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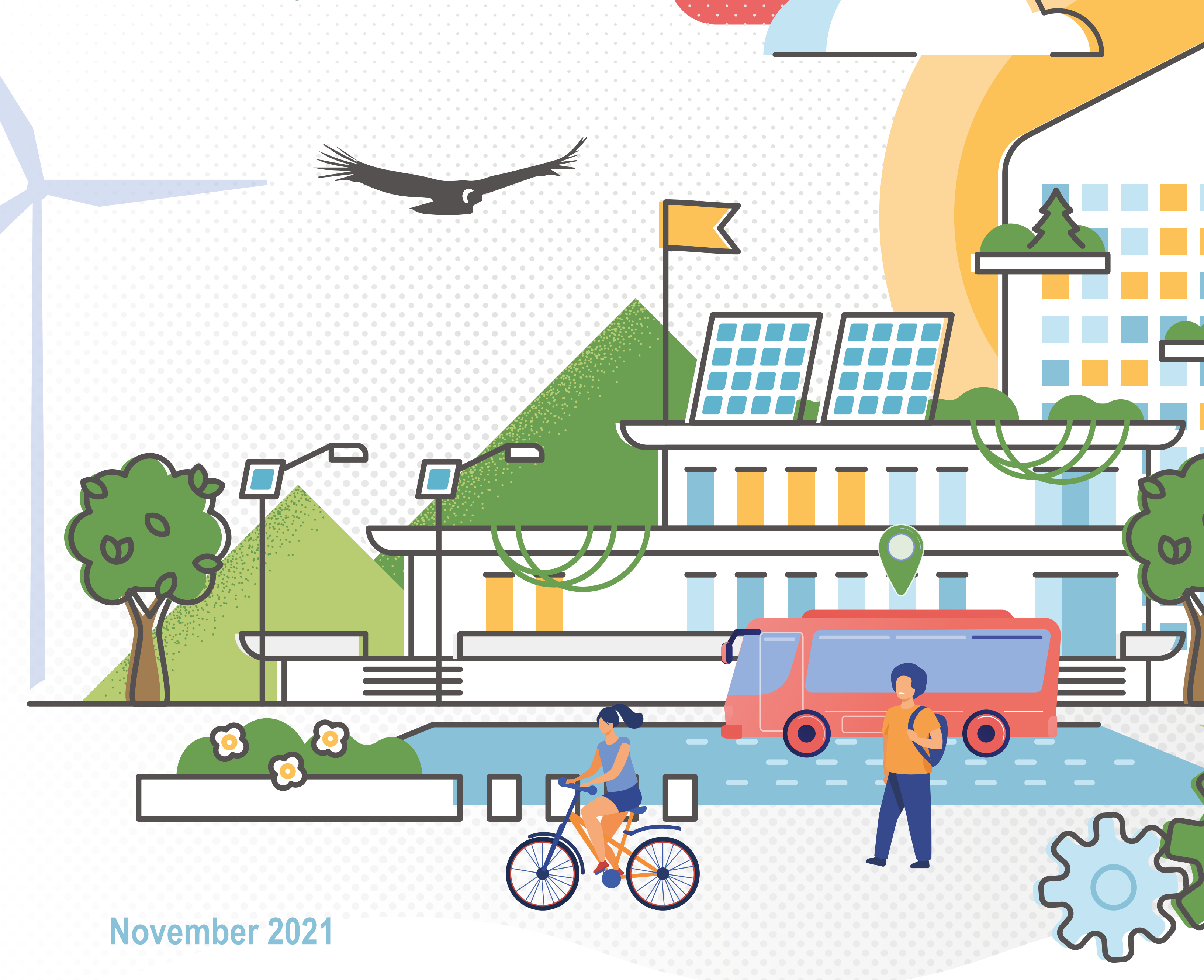
Options to Achieve Carbon Neutrality in Chile:

An Assessment Under Uncertainty



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Preface

Climate change is undoubtedly the greatest challenge we face as a generation and confronting it with determination and a sense of urgency is, for our government, an ethical, social and economic imperative.

The recent report of the Intergovernmental Panel on Climate Change (IPCC) clearly establishes the depth of the climate change impacts that are appearing with increasing intensity and frequency throughout the world, and Chile is no exception. The science is clear and forceful on the urgent need to reach a universal goal for emissions reduction, on which all countries, companies and non-state actors must work: carbon neutrality and resilience to climate change by 2050.

In this respect, in April 2020 Chile submitted to the United Nations its updated Nationally Determined Contribution (NDC) which has been internationally recognized for the significant increase in its ambition.

Chile's new NDC defines an indicator and an absolute, clear and unconditional target of 95 million tonnes equivalent by 2030. It sets peak emissions for 2025 and a maximum carbon budget, between 2020-30, of no more than 1.1 billion tonnes CO_2eq.

I would especially like to highlight the incorporation, for the first time in an NDC, of a social pillar that permeates all its commitments, establishing a fair transition process for decarbonization, together with the contribution of each commitment to the United Nations Sustainable Development Goals, leading to an improved quality of life for Chileans.

To move in this direction and meet our commitments, the government of President Piñera submitted the draft Framework Law on Climate Change to Congress for fast tracking. This law includes reaching the goal of carbon neutrality and resilience for Chile by no later than 2050.

The bill, which was unanimously approved for discussion and is being fast tracked in the Senate, will give Chile a long-term institutional framework that goes beyond the present government in guiding the actions of the State and private sector, marking a clear and decisive path towards carbon neutrality and resilience for the country by 2050.

Chile set the goal of carbon neutrality and of the NDC after intense science-based work with solid support from the Scientific Committee on Climate Change. The transformations needed to achieve these goals require tools and instruments which give us the means to implement actions in all sectors of the economy and in all regions and municipalities of the country. For this reason, we are developing with broad participation our Long-Term Climate Strategy, which we will present at COP26, and which will set the sectoral carbon-budget targets based on the national target presented in the NDC.

The publication *Options to achieve carbon neutrality in Chile* confirms the robustness of our goals and shows us that faced by different scenarios we need to consider strengthening sectoral mitigation actions in order to reduce uncertainty in meeting the set goals. With analysis of more than 1,000 uncertainty scenarios, this study presents us with a challenge, and as such is critical to the development and implementation of the future sectoral mitigation plans proposed in the draft Framework Law on Climate Change.

Achieving carbon neutrality by 2050 will greatly benefit Chile. Although meeting this objective requires an investment in the order of US$50 billion, it will produce direct generation and operational savings, resulting in net benefits to the country in excess of US$30 billion and potentially leading to a 4.4% increase in gross domestic product (GDP) by 2050.

The study confirms this evaluation and shows us that, if we strengthen sectoral actions, these net economic benefits can increase by an additional 0.8% of GDP by 2050.

Thanks to an integrated crosscutting effort that transcends political colors, we are moving forward decisively with clear goals based on science and with a long-term view that gives us the means to make sustainable development the basis for our country's progress.

It is time to debunk the myth that climate action and environmental protection are contrary to economic growth.

Due to its characteristics and natural conditions, Chile can make a commitment to green, sustainable development, harmonious with nature, without sacrificing the country's potential for growth and progress.

Carolina Schmidt
Minister of the Environment of Chile

Prologue

Since March 2020, the COVID-19 pandemic has taken an enormous human, economic and social toll in Chile. Thousands of informal workers have been affected by lockdowns and quarantines, especially impacting the poorest households. In addition, almost 400,000 people have fallen into extreme poverty, doubling the incidence in Chile and aggravating inequality indices.

As we recover from the pandemic, we cannot forget that we are still facing another similar threat, the climate crisis, which also mostly affects poor and vulnerable households. For example, informal workers are more exposed to heat waves because they are more likely to work outdoors.

Climate change is also responsible for melting glaciers, more frequent droughts, lower yields from agricultural land, rising sea levels threatening coastal cities, and destruction of biodiversity, among many other effects. And there is no doubt that all this is already having serious consequences for the economy and people, for example on the income of workers who depend on tourism.

Science clearly shows that to end the climate crisis, it is necessary to reach net-zero carbon emissions by 2050. Achieving this goal should not be seen as a sacrifice but as an opportunity for green growth. This is why climate action is one of the pillars of Vision 2025, the IDB Group's pathway for achieving inclusive and sustainable growth.

The latest IDB Macroeconomic Outlook for Latin America and the Caribbean reveals how a move towards carbon neutrality could create 15 million net new jobs and 1% additional growth in the region by 2030. Indeed, it is already well known that renewable energy is the cheapest in the world, and electric vehicles are or will soon be cheaper than gasoline and diesel vehicles.

While the benefits are clear, the road to net-zero emissions is fraught with obstacles. Some existing regulations may hold back adoption of zero-carbon technologies by the private sector, requiring reforms to facilitate this. And as fossil fuels are replaced by renewables, there are certain to be industries that will find it difficult to adapt.

Along this path, help from governments is essential. Governments are responsible for implementing regulatory reforms and ensuring that meeting environmental targets does not create larger social and economic problems. Key to this is a long-term climate strategy that can promote a multi-sectoral dialogue, anticipate and overcome barriers to achieving a carbon-neutral economy, and design an action plan to remove these barriers and ensure a fair, inclusive and orderly transition.

This study shows how governments can use scientific evidence and input from a wide range of stakeholders to form the basis of the design of long-term climate strategies. The report brings together the inputs of more than 140 specialists consulted in virtual workshops. Experts participated from fields such as energy, transportation, industrial processes, waste management, agriculture and forestry coming from government agencies, universities, think tanks, companies and international organizations. The work also draws on the expertise of the Universidad de Chile and the Pontificia Universidad Católica de Chile, as well as the experience of the RAND Corporation, to simulate different paths to achieving the carbon neutrality target by 2050.

The analysis shows that achieving carbon neutrality is not only technically possible but also beneficial for Chile. The study also anticipates some points where the government's current plans fall short of this goal. Lastly, it suggests options to enhance these plans, to make reaching net-zero emissions by 2050 more certain.

Chile is at the forefront of this climate action agenda. After hosting COP25, it was one of the first countries in the world to officially recognize the goal of achieving net-zero emissions by 2050 in its nationally determined contribution. We remain committed to supporting the country along its path to implementation of this goal, which will also give us the necessary experience to help other countries in the region follow the same path.

María Florencia Attademo-Hirt
General Manager, Southern Cone Countries, and IDB Group Representative in Chile

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This document was edited by Claudia Pasquetti and translated into English by Gabriel Dobson. Graphic design by Sahadia Yusari.

Executive summary

The Chilean government aims to achieve become greenhouse gas (GHG) neutral by 2050. This goal is set out in its Nationally Determined Contribution (NDC) which the country submitted to the international community under the Paris Agreement (Government of Chile, 2020). The target is aligned with the international efforts required to halt the global average temperature increase of between 1.5ºC and 2ºC (IPCCC, 2018).

The NDC sets emission reduction targets maintaining GHG emissions below 95 $MtCO_2eq$ by 2030, defining 2025 as the deadline for peak emissions, and maintaining the GHG emissions budget below 1,100 $MtCO_2eq$ for the period 2020-30. The climate change framework law and the long-term climate strategy, both under discussion in the country, give sectoral ministers responsibility for investigating and implementing emission reduction measures to meet these targets. Several sectoral emission reduction measures, which would achieve the emission reduction targets in one scenario investigated by the government, are listed on an indicative basis in the NDC – for example, transport electrification, phasing out coal-fired power plants, and reforestation (Box RE1).

Chile's climate ambition gives rise to two major public policy challenges. First, actions are needed in many sectors to meet the carbon-neutrality target. Second, successful achievement of NDC targets depends on a wide range of uncertain factors that will determine the performance and costs of these actions in the future, such as forest fires, cost of low-emission technologies, or growth in electricity demand.

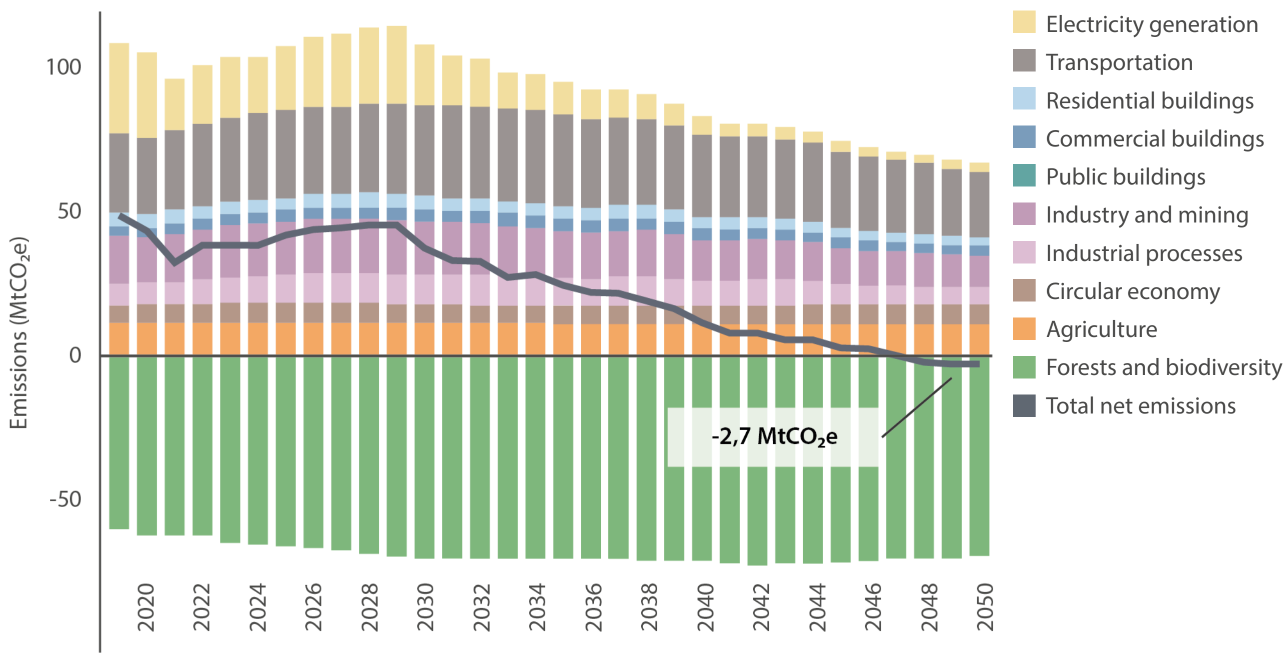
In response to these challenges, this study provides scientific evidence for strengthening public policies aimed at reducing emissions in each sector. The study estimates which sectoral transformations are required to meet the emission reduction targets under a wide range of economic, environmental, and technological scenarios. It then identifies conditions that put compliance with the emission reduction targets at risk. Finally, it evaluates proposals to expand the emission reduction measures, additional to those listed on an indicative basis in the NDC, which can be considered in future sectoral plans for achieving the emission reduction targets with more certainty, including strengthening existing actions and adding others.

The study was conducted in a participatory process, following the *robust decision-making* framework. First, 148 stakeholders were convened from public and private sectors, trade associations, non-governmental organizations (NGOs), academia and international organizations. With their contributions it was possible to generate thematic dialogues to structure the study, obtain suggestions for improvement and recommendations on inclusion of actions additional to those currently proposed.

On this basis, the first model for integrated evaluation of GHG emissions in Chile was developed. This new tool combines existing models and models developed for this project, and covers all sectors of the GHG inventory: energy (power generation, transportation, industry, mining and buildings), industrial processes, circular economy (waste), forests and biodiversity (land use, land use change and forestry) and agriculture. The model also allows an analysis under uncertainty to be made in hundreds of different scenarios.

In a reference scenario, the study confirms that the sectoral transformations set out in the NDC can result in achievement of carbon neutrality by 2050, but finds it may not achieve the 2030 emission reduction targets (Figure RE1). The reference scenario is based on the assumptions that the government used to assess sectoral measures to meet the targets. In that scenario, decreasing emissions in the power sector and increasing carbon sequestration in the forest and biodiversity sector result in slightly negative net emissions in the long term. However, in the medium term, emissions from the electricity sector decrease, but not enough to offset increases in the transportation, buildings, commercial, agriculture, circular economy, industry and mining sectors.

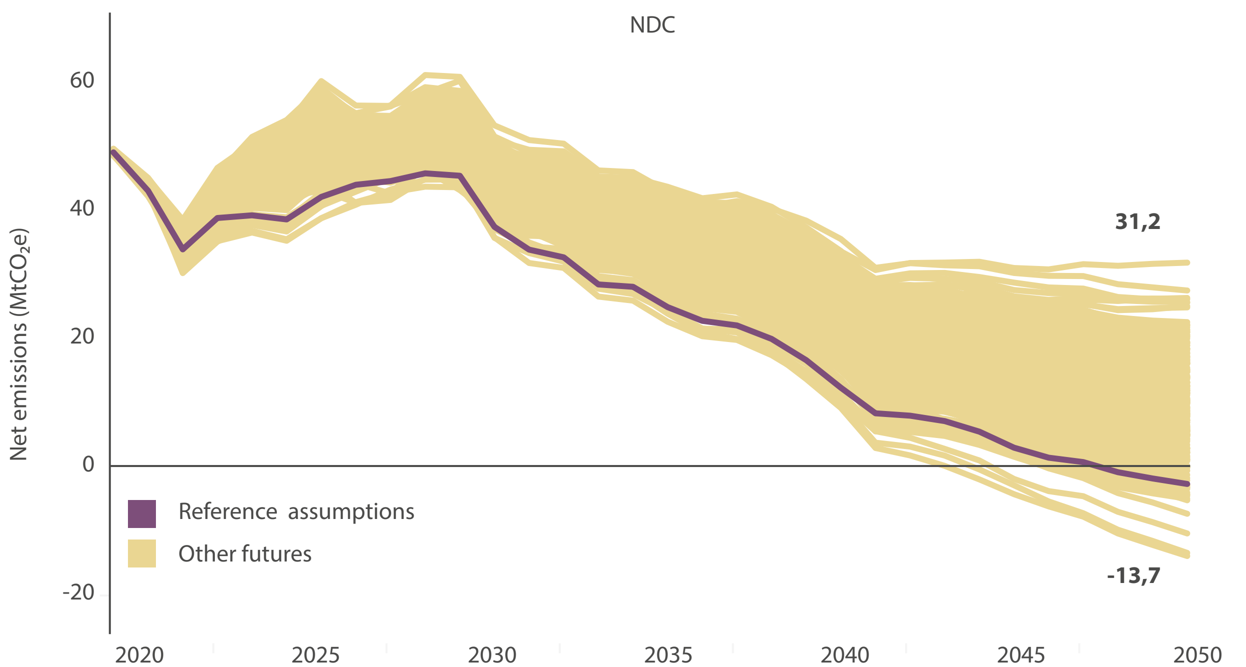
Figure RE1:
Emissions by sector under the NDC strategy, reference scenario.



Source: Prepared by the authors.

Based on the exploration of 1,000 different futures, the study shows that the sectoral measures need to be reinforced to ensure carbon neutrality by 2050 (Figure RE2). The set of futures was developed from dozens of uncertainty factors suggested in the participatory workshops, such as economic (for example, production levels of mining activities), technological (battery costs) and environmental (forest sequestration capacity) factors. Figure RE2 shows how NDC measures performed under each of these futures. Many trajectories end up well above the carbon-neutrality target: 71% of the scenarios presented finish above 5 $MtCO_2eq$.

Figure RE2:
Total net emissions under the NDC strategy in 1,001 futures.



Source: Prepared by the authors.

The study identifies under which conditions the measures fail to achieve net zero emissions by 2050. One of the most determining factors is a low level of forest sequestration combined with low electrification of private transport. If forest clearing or forest fires occur with high frequency, climatic or economic conditions lead to low yields of native forests and plantations, and electric mobility targets are not met, carbon neutrality will probably not be achieved. Other scenarios that fall short of emission neutrality are those that combine a high cost of solar thermal technology, high energy intensive copper production, low electrification of copper mining, and low penetration of hydrogen in freight transport.

Different options were studied to mitigate the identified vulnerabilities. An NDC+ strategy was simulated to consider sectoral measures supplementary to those listed in the NDC (Table RE1). These measures do not represent an official proposal for improvement of the emission-reduction plans from government agencies, rather they are based on some of the ideas of the experts consulted during the participatory process to strengthen sectoral action and achieve compliance with the NDC.

Table RE1:
Sectoral measures in the NDC and additional measures included in NDC.

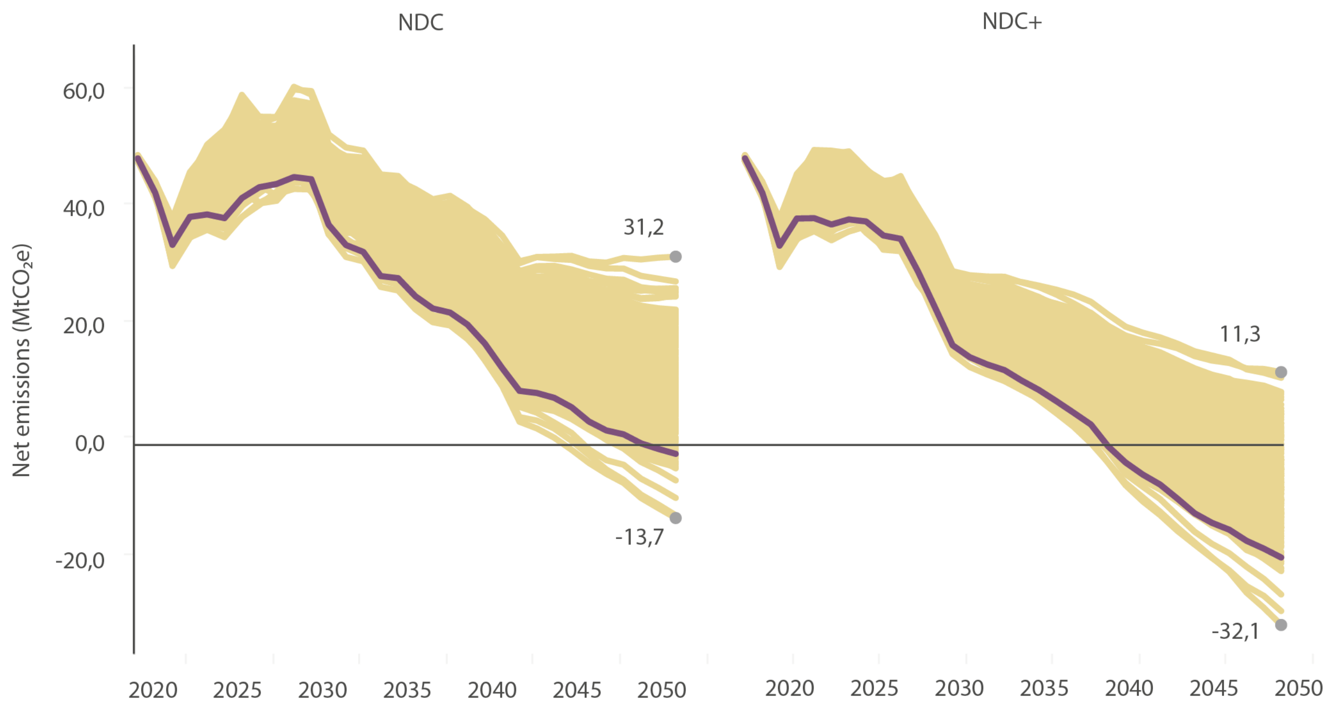
Sector	Sectoral transformation	NDC	NDC+
Power generation	Phasing out of coal-fired power plants.	Phasing out of coal-fired power plants by 2040.	Phasing out of coal-fired power plants by 2030.
	Phasing out of natural gas power plants.	-	Phasing out of natural gas power plants by 2050.
Transportation	Electric mobility.	Private vehicles: 58% by 2050; taxis: 100% by 2040 and 2050; public transport: 100% by 2040.	Private vehicles: 58% by 2050; taxis: 100% by 2040 and 2050; public transport: 100% by 2040.
	Hydrogen.	Freight transport: 85% by 2050; aviation: 0% by 2050.	Freight transport: 85% by 2050; aviation: 10% by 2050.
	Modal shift to public transport.	-	Modal shift to public transport; 10% from private transport by 2050.
	Bicycle.	-	10% from private transport by 2050.
	Telework.	-	10% from private transport by 2050.
Commercial	Electrification of end uses.	70% of demand by 2050.	70% of demand by 2050.
Industry and mining	Solar thermal systems.	33% in miscellaneous industries by 2050; 16% in copper mining by 2050.	46% in miscellaneous industries by 2050; 30% in copper mining by 2050.
	Hydrogen: uses in thermal processes.	3% in miscellaneous industries; 0% in steel industry.	3% in miscellaneous industries; 10% in steel industry (+ 10% biomass).
	Hydrogen: engine use.	37% for opencast mining by 2050; 8% for underground mining by 2050; 12% in miscellaneous industries by 2050; 21% for miscellaneous mines by 2050.	37% for opencast mining by 2050; 8% underground mining by 2050; 12% in miscellaneous industries by 2050; 21% in miscellaneous mines by 2050.
	Electrification of engine use.	88% in miscellaneous industries by 2050; 74% in miscellaneous mines by 2050.	88% in miscellaneous industries by 2050; 74% in miscellaneous mines by 2050.
	Electrification of copper uses.	57% in end use under opencast.	57% in end use under opencast.
Residential	Residential electric heating.	56% in houses by 2050; 70% in apartments by 2050.	72% in houses by 2050 89% in apartments by 2050.
	Electrification for cooking.	36% in houses by 2050; 35% in apartments by 2050.	36% in houses by 2050; 35% in apartments by 2050.
	Thermal solar systems.	52% of domestic hot water (DHW) in houses; 57% DHW in apartments.	80% of DHW in houses; 80% of DHW in apartments.
	Thermal retrofitting.	570,000 to 650,000 houses.	6,197,750 houses.
Industrial processes and product use	Control of hydrofluorocarbons (HFC).	According to the Kigali Amendment.	Increase in HFC regeneration capacity by 2,750 t HFC/year by 2030.
Circular economy	Biogas.	Biogas capture and combustion in 100% of landfills by 2030.	Biogas capture and combustion in 100% of landfills by 2030.
	Sewage treatment.	New sewage treatment plants to cover the 5 most populated cities by 2040.	New sewage treatment plants to cover the 5 most populated cities by 2040.
	New composting plants.	-	60% of organic waste composting by 2050.

Sector	Sectoral transformation	NDC	NDC+
Agriculture	Change in bovine diet.	70% of dairy cows with additive that reduces enteric fermentation by 2037.	70% of dairy cows with additive that reduces enteric fermentation by 2037.
	Biodigesters.	Growth of pig biodigesters in 71% of pig stock by 2040.	Growth of pig biodigesters in 71% of pig stock by 2040.
	Efficient fertilizer use.	Up to 11% reduction of total fertilizer consumption by 2035, considering cereals and seedbeds (20%), for industrial crops and fodder (15%).	Up to 11% reduction of total fertilizer consumption by 2035, considering cereals and seedbeds (20%), for industrial crops and fodder (15%).
	Regenerative agriculture (application of organic amendment).	-	Application of organic amendments to 10% of annual crop area; using organic amendment by 2040, beginning in 2030.
	Change in national diet.	-	Reduction of beef consumption by 2050 (10%).
	Holistic livestock management.	-	10% of grazing cattle from the Los Lagos region by 2039.
Forestry and biodiversity	Forestry management plans.	200,000-hectare increase in area under forest management plans by 2030.	200,000-hectare increase in area under management plans by 2030 and 350,000 by 2050.
	Afforestation.	200,000 hectares forested by 2030.	200,000 hectares forested by 2030 and 500,000 by 2050.
	Decrease in substitution and degradation.	25% reduction of forest degradation by 2030.	25% reduction of forest degradation by 2030.
	Conservation.	-	100,000 addicional hectares of park zones and reserves by 2050; 1,000 hectares of kelp forests under sustainable management by 2030.
	Change in matrix of harvested wood products.	-	10% less paper production, in favor of more sawnwood from 2040.

Source: Prepared by the authors.

The NDC+ strategy meets the carbon-neutrality target in 2050 in a greater number of future scenarios than the measures listed in the NDC (Figure RE3). Eighty-three percent of NDC+ strategy simulations result in net negative or zero emissions by 2050. Furthermore, the NDC+ strategy meets the 2030 emissions reduction target in a significant proportion of the analyzed futures.

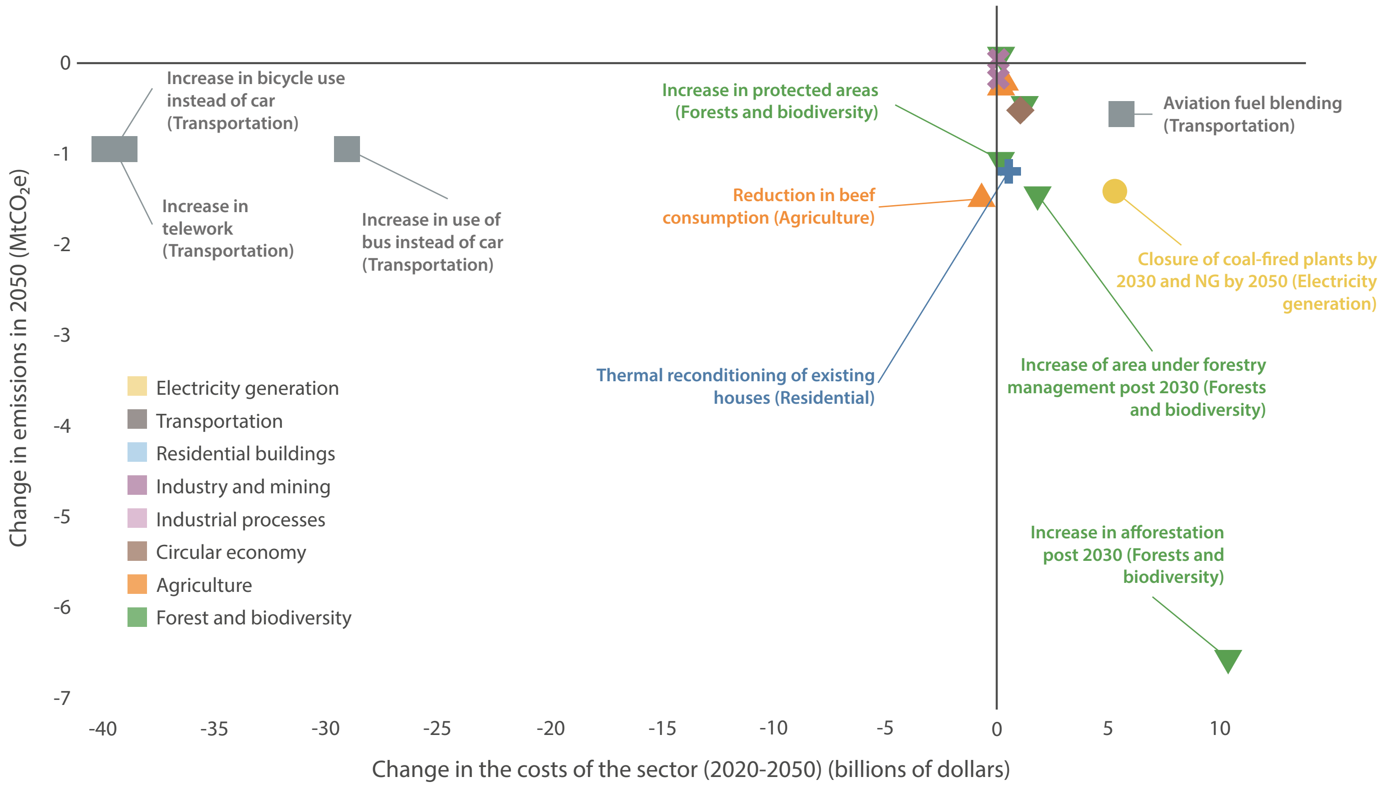
Figure RE3:
Total net emissions for NDC and NDC+ strategies under 1,001 futures.



Source: Prepared by the authors.

The additional measures included in the NDC+ strategy vary in cost and impact on emissions (Figure RE4). Four groups of measures stand out. First, actions that reduce costs and also emissions, such as substitution of private transport by increased use of bicycles, teleworking and public transport. Second, actions with a near-zero cost but with a substantial impact on emissions reduction, such as an increase in protected areas, lower beef consumption, thermal reconditioning of existing housing and an increase in the area under forest management. Third, actions with a higher cost relative to their capacity to reduce emissions by 2050, such as using fuel blending in aviation and bringing forward the timetable for gradual closure of coal-fired power plants. Finally, the fourth group includes actions with high impact on emissions and also high cost, such as increasing afforestation.

Figure RE4:
Impact of additional measures on emissions and costs.



Source: Prepared by the authors.
Note: The cost-impact estimate was calculated individually for each measure. The change in emissions is estimated in $MtCO_2e$ in 2050; the change in costs is estimated in millions of undiscounted dollars.

The analysis suggests opportunities for strengthening the sectoral emission reduction measures. Various measures could cut emissions at zero or negative cost (e.g., telework, non-motorized transport, reduced beef consumption, thermal reconditioning of homes). If they are feasible from a political and institutional point of view, they should be included as a priority. To meet the 2030 reduction target, accelerated retirement of coal-fired power plants can play a key role. In the medium term, what measures can be implemented to ensure that the emissions stay on track depends on how technology costs evolve, the energy intensity of industrial activities, the carbon sequestration capacity of forests, and how successful other actions indicated in the NDC are.

The forest and biodiversity sector is critical to achieving carbon neutrality. By 2050, it must absorb as much carbon as all other sectors combined, or even more. This could be ensured through measures additional to these indicated in the NDC, such as extension of afforestation and forest management measures, along with nature-based solutions. These measures also generate multiple co-benefits (not quantified in this work) but depend on economic incentives and regulations for their implementation.

Implementing the NDC+ strategy would have a positive macroeconomic impact. Annual gross domestic product (GDP) growth rate could increase by 0.06 percentage points above the NDC strategy. This would increase GDP level by 0.8% on average in 2050 relative to the NDC – that is, above the 4.4% gain under the NDC strategy, compared with a situation without NDC, that previous work has documented. The macroeconomic analysis also suggests the need to introduce emission reduction measures gradually to avoid sharp drops in aggregate and sectoral output in activity.

However, the economic analysis presented in this study is limited since only the capital and operating costs associated with each action are considered. It does not include potential economic benefits (for example, reduced environmental pollution, reduced traffic congestion) or social benefits (such as job creation), although other studies in Latin America suggest these could be substantial (Groves et al., 2020, Quirós-Tortós et al., 2021; Saget et al., 2020).

Finally, while this work demonstrates that it is possible and desirable to implement transformations to achieve carbon neutrality, it does not report on the design, effectiveness or implementation times related to any public policies needed to usher such transformations. Further research can inform the design of specific policies.

1
Context and objectives of the study

Chile's Nationally Determined Contribution (NDC) sets the goal of reaching net-zero greenhouse gas (GHG) emissions by 2050 (Government of Chile, 2020). This target is aligned with what scientists have determined needs to be achieved globally to meet the most ambitious goal of the Paris Agreement: limit temperature increase to as close to 1.5°C as possible (IPCC, 2018). In addition, international evidence suggests that moving towards net-zero emissions can bring economic and social benefits, such as increasing economic growth and job creation (Vogt-Schilb, 2021).

Long-term Climate Strategies set out a vision of a carbon-neutral economy, facilitate identification of obstacles along the way, and make known the design of government plans to move towards net-zero emissions (IDB and DDPLAC, 2019). Chile's Long-Term Climate Strategy proposes sectoral targets and indicators to facilitate this process (Government of Chile, 2021). The Strategy is formulated by the Ministry of Environment, in close collaboration with other sectoral ministries and stakeholders in order to ensure its feasibility, relevance and acceptance.

There are several challenges on the pathway to carbon neutrality. One is that achieving net-zero emissions requires the participation and coordination of a wide range of sectors of the economy, which may have different views and priorities. Another is that a 2050 strategy necessarily faces deep uncertainties that could jeopardize compliance with any long-term plan.

In this context, the Chilean government sought support from the Inter-American Development Bank (IADB) to analyze, in collaboration with representatives of the most GHG-emitting sectors, the uncertainties and risks associated with the current strategy, and to propose options for increasing its robustness. Pontificia Universidad Católica de Chile, Universidad de Chile, RAND Corporación and Tecnológico de Monterrey participated in the study.

The study followed the robust decision-making method. The purpose of robust decision making is to implement policies that satisfy the decision makers' objectives under multiple possible futures, rather than making an optimal decision that is valid under only one estimate of the future (Lempert and Kalra, 2011). Instead of using models and data to evaluate policies under a single set of assumptions, computational experiments are run considering hundreds or thousands of different sets of assumptions to describe how plans perform under many plausible conditions. In the case of long-term climate strategies, the method evaluates under what conditions emission reduction strategies have more benefits than costs, and identifies which sectoral transformations are most important for reaching the goal of net-zero emissions (Groves et al., 2020, Quirós-Tortós et al., 2021).

The analysis consisted of several stages. First, a participatory process was held in conjunction with key stakeholders from civil society, private sector, public sector, academia and multilateral agencies, to construct a decision-making framework. This framework highlights criteria for evaluating the Long-Term Climate Strategy, lists actions that can be taken in each sector to achieve the objectives pursued, lists uncertainties that may affect the capacity of the actions to meet those objectives, and compiles existing data and models to quantify the link between these criteria, actions, and uncertainties. Chapter 2 provides a breakdown of GHG emission sources by sector in Chile—that is, energy generation and transformation, transportation, industry and mining, forestry, agriculture and livestock, and waste—and describes the participatory process with representatives from these sectors.

Next, an integrated model for evaluating future GHG emissions was developed, considering the range of transformations required in each of these sectors and their macroeconomic impact. This model, described in Chapter 3, explores different assumptions about the future which reflect the concerns of these stakeholders, and proposes inputs for a more robust carbon-neutrality strategy for Chile. Chapter 4 gives the results of the analysis. The last chapter sets out conclusions and policy recommendations.

2
Greenhouse gas emissions in Chile: sectoral view

In the national greenhouse gas (GHG) emissions inventory, emissions are broken down into five sectors: i) energy (which includes electricity generation, energy use in buildings, and energy use in transportation); ii) agriculture; iii) land use, land-use change and forestry; iv) waste; and v) industrial processes.

In this report, the word "sector" refers to these categories which are used to analyze the sources of GHG emissions. Each GHG emissions sector corresponds to different sectoral ministries or different sectors of economic activity in Chile. For example, the Ministry of Public Works is involved with transportation and electricity generation, which are reflected under these headings in the emissions inventory, and tourism-related economic activities generate emissions in transportation and buildings.

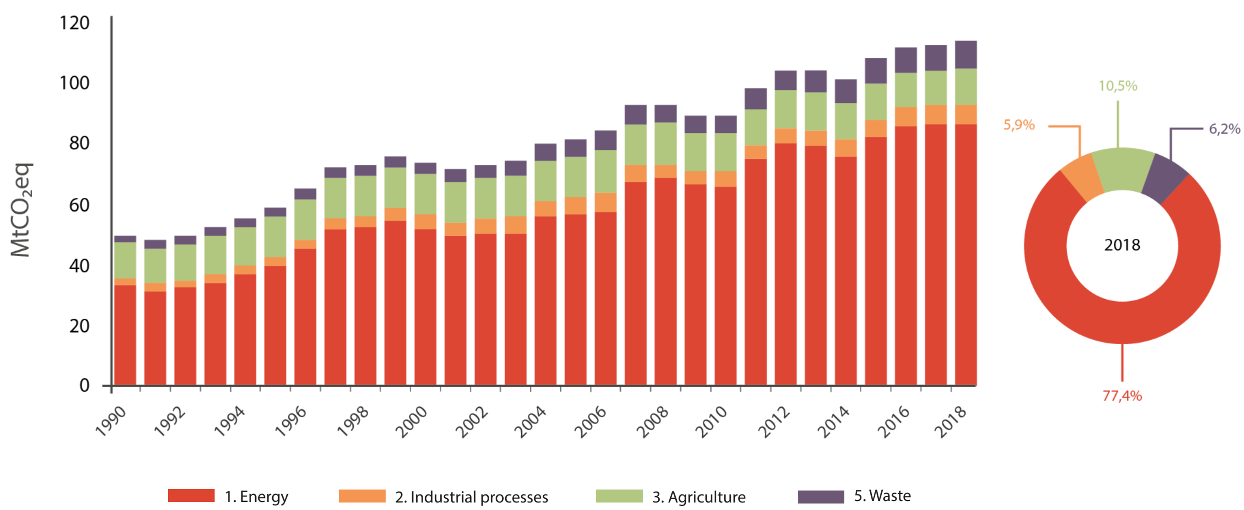
Historical and recent emissions by sector are presented next, followed by the process the team used to collect inputs from stakeholders in each sector.

2.1 Greenhouse gas emissions by sector in Chile

Chile's main source of GHG emissions is the burning of fossil fuels for energy generation. Figure 2.1 shows emissions by sector, omitting for the moment the land use, land use change and forestry sector (see below). The energy sector is the leading national GHG emitter, accounting for 77.4% of total GHG emissions in 2018.

The most important source of emissions in this sector is electricity generation with 29%, followed by 25% transportation, 14% manufacturing industries and construction, and finally 7% the rest of the subsectors. The energy sector is followed by agriculture (10.5%), waste (6.2%), and industrial processes (5.9%).

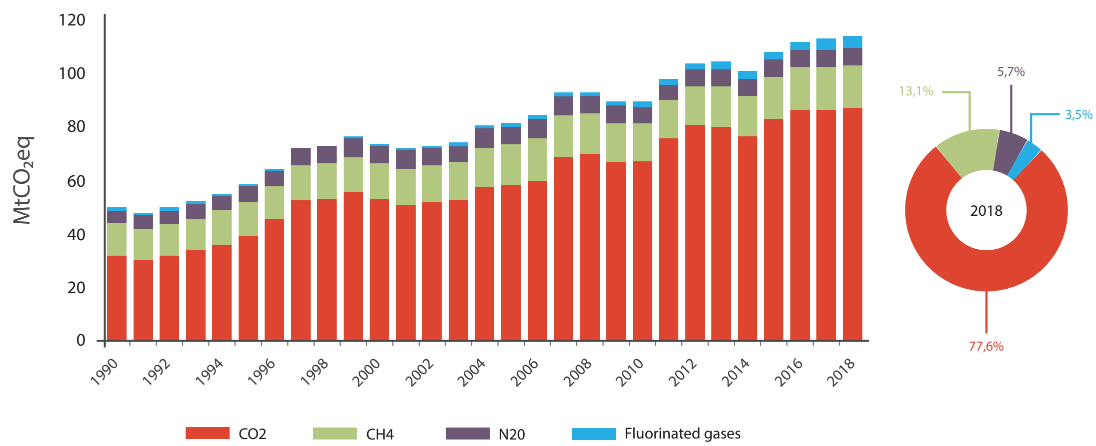
Figure 2.1:
Greenhouse gas emissions by sector, 1990-2018.



Source: Ministry of Environment (2018).

The main GHG is carbon dioxide (CO_2). Figure 2.2 shows GHG emissions by gas type, again omitting captures from the land use, land use change and forestry sector. The leading GHG is CO_2 with 77.6% of emissions in 2018, followed by methane (CH_4) (13.1%), nitrous oxide (N_2O) (5.7%) and fluorinated gases (3.5%). CO_2 emissions come mainly from the energy and land use, land use change and forestry sectors, while CH_4 and N_2O are concentrated in agriculture; fluorinated gases are found in industrial processes, and CH_4 in waste. This distribution of emissions is relevant when considering the duration (half-life) in the atmosphere of the various GHGs, which can vary from a few years (CH_4) to hundreds of years (CO_2 and N_2O), so when thinking about reducing emissions in the medium term, controlling emissions of short-lived climate pollutants becomes significant.

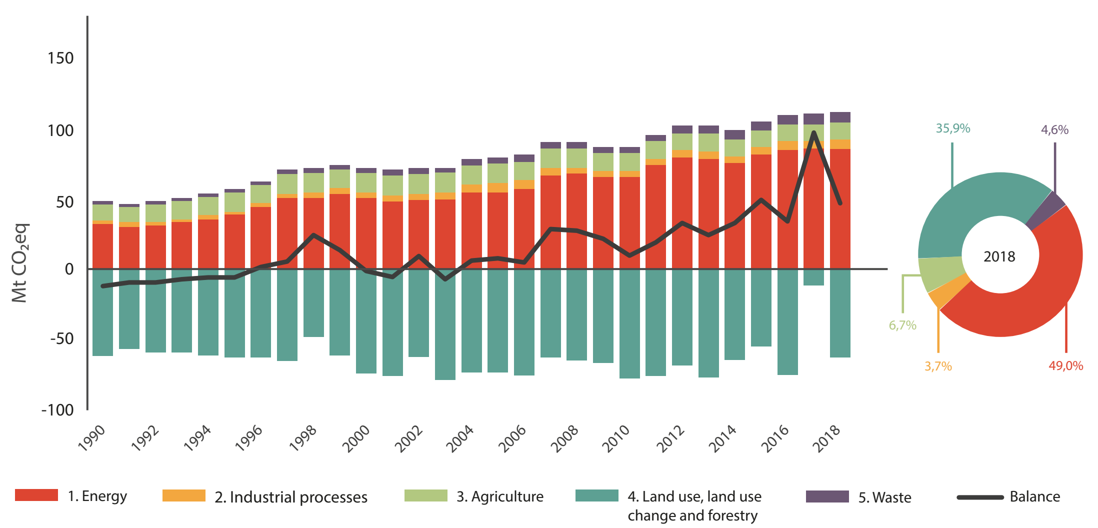
Figure 2.2:
Greenhouse gas emissions by gas type, 1990-2018.



Source: Ministry of Environment (2018).

Finally, Chile's GHG emissions are largely offset by absorptions in natural carbon sinks (Figure 2.3). The land use, land-use change and forestry sector produces negative net emissions, thanks to positive reforestation rates. In 2018 the sector accounted for -36.3% of the GHG emissions balance. This is unusual and could change in the future; in fact, in 2017 sector emissions were 63 $MtCO_2eq$ higher than in 2016, result of a very intense forest fire season. Properly managed, the sector represents a great opportunity for achieving carbon neutrality. However, it can be severely impacted by uncertain climatic and economic stressors; for example, a higher incidence of forest fires resulting from changes in temperature and precipitation patterns.

Figure 2.3:
Greenhouse gas emissions and sinks balance, 1990-2018.



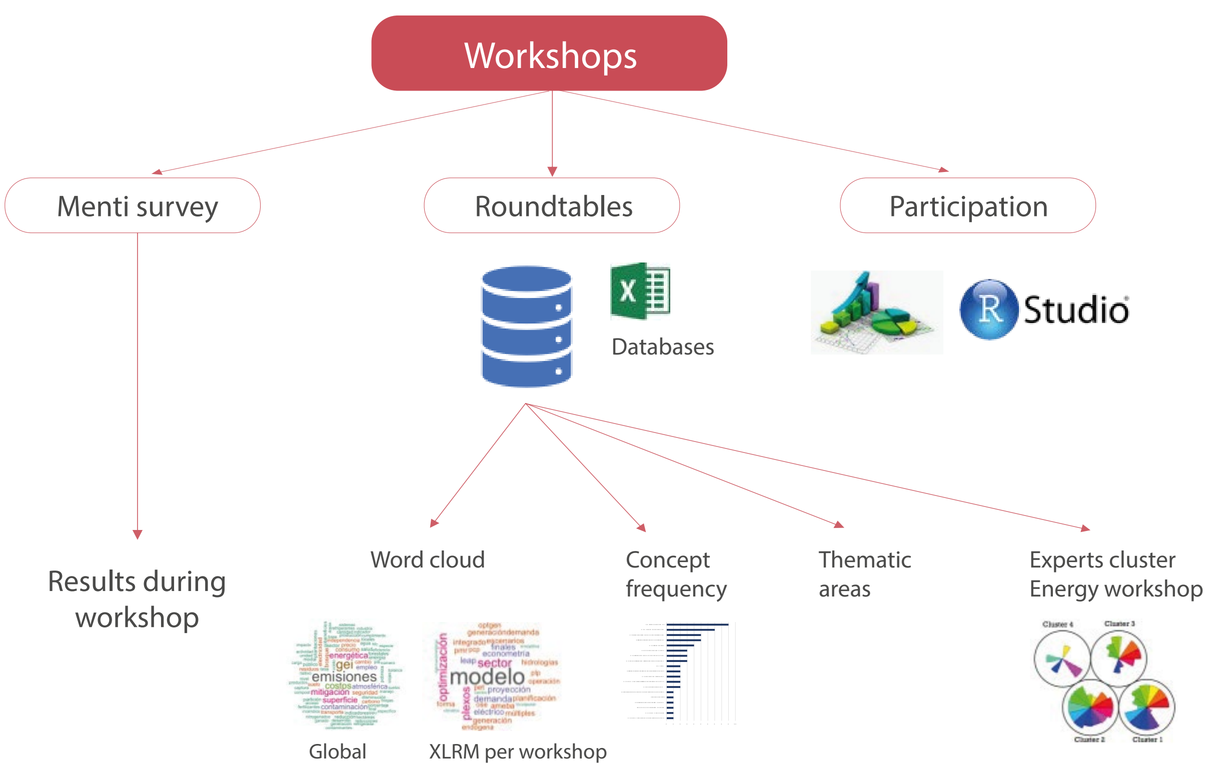
Source: Ministry of Environment (2018).

2.2 Participatory process

The first stage of the study consisted of consulting stakeholders from civil society, private sector, public sector, academia and multilateral organizations to construct a decision-making framework. This participatory process consisted of two workshops: one in June 2020 and another in December 2020. In the first instance, six sectoral workshops were held, focusing respectively on energy; transportation and urban development; industry, mining and infrastructure; forestry and biodiversity; agriculture/livestock; and waste. A total of 148 participants from the public, private and labor sectors, non-governmental organizations, academia and international organizations took part in the workshops. With this diverse participation, it was possible to generate thematic dialogues for structuring a decision-making framework in which it would be possible to evaluate strategies aimed at achieving GHG emissions neutrality by 2050.

During these workshops, experts and key stakeholders were invited to express their views on their priorities and performance metrics, actions in each sector that can contribute to decarbonization, existing data and models, and uncertainties that need to be considered. This informartion is known as the XLRM matrix (eXogenous uncertainties, policy Levers, Relatiohships, and Metrics for success) in the robust decision-making framework. The workshops were held digitally through the Miro platform and presented surveys through the Menti platform. Their results were analyzed and summarized using various tools: frequency histograms, word clouds, surveys, result clustering, among others (see Figure 2.4).

Figure 2.4:
Tools used to summarize and analyze the results of the sectoral workshops.



Source: Prepared by the authors.

The purpose of these analyses was to discuss the following issues, which reflect the concerns of workshop participants:

- Set of factors and ranges of variation to be considered in each dimension of the XLRM matrix.
- Identification of high precision and high ambiguity spaces reported by participants.
- Message strength.
- Highly complex requirements transmitted.

The conclusions of each sectoral session are summarized below.

Energy

The energy sector is the broadest and most diverse in terms of its characterization due to its condition as a fundamental input for the economy and society. Its subsectors in the analysis framework, such as transportation, industry and mining, exert their greatest impact through the quantities and types of energy they use.

From a general synthesis point of view, the prevailing perception taken from the energy workshop focuses on economic variables and energy security with actions oriented to markets, promotion of clean energy and energy efficiency standards. With respect to uncertainties, participants emphasized relative costs of technological options, effects of climate change on future hydrology, retirement of coal-fired power plants and introduction of hydrogen as a viable alternative.

Transportation

An analogous view to that of energy was taken by the transportation workshop (including private transport, public transport and freight transport), with the following main axes: economic, demand, modes of transport, electrification and hydrogen. The most important uncertainties were the relative costs between technologies and growth of transport demand.

Likewise, in transportation and energy, recommendations were made on models and data sources which are summarized in the application of nationally known tools, currently in use in both governmental and academic circles.

Industry and mining

In line with most of the participatory processes of the last decade, the industry and mining workshop placed strong emphasis on the latter given the economic importance of the sector. However, it was also possible to incorporate the view of the industrial processes sector (with a very minor share of emissions, compared to mining) along with manufacturing industry. Thus, issues related to promotion of energy efficiency and integration of renewable energies in production processes were complemented with actions and metrics related to consumption and use of hybrid fiber-coaxial, electric mobility and promotion of (ecological) hydrogen, the latter certainly influenced by initiatives associated with the law of energy efficiency and development of the ecological hydrogen industry, among others. The workshop also made innovative proposals, such as long-term industry and mining policies, circular economy, use of market instruments, and alignment with the Sustainable Development Goals.

Forests and biodiversity

In the forests and biodiversity workshop, many of the comments made by experts emphasized the critical role this sector will have to play. By 2050 the sector will have to make a contribution equal to or greater than all other sectors combined to achieve carbon neutrality. In this respect, participants stressed the need to consider that areas of forest use, both native forest and plantations, are the main driver for modeling emissions in the sector. This is principally shown by the mentioned performance indicators, and is maintained in the actions and uncertainties of the sector, which aim to increase the forest matrix while at the same time taking into account the possible degradation and loss of forests due to climatic and anthropic factors. This is in line with the country's commitments in the NDC, so this aspect will be the central pillar of the modeling of the sector.

Agriculture and livestock

In the agriculture and livestock workshop, there were varied views on emission reduction, mainly due to the broad spread of activities in the sector; however, cross-cutting elements emerged, such as changes in farming practices with a focus on soil care, which will lead to a more resilient agriculture (also contributing to adaptation). In terms of specific measures to reduce emissions, participants mentioned those associated with livestock farming and its activities, application of nitrogen in agricultural soils, and a third component of increasing soil carbon capture capacity, which are fundamental aspects for modeling. Uncertainties in demand for food at international level, or possible changes in diet that lead to food with a lower load of animal products will be considered.

Waste

In the workshop on waste, although topics traditionally related to waste and its GHG emissions were discussed, participants also showed interest in a broader view of the sector, increasing the scope to include non-organic waste, for example. In this respect, the performance metrics discussed are evidence of an interest not only in focusing on GHG emissions, but also on the entire waste management chain. The few models developed show that there is ample room for working on an analysis which evaluates different actions to reduce GHG emissions, and also to mitigate their economic, social and other consequences in the rest of the waste management chain. The uncertainties with highest number of mentions relate to the quantity and composition of the waste generated.

All these observations are considered in the modeling proposal, which is based on characterization of the different stages of the waste management chain, their interactions and development of scenarios that explore the effect of the different actions in a wide range of possible futures.

2.3 Second round of workshops

In more advanced stages of the project, a second round of workshops was held. Seventy-seven stakeholders from the same sectors and areas participated. During the workshops, the progress of the quantitative analysis was presented (for example, uncertainties considered and results at sectoral level). Participants provided feedback on points such as validation of the sectoral models used by universities and the uncertainty ranges considered, as well as general suggestions for improving simulations. These inputs were incorporated into the modeling work, and used to update the data and models used, incorporate new uncertainties and revise uncertainty intervals, as well as simulating uncertainties additional to those proposed in the NDC.

3
Sectoral models

This chapter describes the models developed in the framework of this project. Section 3.1 describes the general structure of the tool. Sections 3.2 to 3.5 contain the methodological approach used in accordance with the emitting sectors identified in Chile's greenhouse gas (GHG) inventory (Chapter 2). These sections cover the general modeling approach, the assumptions used to characterize the Nationally Determined Contribution (NDC) strategy updated with the best available information to 2020, the main uncertainties identified during the participatory process and how they were characterized[1]. Lastly, the NDC+ strategy and additional measures that were obtained from the participatory work are described. Section 3.6 details the macroeconomic model used to examine the marginal impact of implementing the NDC+ strategy over the NDC strategy.

[1] Only NDC measures are considered which have greatest impact on emission reduction and for which data was available to permit a rigorous numerical simulation. Measures such as residential and commercial distributed generation, new MEPS for home appliances, among others with lesser impact, were not included in the models.

3.1
Overview of the simulation tool

An integrated evaluation model was developed to make quantitative estimates of different emission reduction trajectories. The outlined computational tool facilitates exploration of different assumptions on the future to reflect stakeholder concerns and define a robust decarbonization strategy for Chile.

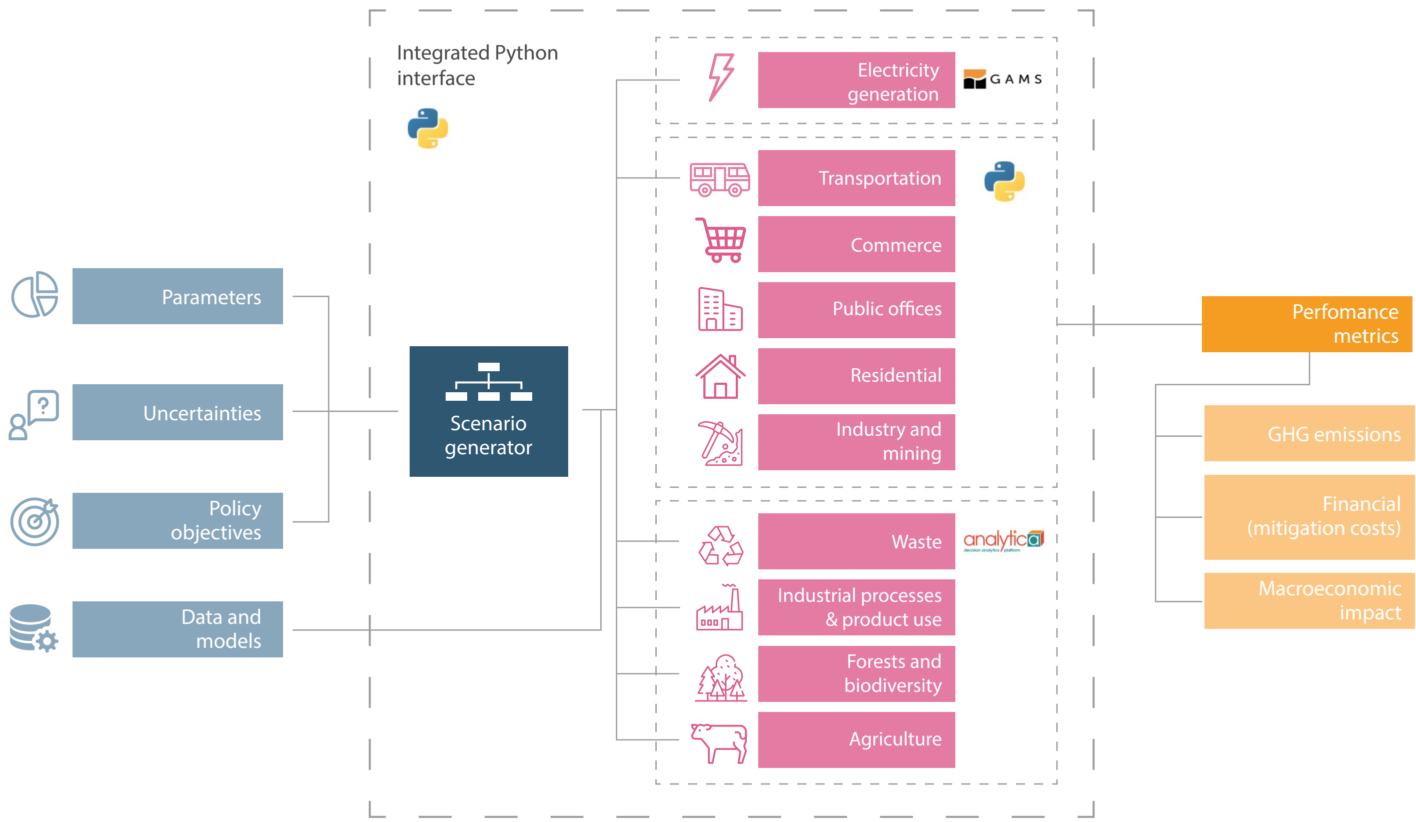
For the purposes of this work, suitable sectoral models were developed to characterize the drivers, mechanics, costs and impacts associated with GHG emissions in Chile between 2019-50. Probably the main difference from previous experiences lies in the existence of a real integration between the sectoral models, to which is added the uncertainty analysis, which is an innovation at national level.

The methodological approach used analyzes the results of different emission reduction strategies in an uncertain future where many elements may differ from what was planned. For this exercise, an updated re-creation was developed, with the best available information for 2020, of the emission reduction policies examined in the NDC approved by Chile (Government of Chile, 2020), explained in more detail in Palma et al. (2019).

In this exercise, Chile achieves carbon neutrality by 2050, but only one future was analyzed, and it was not possible to make an exhaustive analysis of sensitivities to the parameters used. The first step is to evaluate the results of this strategy under other possible futures (for example, other growth trajectories, another rate of adoption of the measures, etc.). Second, an NDC+ strategy was constructed, which included additional measures, over and above the nationally determined contribution measures, which were taken from the participatory work. Using expert criteria, this NDC+ strategy was evaluated under the same analysis framework.

Figure 3.1 shows the general structure of the computational tool used to project national decarbonization scenarios. During the project, sectoral models were implemented for all sectors of the GHG Inventory: electricity generation, transportation, commerce, public, residential, industry and mining, waste, industrial processes, forestry and agriculture. For the electricity generation sector, an energy model developed with prior support from the World Bank was used, based on an optimization approach (Energy Center, 2019). For the transportation, industry and mining, commercial and public sectors, projection models were implemented using the Python programming language. For the waste, industrial processes, forestry and agriculture sectors, the Analytica computational platform was used. All models were integrated into a computational platform implemented in Python programming language. The platform structure was developed to be able to simulate hundreds and thousands of scenarios at national level in limited simulation times, in order to apply the robust decision-making method.

Figure 3.1:
Diagram of modeling platform for analysis of Long-Term Decarbonization Strategy.



Source: Prepared by the authors.

The inputs that feed into the tool are: parameters (gross domestic product [GDP], population, energy prices, etc.), policy objectives or sectoral measures (share of electric mobility, forestation rates, etc.), uncertainties (definition applied to parameters and measures for reducing emissions) and data (sources of information to construct elements of the modeling platform). In turn, these inputs feed the scenario generator which, through random sampling of each source of uncertainty, creates a series of possible futures which feed each sectoral model. Lastly, the outputs of the tool identified for each possible future (hundreds were simulated) the results of the different emission reduction strategies, the results measured in terms of their emissions (especially with respect to reaching carbon neutrality by 2050), and the incremental costs of emission reductions. The macroeconomic impact of these strategies was also evaluated using a macroeconomic model based on the cost associated with investment in technologies (CAPEX) and the annual operation and maintenance cost (OPEX) associated with the sectoral measures.

3.2 Energy sector

Power generation

The simulations of the electricity generation sector were performed using the Partnership for Market Readiness (PMR) energy model, a platform promoted by the World Bank to help countries move to a cleaner economy. The sectoral energy model corresponds to an optimization model whose objective function minimizes the cost associated with energy consumption, the cost associated with investment in technologies, and the cost of operation and annual maintenance. The optimization model determines the lowest-cost expansion plan that satisfies the electricity demand projection. The model is subject to a set of constraints including: nodal balance between generation and demand, maximum production levels for each plant based on availability of the renewable resource, minimum power, maximum feasible power to be installed each year and minimum inertia constraint. The GHG emissions projection is based on the electricity generation projection of thermoelectric power plants (coal, natural gas, diesel and fuel oil) and the emission factors taken from Chile's National Greenhouse Gas Inventories (INGEI).

To characterize the projections made in the NDC, the following assumptions are taken into account:

- **Investment cost:**[2]
Investment cost projection of the Long-Term Energy Planning (PELP) corresponding to the low trend scenario (Scenario E in Ministry of Energy, 2020).

- **Energy prices:**
Energy prices projection from the Long-Term Energy Planning corresponding to the high trend scenario (Scenario E).

- **Electricity demand:**
From the projection estimated by the industry and mining, transportation, commercial, public and residential models. The sectoral models were estimated to obtain an electricity demand similar to that projected in Scenario E of the Long-Term Energy Planning.

- **Hydrology:**
The NDC scenario projection was based on a weighted hydrology: 40% dry, 30% medium and 30% wet.

The measure modeled in the NDC scenario corresponds to the retirement of coal plants, considering the dates corresponding to Scenario E of the Long-Term Energy Planning, which involve complete retirement by 2038. Additionally, the NDC+ scenario considers an earlier retirement of coal plants by 2030 and a retirement of natural gas plants by the end of 2050 (assuming 890 MW of natural gas plant capacity available in 2050).

The main sources of uncertainty modeled are shown in Table 3.1.

Table 3.1:
Sources of uncertainty modeled in the power generation sector.

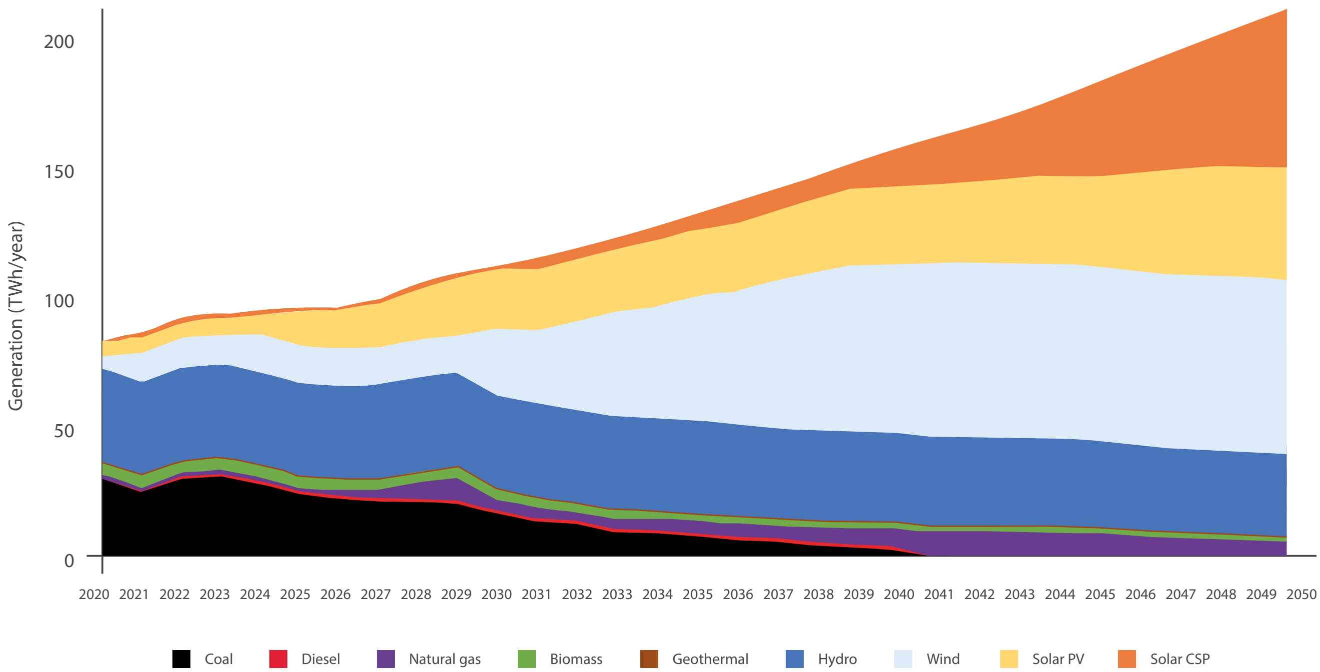
Source of uncertainty	Description
Electricity demand	Different electricity demand projection scenarios, taking into account the uncertainty associated with the sectoral models.
Cost of technology investment	Projection of different investment cost scenarios, between the maximum and minimum scenario of costs from the Long-Term Energy Planning.
Energy prices	Projection of different energy price scenarios, between the maximum and minimum scenario of energy prices from the Long-Term Energy Planning.
Hydrology	Different hydrological conditions, varying between dry and wet.

Source: Prepared by the authors.

[2] Each energy price has 3 projections: low, medium and high. Similarly, NCRE investment costs has 3 projections: low, medium and high. Scenario E of the PELP (Long-term Energy Planning) uses the scenario of high costs of energy prices and low investment costs of NCREs, which corresponds to a favorable scenario for development of NCRE sources.

Figure 3.2 shows the electricity generation projection for the NDC case.

Figure 3.2:
Projection of electricity generation matrix.



Source: Prepared by the authors.

Transportation

The demand projection for this sector is driven by growth in passenger transport demand, characterized by the variable PKM (passenger-kilometer), and freight transport demand, characterized by the variable TKM (tonne-kilometer)[3]. Energy demand and emissions projections are based on characterization of the different modes of transport: private land transport ("cars"), taxis, buses, freight trucks, passenger rail transport, freight rail transport, aviation, maritime transport. GHG emissions are estimated from the demand projection by energy type (gasoline, diesel, etc.) and INGEI emission factors. The model has a spatial resolution at national level and an annual temporal resolution. Model parameters were calibrated to replicate the data of the 2017 National Energy Balance.

The main NDC assumptions used for the transportation sector projection were as follows:

- **Gross domestic product (GDP):**
The GDP projection of the NDC report (Government of Chile, 2020). The projection was updated to take into account the impact of the health crisis.

- **Population:**
The GDP projection of the NDC report (Government of Chile, 2020). The population projection was updated based on new available data.

[3] Transportation demand is determined exogenously. However, potential changes in transportation demand resulting from increased use of public transport, increased cycling and teleworking are covered in Chapter 4.

The measures modeled to characterize the NDC scenario were as follows:

• Electric mobility in private (and commercial) vehicles:
58% share of pure electric and hybrid vehicles by 2050.

• Electric mobility in taxis and buses:
100% share of electric vehicles by 2040 and 2050.

• Electric mobility in buses:
100% share of electric buses by 2040.

• Hydrogen in freight transport:
85% share of hydrogen trucks by 2050.

• Hydrogen in aviation:
10% in the sector by 2050.

The additional measures included in the NDC+ scenario were as follows:[4]

• Increase in share of public transport:
A modal shift of 10% from private transport to bus transport by 2050.

• Increase in share of non-motorized transport:
A modal shift of 10% from private transport to bicycles by 2050.

• Increase in telework share:
A 10% share of telework by 2050, consequently assuming a decrease in private transportation.

The main sources of uncertainty modeled are shown in Table 3.2.

Table 3.2:
Sources of uncertainty modeled in the transportation sector.

Source of uncertainty	Description
GDP	Different GDP projection scenarios, between a maximum and minimum range.
Population	Different population projection scenarios, between a maximum and minimum range.
Vehicle performance by technology	Range of variation of performance between -10% and +10% with respect to reference performance.
Charging rate	Range of variation of performance between -10% and +10% with respect to reference charging rate.
PKM saturation of air transport	Range of transport PKM saturation between 4,5154,741 (NDC saturation value) and 5,4185,690 PKM by 2050. Saturation level of aviation PKM was selected based on the emissions level projected by NDC.

Source: Prepared by the authors.

[4] Modal split shift measures can have impacts on more than one mode of transport. However, in this study, conservatively, only the impact of decreasing private passenger transport was evaluated. Additions of other impact channels would generally contribute to further emission reductions.

The main sources of uncertainty associated with emission reduction measures are shown in Table 3.3.

Table 3.3:
Sources of uncertainty associated with emission reduction measures in transportation.

Source of uncertainty	Description
Electric mobility share in private and commercial vehicles	Range of electric mobility share between 20% and 70% by 2050. The 20% corresponds to the value used in the NDC Reference Scenario.
Share of hydrogen in freight transportation	Range of hydrogen share between 50% and 85% by 2050. The 50% corresponds to the value used in the Ministry of Public Works study financed by the IDB.

Source: Prepared by the authors.

The following models were used to calculate the costs:

$$\mathbf{OPEX}_t = \sum_{u,j} \mathbf{D}_{u,j,t} \times \mathbf{Pr}_{j,t}$$

$$\mathbf{CAPEX}_t = \sum_{u,j} \Delta\mathbf{P}_{u,j,t} \times \mathbf{CI}_{u,j,t}$$

$$\mathbf{P}_{u,j,t} = \mathbf{D}_{u,j,t} / \mathbf{N}_{u,j}$$

Where *OPEX* corresponds to the operating costs associated with energy consumption, $CAPEX_t$ is the annual investment cost in the technologies associated with the different end uses. The variable $D_{u,j,t}$ corresponds to the final energy demand for each end use u, $Pr_{j,t}$ is the price of energy (expressed in US$/Tcal)[5], $P_{u,j,t}$ is the installed capacity in each process, $\Delta P_{u,j,t}$ is the annual capacity increase (the annual increase is used for valuation of the investment cost), $CI_{u,j,t}$ is the investment cost of each technology (expressed in US$/kW or US$/vehicle), and $N_{u,j}$ is the level of activity of each process.

The cost model is the same for all energy sectors (electricity generation, transportation, residential, industry and mining), where the only changes are representation of end uses, activity levels of each process and the units in which investment costs are expressed. In the case of transportation, end uses are associated with private vehicles, trucks, etc., level of activity is expressed in km traveled and investment cost in US$/vehicle. For the residential sector, end uses are associated with heating, cooking, etc., activity levels are associated with average hours of use of appliances for each end use, and investment costs (heaters, stoves, etc.) are expressed in US$/kW. In industry and mining, end uses are associated with uses of heat, motors and other electrical uses, activity levels are associated with average hours of use of each appliance for each end use and investment costs (boilers, motors, etc.) expressed in US$/kW.

Residential

The energy demand projection for the residential sector uses housing as the key variable to determine evolution of the sector. The methodology first projects the number of dwellings and then projects energy demand based on estimates of unit energy consumption by end use and share of the different technologies. The following end uses are considered: heating, domestic hot water, cooking and other electrical appliances. GHG emissions calculations are based on energy demand and INGEI emissions factors.

[5] Conversion parameters are used to transform energy prices expressed in physical units (for example, US$/tonne, US$/m3, etc.) to US$/Tcal units.

The main NDC assumptions considered for the residential sector projection were as follows:

- **Population:**
Population projection from the NDC report. Subsequently, the population projection was updated with new information available.

- **Projected number of dwellings:**
The housing projection used in the NDC report.[6]

- **Occupancy rate:**
Calculated from the population projection and number of dwellings.

- **Energy intensity:**
Estimates of intensities by end use are based on energy demand projection data provided by the Ministry of Energy.

- **Share by type of energy (or technology):**
Estimates of share by type of energy are based on energy demand projection data provided by the Ministry of Energy.

The measures modeled to characterize the NDC were as follows:

- **Residential electric heating:**
56% of houses by 2050 and 70% of apartments by 2050.

- **Electrification for cooking:**
36% of houses by 2050 and 35% of apartments by 2050.

- **Solar thermal systems:**
52% domestic hot water in houses by 2050 and 57% in apartments by 2050.

- **Increase in thermal retrofitting of dwellings:**
between 570,000 and 650,000 by 2050.

Additionally, the following measure was included in the NDC+ scenario:

- Increase in number of dwellings with thermal retrofitting.

The main sources of uncertainty modeled are shown in Table 3.4.

Table 3.4:
Sources of uncertainty modeled in the residential sector.

Source of uncertainty	Description
Population	Different projection scenarios, varying between a maximum and minimum range.
Occupancy rate	The occupancy rate is decreased to 20% less than in the reference scenario. Only a negative change is considered, corresponding to an underestimate of the number of dwellings in 2017 with respect to the results of that year's census.
End-use intensities	Range of variation of intensity between -10% and +10% with respect to the reference intensity estimated from NDC results.

Source: Prepared by the authors.

[6] The 2017 census provides more recent data than those used in the NDC report, but the NDC report data were saved in order to use the same reference base of assumptions.

The main sources of uncertainty associated with emission reduction measures in the residential sector are shown in Table 3.5. The possibility of introducing uncertainty in the electric heating measure was also explored. However, this measure is mainly replacing firewood, consequently exploring scenarios of lower electrification share should see an increase in the share of firewood, which would not have a significant impact on the change in GHG emissions from this sector.

Table 3.5:
Sources of uncertainty associated with emission reduction measures in the residential sector.

Source of uncertainty	Description
Share of solar thermal systems for domestic hot water	Range of share of number of dwellings with solar systems between 30% and 80% by 2050. The upper range (80%) is associated with the new measures included in the NDC+ scenario.
Number of dwellings with thermal retrofitting	Range of number of dwellings undergoing thermal retrofitting between 1 million and 6.1 million. The upper range (6.1 million) is associated with the new measures included in the NDC+ scenario.

Source: Prepared by the authors.

Industry and mining

For the energy demand projection, the various subsectors of the National Energy Balance are characterized as: copper, miscellaneous mines, sugar, cement, pulp and paper, fishing, petrochemicals, iron and steel and miscellaneous industries. Energy consumption is largely driven by the industrial production associated with each subsector. Demand for each one is broken down into three end uses: motors, thermal and other electrical consumption, representing the main energy-demanding processes. This breakdown with data on energy efficiencies is used to calculate the useful energy of the industry, which corresponds to the fraction of energy demanded which is transformed into the energy needed to produce a unit of the good. The final uses are disaggregated with information from the sectoral models provided by the Ministry of Energy.

The main NDC assumptions used for the industry and mining sector projection were as follows:

· GDP:
GDP projection of the NDC report (Government of Chile, 2020). The projection was later updated taking into account the impact of the health crisis.

· Projected production of copper, iron, miscellaneous mines, paper and pulp:
Projections used in the NDC. For the first few years, industrial productions are adjusted by actual data.

· Energy intensity:
Estimates of intensities by end use are based on projection data for energy demand provided by the Ministry of Energy.

· Energy intensity:
Estimates of intensities by end use are based on projection data for energy demand provided by the Ministry of Energy.

· Share by type of energy (or technology):
Estimates of shares by type of energy are based on projection data for energy demand provided by the Ministry of Energy.

The measures modeled to characterize the NDC were as follows:

• Solar thermal systems:
33%[7] in miscellaneous industries, 16% in copper mining by 2050.

• Hydrogen - uses in thermal processes:
3% in miscellaneous industries.

• Hydrogen – motor uses:
37% for open pit mining, 8% for underground mining, 12% for miscellaneous industries, 21% in miscellaneous mines by 2050.

• Biomass:
10% increase in biomass used for electricity generation, measure considered in electricity matrix expansion models.

• Electrification of motor uses:
88% in miscellaneous industries, 74% in miscellaneous mines by 2050.

• Electrification of copper uses:
57% in open pit end use.

Additionally, the following measures were included in the NDC+ scenario:

• Increased share of solar thermal systems in copper mining.
• Introduction of hydrogen in thermal processes in iron and steel sub-sector.

The main sources of uncertainty modeled in industry and mining are shown in Table 3.6.

Table 3.6:
Sources of uncertainty modeled in industry and mining sector.

Source of uncertainty	Description
GDP production	Different projection scenarios, varying between a maximum and minimum range. Projection of the "miscellaneous industries" subsector is correlated with GDP.
Copper production	Range of maximum and minimum production, according to production projections by the Chilean Copper Commission (Cochilco) until 2030 and assumptions of Chile's share in world production by 2050.
Production of miscellaneous mines	Range of variation of -70% with respect to the reference value (NDC value). The lower range was obtained from a previous study.
Iron production	Range of variation between -40% and +40% with respect to reference value.
Pulp and paper production	Range of variation of +23% with respect to reference value. The upper range is associated with the entry into operation of the MAPA project.
Copper sector intensity	Range of variation between -10% and +70% with respect to reference value. Maximum range of variation is estimated from pessimistic projection scenarios of the ore grade of the minerals.
End-use intensities	Range of variation of intensity between -10% and +10% with respect to reference intensity estimated from NDC results.
Demand elasticity/GDP	For the particular case of the miscellaneous industries sector, a sensitivity to demand elasticity/GDP of the sector is used with a range of variation of intensity between -10% and +5% with respect to the reference intensity estimated from NDC results. The lower value is derived from estimates made in previous studies which show that demand in this sector grows at a lower rate than GDP.

Source: Prepared by the authors.
Note: For production of copper and miscellaneous mines, the methodology proposed in Centro de Energía (2020) was used.

[7] Value estimated from outputs of models provided by the Ministry of Energy, but which is different from the value shown in the NDC report. Derived from the above, our estimates may differ slightly from the original estimates used in the NDC documents.

The main sources of uncertainty associated with the emission reduction measures in industry and mining are shown in Table 3.7.

Table 3.7:
Sources of uncertainty associated with industry and mining emission reduction measures.

Source of uncertainty	Description
Share of solar thermal systems	Range of share between 8% and 46% in miscellaneous industries, and between 8% and 30% in copper mining. These subsectors are selected because they are the main contributors to industry and mining sector emissions. The upper range of these measures is associated with the new measures included in the NDC+ scenario.
Electrification of open-pit copper applications	The share of electricity is decreasing to a range of 27%, explained by the difficulty of electrifying the CAEX trucks used in this mining process. At present the only measures where there are some pilot tests consist of hydrogen use. Electrification could be interpreted as use of hydrogen cells, but in the case of NDC this corresponds to another measure.
Hydrogen in thermal processes	Hydrogen partitioning varies between 0% and 10% in the steel industry. The higher level (10%) is associated with the new measures included in the NDC+ scenario.

Source: Prepared by the authors.
Note: In the case of hydrogen partitioning, this is the additional measure that could be implemented according to Holappa (2020).

Commercial

The demand projection for this sector uses an econometric model that relates demand growth to GDP growth by means of the following expression: $D_t = D_{t-1} \times (1 + rpib_t \times e_t)$. Where D_t is the total energy demand in year t, $rpib_t$ is the GDP growth rate and e_t is the demand elasticity/GDP. Next demand D_t is transformed into useful demand by the following expression: $DU_t = D_t \times R$, where DU_t is the useful energy and R is the ratio of final demand to useful demand. Subsequently, useful demand is disaggregated into the following end uses: heating, domestic hot water, motive power and other uses. The "other uses" category includes a large part of demand that is not characterized as end use (due to lack of information). Finally, demand for each end use is broken down into the various types of energy sources (natural gas, diesel, electricity, etc.). GHG emissions are estimated from the demand projection by energy type (gasoline, diesel, etc.) and the INGEI emission factors. The model has a spatial resolution at national level and annual temporal resolution.

The main NDC assumptions used for the commercial sector projection were as follows:

· GDP:
GDP projection from the NDC report. Subsequently, the projection was updated to take into account the impact of the health crisis.

· Demand elasticity/GDP (e_t):
Elasticity is estimated from energy model output data provided by the Ministry of Energy.

· Share by end use and type of energy:
Estimates of shares by end use and type of energy are based on energy demand projection data provided by the Ministry of Energy.

The measures modeled in the commercial sector to characterize the NDC were as follows:

· Electrification of end uses:
Achievement of 70% electrification of end uses.[8]

The main sources of uncertainty modeled in the commercial sector are shown in Table 3.8.

[8] Due to information limitations with respect to end uses in the commercial sector, it is assumed that diesel is replaced until reaching 70% electrification share by 2050.

Table 3.8:
Sources of uncertainty modeled in the commercial sector.

Source of uncertainty	Description
GDP	Different GDP projection scenarios, varying between a maximum and minimum range.
Demand elasticity/GDP	Increase in demand elasticity/GDP to 20% with respect to the reference value. The increase is explained by the fact that the elasticity estimated by the consultant is greater than that used in the NDC.

Source: Prepared by the authors.

Public

Due to the low share of energy demand and emissions, the demand projection for this sector uses a simplified model that correlates sector growth with population growth. The following expression is used: $D_t = I \times P_t$ where D_t is energy demand, P_t is population and I is energy intensity.

The main NDC assumptions used for the public sector projection were as follows:

· Population:
The GDP projection from the NDC report. Subsequently, the population projection was updated with new data available.

No emission reduction measures were included for this sector.

3.3 Industrial processes sector

The modeling of emissions from the industrial processes sector was implemented in Analytica modeling software. The model considers the national INGEI emissions categories and accounting methodology, based on the Intergovernmental Panel on Climate Change (IPCC) methodological guidelines (IPCC, 2006).

The model is composed of six categories. The main ones in terms of emissions correspond to alternative products for ozone depleting substances, and the mineral industry and the metal industry. The model developed is based on the prospective emissions model of the Ministry of Environment, except for the category of use of alternative products for ozone-depleting substances, for which a new methodology was designed and implemented which considers the restrictions imposed by the Kigali Amendment to the Montreal Protocol under an economic logic.

The projection of activity levels is based on econometric relationships observed in the 1990-2016 time series, which—except for some subcategories of alternative products for ozone-depleting substances—depend on historical trends and GDP. In the case of specific subcategories—such as domestic refrigeration and vehicle air conditioning—population is incorporated as a driver of consumption. Additionally, in the particular case of cement, the consumption of this mineral mix was considered as an uncertain variable in the estimate of emissions from the industry and mining sector.

In the current policy scenario, that is, under the assumptions of the measures to achieve carbon neutrality, no new measures are evaluated. However, the effect of the Kigali Amendment on consumption and subsequent emissions by hybrid fiber coaxial is modeled. The modeling has five steps:

1. Modeling consumption without the Kigali Amendment: the estimate of the projection of consumption in a scenario without the Kigali Amendment is based on econometric relationships between the size of HFC banks (installed capacity of systems that uses HFC) and variables such as GDP and population growths.

2. Determination of consumption limits: Kigali establishes a consumption reduction timetable based on consumption between 2020-22, plus a margin that allows in the first few years continuing replacement of ozone-depleting substances with hybrid fiber coaxial (Höglund-Isaksson et al. 2017). Even so, it establishes a consumption freeze between 2024-28, and a 10% reduction in 2029, 30% in 2035, 50% in 2040 and 80% in 2045.

3. Determination of new consumption: New consumption is determined by forcing compliance with consumption limits. For this, different hybrid fiber coaxial applications are prioritized in line with the technology substitution costs obtained from the studies of Purohit and Höglund-Isaksson (2017) and Höglund-Isaksson et al. (2017). This prioritization means that when consumption without the Kigali Amendment exceeds the limit, applications with lower technology substitution costs halt their consumption in order to expand their bank, including as many applications as needed to meet the consumption limit.

4. Determination of the new application banks: Based on the new consumption, and considering the same leakage rates and average useful life taken into account in the INGEI estimate, the new estimate of the bank is performed recursively, where the bank in a year *t* (B_t), depends on the previous year's bank (B_{t-1}), the new bank (N_t) and the fraction of the bank that ends its useful life (N_{t-vu}), for each application:

$$B_t = B_{t-1} + N_t - N_{t-vu}$$

5. Determination of sector emissions: Based on the estimated new bank, the hybrid fiber coaxial emissions are estimated; in particular, emissions from leakage, end-of-life, installation of new banks and containers.

An additional measure is evaluated in the NDC+ scenario, which is the scenario that includes additional decarbonization actions proposed on the basis of stakeholder inputs, as follows:

New refrigerant recovery and reclamation plants:

Progressive installation between 2025-31 to maximum capacity of 2,800 t HFC/year.

Table 3.9:
Sources of uncertainty modeled in the industrial process and product use sector.

Source of uncertainty	Description
Activity levels	This uncertainty is incorporated indirectly and depends mainly on GDP and historical trends, through econometric relationships.
Cement production	Varies in the same way as in the industry and mining sector.
Clinker imports	The fraction of imported clinker is considered to vary between 30% and 60%.
Refrigerant leakage rate in commercial and industrial sector	Future leakage rates for both applications are considered to vary by +/-5% with respect to the central value of the emission rate considered in the INGEI. The range for the commercial sector is 30% to 40% and in the industrial sector 15% to 25%.

Source: Prepared by the authors.

3.4 Waste sector

The modeling of emissions from the waste sector or circular economy was implemented in the Analytica software. This model is a corrected and updated version of the model developed in the MAPS-Chile process, and uses the best data to date, provided by the SNI-Chile team. In practice, the model considers the national INGEI emissions categories and accounting methodology based on the IPCC (2006) methodological guidelines. The model has four categories; the main ones in relation to emissions are household solid waste and domestic water.

For the waste generation projection, macroeconomic projections of population and GDP are used as drivers for projection of the variables that describe the level of activity of the different categories and subcategories. In particular, for urban waste the econometric relationships of World Bank (2018) are used. This study relates generation of waste per capita quadratically to the logarithm of GDP per capita. On waste composition, it is assumed to fluctuate linearly from the composition currently used in the INGEI toward the composition of upper-middle-income countries by 2030, and to the composition of high-income countries by 2050. These compositions are obtained from World Bank (2018). On the level of domestic wastewater, total generation is indexed to population, while protein content is estimated as a function of GDP. For waste and wastewater disposal, the projection only takes into account the changes included in the prospective emissions model of the Ministry of the Environment, which considers projects already committed.

In the current policy scenario, that is under the assumptions of the carbon-neutrality measures, two main measures are evaluated:

· Biogas capture in landfills:
Progressive implementation between 2025-30 of biogas capture and flaring systems in all landfills in the country.

· New wastewater treatment plants:
Installation of new plants in the country's main urban centers, with sufficient capacity to treat wastewater from Gran Concepción (2030), Gran Valparaíso (2035), Antofagasta (2040) and the La Serena-Coquimbo conurbation (2040).

An additional measure is evaluated in the waste sector in the NDC+ scenario, which is the scenario with inclusion of additional decarbonization actions proposed in the input from stakeholders, as follows:

· New composting plants:
Installation of composting plants in all regions of the country, with sufficient capacity to compost 60% of residential organic waste.

Table 3.10:
Sources of uncertainty modeled in the waste sector.

Source of uncertainty	Description
Generation of solid household and assimilable waste	This uncertainty is incorporated indirectly and depends on two variables with uncertainty which have a direct impact on the estimate: population and GDP. Waste generation varies linearly with population, and with the square of the logarithm of GDP per capita, in accordance with the relationship observed by Antosiewicz et al. (2020).
Recycling rates	Implementation of Law 20.920, which promotes recycling and establishes extended producer responsibility schemes, has an impact on the amount of waste actually disposed of at final disposal sites. Range between 85% and 105% is used with respect to the targets set for priority packaging products.
Elasticity of industrial waste generation-GDP	Parameter that describes the change in industrial waste generated with respect to change in GDP. Range between 0 and 1.

Source: Prepared by the authors.

Table 3.11:
Sources of uncertainty associated with emission reduction measures in the waste sector.

Source of uncertainty	Description
Biogas capture efficiency	An average value of 45% from capture and flaring systems with respect to total biogas generated in landfills. Range of uncertainty between +/-10% is considered with respect to the central value.
Investment costs	Although they do not have a direct impact on the emissions projection, investment costs associated with emission reduction actions are considered uncertain. For capture and flaring systems, a range between US$0.45 million and US$1.1 million for a capacity of 1,300 m³/day is considered. For wastewater treatment plants, an investment cost of US$1.7 +/-20%/(m³/year) is considered.

Source: Prepared by the authors.

3.5 Agriculture sector

The modeling of emissions from the agriculture sector (which also considers emissions associated with livestock) used Lumina's Analytica software, with the emission categories and accounting methodology of the national INGEI, based on IPCC (2006) guidelines. The model considers five main GHG emission source categories for the sector, corresponding to about 95% of total sector emissions: enteric fermentation (CH_4 emissions produced in animal digestive systems), manure management (CH_4 and N_2O emissions generated by animal production systems for manure storage and disposal), agricultural land (N_2O emissions produced by microbial processes in the soil, associated with application of nitrogenous compounds) and urea application (CO_2 emissions, product of urea application). These represent, respectively, 39.7%, 17.1%, 38.0% and 3.0% of total sector emissions in 2016 (Ministry of the Environment, 2018).

For the livestock projection, an econometric model was developed based on meat prices (for beef cattle) and corn and soybeans prices (for cattle, pigs and poultry). Price projections were obtained from the world statistics of the Organization for Economic Co-operation and Development (OECD).[9] For projection of synthetic fertilizer consumption, a fertilizer use intensity model associated with soil use by crop type was used through multiple linear regression. Soil use for different crops was projected with an autoregressive model for the main crop categories.

In the current policy scenario, that is, under the assumptions of the measures to achieve carbon neutrality (NDC scenario), three main measures are evaluated:

- **Change in bovine diet:**
This measure progressively increases the change in bovine diet (additives that decrease enteric fermentation by 9% compared to a normal diet), reaching 70% of dairy cows by 2050 after starting conversion in 2030.

- **Biodigesters:**
This measure progressively increases disposal of pig manure in biodigesters, reaching 70% (measured in hog heads) by 2040, remaining constant by 2050.

- **Efficient use of fertilizer:**
This measure progressively increases the efficient use of fertilizers, reaching a 30% reduction in fertilizer use projected to 2030 for certain crops, remaining constant to 2050.

[9] See https://stats.oecd.org/; the 2019-28 price projection for different products is maintained. For projection of these prices into the future, the growth rate in that period was used and kept constant until 2050.

Based on inputs from stakeholders attending the participatory workshops, additional decarbonization actions (NDC+ scenario) are included; in particular three measures:

· Reduction in beef consumption:
Progressive decrease to reach a 10% reduction by 2050, starting in 2025. Beef consumption will be replaced by other types of protein (animal and plant). The measure assumes that the decrease in consumption will only impact domestic production.

· Application of organic amendments to soils:
Increased carbon capture in soils, resulting from of organic amendments (poultry guano) on annual crop land. This would start in 2030, reach 10% of the area in 2040, and remain constant until 2050. Emissions associated with nitrogen content are considered.

· Holistic livestock management:
Increased carbon capture in pastures as a result of a change in livestock management, using shorter grazing times per quadrant, allowing for root growth and more nutritious feed for livestock. The measure begins application in 2030 and reaches 10% of cattle in pastures under holistic management by 2040, only in the Los Lagos Region, remaining constant by 2050.

Table 3.12:
Sources of uncertainty modeled in the agricultural sector.

Source of uncertainty	Description
Beef price	A beef price uncertainty distribution range between +/-35% from the reference value to 2050. This parameter is used to project beef cattle, as main driver, together with corn prices.
Soybean price	A soybean price uncertainty distribution range between +/-45% from the reference value to 2050. This parameter is used to project poultry livestock, in conjunction with corn prices.
Corn price	A corn price uncertainty distribution range between +/-45% is considered for 2050. This parameter is used to project cattle and pigs, as well as poultry.

Source: Prepared by the authors.

Table 3.13:
Sources of uncertainty associated with emission reduction measures in agriculture.

Source of uncertainty	Description
Change of bovine diet	A minimum uncertainty range of -50% and a maximum of 36% (over-compliance of adoption assumption), associated with compliance with adoption rate of the measure.
Efficient use of fertilizer	A minimum uncertainty range of -70% and, as maximum range, the maximum value assumed for the adoption rate of the measure (that is, the measure is not expected to be exceeded).
Pig biodigesters	A minimum uncertainty range of -29% and a maximum of 36%, associated with compliance with the adoption rate of the measure.
Reduction in beef consumption	A minimum uncertainty range of -10% and a maximum of +10% (that is, overcompliance with the meat consumption assumption), associated with compliance with the adoption rate of the measure.
Regenerative agriculture: carbon capture by application of organic amendment	A minimum uncertainty range of -10% and a maximum of +10%, associated with compliance with the adoption rate of the measure.
Holistic livestock management	A minimum uncertainty range of -10% and a maximum of +10% is considered, associated with compliance with the adoption rate of the measure.

Source: Prepared by the authors.
Note: All values were adjusted by the participatory process.

3.6 Forest and biodiversity sector

For the forests and biodiversity sector, which in INGEI is referred to as the land use, land-use change and forestry sector, a model was developed based on Analytica software which emulates the national GHG inventory (INGEI in spanish) results using the sector emissions results, methodologies from the IPCC Guidelines (2006) and average and default parameter values from the Ministry of Environment (2018). The model is divided into distinct nested modules, which contain category-specific modeling of the land use, land use change and forestry sector (LULUCF), and are organized as follows:

4.A Forest land:

Forest Land remaining as such: This module models emissions and captures associated with biomass increase, biomass loss (harvesting, forest fires, firewood use and burning of forest residues), and vegetation change (replacement and restitution).

Land converted to forest land: This module includes emissions and captures associated with land converted to native forest and land converted to plantations.

4.X.1: Land converted to X (where X=B.C.D.E.F): This module groups together the captures and emissions associated with land converted to grasslands (B), croplands (C), wetlands (D), settlements (E) and other land (F).

4.X.2.X: Land X remaining as such (where X=B.C.D.E.F): This module considers the captures and emissions associated with grasslands (B), croplands (C), wetlands (D), settlements (E) and other land (F), remaining as such.

For projection of the sector, an aggregate projection model was developed at national level using autoregressive vectors.[10] The projected categories are as follows:

- Native forest and plantations.
- Land converted to native forest and plantations.
- Crop lands and pastures burned.
- Land converted to other use categories.

This method was used to project land use, to then use the equations from the 2006 IPCC Guidelines (IPCC, 2006) or specific emission factors per hectare for each INGEI category to determine future emissions.

For forest fires, the projection is based on historical information on the area burned annually for forests and plantations separately. For the main exercise, a value of emissions was based on the historical annual average, which in fact tends to decrease, as a result of implementation of greater fire control, in accordance with the commitments of the NDC.

Additionally, percentiles are extracted from the historical annual area burned to determine ranges of forest fire sizes for annual occurrence. This analysis records the high variability for a particular year, which could imply that by 2050 in particular, carbon neutrality will not be reached due to occurrence of an extreme fire season. To simulate this risk, it is considered independently in the sectoral model, conceptualized as a "mega-fire." An analysis of this risk shows that in approximately one out of seven years (13.4%) a high fire season occurs that could put the NDC at risk.

In the model, the following actions are considered in the NDC scenario, associated with increased captures in the sector and conservation of forests and biodiversity:

· Afforestation:

This measure is aimed at increasing the forest area, and includes afforestation of 200,000 ha by 2030, of which 100,000 ha correspond to permanent native forest cover, and the other 100,000 ha to forest plantations. This measure is part of Chile's NDC, known as "Contribution in Integration-UTCUTS-Forestry No. 5 (I5)" (Government of Chile, 2020).

[10] The autoregressive vector forecasting model is an estimation model that can be used when two or more time series influence each other, using as predictors the values of previous years in the time series of each component of the vectors to model the behavior of the series. Projection of changes in the existing area of x at time t is defined as the function of the previous year's value (t-1) (one year lag) and considering the area of other categories in the previous year (k=2 , k=3,...,k=n).

· Increase in native forest area under management plan:
This measure is aimed at management and recovery of native forest by increasing the managed area by 200,000 ha by 2030. The measure is part of Chile's NDC, known as "Contribution in Integration-UTCUTS-Forests No. 4 (I4)" (Government of Chile, 2020).

· Decrease in native forest degradation:
This measure considers three elements of native forest degradation, gradually decreasing to 25% less native forest loss by 2030. The processes that lead to this reduction are: smaller area of forest fires, replacement of native forest with forest plantations, and transfer of native forest to other non-forest land uses. This measure is part of Chile's NDC, known as "Contribution in Integration-UTCUTS-Forests No. 6 (I6)" (Government of Chile, 2020).

The following additional measures, considered in the NDC+ scenario, are intended to reinforce those already mentioned, and supplement them in terms of protection and sustainable management of ecosystems and biodiversity:

· Sustainable management of brown algae forests:
This measure incorporates the GHG capture differential generated by management of brown algae of the species *Lessonia nigrescens, Lessonia trabeculata and Macrocystis spp*. The GHG capture values come from Vásquez et al. (2013). The measure also contributes to conservation of these marine ecosystems.

· Increase in surface area of protected wild areas:
This measure considers creation of new reserves and national parks, which increase the surface area of managed forest and, at the same time, contribute to conservation of native forest and land ecosystems. The measure starts in 2030 considering that by 2050 there will be 100,000 ha more of forest, which enter the carbon capture estimate in the INGEI category of parks and reserves, excluding the hectares corresponding to renewable and balanced forest.

· Reduction of paper production:
Harvested wood products store carbon from the forest harvest for different periods depending on the product. This measure takes into account the effect of a change in the production matrix, assigning a 10% shift from paper, pulp and industrial roundwood to sawnwood, which increases the carbon stored in the medium term.

· Continuation of afforestation measure:
This measure considers extending the proposal in the previously described afforestation measure, gradually adding hectares for afforestation between 2030-50, to reach a total of 300,000 ha at the end of the period, of which 150,000 ha correspond to permanent forest cover and 150,000 ha to forest plantations.

· Continuation of measure to increase area of native forest under management plan:
This measure follows the same line as the NDC measure "Increase area of native forest under management plan" described above. Its purpose is to gradually increase the managed area of native forest between 2030-2050 to reach a total of 150,000 ha managed by the end of the period.

The uncertainties considered in the model are shown in Table 3.14.

Table 3.14:
Sources of uncertainty modeled in the forestry sector.

Source of uncertainty	Description
Fires affecting hectares of native forest	Uncertainty associated with occurrence of forest fires and how much they affect hectares of native forest, given the historical distribution of these events. The distribution range for this uncertainty is between -30% minimum and +30% maximum.
Fires affecting forest plantations	Uncertainty associated with occurrence of forest fires, given the historical distribution of these events. The distribution range is between -47% minimum and +47% maximum.
Probability of occurrence of large-scale fires	Uncertainty associated with occurrence of a large-scale forest fire season for a specific year.
Change in frequency of forest harvests	Production of wood products and therefore the loss and emission of carbon can be affected by the change in frequency of forest harvests. The distribution range is between -10% minimum and +10% maximum.
Yield of forest plantations	Given the change in climatic conditions, it is possible there will be a change in forest plantation yield, which in turn affects the amount of carbon absorbed. The distribution range used for this uncertainty is between -10% minimum and +5% maximum.
Yield of hectares of native forest	Given the change in climatic conditions, it is possible there will be a change in native forest yield, which in turn affects the amount of carbon absorbed. The distribution range used for this uncertainty is between -2% minimum and +10% maximum.
Loss of native forest	Uncertainty about the loss of hectares of native forest due to other effects such as replacement of forest land and change of land use to other uses. The distribution range used for this uncertainty is between -30% minimum and +10% maximum.

Source: Prepared by the authors.
Note: The probability of occurrence of large-scale fires was modeled without integration with the rest of the sectors, since it simulates the randomness of fires in each year. When this element is "off," the model shows expected average fires, rather than the distribution of fire probabilities for each year. This is because for 2050 in particular the fire area is expected to be between x and 20x, but for the average between 2040-60 the value will be around 2x given that for most years the area affected is small and only rarely (~13.4%) are there seasons of large fires.

Table 3.15 shows the uncertainty considered for the measures in both the NDC and NDC+ scenarios.

Table 3.15:
Source of uncertainties associated with emission reduction measures in the forestry sector.

Source of uncertainty	Description
Afforestation	For the afforestation measure, uncertainty is between 20% and 105% of compliance with the measure by 2030.
Increase in native forest area under management plan	In this case, uncertainty is between 50% and 105% for compliance with the measure by 2030.
Decrease in native forest degradation due to forest replacement and change of land use to other uses	For the decrease in native forest degradation, estimated at 25% by 2030, uncertainty is between 70% and 110% of compliance with the measure, which is subject to stricter regulations to prevent forest replacement.
Decrease in degradation of native forest and plantations due to forest fires	Reduce the area of forest fires by 25% by 2030. Uncertainty for compliance is between 0% and 100% due to the more unpredictable nature of these phenomena.
Sustainable management of brown algae forests	Sustainable management of 1,000 ha of brown algae of the species *Lessonia nigrescens, Lessonia trabeculata and Macrocystis spp* by 2030. Uncertainty for level of implementation of this measure is between 90% and 110%.
Reduction in paper production	This measure determines the effect of a change in the production matrix, assigning a 10% change from industrial paper and roundwood to sawnwood. Uncertainty for level of implementation of this measure is between 90% and 110%.
Increase in protected areas	Uncertainty for level of implementation of this measure is between 90% and 110%, based on the 100,000 hectares proposed.
Continuation of the afforestation measure through 2050	Uncertainty for level of implementation of this measure is between 90% and 110%, based on the 300,000 hectares proposed.
Continuation of the measure to increase management plans through 2050	Uncertainty for level of implementation of this measure is between 90% and 110%, based on the 150,000 hectares proposed.

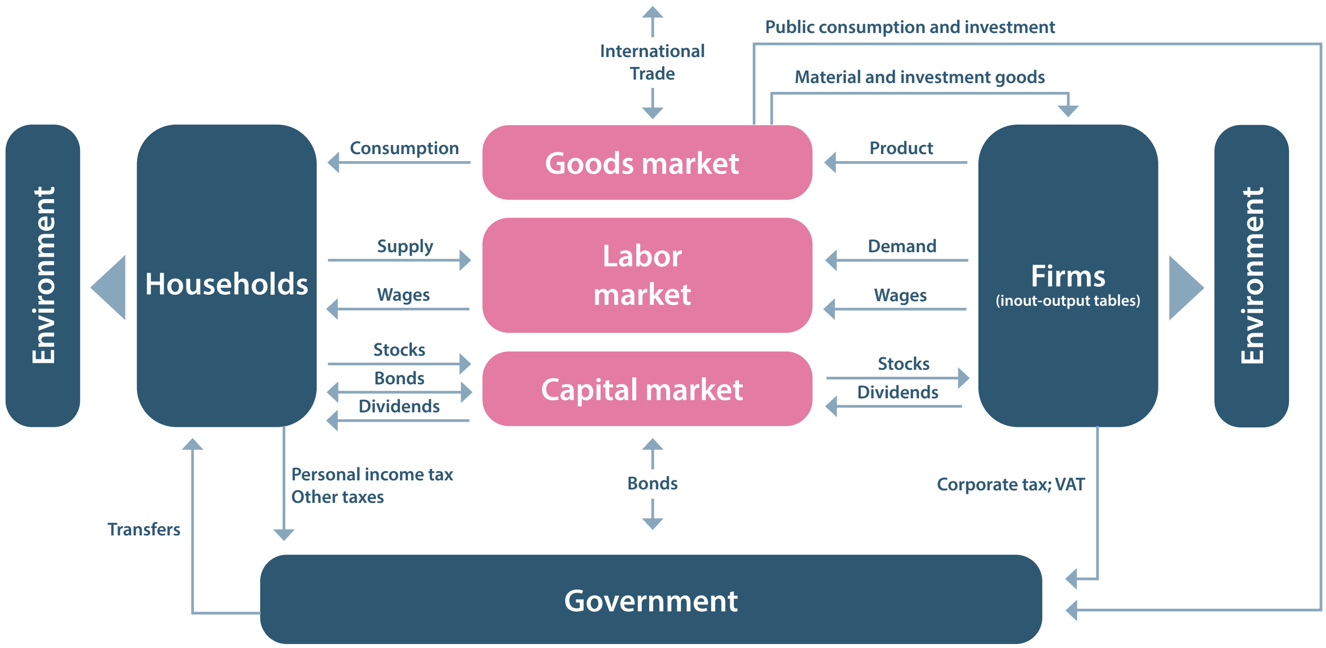
Source: Prepared by the authors.

3.7 Macroeconomic model

MEMO Overview

To evaluate the policy package, the study uses the MEMO dynamic stochastic general equilibrium model, which combines two lines of research: input-output and general equilibrium models. Its main agents and their interrelationships are shown in Figure 3.3.

Figure 3.3:
Schematic diagram of interactions of the Chilean economy in the MEMO model.



Source: Antosiewicz et al. (2020).

The model consists of the household sector (which, through a representative agent, maximizes utility of consumption and leisure); the business sector (which maximizes profits); and the government sector (which collects taxes and finances public consumption). An external sector responsible for trade with the rest of the world is also considered. The main features of the model are: i) division of the firm into sectors calibrated in an input-output matrix, with the aim of adapting the labor market to model workers' transitions between sectors, and ii) endogenous adaptation of technology related to energy use.

The sectoral structure of the model is calibrated using the most recent Chilean industry data obtained from an input-output matrix.[11] The following sectors and products are defined: agriculture and forestry, coal mining, petroleum mining, gas mining, copper mining and others, manufacturing industry, refined petroleum products manufacturing, fossil fuel electricity, renewable electricity, gas distribution, construction, transportation, commercial services and public services. Technical details, such as exact equations, calibration and solution methods of the MEMO model, can be found in Antosiewicz and Kowal (2016). The exact specification of the model used in this study differs slightly from the model described in Antosiewicz and Kowal (2016) following its adaptation to the needs of the present evaluation.

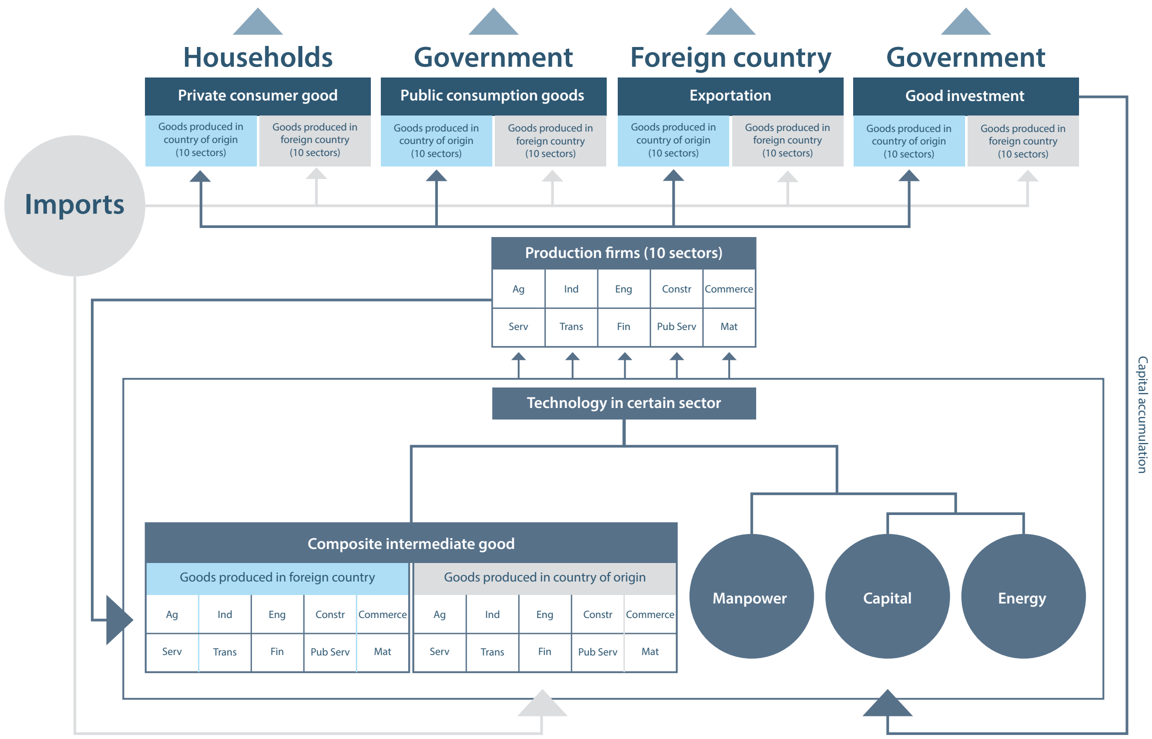
Structure and emissions by sector based on the input-output matrix

There are several distinct sets of parameters whose values need to be calculated. The main set contains the parameters that drive the production side of the model. These parameters can be further specified as those that drive the value-added structure of the sectors, investment and employee compensation in each sector, intermediate use structure that considers domestically produced and imported goods, and end use structure that also takes into account domestically produced and imported goods.

[11] Calibrating the MEMO model requires use of a symmetric input-output matrix that distinguishes domestic and imported intermediate and final use. The symmetric input-output matrix provided by the Central Bank of Chile (BCC) does not distinguish domestic and imported use. However, the BCC asymmetric input-output matrix does distinguish domestic and imported use, but it is constructed in an output-by-activity format. Therefore, it is not possible to directly calibrate the complete production structure of the model to this matrix. However, it was used to disaggregate the use of some sectors where disaggregation of the matrix of the Organization for Economic Cooperation and Development (OECD) was insufficient.

Figure 3.4 contains a schematic diagram of the production structure. Each firm operates a production function using a constant elasticity of substitution specification, nested to combine the factors of production. In the first stage, the firm combines capital and energy; the second stage consists of adding labor, while in the final stage this package is combined with materials (intermediate use). The materials package is composed of outputs from each sector, which are further broken down into imported and domestically produced parts. On the use side, the goods produced by each sector are purchased by households as private consumption, by government as public consumption, and by firms as investment and intermediate use, or for export.

Figure 3.4:
Sectoral aggregation scheme in MEMO model.



Source: Antosiewicz et al. (2020).

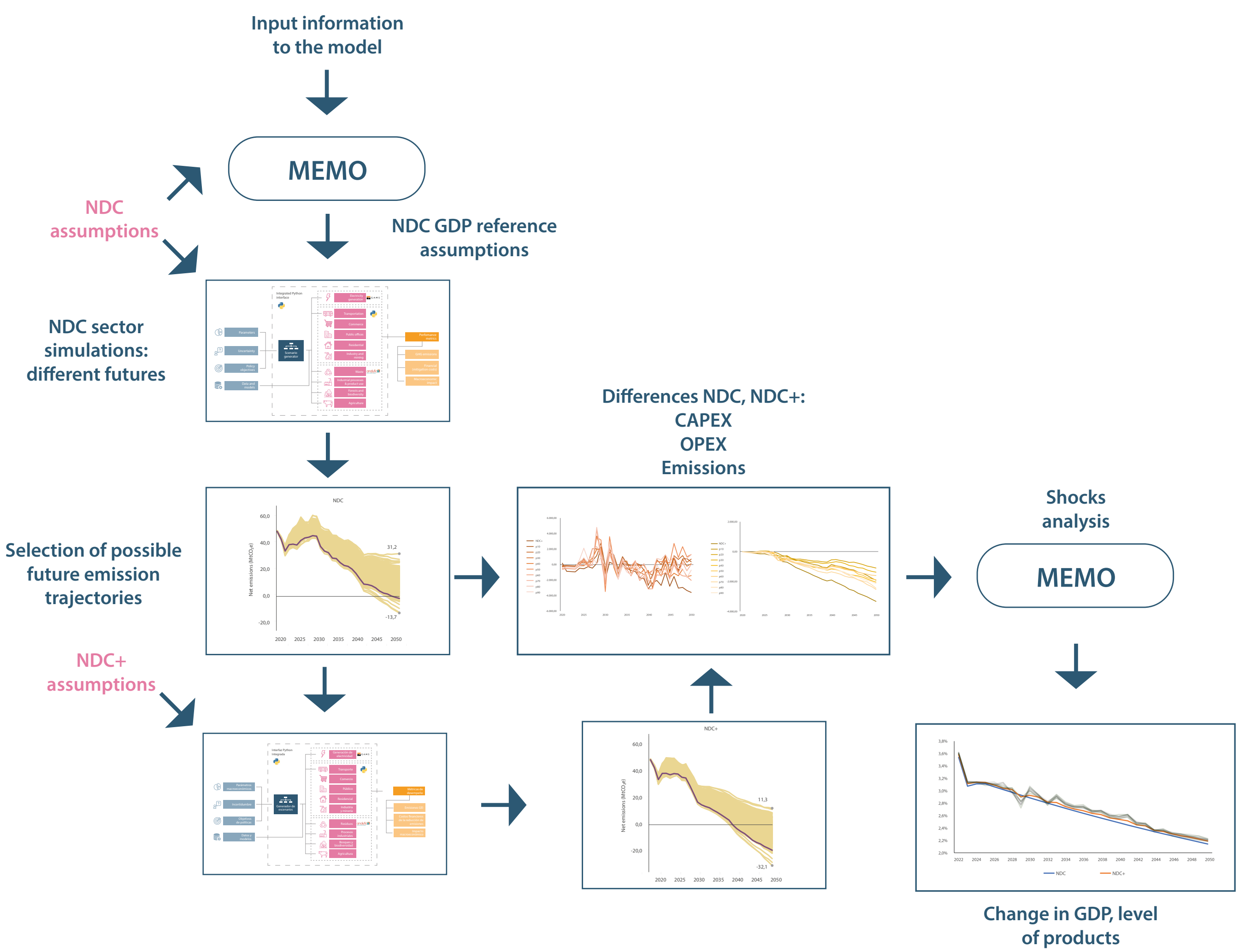
To calibrate the firm side of the model, the input-output matrix from the OECD statistics database was used. This is a 36-activity by 36-activity matrix using the International Standard Classification of All Economic Activities (ISIC-Rev4). However, for this study some sectors and products are disaggregated which are collapsed into a single activity in the OECD matrix. To make this disaggregation, such as the disaggregation of specific fossil fuels, the information has been supplemented with a highly disaggregated input-output matrix from the Central Bank of Chile (BBC). This additional matrix is in a format of 181 products by 111 activities (see Figure 3.4).

In the first step, the OECD input-output matrix is aggregated into the following sectors: 1) AGR: Agriculture, Forestry and Fishing; 2) MIN ENE: Mining of Energy Products; 3) MIN OTH: Mining of Metals and other ores; 4) RPP: Refined petroleum products manufacturing; 5) IND: Rest of manufacturing industry; 6) ENERGY: Electricity, gas, water supply and sewerage; 7) CONSTR: Construction; 8) TRANS: Transportation; 9) SERV: Commercial services; 10) PBL: Public utilities.

In the second step, various sectors related to the fossil fuel and electricity sector are disaggregated using the expanded input-output matrix supplemented with information from the International Energy Agency (IEA) on electricity generation by source.

A representation of the complete modeling process can be seen in Figure 3.5. In first instance, the production outputs obtained in the modeling exercise of the Nationally Determined Contributions package analyzed in Antosiewicz et al. (2020) are used as input to the sectoral models. Second, the sectoral models model the emissions with uncertainty analysis, and the CAPEX and OPEX paths are obtained for each emission future. Third, packages of emission reduction measures are compared with their respective emission changes, CAPEX and OPEX, in comparison with the reference strategy (in this case the NDC trajectory). Finally, impacts on aggregate demand and output variables by economic sector are obtained for each year, compared to the reference strategy.

Figure 3.5:
Schematic diagram of modeling strategy incorporating MEMO module.



Source: Prepared by the authors.

Modeling of packages of measures and selection of futures

The MEMO model analyzes the incremental impact of a "more robust" strategy (termed NDC+) compared to the current carbon-neutral strategy (NDC). Thus, the question that MEMO seeks to answer is "What will be the impact on GDP, aggregate demand components and sectoral activity of taking additional emission reduction actions beyond those analyzed in the NDC strategy?"

Given the complexity associated with the multitude of sectoral uncertainties and the large number of measures analyzed, this analysis would require tens of thousands of simulations in MEMO, which due to time constraints would not be possible. As a result, the following macroeconomic simulation strategy was chosen:

1. Model a sample of 10 scenarios, representing a set of possible futures. For this, nine cut-off points were chosen from the 2050 emission deciles of the NDC strategy, additionally into the future with the parameters evaluated with the reference assumptions.

2. For each sector, a package of incremental emission reduction actions was developed.

3. For the 10 selected futures, incremental CAPEX and OPEX reductions were calculated for each sectoral package of measures.

4. The MEMO model was run for the 10 selected futures based on the priors estimated in the previous step.

This provided a range of incremental impact on GDP, macroeconomic variables such as household consumption, total investment (public plus private), government spending, exports and imports of the NDC+ strategy, in relation to the current carbon-neutrality strategy known as NDC. The results are presented in Chapter 4.

4
Results

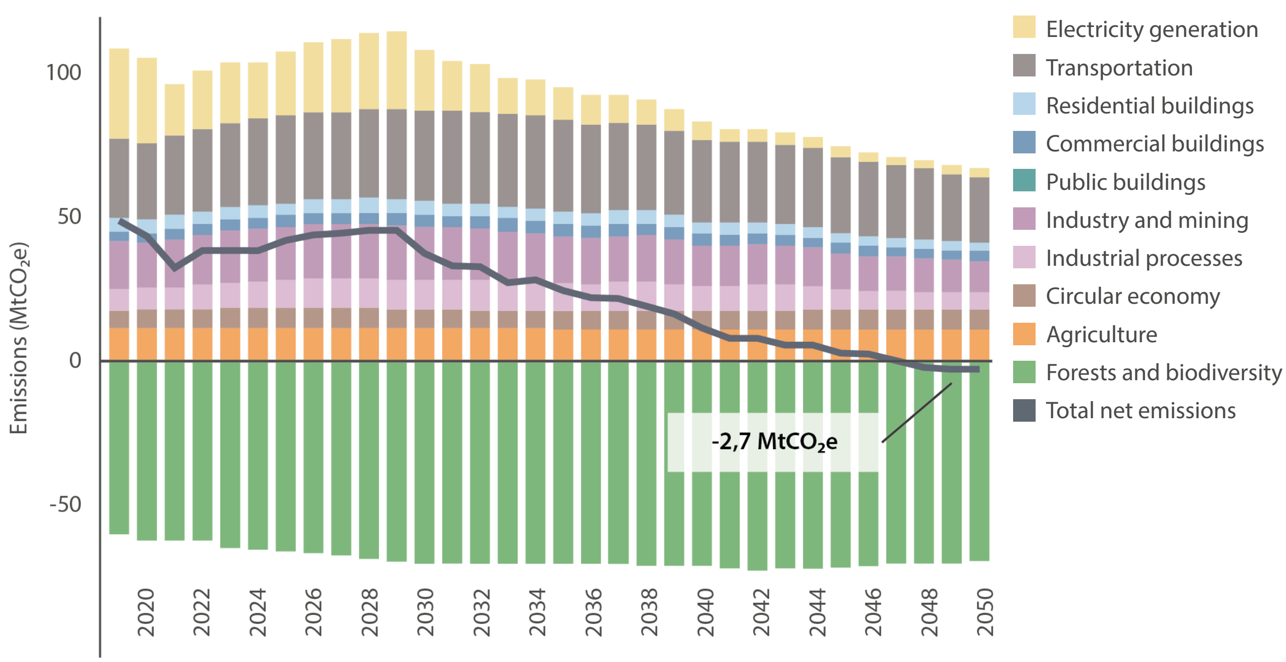
4.1 Introduction

This chapter describes the results derived from the integrated evaluation model set out in the previous chapter and from applying the robust decision-making framework. The first section deals with the results of the original Nationally Determined Contribution (NDC) carbon-neutrality strategy under the trend assumptions, with special emphasis on sector-level results and the capacity of the NDC to meet the carbon-neutrality target in 2050. The second addresses the results of the NDC strategy under uncertainty. On this basis, the third section presents the results of the analysis of the NDC vulnerability under uncertainty, identifying the particular conditions under which this strategy fails to meet the carbon-neutrality target in 2050. Finally, the last two sections of this chapter analyze different NDC robustness options and the macroeconomic implications of the more expansionary strategy (NDC+) under different futures.

4.2 Results of the carbon-neutrality strategy under the reference future

The results of this analysis indicate that the NDC is capable of meeting the carbon neutrality target in 2050, but has difficulties in meeting the emission reduction and carbon budget targets set for 2030. Figure 4.1 shows the simulation results for the current carbon-neutrality strategy (NDC) under the reference future (current assumptions). The bars reflect the dynamics of emission reductions in the different sectors; the solid line indicates the net emissions trajectory considering the dynamics of all sectors. Under the reference future, net emissions decrease from 50 MtCO2eq in 2019 to slightly less than zero in 2050. A substantial proportion of this decrease is due to reduced emissions in the power sector and increased carbon sequestration in the forest and biodiversity sector.

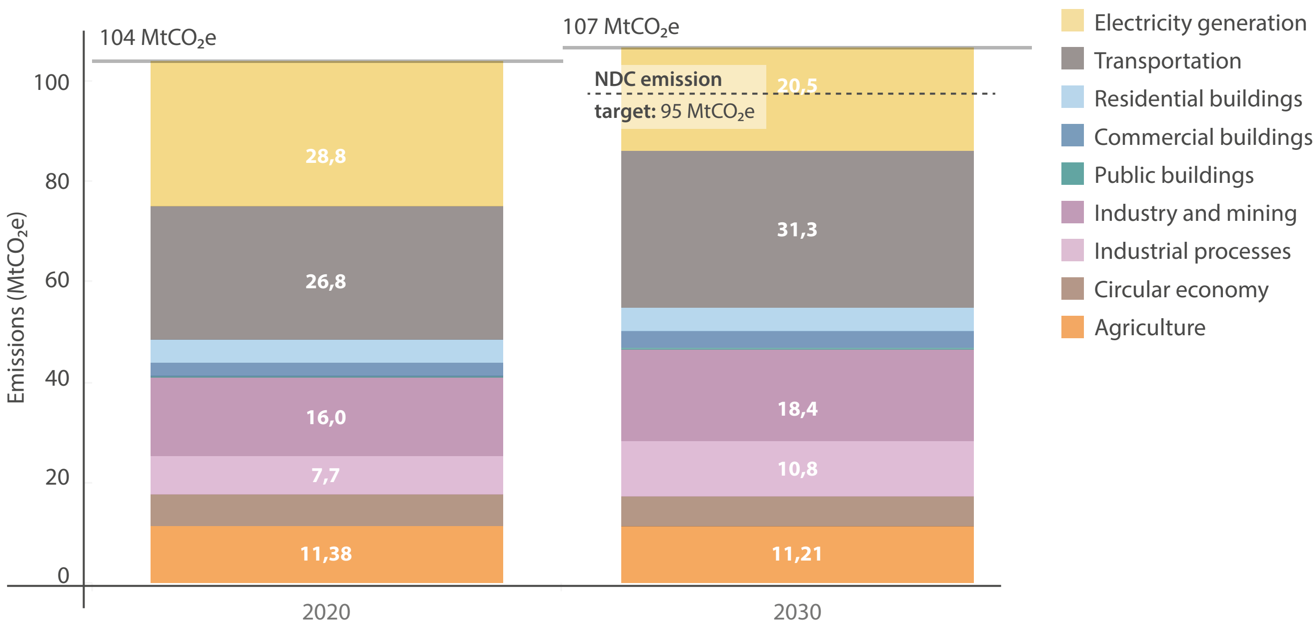
Figure 4.1:
Emissions by sector for reference scenario and NDC strategy.



Source: Prepared by the authors.

Figure 4.2 depicts the results of the NDC strategy comparatively in 2020 and 2030 for all sectors except forests and biodiversity. The dotted line indicates the 2030 emissions target set by the Chilean government, but in 2030 the NDC strategy does not meet this target. In fact, total emissions increase slightly mostly due to the transportation, industrial transformation, industry and mining sectors. Emissions from the electricity sector decrease, but not enough to offset increases in the sectors listed above. Finally, with respect to the carbon budget proposed by the NDC, these results imply that total emissions from 2020 to 2030 in the reference simulation (1,163 $MtCO_2eq$) exceed the proposed carbon budget of 1,100 $MtCO_2eq$, which highlights the importance of considering bringing forward implementation of NDC+ strategy measures, if the aim is to increase the probability of meeting the NDC targets by 2030.

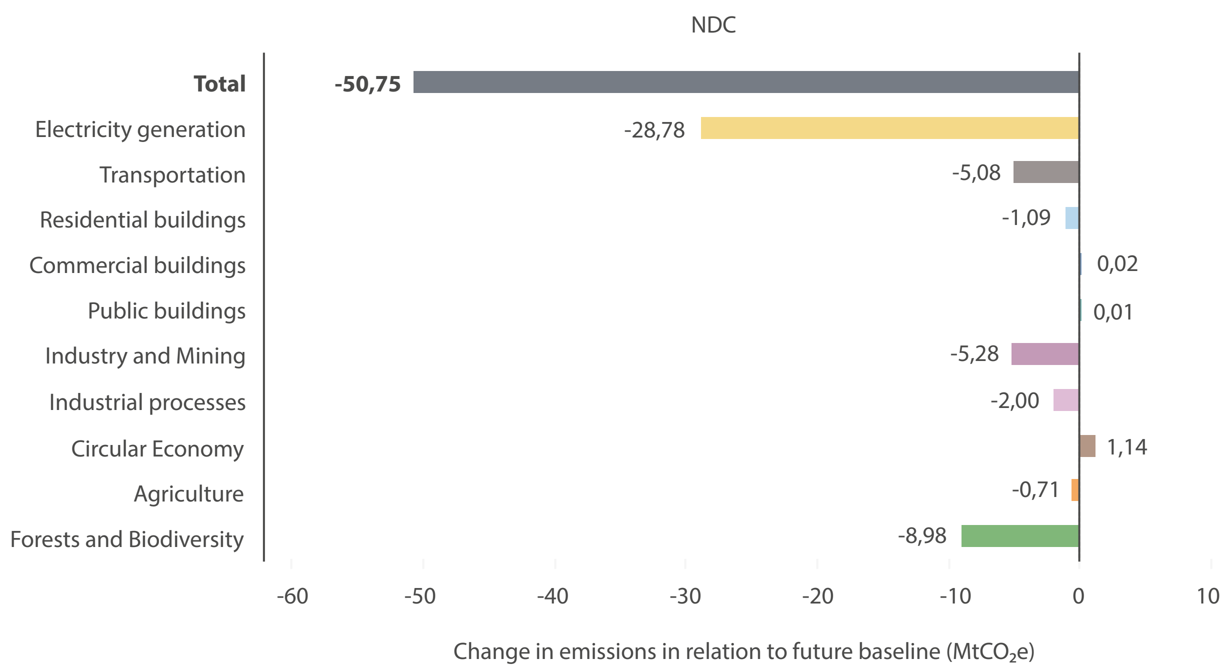
Figure 4.2:
Emissions 2020 and projected emissions for 2030.



Source: Prepared by the authors.

Figure 4.3 depicts the net change in emissions by sector between 2019-50 under the reference future. The NDC strategy would reduce emissions by 51 $MtCO_2eq$. The most significant reductions take place in the electricity sector (for example, -29 $MtCO_2eq$, 56% of total), followed by increases in carbon sequestration capacity in forests and biodiversity (-9 $MtCO_2eq$), and finally in the industry and mining, and transportation sectors. The rest maintain a level of emissions comparable to 2019.

Figure 4.3:
Change in emissions by sector, 2019-50.



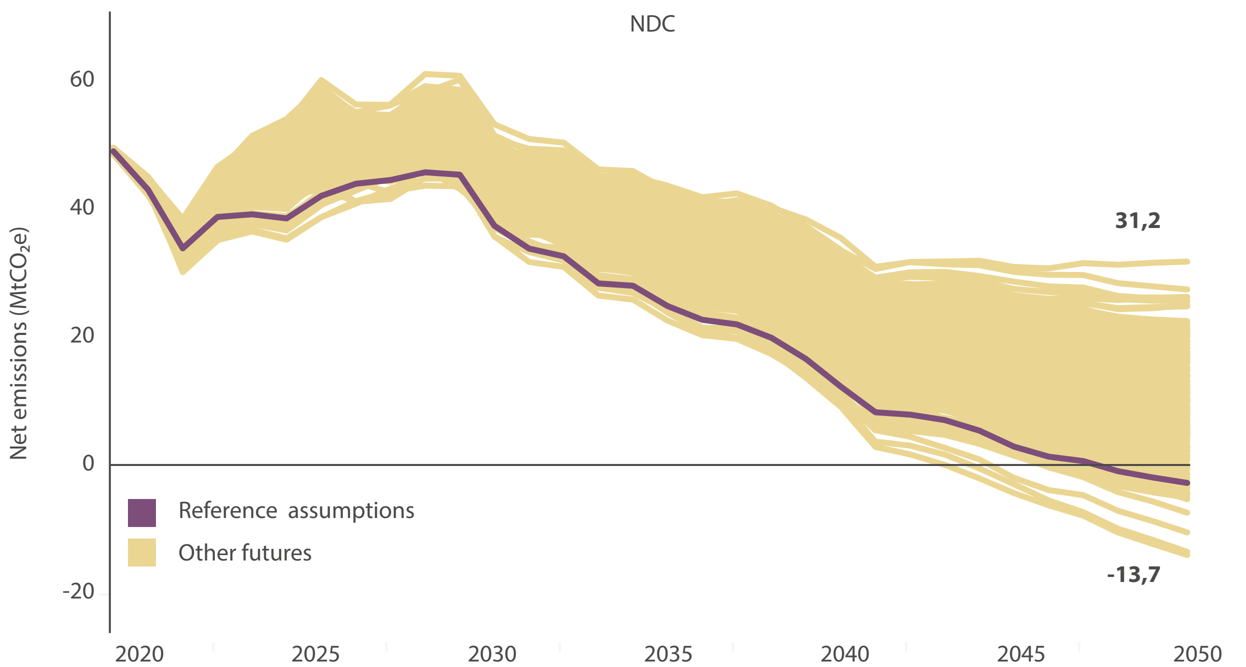
Source: Prepared by the authors.

4.3 NDC with uncertainties

Figure 4.4 reflects the results of the NDC strategy under 1,000 different futures. These futures simultaneously consider the uncertainty associated with a wide range of economic, technological and environmental factors (see Chapter 4). The solid line denotes the reference base future described in Section 5.2; the gray lines denote individual futures within the ensemble of 1,000 futures considered.

The behavior of each of these futures with the carbon-neutrality target in 2050 shows that there are many plausible emissions trajectories in which emissions end up well above the carbon-neutrality target. In fact, the range of emissions in 2050 is quite wide, covering between -13.7 $MtCO_2eq$ and 31.2 $MtCO_2eq$.

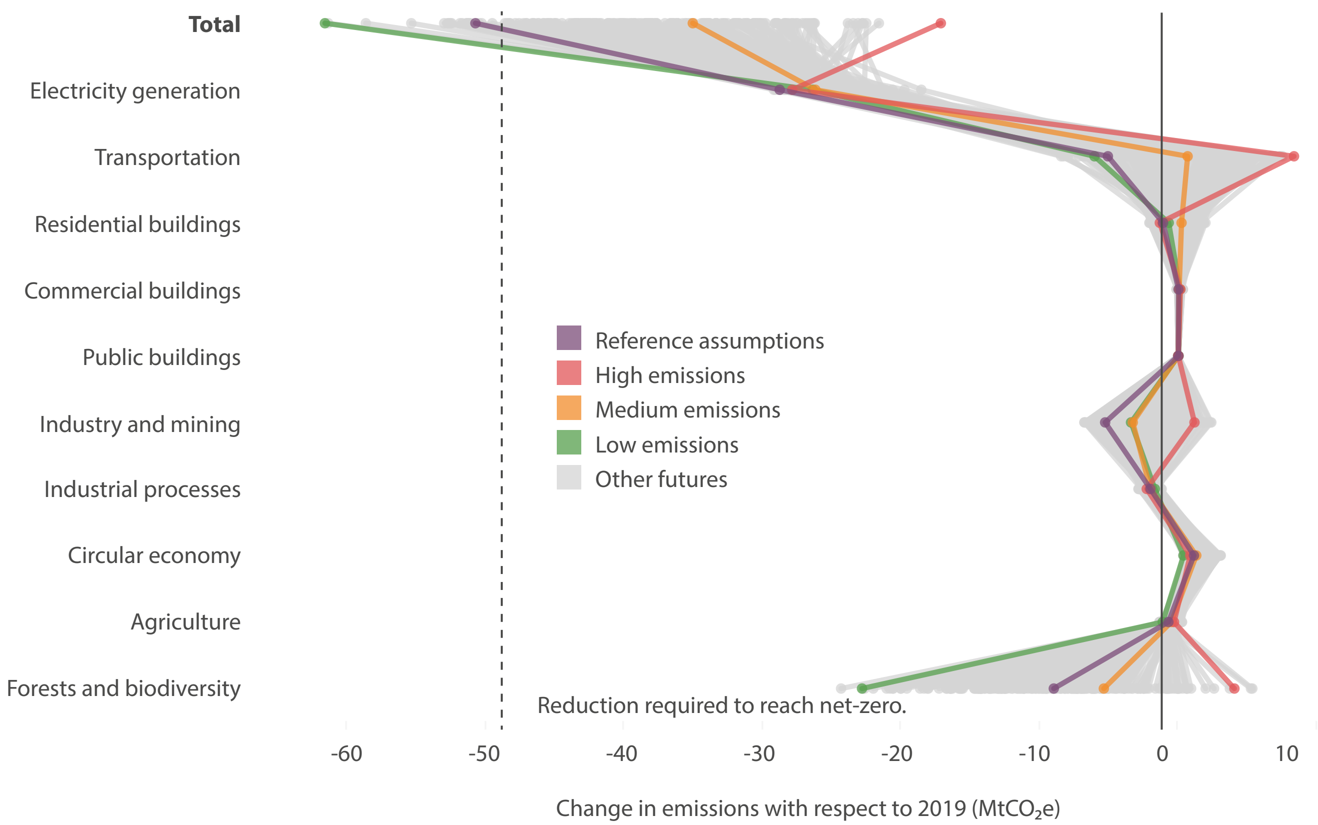
Figure 4.4:
Total net emissions to 2050 in 1,000 futures for NDC strategy.



Source: Prepared by the authors.

Figure 4.5 depicts the change in emission reductions for the 10 sectors analyzed, under the ensemble of 1,000 futures considered. Each line connects a specific future and the rows show the NDC results in each sector. Uncertainty in emission reductions originates mainly due to the uncertainty associated with the transportation and forest and biodiversity sectors. The cases of higher emission reductions are mostly due to a substantial increase in the carbon sequestration capacity of the forest and biodiversity sector (green line in Figure 4.5). The cases of smaller emission decreases result from increases in emissions in the transportation sector, combined with net increases in emissions in forests and biodiversity (red line in Figure 4.5). Finally, it follows from these results that in theory a future could be feasible in which total net emission emissions reductions would be even smaller if emission reductions in industry and mining were greater than those proposed by the NDC, in combination with favorable results in all other sectors, similar to that shown as "low emissions" in Figure 4.5. This would reduce emissions by another 3 $MtCO_2eq$.

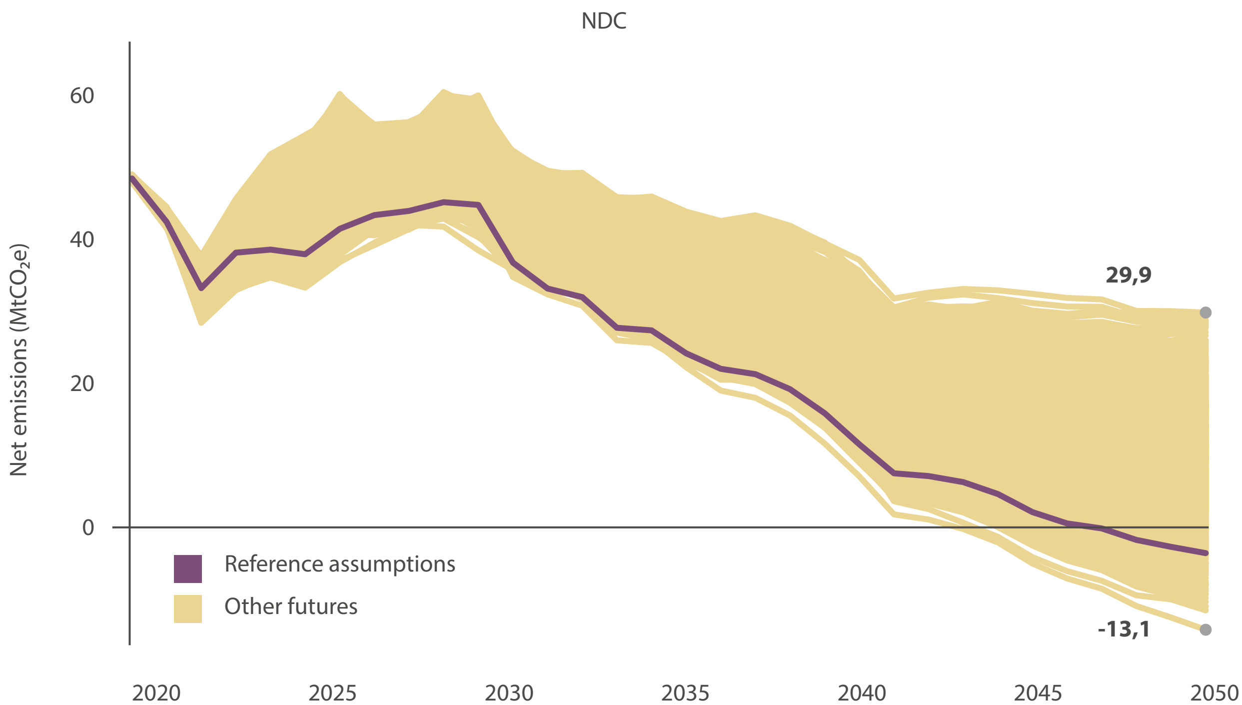
Figure 4.5:
Change in emissions by sector for each of the 1,000 futures.



Source: Prepared by the authors.

Next, an experiment considering 1,001 futures instead of 101 was run to verify whether these findings depended on the sample size; it was observed that the range of variation of the 1,001 futures ensemble is very similar to that described previously (see Figure 4.6).

Figure 4.6:
Total net emissions to 2050 in 1,001 futures for NDC strategy.

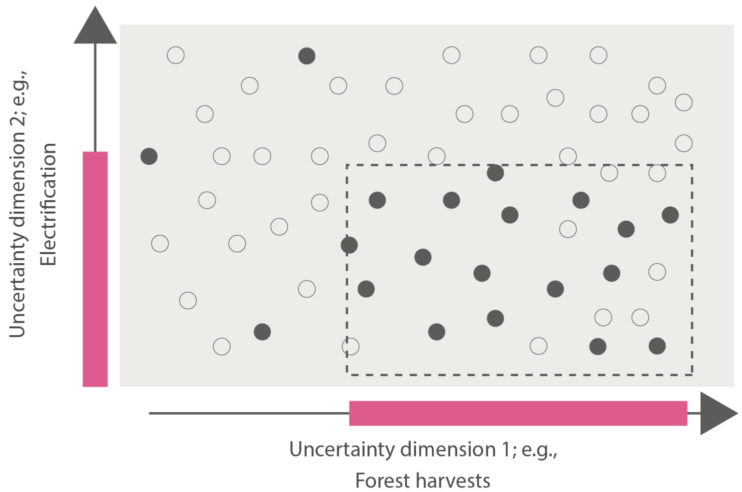


Source: Prepared by the authors.

4.4 Vulnerability analysis

Vulnerability analysis in a study of robust decision making is based on application of the scenario discovery method (Bryant and Lempert, 2010; Groves and Lempert, 2007; Molina-Pérez, et al., 2019). The method consists of performing simulation experiments using uniform stratified sampling on the uncertainty factors considered through variance reduction techniques (Latin hypercube), which make the experiment highly efficient. These results are then classified into two groups: those that meet the strategic objectives (success: achieving carbon neutrality) and those that do not (failure: not meeting the carbon neutrality target). Finally, statistical learning techniques are used to identify clusters with high density of cases of interest (failure). The objective is to be able to describe the vulnerability conditions of a strategy as a cluster of outcomes which in turn is described as the combination of specific uncertainty ranges (Figure 4.7). This process makes it possible 1) to discriminate the most relevant uncertainty factors for the analysis and 2) to synthesize the results of the numerical analysis.

Figure 4.7:
Example of futures clustering for two dimensions.



Source: Prepared by the authors.

For this study, the vulnerability analysis was performed in two phases. In the first, a standard sensitivity analysis was conducted to identify the uncertainty factors that will have the greatest marginal impact on total emissions in 2050. In the second phase, the results of the sensitivity analysis were used as inputs for the scenario discovery process described above. The objective of this second phase is to identify combinations of ranges of values of uncertainty factors that lead to conditions of vulnerability (for example, not meeting the carbon-neutrality target in 2050).

Figure 4.8 is a tornado plot showing the results of the sensitivity analysis. Each factor has been arranged according to the marginal impact on the response of interest (for example, total emissions in 2050). The size of the bar indicates the type of shock simulated in the uncertainty factors. The larger bar indicates positive variations with respect to the reference; the smaller bar indicates negative variations. The horizontal axis denotes the type of disturbance generated by the parameter variation. On the right, positive perturbations over the level of emissions in 2050; on the left, negative perturbations. The first column describes the sensitivity of exogenous factors (Xs); the second, the sensitivity of emission reduction actions (xLs).

According to the results, the four exogenous factors that generate the greatest disruption in emissions levels in 2050 are associated with the forestry sector:

- Frequency of forest harvesting.
- Native forest yields.
- Plantation yields.
- Demand for firewood.

In addition, two factors in the transportation sector also show a considerable marginal impact on the level of emissions in 2050:

- Electrification of private transport.
- Adoption of hydrogen in trucks.

Finally, there are other important factors associated with the industry and mining sector and the electricity sector. These are: gross domestic product (GDP), cost of concentrated solar power (CSP) investment, probability of hydrological surplus, copper production levels and energy intensity of miscellaneous industrial activities.

Figure 4.8:
Analysis of sensitivity to variation of one factor in emissions in 2050.

Source: Prepared by the authors.

This sensitivity analysis identifies the individual effect on emissions in 2050 of each of the uncertainties considered. However, based on these results, it is not possible to examine why the interactions between these factors generate conditions of vulnerability. Thus, in the second phase of the analysis, the scenario discovery method was used to quantitatively identify the combinations of uncertainty factors associated with high-emission futures in the experimental ensemble considered. For this purpose, the different emissions trajectories were transformed into a set of results with two categories: i) vulnerable futures, that is, those resulting in high emissions in 2050 (above 5 MtCO_2eq), and ii) non-vulnerable futures, that is, those involving carbon-neutral emissions trajectories. From this approach, the combination of factors associated with a high proportion of vulnerable futures is defined as an NDC vulnerability condition.

To identify these vulnerability conditions, different combinations of values were analyzed for the most sensitive uncertainty factors, considering the 1,000 trajectories of the NDC strategy. The analysis gave rise to two vulnerability conditions: i) one corresponding to "Low level of forest sequestration and low rate of transport electrification" (vulnerability 1 or V1) and ii) another identified as "High cost of solar technologies, low decarbonization of freight transport and high energy intensity in copper production" (vulnerability 2 or V2).

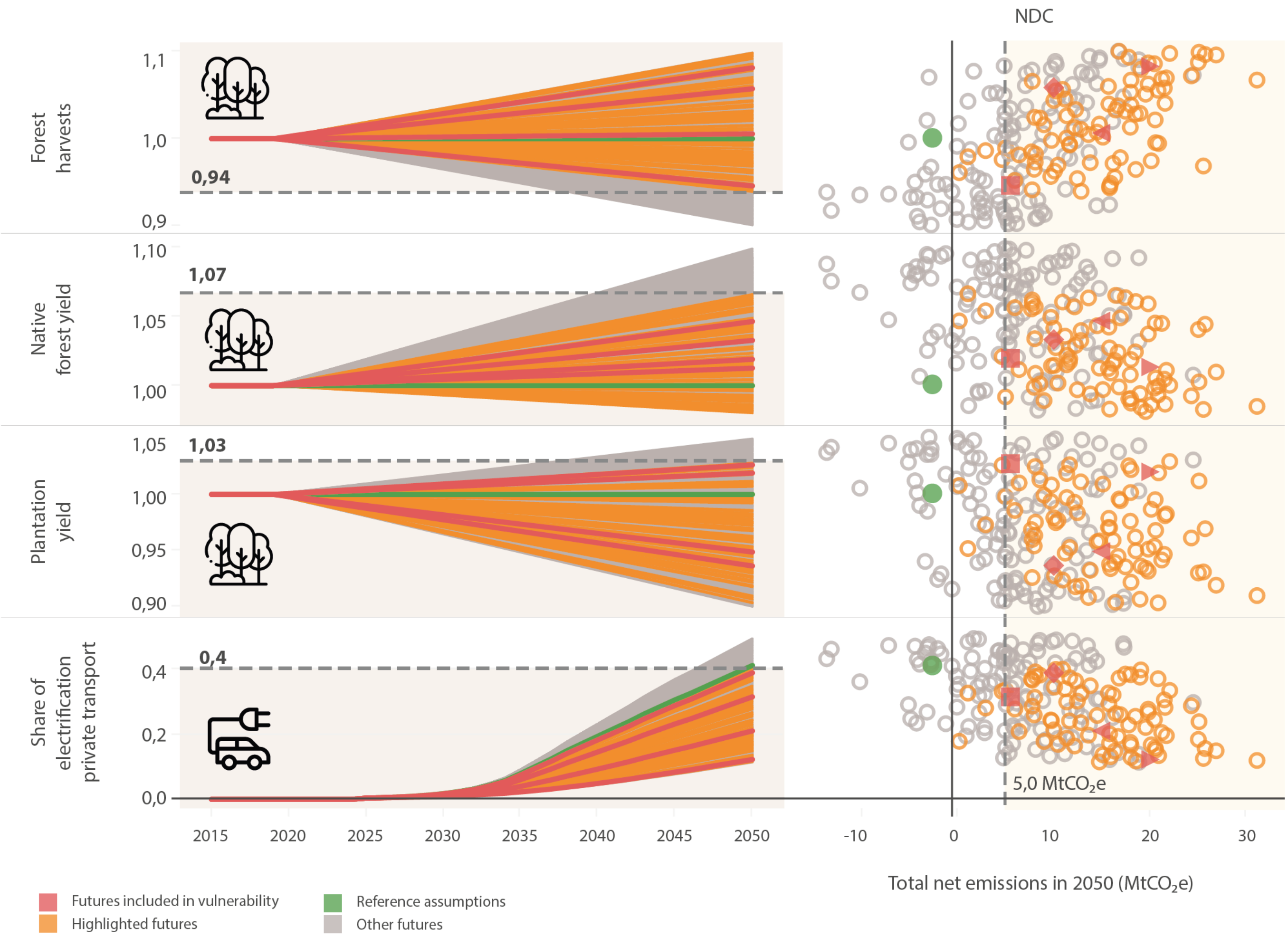
Vulnerability 1 is defined by the combination of four conditions:

- High frequency of forest harvesting.
- Low native forest yields.
- Low plantation yields.
- Low electrification of private transport (with respect to the total).

These conditions capture 55% of all cases where emissions in 2050 are above 5.0 MtCO_2eq (79/143). Additionally, in the set of futures that share these conditions, 94% constitute high emissions cases.

Figure 4.9 describes these vulnerability conditions quantitatively. The left panel shows the trajectories over time for each of these uncertainty factors. The right panel reflects dispersion of results with respect to each of these uncertainty dimensions and total emissions in 2050. The futures included in this vulnerability condition are indicated by orange lines in the left panel and by orange circles in the right panel. The four red lines and four red dots represent four futures within the vulnerability, leading to approximately 5 MtCO_2eq, 10 MtCO_2eq, 15 MtCO_2eq and 20 MtCO_2eq of emissions. These futures are used as a reference when evaluating how the distribution of outcomes changes under the revised strategies described below.

Figure 4.9:
Vulnerability 1 factors over time and scatter plot of 2050 factor value and net emissions in 2050 for 1,000 futures for NDC strategy.



Source: Prepared by the authors.
Note: Vulnerability 1 factors over time are on the left; the scatterplot of the 2050 factor value and net emissions in 2050 for 1,000 futures on the right. Orange lines and circles correspond to futures described by vulnerability 1. Gray lines and circles correspond to futures that are not described by vulnerability 1. Green lines and dots indicate factors and outcomes of emissions for the reference future. Dark red lines and dots indicate three futures selected to show a range of emission outcomes (~ 5, ~ 10 and ~ 20 $MtCO_2eq$).

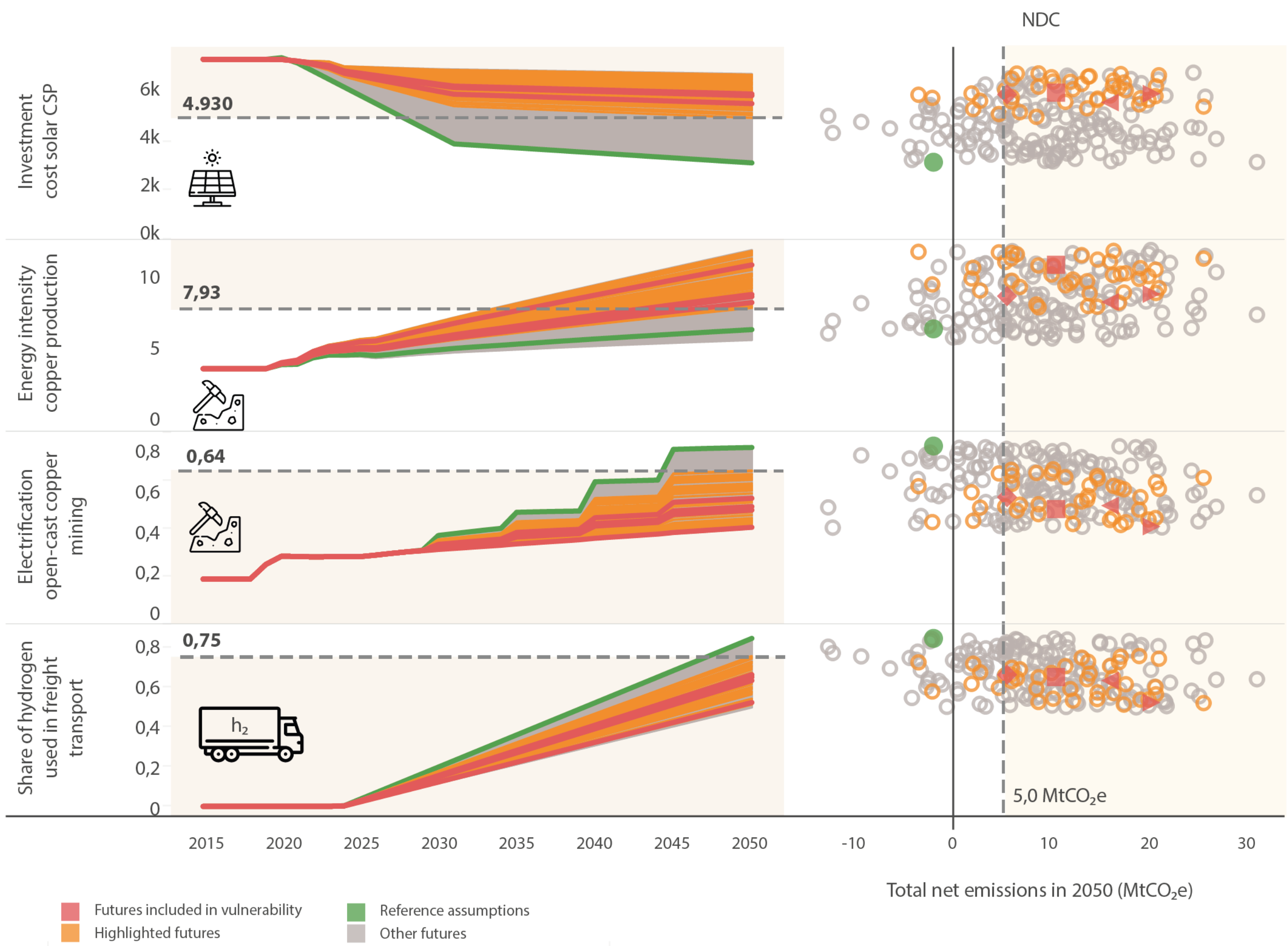
Vulnerability 1 does not capture all the high-emission futures (it excludes 45% of high-emission futures). To identify the uncertainty factors associated with the vulnerable futures not captured by vulnerability 1, an additional experiment was run in which the four factors associated with vulnerability 1 are held constant, while the rest of the uncertainties considered vary across the 1,000 futures analyzed.

Similarly, the scenario discovery method was used to identify vulnerability condition 2 ("High cost of solar technologies, low decarbonization of freight transport and high energy intensity of copper production") which captures 42% of the remaining high emission cases not identified by vulnerability 1. Specifically, vulnerability condition 2 is described by the following ranges of values:

- Cost of concentrated solar thermal power technology.
- Energy intensity of copper production.
- Electrification of open-pit copper mine.
- Use of hydrogen in freight transport.

Figure 4.10 describes quantitatively the combination of uncertainty conditions associated with vulnerability 2. The four red lines and four red dots represent four futures in vulnerability 2 leading to approximately 5 $MtCO_2eq$, 10 $MtCO_2eq$, 15 $MtCO_2eq$ and 20 $MtCO_2eq$ of emissions. These futures are used as a reference when evaluating how the distribution of outcomes changes under the strategies reviewed below.

Figure 4.10:
Vulnerability 2 factors over time and scatter plot of the 2050 factor value and net emissions in 2050 for 1,000 futures for NDC strategy.



Source: Prepared by the authors.
Note: Nota: Vulnerability 2 factors over time are on the left; scatterplot of the 2050 factor value and net emissions in 2050 for 1,000 futures on the right. The orange lines and circles correspond to futures described by vulnerability condition 2. Gray lines and circles correspond to futures not described by vulnerability 2. Green lines and dots indicate emission factors and outcomes for the reference future. Dark red lines and dots indicate three futures selected to show a range of emission outcomes (~ 5, ~ 10 and ~ 20 $MtCO_2eq$).

The two vulnerability conditions described in this section capture most of the futures where 5 $MtCO_2eq$ net is exceeded in 2050. There are other futures with high emissions in the ensemble of futures analyzed; however, these two vulnerabilities are the most dominant.

4.5 Expansion of the nationally determined contribution

Once the vulnerability conditions of the NDC strategy have been identified, the next step is to examine proposals for expansion of the reference strategy that can mitigate vulnerabilities. For this purpose, as a first exercise, the NDC+ strategy was designed, which considers all the possible expansion actions recommended by the experts consulted in the project working groups. Table 4.1 describes the additional actions included in this NDC+ strategy.

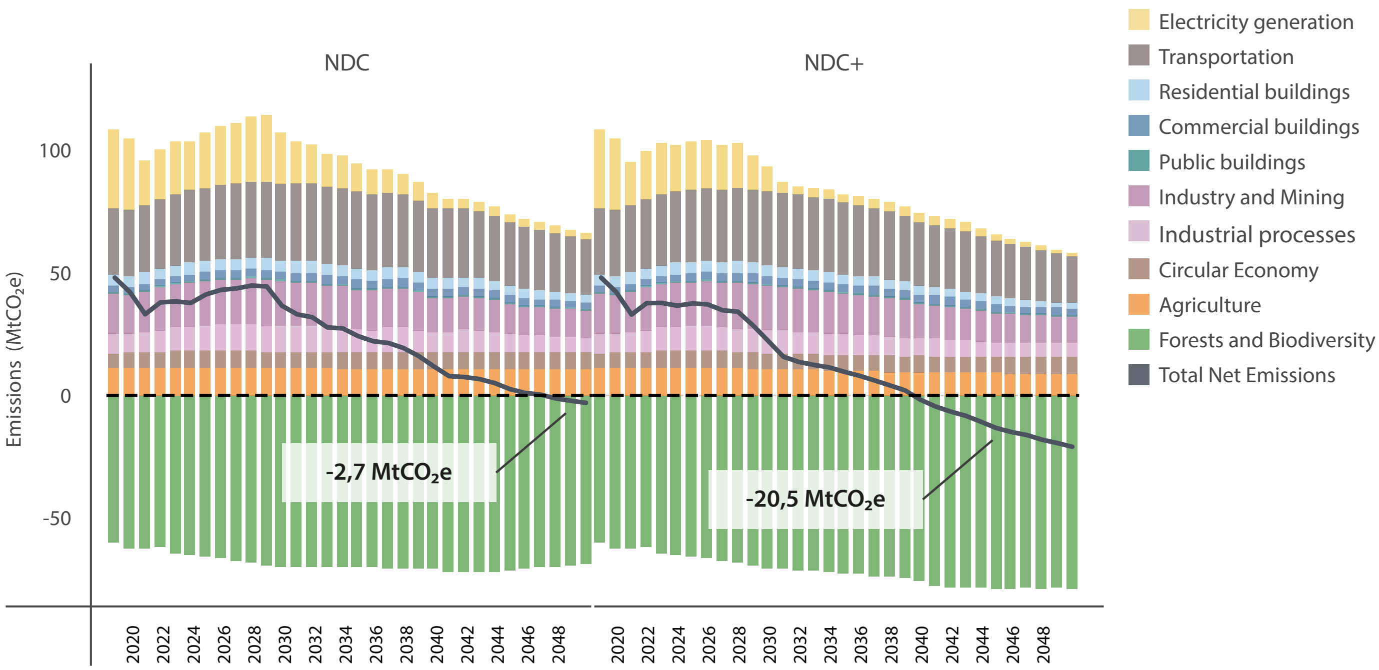
Table 4.1:
Additional actions included in the NDC+ strategy.

Sector	Action
Electricity	Retirement of coal plants.
Transportation	Increased use of bicycles instead of private automobiles. Increased use of public transport instead of private automobiles. Increase in teleworking. Blending with alternative fuels in aviation.
Residential	Thermal retrofitting of existing dwellings.
Industry and mining	New energy sources for copper and steel production.
Industrial processes	New refrigerant handling plants.
Circular economy	New composting plants.
Agriculture	Regenerative agriculture: application of organic amendment. Holistic livestock management. Reduction in beef consumption.
Forests and biodiversity	Increased afforestation post 2030. Increase in forest management area post 2030. Increase in protected areas. Sustainable management of brown algae. Reduction of paper production.

Source: Prepared by the authors.

Figure 4.11 shows comparative results of the NDC+ strategy and of the original NDC strategy under the reference future. The results of the NDC+ strategy under the reference future assumptions show two important differences from the original NDC strategy: i) NDC+ strategy achieves a higher degree of emission reductions in 2050 (-20 $MtCO_2eq$) and ii) also achieves carbon neutrality faster than the original NDC (2040).

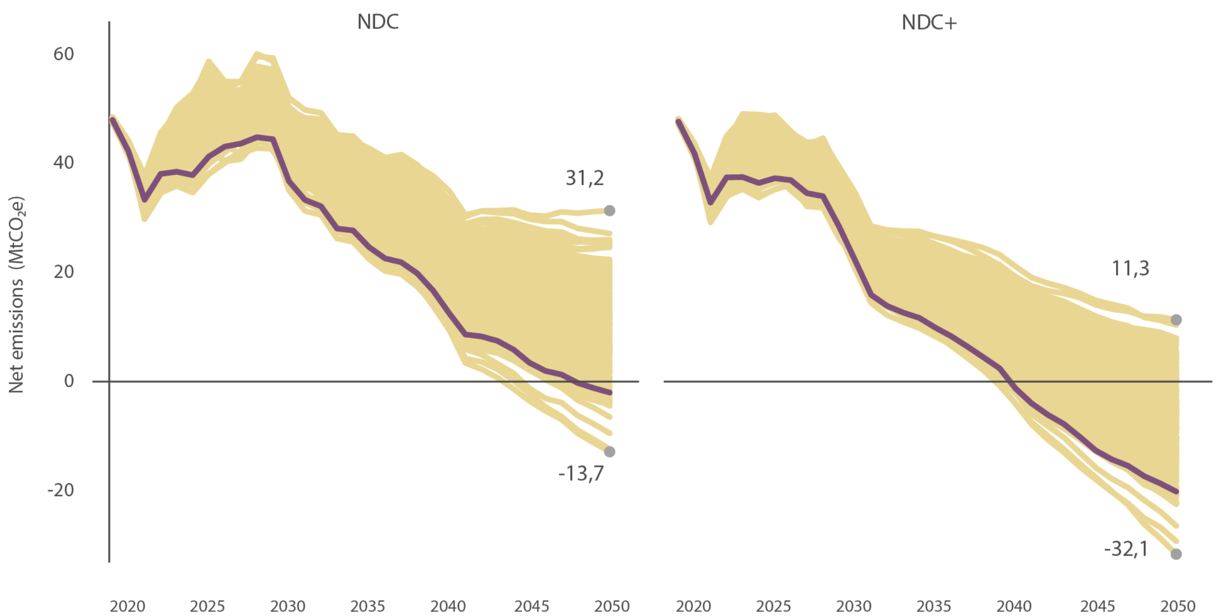
Figure 4.11:
Emissions by sector for NDC and NDC+ strategies under reference case assumptions.



Source: Prepared by the authors.

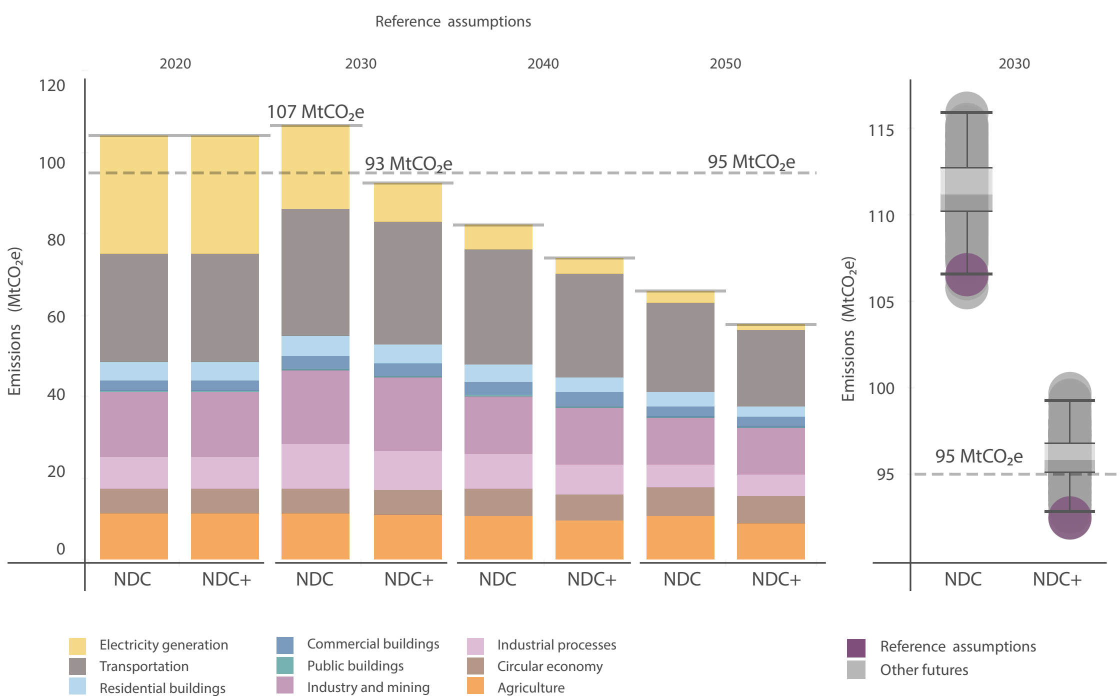
Similarly, Figure 4.12 compares the results of the NDC and NDC+ strategies under the same set of 1,000 futures considered in this study. The NDC+ strategy meets the 2050 carbon-neutrality target in a larger number of futures than the original NDC. In fact, the NDC+ strategy reduces the change in level of net emissions in 2050 in a range between -32.1 $MtCO_2eq$ and +11.3 $MtCO_2eq$, and in this case 83% of the simulations result in futures where net emissions are equal to or less than zero in 2050. However, a considerable number of futures show that the level of abatement in 2050 is much higher than the carbon-neutrality target.

Figure 4.12:
Total net emissions for NDC and NDC+ strategies under 1,000 futures.



Source: Prepared by the authors.

Figure 4.13:
Emissions in 2030 for reference assumptions and in 1,000 futures for NDC and NDC+ strategies.

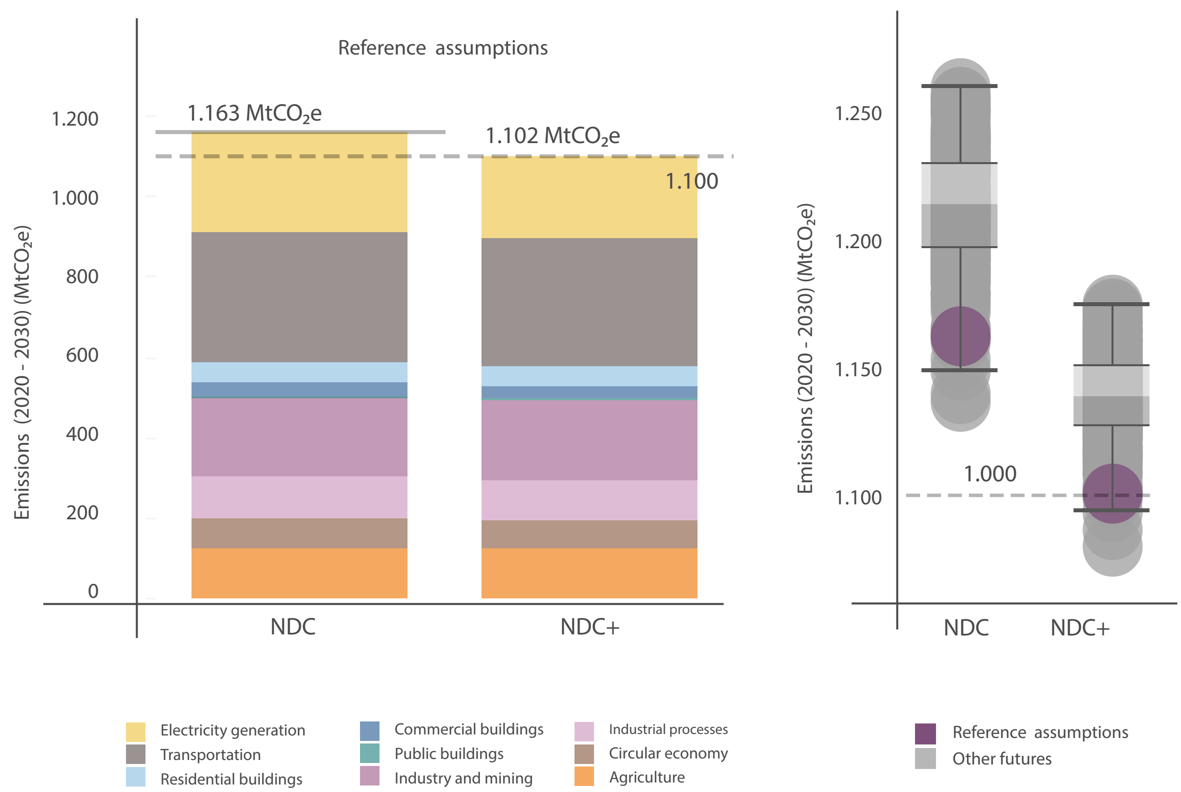


Source: Prepared by the authors.

When comparing the results of these strategies with respect to the 2030 emission reduction targets, significant differences are apparent. Figure 4.13 performs the operation on 10-year time slices, taking as a reference the emission reduction target of 95 $MtCO_2eq$ in 2030. The left panel presents this comparison for the reference future; the right panel compares its results considering the 1,000 futures ensemble. The first shows that, in contrast to the original NDC strategy, NDC+ meets the Chilean government's stated goal of reducing emissions by 2030. This is even more remarkable considering the results of both strategies under uncertainty (right panel). In this case, the original NDC strategy never meets the 2030 emission reduction target, while the NDC+ strategy is capable of meeting this target in 25% of considered futures.

Figure 4.14 shows the differences in results of the two strategies with respect to the carbon budget proposed by the Chilean government between 2020-30. In this case, the NDC+ strategy comes very close to meeting the carbon budget target of 1,100 $MtCO_2eq$ (between 2000-30) for the reference assumptions, while the original NDC strategy does not meet this target under the same assumptions. However, when considering the ensemble of 1,000 futures in this study, NDC+ meets the carbon budget in only a small proportion of the futures considered.

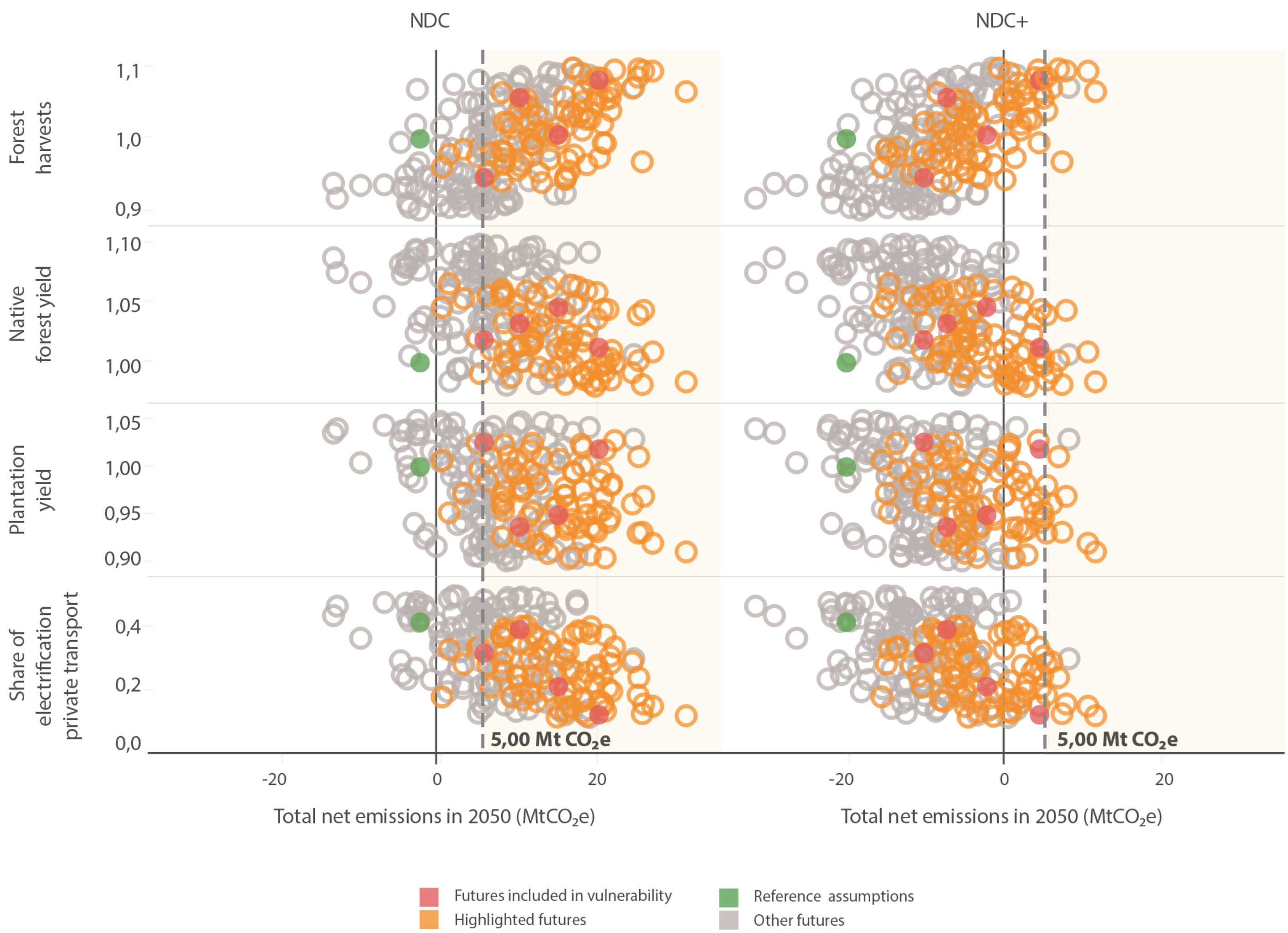
Figure 4.14:
Carbon budget (total emissions between 2020-30) for reference assumptions and in 1,000 futures for NDC and NDC+ strategies.



Source: Prepared by the authors.

Figure 4.15 compares the results of the two strategies considering the uncertainty conditions of vulnerability 1; the horizontal axis indicates the vulnerability threshold for high-emission futures (5 $MtCO_2eq$). In this case, two differences in the results of these strategies emerge as relevant. The first is that in the NDC+ strategy the number of cases above the 5 $MtCO_2eq$ threshold decreases substantially compared to the original NDC strategy. The second is that many of the cases identified as vulnerable under the original NDC strategy (orange circles) are no longer vulnerable under the NDC+ strategy.

Figure 4.15:
Net emissions in 2050 versus vulnerability 1 factors for NDC and NDC+ strategies.



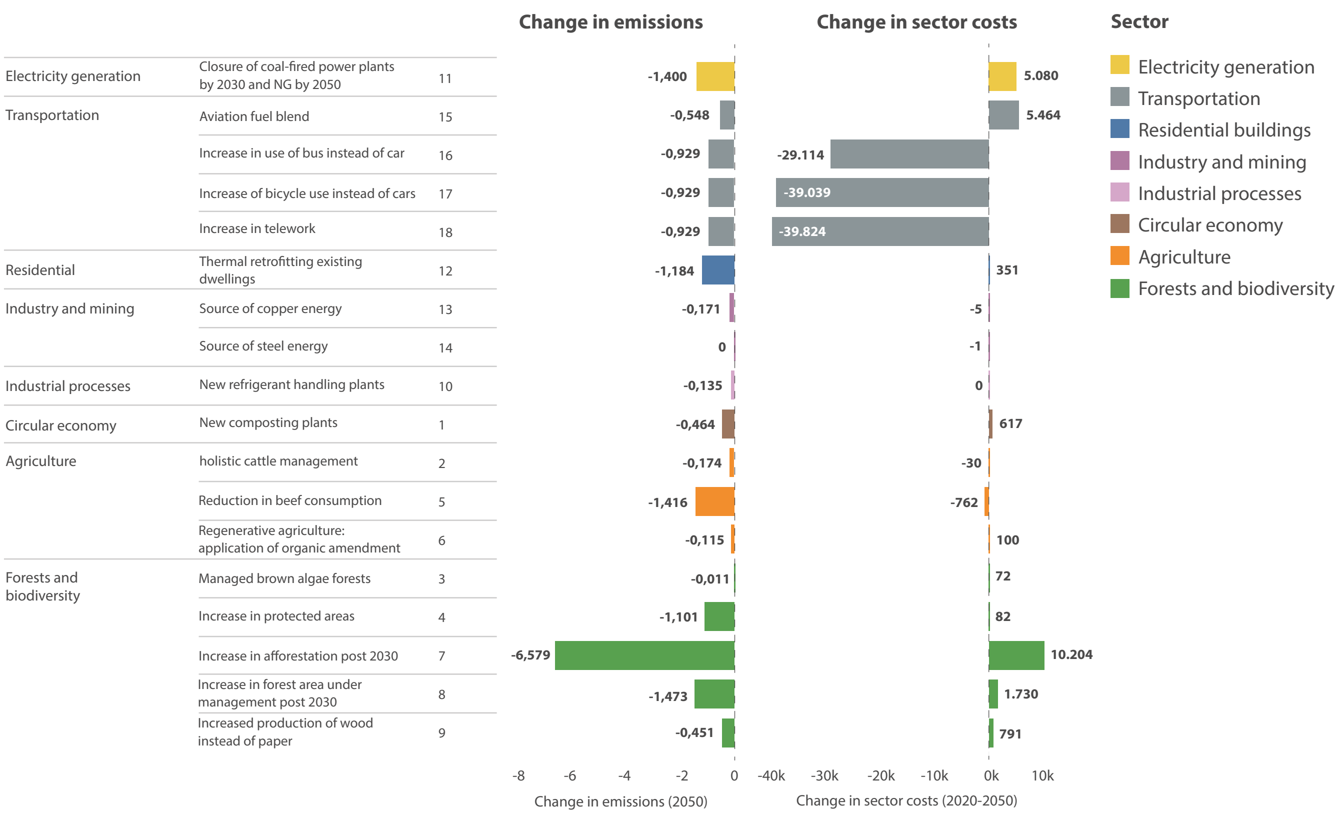
Source: Prepared by the authors.
Note: Orange circles correspond to futures described by vulnerability 1. Gray circles correspond to futures not described by vulnerability 1. Green dots indicate emission factors and results for the reference future. Dark red dots indicate three futures selected to show a range of emission outcomes (~ 5, ~ 10 and ~ 20 $MtCO_2eq$) under the NDC strategy.

4.6 Increasing the robustness of the NDC strategy

Analysis of the results of the NDC+ strategy clearly shows that the expansion of emission reduction actions reduces the vulnerabilities identified in the original NDC strategy. However, in a significant number of futures, the NDC+ strategy overstates the degree of emission reductions required to achieve the carbon-neutrality target, which can lead to a very costly strategy. In this regard, it is important to understand the implications in terms of emission reduction effects and the cost of each of the actions included in the NDC+ strategy, since each additional action in the NDC+ strategy decreases emissions and changes the costs of emission reductions in the associated sector. While some emission reduction actions entail higher costs, as in the case of afforestation actions, other emission reduction actions result in lower costs because they incentivize efficiency. For example, greater use of public transport reduces the costs of the transport system because it is economically more efficient than private transport in a large proportion of cases.

Figure 4.16 shows the change in net emissions in 2050 and individually of costs for the set of additional actions included in the NDC+, under the reference future. Higher emission reductions are associated with more afforestation; however, this measure also results in higher costs. The next four actions with greatest potential for emission reductions are: bringing forward closure of coal-fired power plants, thermal retrofitting of homes, changes in the national diet, and more integrated forest management. Not all of these measures are also associated with increases in the costs of the emission reduction strategy; for example, increase in teleworking and the decrease in beef consumption. It should be noted that this cost-benefit ratio of NDC+ actions can change under uncertainty and that these results are only associated with the reference future.

Figure 4.16:
Change in net emissions by 2050 and sector costs.



Source: Prepared by the authors.

Figure 4.17 shows the cost-benefit ratio for the reference future on a comparative basis for all additional actions included in the NDC+ strategy. The horizontal axis indicates the change in emission reduction costs associated with the expanding sector; the vertical axis presents the marginal impact of each of these actions on emissions in 2050. There are four groups:

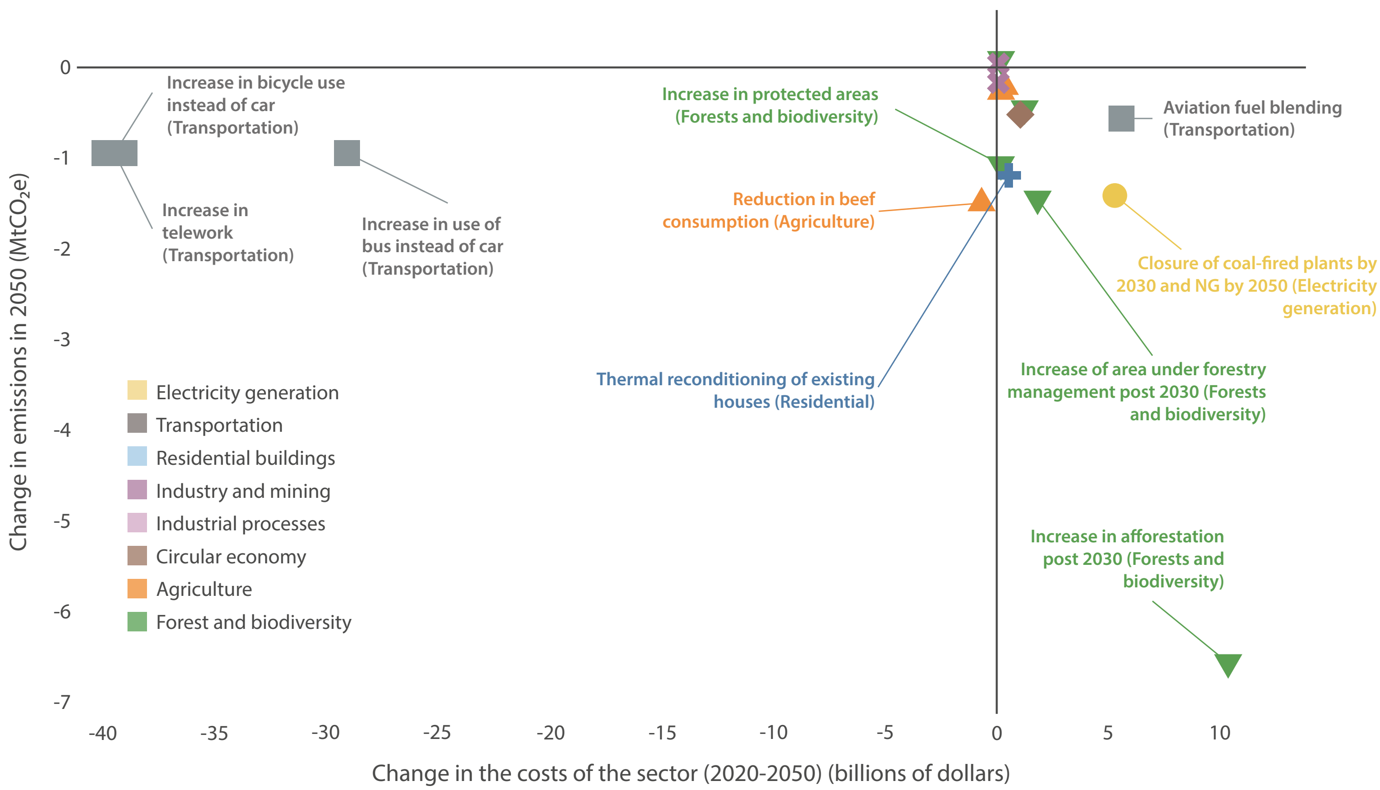
1. Actions that reduce costs and net emissions in 2050, such as replacing private transport with increased use of bicycles, telework and public transport.

2. Actions with near-zero cost, but with a substantial marginal impact on emission reduction, such as increasing protected areas, reducing beef consumption, thermal retrofitting for existing housing and increasing the area under forest management post 2030.

3. Actions with a higher marginal cost relative to their capacity to reduce emissions, such as fuel blending in aviation and changing the timetable of coal plant closures.

4. High-impact, high-cost emission reduction actions, such as increased afforestation post 2030.

Figure 4.17:
Scatterplot of change in net emissions by sector costs by 2050.



Source: Prepared by the authors.
Note: Cost-impact was estimated individually for each measure. Change in emissions is estimated in $MtCO_2e$ in 2050; the change in costs is estimated in millions of undiscounted dollars.

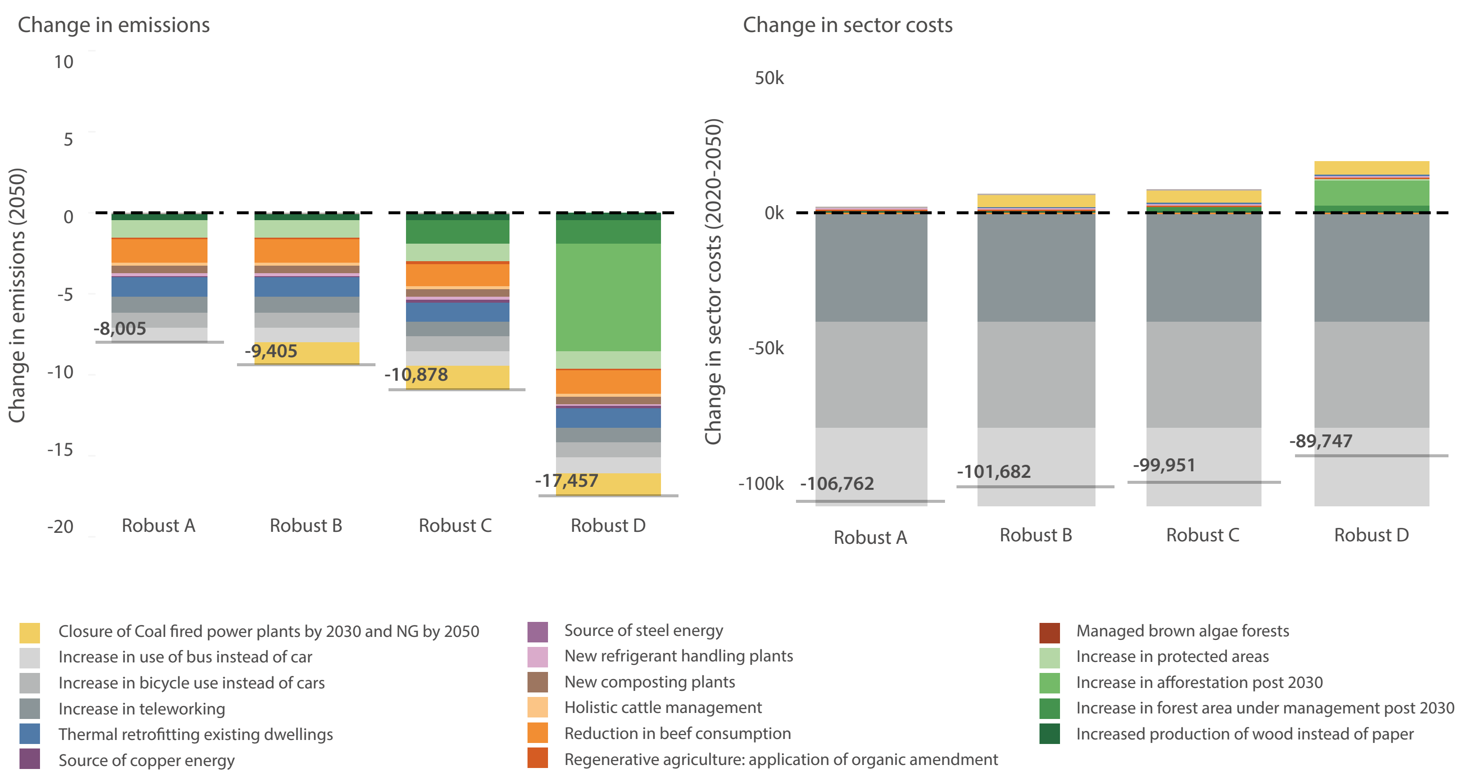
According to Figure 4.17, several of the options analyzed in NDC+ reduce emissions in 2050 and, at the same time, reduce implementation costs. Assuming there are no startup challenges, these actions should be implemented irrespective of future conditions. To explore cost-benefit implications more broadly, variations of the NDC+ strategy are defined through different combinations of the actions shown in Figure 4.16.

Figure 4.18 shows the four variations of the NDC+ strategy in this study. Robust strategy A considers all actions in the original NDC, and adds all actions included in Figure 4.17, except those resulting in higher costs:

- Phase out of coal plants by 2030 and natural gas by 2050.
- Increase in area under forest management post 2030.
- Increased afforestation post 2030.
- Use of blended aviation fuel.

The remaining strategies (Robust B, Robust C, Robust D) incrementally add each of the higher cost elements, so that each variation represents a step-up from the original NDC strategy to the NDC+ strategy, which is equivalent to adding all the higher cost elements.

Figure 4.18:
Estimated change in emissions and change in costs, compared to NDC strategy, for the four robust alternatives.

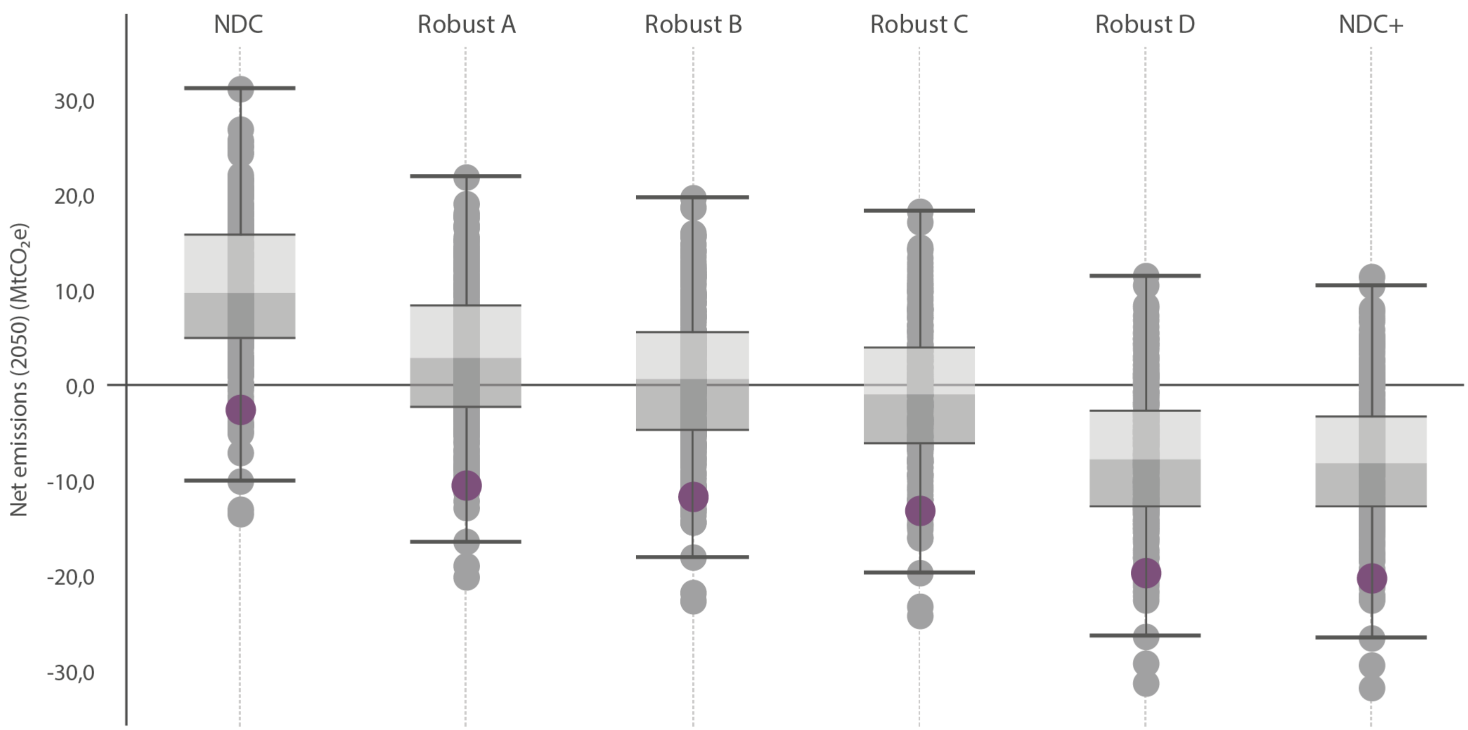


Source: Prepared by the authors.

Assuming that the effects of the actions are additive and linear, Figure 4.18 shows that, considering the reference future, Robust strategy A would reduce emissions by 8 $MtCO_2eq$ relative to the original NDC while resulting in substantial savings in the transportation sector. Robust strategy B would reduce emissions by an additional 1.5 $MtCO_2eq$ and also reduce the costs of the strategy by bringing forward closure of coal plants. Robust C and Robust D strategies show a higher capacity to reduce emissions due to more actions in the forestry sector, but also result in higher costs.

To compare the behavior of these alternatives under uncertainty, their results were evaluated under the 1,000-futures ensemble considered in this study. Figure 4.19 reflects these results with respect to net emissions achieved in 2050 (vertical axis) for each of the strategies (horizontal axis). The robustness of the strategy (percentage of futures in which the carbon-neutrality target is met) increases gradually with each expansion of the original NDC strategy until reaching the NDC+ strategy.

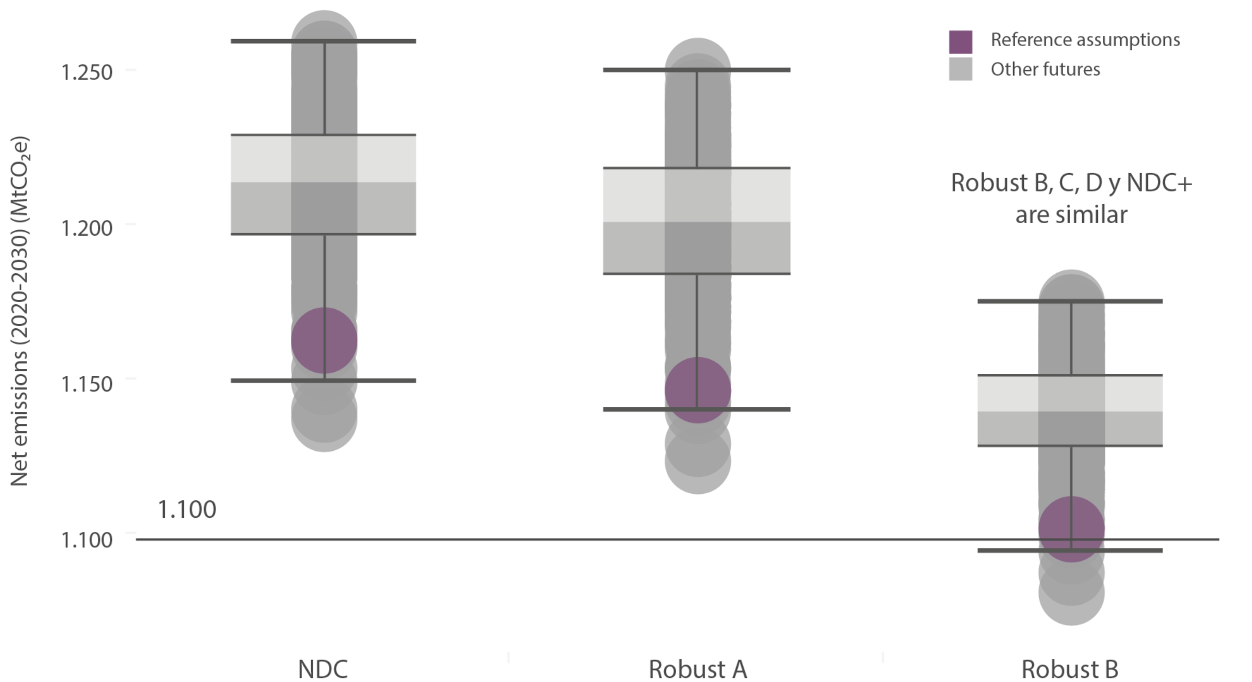
Figure 4.19:
Emissions in 2050 in 1,000 futures for NDC, robust A-D and NDC+ strategies.



Source: Prepared by the authors.

The results of these strategies were also compared with short-term emission reduction targets (2030). Figure 4.20 shows the results of the alternatives analyzed, but this time with reference to the 2020-30 emission reduction target (vertical axis). The results show the importance of bringing forward the retirement of coal plants, included in Robust B, C and D, but not in Robust A, to achieve carbon budget targets by 2030, since all the strategies analyzed, except Robust A, can meet that short-term target under the reference future. However, it is worth noting that, if future conditions become less favorable in a significant proportion of the futures analyzed, the strategies studied will not meet the short-term emission reduction target.

Figure 4.20:
Carbon budget (total emissions 2020-30) for reference assumptions and in 1,000 futures for NDC, Robust A and Robust B strategies.

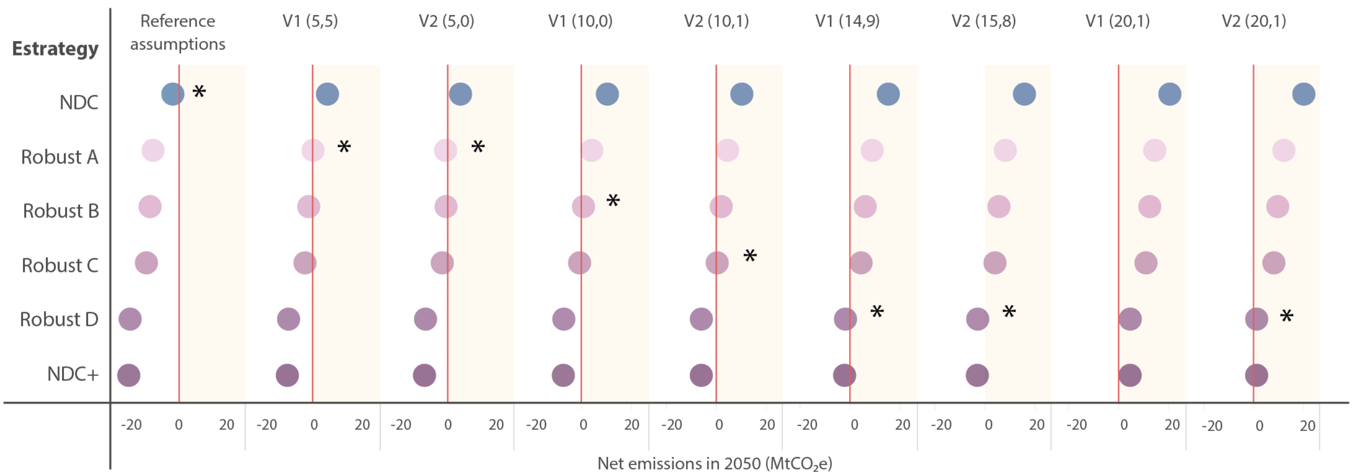


Source: Prepared by the authors.

Analysis of the results of the NDC+ strategy and its alternatives suggests that all these strategies result in lower net emissions in 2050. However, these results also show that the level of investment required to achieve these emission reduction targets depends on how the uncertainty factors considered play out in the future.

Figure 4.21 illustrates this point: the vertical axis denotes each of the strategies considered in the study, the horizontal axis indicates net emissions in 2050, and the columns represent each of the futures used as a reference in the vulnerability analysis (vulnerabilities V1 and V2).

Figure 4.21:
Change in estimated emissions, compared to the NDC strategy, for the four robust alternatives and NDC+ for selected futures.



Source: Prepared by the authors.
Note: The asterisk indicates the least aggressive strategy required to meet the net-zero emissions target by 2050.

The results indicate that for futures that achieve net emissions of 5 $MtCO_2eq$ in 2050 (columns 2 and 3) under NDC, the Robust A alternative strategy comes closest to the carbon-neutrality target in that year, without going to an unnecessary degree of additional emission reduction. For futures in which the NDC strategy results in 10 $MtCO_2eq$ in 2050 (columns 4 and 5), Robust B and Robust C are the least aggressive in achieving carbon neutrality. Similarly, for futures where the NDC strategy results in 15 $MtCO_2eq$, Robust D is the strategy that meets the carbon-neutrality target most efficiently. Finally, for futures that result in 20 $MtCO_2eq$ in 2050 (columns 8 and 9), Robust D strategy is sufficient to achieve carbon neutrality under vulnerability V2, but not under vulnerability V1. This difference is because of the differences of these two futures under V1 and V2. V1 describes futures that lead to high emissions due to factors in the forestry sector. These factors make the additional forestry actions implemented in Robust C and Robust D less effective in these futures vis-à-vis futures that result in similar levels of emission reduction, but caused by other factors unrelated to the forestry sector. Note the zero marginal change between Robust D and NDC+, indicating that the "aviation blend" action provides few benefits from emission reduction and significantly increases the costs of the strategy.

4.7 Macroeconomic analysis

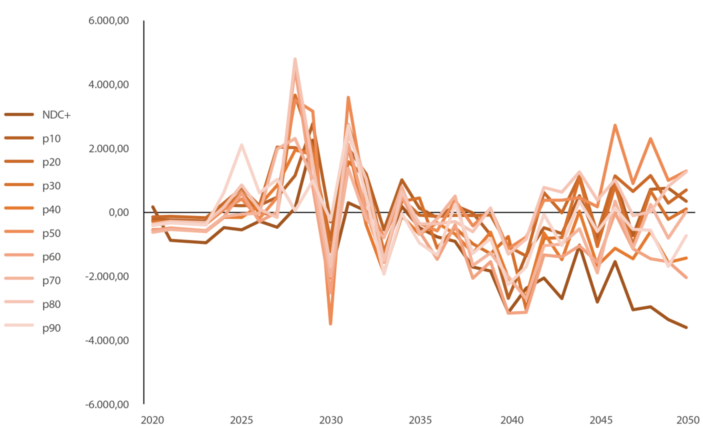
Once the various emission futures have been estimated by means of the sectoral models using parameters and uncertainty as inputs under the carbon-neutrality targets, these sectoral models provide two important inputs for estimating the macroeconomic behavior[12] of the economy: 1) physical asset costs (investment) and 2) operating costs for each sector and each future using the range of uncertainty constructed.

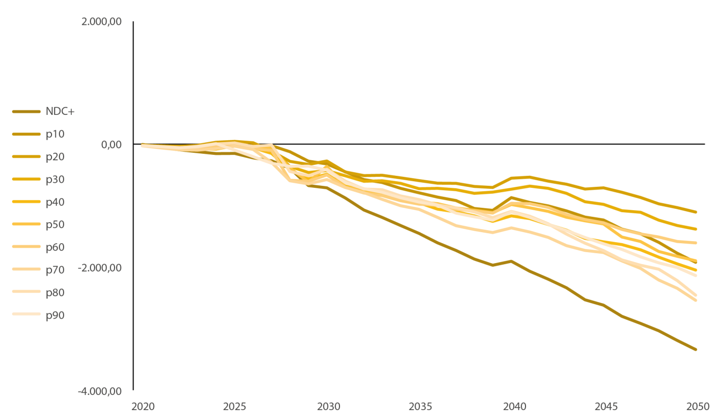
The estimation strategy assumes that the pathway Chile is following corresponds to the latest NDC update which, in addition to providing an update to the first commitment, traces a path to 2030 with a view to carbon neutrality by 2050.

The next step, based on this scenario, is to obtain the package of strengthening measures aimed at reducing uncertainties related to carbon neutrality compliance (NDC+) and its consequent sensitivities in percentiles of possible emission futures.

Figure 4.22 shows the trajectories of the difference in investment and operating costs between the NDC+ alternative measures and NDC, together with the associated measures in the emission percentiles, generated by combinations of NDC+ parameters and variables.

Figure 4.22:
Investment and operating expenditure trajectory associated with NDC+ package and percentiles 2020-50.





Source: Prepared by the authors.

[12] The variables analyzed correspond to aggregate demand: private consumption, total investment (public plus private), government expenditure, exports and imports, as well as a breakdown of value added by economic activity.

These trajectories can also be analyzed at present value with the 6% discount rate used in the evaluation of Chile's projects by sector, as presented in Table 4.2. The NDC+ package has a lower present value in fixed capital investment of US$11.536 billion, while operating costs constitute a lower expenditure of US$13.026 billion, both with respect to the NDC alternative. This lower expenditure is explained by savings in transport measures and an increase in expenditure in the forest and biodiversity sector.

Table 4.2:
Investment and operating expenditure by sector 2020-50 discounted at 6% of NDC+ plan (in millions of dollars).

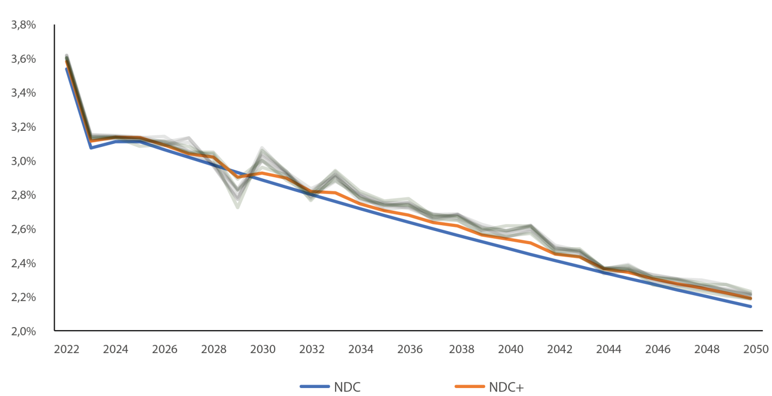
	CAPEX			OPEX		
	min	NDC+	max	min	NDC+	max
Forest and biodiversity	2,931.9	3,271.1	3,508.3	455.3	483.8	522.5
Agriculture	12.0	12.9	14.0	-237.8	-140.2	-86.5
Circular economy	107.2	107.4	108.4	96.7	96.7	96.7
Industrial processes	0.6	1.1	1.2	2.7	4.5	4.8
Industry and mining	28.6	76.0	176.3	-60.5	-60.5	7.7
Residential buildings	3,351.1	8,259.0	8,259.0	-3,907.2	-3,907.2	-1,728.8
Transportation	-24,381.1	-24,381.1	-5,813.3	-9,138.8	-9,138.8	-2,107.9
Electric generation	1,117.7	1,117.7	3,895.1	-1,786.8	-364.5	-245.7
Total	**-11,536.0**	**-11,536.0**	**4,930.0**	**-13,026.2**	**-13,026.2**	**-4,451.6**

Source: Prepared by the authors.

With these input data obtained from the simulation of the sectoral models, the Antosiewicz et al. (2020) and the MEMO model (see Chapter 4) are used to obtain the range of impact on the output of the economy captured in the change in GDP.

Figure 4.23 shows that, from a reference scenario where the NDC is in execution and with an average annual GDP growth rate of 2.5% between 2020-50, implementation of NDC+ would result in an additional gain of 0.06 percentage points on average, in a range of 0.04 to 0.07 percentage points per year.

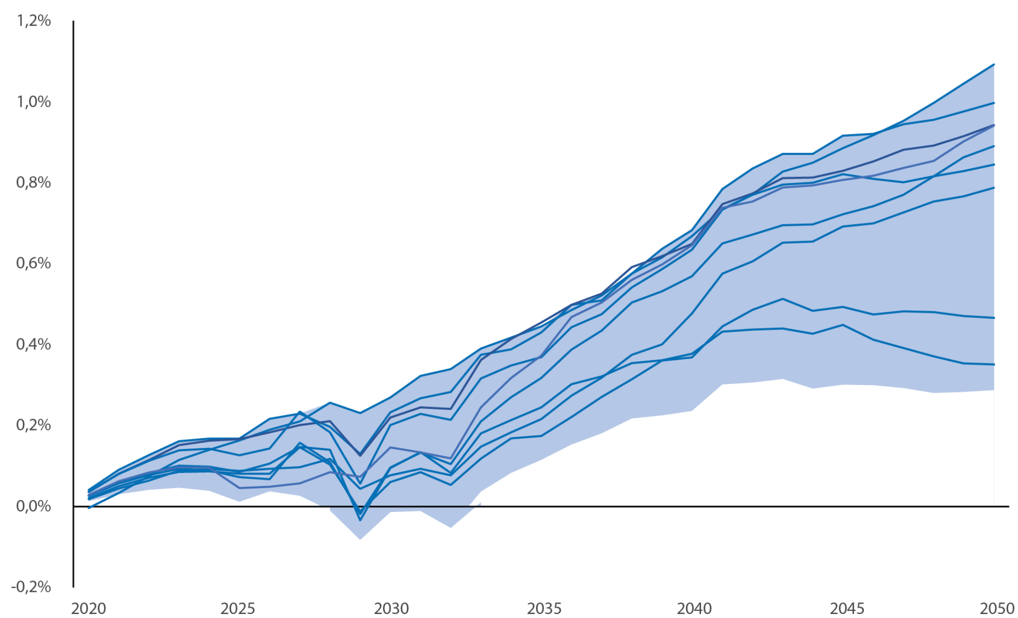
Figure 4.23:
Annual rate of change of GDP of reference scenario (NDC) and NDC+



Source: Prepared by the authors based on own data and Antosiewicz et al. (2020).

To understand the contribution of these additional points of growth per year from the NDC+ package, it is worth analyzing the impact on output level 30 years after the measures are implemented. In Figure 4.24 the level of GDP by 2050 can be expanded in a range between 0.3% and 1.1%, in which case the NDC+ scenario achieves the upper end of the range. This represents an annual increase of US$66 million and US$243 million per year until the end of the period, totaling between US$1.989 billion and US$7.293 billion additional in 2050.

Figure 4.24:
Percentage change in product level with implementation of NDC+ and percentiles.



Source: Prepared by the authors.

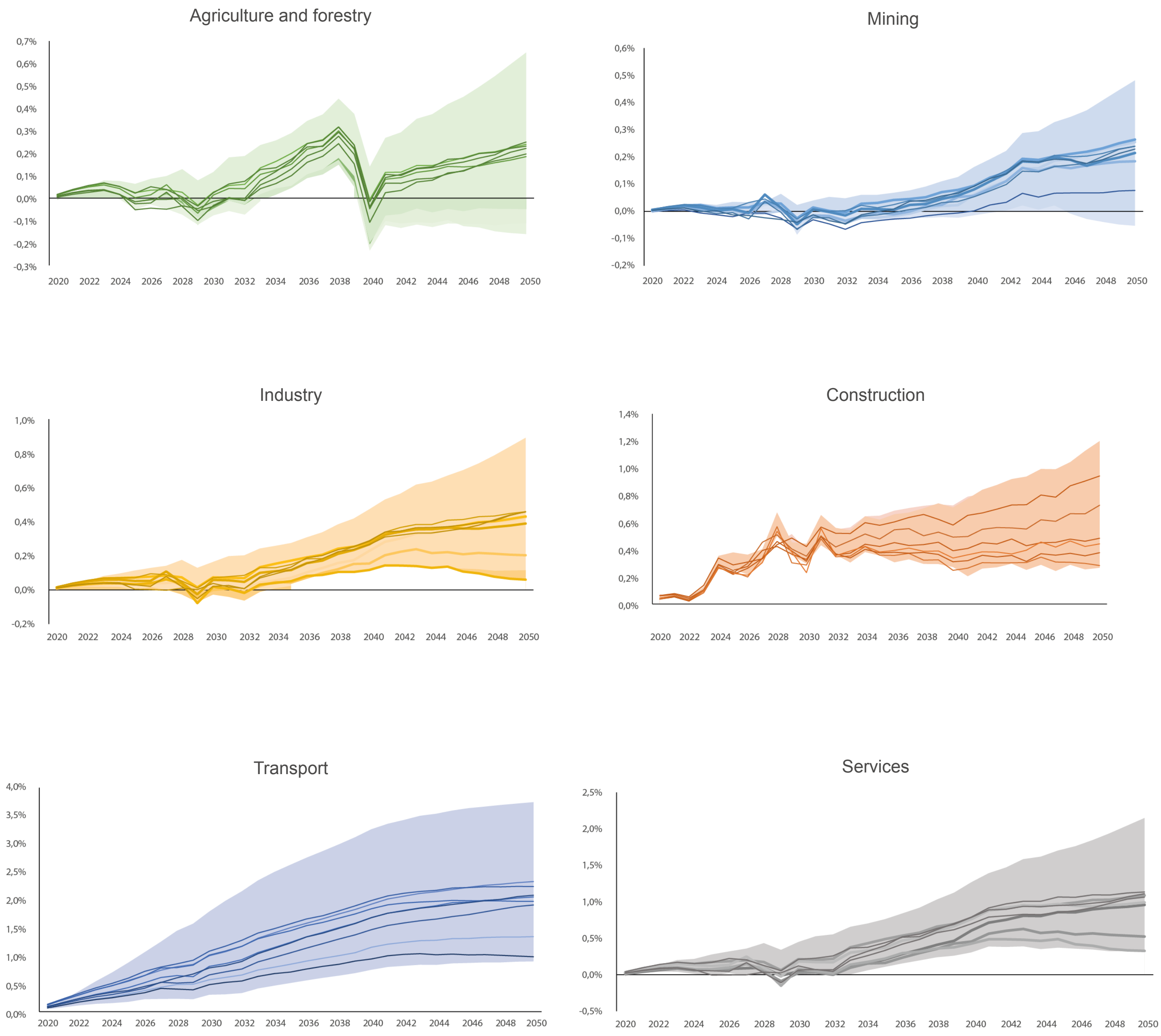
The expanded structure of the general equilibrium model shows the trend in economic activities with implementation of NDC+ and its variants with respect to the NDC pathway (Figure 4.25). All sectors show the effort to meet the intermediate targets set for 2030, and consequently the speed up of closure of coal power plants and the increase in investment in reforestation and biodiversity measures, which leads to contractions in output level in the years around 2030 in four activities (agriculture and forestry, mining, industry and services). An analysis of the panels with impacts on the six activities in Figure 4.25 identifies two groups of sectors: i) agriculture-forestry, mining, industry and services; ii) construction and transportation.

In the first group, activities suffer contractions in the investment trajectory by 2050. The agriculture-forestry sector (panel [a]) has a range of impact on output level between -0.2% and 0.6% in 2050; mining (panel [b]) has a range of variation between -0.1% and 0.5%; industry (panel [c]) between 0.1% and 0.9%; and services (panel [f]), between 0.3% and 2.1%.

In the second group, construction (panel [d]) and transportation (panel [e]) have a positive trajectory and achieve the highest ranges of increase in the output level of their activities, with ranges between 0.3%-1.2% and 0.9%-3.7%, respectively.

This analysis makes clear the need for gradualism, since shock or one-time implementation measures can lead to significant losses in both sectoral and aggregate output.

Figure 4.25:
Percentage change in product level with implementation of NDC+ and percentiles, by sector.

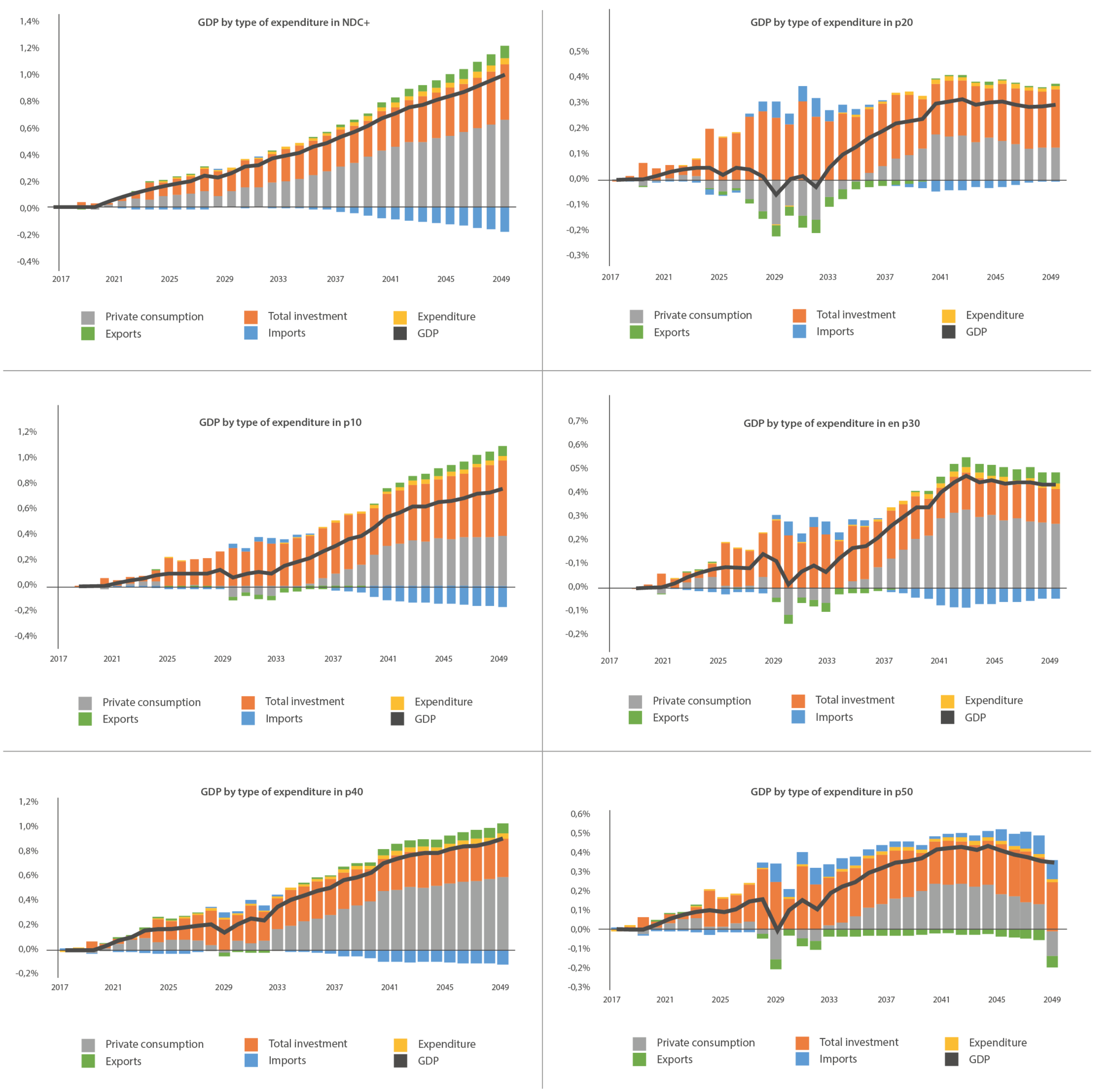


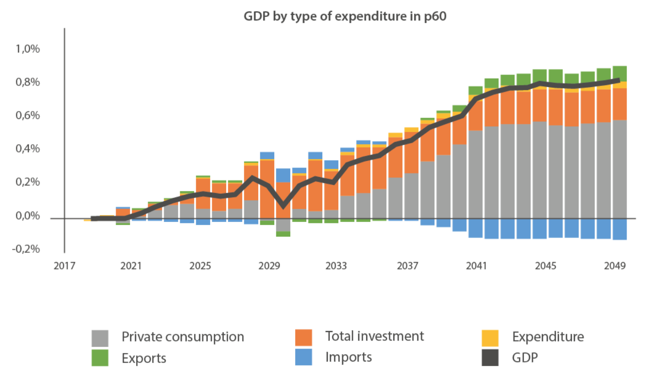
Source: Prepared by the authors.

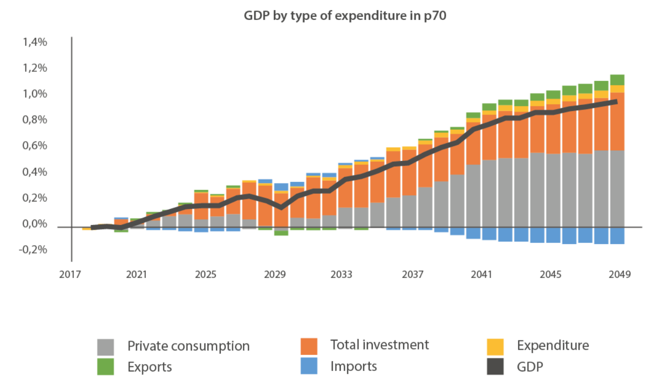
Another way of analyzing the results of the model is to consider the contribution of the components of aggregate demand: household consumption, total investment (public and private), public spending and external consumption (exports and imports).

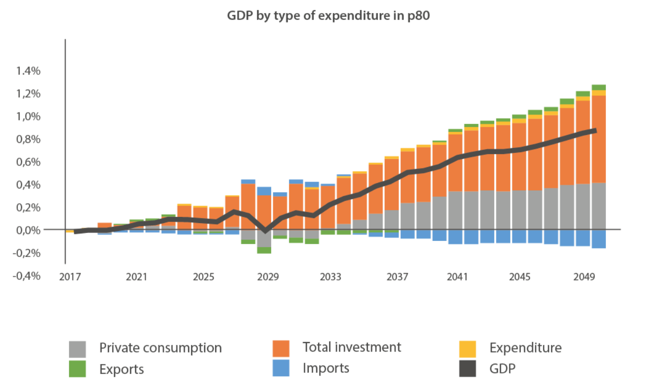
Splitting the analysis into each of the selected emission percentiles and the NDC+ reference scenario produces the dominant contribution of private consumption and investment in all scenarios, whose incidence changes because of the specific plans in each scenario (Figure 4.26).

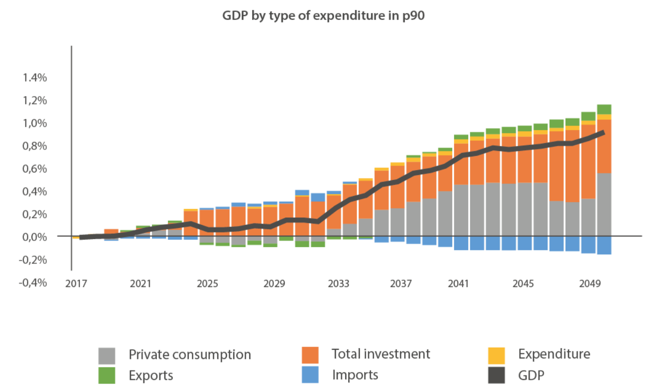
Figure 4.26:
Percentage change in output level with NDC+ implementation and percentiles, GDP by type of expenditure.











Source: Prepared by the authors.

On average, the levels of the variables have an annual variation in the following ranges: private (household) consumption between 0.05% and 0.55%; private investment between 0.36% and 0.85%; expenditure between 0.04% and 0.14%, while net exports are in balance, that is growth of exports is offset by imports.

It should be noted that, in the episodes when output level falls between 2029-32, the most affected variables are household consumption and exports.

5
Conclusions and recommendations

This study uses an integrated evaluation model to estimate emission trajectories and emission reduction costs, considering the key sectors of Chile's economy under a broad spectrum of uncertainty.

Under the extrapolation of current conditions, the carbon-neutrality strategy included in the Nationally Determined Contribution (NDC) would meet the carbon-neutrality target in 2050, but would exceed the short-term carbon budget by 2030.[13]

The NDC results are considered under more than 1,000 alternative futures, which simultaneously consider the uncertainty associated with a wide range of environmental, economic and technological factors, as well as the uncertainty associated with the results of several of the actions included in the NDC.

In analyzing NDC results under this ensemble of futures with respect to the 2050 carbon neutrality target, two key conditions were identified under which the NDC would not meet the carbon neutrality target (net emissions in 2050 greater than 5 $MtCO_2eq$ in 2050). The first condition results from the combination of three factors: 1) high forest harvests, 2) low yields of native forests and forest plantations, and 3) low penetration of electric mobility in the transportation sector. For the second condition, three additional factors come into play: 1) lower penetration rates of alternative energies in the electricity sector (resulting from higher costs of concentrated solar power), 2) higher emissions from the mining sector (resulting from higher production levels and lower energy efficiency), and 3) low conversion of freight transport to hydrogen.

[13] Some low-impact mitigation measures were not considered in the study due to lack of information or modeling limitations. However, exclusion of these measures does not substantially affect the results of the study.

To mitigate these vulnerabilities, the original NDC needs to be expanded. To do that, actions were considered which together reduce, on average, net emissions by 18 MtCO2eq relative to the original NDC. These alternatives were labeled Robust A, Robust B, Robust C and Robust D, and were defined ordinally according to the number of additional actions included. In addition to analyzing results in terms of their mitigation capacity, the additional costs (or savings) incurred in expanding the original strategy were estimated for each of these strategies.

Analysis of the set of robust strategies considered suggests the following:

- The NDC must be strengthened through accelerated phase out of coal-fired power plants to achieve short-term NDC targets. This requires adoption of at least Robust B strategy. This strategy also generates cost savings, in particular through modal shift actions in the transportation sector.

- To improve NDC results under a wider range of future conditions, additional actions are required in the forestry sector, including in Robust C and D strategies; specifically, increased afforestation and expansion of protected areas.

- The number of additional emission reduction actions needed in the forestry sector will depend on how trends evolve and how successful other emission reduction actions included in the NDC are. In particular, this analysis suggests that there is a wide range of actions that can be implemented to ensure that the NDC remains on track to achieve the short- and long-term emission reduction targets.

The sectoral results show that emissions from the energy sector could double if the targets assumed in the NDC are not met. Several measures that have a low level of maturity in the country—such as electric mobility or hydrogen in the transportation sector, solar thermal systems, or truck electrification—are critical for reducing emissions. Achieving the goals set out in the NDC will require public policies to implement these measures on a mass scale in the short term. Likewise, reducing emissions in the residential sector is strongly dependent on the assumptions of electrification and introduction of solar thermal systems, which also have a low level of maturity at national level.

Under the Kigali Amendment, the industrial processes sector has a lower range of uncertainty associated with 2050, resulting in a large reduction in emissions. However, there is a significant level of uncertainty in the emissions trajectory to 2030, which could be relevant in the case of medium-term commitments.

The waste sector has significant uncertainties associated with generation trajectories and composition of household waste, as well as the efficiency of methane capture systems in landfills. Supplementary measures to prevent organic waste from ending up in landfill sites can reduce the range of uncertainties.

In the agriculture sector, the greatest uncertainties are associated with meat and corn prices, along with the uncertainty linked to implementation of biodigesters in pig farms, in relation to the NDC+ strategy, with the possibility of generating significant reductions in their greenhouse gas (GHG) emissions, additional to the NDC strategy. Implementation of these measures generates net benefits but requires investment, in some cases productivity reductions in the short term and changes in practices, so technical and financial support will be necessary to put these actions through.

In the forests and biodiversity sector, the uncertainties with the greatest impact on GHG emissions are associated with frequency of forest harvests, forest and plantation yields, changes in firewood demand and forest fires. This sector is critical for achieving carbon neutrality, given its relative size in 2050 which must be greater than or equal to all other sectors combined. This could be achieved because the sector has net captures and a high potential for implementing measures additional to the NDC strategy (~10 MTon CO_2eq/year by 2050). To achieve this, afforestation and forest management measures need to be extended, and new actions taken, especially nature-based solutions, which—together with emission reductions—generate multiple co-benefits, although their implementation depends on strong economic incentives.

A fundamental point, which is not addressed in this study and which requires further discussion, is related to the design, effectiveness and implementation timelines of the public policies necessary for the evaluated emission reduction measures to take place on the required scale. This is a cross-cutting concern in all sectors, but is particularly significant for forests and biodiversity.

Consider, for example, that forest fires appear as a limited risk when evaluating the NDC strategy, even though the last decade has seen an increase in this type of event. This is because the model considers implementation of the action "Reduction of native forest and plantation degradation caused by forest fires," which reduces the area affected by fires. To address this type of issue, a series of measures are needed whose private cost is higher than the private benefit (not the social benefit), which has to be corrected through regulation. Consequently, although it is possible and desirable to implement the necessary transformations to achieve carbon neutrality, this study does not address the difficulties associated with design and execution of public policies and indispensable actions, which—if properly implemented—will generate important social, economic and environmental benefits for the country.

In terms of the lessons learned from a macroeconomic impact perspective, an analysis of the components of aggregate demand and sectoral output shows that on average implementation of a more robust NDC would lead to an increase of 0.06 percentage points in the gross domestic product (GDP) annual growth rate over the NDC strategy, leading to a 0.8% higher GDP on average in 2050 with respect to the NDC, with spending on CAPEX and OPEX measures lower than the NDC by US$1.031 billion and US$7.918 billion, on average, respectively. These results should be interpreted in the context of an economy in which regulation of price norms and command and control norms is based on the calibration reference year. Possible losses or gains arising from regulatory changes that have not been incorporated in the exercise remain to be analyzed. Finally, emission reduction measures need to be introduced gradually, since the exercise revealed the existence of a set of combinations that produce significant falls in aggregate and sectoral output.

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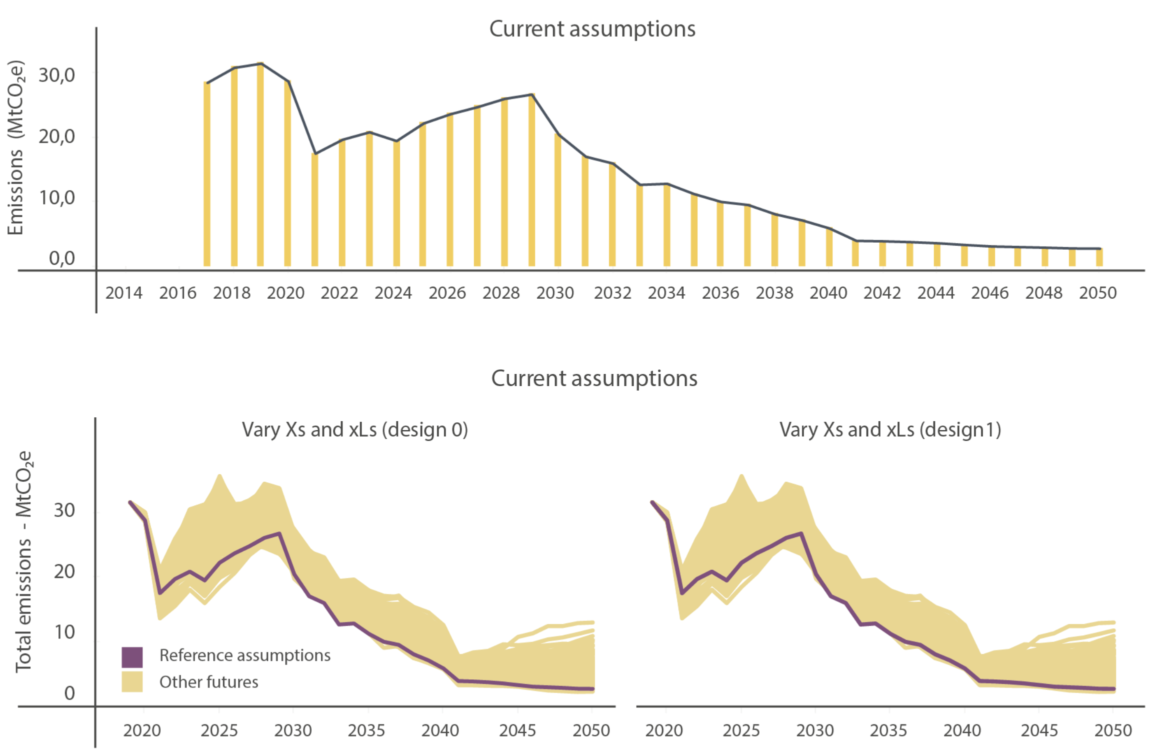
Annex

A.1
Sectoral emissions results

Power generation

Figure A1 shows the emissions projection for the deterministic case (top panel) and for cases that consider uncertainty in the different modeled parameters (bottom left and right panels). Introducing uncertainty shows that most of the evaluated scenarios increase emissions in 2050 over the NDC scenario. NDC scenario projections considers an optimistic scenario for development of renewable sources (low investment costs and high fuel prices). Therefore, when exploring alternative scenarios of investment costs (higher) and fuel prices (lower), coupled with less favorable hydrological conditions (drier), there is a tendency for the share of renewable energy to decrease and thermoelectric generation (mainly natural gas) to increase.

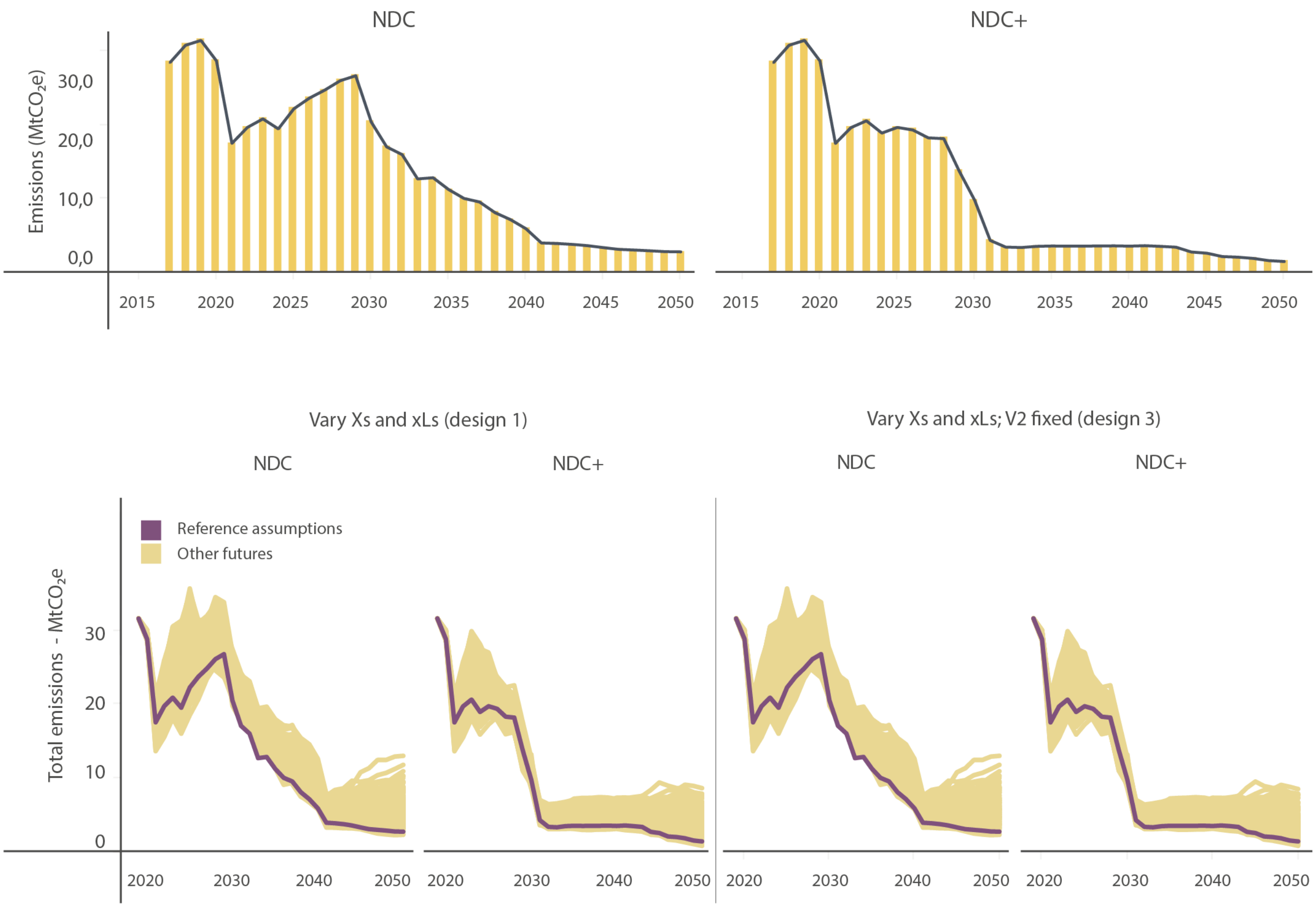
Figure A1:
Projected emissions of power generation sector.



Source: Prepared by the authors.

Figure A2 shows the results of the NDC+ scenario for the power generation sector compared to the results of the NDC scenario. Inclusion of additional measures reduces emissions by 1.3 million tCO_2 in 2050. A more significant effect of these additional measures is observed in 2030 when the NDC+ scenario has 10.3 million tCO_2 less than the NDC scenario. Also, inclusion of additional measures decreases the variability of emissions in 2050 when NDC+ scenario emissions vary between 0.9 million tCO_2 and 8.7 million tCO_2.

Figure A2:
Projected emissions of power generation sector for NDC+ scenario, compared to NDC scenario.

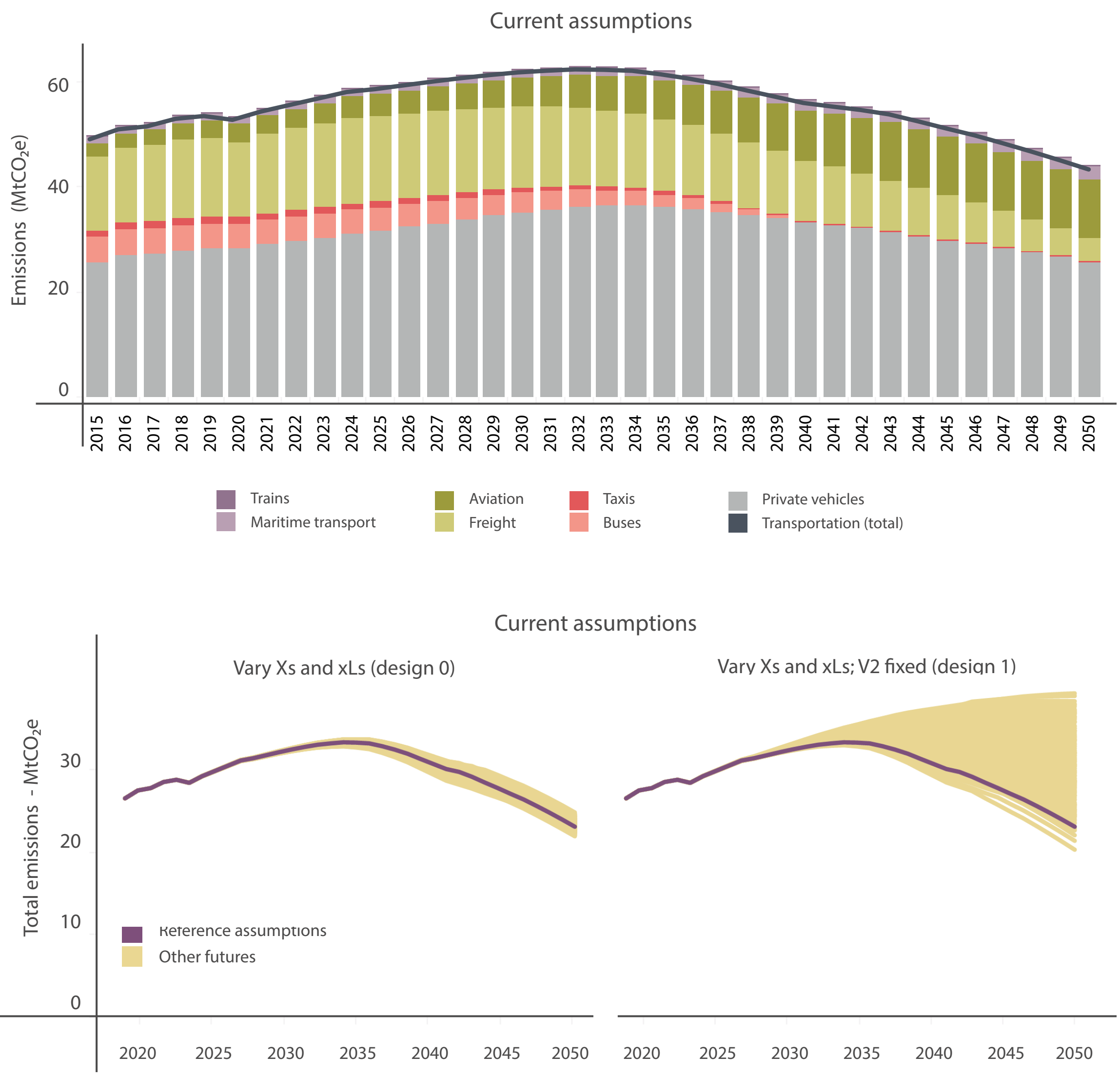


Source: Prepared by the authors.

Transportation

[Figure A3](#) shows transportation sector emissions projection for the deterministic case and for the cases that consider uncertainty in the different modeled parameters. The lower left panel considers only uncertainty in parameters such as GDP, population, vehicle performance, etc., while the lower right panel also includes uncertainty in the measure of electric mobility in private vehicles and introduction of hydrogen in trucks. The results show that emissions by 2050 could double if electric mobility and hydrogen share targets are not met, which has a significant impact on emissions at national level.

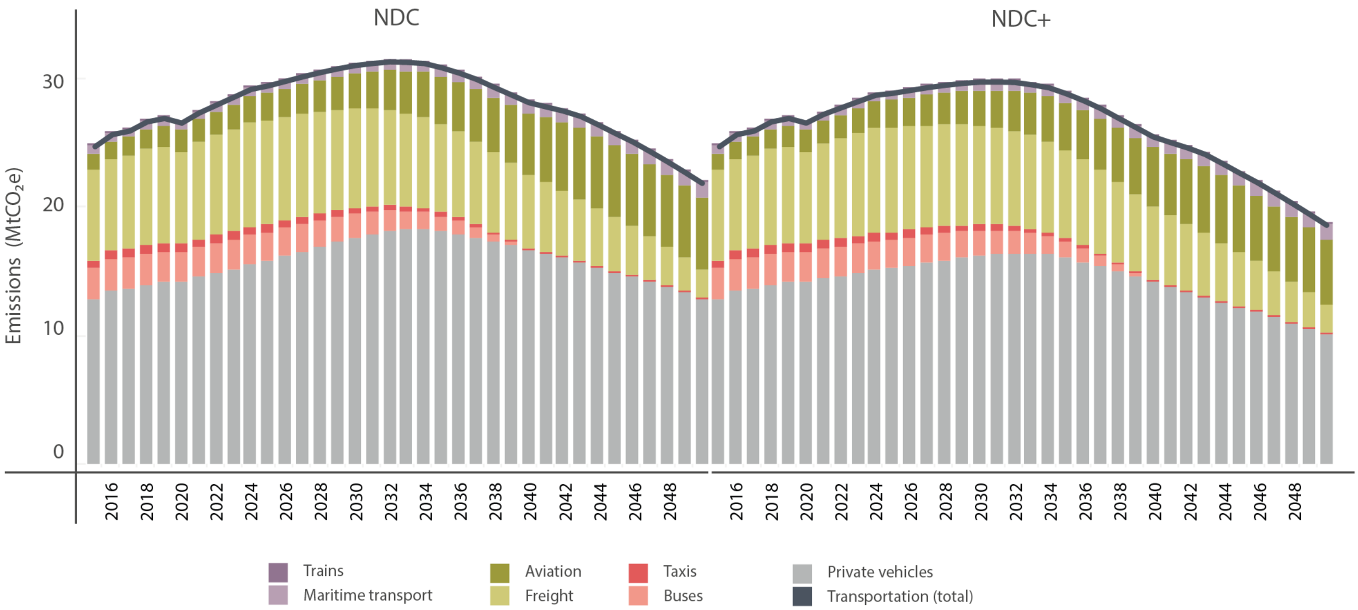
Figure A3:
Projected transportation sector emissions for NDC scenario.

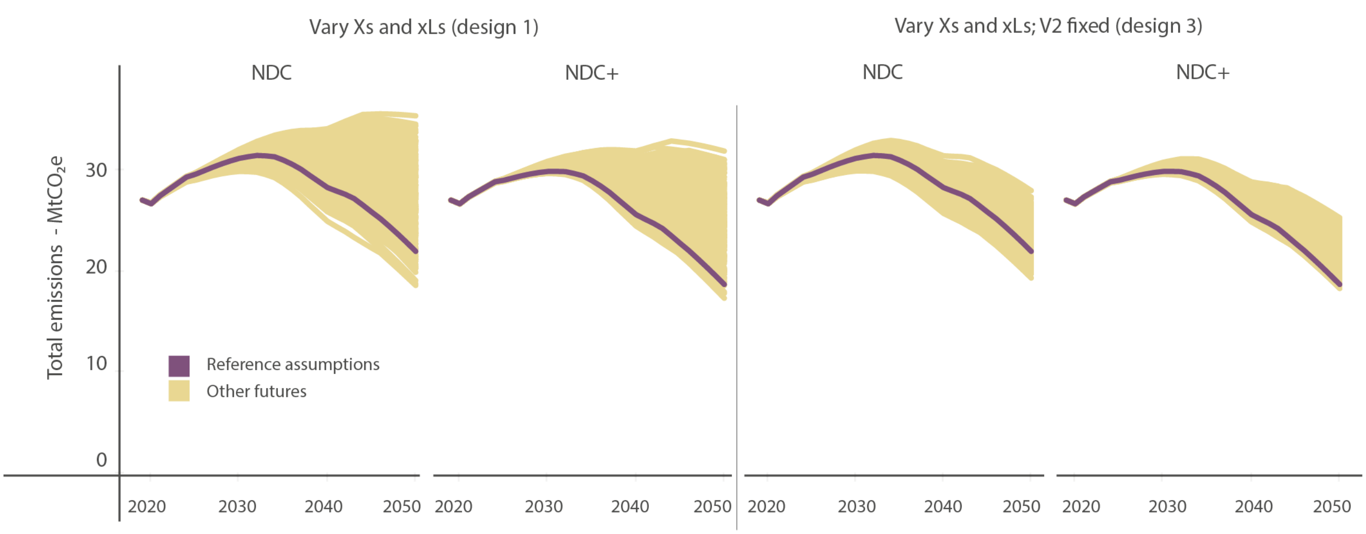


Source: Prepared by the authors.

Figure A4 shows the results of the NDC+ scenario for the transportation sector, compared to those of the NDC scenario. Inclusion of additional measures reduces reference scenario emissions by 3 million tCO_2 in 2050 with variability between 17.4 million tCO_2 and 32 million tCO_2 in the same year.

Figure A4:
Projected transportation sector emissions for NDC+ scenario.



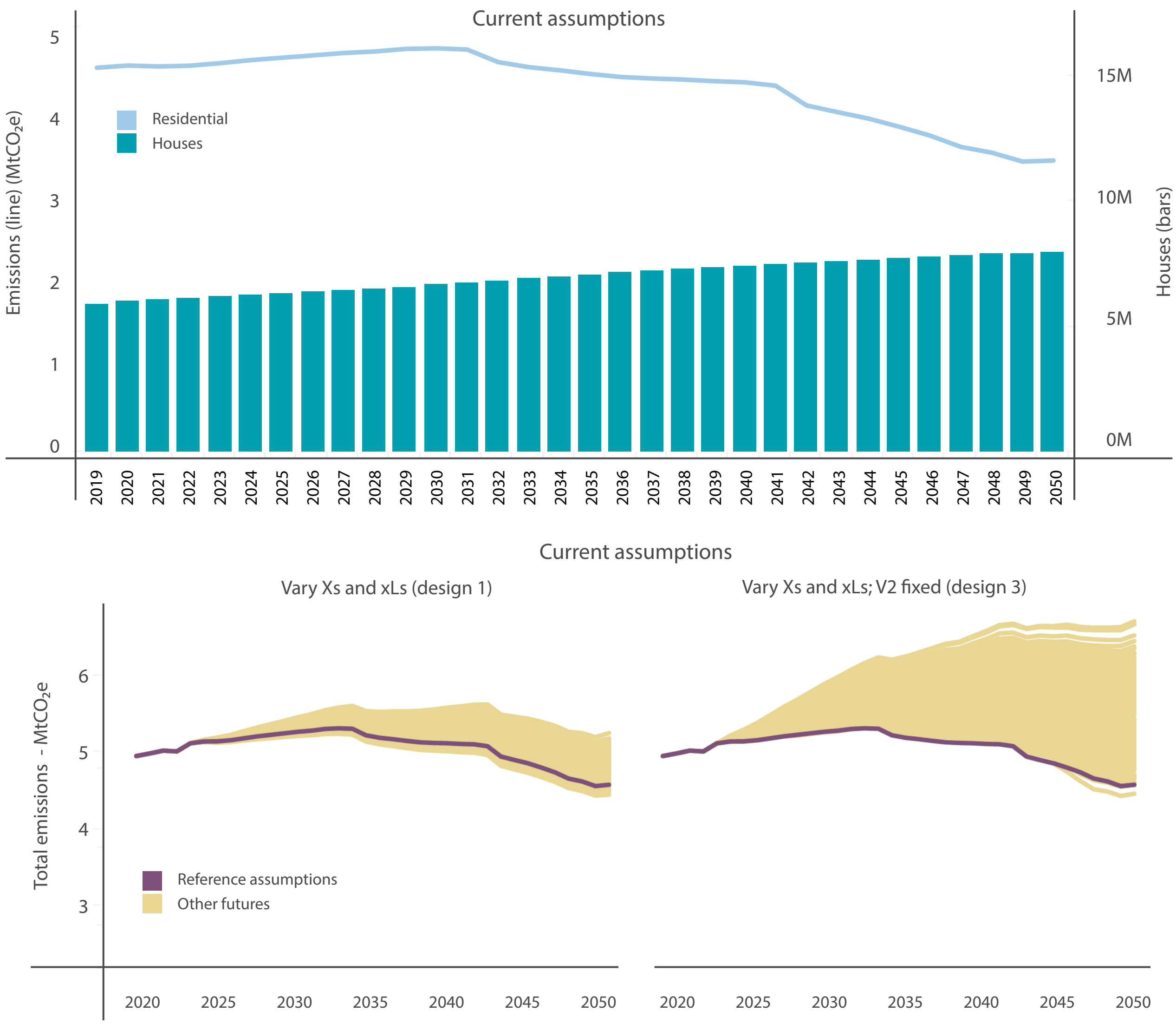


Source: Prepared by the authors.

Residential

The emissions projection for the deterministic case and for the cases that consider uncertainty in the different modeled parameters of the residential sector are shown in Figure A5. The lower left panel considers only uncertainty in parameters such as population, occupancy rate, energy intensity, etc., while the lower right panel also includes uncertainty in the measure of share of solar thermal systems for domestic hot water. The lower left panel indicates a rising trend in emissions because the scenarios explored had a greater tendency to increase the number of dwellings with respect to NDC (which was controlled by decreasing the occupancy rate). This tendency increases even more when analyzing scenarios with a lower level of share of solar thermal systems, leading to emissions increasing by more than 50%.

Figure A5:
Residential sector projected emissions for NDC scenario.

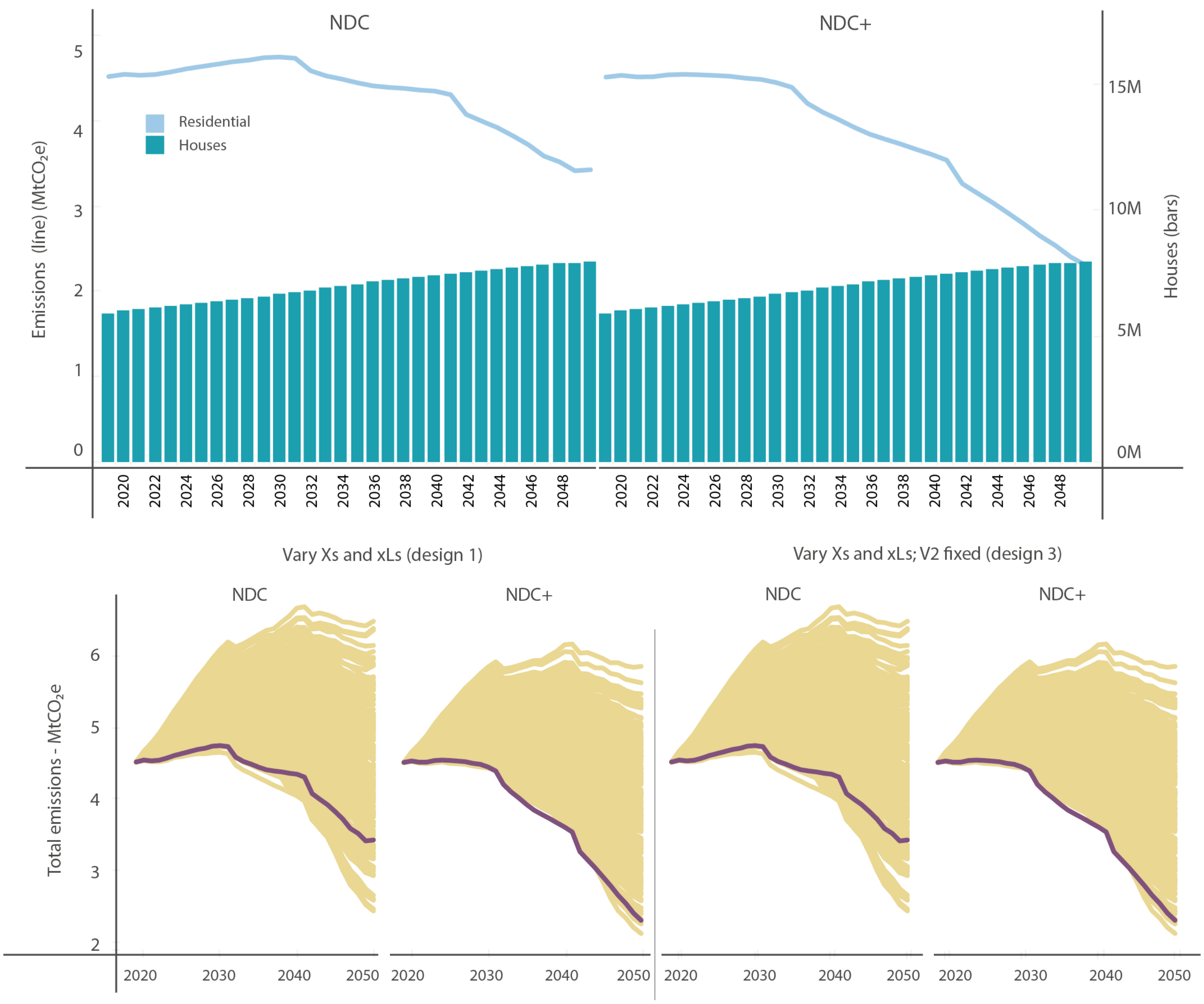


Source: Prepared by the authors.

Figure A6 shows the results of NDC+ scenario for the residential sector compared to the NDC scenario results. Emissions fall from 3.4 million tonnes (between 2.4 million and 6.5 million tonnes) to 2.3 million tonnes (between 2.1 million and 5.9 million tonnes). In this case, the measures reduce emissions by more than 1 million tonnes and also reduce the range of variability, although most of the resulting futures are in the zone of higher emissions than the reference scenario.

The solar thermal systems measure, particularly that associated with use in apartments, is the one that contributes most uncertainty to the emissions result in this sector. Similarly, the variability associated with the driver of the residential occupancy rate generates a strong impact on this uncertainty in total sector emissions.

Figure A6:
Residential sector projected emissions for NDC+ scenario, compared to NDC scenario.

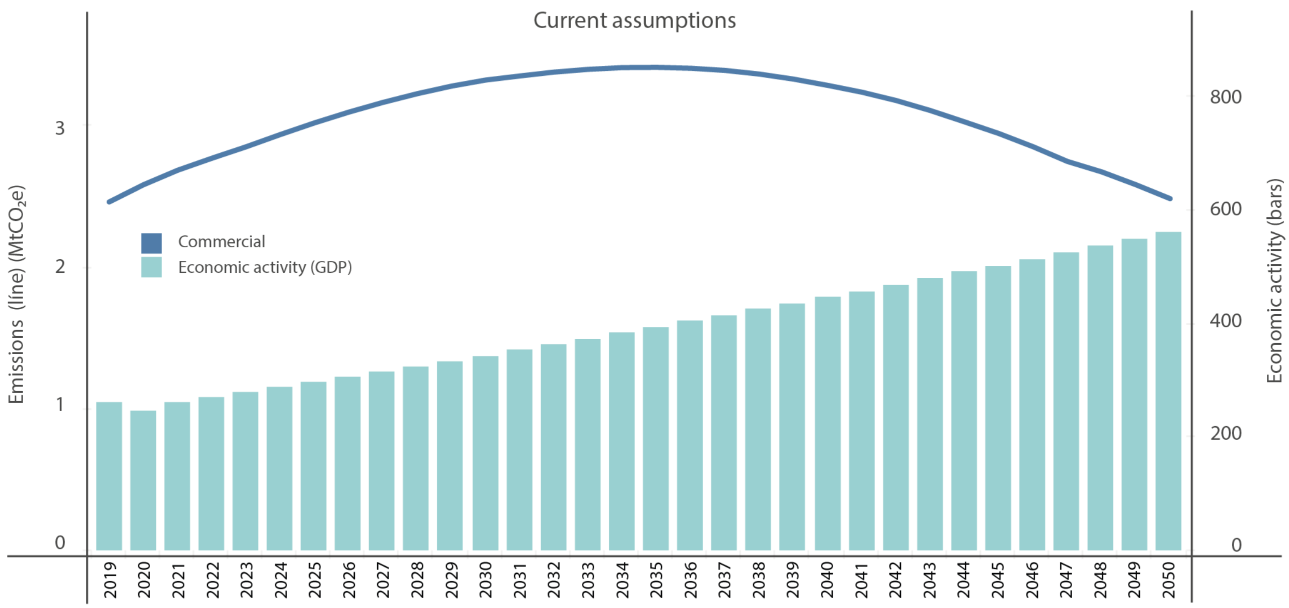


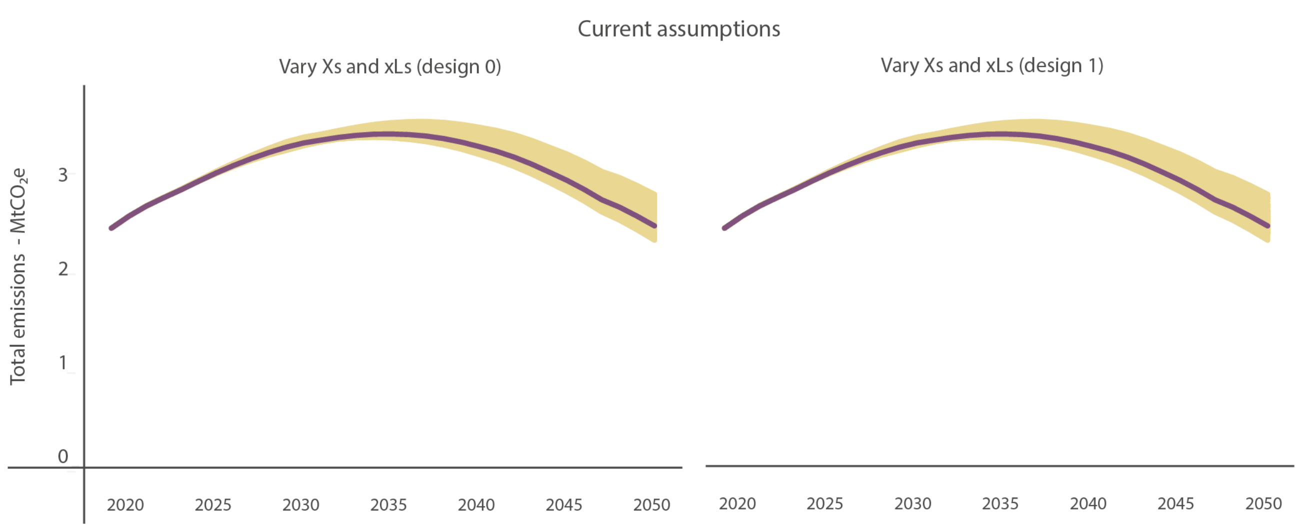
Source: Prepared by the authors.

Commercial

For the commercial sector, Figure A7 shows the emissions projection for the deterministic case and for the case that takes into account uncertainty in the modeled parameters: GDP and demand elasticity/GDP. Uncertainty was not considered in the modeled measures. The results indicate that the uncertainty in the modeled parameters does not have a significant impact on the change in projected emissions to 2050.

Figure A7:
Commercial sector projected emissions.



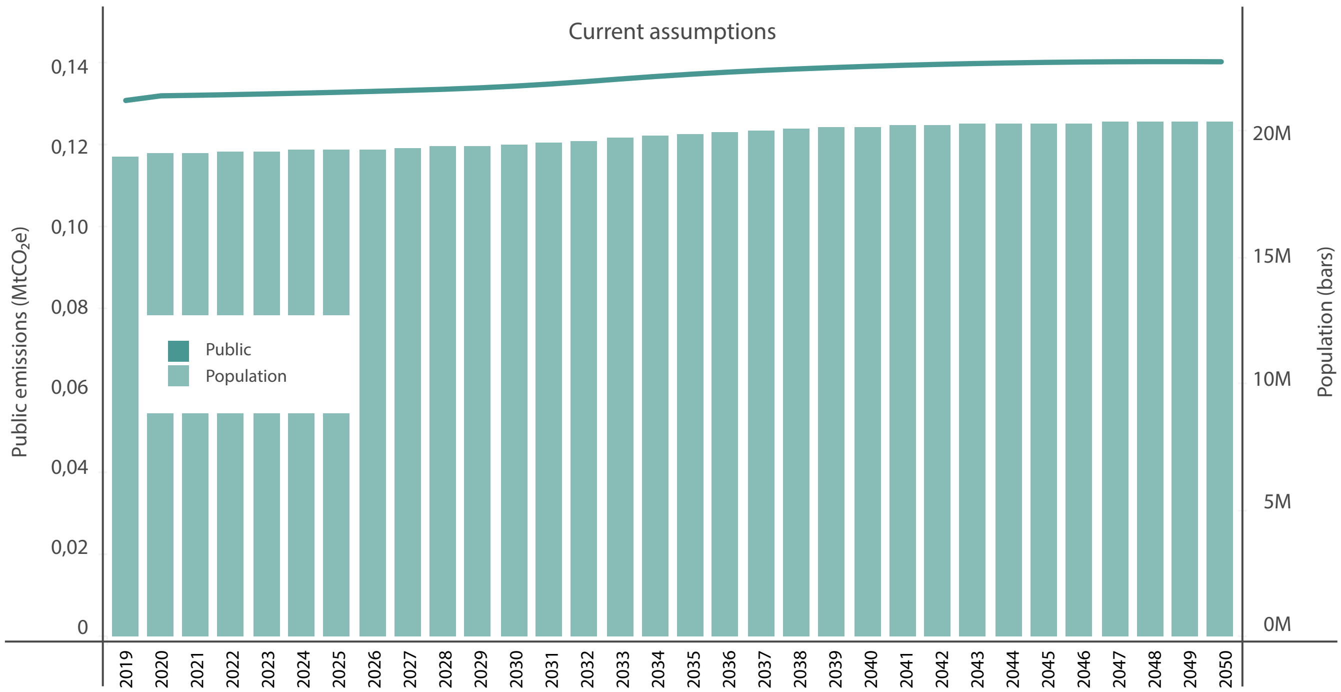


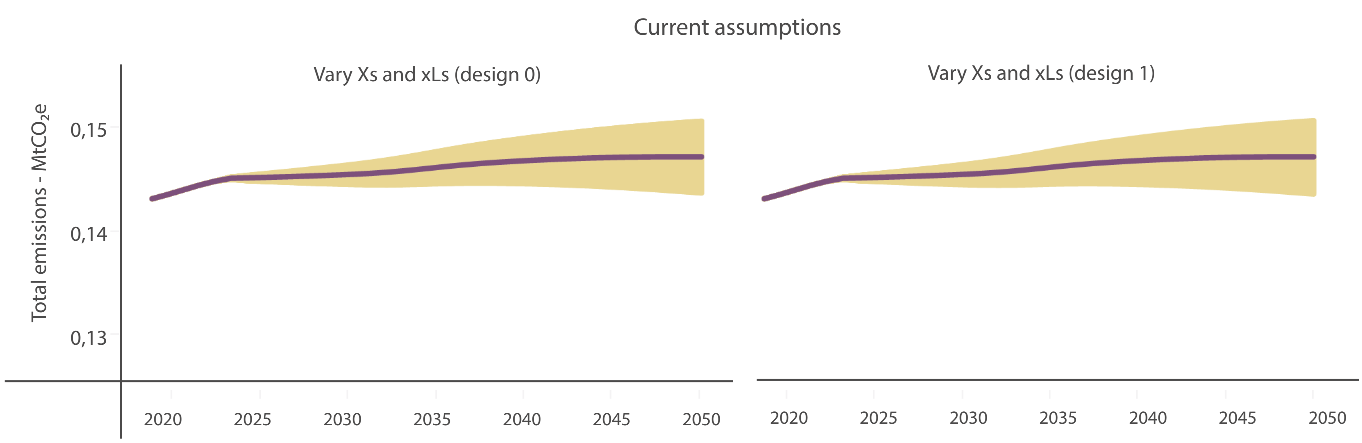
Source: Prepared by the authors.

Public

For the public sector, Figure A8 presents the emissions projection for the deterministic case and for the case that considers uncertainty. The emissions projection for this sector has a low impact at national level.

Figure A8:
Projected public sector emissions.



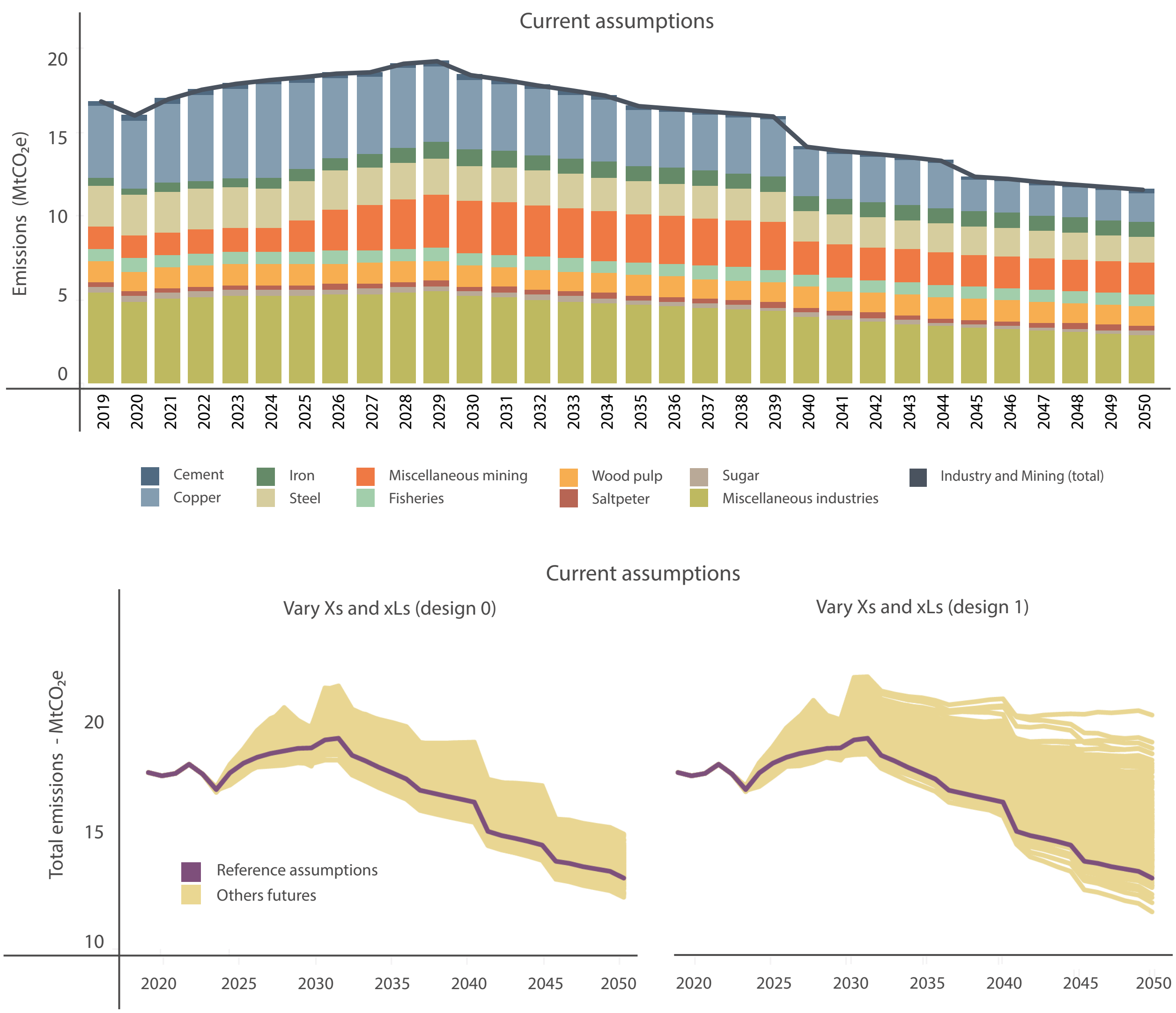


Source: Prepared by the authors.

Industry and mining

The deterministic case and the cases that considered uncertainty in the different parameters modeled for the industry and mining sector are shown in Figure A9. The lower left panel only takes into account uncertainty in parameters such as GDP, industrial production, energy intensities, etc., while the lower right panel also includes uncertainty in the measure of share of solar thermal systems and electrification of open-pit mine end-uses. The uncertainty in the parameters results in a distribution around the reference scenario with a rising trend in emissions. Incorporating uncertainty, emissions in 2050 could increase to 100% with respect to the reference scenario.

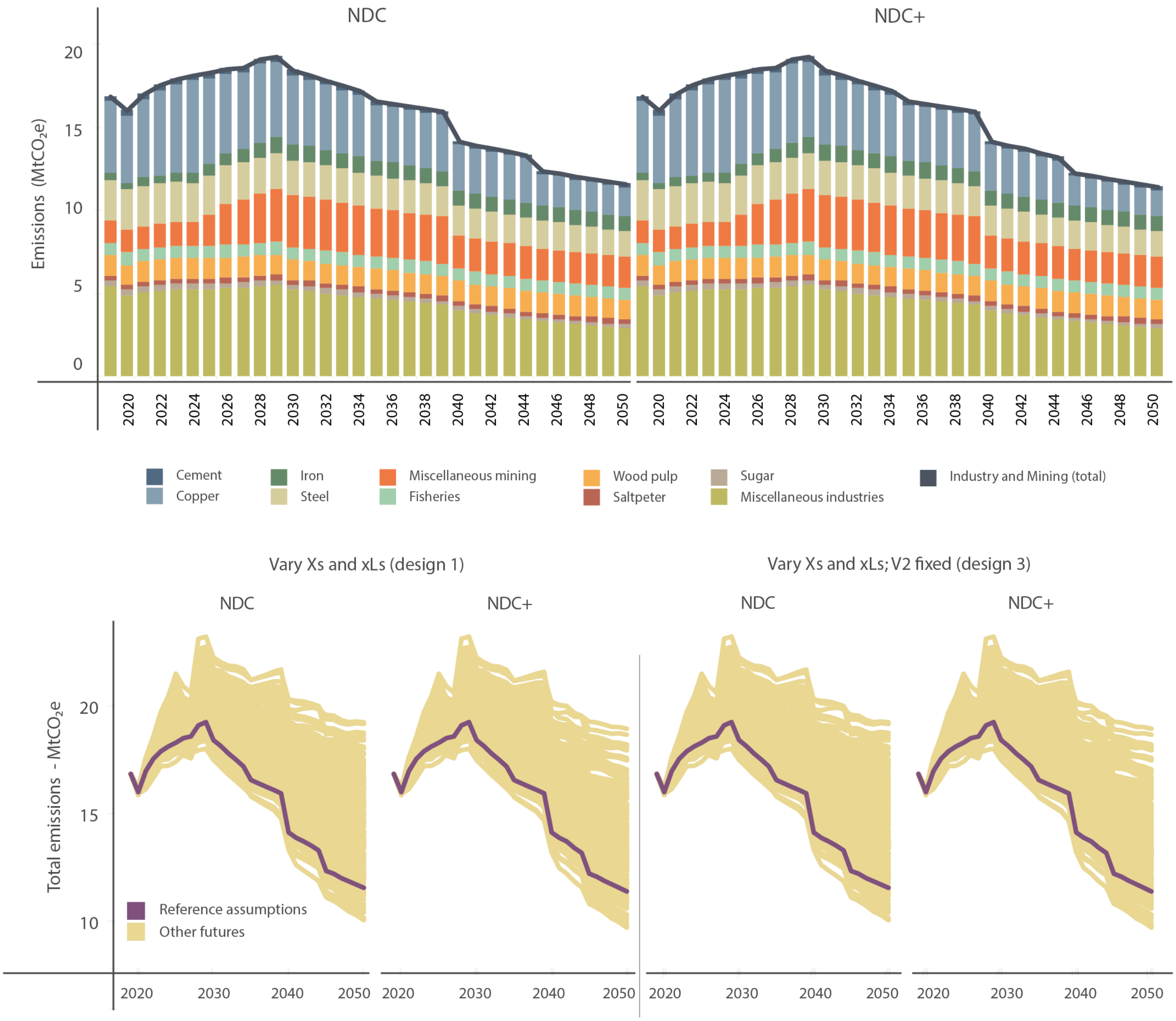
Figure A9:
Industry and mining sector projected emissions.



Source: Prepared by the authors.

A comparison of emissions between the reference scenario (NDC) and the NDC+ scenario shows that emissions decrease from 11.3 million tonnes (between 9.8 million and 19.0 million tonnes) to 11.1 million tonnes (between 10.1 million tonnes and 19.2 million tonnes). In this case, the emission reduction measures applied to NDC+ reduce emissions by 0.2 million tonnes, maintaining the range of variability between the two scenarios.

Figure A10:
Industry and mining sector projected emissions for NDC+ scenario, compared to NDC scenario.



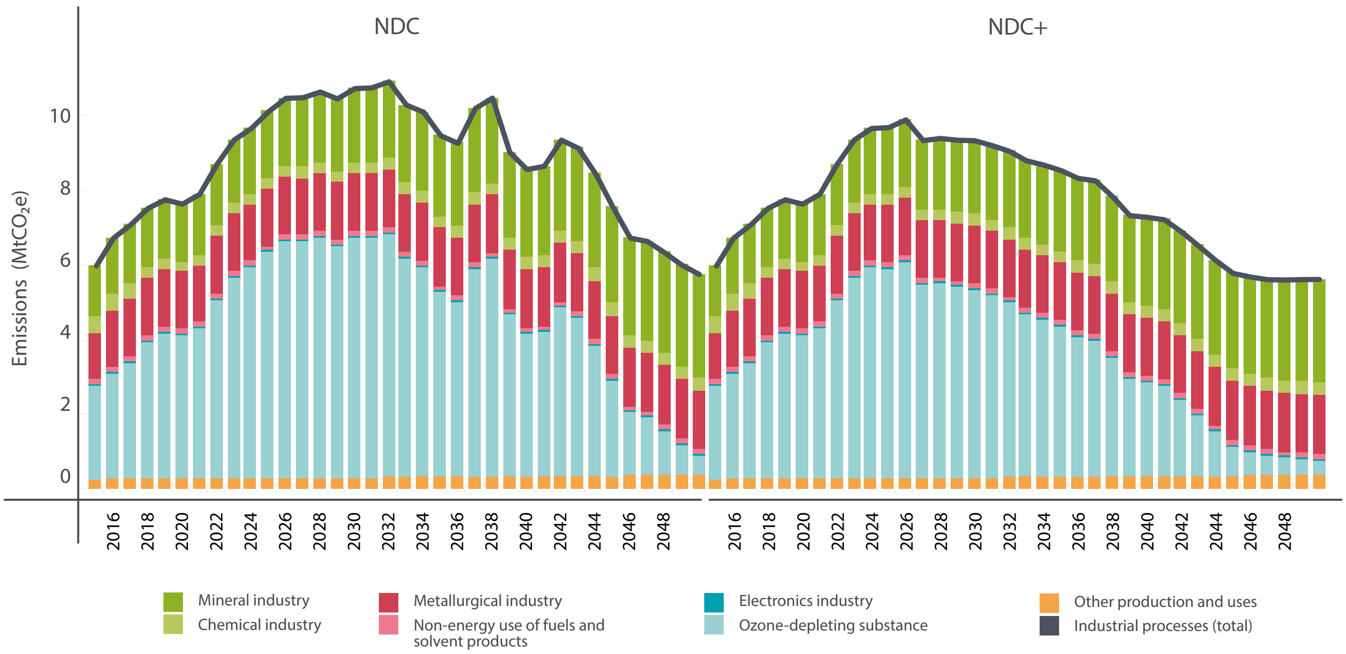
Source: Prepared by the authors.

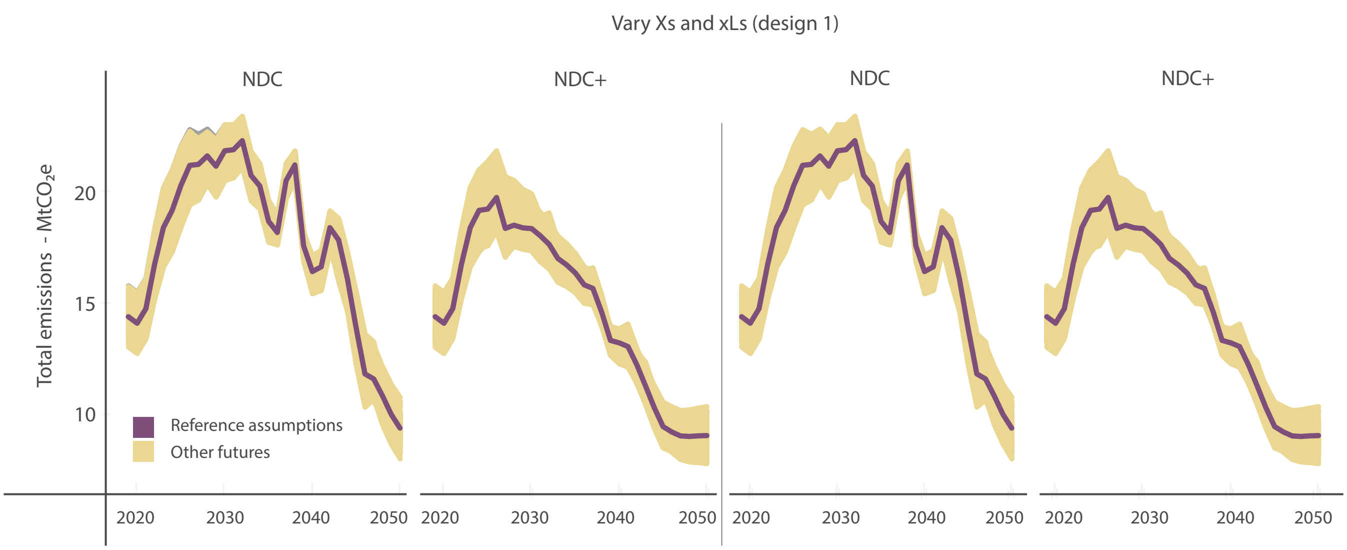
The measures that most influence the uncertainty of the results of this sector correspond to use of hydrogen in trucks in the mining industry, together with use of solar thermal systems in various industries. Similarly, the variability associated with the engines used in copper production and miscellaneous mines, in addition to energy intensity in copper production, have a strong impact on this uncertainty in total sector emissions.

Industrial processes

Figure A11 shows the projected emissions from the industrial processes sector for the deterministic case and for the cases that considered uncertainty in the various modeled parameters for both NDC and NDC+ scenarios. In this sector, by 2050 projected emissions are lower than in the early years, a reduction mainly due to the effect of the Kigali Amendment on hybrid fiber-coaxial emissions, observable in the category use of alternative products to ozone-depleting substances. This same category is mainly responsible for the increase in the first few years. A comparison of the two scenarios shows that, although the contribution of additional measures is small by 2050, these measures do have a significant effect on the trajectory.

Figure A11:
Industrial process emissions in multiple futures for NDC and NDC+ strategies.



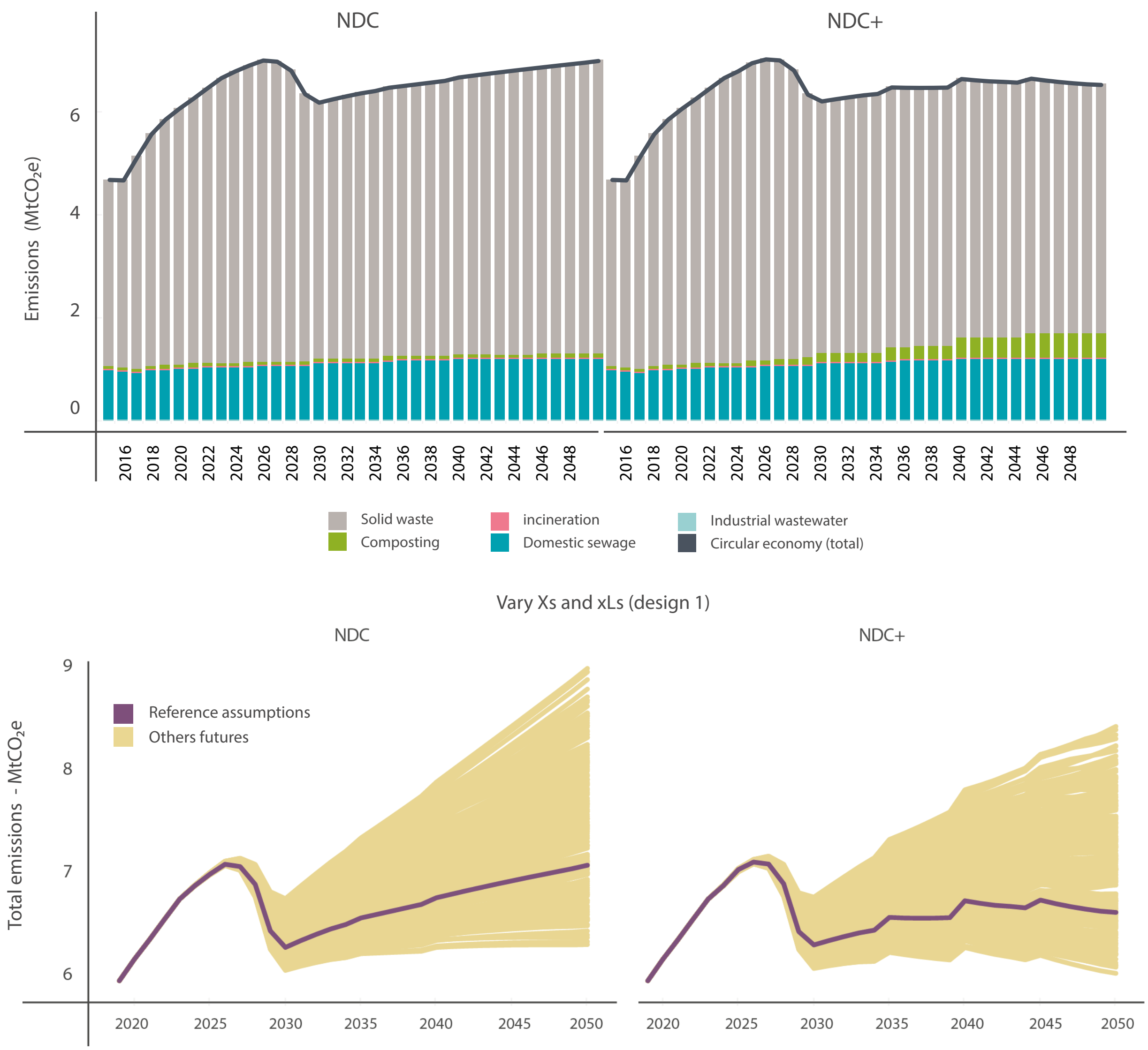


Source: Prepared by the authors.

Waste

The emissions projection from the waste sector for the deterministic case and for the cases that considered uncertainty in the different modeled parameters for both NDC and NDC+ scenarios are shown in Figure A12. Sector emissions record significant growth in the first few years, a situation that reaches its highest point towards the end of the 2020s. This is associated with the incorporation of new emission reduction measures, especially biogas capture and flaring in landfills. The same effect is seen in the NDC+ scenario where gradual incorporation of composting plants avoids a steeper increase in solid waste emissions. This measure also helps to make a slight reduction in the uncertainty margin of the emissions.

Figure A12:
Waste emissions in multiple futures for NDC and NDC+ strategies.

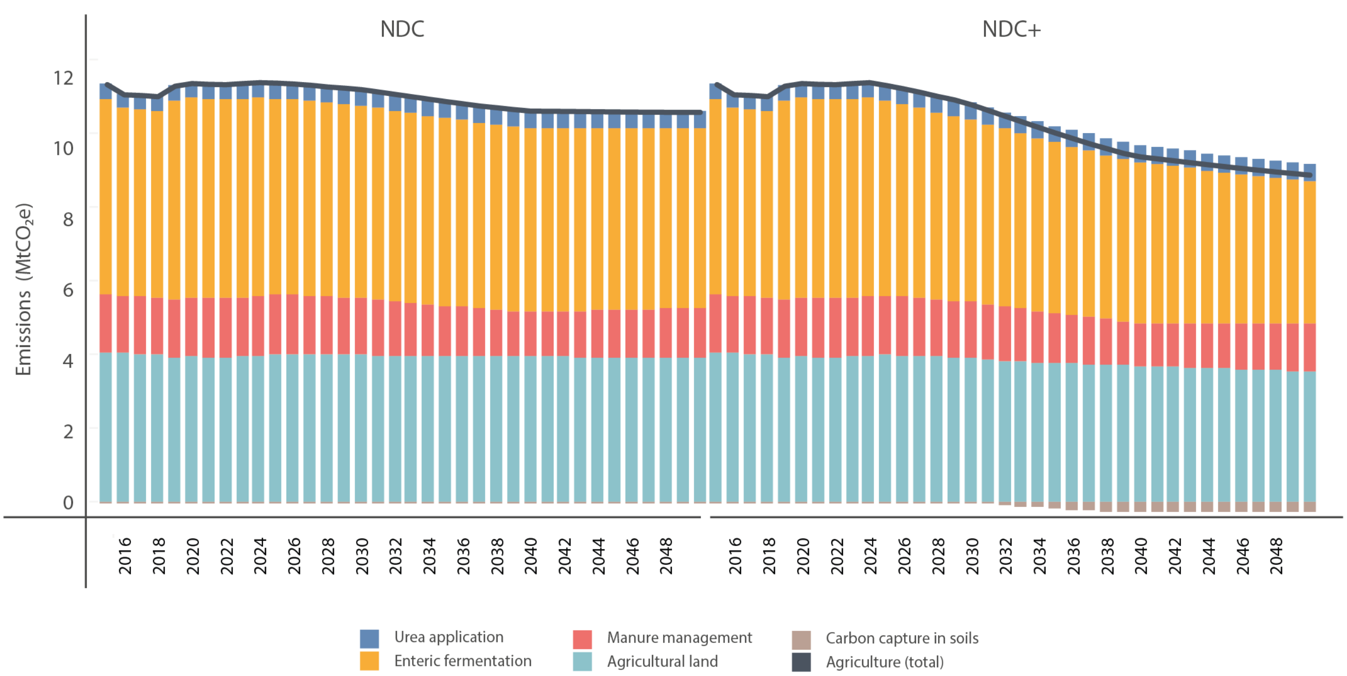


Source: Prepared by the authors.

Agriculture

Figure A13 shows the future GHG emissions scenarios for 2050 (in $MtCO_2eq/yr$) for the agriculture sector, corresponding to the scenario evaluated under the measures proposed in the NDC to achieve carbon neutrality by 2050 and the scenario that considers measures additional to the NDC for the same year. The first presents a total of 10.5 $MtCO_2eq/yr$ for 2050 (NDC scenario, left panel); the second, a total of 8.8 $MtCO_2eq/yr$ for the year mentioned (NDC+ scenario, right panel), taking into account the reference assumptions (without uncertainty) with their respective subcategory composition. Measures considered for the NDC scenario include a change in cattle diet, creation of biodigesters for pig farms and efficient use of fertilizer. Additional measures include regenerative agriculture, which includes holistic (beef) cattle management, application of organic amendments and changes in beef consumption (domestic meat production), of which the latter is most significant among the additional measures.

Figure A13:
Agriculture sector emissions for NDC and NDC+ strategies to 2050.

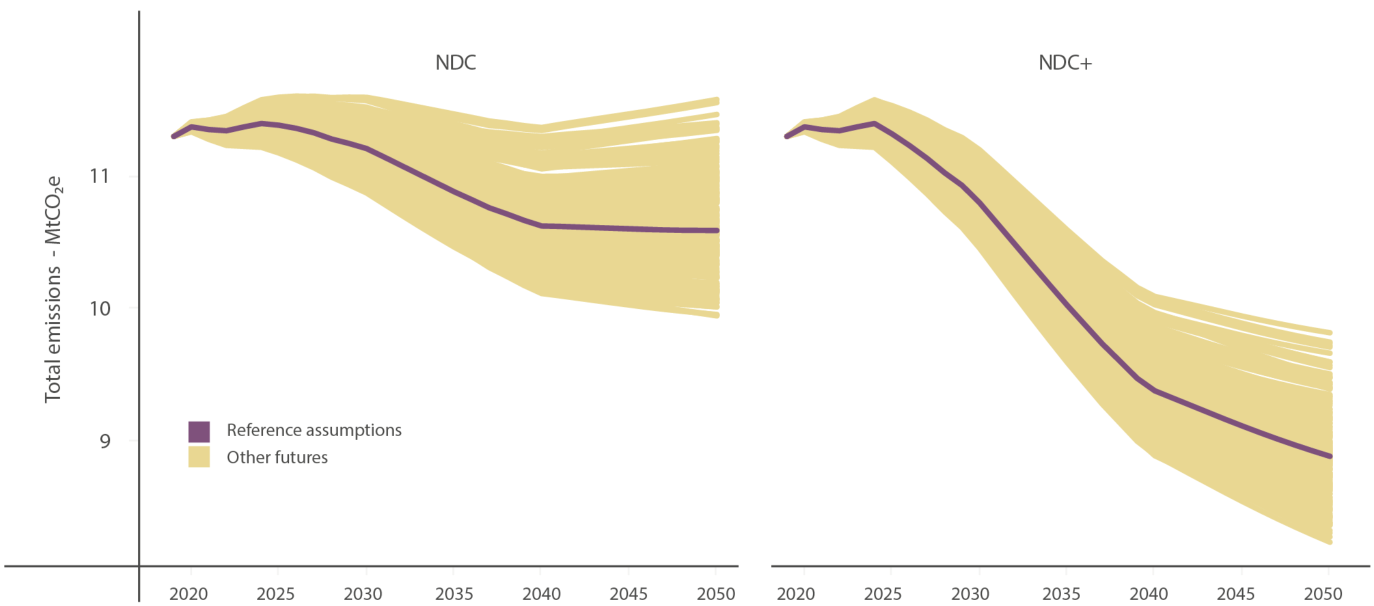


Source: Prepared by the authors.
Note: The bars correspond to each of the sector categories, and the navy-blue line to the sector total.

On the uncertainties associated with projected sector emissions (including emission reduction measures), Figure A14 shows emissions under a series of alternative futures for the NDC scenario (left panel) and NDC+ scenario (right panel), considering uncertainty in the different modeled parameters. Uncertainty was considered in the projection parameters of beef, corn and soybean prices, and also in the measures of the scenario specified in section 3.6 of chapter 3, under expert opinions taken from the participatory process developed in the framework of this project.

The uncertainty in the parameters results in a distribution around the reference scenario with a slightly rising trend in emissions for both NDC and NDC+ scenarios. For the NDC scenario (left), the sector 2050 capture is between 11.56 $MtCO_2eq$ in the most pessimistic future and 9.95 $MtCO_2eq$ in the most optimistic, with a percentage fluctuation relative to the reference scenario between a 9.1% increase and a 6.1% decrease. For the NDC+ scenario (right), sector capture by 2050 is between 9,823 $MtCO_2eq$ in the most pessimistic future and 8,242 $MtCO_2eq$ in the most optimistic, with a percentage range relative to the reference scenario of between a 10.5% increase and a 7.3% decrease.

Figure A14:
Agriculture sector total emissions for NDC and NDC+ strategies to 2050, considering uncertainties.

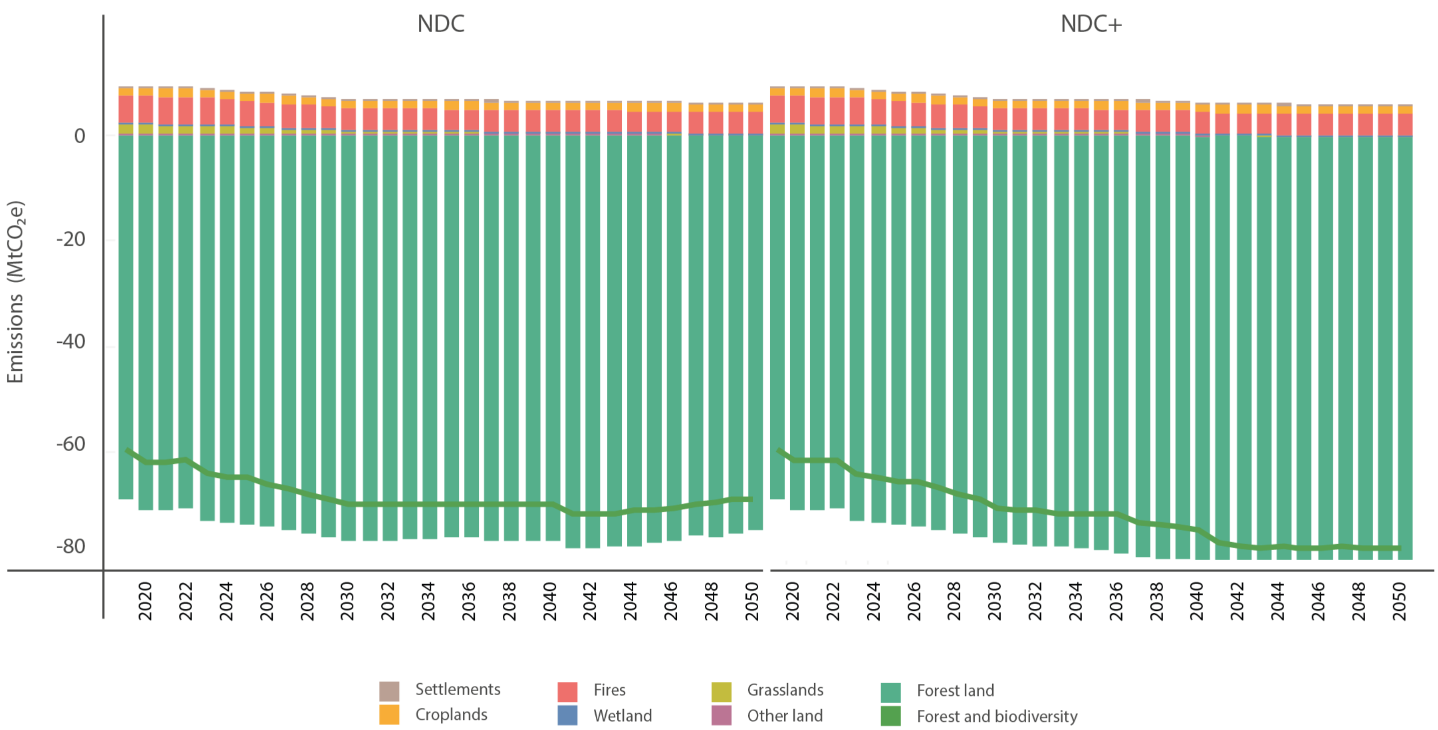


Source: Prepared by the authors.
Note: Emission trajectories are shown for different futures (yellow). The future that reflects the reference assumptions is shown in purple.

Forest and biodiversity

The left panel of Figure A15 shows the results without uncertainty (reference assumptions) for the various land-use categories, with the forest land category accounting for sector captures. In total, for the forest and biodiversity sector, a net capture of 68.6 $MtCO_2eq$ is projected for 2050 in the NDC scenario, and 78.2 $MtCO_2eq$ for 2050 in the NDC+ scenario, in which case the additional measures imply a 14% increase in sector captures. These additional measures include management of brown algae forests, expanding the area of national parks and reserves, quantification of capture in harvested wood products, and continuing afforestation measures and increased management plans until 2050.

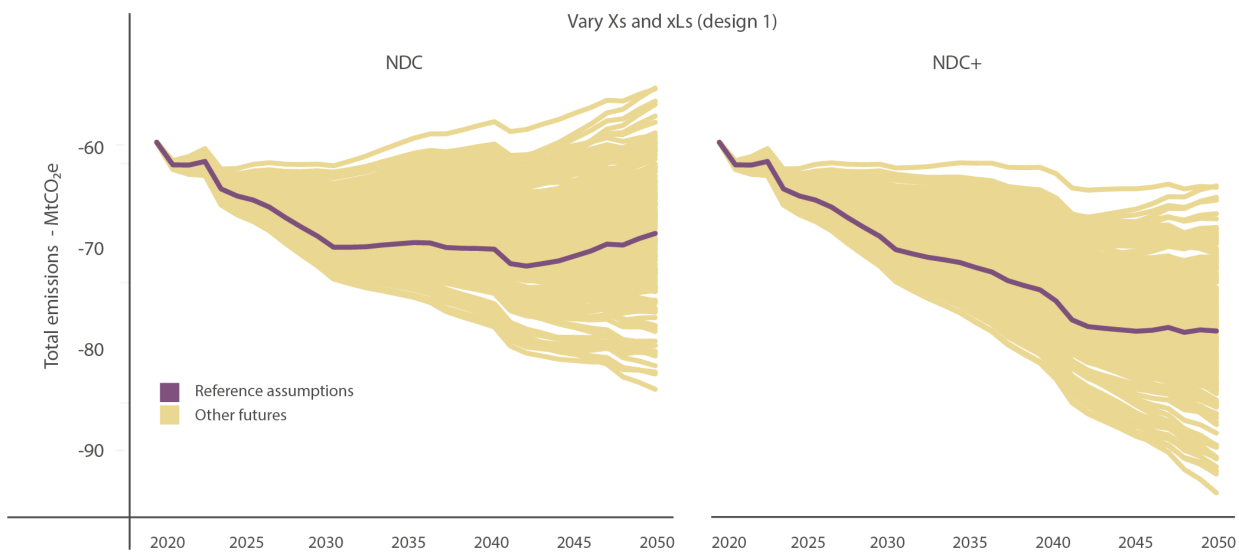
Figure A15:
Forest and biodiversity sector emissions for NDC and NDC+ strategies to 2050.



Source: Prepared by the authors.
Note: The bars correspond to each of the land use categories of the sector and the green line to the sector total.

Figure A16 considers the modeling of the sector including the uncertainties mentioned in Section 3.6 of Chapter 3, considering the NDC (left) and NDC+ (right) strategies associated with the modeling of the sector and application of the measures associated with each strategy. This generates a deviation in other future assumptions from the reference scenario. For the NDC scenario (left), sector capture for 2050 is between 54.4 $MtCO_2eq$ in the most pessimistic future and 84.0 $MtCO_2eq$ in the most optimistic. When considering the NDC+ scenario with additional measures, the capture for 2050 is between the most pessimistic and the most optimistic future of 64.0 and 94.2 $MtCO_2eq$, respectively.

Figure A16:
Forest and biodiversity sector total emissions for NDC and NDC+ strategies to 2050, considering uncertainties.

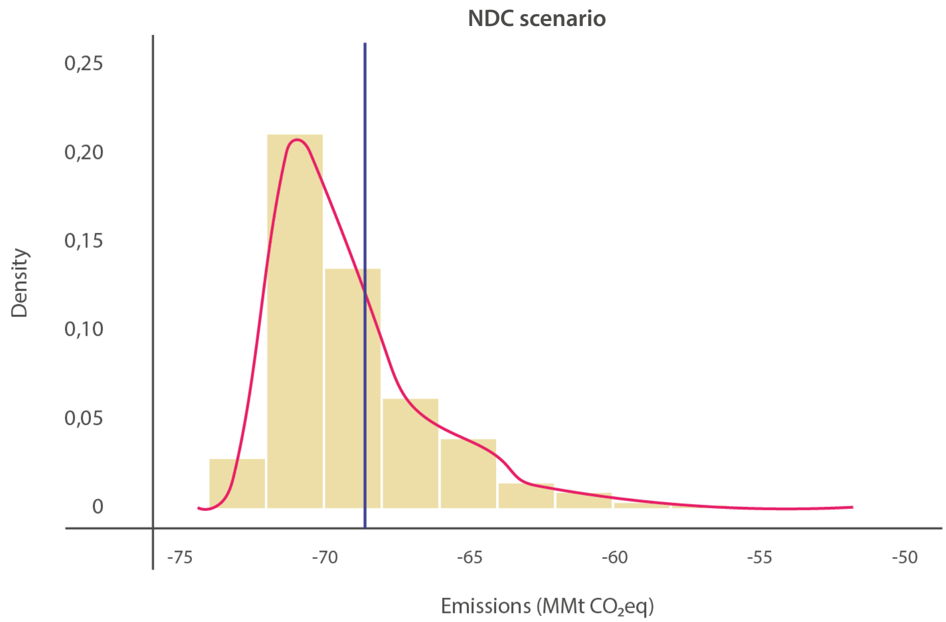


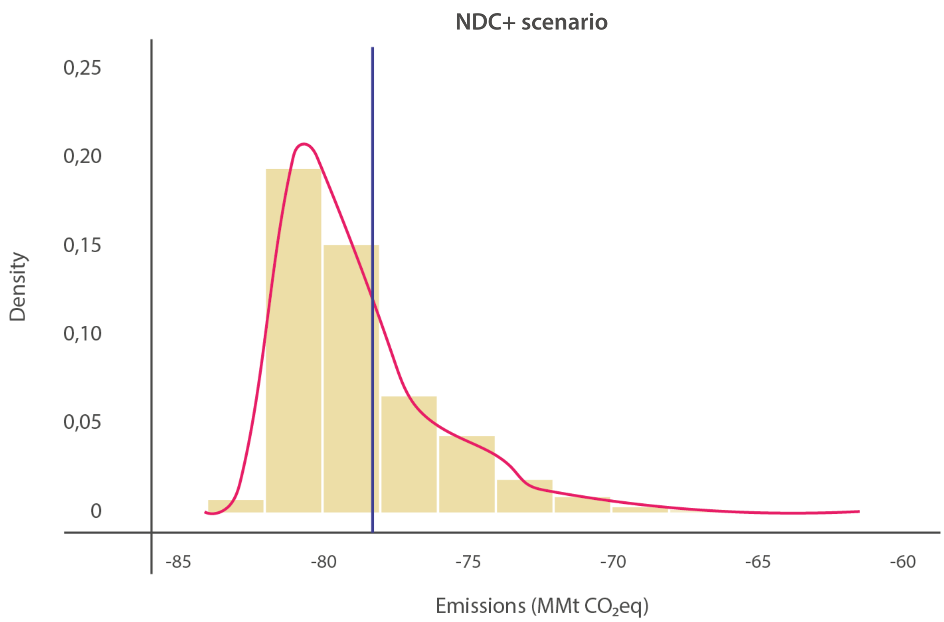
Source: Prepared by the authors.
Note: Emission trajectories are shown for different futures (yellow). The future that reflects the reference assumptions is shown in purple.

Fires represent a source of high variability for the sector, which for the purposes of integrated modeling was smoothed by using average fire values. However, if carbon neutrality is the target for 2050 as a specific year, there is a risk of a "mega-fire" occurring in that year; this could strongly skew emissions for that year, which already happened in 2017, since it can create peaks in emissions that significantly affect the sink condition of the sector. Figure A17 shows histograms and frequency distributions obtained from a sample of 500 possible futures considering fire area distributions at historical level. In these figures the blue line represents the 2050 sector emission under the reference assumptions.

In both strategies, in 30% of cases, sector capture due to forest fires is lower than capture considering the reference assumptions (in the figures, cases to the right of the blue line). This directly impacts the chances of achieving carbon neutrality. By 2050, in the NDC strategy, in approximately one in seven futures (13.4%), it would not be possible to achieve carbon neutrality due to increased emissions from larger scale fires than those considered in the reference assumptions. By contrast, in the NDC+ strategy, carbon neutrality is achieved in all futures considered, even those that consider larger fire areas. This result emphasizes the need to take into account measures additional to those indicated as reference in the NDC.

Figure A17:
Histogram and frequency distribution of emissions associated with forest and biodiversity sector in 2050, considering a sample of 500 futures for NDC and NDC+ strategies.





Source: Prepared by the authors.
Note: The blue line represents sector emissions for the reference future.

A.2
Organizations consulted

The study is based on valuable input and feedback obtained during numerous workshops with stakeholders, including the following agencies and organizations:

- Acción Empresas
- Agencia de Sostenibilidad Energética
- Agencia de Sustentabilidad y Cambio Climático
- Agencia de Sustentabilidad y Cambio Climático
- AGH Consultoría Estratégica
- Agricom
- Anagea
- Anglo American Chile
- Antofagasta Minerals
- Arauco
- Asociación de Empresas Eléctricas, AG
- Asociación de Generadoras
- Asociación de Municipalidades de Chile
- Asociación de Municipalidades para la Sustentabilidad Ambiental
- Asociación Empresas Gas Natural
- Asociación Chilena de Energías Renovables y Almacenamiento
- Banco Interamericano de Desarrollo
- BID Invest
- Camara Chilena de la Construcción
- Cámara Chilena de Refrigeración y Climatización A.G.
- Carnes Manada
- Casa de la Paz
- CCU
- Cementos Bío Bío
- Centro Avanzado de Tecnología para la Minería
- Centro de Cambio Global UC
- Centro de Ciencia del Clima y la Resiliencia
- Centro de Desarrollo Urbano Sustentable UC
- Centro UC de innovación en Madera
- Chile Sustentable
- Colbún
- Comisión Chilena del Cobre
- Comisión Económica para América Latina y el Caribe
- Comisión Nacional de Riego
- Compañía Manufacturera de Papeles y Cartones
- Consejo de la Sociedad Civil Ministerio de Energía
- Consejo Minero
- Consorcio Lechero
- Construye 2025
- Consultora EBP
- Corporación Capital Biodiversidad
- Corporación Chilena de la Madera AG
- Corporación de Estudios para Latinoamérica
- Corporación de Fomento de la Producción
- Corporación Nacional del Cobre de Chile
- Corporación Nacional Forestal
- Corporate Leaders Group for Climate Change-Chile
- Departamento de Ingeniería de Minas - Universidad de Chile
- Departamento de Ingeniería y Gestión de la Construcción
- Departamento Nacional de Planeación de Colombia
- Deuman
- Dinámica Plataforma
- EBP Chile
- Ecoscience
- Efecto Manada
- Empresas Eléctricas A.G.
- EnergyLab - SOFOFA
- Fondo Forestal Atacama Invest
- Fondo Mundial para la Naturaleza (WWF)
- Fundación Chile
- Fundación Terram
- Generadoras de Chile
- GIZ (Sociedad Alemana de Cooperación Internacional)
- GPM AG
- Instituto de Investigaciones Agropecuarias
- Instituto Forestal
- KDM
- LincGlobal
- Madera Alto Valor
- Melón
- Ministerio de Ciencias
- Ministerio de Defensa
- Ministerio de Economía
- Ministerio de Energía
- Ministerio de Hacienda
- Ministerio de Minería
- Ministerio de Obras Públicas
- Ministerio de Relaciones Exteriores
- Ministerio de Transportes y Telecomunicaciones
- Ministerio de Vivienda y Urbanismo
- Ministerio Medio Ambiente
- Ministerio Obras Públicas
- Nissan Latam
- Oficina de Cambio Climático
- Oficina de Estudios y Políticas Agrarias
- Partnership for Market Readiness Chile
- PEFC Chile
- Polpaico
- Pontificia Universidad Católica de Chile
- SAAM
- Secretaría de Planificación de Transporte (SECTRA)
- Sistema Chileno de Certificación de Manejo Forestal Sustentable
- Subsecretaría de Desarrollo Regional y Administrativo (SUBDERE)
- Subsole
- The Nature Conservancy (TNC)
- Tikuna
- Transelec
- UNEP-DTU Partnership
- Unidad Ozono - Ministerio Medio Ambiente
- Unión Internacional para la Conservación de la Naturaleza
- Universidad Adolfo Ibáñez
- Universidad Austral de Chile
- Universidad Bernardo O'Higgins
- Universidad de Chile
- Universidad de Concepción
- Universidad de La Frontera
- Universidad Mayor
- Universidad Técnica Federico Santa María
- Universidad Técnica Federico Santa María
- Uno.Cinco
- Verra
- Viña Emiliana
- Vínculo Agrario
- World Conservation Society

Chile aims to reach carbon neutrality. Its Nationally Determined Contribution (NDC) commits the country to reach net-zero emissions of greenhouse gases by 2050 and sets targets for emissions to be reduced progressively over time.

To comply with the goals of the NDC, line ministries have considered a set of sectoral transformations, such as closing coal-fired power plants, promoting electric mobility, and increasing forest captures which, taken together, could bring emissions down to zero.

This study evaluates how these sectoral transformations would fare under a wide range of economic, environmental and technological uncertainties. It identifies the vulnerabilities of the strategy, that is, under what conditions sectoral transformations are insufficient to achieve net-zero emissions. It then quantifies options for making sectoral plans to deliver the NDC more robust, that is to reduce the likelihood of not achieving carbon neutrality.

Additional measures discussed include speeding up retirement of coal-fired power plants, promotion of telework and non-motorized transport, reduction of beef consumption, expansion of thermal retrofitting of houses, increased afforestation, sustainable forest management, and expansion of protected areas. These measures are based on ideas proposed by sectoral experts during a participatory process.

Finally, a macroeconomic evaluation finds that enhancing the set of measures put forward to comply with the NDC would result in a net gain of 0.8% of gross domestic product (GDP) by 2050, on the top of 4.4% GDP gain that the current NDC plans would bring.