework of the formulation of the Colombian E2050 long-term strategy.

Contrary to what is presented for the other sectors, in the energy sector no individual mitigation measures were modeled, but instead, least-cost technology and energy baskets compatible with the emission restrictions of each scenario were constructed. The selection of technologies and the configuration of the energy basket are the equivalent of sectoral mitigation measures and are identified during the optimization process conducted by the model.

VALUATION OF THE MEASURES.

The process of estimating costs and benefits was carried out in two stages. In the first stage, the total costs of the energy system were estimated for each of the scenarios. The differences between these costs can be understood as additional requirements or avoided expenses and investments. The total cost of the system is the present value, deducted at the corresponding rate, from the annual cash flows. These annual flows are the sum of the following items: (**i**) capital costs; (**ii**) fixed and variable operating and maintenance costs of each of the technologies installed and in operation; (**iii**) resource production costs; and (**iv**) internal costs of imports or income from energy exports.

The second stage in the estimation of costs and benefits corresponds to the valuation of the damage caused by GHG emissions. For this analysis, the level of emissions for each scenario was tracked and the damage caused was measured using a valuation for the social cost of carbon (SCC). In each period, the cost of damage caused by GHG emissions was totaled with a high social cost of carbon for the low climate ambition scenarios (Reference and least-cost) and low for the Mitigation scenario. These annual costs were converted to present value using the corresponding discount rate.

The avoided costs (which are equivalent to savings since in any case the energy demand must be met) range from 0.15 thousand million constant 2015 dollars (Mitigation scenario versus Least-cost scenario with a discount rate of 9%) up to 46.9 thousand million dollars (Mitigation scenario versus Reference scenario with a discount rate of 3.1%). The total mitigation achieved in the Mitigation scenario compared to the other two scenarios is between 1,042 million tons of CO_2e and 2,210 million tons of CO_2e, resulting in an average mitigation cost, depending on the selected discount rate, of between -0.1 dollars per ton of CO_2e up to -21.2 dollars per ton of CO_2e. These values represent the average savings that the energy system would have by mitigating each ton of CO_2e. However, it is important to review the cost structure to identify possible barriers that may prevent these cost and emission savings from occurring, the mitigation requires higher investment costs at the beginning of the projects and generates savings during the project operation. Another item to consider is that although the average[2] cost of mitigation is negative the marginal cost of mitigation exceeds several hundred dollars per ton of

2 The calculation does not include additional barriers and the costs to overcome them. For example: financial barriers requiring high investment costs and receiving returns throughout the project, costs of adopting and implementing new technologies, cultural barriers, and the costs to overcome them through education or publicity campaigns, among others.

CO_2e. This is important because the payers (of the investments) and the beneficiaries of the savings are not necessarily the same. Society perceives net benefits from mitigation, but within that society, some agents could face very high costs, and others could perceive very large savings. This situation must be addressed to enable the actual implementation of the modeling result.

The estimate of savings from avoided damages by reducing GHG emissions, quantified using the Social Cost of Carbon (SCC), shows that in all cases the reduction in emissions implies savings when the mitigation scenario is used instead of an emissions-intensive scenario. These avoided costs mean that in the mitigation scenario, total savings levels of between 6,100 and up to 71,000 million dollars are achieved depending on the discount rate used and the selected comparison scenario.

Key messages

i) The estimated costs show that there are net economic benefits from developing a low-carbon energy sector. The model shows that energy exports can be sustained, subject to the availability of reserves and the competitiveness of resources in international markets, and to the transformation of domestic demand and supply of fuels and electricity. However, these exports are subject to the exogenous behavior of international demand and the prices at which these energies are traded, being possible that some national hydrocarbon reserves may lose competitiveness in the future (due to low international prices resulting from lower demand if the world moves towards reducing emissions) and may not be extracted.

ii) The low-carbon development trajectory requires higher levels of upfront investment and offers returns in the form of lower operating costs and international energy trade over several years (since the investment must be made earlier in time). Another important aspect is that, although the average cost of mitigation is negative (on average, money is saved for each ton mitigated), the marginal cost of mitigation in some cases exceeds US$400 per ton of CO_2e. This is because while there are activities in the energy sector that can mitigate at low cost or even save money, there are other sectors where the transformation is technically more difficult. In this study, the industry sector was identified as the most difficult to decarbonize, particularly because of its direct heat requirements. This disparity between agents with mitigation savings or that must sustain higher costs requires attention to achieve, among society, a distribution of the costs and benefits of mitigation.

iii) In the different scenarios assessed, the use of fossil fuels has a differentiated behavior over time. In the first place, it is coal, which is the energy source that reduces domestic consumption rapidly as it follows a low-carbon development path. Even in a scenario without emissions restrictions, the evolution of the costs of renewable technologies causes coal-fired generation to decrease, although its low cost makes it remain an energy source in the industrial sector.

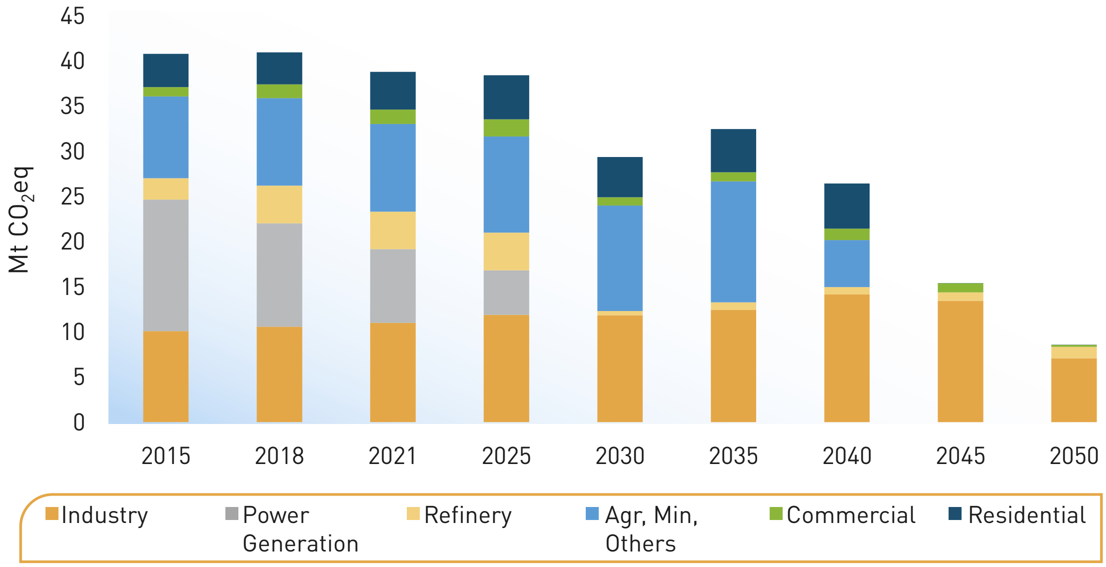
iv) On the other hand, natural gas remains an energy source until the end of the study horizon in all the scenarios modeled. However, its use varies according to the scenario, with those in which emissions restrictions are applied a stabilization of consumption is reached by 2050, while in a carbon-neutral scenario, the peak of consumption is reached around 2035.

v) Finally, oil and its derivatives. These energy sources are examined in greater detail in the following section, which evaluates the energy basket and the emissions in the transportation sector. From the aggregate point of view of the energy sector, oil reserves are fully extracted in all scenarios assessed and the decrease in domestic consumption is compensated by increases in exports. It is important to highlight that these exports occur under a scenario of international prices that make them profitable. However, these international prices are beyond the country's control and could eventually lead to situations in which these exports lose competitiveness and are not carried out. Colombia must consider that in scenarios of global climate action, the demand for fossil fuels will decrease and, therefore, a plausible scenario is that of not achieving the extraction of the total potential of reserves or that some of them lose their economic viability.

vi) The assumption that the reserves (oil and coal) can be extracted for domestic consumption and for export makes it possible for mining activities to be compatible with the decarbonization scenario. The major changes are at the level of transformation processes (changes in refining, electricity generation, and hydrogen production) and at the final consumption sectors. The results show that, when facing changes in domestic consumption of fossil fuels, both coal and oil would depend on the dynamics of international markets to maintain activity levels. Natural gas is different, and its growth depends on changes in domestic consumption and finds a place in the industry and long-distance heavy transportation until new technologies and emission restrictions can shift it towards the end of the time horizon.

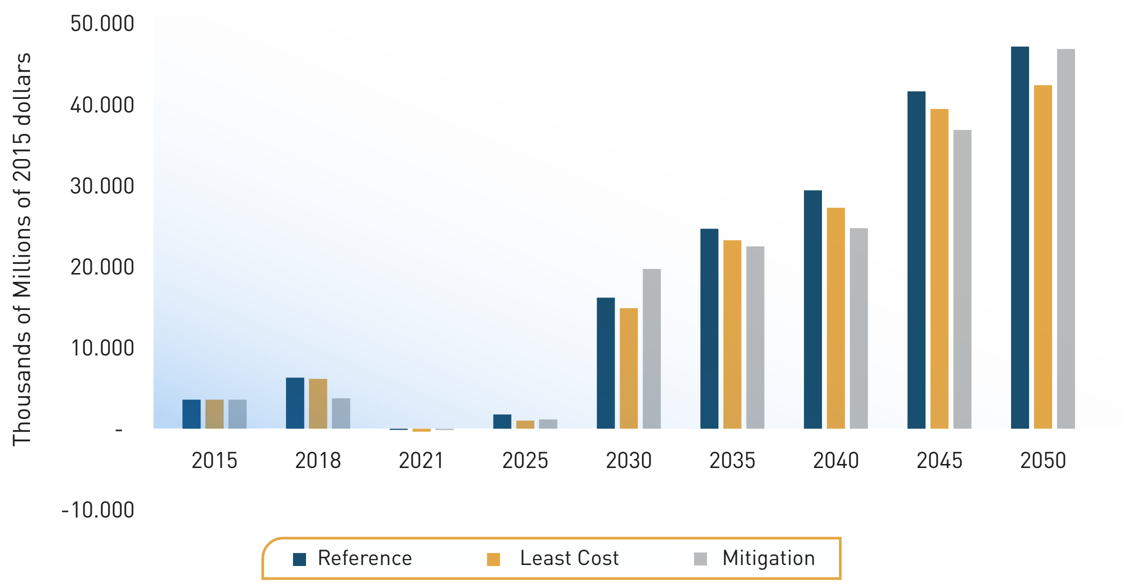
Figure 4 presents the composition of emissions from fuel combustion at the sectoral level in the mitigation scenario. Figure 5 shows the annual costs, which are the discounted sum of capital costs, fixed and variable operating costs, and international energy trade costs/revenues. The costs presented were obtained by running the model with a discount rate of 9%. With different rates, the solution to the minimization problem is different, and the costs have variations in the periods that will be summarized later in Table 2. Table 2 summarizes the incremental costs of the different scenarios assessed (negative values indicate net savings).

Figure 4. *Emission trajectories from fuel combustion discriminated by sector in the energy sector excluding transportation. Mitigation Scenario (2015-2050)*



Source: Own design.

Figure 5. *Total annual costs for different emission scenarios with a 9% discount rate.*



Source: Own design.

Table 2. *Summary of incremental costs of the energy system, estimated social cost of carbon, and net system cost-benefits including the SCC*

	Segment	Energy sector (excluding transportation)		
	Discount rate	9.0 %	6.4 %	3.1 %
Incremental cost of energy system (Mitigation - Reference)	Thousands of millions of dollars	-8.8	-23.9	-46.9
Energy system incremental cost (Mitigation - Lowest Cost)	Thousands of millions of dollars	-0.15	-2.63	-15.6
Difference Social Cost of Carbon (Mitigation - Reference)	Thousands of millions of dollars	-7.6	-12.4	-24.0
Difference Social Cost of Carbon (Mitigation - Lowest Cost)	Thousands of millions of dollars	-6.0	-8.3	-7.6
Net Cost/Benefit including SCC (Mitigation - Reference)	Thousands of millions of dollars	-16.5	-36.4	-71.0
Net costs/benefits including SCC (Mitigation - Lowest Cost)	Thousands of millions of dollars	-6.1	-10.9	-23.2

Source: Own design.

III. Transportation sector

In the transportation sector, between the years 2015 and 2050, passenger demand is projected to grow 3.39% yearly and freight by 3.44% per yearly.

In the baseline scenario, the priority participation of the road segment added to the fossil fuel-based energy matrix is reflected in a high contribution to GHG emissions. In passengers, the road segment accounts for 83% to 87% of GHG emissions in the period 2015-2050, followed by domestic aviation (13% to 17%), and lastly navigation and rail transportation (4%). Similarly, in cargo transportation, emissions are mainly contributed by the road segment (91.7% to 93.4%), followed by aviation (2.2% to 3.8%), navigation (2.6% to 2.5%), and rail (0.7% to 2.0%). Due to the configuration of the segments, modes, and energy basket, the transportation demand, energy consumption, and GHG emissions grow in a coupled manner in the baseline scenario.

Mitigation measures.

The mitigation analysis consisted of designing a scenario that would allow covering the demand for cargo and passengers with the least amount of GHG emissions, pursuing the decarbonization of the sector by 2050. According to the results, multimodality is essential to increase transportation efficiency, recognizing that different alternatives have a place in a decarbonization scenario because they can act in a complementary manner (e.g., train-river-road in interurban cargo and subway-walking or bus-bicycle-walking in urban passenger transportation). The second factor for reducing GHG emissions is to take advantage of the new technologies and low-emission energy sources to meet the requirements of the different transportation users in terms of autonomy and level of activity.

In urban passenger transportation, the growth of walking and cycling trips was assessed, maintaining public transportation as the main mode in urban centers but combining buses with other technologies for collective and mass transportation, such as urban trains, subways, streetcars, and cables. In interurban passenger transportation, a combination of air travel, trains, navigation, and road modes was analyzed. In this case, the results of previous studies at the national level were considered, which indicate that it is possible to increase the participation of navigation and trains and that these are characterized by a lower carbon intensity for short interurban trips compared to other modes such as aviation. In this way, an "ideal" scenario for minimizing GHG emissions was configured. In 2050, 40% of passenger transportation demand is covered by trains (urban and interurban), cables, and subways; followed by buses (20%); light vehicles (20%); walking and cycling (15%); and the remaining proportion between aviation and navigation. In cargo transportation, trains cover 42% of the demand, followed by trucks (25%), light vehicles (18%), navigation (15%), and national aviation covering the rest. The entry times for the new technologies were considered according to international literature, and a gradual change from the yeas 2026 to 2050 was considered. The modeling did not include the possible additional time needed for new technologies to become ready in the country.

The mitigation scenario implies drastic changes in the energy basket. In 2050, electricity becomes the dominant source, representing 62% of the basket in passenger transportation and 84% of cargo transportation. The passenger segment is followed by advanced biofuels (18%), hydrogen (16%), and fossil fuels (2%); while the cargo segment, is followed by hydrogen (9.3%), advanced biofuels (5.3%), and fossil fuels (2%).

Valuation of the measures.

In terms of costs, the mitigation scenario is very favorable. The savings in energy consumption derived from having much more efficient transportation systems are the main advantage, and these surpass the higher investments represented by some of the new technologies. Since transportation has been characterized as the main energy-consuming sector in the country, this would have implications for the entire national energy system. Transportation energy demand in the mitigation scenario is 40% of the demand estimated in the baseline scenario.

The mitigation scenario generates savings ranging from 133,500 to 573,600 million dollars over the period of 2020-2050 depending on the discount rate used for the assessment (3.1% - 9.0%). These savings are related to investment, operation, and maintenance costs of new technologies plus the energy consumption.

The transportation mitigation portfolio allows for a reduction of 894 million tons of CO_2e over the entire analysis period, which is equivalent to mitigating 40% of the projected emissions in the baseline and 99% of the emissions in 2050.

In addition to the reduction in GHG emissions, the mitigation scenario generates co-benefits of 58,300 to 69,300 million dollars by 2050. Health benefits from increasing physical activity (walking and cycling) represent 45% of the co-benefits, traffic congestion reduction 39%, accident reduction 12%, air quality improvements 3.4%, and noise reduction 0.4% of the net co-benefits.

The mitigation scenario implies net benefits of up to 237,000 million dollars per year. Most of this is explained by the savings in investment, operation, technology maintenance, and energy costs. Co-benefits contribute 34% of the total benefits and SCC savings an additional 0.5%.

Key Messages

The following messages stand out from the analysis:

i) The mitigation portfolio analyzed in this exercise shows that a commitment to more efficient modal distribution and less carbon-intensive technologies and energy sources would allow for a significant reduction in energy consumption in the transportation sector. Since transportation has been characterized as the main energy-consuming sector, this would have implications for the entire national energy system. Under the mitigation scenario, the energy demand in 2050 in the mitigation scenario is 40% of the demand of the reference scenario.

ii) For the new technologies (e.g., electric fleet and hydrogen technologies), a reduction in investment costs is projected in the coming decades, making them competitive with the conventional options in several cases. These advantages are not evident in short-term analyses and therefore these possibilities tend to be left out.

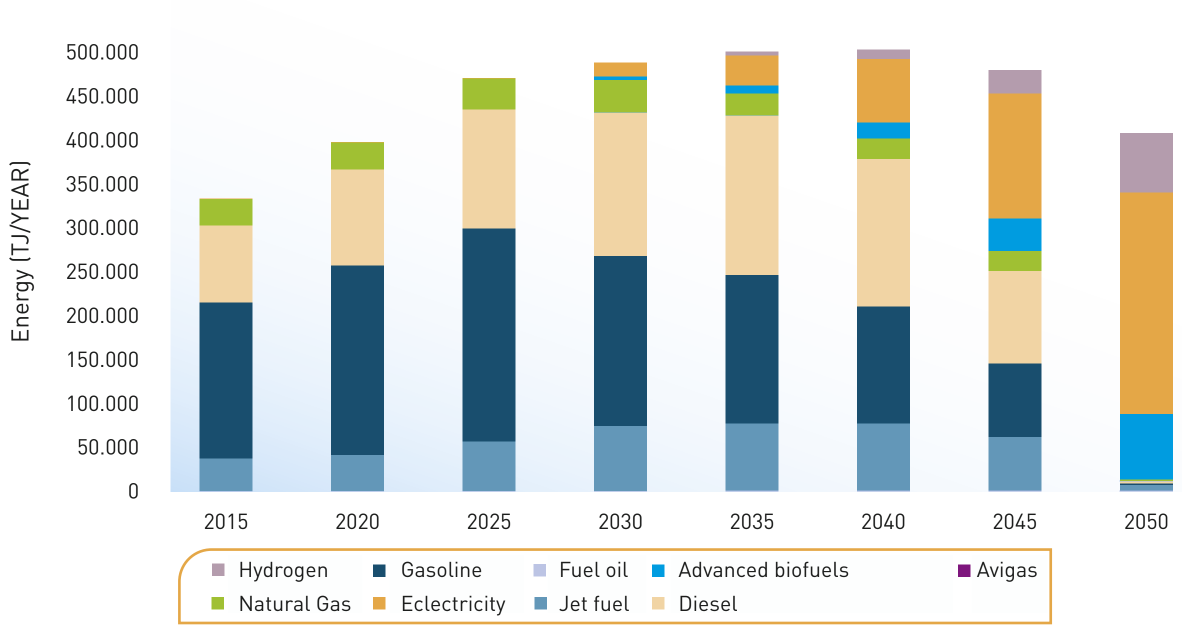
iii) There are additional costs in areas such as production, marketing, and services associated with new technologies; however, these factors in turn are recognized in the literature for their potential co-benefits in terms of the development of new industries and job creation.

iv) The infrastructure costs were not included in the comparison of the scenarios. To maintain the status quo with the predominant road mode, as well as to achieve greater participation of different segments and modes, investments are required for the creation, operation, and maintenance of the infrastructure. It is important to evaluate the costs of both the baseline and the mitigation scenario in future studies for the decarbonization of transportation in Colombia.

v) Adoption times for new technologies can take decades, for that reason, it is not clear the benefit of going through a set of transition technologies and energy sources before implementing those corresponding to a decarbonization scenario. Different studies at the international level support that the transition technologies and energies could generate greater dependence on fossil fuels in the long term, thus adding barriers to the decarbonization of the sectors. Given that the selection of technologies and energy sources for decarbonization in each of the final energy consumption sectors will have to be consistent with an optimized portfolio for the entire national economy, and not only for transportation, it is also necessary to better understand how betting on transitional energy sources such as natural gas (Law 2128 of 2021) or the use of conventional biofuel blends can contribute to the decarbonization of the economy.

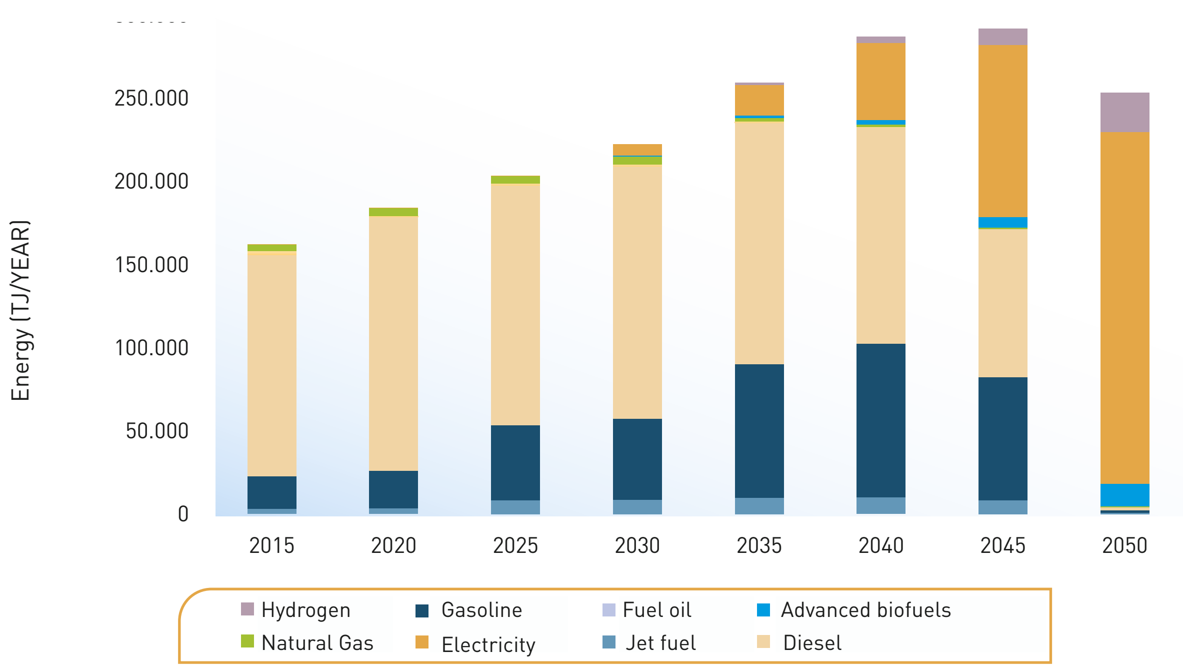
Figure 6 and Figure 7 present the results for the energy demand of the passenger and cargo transportation sectors, respectively. Table 3 summarizes the incremental costs in the scenarios assessed. As can be seen, even without including the savings from avoided carbon emission damages, the assessed measures already represent economic savings for society (negative cost values).

Figure 6. *Energy - Energy basket in the passenger transportation mitigation scenario.*



Source: Own design.*Avigas: aviation fuel.

Figure 7. *Energy basket in the mitigation scenario for cargo transportation.*



Source: Own design.

Table 3. Incremental costs between the mitigation scenario and the baseline: investment, operation, maintenance, and energy.*

	Segment	Passenger Transportation			Cargo Transportation			Transportation total		
	Discount rate	9.0 %	6.4 %	3.1 %	9.0 %	6.4 %	3.1 %	9.0 %	6.4 %	3.1 %
Cost Baseline Scenario	Thousands of millions of dollars	832	1,157	1,946	255	361	623	1,087	1,518	2,569
Cost Mitigation Scenario	Thousands of millions of dollars	725	959	1,485	229	312	510	954	1,271	1,995
Incremental cost (mitigation - baseline)	Thousands of millions of dollars	-107	-199	-461	-27	-49	-113	-134	-247	-574
CO_2e emissions reduced	Millions of tons	579.1			315.3			894.4		
Cost effectiveness	USD/t CO2e	-185	-343	-796	-84	-155	-357	-149	-276	-641

*Excluding the social cost of carbon

IV. Waste and wastewater management

This study focused on the management of municipal solid waste and industrial wastewater. In the reference scenario, the predominant GHG emissions are those generated by the final disposal of municipal solid waste (39.4% in 2050) and by industrial wastewater management (50.8% in 2050). 71.6% of industrial wastewater emissions come from starch, organic chemicals, and other food subsectors.

A mitigation scenario was designed to meet the needs of materials management and waste treatment (solid and wastewater) with the lowest possible level of GHG emissions.

Mitigation measures.

For the household solid waste, the impact of anaerobic digestion of all the food and garden waste and subsequent composting of the biosolids obtained from digestion for their use as fertilizer was assessed. This action was complemented by recycling 70% of the paper sent to final disposal sites. The incineration with energy recovery of the entire diaper fraction of household solid waste and the remaining 30% of the paper was also evaluated.

The anaerobic digestion plants proposed for the utilization of the organic fraction of municipal waste could evolve in the future towards the concept of biorefineries, where, in addition, produce not only fertilizers and biogas for energy production, it is also possible to obtain products such as fuels, plastics, synthetic materials and supplies for the chemical industry. Biorefineries could also include wastewater treatment systems and the utilization of the sludge generated. This biorefinery concept requires the maturity of the technologies used, most of which are still in the pilot research and development or at a small-scale demonstration stage, and there are challenges regarding the financing of the technological development to reach the industrial scale.

The mitigation scenario assessed for household solid waste allows for a reduction of 49% of GHG emissions in 2030, 83% of emissions in 2050, and 52% of cumulative CO_2e emissions between 2015 and 2050 compared to baseline emissions. For the wastewater treatment and disposal subsector, the reduction is 58% of emissions in 2050 and 45% of cumulative emissions between 2015 and 2050.

The mitigation scenario assessed for household solid waste allows to reduce 49% of GHG emissions in 2030, 83% of emissions in 2050, and 52% of cumulative CO_2e emissions between 2015 and 2050 compared to baseline emissions. For the wastewater treatment and disposal subsector, the reduction is 58% of emissions in 2050 and 45% of cumulative emissions between 2015 and 2050.

In the mitigation scenario, GHG emissions continue to be present in 2050. Although not all emission sources were impacted by the proposed measures, the subsectors in which the measures were implemented still present a gap to achieving carbon neutrality, due to GHG leakage in the systems and the use of fossil fuels in the processes. To achieve carbon neutrality in the sector, it can be considered, on the one hand, the savings in emissions attributed to the surpluses in energy production and the heat from the proposed anaerobic digestion and incineration systems and, on the other hand, the emissions compensation in other sectors such as the agricultural sector. Similarly, when considering a tendency to increase the treatment of domestic wastewater, it would be necessary to consider systems for using the resulting sludge to reduce GHG emissions and contribute to supplying the energy required for the treatment process.

Furthermore, although the proposals would achieve mitigation of emissions from the detour of organic waste of the final disposal sites, it is important to consider that the waste would be managed through other alternatives only beginning in 2025 and that the final disposal sites will continue to emit GHGs produced by the anaerobic decomposition of waste disposed of in previous years. For this reason, in addition to the mitigation measures proposed for waste generated since 2025, it is recommended to consider the implementation of systems to capture and burn or use biogas at the final disposal sites during their remaining operational and closure period.

Assessment of the measures.

The results of the costs of the mitigation measures show for all cases a higher cost than the costs of waste management in the baseline. The anaerobic digestion of solid waste proved to be the measure with the highest incremental costs (between 3,200 and 7,000 million dollars depending on the discount rate), but it is also the measure with the highest emissions mitigation among the proposed solid waste management options. This is due to the high capital costs required at the start-up of the measure, which utilizes all of the food and yard waste, which is the main source of emissions in the solid waste sub-sector. It should be noted that the measures proposed for the use of solid waste in the mitigation scenario are being compared with final disposal in sanitary landfills, which is one of the lowest-cost alternatives for waste management. The incremental cost of the incineration scenario is between 120 and 390 million dollars, and that of recycling is between 146 and 307 million dollars.

Regarding the use of industrial wastewater sludge, the anaerobic digestion scenario showed the highest GHG emission abatement of all the proposed measures, and the high mitigation potential compensates for the high capital cost that must be invested at the beginning of the implementation of the measure. In this case, the incremental cost was estimated to be between 714 and 1,600 million dollars.

For the waste sector, the co-benefits assessed include the sale of recycled materials and fertilizers, the potential for electricity production, and SCC. Within the net co-benefits of the measures, SCC excels in the anaerobic digestion of waste and sludge. In the case of recycling, the greatest co-benefit is provided by selling paper to the industry, allowing to obtain money savings from implementing the measure. The co-benefit associated with the contribution of electricity to the grid represents a significant percentage, especially in the case of incineration with energy recovery. When considering the co-benefits in the net costs of the mitigation measures, a significant reduction in the abatement costs per ton is generated; these are reduced between 44% and 66% compared to the abatement costs without considering the co-benefits. The mitigation scenario for the entire waste sector (solid waste and wastewater) considering the co-benefits results in a marginal abatement cost between 5.5 and 4.7 dollars per ton, depending on the discount rate used.

KEY MESSAGES

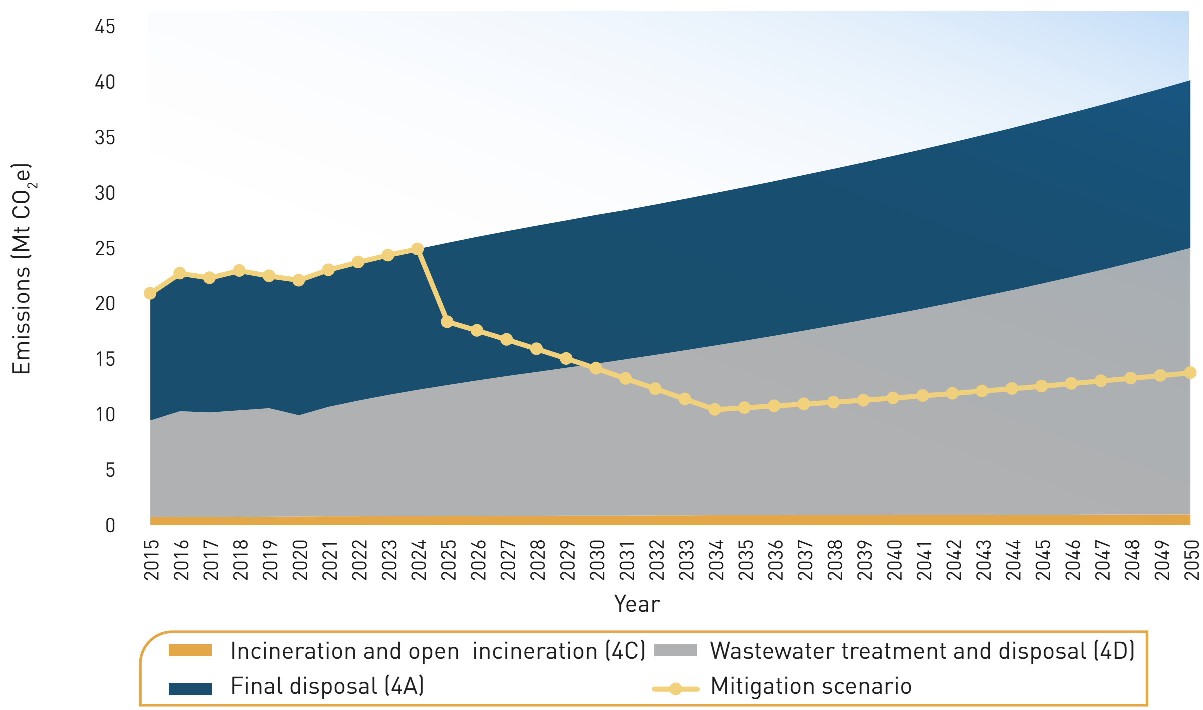
i) One of the main challenges for the implementation of measures in the country continues to be the separation at the source and the differentiated recollection of waste. Without this factor, it will not be possible to generate better waste management alternatives. The speed of implementation of the proposed measures depends on the one hand, on the time required to establish the differentiated collection scheme, and, on the other hand, on the time required for the installation and start-up of the technologies.

ii) Other benefits were not considered in the analysis but could complement it. These are related to impacts on soil and water bodies due to the disposal of waste in final disposal sites, impacts on human health and quality of life with factors such as odors, noise, perception of the environment, impacts on air quality, and disruption of land use, among others.

iii) Waste is the only sector evaluated in this study where the path toward carbon neutrality results in positive net costs. Although the co-benefits typically considered for the sector were quantified, other benefits could complement the analysis of net costs derived from the GHG emissions mitigation trajectory in waste management. Additional benefits generated by the measures and that could be included in the cost analysis involve greater efficiency in the use of materials by reincorporating them into the production chains (additional materials to those evaluated in this study); lower environmental impacts on soil and water bodies due to better waste management; lower impacts on human health due to factors such as exposure to odors and proliferation of disease vectors due to inadequate waste management; better environmental quality of the surroundings; lower impacts on air quality and therefore on public health; and less disruption of land use. These co-benefits imply gains for society, and their inclusion in subsequent analyses will lead to more favorable economic results of the mitigation scenarios for the waste management sector.

Figure 8 presents the modeled emission scenarios for the waste sector and Table 4 shows a summary of the incremental costs among the modeled scenarios.

Figure 8. *Waste sector mitigation scenario 2015- 2050.*



Source: Own design.

Table 4. *Incremental costs between the mitigation scenario and the baseline and quantification of co-benefits for the proposed mitigation measures.*

	Segment	Anaerobic digestion solid waste			Incineration			Recycling		
	Discount rate	9.0 %	6.4 %	3.1 %	9.0 %	6.4 %	3.1 %	9.0 %	6.4 %	3.1 %
Incremental cost (mitigation - baseline)	Millions of dollars	3,205	4,402	7,003	118.3	194.3	388.4	146.1	198.5	307.3
Co-benefits*	Millions of dollars	611.0	1,035	2,136	58.5	99.6	206.6	270.5	456.8	939.0
CO_2e emissions reduced	Millions of tons		194.2			19.9			38,5	
Cost efficiency	Dollars/t CO2e	13.35	17.34	25.06	3.00	4.76	9.14	-5.28	-8.92	-18.33

	Segment	Anaerobic digestion sludge		
	Discount rate	9.0 %	6.4 %	3.1 %
Incremental cost (mitigation - baseline)	Millions of dollars	714.3	979.9	1,555.8
Co-benefits *	Millions of dollars	88.5	145.9	293.5
CO_2e emissions reduced	Millions of tons		247,5	
Cost efficiency	Dollars /t CO2e	2.53	3.37	5.10

* Excluding the social cost of carbon

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