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Potential Greenhouse Gas Reductions Beyond Chile's Nationally Determined Contribution to 2030: Preliminary Modeling Results

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Potential greenhouse gas reductions beyond Chile's nationally determined contribution to 2030

Preliminary modeling results

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Abstract

The Climate Action Teams (CAT) initiative is a mechanism that supports international resource transfers for climate mitigation. CAT operates through government-to-government agreements based on verified mitigation outcomes beyond nationally determined contribution (NDC) commitments in one country (the host) in exchange for financial and technological support from one or more countries (the partners) that form part of the CAT. The mitigation outcomes are "credited" to the partner countries and can potentially contribute to their NDC commitments.

A prospective emissions open-access model was developed by a modeling team from the Global Change Center of the Pontifical Catholic University of Chile to explore mitigation opportunities beyond Chile's NDC. The results represent a first approximation of the mitigation potential and its costs, since the implementation of any of the actions presented may require a whole set of

analyses to determine a more accurate estimate. Nevertheless, some of the results are of particular interest and the structure of the model can be used for some preliminary investigations. For example, in the Reference future scenario, 62 $MtCO_2e$ are estimated to be available beyond the budget commitment. Preliminary results from new runs based on different carbon prices suggest that 70% of the 62 $MtCO_2e$ could be obtained at a marginal cost of less than US$50/$tCO_2e$. In addition, estimates of the capital cost required to achieve this 70% is about US$2.8 billion.

Keywords

Climate Action Teams, open-access model, mitigation, Chile's NDC, marginal carbon costs.

JEL Classification Numbers

Q5, Q54

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Contents

1. Introduction

The Climate Action Teams (CAT) initiative is a mechanism that supports international resource transfers for climate mitigation. It takes a fundamentally different approach to international transfers relative to project-based mechanisms or carbon market linking, since it is an agreement among a small group of cooperating governments on mitigation outcomes for a country.

CAT operates through government-to-government agreements based on verified mitigation outcomes beyond nationally determined contribution (NDC) commitments in one country (the host) in exchange for financial and technological support from one or more countries (the partners) that form part of the Climate Action Team. The mitigation outcomes are "credited" to the partner countries and can potentially contribute to their NDC commitments.

The CAT mechanism facilitates mitigation outcomes at lower abatement costs, but unlike a project-based mechanism, it does not require a costly institutional infrastructure, thereby reducing transaction costs considerably. Currently, the CAT initiative has developed a project with Chile, New Zealand and Switzerland.

The Chilean NDC (Gobierno de Chile, 2020), updated in 2020, establishes a series of commitments. The most important for the case of the CAT initiative are:

- a long-term vision of achieving greenhouse gas (GHG) neutrality by 2050
- a GHG emission budget not exceeding 1,100 $MtCO_2e$ between 2020 and 2030 (excluding land use, land-use change and forestry, LULUCF), with a GHG emissions maximum (peak) by 2025, and a GHG emissions level of 95 $MtCO_2e$ by 2030
- a reduction in total black carbon emissions by at least 25% by 2030, with respect to 2016 levels
- sustainable management and recovery of 200,000 ha of native forests, representing GHG captures of around 0.9–1.2 $MtCO_2e$ annually by 2030
- afforestion of 200,000 ha, of which at least 100,000 ha will comprise permanent forest cover with at least 70,000 ha of native species, representing captures of 3.0–3.4 $MtCO_2e$ annually by 2030
- reduction in emissions in the LULUCF sector associated with degradation and deforestation of the native forest by 25% by 2030, with respect to average emissions in the period 2001–13.

Other important commitments are not quantified or are not directly related to mitigation.

As part of the technical work in Chile, a modeling team from the Global Change Center of the Pontifical Catholic University of Chile has built open-access models to explore mitigation opportunities in more depth beyond the NDC. This progress report presents preliminary results of the developed models and the analyzed mitigation scenarios. The final output will be shared and discussed for a broader discussion.

The main objectives of this report are to:

- develop GHG emission models that cover all the sectors identified in the GHG national inventory
- analyze mitigation actions, considering both those evaluated for the Chilean NDC and potential additional actions
- analyze the GHG emission pathways under different scenarios (mitigation strategies) and futures (exogenous conditions)
- check the fulfillment of the Chilean NDC goals under each scenario and future.

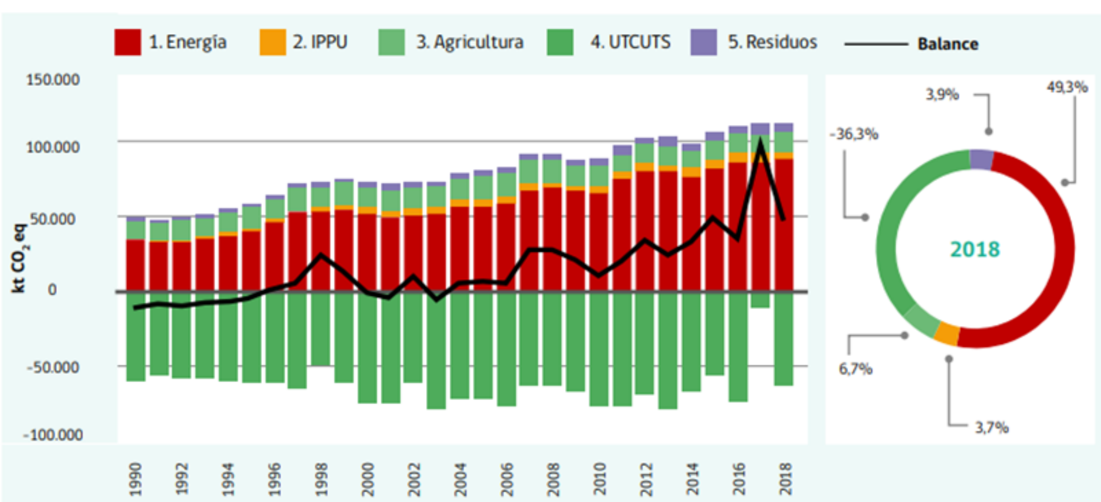
2. Model description

This initial effort has focused on developing a set of sectoral GHG emission models that represent all the emissions included in Chile's national GHG inventory. For the modeling, all the sectoral models use consistent information to elaborate and analyze emission pathways under different conditions and consider the implementation of mitigation measures that affect all the sectors. The current exercise focuses the analysis on the changes that are needed to reduce emissions (technologies and behaviors) rather than on the specific policies needed to achieve these changes, the only exception being the policies that are currently in place (e.g., the carbon tax on electricity generation).

The GHG national inventory identify five emission sectors: energy; industrial processes and product use (IPPU); agriculture; land use, land-use change and forestry (LULUCF, or UTCUTS in Spanish); and waste. As can be seen in Figure 1, LULUCF has significant net captures (-64 $MtCO_2e$ in 2018). This is because forestry plantations and native forest under conservation are still growing with respect to the year 1990, despite the fact that the sector has shown some level of degradation due to forest fires and woodfire extraction. The other four sectors are net emitters (112.3 $MtCO_2e$ in 2018), the main one being the energy sector (87 $MtCO_2e$ in 2018, or 77.4%), followed by agriculture (11.8 $MtCO_2e$ in 2018, or 10.5%), waste (7 $MtCO_2e$ in 2018, or 6.2%) and IPPU (6.6 $MtCO_2e$ in 2018, or 5.9%).

FIGURE 1

Historical GHG emissions in Chile by sector



Source: Ministerio del Medio Ambiente de Chile (2021).

The energy sector is the main contributor due to the intensive use of fossil fuels to produce energy. This sector can be further divided into subsectors: electricity generation (29% of the sector's emissions), transport (25%), industry and mining (14%), and buildings (7%).

Taking into account the relative importance of the different sectors and subsectors, the following models were developed:

- Energy: electricity generation
- Energy: transport
- Energy: industry and mining
- Energy: buildings
- Waste
- IPPU
- Agriculture
- LULUCF.

The energy models were built using the Low Emissions Analysis Platform (LEAP)[1] and the models for the other sectors were developed using Lumina's Analytica software.[2] Both of these platforms allow users free access to explore and run the models. The models were developed using the same information applied by the Chilean government in 2019 (Palma Behnke et al., 2020), but updating some parameters in order to use the best current public information available. In addition, the analysis considers a different methodology to address futures and scenarios, in contrast with the work of the government, which considered only one mitigation scenario without addressing uncertainty.

2.1 Futures and scenarios

For the purpose of this analysis, it is necessary to address the future conditions that would drive GHG emissions. The different variables affecting emissions can be exogenous (generated at the international level or related to climate conditions) or endogenous (generated from the results arising from other parts of the model or by the level of implementation of the mitigation actions). Acknowledging these, two categories of pathways were developed:

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1 https://leap.sei.org
2 https://lumina.com

- **Futures** These include a trajectory of exogenous parameters representing a possible set of conditions that could facilitate (or impede) the mitigation strategies.
- **Scenarios** These represent different mitigation strategies implemented at a national level, with each strategy considering a set of mitigation measures and their specific level of implementation.

For the futures, it is possible to identify the following categories of emission drivers and their relationships:

- **Economic activity and commodities prices** Chinese GDP will affect national GDP, energy prices, copper price, agriculture products prices, copper production and pulp production.
- **Climate variables** The level of precipitation will affect electricity generation and the intensity of forest wildfires.
- **Clean technology costs** The level of mitigation at the global level will impact on the prices of different clean technologies.
- **Climate action in Chile** The government's level of commitment to climate action and efficiency will impact on how quickly and timely Chile will implement the planned mitigation measures.

Normally, a decision-maker analyzes one pathway of drivers and over these sets of conditions projects GHG emissions. For the current analysis, three futures were considered. The first of these is the Reference future, which considers that all drivers will show their respective expected value. In order to have a sensitivity analysis, Green and Red futures were also developed.

Table 1 presents the differences between the three models.

TABLE 1

Differences between the selected futures

Group of variables	Futures		
	Red	Reference	Green
Chinese GDP growth, commodities prices and national production level	All high	All medium	All low
Climate variables (representative decade)	Drought (2010–19)	Medium (1990–99)	Wet (1980–89)
Green technology prices	High	Medium	Low
Climate action	Delayed	Conventional	Early and active

For the mitigation strategies, three scenarios were analyzed:[3]

- Current policies (CP): expected emissions under current regulation and incentives (12 measures).
- Intermediate mitigation (IM):[4] considers the implementation of all mitigation measures analyzed to develop the NDC commitment (41 measures).
- Accelerated mitigation (AM): considers enhanced mitigation measures to overachieve the carbon budget (60 measures).

The following sections present a brief explanation of the different models developed. These models are accessible by anyone to explore in depth (Ministerio del Medio Ambiente de Chile [MMA], 2021a).

3 Details of the mitigation measures considered in each sector and scenario are presented in the following sections.
4 The CP strategy is different from the IM strategy, because even if Chile analyzed a set of possible mitigation policies to achieve its NDC commitment, not all of these policies are currently in place.

2.2 Energy: electricity generation

The electricity generation sector covers power plants and the electric grid, including the expansion needed to meet a specified electricity demand. Therefore, modeling this sector simulates the operation of the power plants already existing and the planned installation of new plants. These questions are answered by the LEAP model, which minimizes the cost of the system given the constraints of the decarbonization policies.

The "Electric Generation" and "Electric Distribution" modules from LEAP are used to calculate this sector's emissions. These modules allow LEAP to act as an optimization tool focused on determining carbon dioxide (CO_2) emissions, where it minimizes the cost of a given electric grid by controlling its operation and expansion. This grid is represented by only one electric node, which links all the generation and demand of the system, and thermal losses are simplified to a single loss factor.

These simulations on the LEAP platform are not expected to serve as forecasts of the Chilean electric grid beyond 2030. This is due to the limitations of the platform, such as the simplification of the transmission network into only one node, and the fact that energy storage processes are not represented in the simulations but are expected to play an important role beyond 2030. Instead, the value of these simulations resides in allowing our team to analyze the different costs and benefits associated with different policies, therefore link actions and policies to CO_2 mitigation in the future.

The scope of LEAP requires a huge amount of data from different sources to devise an accurate simulation. Such inputs and sources are as follows:

- installed capacity (CNE[5])
- investment, operative and fuel costs projections (PELP[6])
- electricity daily demand curve (CEN[7])
- wind and solar daily capacity factor shape (CEN)
- capacity factor for each technology (PELP)
- thermal efficiency for thermal power plants (PELP)
- threshold for new capacity added (PELP)

5 Comisión Nacionale de Energía (National Energy Commission).
6 Planificación Energética de Largo Plazo (Long-Term Energy Plan).
7 Coordinator Eléctrico Nacional (National Electricity Coordinator).

- coal phase-out schedule (CEN)
- carbon tax (PELP)
- electricity demand projection
- transmission loss factor
- discount rate
- power plant lifetime.

The LEAP model was calibrated and tested with data from the Chilean Ministry of Energy and its Long-Term Energy Plan (PELP) up to 2050. It was also compared against the updated NDC by the Ministry of Energy. Further data about other parameters, such as the coal phase-out schedule and the carbon tax, can be found in the appendixes.

The Chilean approach to addressing CO_2 emissions in the electricity sector is to phase out coal-powered plants. The CP and IM scenarios correspond to a full decarbonization of the grid by 2040. Two AM scenarios were analyzed, the first corresponding to a full phase-out of coal power plants by 2025 (AM 2025), and the second to a full phase-out of coal power plants by 2040 but with a more severe carbon tax between 2025 and 2050 (AM Heavy Tax).

The loss of baseload previously provided by coal in the CP and IM scenarios is replaced mainly by a mix of concentrated solar power, new hydropower and geothermal power plants. In contrast, the loss of baseload in the AM 2025 scenario is too rapid to be replaced immediately by renewable energy. Therefore, the gas power plants already existing need to temporarily increase their share of electricity generation while the system adjusts. Something similar happens in the AM Heavy Tax scenario, but this shows a sudden decrease in coal usage in the Red and Reference futures when the higher tax policy starts in 2025—up to an 80% reduction in coal generation. However, the Green future has a smoother decrease in coal generation due to its lower cost of fossil fuel.

The main difference between the AM 2025 and AM Heavy Tax scenarios is the nature of their coal-reduction methods. AM 2025 forces coal phase-out according to a rigid schedule, whereas AM Heavy Tax relies on the economic penalty of the carbon tax to reflect the externalities of coal generation. As will become apparent later in Section 3, this economic approach works as intended for the Red and Reference futures, where it achieves less mitigation than AM 2025 but at a slightly lower cost. However, the carbon tax is not strong enough to deter coal generation in the Green future and the emissions in this scenario end up closer to the IM scenario.

It is important to note that the technologies used to replace coal are not fixed by scenario, but instead are chosen by the model based on their cost and availability. Also, the electricity demand for each of the studied scenarios was provided by the energy demand sector. These demand scenarios all differ from one another and therefore directly affect the nature of the decisions made by the model.

Table 2 lists the mitigation actions presented by the model for the electricity generation sector.

TABLE 2

Mitigation actions for the electricity generation sector

Action	Action level		
	CP / IM	AM 2025	AM Heavy Tax
Coal phase-out	44% of coal power plants by 2025 60% of coal power plants by 2030 100% of coal power plants by 2040	100% of coal power plants by 2025	44% of coal power plants by 2025 60% of coal power plants by 2030 100% of coal power plants by 2040
Carbon tax	US$5/t$CO_2$ until 2030 US$5–32.5/t$CO_2$ between 2030 and 2050	US$5/t$CO_2$ until 2030 US$5–32.5/t$CO_2$ between 2030 and 2050	US$5/t$CO_2$ until 2025 US$50–100/t$CO_2$ between 2025 and 2050

2.3 Energy: demand sectors

The energy demand sector modeling considers the development of three models that cover the main demand sectors: transport, industry and mining, and buildings. These models follow the same steps for the projection, and are based on the models used by the Chilean Ministry of Energy for the development of the PELP (Ministry of Energy, 2020b). They were developed using a mix between Microsoft Excel spreadsheets and LEAP, with the activity -evel projections for each of the different subsectors developed in Excel and then fed into LEAP. In general, the modeling process consists of the following steps:

1. **Updating data** The Chilean Ministry of Energy data is updated with the energy balance for 2014–19[8] for 15 Chilean regions, for each type of fuel and electricity consumed. The energy balances are published by the Ministry of Energy. The information from activity data (i.e., sectors production, distances traveled, etc.) is also updated from available public information, with the specific sources of information used dependent on the different activities considered.
2. **Energy intensity calculations** Energy intensities for the different activities are estimated, using both the total energy consumption and the activity level. These results are compared with previous data and differentiated by the final use of energy.
3. **Projection of activity level** Econometric relationships are calculated based on the historical data, which allows the projection of activity data based on macroeconomic parameters for each of the different futures.
4. **Results estimation** The information is fed into a LEAP model to calculate the different futures and mitigation scenarios.
5. **Connections with regard to the other sectoral models** Some of the results are then fed into other models. Notably, the electricity demand is a relevant input for the electricity generation model, and the residential wood consumption is a variable for the LULUCF model. Some other variables are also fed into the IPPU models.

The set of mitigation actions considered in the scenarios is taken from previous studies, prioritizing actions that are expected to achieve the highest reductions and those that could be modeled with the tools and models selected. While further mitigation actions exist and may be implemented in Chile, further analysis and modeling are needed for these, including the possibility of modifying the resolution and/or approach of the models. In particular, three initiatives were considered for their mitigation actions, given they follow the same demand sector structure as the present study:

- Mitigation Action Plans and Scenarios (MAPS) Chile Initiative (see Mitigation Action Plans and Scenarios Chile, 2014)
- the 2020 Chilean NDC mitigation process (see Palma et al., 2019)

8 The most up-to-date energy balance is for 2019.

- a recent study of the carbon neutrality goal under uncertainties (see Benavides et al., 2021).

More details of the models for each of the three main sectors are presented below.

2.3.1 Transport

The transport modeling has a demand-based focus, where the demand for transportation is satisfied by a mix of modes, each of which has different characteristics, such as occupation rate and energy intensity. The original demand projection comes from the Chilean Ministry of Energy and is based on a series of studies carried out by the Ministry of Transport from 1997 to 2013. The modeling considers four subsectors: road transportation, railway transportation, maritime transportation and air transportation. In addition, two types of transportation demand are considered: demand for passenger transportation (expressed as passenger-kilometer, pkm), and demand for freight transportation (expressed as tonne-kilometer, tkm). Each of these demands is estimated for the four subsectors.

According to Chile's last GHG inventory, series 1990–2018 (MMA, 2021a), most of the country's GHG emissions come from the road transportation subsector of the transport sector. The modeling of this subsector is complex, as it considers a detailed disaggregation of the sector (see Table 3).

TABLE 3

Disaggregation of the road transport sector

Demand	Subdemand	Mode	Fuel
Passengers	Urban	Private car Taxi Motorcycle Bus	Gasoline Hybrid gasoline Diesel Hybrid diesel Electric Liquefied petroleum gas Compressed natural gas Hydrogen
	Interurban	Private car Bus	
Freight	Urban	Light truck Medium truck Heavy truck	Diesel Hybrid diesel Hydrogen
	Interurban	Heavy truck	

The fuel consumption projected by the original Ministry of Energy model was compared with the actual fuel consumption for the 2014–19 period. An underestimation in demand of around 20% for the year 2018 is observed, which is concentrated in the country's less populated regions. Because of this difference, the demand for the period 2014–19 is adjusted and the projection corrected to account for this new estimation.

The different futures modeled apply different demand projections. These are related to macroeconomic parameters such as GDP, population, and some secondary projections from the industry and mining model such as copper and cellulose production, which affects the demand in specific regions. These econometric models are developed on a regional scale, based on the original Ministry of Energy models but corrected with the fuel consumption recorded for the 2014–19 period. This enables a projection of GHG emissions that is closer to the actual GHG emissions reported on the GHG emission inventory.

The mitigation scenarios consider three kinds of mitigation action: change from fossil-fuel to zero-emission vehicles,[9] change in the mode of transport from a GHG emission-intensive mode to a less intensive mode (e.g., from private car to bus), and reduction from the total demand through actions that incentivize active transport (e.g., walking, cycling) or a reduction in transportation demand (e.g., remote working). The actual actions considered in the models are presented in Table 4.

TABLE 4

Mitigation actions for the transport sector

Subsector	Action	Action level		
		CP	IM	AM
Road transportation	Electromobility: private cars	33% of the private car market in 2050 Exponential penetration, with	58% of the private car market in 2050 Exponential penetration, with	68% of the private car market in 2050 Exponential base penetration plus a subsidy for electric car

9 At least in terms of exhaust emissions, they certainly mean a demand for electricity and hydrogen that could need to be satisfied by fossil fuels. As an assumption, the hydrogen modeled is considered "green hydrogen" produced using solar energy. In the case of electric vehicles, the additional electricity demand is considered in the electricity generation projections.

	an estimation of 2.6% of private cars in 2030	an estimation of 3.2% of private cars in 2030	equivalents in the period 2025–30, to a fifth of all new cars in 2025, a fourth in 2026, and a third in the period 2027–30. This results in 13.5% of private cars in 2030
Electromobility: taxis	100% of taxis in 2040 Exponential penetration, with an estimation of 24.0% of taxis in 2030	100% of taxis in 2040 Exponential penetration, with an estimation of 24.0% of taxis in 2030	100% of taxis in 2040 Exponential penetration, with an estimation of 24.0% of taxis in 2030
Electromobility: buses	100% of buses in 2040 Exponential penetration, with an estimation of 21.0% of public buses in 2030	100% of buses in 2040 Exponential penetration, with an estimation of 21.0% of public buses in 2030	100% of buses in 2040 Exponential penetration, with an estimation of 21.0% of public buses in 2030
Hydrogen on freight trucks	Same as 2018 (0%)	85% of freight trucks in 2050 Linear growth starting in 2024 with 0.4% of trucks. By 2030, it is estimated that 19.9% of freight trucks could use hydrogen	85% of freight trucks in 2050 Linear growth starting in 2024 with 0.4% of trucks. By 2030, it is estimated that 19.9% of freight trucks could use hydrogen
New bus rapid transit (BRT) corridors in Santiago	Same as 2018 (95 km)	Same as 2018 (95 km)	Installation of 150 km of new BRT corridors (total of 245 km) between 2027 and 2032 Estimated to result in an increase of 7% in the use of buses from passengers that switch from private cars

	Incentivize new bicycle infrastructure	Normal increase of bicycle infrastructure from historical tendency	Normal increase of bicycle infrastructure from historical tendency	3,000 km of new bikeways installed between 2025 and 2030. Estimated to result in a reduction of 10% in urban demand for transportation
Air transportation	Hydrogen on commercial flights	No hydrogen on commercial flights	No hydrogen on commercial flights	10% of flights using hydrogen in 2050, a linear increase from 2035

2.3.2 Industry and mining (I&M)

The industry and mining energy demand sector (I&M) covers GHG emissions associated with the energy use of fossil fuels in industrial processes. For I&M modeling, the demand is estimated from the final use of energy, with detailed characterization for each of the 15 administrative regions. This model is an updated version of the model originally used by the Ministry of Energy Ministry for the development of the PELP (Ministry of Energy, 2020b), where both the data from 2014–19 for the energy balance and the production of each region were updated. The model is disaggregated by subsectors associated with each main industry. Some of these subsectors are specific to mining, since this is a major economic activity in Chile, especially copper mining. In addition, for each subsector some level of detail is characterized. Specifically, the copper industry is modeled by type of mining and type of process (categories are open-pit mining, underground mining, concentration, leaching, smelting, refining and associated services), while all the other subsectors are modeled in detail by process type: motor processes, thermal processes and other electricity uses. This categorization is described in more detail in Table 5.

TABLE 5

Description of the industry and mining subsectors

Subsector	Subsector description
Copper	Exploitation, extraction and metallurgical processes associated with copper mining. Modeled following the projection of the Chilean Copper Commission (Comisión Chilena del Cobre, 2020). Modeled by type of mining and type of process, where the categories are open-pit mining, underground mining, concentrate, leaching, smelting, refining and associated services
Various industries	Industries not included in other categories, such as construction and agroindustry. Modeled according to the projected growth of the national GDP
Various mines	Exploitation, extraction and metallurgical processes associated with metallic and nonmetallic mines other than copper, iron and saltpeter. Modeled based on projected global GDP growth
Steel industry	Industries and foundries that work with iron and steel
Iron	Exploitation, extraction and metallurgical processes associated with iron mining. Modeled based on projected Asia-Pacific GDP growth
Saltpeter	Exploitation, extraction and metallurgical processes associated with saltpeter mining. Modeled based on projected Asia-Pacific GDP growth
Paper and pulp	Paper and pulp production; does not include printing. Modeled based on a national projection of the sector
Fishing	Stationary and mobile fishing. Modeled based on a national projection of the sector
Petrochemical industry	Methanol and ethylene production. Modeled based on a national projection of the sector
Sugar	Beet sugar production. Modeled according to the projection of beet production
Cement industry	Cement kilns, considering only the combustion of fuel. Process emissions are modeled on the IPPU GHG emissions model. Modeled according to the projected growth of the national GDP

Comparison of the projected fuel consumption by model and the fuel consumption recorded for the 2014–19 period shows an underestimation of demand of around 4% for the year 2019, where this difference is concentrated in the copper mining industry. This difference needs additional adjustment.

The different modeled futures are generated by different demand projections, which are related to macroeconomic parameters such as national, Asian[10] or global GDP according to each subsector. These econometric models are developed on a regional scale, based on the original models of the Ministry of Energy and corrected with the actual fuel consumption for the period 2014–19.

The scenarios modeled consider two kinds of mitigation actions: change from the use of fossil fuels to the use of electricity; and change from fossil-fuel and electricity use to energy sources without GHG emissions, such as biomass, solar energy and hydrogen.[11] The actual actions considered in the models are presented in Table 6.

TABLE 6

Mitigation actions for the industry and mining sector

Subsector	Action	Action level		
		CP	IM	AM
Copper	Solar thermal systems	Same as 2019 (0%) for smelting and refining, and linear growth of 0.02% from 0% in 2013 for leaching and services, with an estimated penetration of 0.38% in 2030	16% by 2050 Linear growth starting in 2021, with an estimated penetration of 5.3% in 2030 for smelting and refining, and 5.4% for leaching and services	30% by 2050 Linear growth starting in 2021, with an estimated penetration of 10.0% in 2030 for smelting and refining, and 10.1% for leaching and services

10 In this case Asian GDP was used as a parameter, without prejudice to the fact that Chinese GDP was used as a parameter in other sectors.
11 Modeled hydrogen is assumed to be "green hydrogen" produced by solar energy, as was the case with modeled hydrogen in the transport energy demand sector.

	Electrification in thermal processes	Same as 2019 (varies for each process and region, from 37.2% to 92.7%)	Additional 25%, when possible Linear growth starting in 2021, with an estimated penetration that varies for each process and region, from 45.5% to 88.9%[12] in 2030	Additional 25%, when possible Linear growth starting in 2021, with an estimated penetration that varies for each process and region, from 45.5% to 88.9% in 2030
	Electrification in motor processes	Same as 2019 (varies for each region, from 3.5% to 21.2%)	57% in open-pit mining by 2050 Linear growth starting in 2021, with an estimated penetration that varies for each region, from 21.3% to 33.1% in 2030	63% in open-pit mining by 2050 Linear growth starting in 2021, with an estimated penetration that varies for each region, from 23.3% to 35.1% in 2030
	Hydrogen in motor processes	Same as 2019 (0%)	37% in open-pit mining by 2050 Linear growth starting in 2021, with an estimated penetration of 12.3% in 2030	37% in open-pit mining by 2050 Linear growth starting in 2021, with an estimated penetration of 12.3% in 2030
	Electrification in thermal processes	Same as 2019 (0%)	8% in underground mining by 2050 Linear growth starting in 2021, with an estimated penetration of 2.7% in 2030	8% in underground mining by 2050 Linear growth starting in 2021, with an estimated penetration of 2.7% in 2030
Various industries	Solar thermal systems	Same as 2019 (0%)	33% by 2050 Linear growth starting in 2021, with an estimated penetration of 11.0% in 2030	46% by 2050 Linear growth starting in 2021, with an estimated penetration of 15.3% in 2030
	Hydrogen in thermal processes	Same as 2019 (0%)	3% by 2050 Linear growth starting in 2021, with an	3% by 2050 Linear growth starting in 2021, with an

12 This value is lower than the starting point because, where necessary, compliance with the solar thermal systems action was prioritized over this electrification action.

			estimated penetration of 1.0% in 2030	estimated penetration of 1.0% in 2030
	Hydrogen in motor processes	Same as 2019 (0%)	12% by 2050 Linear growth starting in 2021, with an estimated penetration of 4.0% in 2030	12% by 2050 Linear growth starting in 2021, with an estimated penetration of 4.0% in 2030
	Electrification in motor processes	Same as 2019 (varies for each region, from 18.6% to 88.6%)	88% by 2050 Linear growth starting in 2021, with an estimated penetration that varies for each region, from 41.8% to 88.4% in 2030	88% by 2050 Linear growth starting in 2021, with an estimated penetration that varies for each region, from 41.8% to 88.4% in 2030
Various mines	Hydrogen in motor processes	Same as 2019 (0%)	21% by 2050 Linear growth starting in 2021, with an estimated penetration of 7.0% in 2030	21% by 2050 Linear growth starting in 2021, with an estimated penetration of 7.0% in 2030
	Electrification in motor processes	Same as 2019 (varies for each region, from 0% to 94.4%)	74% by 2050 Linear growth starting in 2021, with an estimated penetration that varies for each region, from 24.7% to 87.6% in 2030	79% by 2050 Linear growth starting in 2021, with an estimated penetration that varies for each region, from 26.3% to 89.2% in 2030
Steel Industry	Hydrogen in thermal processes	Same as 2019 (0%)	Same as 2019 (0%)	10% by 2050 Linear growth starting in 2021, with an estimated penetration of 3.3% in 2030
	Biomass in thermal processes	Same as 2019 (0%)	Same as 2019 (0%)	10% by 2050 Linear growth starting in 2021, with an estimated penetration of 3.3% in 2030

2.3.3 Buildings

Just as in the other demand sectors, building modeling has a demand-based focus, where the demand is estimated according to the final use of the energy. This model is an updated and improved version of the model originally used by the Ministry of Energy to develop the PELP (Ministry of Energy, 2020b). The model is divided into three subsectors: residential, commercial and public. The subsectors are then characterized according to the 15 administrative regions of the country and further characterized into subdivisions, as shown in Table 7.

TABLE 7

Subsectors and subdivisions of the buildings sector

Subsector	Subdivision	Final use
Residential	Houses and apartments	Heating Hot sanitary water Cooking Appliances
Commercial	Banks	Hot sanitary water Pump and ventilation Heating and climatization Office equipment Lighting Others uses
	Supermarkets	Hot sanitary water Cooking Heating and climatization Refrigeration Lighting Other uses
	Shopping malls	Hot sanitary water Cooking Heating and climatization Motors Lighting Others uses
	Others commercial buildings	General uses

	Private hospitals	Hot sanitary water Pumps and ventilation Cooking Heating and climatization Office equipment Sterilization Refrigeration Lighting Laundry Others uses
Public	Public hospitals	
	Schools	Hot sanitary water Cooking Computers Lighting Other uses
	Universities	
	Other public buildings	General uses

The original model developed by the Ministry of Energy was updated using 2014–19 data from the energy balance for each of the regions, and with complementary information about the different activities, such as number of new buildings in the different categories. The original results of the Ministry of Energy model overestimated GHG emissions by 7% compared with the GHG emissions inventory, which is equivalent to 0.5 ktCO_2e. It is important to highlight the fact that information collected from the latest census allowed us to produce a more accurate estimation of the level of activity from the different sources of GHG emissions considered. This new information was included in the revision of the energy projections, and when compared to the original projection the resulting updated projection is higher for the public sector and lower for the residential and commercial sectors.

These updated projections are based on econometric models that correlate the different variables with macroeconomic models such as population and GDP. With regards the saturation of electrical equipment in homes, data from the U.S. are used and are assumed to be the same for similar levels of GDP per capita. This approach has been used in previous studies in Chile, most notably in Fundación Chile (2014).

The different futures modeled are differentiated by building area and the penetration rate of the different appliances in those buildings, all estimated from macroeconomic parameters such as GDP and population.

The scenarios represent different mitigation actions, which can be summarized as: change from fossil-fuel to zero-emission[13] technologies; and reduction in energy demand with better thermal insulation on buildings. Table 8 presents the mitigation actions considered.

TABLE 8

Mitigation actions for the buildings sector

Subsector	Action	Action level		
		CP	IM	AM
Commercial	Electrification of end uses	Close to 50% of the final demand is electricity by 2050, similar to the level in 2020	Close to 75% of the final demand is electricity by 2050, considering an exponential growth from 2030 (52.4%)	Close to 90% of the final demand is electricity by 2050, considering an exponential growth from 2022 (52.4%) In 2030 electricity represents 56.5% of the energy consumption
Public	Solar water heaters in public hospitals	Same as 2018 (0%)	10% in hospitals by 2050, starting from 2020 and with linear growth By 2030, 3.3% of hot sanitary water comes from solar roofs	50% in hospitals by 2050, starting from 2020 and with linear growth By 2030, 16.7% of hot sanitary water comes from solar roofs
	Electric heating in public hospitals	Same as 2018 (0%)	48% in hospitals by 2050, starting from 2022 and with linear growth	100% in hospitals by 2050, starting from 2022 and with linear growth

13 Although the changes to use of electric appliances result in an increase in electricity demand.

	Solar photovoltaics (PV) on public buildings	Same as 2018 (0%)	Same as 2018 (0%)	50% of the electric demand cover by solar PV on nonspecific public buildings for northern regions (down to Región VII) by 2050 Linear growth starting in 2021. By 2030, 16.7%
Residential	Electric residential heating	20% of houses by 2050 40% of apartments by 2050	72% of houses by 2050 89% of apartments by 2050 Linear growth from 2021. By 2030, around 35% of houses, and around 55% of apartments	72% of houses by 2050 89% of apartments by 2050 Linear growth from 2021. By 2030, around 35% of houses, and around 55% of apartments
	Electric residential cooking	20% of houses and apartments by 2040 Linear growth from 2018. By 2030, 11%	36% of houses by 2050 35% of apartments by 2050 Linear growth from 2018. By 2030, 14%	72% of houses by 2050 89% of apartments by 2050 Linear growth from 2018. By 2030, 32%
	Solar water heaters	Same as 2018 (0%)	63% hot sanitary water in houses by 2050 57% hot sanitary water in apartments by 2050 Linear growth from 2021. By 2030, 22% of houses and 19% of apartments	63% hot sanitary water in houses by 2050 57% hot sanitary water in apartments by 2050 Linear growth from 2021. By 2030, 22% of houses and 19% of apartments
	Retrofit of thermal insulation	0 new houses with retrofit of thermal insulation by year 2030	20,000 new houses with retrofit of thermal insulation by year 2030	40,000 new houses with retrofit of thermal insulation by year 2030

2.4 Waste

The waste sector is represented in an Analytica model, which has been used previously by the modeling team in GreenLab (2014) and Benavides et al. (2021). Although the model was originally developed in 2013, it has been updated, including the same methodologies and data used in the last GHG inventory (MMA, 2020).[14]

The model is developed considering four modules for each of the sector's four categories: solid waste disposal, biological treatment of solid waste, incineration and open burning of waste, and wastewater treatment and discharge. These modules not only use the same key inputs such as population and GDP, but there are also some interconnections between them that need to be considered. For example, the fraction of organic waste that is destined for compost influences both solid waste disposal and the biological treatment of solid waste. Another relevant interconnection between the modules is the sludge generation from the wastewater treatment plants and its disposal in landfills.

Of the four categories included in the waste model, solid waste disposal has historically represented the main category of emissions. The module for this category follows the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines, modeling the emissions following a first decay order modeling, which estimates the generation of methane (CH_4) from the decomposition of the organic fraction of waste. This method relies heavily on the use of historical data, estimating for each year the emissions of the accumulated waste in the different landfills. For this, the model considers a series of waste generation data from 1950 onwards, reconstructed by the Ministry for the Environment and as used to create the national GHG inventory. The projection of CH_4 generation is based on the econometric relationship between waste generation and GDP per capita data from the World Bank (Kaza et al., 2018). The data of waste generation is disaggregated by the 15 administrative regions of Chile.

The composition of the generated waste is divided into nine categories: food waste and similar, paper and cardboard, wood, textiles, sludge (only from wastewater treatment plants), plastics, glass, metal, and other non-organic waste. Of these categories, only the first five decompose into CH_4, while the remaining four do not produce GHG emissions in landfills.[15] The final disposal sites of the waste changes both in time and by region, based on the historical data and projected

14 Base year 2018. Includes the 1990–2018 series.

15 This level of detail is used in order to model some policies and co-benefits of potential mitigation actions. Also, it is worth noting that if the plastic fraction were incinerated, it would emit nonbiogenic CO_2 and other GHGs.

new landfill sites. The model distinguishes between four different types of final disposal sites, considering their physical characteristics and usual modes of operation. In addition, climate affects the decomposition rate for each of the waste fractions.

Finally, the model considers some options that affect the estimation of CH_4 emissions, taking into account technologies such as the capture and burning of the biogas generated. These are based on the historical records. For example, in Chile there has been some capturing and burning of biogas since 2004; this practice grew rapidly until 2010, since when it has stabilized at 55–65 ktCH_4 per year.

The other four categories are both less relevant in terms of total emissions, and less complicated to estimate. Some of the main considerations in these categories are:

- **Biological treatment of solid waste** This considers historical data from industrial composting. It could be underestimating the emissions as it does not consider small-scale composting and relies solely on a database of registered composting projects reported with the GHG emission inventory (MMA, 2021a).
- **Incineration and open burning** This considers incineration of hospital waste and cremation, and industrial waste incineration. The data come from health statistics (hospital waste and cremation) and the declaration from the industry on the registry for waste generation, transfer and disposal (MMA, 2021b). It is important to note that the data from the industry has been available only since 2014.
- **Wastewater treatment and discharge** This considers CH_4 emissions from residential wastewater, and nitrous oxide from both residential and industrial wastewater. The data come from official sources related to the sanitary companies report presented in the GHG emission inventory (MMA, 2021a). The residential wastewater method distinguishes between rural and urban wastewater as the type of treatment varies significantly between them.

As with any estimating model, the analysis of the results has to consider the uncertainty of the modeling process because the estimation can vary in time as the assumptions, methodologies and data are refined. In this respect, some of the uncertainties around the projections are captured by the futures developed for the model. This model is especially sensitive to population projections and to GDP projections. These parameters affect the generation of residential solid waste, industrial generation of waste, wastewater generation, the amount of protein in wastewater, and the level of incineration activity and amount of hospital waste incinerated, among others.

The different modeled mitigation actions for each of the scenarios are listed in Table 9.

TABLE 9

Mitigation actions for the waste sector

Subsector	Action	Action level		
		CP	IM	AM
Solid waste disposal	Increased capture and burning of landfill gas	Same as 2018. New project in Tarapacá region (2021)	100% of capture and burning in managed landfills by 2030	100% of capture and burning in managed landfills by 2030
	New composting plants	Same level as 2018 (316 kt/year)	Same level as 2018 (316 kt/year)	50% of residential organic waste composted by 2050. By 2030, 9.5% is composted
Wastewater treatment and discharge	New wastewater treatment plants for the most populous cities	Same level as 2018: only in Santiago	New plants: Gran Concepción (2030), Gran Valparaíso (2035), La Serena—Coquimbo (2040), Antofagasta (2040)	New plants: Gran Concepción (2028), Gran Valparaíso (2033), La Serena—Coquimbo (2038), Antofagasta (2038)

2.5 Industrial processes and product use (IPPU)

IPPU is a sector that covers GHG emissions from industrial processes, from the use of GHGs in products and from non-energy use of fossil-fuel carbon (Harnisch and Agyeman-Bonsu, 2006). For the purpose of this study, these emissions are modeled in Analytica, based on a previous model developed by Benavides et al. (2021).

Since the original development of the model, a new official GHG inventory was published by the Chilean government. This applied new methodologies for some subsectors of the IPPU subsector—for example, it applied a Tier 3 methodology for the production of nitric acid and a Tier 2 methodology for refrigeration and air conditioning, when in the previous inventory a lower tier methodology was used. These methodological changes and updated data were included in the new version of our model, which means the resulting estimation is closer to the official GHG inventory series (1990–2018).

The model consist of six modules representing the six categories of GHG sources included in the inventory: mineral industry, which includes cement, lime and glass industries; chemical industry, which includes nitric acid and petrochemical industries; metallic industry, which includes iron, steel and lead industries; non-energy products from fuel and solvent use; emissions of fluorinated substitutes for ozone-depleting substances, which includes different applications of these substances; and other product manufacture and use, which includes mainly the sulfur hexafluoride (SF_6) emissions from the manufacture of electrical equipment.

This model is conceived as a second stage model, meaning that it receives both primary projections such as GDP and population, and secondary projections such as cement production or projections of transportation. This information is complemented with industry-level information and historical data to establish relationships between the level of production and variables such as GDP. These relationships are then used to estimate the future level of activity for each of the futures and scenarios, and hence the projections of emissions.

This process complexity varies across the different modules depending on the methodology used to estimate emissions in the GHG inventory, on the information available for projections, and on the relevance of each category in terms of total emissions. For those categories with more emissions, a more detailed modeling is conducted to get more sensitive estimations to the multiple factors that could impact on the final results. In the last inventory the most relevant category is the emissions of fluorinated substitutes for ozone-depleting substances, which is also the category with the biggest growth rate.

Emissions of fluorinated substitutes for ozone-depleting substances consist mainly of hydrofluorocarbon (HFC) emissions due to the installation, fugitive emissions and end-of-life emissions of refrigeration and air-conditioning equipment and systems. In addition, there is the contribution of the use of HFCs in products such as metered-dose inhalers and solvents. This category has an additional complexity because it is affected by the Kigali Amendment to the

Montreal Protocol, which regulates the consumption of HFCs. This means that the use of historical data to represent future scenarios might not be sufficient. For this reason, a five-step method is used:

1. **HFC consumption base projection** This projection does not consider the impact of the Kigali Amendment, and it depends on the relationship between the banks of HFCs on the different applications and macroeconomic variables.

2. **Determination of the HFC consumption limit** The Kigali Amendment establishes a timeline of reductions, which depends on a base consumption determined from actual consumptions between the years 2020 and 2022, plus a margin related to past hydrochlorofluorocarbon (HCFC) consumption. For Chile, the Kigali Amendment means a freeze in HFC consumption between the years 2024 and 2028, a 10% reduction from 2029, a 30% reduction from 2035, a 50% reduction from 2040, and an 80% reduction from 2045.

3. **Determination of new HFC consumption** The HFC consumption limit is forced following a cost-based prioritization list of the different applications and sub-applications. This list is based on the cost of alternative technologies developed by Purohit and Hoglund-Isaksson (2017) and Hoglund-Isaksson et al. (2017). The prioritization means that when the total consumption of the base projections is greater than the limit, the sub-applications with lower technological substitution costs will reduce their consumption until the limit is reached. The model will reduce consumption in as many sub-applications as is necessary to achieve the restriction.

4. **Estimation of the application banks** Considering the new HFC consumption by application, and the fugitive emission rate and average life for the equipment, a new estimation of the banks is estimated in a recursive way, where the bank of a year t (B_t) depends on the bank of the previous year (B_{t-1}), the new bank (N_t) and the fraction of the banks that finish their lifespan (N_{t-ls}):

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

5. **Estimation of emissions** Considering the estimation of the banks and consumption under the influence of the Kigali Amendment, new emissions are estimated using the same parameters as in the GHG emissions inventory.

The results of the projections represent the best estimation, but they have to be viewed carefully as they have uncertainties. These uncertainties have different origins, and some are considered through the use of different futures, as explained at the beginning of this section. Some of the parameters that vary between the different sectors are both primary projections such as GDP and population, and secondary projections that come fundamentally from the energy demand sector models. These parameters affect the activity level considered in the most relevant categories, such as HFC consumption, and the industry's activity.

It is relevant to note that the scenario considered by the Chilean government for the construction of the NDC does not consider any mitigation action for the IPPU sector, although the Kigali Amendment is considered in the business-as-usual (BAU) scenario. The mitigation actions for the IPPU sector for each of the scenarios are presented in Table 10.

TABLE 10

Mitigation actions for the IPPU sector

Subsector	Action	Action level		
		CP	IM	AM
Emissions of fluorinated substitutes for ozone-depleting substances	HFC consumption restriction	Kigali Amendment	Kigali Amendment	Kigali Amendment
	Recovery and regeneration of refrigerant plants	Just the capacity installed in 2018: 350 t/year	Just the capacity installed in 2018: 350 t/year	New installed capacity for 2,800 t/year in 2030

2.6 Agriculture

The agriculture sector model has been developed in Analytica software, based on the model developed for the Benavides et al. (2021) study. The emissions estimation reported in the national GHG inventory (MMA, 2021a), based on the 2006 IPCC methodological guidelines of (Eggleston et al., 2006), was used for this category. The current model considers the updates of the last inventory report (1990–2018) for the sector to date.

The emissions considered from the agriculture sector are subdivided into seven categories: enteric fermentation, manure management, rice cultivation, agricultural soils, urea application, agricultural burn, and liming. Within this sector, 82% of emissions come from the enteric fermentation and agricultural soils categories (based on the final year records included in the inventory report), with a distribution of 42.2% and 39.8%, respectively. The third largest contributor is manure management emissions, at 12%. Together, these three categories add up to 94.7% of the total emissions of the sector (MMA, 2021a).

The enteric fermentation category considers CH_4 emissions that are produced in the digestive systems of livestock. Cattle and sheep represent 93.9% of the emissions of this category, followed by pigs and other species. The manure management category, includes CH_4 and nitrous oxide (N_2O) emissions generated by manure storage in livestock production systems, mainly of pigs and cattle. It also includes emissions from other species, such as poultry, camelids, horses and goats.

The historical series was estimated in the model using data at the regional level for number of heads of cattle by cattle type. These data were based on official information generated by the Chilean Office of Agrarian Studies and Policies (ODEPA),[16] mainly from the 2007 Agricultural and Forestry Census (Instituto Nacional de Estadísticas [INE], 2007) and annual reports. Emission factors used correspond to Tier 1 and Tier 2.

For the projection of number of heads of cattle, an econometric model was developed based on the beef producer price and the corn producer price. The projected number of pig heads was based on the projection of the corn producer price, and the projection of the number of heads of poultry was based on the projection of the corn producer price and soy producer price. The price projections were obtained from Organisation for Economic Co-operation and Development (OECD) world statistics, updated to 2020, corresponding to the period 2020–29, and for the year 2030 the growth rate of each of the prices obtained from the OECD statistics was maintained.

The emissions corresponding to the rice crop category include CH_4 emissions, produced by the anaerobic decomposition of organic material in flooded rice fields, and based on Tier 1 of the IPCC methodology and national rice harvest area data from ODEPA. For the rice surface

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[16]ODEPA, Office of Agrarian Studies and Policies, for its acronym in Spanish

projection, a logarithmic trend from the period 1990–2018 was developed, presenting a slight decrease of 5% by 2030 compared to the base year 2019.

The emissions corresponding to the category agricultural soils correspond to N_2O emissions generated from the soil surface as a result of microbial processes associated with the application of nitrogen in its different forms. These include inorganic fertilizer, organic fertilizer (livestock manure), nitrogen from urine and manure from grassland grazing animals, and nitrogen available in crop residues.

The data for synthetic fertilizer use in agriculture for historical periods was obtained from ODEPA, based on fertilizer import data provided by the National Customs Service. For the estimation of future synthetic nitrogen, a parameter that represents the intensity use level of nitrogen by crop was applied (González-Ulibarry, 2019). The future area by different crop types was estimated based on their historical trend (1990–2018) and projected up to 2030, and the estimated future consumption of fertilizer used a conventional dose of nitrogen (N) application by type of crop (kgN/ha). The estimation of organic fertilizer applied to soils was based on the available manure in confined production systems (a variable integrated with projections of livestock), as were emissions of nitrogen from urine and manure from grazing animals.

The results of the projections were compared with MAPS initiative and national estimates from the Ministry for the Environment. Differences were mainly in numbers of cattle and pigs.

As discussed earlier, three different futures were considered, based on different parameters. The Green future considers low prices of bovine meat, maize and soy, and for mitigation actions considers an early implementation of one year. The Red future considers high prices of bovine meat, maize and soy, and a late implementation of mitigation actions. A specific population-dependent parameter was considered to project meat consumption in the future.

The mitigation actions for the agriculture sector for each of the scenarios are presented in Table 11.

TABLE 11

Mitigation actions for the agriculture sector

Action	Action level		
	CP	IM	AM
Change in bovine diet (lipids)	No additional adoption	70% of the dairy cattle in 2037, implementation starts in 2030	Implementation starts in 2025
Porcine biodigesters	27% of total porcine head purines managed with biodigesters to 2030	Additional 17% of total porcine head purines managed with biodigesters, reaching 44% of total heads in 2030	No additional adoption
Efficient use of fertilizer	No additional adoption	Reduction of 5% of the intensity of use of synthetic fertilizer to 2030, starting in 2026	No additional adoption
Application of organic amendments	No additional adoption	No additional adoption	Application of organic amendments to 10% of national cereal surface to 2030, starting in 2025
Holistic management of cattle	No additional adoption	No additional adoption	20% of bovine grazing grassland of X Región (Los Lagos) by 2030, starting in 2025
Bovine biodigesters	No additional adoption	No additional adoption	Management of dairy cattle slurry in confinement, reaching 80% of heads of cattle by 2030, starting in 2025

Reduction of agricultural burns	No additional adoption	No additional adoption	Reduction in the area of agricultural burns by 80% by 2027, starting in 2023
Biochar	No additional adoption	No additional adoption	Implementation of a biochar production plant, starting in 2024
Meat tax	No additional adoption	No additional adoption	10% tax on consumer prices, reducing national meat production

2.7 Land use, land-use change and forestry (LULUCF)

The LULUCF sector model was developed using Analytica software. A GHG emissions projection model was built, which is consistent with the historical emissions of Chile's national GHG emission inventory for the period 1990–2018. As a basis this uses the GHG data for the different subcategories of the sector provided by the 2020 national inventory (MMA, 2021c) and applying the 2006 IPCC methodology used in the inventory (Eggleston et al., 2006). The model is divided into different nested modules that contain the specific modeling for each category of the LULUCF sector and are organized as follows:

- **Forest land**:
  - Forest land remaining as forest land. This module modeled emissions and captures associated with the following subcategories: increase of forest biomass (growth), loss of forest biomass (harvests, wildfires, use of firewood and burning of forest residues), and change in vegetation (substitution and restoration).
  - Land converted to forest land. This module includes emissions and captures associated with land converted to native forest, and land converted to plantations.
- **Land converted to X (where X = BCDEF)**. This module groups the captures and emissions associated with land converted into grasslands (B), croplands (C), wetlands (D), settlements (E), and other lands (F).
- **X that remains as X (Where X = BCDEF)**. This considers captures and emissions associated with grasslands (B), croplands (C), wetlands (D), settlements (E) and other lands (F) remaining as such.

For the projection of the sector to 2030, we applied the methodology and modeling approach used by Benavides et al. (2021). The approach calibrated an autoregressive vector model for the subcategories of increase of forest biomass, harvests, and land converted to forest land, croplands, grasslands, wetlands and other lands. For burning of forest residues, change in vegetation and harvested wood products, the approach used the corresponding average of the last five years. Projections of the areas of plantations, native forest, croplands and grasslands affected by wildfires used the average from different reference decades: for the Green future scenario, the period 1980–89 was used; for the Reference scenario the period 1990–99 was used; and for the Red future scenario the period 2000–09 was used. This projection starts in 2021, and for the years 2019 and 2020 official data of areas affected by wildfires provided by the National Forestry Corporation (CONAF) were used (Corporación Nacional Forestal, 2021b). Projection of the biomass loss through firewood extraction follows the trend of residential wood consumption in the demand energy sector.

The projection method for native and exotic afforestation measures (and the increase in hectares afforestation measure used in the AM scenario) is the same as the approach applied by Benavides et al. (2021), who use emission factors derived from the historical calculation of GHG emissions from the land converted to forest lands subcategory (native forest and plantations). For the measure of increases in hectares of native forest under forest management (and the measure that increases the hectares managed in the AM scenario) and the measure of the increase in protected areas, the same methodology described by Benavides et al. (2021) was used. The method uses emissions factors derived from the historical calculation of GHG emissions from the increase of forest biomass subcategory, derived from the 2006 IPCC equations applied by the 2020 national inventory report (MMA, 2021a). Similarly, the same approach was used for the projection of fire degradation control measures for the subcategory of loss of biomass.

For the kelp forest management projection, the emission factors were taken from Vásquez et al. (2014) for the three species of kelp used in the model.

For economic evaluation of the exotic afforestation measure, cost data were taken from different sources and adjusted by inflation if necessary. One of the sources was provided by CONAF (2012), where the investment costs were calculated using an average of the values of macro zones within Chile with a density of 1,100 plants per hectare, considering manual plantating for each plant, subsoiling at 40 cm and protection against lagomorphs. Another source of data of plantation establishment was provided by the Chilean Wood Corporation (Corporación Chilena de la Madera [CORMA], 2021). The mean of the total investment cost for exotic afforestation was used.

For the operating values of plantation forestry, costs of first pruning, first thinning, pruning and commercial thinning, and technical advice, CONAF (2012) values were used. CORMA (2021) also provided operating cost data, which include land lease and marginal administration costs. The mean of the total operation cost for exotic afforestation was used.

For incomes, mean of yield given by Corvalán & Hernández (2012) were used and prices of harvested wood were given by the Forestry Institute (Instituto Forestal [INFOR], 2021).

For the values of investments in afforestation with native species, the same sources were used (CORMA, 2021; CONAF, 2012), but these were also averaged with the values per hectare provided by a CONAF call for tenders, code 1859-4-LQ21. The operating costs of this measure are the same as those provided by CONAF (2012) for the exotic forestation measure.

For the measure of investment costs of the increase of hectares under forest management, different sources of cost information were used. The first source of investment cost are the mean values of ecological enrichment, infiltration ditch, direct seeding, control and elimination of exotic species, firebreaks, fuelbreaks and surveillance trails provided by CONAF (2020); CORMA (personal communication, 2021) also gives values of management establishment. The mean between both sources of data was used. Operating costs are divided into costs counted only one year after the application of the management plan, for which the control values of exotic species and sanitary felling extracted from CONAF (2020) were used; and other operating costs, corresponding to the set of silvicultural interventions and harvesting activities that allow the objectives established for the use of a forest to be met. The income values for the harvest of native wood were taken from ODEPA (2003). These were used to make a projection of income, costs and surface data, from which the projections for year 20 were used. Another source of operation cost for land lease and marginal administration was provided by CORMA (personal communication, 2021).

The investment costs of the measure of increase of protected areas were calculated based on the average of the values per hectare of the private investments in conservation in Chile (Ministerio del Medio Ambiente et al., 2010). The operating costs and average income were extracted from Toledo (2017) and converted to values per hectare using the area data provided by MMA (2021c).

The investment and operation cost of the kelp forest management measure were taken from Burg et al. (2016).

For costs of activities in the reduction of native forest degradation caused by wildfires, the clear-cutting and chipping of extracted biomass was considered using values provided by CONAF (2020). For operation costs, the value of sanitary felling was considered. For the income value, the average costs of the land in classes V, VI, VII and VIII as a function of soil distribution were considered using information from Zelada and Maquire (2005) as a reference, and considering the probability of forest fire using data from CONAF (2021a).

All values were converted to current values using the variation of the consumer price index provided by INE (2021), and the values of the U.S. Dollar (USD) and Unidad Tributaria Mensual (UTM) were converted using the monthly average data provided by the the Internal Revenue Service (Servicio de Impuestos Internos [SII], 2021a, 2021b). The investment and operating values of all the measures increase by 20% annually until 2030, in accordance with the methodology used by Benavides et al. (2021). Finally, a social discount rate of 6% was adopted.

The mitigation actions for the LULUCF sector for each of the scenarios are presented in Table 12.

TABLE 12

Mitigation actions for the LULUCF sector

Action	Action level		
	CP	IM	AM
Native afforestation	No additional adoption	Forestation of 100,000 ha of permanent forest cover with native species in 2030	100,000 ha of permanent forest cover with native species in 2030

Exotic afforestation	No additional adoption	Forestation of 100,000 ha with exotic species in 2030	Forestation of 100,000 ha with exotic species in 2030
Native forest management	No additional adoption	Increase in the managed native forest land to 200,000 ha in 2030	increase the managed native forest land to 200,000 ha in 2030
Native forest degradation reduction—wildfires	No additional adoption	25% reduction of native forest loss by wildfires in 2030	25% reduction of native forest loss by wildfires in 2030
Increase in protected areas	No additional adoption	No additional adoption	100,000 ha of protected areas in 2030
Kelp forest management	No additional adoption	No additional adoption	1,000 ha of managed kelp forest in 2030
Native afforestation—increase in hectares	No additional adoption	No additional adoption	20,000 ha of permanent forest cover with native species in 2030
Native forest management—increase in hectares	No additional adoption	No additional adoption	Increase in the managed native forest land to 20,000 ha in 2030

3. Results

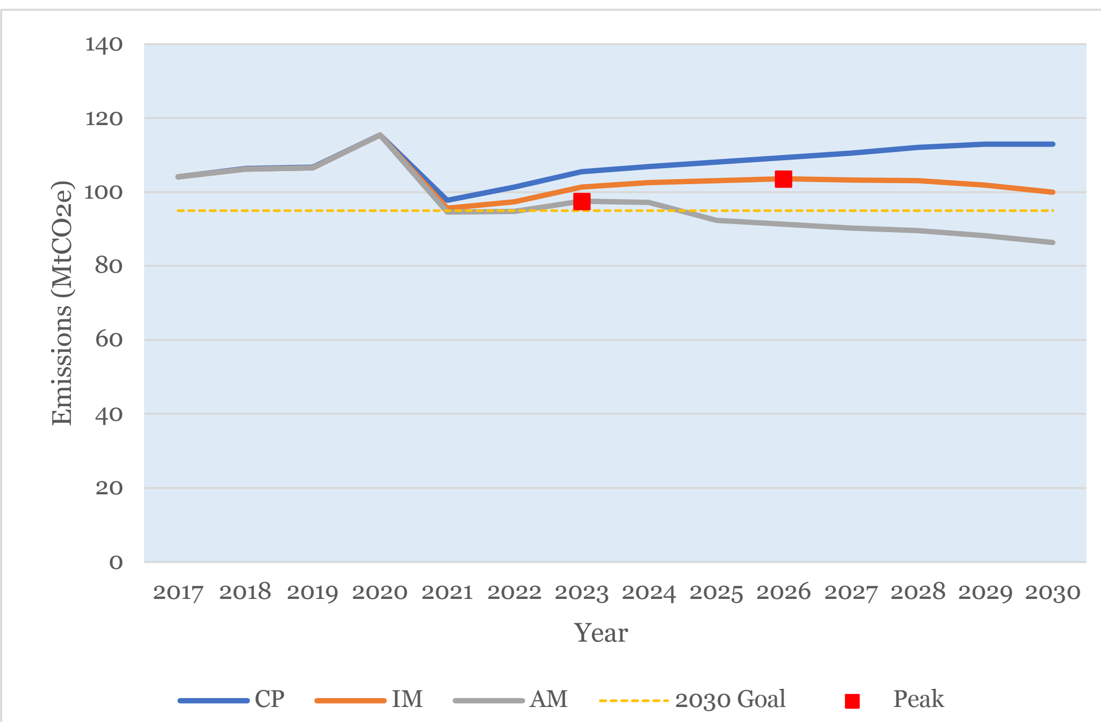
This section presents the aggregated results of the modeling exercise. The first part presents the GHG emission results, the second part presents an analysis of the fulfillment of the carbon budget as defined on the Chilean NDC, and the last part presents the mitigation cost results.

3.1 Emissions

This section presents the GHG emission results for all the sectors. Figure shows the total aggregated emissions for the agriculture, energy, IPPU, transport and waste sectors for the three scenarios for the Reference future. The CP and IM scenarios shows an increase in emissions by 2030. The only scenario that achieves an absolute decrease in emissions is the AM scenario, which is t also he only scenario that has its peak of emissions before 2025.

FIGURE 2

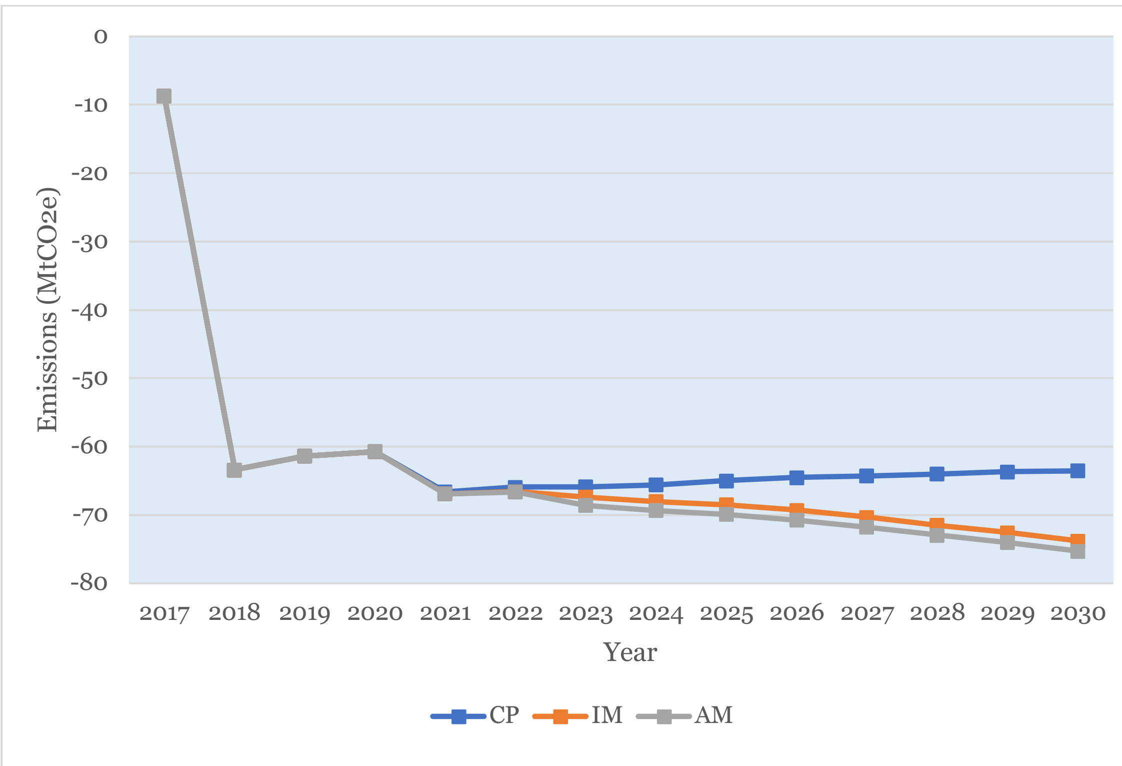
Total aggregated emissions of the carbon budget sector under three different scenarios in the period 2020–30



The LULUCF sector has net captures and independent goals on the NDC, so the results are presented separately. Figure shows the emissions of LULUCF for the different scenarios for the Reference future. For all pathways the sector captures more GHG than it emits, but the IM and AM scenarios increase net captures of the sector by 2030.

FIGURE 3

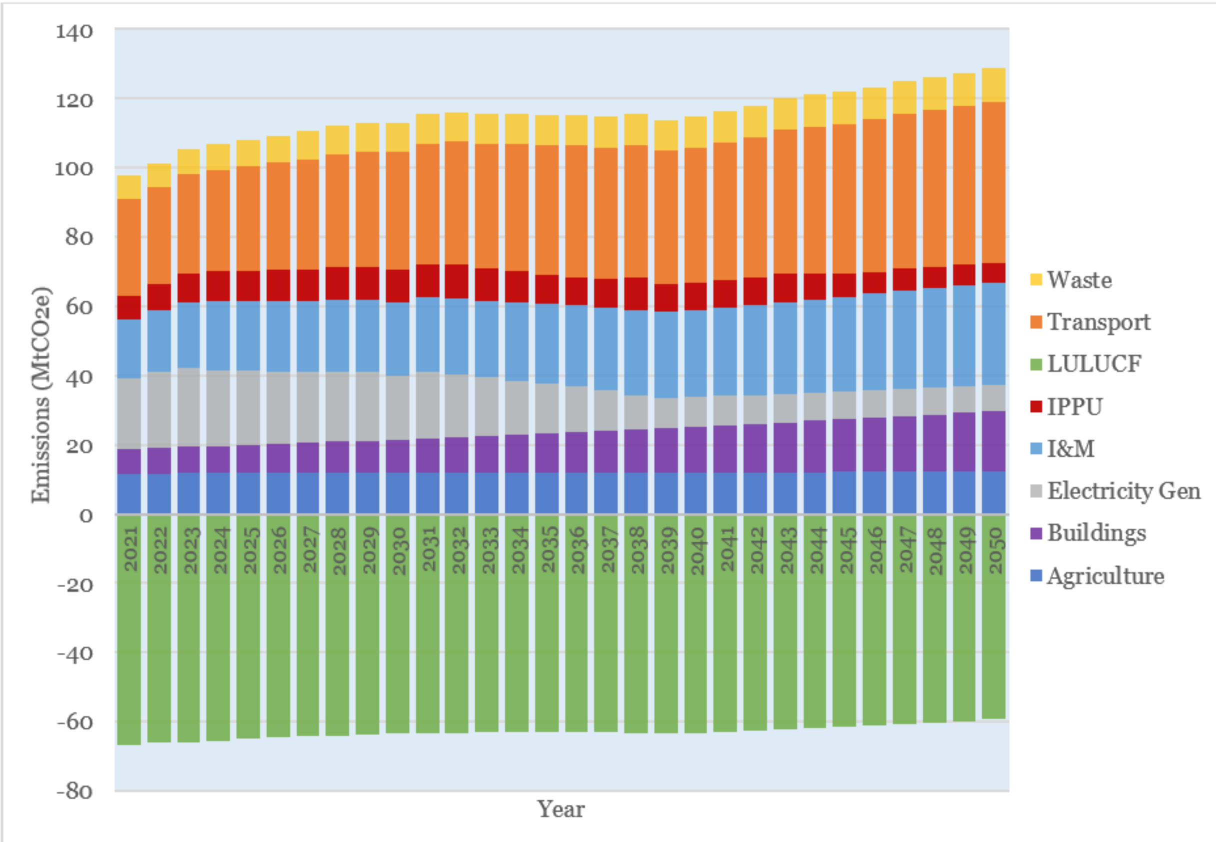
Total emissions of the LULUCF sector under three different scenarios in the period 2020–30



More detailed results are presented in Figure 4, Figure 5 and Figure 6, in which the projected emissions for all the sectors are shown 2050 in more detail for each scenario. Under the CP scenario (Figure 4), there is a steady increase in emissions related to the transport, buildings and I&M energy demand sectors, and a decrease in net captures of the LULUCF sector. These heavily increase absolute emissions by 2050, despite the reductions in the electricity generation sector.

FIGURE 4

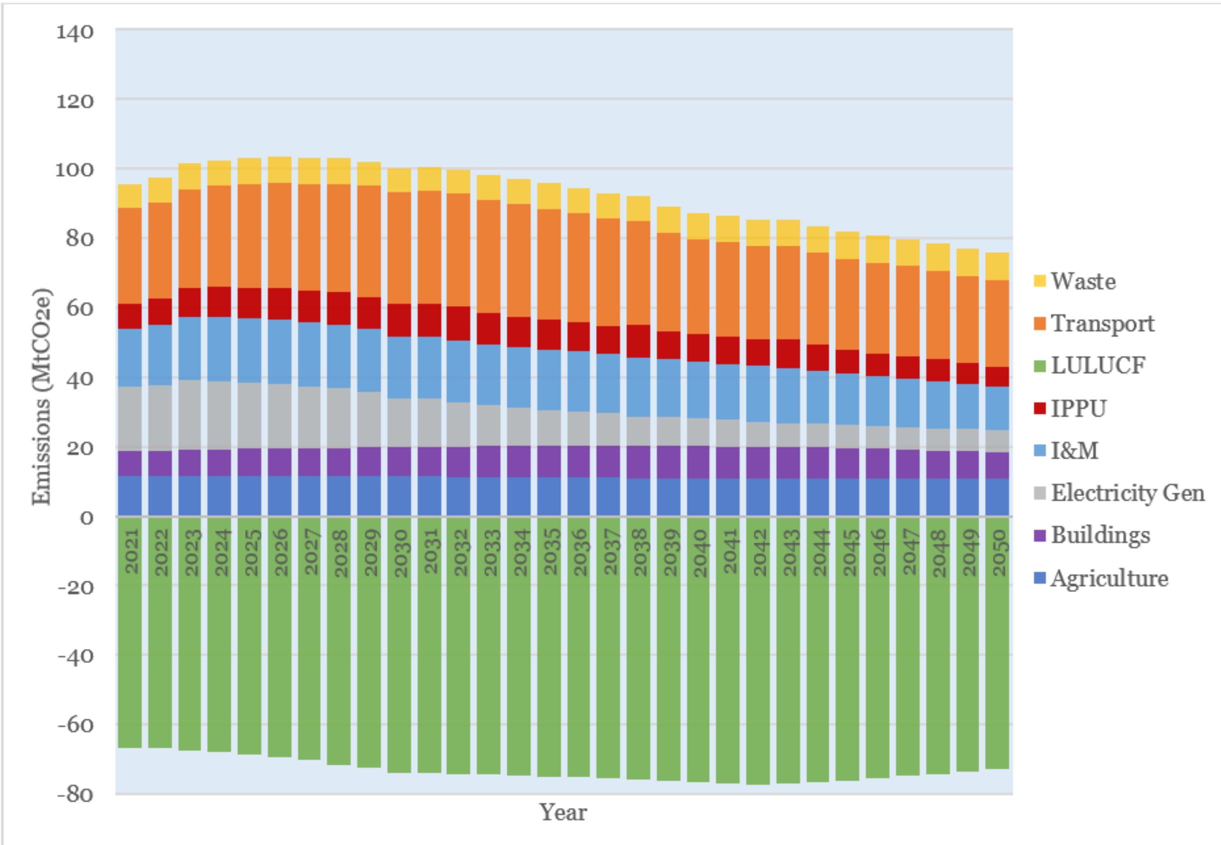
Emissions for the CP scenario in the Reference future



Under the IM scenario (Figure 5), absolute emissions peak around 2026 but decline by 2050. This is related to a decrease in emissions in most sectors and an increase in the levels of capture in the LULUCF sector. The electricity generation sector contributes heavily through mitigation by 2040, but afterwards starts to increase its level of emissions again.

FIGURE 5

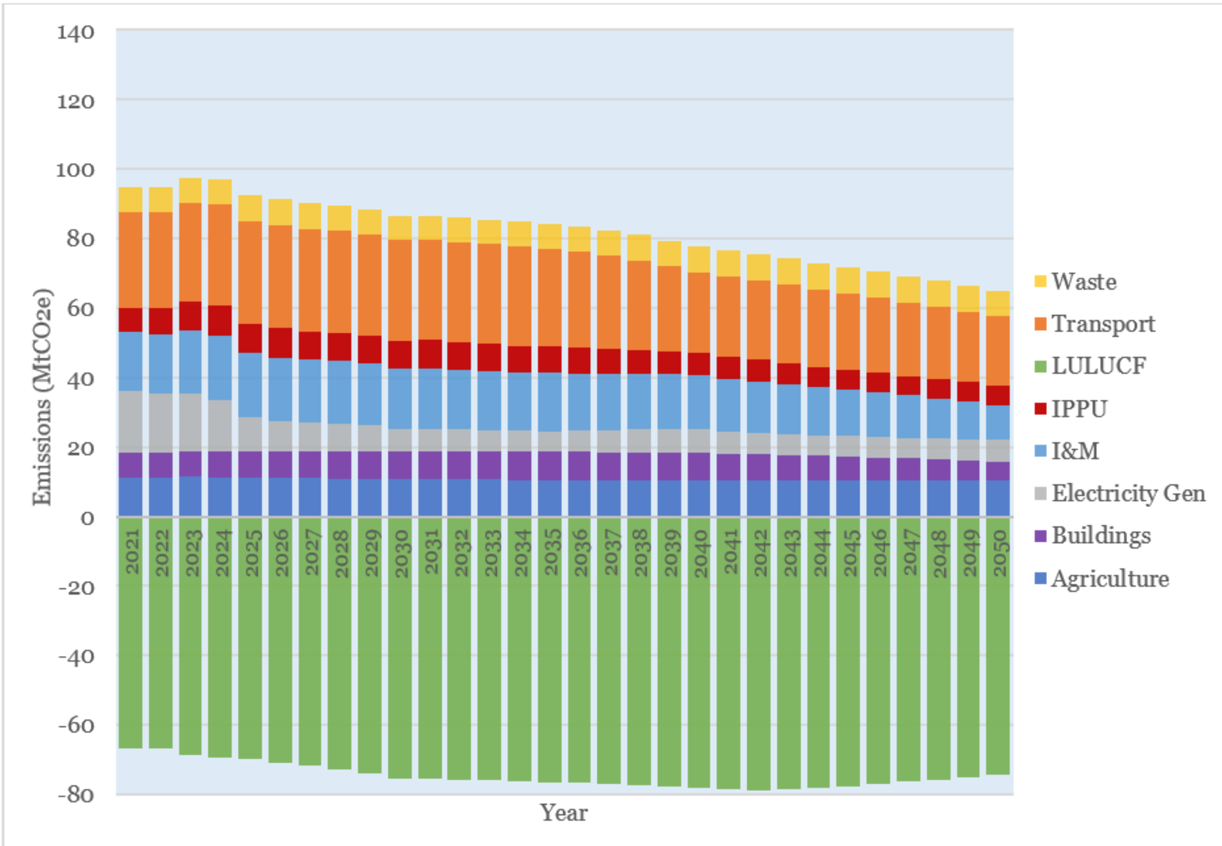
Emissions for the IM scenario in the Reference future



For the AM scenario (Figure 6), absolute emissions peak by 2023 and decline steadily until 2050. This is related to a decrease in emissions in all the sectors and an increase in the levels of capture in the LULUCF sector.

FIGURE 6

Emissions for the AM scenario in the Reference future



3.2 Emissions over futures: sensitivity analysis

As explained earlier, this modeling exercise developed different futures that address exogenous uncertainties. This section presents a sensitivity analysis of the GHG emissions under the different scenarios.

Figure 7 shows aggregated total emissions for all net emitter sectors. Shaded intervals represent different futures for the three simulated scenarios. The results show that the AM senario has significantly lower emissions than the other two scenarios, but it is also more sensitive to deviation to higher levels of emissions than lower levels.

FIGURE 7

Total aggregated emissions of the carbon budget sectors under the three different scenarios in the period 2020–30 (shaded intervals created by different futures modeled)

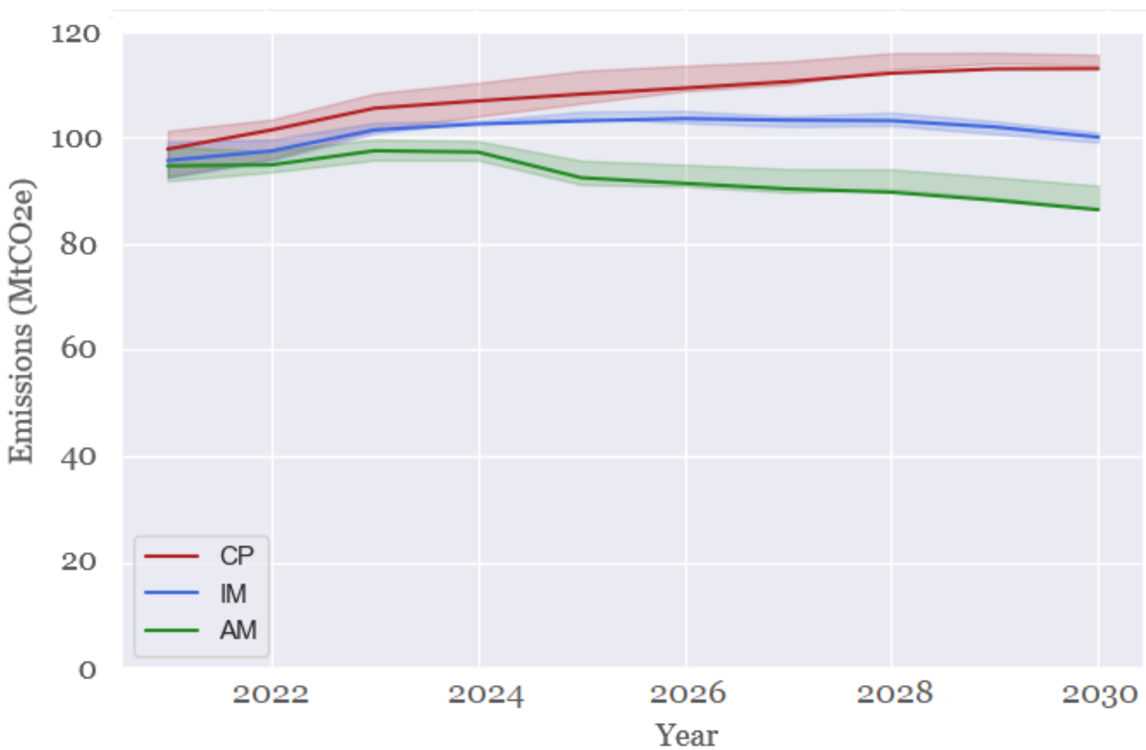


Figure 8 and Figure 9 show the sensitivity analysis for LULUCF sector net captures under the different scenarios, with the shaded intervals showing different simulated futures. The LULUCF sector is highly sensitive to climate conditions, because these affectsthe incidence and severity of forest fires. This fact explains the wide interval for all the scenarios at the beginning of the period. By 2030, however, the IM and AM scenarios reduce their interval, a response related to the NDC commitment of reducing forest fires.

FIGURE 8

Emissions of the LULUCF sector under the three different scenarios at 2030

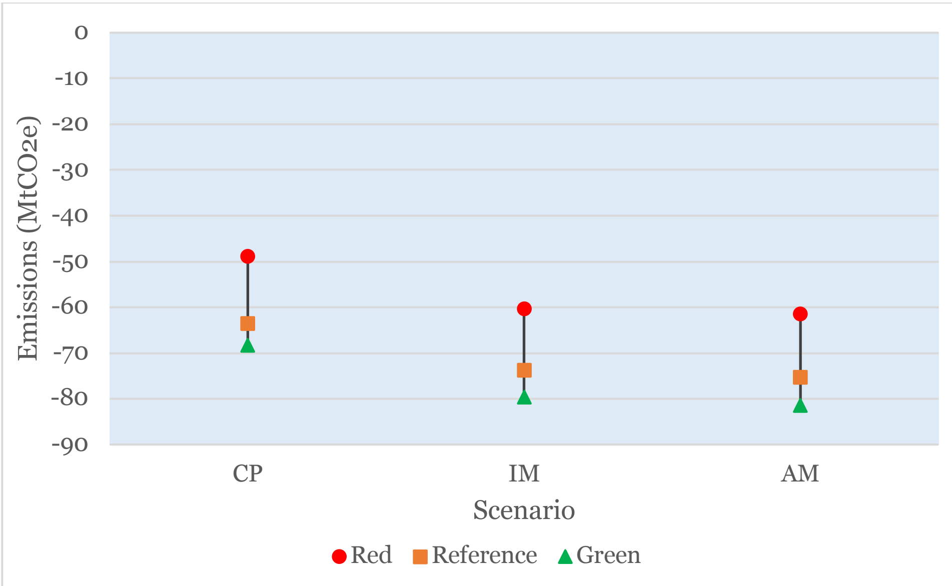
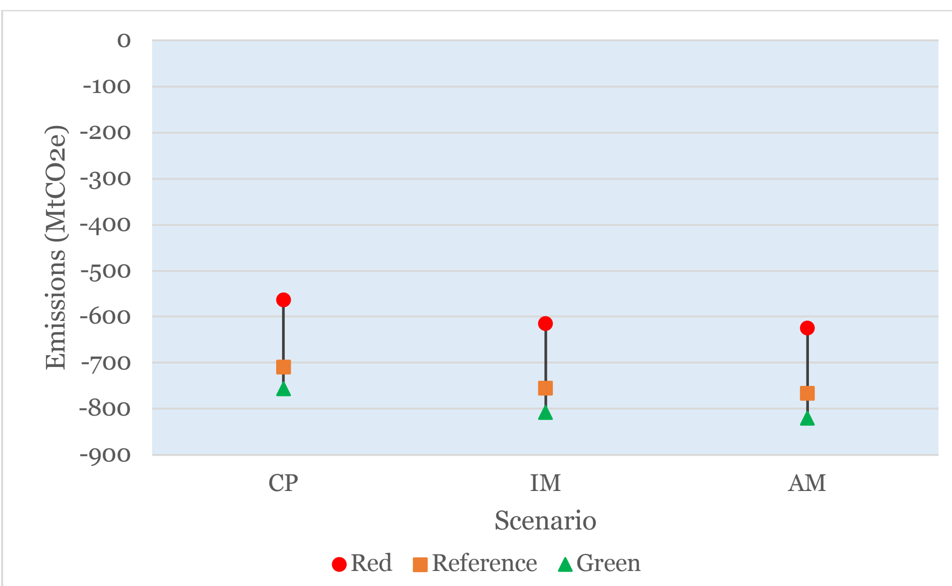


FIGURE 9

Aggregated emissions of the LULUCF sector under the three different scenarios in the period 2020–30



Appendix 2 provides more detailed results of the sensitivity analysis, presenting the sectoral emissions under each scenario and future.

3.3 Alternatives to accelerate mitigation in the electricity sector

Currently in Chile there is a lot of political pressure to accelerate the closure of coal power plants. Specifically, Congress is discussing a law to force the decommissioning of all coal power plants by 2025. Because forced phase-out does not necessarily inherently follow an optimal economic path, it is interesting here to evaluate the performance of another form of accelerated mitigation. For this comparison, a phase-out by 2040 will be maintained, but the carbon tax will be increased to a level equivalent to the externality produced by CO_2 emissions (US$50/t$CO_2$e by 2025, and US$100/tCO_2e by 2050), thus sending an economic signal to every power plant that depends on fossil fuels.

Table 13 shows that the GHG mitigation under the AM Heavy Tax scenario is lower than, although similar to, the AM 2025 secanrio for the Red and Reference futures (Figure 10, Figure 11, Figure 12 and Figure 13).

TABLE 13

Mitigation cumulative emission reductions 2020–30 per scenario and future

Emissions (MtCO_2e)	IM	AM 2025	AM Heavy Tax
Red future	56.88	90.57	76.33
Reference future	**27.51**	**92.37**	**81.1**
Green future	7.91	83.85	38.39

However, the lower fuel prices in the Green future disincentivize the transition to cleaner technologies, and therefore this scenario does not reduce coal generation as quickly and its GHG mitigation is underwhelming (Figure 14 and Figure 15). Table 14 shows that for each future the AM Heavy Tax scenario has lower costs than the AM 2025 scenario, but this is achieved at the expense of GHG mitigation.

FIGURE 10

Red future under the AM Heavy Tax scenario for the year 2030

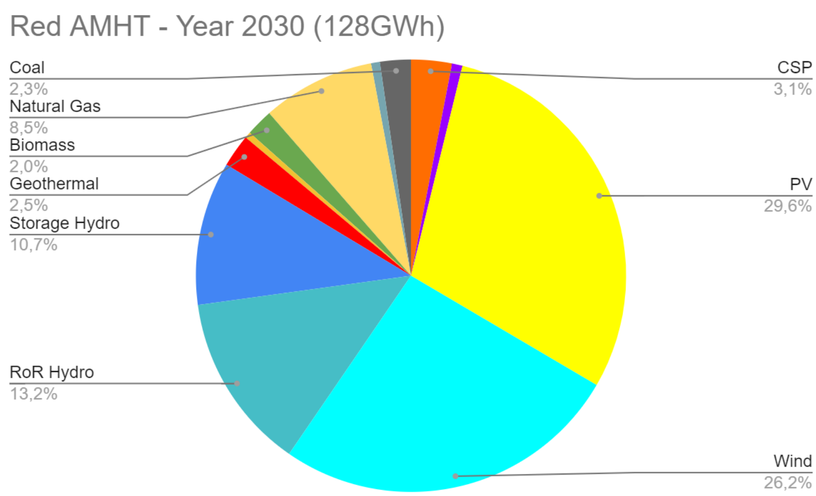


FIGURE 11

Red future under the AM 2025 scenario for the year 2030

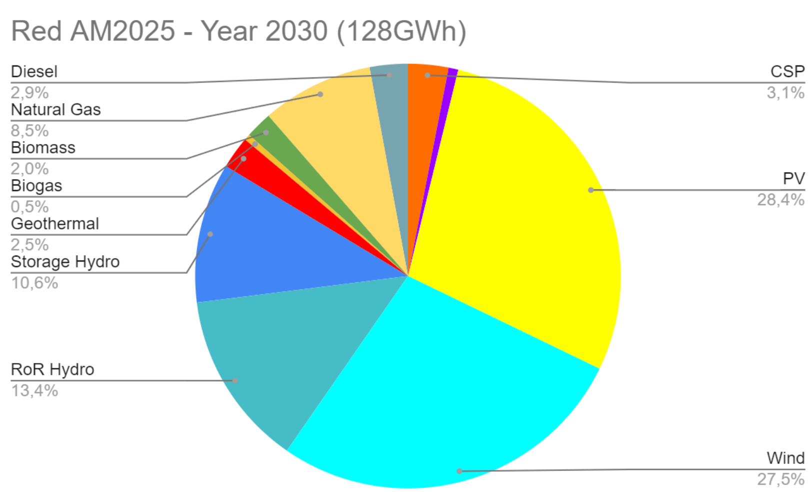


FIGURE 12

Reference future under the AM Heavy Tax scenario for the year 2030

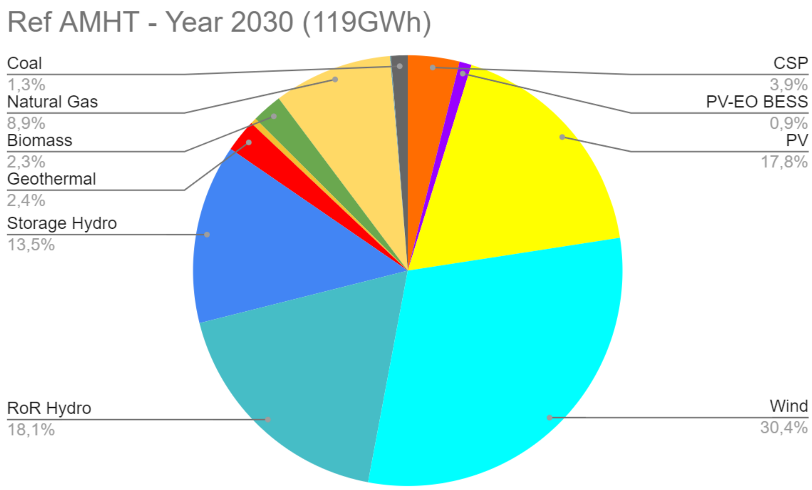


FIGURE 13

Reference future under the AM Heavy Tax scenario for the year 2030

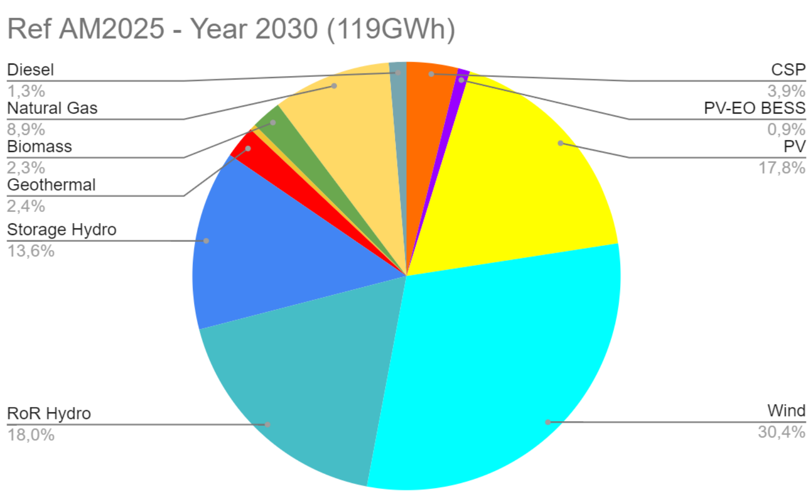


FIGURE 14

Green future under the AM Heavy Tax scenario for the year 2030

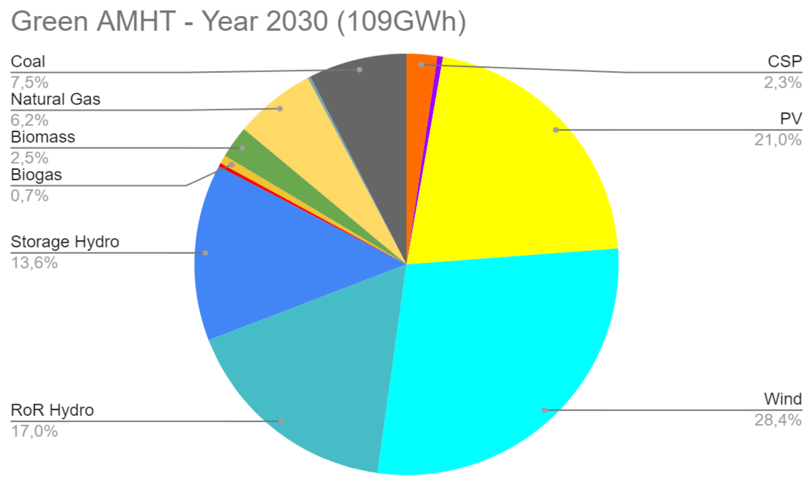
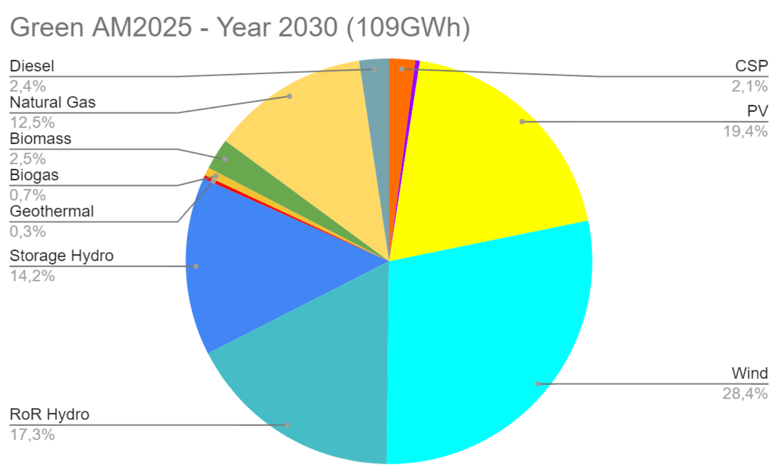


FIGURE 15

Green future under the AM 2025 scenario for the year 2030



The results presented above pose a dilemma: setting a higher carbon tax is expected to achieve lower overall emission reductions at lower mitigation costs, but higher uncertainty in the reductions. On the other hand, a forced phase-out of coal power plants by 2025 has lower uncertainty around the mitigation goal but higher costs.

TABLE 14

Mitigation cost per scenario and future

Cost (US$/t$CO_2$e)	IM	AM 2025	AM Heavy Tax
Red future	154.05	143.26	140.09
Reference future	**83.09**	**88.33**	**85.48**
Green future	53.45	47.95	44.6

3.4 Fulfillment of the carbon budget

In its NDC Chile commits to a GHG emission budget not exceeding 1,100 MtCO_2e between 2020 and 2030, with a GHG emissions maximum (peak) by 2025 and a GHG emissions level of 95 MtCO_2e by 2030 (Gobierno de Chile, 2020).

To determine whether the carbon budget will be achieved by 2030 and carbon neutrality (zero net emissions) by 2050 as established in the NDC with the mitigation measures proposed for each sector, we considered the projected emissions of all sectors under the three different scenarios (CP, IM and AM) and under the three proposed futures (Green, Reference and Red).

As seen in Figure 16, only in the AM scenario—that is, where measures additional to the Chilean NDC are considered—is the commitment to emit below 1,100 MtCO_2e between 2020 and 2030 fulfilled. The IM scenario shows a close approach to meeting the commitment, but it does not reach 1,100 MtCO_2e. In this scenario all three futures are very close to reaching the goal, especially the Reference future (1,128 MtCO_2e). The futures under the IM scenario are very similar because the NDC mitigation measures are projected to result in carbon neutrality by 2050 and therefore many are established to begin around 2030 (which is why large captures are not seen for the period 2020–30). In light of this, Chile can meet the carbon budget established between 2020 and 2030 only if additional measures to those established in the current NDC are taken.

An analysis of GHG emissions in 2030 (Figure) shows something very similar to the previous case. The target of emitting 95 MtCO_2e in 2030 is achieved only in the AM scenario and under the three different futures. Although it does not meet the NDC target, the IM scenario does come close to it.

FIGURE 16

Total absolute cumulative emissions emitted between 2020 and 2030 under each scenario and in each future

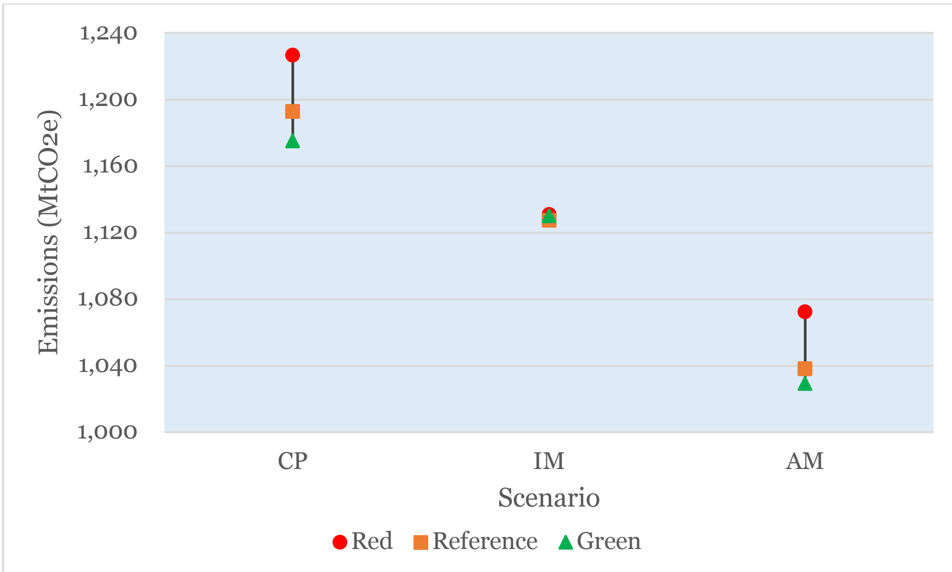
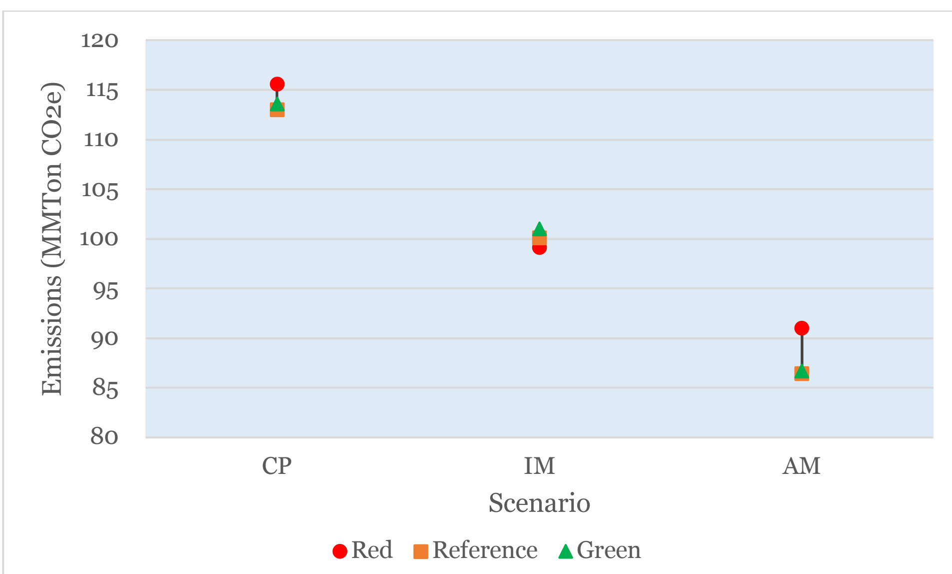


FIGURE 17

Forecast of absolute emissions in the year 2030 under each scenario and in each future



In comparison with the other scenarios, the emissions under the IM scenario in the Red future are slightly lower than in the other futures. This is because the expected emissions from the electricity sector under the optimization model seek to minimize the cost of the system across the overall period. In the IM scenario, the Red future has a greater energy demand compared to the Green and Reference futures, together with a high electrification of energy uses and an earlier coal phase-out. This leads to an earlier significant increase in the renewable capacity. This action occurs a few years later in the other futures, because until then the electricity demand is not high enough to justify a higher investment and the existing natural gas capacity will be preferred for electricity production, reflected in slightly higher GHG emissions for those futures.

More detailed results of the changes in emissions between 2020 and 2030 can be seen in Figure 18. Here, it can be seen that the electricity generation sector, which represents 29% of Chile's total emissions in 2018 (MMA, 2021a), shows a decrease in emissions from 2020 to 2030 under all the scenarios and futures analyzed. Being such a representative sector, this means that although emissions in the other sectors (except agriculture) increase slightly by 2030, total emissions decrease. The decrease is further aided by the addition of the LULUCF sector captures, although these are small for 2030. Therefore, at least under the AM scenario, the target of achieving 1,100 $MtCO_2e$ between 2020 and 2030 could be fulfilled, as well as the emission target of 95 $MtCO_2e$ for 2030. Finally, Figure 18 shows that despite the aggregation of the differences of all sectors being negative in all the scenarios, only the AM scenario achieves the NDC commitments and could have extra reductions to offer for the CAT initiative (the sensitivity analysis of all sectors for each scenario with each of the futures can be found in Section 3.2).

Figure shows that under the IM scenario carbon neutrality is achieved only in the Green future (-7.4 $MtCO_2e$). In the other futures emissions decrease significantly compared to the CP scenario, but it is not possible to reach zero emissions. On the other hand, if the AM scenario were implemented, the carbon neutrality commitment would be overachieved by 2050 under the Green future (-18.5 $MtCO_2e$) and under the Reference future (-9.4 $MtCO_2e$), but not under the Red future.

FIGURE 18

Difference between projected emissions by 2030 compared with 2020 ($MtCO_2e$) for each scenario in the Reference future

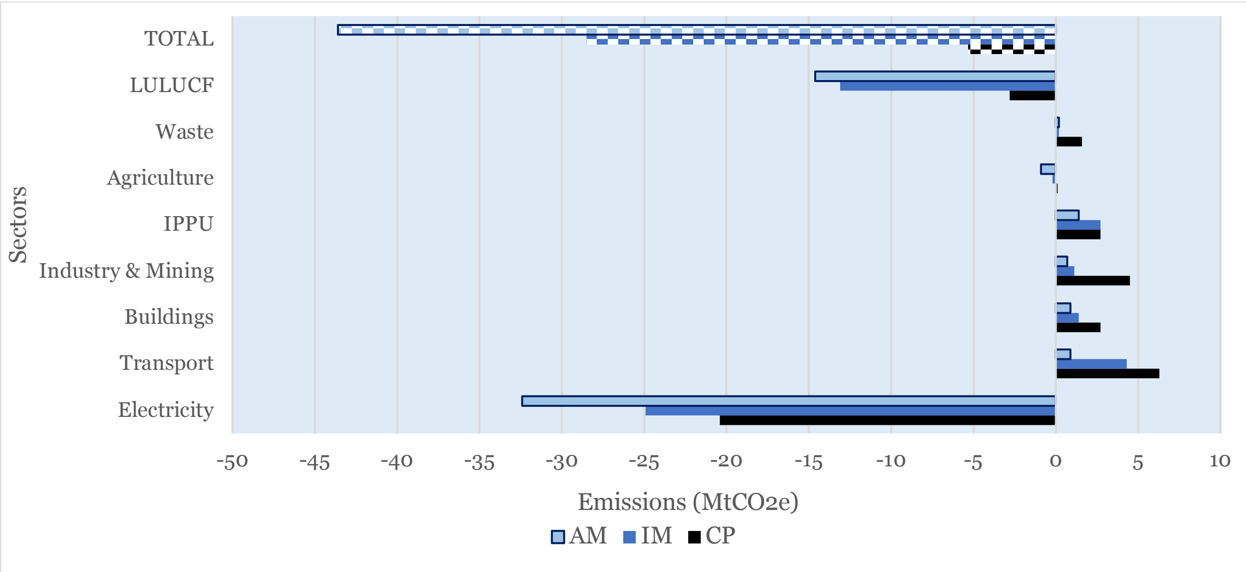
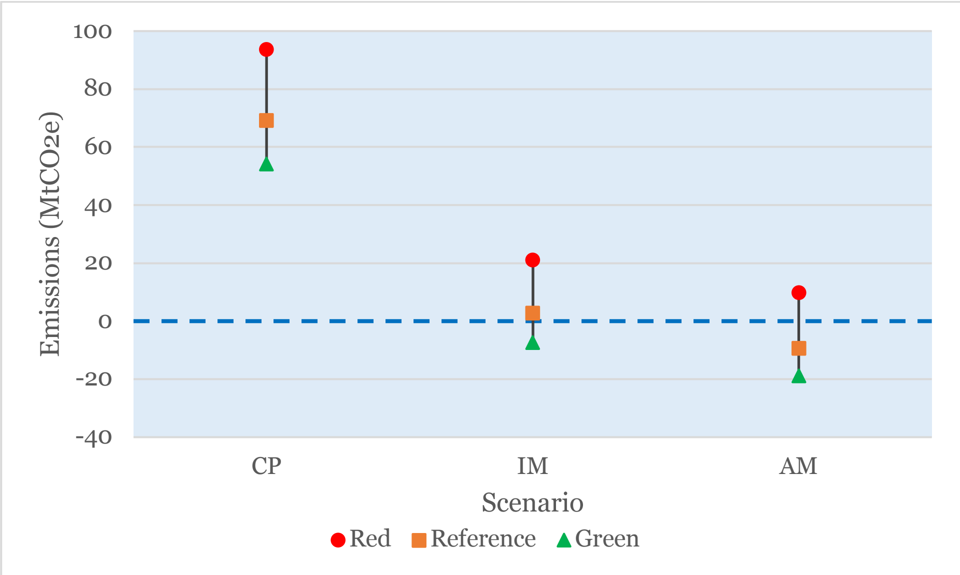


FIGURE 19

Forecast of net emissions ($MtCO_2e$) in the year 2050 under each scenario and for each future



The results show that the NDC measures (in the Reference future) allow Chile to get close to the goals established in the NDC (2.9 MtCO_2e to 2050) but are not enough to meet them. The AM scenario shows that under all the futures the targets set for 2030 could be overachieved (Figure 17), but for the Red future carbon neutrality would not be reached by 2050. In conclusion, it would be necessary for Chile to include additional measures to the IM scenario if the country is to achieve its NDC goals and be able to sell credits on the CAT initiative.

3.5 Mitigation costs: marginal abatement cost curve (MACC)

To study mitigation costs, each of the mitigation actions was characterized by its abatement potential and the average cost of mitigation of 1 tCO_2e. This is presented in the appendixes of this report. Although different metrics can be used to represent both the abatement potential and the average cost, the following definitions are used:

- **Mitigation potential** Corresponds to the difference of emissions between the CP scenario and a scenario with only the mitigation action, considering the direct impact on emissions (in the same sector as the mitigation action is implemented) and the indirect impact on emissions of other sectors (e.g., caused by changes on electricity or wood demand). This difference applies only to the period 2020–30, which coincides with the NDC carbon budget commitment.
- **Average cost of mitigation** Corresponds to the discounted costs of investments, operating costs and savings, divided by the total mitigation potential on the period 2020–50. It is important to note that the average cost has a different horizon for its calculation than the abatement potential. This corresponds to a methodological decision to better represent the real average costs of mitigation action where the cost and the GHG reductions do not occur at the same time. For example, this provides a better evaluation of an action with an important investment and mitigation that occurs in the future.

To better understand the mitigation cost, a marginal abatement cost curve (MACC) is presented (Figure 20). The legend is described in Table 15, and the values of abatement costs and emissions reductions associated with the MACC are presented in Table 16 for each action. In the MACC, 44 mitigation actions are included from the different sectors modeled. The abatement potential is considered to be the mitigation estimated between the CP and AM scenarios for each of the actions included in the AM scenario.

FIGURE 20

MACC for the 2020–30 period for the Reference future (see Table 15 for legend)

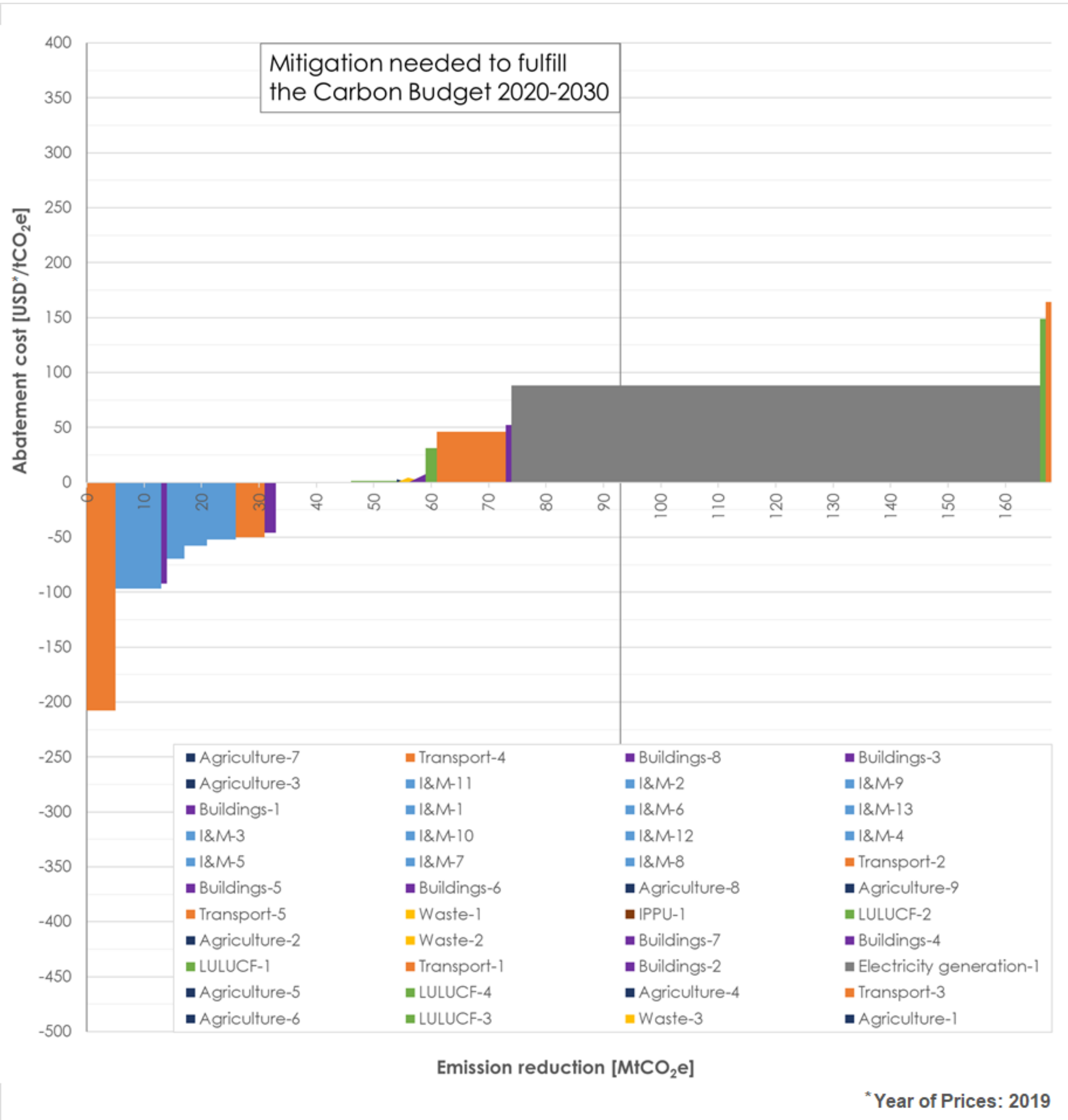


TABLE 15

Mitigation actions legend for the MACC presented in Figure 20

Sector	ID	Full name of mitigation action
Electricity generation	1	Decarbonization through the phase-out of coal power plants
Transport	1	Electromobility—private cars: 58% of private cars in 2050
	2	Hydrogen on freight trucks: 85% of freight trucks in 2050
	3	New bus rapid transit (BRT) corridors in Santiago: installation of 150 km of new BRT corridors (total of 245 km) between 2027 and 2032
	4	Incentive for new bicycle infrastructure: 3,000 km of new bikeways installed between 2025 and 2030. Estimated impact is a reduction on 10% in urban demand for transportation
	5	Hydrogen on commercial flights: 10% of flights with hydrogen in 2050, linear increase from 2035
I&M	1	Copper—solar thermal systems: 16% by 2050, AM 30% by 2050
	2	Copper—electrification in thermal processes: additional 25%
	3	Copper—electrification in motor processes: 57% in open-pit mining by 2050, AM 63% in open-pit mining by 2050
	4	Copper—hydrogen in motor processes: 37% in open-pit mining by 205
	5	Copper—hydrogen in motor processes: 8% in underground mining by 2050
	6	Various industries—solar thermal systems: 33% by 2050, AM 46% by 2050
	7	Various industries—hydrogen in thermal processes: 3% by 2050
	8	Various industries—hydrogen in motor processes: 12% by 2050
	9	Various industries—electrification in motor processes: 88% by 2050
	10	Various mines—hydrogen in motor processes: 21% by 2050
	11	Various mines—electrification in motor processes: 74% by 2050

	12	Steel industry—hydrogen in thermal processes: 10% by 2050
	13	Steel industry—biomass in thermal processes: 10% by 2050
Buildings	1	Commercial: electrification of end uses
	2	Public: solar water heaters in public hospitals
	3	Public: electric heating in public hospitals
	4	Public: solar PV on public buildings
	5	Residential: electric heating
	6	Residential: electrification of residential cooking
	7	Residential: solar water heaters
	8	Residential: retrofit of thermal insulation
Waste	1	Increased capture and burning of landfill gas: 100% of capture and burning in managed landfills by 2030
	2	New composting plants: 50% of residential organic waste composted by 2050
	3	New wastewater treatment plants for the most populous cities
IPPU	1	Recovery and regeneration of refrigerant plants: new installed capacity for 2,800 t/year in 2030
Agriculture	1	Change in bovine diet (lipids)
	2	Porcine biodigesters
	3	Efficient use of fertilizer
	4	Application of organic amendments
	5	Holistic management of cattle
	6	Bovine biodigesters
	7	Reduction of agricultural burns

	8	Biochar
	9	Meat tax
LULUCF	1	Native forest management—increase in hectares
	2	Increase in protected areas
	3	Kelp forest management
	4	Native afforestation—increase in hectares

TABLE 16

Abatement costs and emission reductions of the mitigation actions included in the MACC associated with the Reference future presented in Figure

Mitigation action	Abatement cost [US$/$tCO_2e$]	Emission reduction [$MtCO_2e$]
Electricity generation-1	88.3	92.4
Transport-1	45.9	12.9
Transport-2	-50.0	5.0
Transport-3	164.1	0.8
Transport-4	-208.0	5.0
Transport-5	–	–
I&M-1	-69.8	0.9
I&M-2	-96.7	1.2
I&M-3	-58.0	3.3
I&M-4	-52.0	2.3
I&M-5	-52.0	0.1
I&M-6	-69.8	2.8
I&M-7	-52.0	0.2
I&M-8	-52.0	1.7

I&M-9	-96.7	3.4
I&M-10	-52.0	0.7
I&M-11	-96.7	3.1
I&M-12	-52.0	0.0
I&M-13	-58.0	0.1
Buildings-1	-92.1	0.7
Buildings-2	52.3	0.0
Buildings-3	-130.2	0.0
Buildings-4	29.0	0.2
Buildings-5	-46.1	1.7
Buildings-6	-46.1	1.1
Buildings-7	7.7	3.1
Buildings-8	-172.9	0.2
Waste-1	0.2	4.2
Waste-2	4.3	-0.1
Waste-3	344.6	0.1
IPPU-1	0.2	5.5
Agriculture-1	359.7	0.2
Agriculture-2	2.6	1.3
Agriculture-3	-123.0	0.3
Agriculture-4	154.0	0.3
Agriculture-5	99.6	0.4
Agriculture-6	193.1	0.1
Agriculture-7	-344.0	0.1
Agriculture-8	-27.0	0.1
Agriculture-9	–	2.5
LULUCF-1	30.9	1.6
LULUCF-2	1.2	8.8
LULUCF-3	330.2	0.1
LULUCF-4	148.8	0.3

As seen in Figure 20, to fulfill its carbon budget 2020–30 Chile needs to mitigate an additional 93 MtCO_2e; beyond this, any mitigation could be sold. It can also be seen that 169 MtCO_2e could be mitigated in the period 2020–30 if every mitigation action is implemented. As shown in Table 16, the mitigation cost ranges from US$-344/t$CO_2$e (reduction of agricultural burning) to US$360/t$CO_2$e (change in bovine diet). It is also noticeable that 34 MtCO_2e has a mitigation cost below US$0/t$CO_2$e, and 61 Mt$CO_2$e could be mitigated with a cost below US$40/t$CO_2$e. The mitigation action with the larger mitigation abatement (the big gray area along the horizontal axis in Figure 20) is the accelerated coal phase-out (no coal electricity generation after 2025), with 92 MtCO_2e of mitigation potential (at an average cost of US$88/t$CO_2$e), followed by electromobility in private cars, with 13 MtCO_2e available for mitigation at a cost of US$46/t$CO_2$e).

It is important to note that there is intense political pressure to accelerate the decommissioning of coal power plants, so it is very likely that Chile will implement this action even if is not the cheapest one. This will leave around 60 MtCO_2e that could be sold at around US$40/t$CO_2$e. For comparison, Figure 21 presents a MACC assuming that decommissioning of coal power plants will occur. In this case, if all measures with a cost below zero are implemented, this would lead to a potential reduction of 126 MtCO_2e, leaving 33 MtCO_2e above Chile's carbon budget.

FIGURE 21

MACC for the 2020–30 period for the Reference future, assuming the decommissioning of coal power plants is a certainty

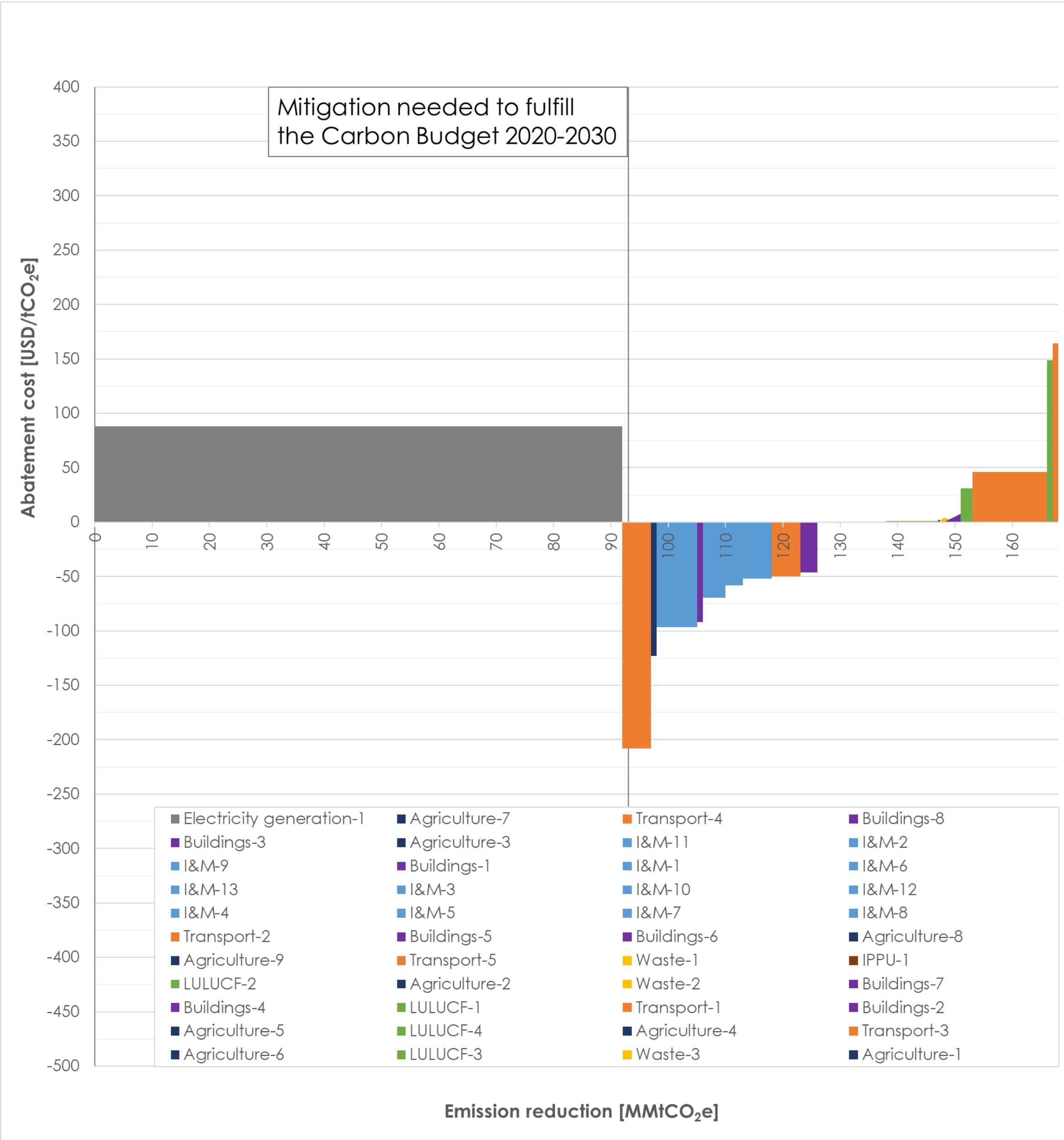


Table 17 shows the mitigation abatement for the 2020–30 period by sector for the Reference future. It shows the importance of the electricity generation sector, followed by the transport and I&M sectors, each with a contribution of around 22 $MtCO_2e$. These are followed by

LULUCF, with around 11 $MtCO_2e$ of mitigation potential. The remaining sectors (agriculture, buildings, IPPU and waste) contribute close to 6 $MtCO_2e$ each.

TABLE 17

Mitigation abatement for the 2020–30 period by sector for the Reference future

Sector	Abatement potential: IM vs CP ($MtCO_2e$)	Abatement potential: AM vs IM ($MtCO_2e$)	Total abatement potential for 2020–30 ($MtCO_2e$)
Electricity generation	28	65	92
Transport	8	16	24
I&M	16	3	20
Buildings	5	2	7
Waste	4	-0.03[17]	4
IPPU	–	6	6
Agriculture	2	4	5
LULUCF	–	11	11
TOTAL	**63**	**106**	**169**

It is important to consider these results as a preliminary approach to mitigation potential and costs, as a whole set of studies to determine a more precise estimation could be required before any of the actions presented are implemented. Nevertheless, the current results represent the best estimation given the resources available to the modeling team. Is important to consider that

17 This figure is negative because of the composting mitigation action. This action, which produces some CH_4 emissions during the composting process (in the same year), avoids larger future emissions of CH_4 through decomposition of organic waste in landfills, which takes place over a longer period of time. The imbalance between the emissions periods of composting and landfills results in a small emission in the first years of composting, but a GHG reduction in the long term.

more mitigation action could be included in future exercises, but doing so will modify the results, changing the MACC and the conclusions derived from it.

The MACC associated with the Green and Red futures are presented in Appendix 3.

3.6 Analysis of measures with negative mitigation costs

The previous section presented several mitigation actions that had negative mitigation costs. This should mean that these actions happen on their own, because it is profitable for them to do so even without considering the environmental benefits. There are many reasons why a mitigation action that has a negative mitigation costs from a social perspective is not being implemented. These include:

- higher discount rate of the decision-makers: all the mitigation actions were analyzed with a social discount rate (6% in Chile), but in some cases the decision-makers have higher discount rates
- risk perception of the investment
- the developer of the project does not benefit from the action
- imperfect information.

4. Conclusions and further work

The current work and results represent an ambitious first step in the development and integratation of a prospective model for GHG emissions in Chile. They focus on near-term emissions, but extend projections to the middle of the century. The results should be interpreted as the "current" results because the prospective modeling has been constructed as an iterative process. Under this concept, the main work presented in this report is the architecture of the open-access models, the combination of scenarios and futures, and the results, which indicate that there exists a potential to achieve reductions beyond Chile's ambitious NDC. However, these additional reductions are costly, which should be considered when analyzing any mechanism that supports international resource transfers for climate mitigation.

The modeling process took advantage of earlier experience, calibrating previously developed models to better represent the situation observed in recent years. This includes consideration of impacts such as the Covid-19 pandemic and the social unrest Chile experienced in the final months of 2019. At the same time, recent actions are also included, which are expected to impact on Chile's GHG emissions in the short term. These include acceleration of the closure of some of the country's coal-fired power plants, promotion of the electrification of public transport amd application of laws to encourage recycling.

However, any modeling process has its limitations. The main limitations for each of the sectoral models are:

- **Electricity sector**
  - The oversimplification of the transmission grid, which is a relevant factor in a country like Chile that has clear regional differentiation in terms of resource availability and electric demand.
  - The lack of consideration in a model such as LEAP of the effect of saturated transmission lines, which arises when certain technologies such as PV are placed very close to one another.
  - The lack of representation of pure energy storage processes, when they are expected to become important beyond 2030.
  - The lack of a refined temporal resolution in the model, meaning that it had a scenario for winter and another for summer. This simplification might not be sufficient to accurately reflect the marginal costs of the real system.

  - The lack of integration with other areas, such as energy, which would help to make this a more comprehensive model. These aspects remark the importance of using more refined planning models in future work.
- **Energy demand sector**
  - The transport sector follows a bottom-up approach that is based on a regional transportation demand. This approach makes it particularly difficult to model territorial mitigation actions, since a series of assumptions are needed in order to include these kinds of actions.
  - The modeling of electricity penetration in households, industry and transportation follows a logic based on historical data and comparative penetration rates from developed countries. However, the projected rates are not sensible to the cost of this technology, which could modify the actual penetration rates.
- **Waste sector**
  - Although the total amount of waste generation dependes on GDP and population, the distribution of different kinds of waste is based on data from developed countries and is not sensitive to GDP.
  - Recently, the Chilean government published a strategy for organic waste that sets ambitious goals, but there are questions around the actions required to fulfill these goals. The goals are considered only partially in the modeling.
- **IPPU sector**
  - There is room to better connect the IPPU model with the other sectoral models. The lack of data, especially in the industrial refrigeration sector, is one of the main difficulties in achieving this.
  - Only the installation of HFC regeneration facilities is modeled as a mitigation action in the sector. With a small rate of clinker used and a petrochemical industry that already has abatement systems installed, actions in the industrial process subsectors were not considered. There may be additional actions that could be modeled to go beyond the Kigali Amendment in the product use subsector.
- **Agriculture sector**
  - An economic model was used for the projection of cattle and pigs (responsible for 68% of emissions in the agricultural sector), explained by national projections of commodity prices. These present high variability for the different futures to consider.

  - Regarding mitigation measures, there was a strong emphasis on those with mitigation potential through carbon storage in the soil. However, in the national inventory of GHGs, the current accounting category (soil carbon in agricultural land) is not estimated, because there is not enough information to determine the carbon shift at the national level. If these types of mitigation measures are considered for the sector, an additional effort must be made to include information that allows the to be accounted for.
- **LULUCF sector**
  - This model is a national approach to the sector, and due to the lack of complete regional data makes projections based on emission factors derived from the historical calculation of GHG emissions of the subsectors.
  - Wildfire emissions are still a big source of uncertainty since the size of the area that is burned every year, and thus the associated emissions, depends on a small number of fires that escape suppression and control. These few wildfire events are unpredictable.
  - The model does not consider uncertainties such as future yield changes of native forests and plantations or changes in harvest frequencies due to climate change.
  - Kelp forest management costs were determined using data based on implementations in developed countries.

There is space for improvement in the modeling. In this regard, some key aspects have already been identified as needing to be corrected or assessed for further improvement. Although the level to which future steps can be made will depend on the resources available, the recommendation of the modeling team is to advance the work along the following lines:

1. Implement modifications based on comments and suggestions received during the diffusion phase of the modeling process and its results. This includes:
   a. Revisit definitions used in the model architecture to be sure they are in line with those used in other CAT initiatives.
   b. Increase the ambition in measures that may have been modeled with timid penetration.

c. Differentiate the penetration of measures that remained identical to the BAU scenario, or between the IM and AM scenarios, when possible and realistic.[18] This may be done by modeling earlier penetration, as well as changing the level of penetration itself. Note that this is not a complex task.

d. Assess if other factors should be considered in the projections—e.g., the GDP of Southeast Asia.

e. Evaluate possible modifications of the assumptions of the model—e.g., the projected hydrology for each future could be modified for drier scenarios, which could more likely be based on past data.

2. Take further steps in the generation of a transparent and open-access model architecture that generates relevant information for the stakeholders:

   a. Improve the model integration, especially the integration of economic costs and savings analysis for the mitigation actions and scenarios.

   b. Advance the creation of front-end for the prospective models that allows the user to explore different combinations of actions and levels of ambitions.

   c. Explore the impact of new technologies with high levels of uncertainty in their cost and potential in sectors that are more sensitive to them, such as electricity generation and transportation.

As a general conclusion, the first results of this modeling exercise show that Chile needs to implement additional mitigation efforts in order to fulfill its NDC in relation to its carbon budget. The main point of difference from the results developed by the Chilean government (Palma et al., 2019) is related to the contribution of the electricity sector.

A set of additional mitigation actions would allow Chile to fulfill its 2020–30 carbon budget and even overachieve it. The mitigation cost of overachieving the NDC is costly, but it is possible that the decommissioning of coal power plants will take place earlier (2025).

In the case of the agriculture sector, which represents around 10.6% of national emissions for the year 2018, it has a relatively low future mitigation potential. This is mainly due to the additional cost efforts that must be made, which are relatively high and have high levels of uncertainty, in addition to it being a highly socially sensitive sector due to the impact it may have on food security. Emissions from cattle currently represent around 55% of the sector's

18 Although changing the penetration levels of the actions is not a complex action from a strictly mathematical modeling point of view, defining the realistic penetration level requires a more in-depth and time-intensive analysis.

emissions (2018), but a slight decrease in national production is projected by 2030. Projections for pigs show an increase for 2030, which represents around 12% of the sector's emissions. However, this differs from the projections for pigs made by the Food and Agriculture Organization for the same year. The mitigation challenges presented by the sector mainly lie in future technological opportunities, complemented by an improvement in the intensity of emissions, such as more sustainable practices.

In the case of the LULUCF sector, the mitigation options assessed were mainly those associated with Chile's NDC, namely forestation, natural forest management and forest degradation reductions through wildfire prevention. Additional measures were assessed for an AM scenario; these were kelp forest management and increases in protected natural areas. The outcomes from the implementation of each of these mitigation actions show that by far, and from the mitigation standpoint only, forestation with exotic species is the best option. Mitigation costs are the lowest among all measures and sequestration potential by 2030 is the highest. However, there are some controversies in Chile around exotic forestation, mainly related to the water usage and proneness to wildfire of these plantations. When compared to forestation with native species, the abatement cost is very high because of the slower growth rates of native species—these are almost 18 times slower than in exotics and the costs are four times higher without considering income. Natural forest management is also a reasonable option, not only because it has a high mitigation potential with costs per tCO_2e much lower than for plantations with native species, but also because it is linked to multiple co-benefits, such as biodiversity, water and soil conservation, landscape connectivity and recreation, among others.

Measures aimed to decrease native forest degradation by wildfires are also a low-cost mitigation option, with a large mitigation potential by 2030, although lower than the exotic forestation and forest management options. However, better wildfire management (in this case using firebreaks) is subject to great uncertainty, because the occurrence of large wildfires is highly unpredicatable, and investing in wildfire prevention is probably a risk-proof option and in general more efficient than investing in wildfire suppression. Considering all these results (total costs, unitary cost per tonne of CO_2 and mitigation potential), the NDC scenario must be considered a bottom line for the LULUCF sector, a minimum that Chile must aim to improve on.

The additional measures considered (kelp management and more natural protected areas) are marginal to the overall big picture for LULUCF. The differences between the IM and AM scenarios are in the range of 1.24–1.77 $MtCO_2e$, which seems marginal for an expected (IM scenario, Reference future) mitigation of -73.8 $MtCO_2e$.

It is important to consider these results as a preliminary approach to mitigation potential and costs, as the implementation of any of the actions presented could require a whole set of analysis to determine a more precise estimation. Nevertheless, some of the results are of special interest and the structure of the model can be used for some preliminary research. For example, in the Reference future we estimate that 62 $MtCO_2e$ are available in excess of the carbon budget commitment. Preliminary results of new runs based on different carbon prices suggeststhat 70% of this 62 $MtCO_2e$ is available, with a marginal cost of less than US$50/$tCO_2e$. Furthermore, the central estimates of the capital cost needed to achieve this 70% is around US$2.8 billion.

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Appendixes

Appendix 1: Description of the mitigation measures

Electricity generation actions

Name	**Decarbonization by the phase-out of coal power plants**
General overview	Actively decarbonizes the electric grid by shutting down highly contaminant power plants and replacing them with cleaner alternatives.
	Modeling
Main assumptions	Power plants have a lifespan of 30 years. The discount rate for investments is 10%. The transmission losses start at 7.9% and decrease to 5% by 2030. Carbon tax starts at US$5/t$CO_2$e and goes up linearly between 2030 and 2050, reaching a cap of US$32.5/t$CO_2$e according to the PELP (2020). The phase-out of the coal power plants follows the decarbonization plan proposed by the Ministerio de Energía (MEN, 2020) and the Coordinador Eléctrico Nacional (CEN, 2020):

Year	IM [MW]	AM [MW]
2019	+202	+44
2020	-288	-738
2021	-120	
2022	-570	-1324
2023		-614
2024	-268	-632
2025	-1102	-1902
2027	-292	
2028	-312	
2029	-136	
2030	-174	
2033	-152	
2034	-152	
2035	-177	
2036	-178	

2037	-370	
2038	-702	
2039	-375	

Cost elements	The following are considered: investment for the installation of new power plants and their operating costs (variable and fixed costs).	
References	Comisión Nacional de Energía (2021), Coordinador Eléctrico Nacional (2020, 2021), Ministerio de Energía (2020a, 2020b)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	Red: 28.29 Ref: 24.85 Green: 21.77	Red: 30.26 Ref: 32.44 Green: 30.08
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	Red: 56.88 Ref: 27.51 Green: 7.91	Red: 90.57 Ref: 92.37 Green: 83.85
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost (MM US$)	Red: 30451.57 Ref: 22971.71 Green: 11337.55	
Abatement cost (US$/$tCO_2e$)	Red: 143.26 Ref: 88.33 Green: 47.95	

Name	**Decarbonization by the increase of the carbon tax**
General overview	Greatly raises the carbon tax from 2025 onwards, reaching a peak of US$100/t$CO_2$e during 2050.
	Modeling
Main assumptions	Power plants have a lifespan of 30 years. The discount rate for investments is 10%. The transmission losses start at 7.9% and decrease to 5% by 2030. Carbon tax starts at US$5/t$CO_2$e. For the IM scenario it goes up linearly between 2030 and 2050, reaching a cap of US$32.5 /t$CO_2$e according to the PELP (2020). However, for the AM scenario, the carbon tax changes to US$50/t$CO_2$e in 2025 and goes up linearly until it reaches US$100/t$CO_2$e in 2050. The phase-out of the coal power plants follows the decarbonization 2040 plan proposed by MEN (2020) and CEN (2020):

Year	IM [MW]	AM [MW]
2019	+202	+202
2020	-288	-288
2021	-120	-120
2022	-570	-570
2023		
2024	-268	-268
2025	-1102	-1102
2027	-292	-292
2028	-312	-312
2029	-136	-136
2030	-174	-174
2033	-152	-152
2034	-152	-152
2035	-177	-177
2036	-178	-178
2037	-370	-370
2038	-702	-702
2039	-375	-375

Cost elements	The following are considered: investment for the installation of new power plants and their operating costs (variable and fixed costs).
References	Comisión Nacional de Energía (2021), Coordinador Eléctrico Nacional (2020, 2021), Ministerio de Energía (2020a, 2020b)

Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	Red: 28.29 Ref: 24.85 Green: 21.77	Red: 29.52 Ref: 32.12 Green: 25.93
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	Red: 56.88 Ref: 27.51 Green: 7.91	Red: 76.33 Ref: 81.1 Green: 38.39
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost (MM US$)	Red: 26978.51 Ref: 21684.87 Green: 8827.52	
Abatement cost (US$/$tCO_2e$)	Red: 140.09 Ref: 85.48 Green: 44.6	

Transport actions

Name	**Electromobility—private cars: 58% of private cars in 2050**	
Source	Chilean NDC.	
General description	Incentives to accelerate the transition to private electric cars and to achieve the goals defined in the electromobility strategy.	
Modeling		
Main assumptions	Same penetration rate as the one assumed on the design of the NDC.	
Cost elements	Considers the investment in private electric cars and the implementation of charging points, and the increase in the electricity use. The decrease in fossil fuels consumption was also accounted for.	
References	Benavides et al. (2021), Gobierno de Chile (2020)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.56** 0.54 ~ 0.59	**3.80** 3.86 ~ 3.72
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**2.65** 2.53 ~ 2.84	**12.91** 12.78 ~ 13.02
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$D)	**592.8** 586.5 ~ 597.5	
Abatement cost (US$/$tCO_2e$)	**45.90**	

Name	Hydrogen on freight trucks: 85% of the freight trucks on 2050	
Source	Chilean NDC.	
General description	Incentives to accelerate the transition from diesel trucks to green hydrogen trucks.	
	Modeling	
Main assumptions	Same penetration rate as assumed on the design of the NDC. The hydrogen is assumed to come from solar power.	
Cost elements	The investment in hydrogen trucks and their operating costs were accounted for, as was the reduction in the use of diesel and the investment avoided in trucks with a diesel engine.	
References	Benavides et al. (2021), Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**1.43** 1.40 ~ 1.46	**1.43** 1.40 ~ 1.46
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**4.97** 4.86 ~ 5.09	**4.97** 4.86 ~ 5.09
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**-248.4** -243.0 ~ -254.7	
Abatement cost (US$/$tCO_2e$)	**-50.00**	

Name	**New bus rapid transit (BRT) corridors in Santiago: installation of 150 km of new BRT corridors (total of 245 km) between 2027 and 2032**	
Source	Expert opinion of the authors and the reference cited below.	
General description	Investment in new corridors specifically for buses (150 km) as a way to incentivize public transport.	
Modeling		
Main assumptions	The new corridors are installed in Santiago. Based on previous studies, it is supposed that an investment of this magnitude could yield an increase in bus usage of 7%. It is assumed that all of this increase comes from a switch from private cars.	
Costs elements	The investment cost associated with the new BRT corridors in Santiago were considered, as well as the associated reduction in the use of private cars powered by fossil fuels.	
References	Sistemas Sustenables (2014)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.0**	**0.36** 0.31 ~ 0.41
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.0**	**0.76** 0.74 ~ 0.78
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**125.1** 128.3 ~ 122.0	
Abatement cost (US$/$tCO_2e$)	**164.10**	

Name	**New bicycle infrastructure: 3,000 km of new bikeway installed between 2025 and 2030. Estimated impact a reduction of 10% in urban demand for transportation**	
Source	Expert opinion of the authors and the reference cited below.	
General description	Investment in new infrastructure for bicycles: a total of 3,000 km of new bikeways	
Modeling		
Main assumptions	The new infrastructure impacts only on private cars. The impact is a reduction of 10% of emissions in urban areas, based on previous studies.	
Cost elements	The investment costs associated with the new bicycle infrastructure were considered, as was the reduction in the use of private cars powered by fossil fuels.	
References	Sistemas Sustenables (2014)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.0**	**1.52** 1.48 ~ 1.56
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.0**	**5.00** 4.89 ~ 5.12
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**-2,103.0** -2,151.1 ~ -2,055.0	
Abatement cost (US$/$tCO_2e$)	**-420.30**	

Name	**Hydrogen on commercial flights: 10% of flights with hydrogen in 2050, a linear increase from 2035**	
Source	Expert opinion of the authors and the reference cited below.	
General description	Replace of aviation kerosene with hydrogen for 10% of the flights in 2050.	
Modeling		
Main assumptions	The action is modeled as starting in 2035, and the rate of participation of hydrogen grows linearly between 2035 and 2050. It is assumed that the hydrogen comes from solar power.	
Costs elements	As this action is modeled from 2035, no details on the modeled costs are presented here.	
References	Benavides et al. (2021)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.0**	**0.0**
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.0**	**0.0**
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**0.0**	
Abatement cost (US$/$tCO_2e$)	**0.0**	

Industry and mining actions

Name	**Copper—solar thermal systems: 16% by 2050, NDC+ 30% by 2050**	
Source	Chilean NDC.	
General overview	Incentives to accelerate transition from fossil fuel combustion in thermal processes to solar thermal systems.	
Modeling		
Main assumptions	Same penetration rate as assumed on the design of the NDC on the IM scenario, 14% more penetration for AM scenario.	
Cost elements	Considers the investment in solar thermal systems, and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.	
References	Benavides et al. (2021), Gobierno de Chile (2020)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.052** 0.048 ~ 0.056	**0.108** 0.101 ~ 0.115
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.43** 0.39 ~ 0.47	**0.88** 0.80 ~ 0.95
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**-61.11** -55.99 ~ -65.99	
Abatement cost (US$/$tCO_2e$)	**-69.80**	

Name	**Copper—electrification in thermal processes: additional 25%**	
Source	Chilean NDC.	
General overview	Incentives to accelerate transition from fossil fuel combustion in thermal processes to electricity use.	
	Modeling	
Main assumptions	Same penetration rate as assumed in the design of the NDC.	
Cost elements	Considers the investment in electric motors, the reduction in diesel consumption, and the increase in electricity use. In the CP scenario the purchase of diesel engines is accounted for.	
References	Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.16** 0.15 ~ 0.17	**0.18** 0.17 ~ 0.19
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.88** 0.75 ~ 1.04	**1.20** 1.10 ~ 1.28
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**-116.10** -106.6 ~ -123.93	
Abatement cost (US$/$tCO_2e$)	**-96.70**	

Name	**Copper—electrification in motor processes: 57% in open-pit mining by 2050, NDC+ 63% in open-pit mining by 2050**	
Source	Chilean NDC and expert opinion of the authors for the AM scenario.	
General overview	Incentives to accelerate transition from fossil fuel in motor processes to electricity use.	
Modeling		
Main assumptions	Same penetration rate as assumed in the design of the NDC in IM scenario, 6% more penetration for AM scenario.	
Cost elements	Considers the investment in electric motors, the reduction in diesel consumption, and the increase in electricity use. In the CP scenario the purchase of diesel engines is accounted for.	
References	Gobierno de Chile (2020)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.66** 0.56 ~ 0.77	**0.77** 0.64 ~ 0.89
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**2.80** 2.31 ~ 3.36	**3.31** 2.83 ~ 3.69
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**-191.7** -164.3 ~ -214.2	
Abatement cost (US$/$tCO_2e$)	**-58.00**	

Name	**Copper—hydrogen in motor processes: 37% in open-pit mining by 2050**	
Source	Chilean NDC.	
General overview	Incentives to accelerate transition from fossil-fuel combustion in motor processes to green hydrogen use.	
	Modeling	
Main assumptions	Same penetration rate as assumed in the design of the NDC. The hydrogen is assumed to come from solar power.	
Cost elements	Considers the investment in hydrogen motors and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.	
References	Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.43** 0.36 ~ 0.50	**0.43** 0.36 ~ 0.50
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**2.30** 1.98 ~ 2.63	**2.30** 1.98 ~ 2.63
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**-119.7** -103.2 ~ -136.9	
Abatement cost (US$/$tCO_2e$)	**-52.00**	

Name	Copper—hydrogen in motor processes: 8% in underground mining by 2050	
Source	Chilean NDC.	
General overview	Incentives to accelerate transition from diesel trucks to green hydrogen use.	
Modeling		
Main assumptions	Same penetration rate as assumed in the design of the NDC. The hydrogen is assumed to come from solar power.	
Cost elements	Considers the investment in hydrogen motors and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.	
References	Gobierno de Chile (2020)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.012** 0.010 ~ 0.014	**0.012** 0.010 ~ 0.014
Reduction of cumulative emissions from 2020 (MtCO2e)	**0.059** 0.050 ~ 0.067	**0.059** 0.051 ~ 0.067
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**-3.07** -2.64 ~ -3.50	
Abatement cost (US$/$tCO_2e$)	**-52.00**	

Name	**Various industries—solar thermal systems: 33% by 2050, NDC+ 46% by 2050**	
Source	Chilean NDC.	
General overview	Incentives to accelerate transition from fossil fuel combustion and electricity use in motor processes to solar thermal systems.	
	Modeling	
Main assumptions	Same penetration rate as assumed in the design of the NDC for IM scenario, 13% more penetration for AM scenario.	
Cost elements	Considers the investment in solar thermal systems, and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.	
References	Benavides et al. (2021), Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.36** 0.34 ~ 0.37	**0.50** 0.48 ~ 0.51
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**2.11** 2.10 ~ 2.11	**2.84** 3.03 ~ 2.97
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**198.4** 207.0 ~ 211.2	
Abatement cost (US$/$tCO_2e$)	**69.80**	

Name	Various industries—hydrogen in thermal processes: 3% by 2050	
Source	Chilean NDC.	
General overview	Incentives to accelerate transition from fossil fuel combustion and electricity use in thermal processes to green hydrogen use.	
Modeling		
Main assumptions	Same penetration rate as assumed in the design of the NDC. The hydrogen is assumed to come from solar power.	
Cost elements	Considers the investment in hydrogen thermal systems and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.	
References	Gobierno de Chile (2020)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.032** 0.031 ~ 0.033	**0.032** 0.031 ~ 0.033
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.163** 0.159 ~ 0.167	**0.163** 0.159 ~ 0.167
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**-8.47** -8.27 ~ -8.68	
Abatement cost (US$/$tCO_2e$)	**-52.00**	

Name	**Various industries—hydrogen in motor processes: 12% by 2050**	
Source	Chilean NDC.	
General overview	Incentives to accelerate transition from fossil fuel combustion in motor processes to green hydrogen use.	
	Modeling	
Main assumptions	Same penetration rate as assumed in the design of the NDC. The hydrogen is assumed to come from solar power.	
Cost elements	Considers the investment in hydrogen motors and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.	
References	Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.34** 0.33 ~ 0.35	**0.34** 0.33 ~ 0.35
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**1.70** 1.66 ~ 1.74	**1.70** 1.66 ~ 1.74
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**-88.5** -86.4 ~ -90.6	
Abatement cost (US$/$tCO_2e$)	**-52.00**	

Name	**Various industries—electrification in motor processes: 88% by 2050**	
Source	Chilean NDC.	
General overview	Incentives to accelerate transition from fossil fuel in motor processes to electricity use.	
	Modeling	
Main assumptions	Same penetration rate as assumed in the design of the NDC.	
Cost elements	Considers the investment in electric motors, the reduction in diesel consumption, and the increase in electricity use. In the CP scenario the purchase of diesel engines is accounted for.	
References	Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.73** 0.71 ~ 0.76	**0.73** 0.71 ~ 0.76
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**3.27** 3.13 ~ 3.42	**3.35** 3.26 ~ 3.40
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**-324.0** -315.7 ~ -328.5	
Abatement cost (US$/$tCO_2e$)	**-96.70**	

Name	**Various mines—hydrogen in motor processes: 21% by 2050**	
Source	Chilean NDC.	
General overview	Incentives to accelerate transition from fossil fuel combustion in motor processes to green hydrogen use.	
Modeling		
Main assumptions	Same penetration rate as assumed in the design of the NDC. The hydrogen is assumed to come from solar power.	
Cost elements	Considers the investment in hydrogen motors and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.	
References	Gobierno de Chile (2020)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.14** 0.13 ~ 0.16	**0.14** 0.13 ~ 0.16
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.73** 0.68 ~ 0.78	**0.73** 0.68 ~ 0.78
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**-38.0** -35.6 ~ -40.5	
Abatement cost (US$/$tCO_2e$)	**-52.00**	

Name	**Various mines—electrification in motor processes: 74% by 2050**	
Source	Chilean NDC and expert opinion of the authors for the AM scenario.	
General overview	Incentives to accelerate transition from fossil fuel in motor processes to electricity use.	
	Modeling	
Main assumptions	Same penetration rate as assumed in the design of the NDC in IM scenario, 5% more penetration for AM scenario.	
Cost elements	Considers the investment in electric motors, the reduction in diesel consumption, and the increase in electricity use. In the CP scenario the purchase of diesel engines is accounted for.	
References	Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.41** 0.38 ~ 0.45	**0.47** 0.43 ~ 0.50
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**1.83** 1.68 ~ 2.01	**3.11** 2.25 ~ 3.11
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**-301.0** -217.5 ~ -283.6	
Abatement cost (US$/$tCO_2e$)	**-96.70**	

Name	**Steel industry—hydrogen in thermal processes: 10% by 2050**		
Source	Benavides et al. (2021)		
General overview	Incentives to accelerate transition from fossil-fuel combustion in thermal processes to hydrogen use.		
	Modeling		
Main assumptions	10% more penetration rate than BAU (and of the NDC without associated measures). The hydrogen is assumed to come from solar power.		
Cost elements	Considers the investment in hydrogen motors and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.		
References	Benavides et al. (2021)		
	Emission reduction		
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		**0.0**	**0.0065** 0.0061 ~ 0.0068
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		**0.0**	**0.035** 0.034 ~ 0.037
	Cost evaluation (period 2020–50)		
		Discount rate 6%	
Total cost (MM US$)		**-1.8** -1.7 ~ -1.9	
Abatement cost (US$/$tCO_2eq$		**-52.00**	

Name	Steel industry—biomass in thermal processes: 10% by 2050	
Source	Benavides et al. (2021)	
General overview	Incentives to accelerate transition from fossil-fuel combustion in thermal processes to biomass use.	
	Modeling	
Main assumptions	10% more penetration rate than BAU (and of the NDC without associated measures).	
Cost elements	Considers the investment in biomass thermal systems, and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.	
References	Benavides et al. (2021)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.0**	**0.0088** 0.0084 ~ 0.0092
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.0**	**0.048** 0.046 ~ 0.051
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**-2.8** -2.7 ~ -2.9	
Abatement cost (US$/$tCO_2e$)	**-58.00**	

Building actions

Name	**Commercial: electrification of end uses**		
Source	Chilean NDC		
General overview	Incentives to accelerate electrification in the commerce sector.		
	Modeling		
Main assumptions	Same penetration rate as the one assumed in the design of the NDC: by 2050 the electrification is around 70% of the consumption of energy. On the baseline this is close to 50%.		
Costs elements	Considers the investment in electric motors, the reduction in diesel consumption, and the increase in electricity use. In the CP scenario the purchase of diesel engines is accounted for.		
References	Benavides et al. (2021), Gobierno de Chile (2020)		
	Emission reduction		
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		**0.000**	**0.188** 0.187 ~ 0.172
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		**0.033** 0.02 ~ 0.04	**0.661** 0.67 ~ 0.61
	Cost evaluation (period 2020–50)		
		Discount rate 6%	
Total cost (MM US$)		**-60.8** -61.3 ~ -55.8	
Abatement cost (US$/$tCO_2e$)		**-92.08**	

Name	Public: solar water heaters in public hospitals		
Source	Chilean NDC		
General overview	Installation of solar energy collectors on hospital roofs for heating sanitary water.		
Modeling			
Main assumptions	Same penetration rate as the one assumed in the design of the NDC: by 2050 solar power is around 10% of the consumption of energy for hot sanitary water. For the NDC+ scenario a level of 50% is achieved by 2050. On the baseline this is close to 0%		
Costs elements	Considers the investment in solar thermal systems, and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.		
References	Benavides et al. (2021), Gobierno de Chile (2020)		
Emission reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		**0.00107** 0.00111 ~ 0.00102	**0.0053** 0.0056 ~ 0.0051
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		**0.0052** 0.0050 ~ 0.0054	**0.026** **0.025 ~ 0.027**
Cost evaluation (period 2020–50)			
		Discount rate 6%	
Total cost (MM US$)		**1.36** 1.31 ~ 1.41	
Abatement cost (US$/$tCO_2e$)		**52.30**	

Name	**Public: electric heating in public hospitals**	
Source	Chilean NDC	
General overview	Incentives to accelerate the electrification of the heating in public hospitals.	
Modeling		
Main assumptions	Same penetration rate as the one assumed in the design of the NDC: by 2050 the electrification is 48% of the consumption of energy for heating in hospitals. For the NDC+ scenario a level of 100% is achieved by 2050. On the baseline this is close to 0%	
Costs elements	Considers the investment in electric motors, the reduction in diesel consumption, and the increase in electricity use. In the CP scenario the purchase of diesel engines is accounted for.	
References	Benavides et al. (2021), Gobierno de Chile (2020)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.0024** 0.0021 ~ 0.0029	**0.0072** 0.0067 ~ 0.0070
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.009** 0.007 ~ 0.011	**0.030** 0.028 ~ 0.031
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**-3.96** -3.66 ~ -4.03	
Abatement cost (US$/$tCO_2e$)	**-130.20**	

Name	**Public: solar PV on public buildings**	
Source	Expert opinion of the authors.	
General overview	Incentives for the installation of PV on public buildings on the center and north of Chile.	
	Modeling	
Main assumptions	Installation of PV solar panels on public installations for the eight northern regions. Enough panels to supply 50% of the electric demand in 2050. It considers a linear penetration starting from 2021.	
Cost elements	Considers the investment in solar PV panels, and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.	
References	Benavides et al. (2021), Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.0**	**0.038** 0.039 ~ 0.042
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.0**	**0.238** 0.244 ~ 0.246
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**6.90** 7.09 ~ 7.13	
Abatement cost (US$/$tCO_2e$)	**29.00**	

Name	**Residential: electric heating**		
Source	Chilean NDC		
General overview	Program to replace combustion heaters with electric heaters.		
	Modeling		
Main assumptions	Same penetration rate as the one assumed in the design of the NDC: by 2050 the heating electrification is around 72% in houses and 89% in apartments The baseline considers that by 2050 around 20% of houses and 40% of apartments have electric heating. The heaters replaced are distributed as the distribution in the BAU scenario, including both fossil-fuel heaters and wood heaters. The impact on the reduction of wood is not included on the quantification reduction, although it is included in the LULUCF model.		
Cost elements	Considers the investment in electric motors, the reduction in fossil fuels and wood consumption, and the increase in electricity use. In the CP scenario the purchase of conventional heating devices is accounted for.		
References	Benavides et al. (2021), Gobierno de Chile (2020)		
	Emission reduction		
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		**0.45** 0.42 ~ 0.51	**0.45** 0.42 ~ 0.51
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		**1.73** 1.56 ~ 1.97	**1.73** 1.56 ~ 1.97
	Cost evaluation (period 2020–50)		
		Discount rate 6%	
Total cost (MM US$)		**-79.7** -71.8 ~ -90.7	
Abatement cost (US$/$tCO_2e$)		**-46.13**	

Name	**Residential: electrification of residential cooking**	
Source	Chilean NDC	
General overview	Program to replace combustion stoves for electric stoves.	
	Modeling	
Main assumptions	Same penetration rate as the one assumed in the design of the NDC: by 2050 stove electrification is around 36% in houses and 35% in apartments. The NDC+ scenario considers 72% of houses and 89% of apartments with electric stoves. The baseline doesn't consider penetration of stove electrification. The stoves replaced are distributed as the distribution in the BAU scenario, including both fossil-fuel stoves and wood stoves. The impact on the reduction of wood is not included on the quantification reduction, although it is included on the LULUCF model.	
Cost elements	Considers the investment in electric motors, the reduction in fossil-fuel consumption, and the increase in electricity use. In the CP scenario the purchase of conventional cooking devices is accounted for.	
References	Benavides et al. (2021), Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.072** 0.068 ~ 0.252	**0.219** 0.211 ~ 0.219
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.379** 0.354 ~ 0.412	**1.051** 1.013 ~ 1.047
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**-48.5** -48.3 ~ -46.7	
Abatement cost (US$/$tCO_2e$)	**-46.13**	

Name	**Residential: solar water heaters**		
Source	Chilean NDC		
General overview	Installation of solar thermal roofs on residential houses to supply hot sanitary water.		
	Modeling		
Main assumptions	Same penetration rate as the one assumed in the design of the NDC: by 2050 heating electrification is around 63% in houses and 57% in apartments. The baseline considers that by 2050 there are 0 solar thermal roofs. The impact on the reduction of wood is not included in the quantified reduction, although it is included in the LULUCF model.		
Cost elements	Considers the investment in solar thermal systems, and the reduction in diesel consumption. In the CP scenario the purchase conventional water heating devices is accounted for.		
References	Benavides et al. (2021), Gobierno de Chile (2020)		
	Emission reduction		
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		**0.584** 0.578 ~ 0.582	**0.564** 0.561 ~ 0.572
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		**3.18** 3.15 ~ 3.19	**3.07** 3.05 ~ 3.11
	Cost evaluation (period 2020–50)		
		Discount rate 6%	
Total cost (MM US$)		**23.6** 23.5 ~ 23.9	
Abatement cost (US$/$tCO_2e$)		**7.70**	

Name	**Residential: retrofit of thermal insulation**		
Source	Chilean NDC		
General overview	Improvement of thermal insulation for houses to reduce the demand for heating.		
Modeling			
Main assumptions	Same penetration rate as the one assumed in the design of the NDC: 20,000 houses insulated per year. For the NDC+ scenario a level of 40k houses retrofitted per year is considered. On the baseline this is close to 0 houses per year. The houses are regionally distributed in the same distribution of houses observed on the last census (2017). The impact on the reduction of wood is not included in the quantification reduction, although it is included in the LULUCF model.		
Cost elements	Considers the investment in thermal insulation, and the reduction in fossil-fuel and electricity consumption.		
References	Benavides et al. (2021), Gobierno de Chile (2020)		
Emission reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		**0.0157** 0.0154 ~ 0.0160	**0.0377** 0.0372 ~ 0.0387
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		**0.093** **0.092 ~ 0.095**	**0.186** 0.189 ~ 0.184
Cost evaluation (period 2020–50)			
		Discount rate 6%	
Total cost (MM US$)		**-32.1** -31.8 ~ -32.7	
Abatement cost (US$/$tCO_2e$)		**-172.90**	

Waste actions

Name	**Increased capture and burning of landfill gas: 100% of capture and burning in managed landfills by 2030**	
Source	Chilean NDC	
General overview	Obligation to install and operate biogas capture and burning on managed landfill operations by 2030.	
	Modeling	
Main assumptions	The installation of torch burners on landfills starts in 2024 and grows linearly until 2030, when all the landfills have torch burners. A 45% capture efficiency is considered	
Cost elements	Considers the investment in new torch burners, and the costs of operating and maintaining them.	
References	Benavides et al. (2021), GreenLab (2014), Gobierno de Chile (2020)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**1.59** 1.58 ~ 1.60	**1.59** 1.58 ~ 1.60
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**4.17** 4.14 ~ 4.20	**4.17** 4.14 ~ 4.20
	Cost evaluation (period 2020–50)	
	Discount rate 6%	
Total cost (MM US$)	**5.80** 5.76 ~ 5.84	
Abatement cost (US$/$tCO_2e$)	**0.15**	

Name	New composting plants: 50% of residential organic waste composted by 2050	
Source	Expert opinion of the authors.	
General overview	Installation of enough composting plants to recover and compost 50% of the organic residential waste.	
Modeling		
Main assumptions	Starting from 2025, a timeline is proposed for each region considering plants with a capacity of 30–50 kt of organic waste per year. The total capacity (t of organic waste/per year) installed is: 2025, 240k; 2030, 570k; 2035, 980k; 2040,1.65M; 2045, 2.14M; 2050, 52.14M An 80% average plant factor is considered.	
Cost elements	Considers the investment and operational costs associated with the new composting plants, including the costs associated with transporting organic waste. Income associated with the sale of compost and the savings related to the reduction in landfill use were included.	
References	Benavides et al. (2021), GreenLab (2014)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.0**	**-0.08**
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.0**	**-0.09**
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (MM US$)	**179.7**	
Abatement cost (US$/$tCO_2e$)	**4.31**	

Name	**New wastewater treatment plants for the most populous cities**		
Source	Chilean NDC		
General overview	Installation of wastewater treatment plants (similar to the ones installed in Santiago) in the most populous cities and their urban surroundings: Gran Concepción, Gran Valparaíso, La Serena-Coquimbo and Antofagasta		
	Modeling		
Main assumptions	The capacity of treatment needed for each of the wastewater plants is estimated from the estimation of the demand in 2050. Plants begin operating in the year they are installed. This varies between cities and scenarios. In the NDC scenario the installation is expected to occur in 2030 in Gran Concepción, 2035 in Gran Valparaíso, and 2038 in La Serena/Coquimbo and Antofagasta. On the NDC+ scenario the installation is expected to occur two years before.		
Cost elements	Considers the investment and operational costs, relative to the different flows for each city.		
References	Benavides et al. (2021), GreenLab (2014)		
	Emission reduction		
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		**0.03**	**0.03**
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		**0.03**	**0.09**
	Cost evaluation (period 2020–50)		
		Discount rate 6%	
Total cost (MM US$)		**493.8**	
Abatement cost (US$/$tCO_2e$)		**344.61**	

IPPU actions

Name	**Recovery and regeneration of refrigerant plants: new installed capacity for 2,800 t/year in 2030**		
Source	Based on the authors' expert opinion, this measure is considered in addition to compliance with the Kigali Amendment, which restricts HFC consumption and is modeled as BAU.		
General overview	Subsidized installation of new regeneration sites of HFC, increasing from 350 t/year (actual capacity) to 3,150 t/year by 2030 (increase of 2,800 t/year capacity).		
	Modeling		
Main assumptions	Two plants, each of 350 t/year, are assumed to be installed in 2025, 2027 and 2030. It also considered an increase of the plant factor from the actual 10% to 40% in 2030 and 80% in 2050.		
Cost elements	Considers the investment associated with the implementation of the two refrigerant regeneration plants and their cost of operation.		
References	GISMA (2014), Hoglund-Isaksson et al. (2017)		
	Emission reduction		
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		**0.0**	**1.317** 1.318 ~ 1.327
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		**0.0**	**5.53** 5.54 ~ 5.57
	Cost evaluation (period 2020–50)		
		Discount rate 6%	
Total cost (MM US$)		**5.57** 5.58 ~ 5.61	
Abatement cost (US$/$tCO_2e$)		**0.18**	

Agriculture actions

Name	**Change in bovine diet (lipidic additive)**
General overview	This measure considers an additional component in the diet in cattle through the use of concentrate (pellet) in combination with additives to optimize the functioning of the rumen, decreasing methanogenesis excretion.
	Modeling
Main assumptions	In the NDC scenario, this measure considered an improvement of diet of 70% in dairy-producing cattle by 2040, starting its implementation in 2030 and considering a linear growth. In the accelerated scenario (NDC+), this measure starts the implementation in 2025, reaching 35% of dairy-producing cattle by 2030. It was considered that a dairy cow lives seven years and that the management systems are 75% grazing and 25% confinement. In addition, it was considered that the enteric methane emission factor of animals fed an improved diet with incorporation of concentrates with lipids (3% additional), is reduced by 17% (Beauchemin et al., 2007).
Cost elements	No investment costs were considered for this measure. The operating costs are associated with the use of food with a higher concentration of lipids (3% additional), for which an additional cost of 14% was considered compared to the original diet. The annual cost of feeding a dairy cow without the measure was estimated at $721,016CLP/cattle, and a Price of $820.392 CLP/cattle, with the lipidic additive.
References	Beauchemin et al. (2007), sunflower seed oil price: Pino (2021

Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction in 2030 ($MtCO_2e$)	**0.0015** 0.013 ~ 0.017	**0.051** 0.045 ~ 0.059
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.0015** 0.013 ~ 0.017	**0.189** 0.16 ~ 0. 21
Cost evaluation (period 2020–50)		
	Discount rate 6%	
Total cost (including accelerated scenario) (MM US$)	**703** 597.25 ~ 840.5	
Abatement cost (US$/$tCO_2e$)	**359.7** 359.7 ~ 359.8	

Name	Efficient use of fertilizers		
General overview	This measure considers the implementation of a comprehensive program of training, cooperation and technical support to improve the use of fertilizers in crops, specifically the practices associated with the excessive use of mineral fertilizers.		
Modeling			
Main assumptions	This measure analyzed four types of nitrogen fertilizers (urea, potassium saltpeter, sodium saltpeter and ammonium phosphate), which correspond to nitrogen fertilizers provided by ODEPA as inputs for producers. By 2035, it was considered that there would be 20% less application of nitrogen fertilizers without inhibitors in cereal crops and cereal seedbeds, and 15% less nitrogen fertilizers without inhibitors for industrial and forage crops, because of the technical assistance measures applied in rainfed soils and non-mechanized irrigation (leaching/runoff) or volatilization. No accelerated scenario was considered. The weight of each of these fertilizers was based on the average amount of imports between 2015 and 2017 provided by FAO. The linear implementation date for the measure was considered to be from 2025 to 2035.		
Cost elements	This measure does not require investment costs. To calculate the savings, a weighted mineral nitrogen price of US$537/ton was considered.		
References	FAO (2021)		
Emission reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction in 2030 ($MtCO_2e$)		**0.112** 0.10 ~ 0.12	**0.12** 0.10 ~ 0.12
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		**0.34** 0.30 ~ 0.37	**0.34** 0.30 ~ 0.37
Cost evaluation (period 2020–50)			
		Discount rate 6%	
Total cost accumulated (MM US$)		**-555** **-494.7 ~ -615.2**	
Abatement cost (US$/tCO2e)		**-123** -122 ~ 123.8	

Name	**Porcine biodigesters**		
General overview	This measure considers the implementation of biodigesters at the property level to transform CH_4 emissions generated in wells or lagoons used for the accumulation of organic waste (slurry and/or manure) into CO_2, reducing the emission factor associated with gas generation.		
	Modeling		
Main assumptions	This measure considered the implementation of biodigesters and a biogas plant for power generation, with an average slurry processing capacity of 31,102 m^3. An annual manure generation of 2.02 m^3/year/pig was considered for pigs. The implementation of this measure was considered from 2020 for the treatment of pig slurry, starting from a penetration of 27% and considering a gradual growth until 2030 with 42% of heads of pig.		
Cost elements	A unit capex of US$1,555,024 per plant unit is considered and an annual opex of $198.976 per plant unit, and an additional saving in the thermal and electrical energy produced by the biogas plant.		
References	Caroca (2015)		
	Emission reduction		
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		**0.29** 0.28 ~ 0.29	**0.29** 0.28 ~ 0.29
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		1.286	1.286
	Cost evaluation (period 2020–50)		
		Discount rate 6%	
Total cost accumulated (MM US$)		**49.09** 15.2 ~ 95.7	
Abatement Cost (US$/$tCO_2e$)		**2.62** 0.72 ~ 5.62	

Name	Application of organic amendments (poultry manure)	
General overview	Increase in carbon sequestration in soils as a result of the application of organic amendments (poultry manure) to soils under annual crops. Implementation starting in 2025, reaching 10% of the surface by 2030, and remaining constant until 2050.	
Modeling		
Main assumptions	Using the IPCC Tier 1 methodology (2006: vol. 4, chapter 2, equation 2.25), different management options were considered (vol. 4, chapter 5, table 2—Relative factors of change in stock [FLU, FMG and FI] [over 20 years] for different activities of management in croplands), considering the FI (income factor), high in manure for a temperate thermic regime. It is assumed that 12% of carbon inputs of poultry manure is retained as soil organic carbon (Maillard and Angers, 2014). Nitrogen emissions were considered.	
Cost elements	The cost estimation considers the average price delivered for three quotations per cubic meter of bird guano and considering unit cost of transportation and data on unit labor = US$39.6 for the value per m^3 of manure. Also, it considers an additional yield increase of 30 kg/ha * 0.5 tCO_2e/ha.	
References	FAO (2017)	
Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	0	**0.069** 0.07 ~ 0.061
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	0	**0.26** 0.23 ~ 0.29
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost accumulated to 2030 (MM US$)	**226.4** 203.7 ~ 249.	
Abatement cost (US$/$tCO_2e$)	**154.2** 154.2 ~ 154.2	

Name	Holistic livestock management—regenerative livestock
General overview	Regenerative livestock farming is defined as the pursuit of restoring and maintaining natural systems, such as water and carbon cycles, to allow the soil to continue producing food in a healthier way for people and for the long-term health of the planet and its climate (The Carbon Underground, 2017). Holistic livestock management is an approach that seeks to optimize decision-making in different areas, balancing social, environmental and financial considerations, regulating the planning, monitoring, control and replanning of grasslands and animal load, increasing the contents of organic matter in soils, and being able to improve the productivity of grasslands. Carbon capture is produced by an increase in organic matter content in soils.
Modeling	
Main assumptions	It is considered that 20% of the area of bovine grasslands of the Los Lagos Region (approximately 32% of cattle) apply holistic livestock management practices, increasing the productivity of grasslands, increasing prairie productivity from 10,026 kg DM/ha/year to 12,254 kg MS/ha/year, increasing the organic matter content in soils. An average annual catch of -0.2 tCO_2e/ha/year was considered. The growth of grasslands was estimated under the CropSys V 4.19.07 model, considering the difference of kg DM/ha for regenerative grasslands vs traditional for a period of five years (2014–18).
Cost elements	An increase in kg MS/ha and grazing measurement planning man-hours was considered, considering a value of CLP$30,000 person-day a required amount per ha/year of 0.48, and an annual cost of CLP$14,400/year. It was also considered labor separation properties/maintenance of fences at a value of CLP$20,000 person-day, considering an amount required per ha /year of 4.8, with an annual cost of CLP$96,000/year. This generates an extra annual operating cost of $110,400. A power saving per kg MS/ha/year increase of CLP$51,784/year is considered. The total cost of the measure per ha is US$73.99/year, considering the average price of the value of the dollar in the year 2020 (CLP$792/US$).
References	The Carbon Underground (2017)

Emission reduction

	Year 2030 IM	Year 2030 AM
Emission reduction ($MtCO_2e$)	0	**0.11** 0.09 ~ 0.12
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	0	**0.415** 0.37 ~ 0.45

Cost evaluation (period 2020–50)

	6% discount rate
Total cost (MM US$)	**267.5** 240.7 ~ 294.2
Abatement cost (US$/$tCO_2e$)	**99.55** 99.55 ~ 99.55

Name	Meat tax		
General overview	Application of a 10% tax to the consumer based on the producer price, affecting national production.		
	Modeling		
Main assumptions	Chile has the fifth-highest per capita consumption of beef in the world.[19] An average consumption of 149 g/meat/day was considered, of which 44 g/day is beef (Universidad de Chile, 2011). The consumption of beef meat was projected based on population (INE, 2019) and the elasticity of demand (Báez, 2020), and the projection of the producer price was used to project the head of cattle (OECD & FAO, 2020). Consumption without tax and with tax was estimated from the year 2021. The impact on meat imports was not considered in the analysis. The decrease in demand as a result of the tax, in the case of this measure, considers only an impact on national meat production, not increases in other types of livestock considered as a replacement for this feed.		
Cost elements	Costs were not considered given their high complexity in distribution.		
References	Báez (2020), Universidad de Chile (2011)		
	Emission reduction		
		Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)		0	**0.25** 0.22 ~ 0.29
Reduction of cumulative emissions from 2020 ($MtCO_2e$)		0	**2.55** 2.27 ~ 2.83
	Cost evaluation (period 2020–50)		
		Discount rate 6%	
Total cost (MM US$)		N/A	
Abatement cost (US$/$tCO_2e$)		N/A	

[19] https://data.oecd.org/agroutput/meat-consumption.htm

Name	Reduction of agricultural burning
Source	Baseline of total biomass burned from cereals and other crops: Climate Change Office and Environmental Information and Economics Division of the Ministry of the Environment; Office of Agricultural Studies and Policies (ODEPA) of the Ministry of Agriculture.
General overview	This measure considers the replacement of traditional agriculture (which involves stubble burning) with zero-tillage agriculture in 80% of the total hectares where agricultural burning is carried out. The measure is expected to be implemented in the year 2023. By reducing the burning of agricultural residues, CH_4 and N_2O emissions are reduced (MMA, 2021b) and there are savings in the purchase of fertilizers by taking advantage of the nutrients in crop residues (Acevedo, 2003; ODEPA, 2017).
Modeling	
Main assumptions	Given that the area of agricultural burning has been maintained between 2007 and 2016, it was decided to calculate the average number of hectares burned in the last 10 years and to maintain those hectares to 2030.
Cost elements	The following are considered: investment for the purchase of no-tillage machinery (tractor, no-tillage planter, sprayer, spinning top), operating costs (inputs, machinery, labor, land rental) and savings in fertilizer use (for these, the nutrients present in the wheat stubble were considered) (Acevedo, 2003; Araya et al., 2009).
References	Acevedo (2003), Araya et al. (2009), Ministerio de Medio Ambiente (2021b), Oficina de Estudios y Políticas Agrarias (2017)

Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	0	**0.024** 0.021 ~ 0.026
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	0	**0.13** 0.12 ~ 0.15
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost (MM US$)	**-213.6** -192.3 ~ -235	
Abatement cost (US$/$tCO_2e$)	**-344** -344 ~ 344	

Name	Biochar utilization
Source	Industrial waste database 2018 of the National Waste Declaration System (SINADER).
General overview	This measure considers the implementation of a medium-sized biochar production plant, where the product is applied to agricultural land in order to sequester carbon in the soil. Biochar is generated from wood waste through the pyrolysis of this biomass. It is assumed that after pyrolysis, the carbon content in biochar is 72% and that 68% of that total remains as stabilized carbon in the soil for more than 100 years (Shackley et al., 2011; Singh and Singh, 2020); that is, biochar acts as a carbon sink in the soil for long periods of time, possessing high levels of resistance to chemical and biological degradation, which ultimately increases terrestrial carbon stocks (Qambrani et al., 2017).
Modeling	
Main assumptions	Construction of a medium-sized plant with a capacity of 16,000 oven-dry (od) ton/year (Bridgwater *in* Shackley et al., 2011) fed from bark and wood waste produced in the commune of Collipulli in the Araucanía region. It is assumed that the plant will be installed next to the waste production site, so there would be no costs related to transporting the material to be processed. It is assumed that the plant will start operating in 2023. It is assumed there will be an application of 30 ton/ha of biochar versus 20 ton/ha of compost per year (Shackley et al., 2011; Qambrani et al., 2017; Servicio Agrícola y Ganadero, 2017).
Cost elements	The investment cost of the plant, the operating cost, the cost of storage, logistics and application of biochar in the field were considered (Shackley et al., 2011). In addition, energy utilization savings were assumed by using syngas and bio oil from pyrolysis as fuels for the same plant (Rebolledo, et al., 2016; Qambrani et al., 2017). In addition, the market price of compost (Vuelta Verde, s. f.; Gordillo & Chávez, 2010; Lizama, 2018) was used as a substitute amendment and point of comparison to perform a sales price differential between biochar and compost (Oldfield et al., 2018).
References	Gordillo and Chávez (2010), Lizama (2018), Oldfield et al. (2018), Qambrani et al. (2017), Servicio Agrícola y Ganadero (2017), Shackley et al. (2011), Singh and Singh (2020), Vuelta Verde (n.d.), Escalante Rebolledo et al. (2016)

Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	0	0.013 0.013 ~ 0.013
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	0	0.09 0.07 ~ 0.1

Cost evaluation (period 2020–50)	
	6% Discount rate
Total cost accumulated (MM US$)	-9.752
Abatement cost (US$/$tCO_2e$)	-26.94

LULUCF actions

Name	**Native afforestation**	
Source	Chilean NDC.	
General overview	This measure is aimed at increasing the forest area, and considers the afforestation of 200,000 ha by 2030, of which 100,000 ha correspond to permanent forest cover of native forest, and the other 100,000 ha to forest plantations. This measure is part of Chile's NDC and is called "Contribution in Integration—LULUCF—Forests No. 5 (I5)."	
	Modeling	
Main assumptions	It assumes that 100,000 ha of permanent forest cover are under native forest. The goal is fulfilled in 2030, starting the afforestation in 2023 with 6,500 ha, which increase progressively until 2027; for the period 2028–30 15,500 ha are planted per year.	
Cost elements	The investment costs assume 1,100 plants per hectare, manual box costs per plant, subsoiling at 40 cm and protection against lagomorphs. For the operating values of native forestry, the costs of first pruning, first thinning, technical forestation advice, technical advice on field are considered.	
References	CONAF (2012), CORMA (personal communication, 2021)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.2357** 0.21 ~ 0.26	**0.2357** 0.21 ~ 0.26
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0.93** 0.84 ~ 1.02	**0.93** 0.84 ~ 1.02
	Cost evaluation (period 2020–50)	
	6% Discount rate	
Total cost (MM US$)	**1361.7** 1.226 ~ 1.498	
Abatement cost (US$/$tCO_2e$)	**209.9** 209.3 ~ 210.6	

Name	**Exotic Afforestation**
Source	Chilean NDC.
General overview	This measure is aimed at increasing the forest area, and considers the afforestation of 200,000 ha by 2030, of which 100,000 ha correspond to permanent forest cover of native forest, and the other 100,000 ha to forest plantations. This measure is part of Chile's NDC, and is called "Contribution in Integration—LULUCF—Forests No. 5 (I5)" (Gobierno de Chile, 2020).
	Modeling
Main assumptions	It assumes 100,000 ha are forest plantations. The goal is fulfilled in 2030, starting the afforestation in 2023 with 6,500 ha, which increases progressively until 2027; for the period 2028–30 15,500 ha are planted per year.
Cost elements	The investment costs assume 1,100 plants per hectare, manual box costs per plant, subsoiling at 40 cm and protection against lagomorphs. For the operating values of exotic and native forestry, the costs of first pruning, first thinning, technical forestation advice, technical advice on the ground are considered.
References	CONAF (2012), CORMA (personal communication 2021), Corvalán and Hernández (2012), INFOR (2021)

Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**4.15** 3.735 ~ 4.57	**4.15** 3.735 ~ 4.57
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**16.39** 14.75 ~ 18.03	**16.39** 14.75 ~ 18.03
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost (MM US$)	**-1014** -912.9 ~ -1116	
Abatement cost (US$/$tCO_2e$)	**-21.35** -40.96 ~ -11.67	

Name	Increase in hectares of native forest management
Source	Chilean NDC
General overview	This measure is aimed at the management and recovery of the native forest, and aims to increase the area managed by 200,000 ha by 2030. This measure is part of Chile's NDC, and is called "Contribution in Integration—LULUCF Bosques No. 4 (I4)."

	Modeling
Main assumptions	The goal is fulfilled in 2030, starting the increase in hectares under forest management in 2023 with 13,000 ha, which increases progressively until 2027; for the period 2028–30, 31,000 ha per year are passed to forest management.
Cost elements	For the investment costs of the measure, the mean values of ecological enrichment, infiltration ditch, direct seeding, control and elimination of exotic species, firebreaks, fuelbreaks and surveillance trails were used. In turn, for operating costs two types of cost were used: costs counted only one year after the application of the management plan, which includes the control values of exotic species and sanitary cutting costs; and set of silvicultural interventions and harvest activities that occur every year. The income values from the timber harvest were also used.
References	CONAF (2021a), CORMA (personal communication, 2021), ODEPA (2003)

Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**1.96** 1.59 ~ 2.38	**1.96** 1.59 ~ 2.38
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**7.76** 6.28 ~ 9.39	**7.76** 6.28 ~ 9.39
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost (MM US$)	**1783.8** 1605.4 ~ 1962.2	
Abatement cost (US$/$tCO_2e$)	**33.29** 30.26 ~ 36.99	

Name	Degradation reduction caused by forest fires
Source	Chilean NDC
General overview	In this measure are considered one of the three elements of native forest degradation, which gradually decreases until reaching 25% less loss of native forest by 2030, corresponding to a decrease in forest fires. This measure is part of Chile's NDC, and is called "Contribution in Integration—LULUCF—Forests No. 6 (I6)."
	Modeling
Main assumptions	To determine the reduction of fires caused by firebreaks, an analysis was carried out with information on fires for the period 1985–20, dismissing all fires greater than 100 ha under the assumption that firebreaks will be implemented around the perimeter of 100 ha of forest or forest plantation. To determine how many kilometers of firebreaks are required to protect 1 ha of forest, the application of firebreaks in stands with an area of 100 ha on a homogeneous plot of 400,000 ha was modeled.
Cost elements	For the cost of the activities, the clean-cutting and chipping of extracted biomass was considered. For the operation cost, the value of sanitary felling was considered. For the value of income the average costs of land of classes V, VI, VII and VIII as a function of soil distributions was considered with reference to Zelada and Maquire (2005), and taking into consideration the probability of forest fires measured by data provided by CONAF.
References	CONAF (2020, 2021b), ODEPA and Pontificia Universidad Católica de Chile (2009), Zelada and Maquire (2005)

Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0.95** 0.95 ~ 2.868	**0.95** 0.95 ~ 2.868
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**4.75** 4.75 ~ 14.34	**4.75** 4.75 ~ 14.34
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost (MM US$)	**3.46** 3.46 ~ 3.46	
Abatement cost (US$/$tCO_2e$)	**23.03** 13.7 ~ 23.03	

Name	**Increase in protected areas**
Source	Benavides et al. 2021
General overview	This measure considers the creation of new national parks and reserves, which, on one hand, increase the area of forest under management, and on the other, contribute to the conservation of native forests and terrestrial ecosystems. The measure begins in 2023, the year in which 100,000 ha of forest are added to the estimate of carbon sequestration in the national GHG inventory in the subcategory of "Parks and Reserves," where those hectares corresponding to renewals and forest in equilibrium are excluded.
	Modeling
Main assumptions	100% of the measure is implemented in 2023. The emissions corresponding to the extraction of biomass for the construction of trails or other human interventions are not considered. For costs, income starts to be received one year after the creation of the parks and reserves.
Cost elements	The investment costs of the measure to increase protected areas were calculated based on the average of the values per hectare of private investments, and the operating costs and income are derived based on economic data from the current protected areas.
References	MMA (2021c), MMA et al. (2010), Toledo (2017)

Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0** 0 ~ 0	**1.1** 0.89 ~ 1.33
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0** 0 ~ 0	**8.81** 7.14 ~ 10.66
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost (MM US$)	**41.28** 37.15 ~ 45.41	
Abatement cost (US$/$tCO_2e$)	**1.171** 1.07 ~ 1.3	

Name	Kelp forest management
Source	Benavides et al. 2021
General overview	This measure incorporates the GHG capture differential that is generated through the management of kelp forest of the species *Lessonia nigrescens*, *Lessonia trabeculata* and *Macrocystis* spp., where the GHG capture values are obtained from Vásquez et al. (2014). In addition, the measure contribute to the conservation of these marine ecosystems.
Modeling	
Main assumptions	The measure assumes 1,000 ha: 66 ha of *Lessonia nigrescens*, 841 ha of *Lessonia trabeculata* and 93 ha of *Macrocystis* spp. Distribution is based on the available hectares of kelp forests provided by Vásquez et al. (2014).
Cost elements	Activity and operation values obtained from Burg et al. (2016).
References	Burg et al. (2016), Vásquez et al. (2014)

Emission reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0** 0 ~ 0	**0.012** 0.011 ~ 0.013
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0** 0 ~ 0	**0.07** 0.064 ~ 0.078
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost (MM US$)	**125.9** 113.4 ~ 138.6	
Abatement cost (US$/$tCO_2e$)	**330.2** 330.2 ~ 330.2	

Name	**Native afforestation—increase in hectares**	
Source	An increase on the commitment of the Chilean NDC.	
General overview	This measure corresponds to an increase in forested hectares with native vegetation. It is oriented toward increasing forest area, and considers the afforestation of 20,000 ha by 2030, of which 100% corresponds to permanent forest cover of native forest.	
	Modeling	
Main assumptions	The goal is met in 2026, with increases in the forested area starting in 2023, and 5,000 ha each year.	
Cost elements	The investment costs assumes 1,100 plants per hectare, manual box costs per plant, subsoiling at 40 cm and protection against lagomorphs. For the operating values of the exotic and native forestry, the costs of first pruning, first thinning, technical forestation advice, technical advice on field are considered.	
References	CONAF (2012), CORMA (personal communication 2021)	
	Emission reduction	
	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0** 0 ~ 0	**0.047** 0.042 ~ 0.052
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0** 0 ~ 0	**0.31** 0.27 ~ 0.34
	Cost evaluation (period 2020–50)	
	6% Discount rate	
Total cost (MM US$)	**281.6** 196.7 ~ 240.5	
Abatement cost (US$/$tCO_2e$)	**148.8** 148.4 ~ 149.4	

Name	**Increase in hectares of native forest management—increase in hectares**
Source	An increase on the commitment of the Chilean NDC.
General overview	This measure is aimed at the management and recovery of the native forest and aims to increase the area managed by 20,000 ha by 2030. This measure is part of Chile's NDC, and is called "Contribution in Integration—LULUCF Bosques No. 4 (I4)" (Gobierno de Chile, 2020).
	Modeling
Main assumptions	The goal is met in 2026, with the increase in hectares under forest management starting in 2023 by 5,000 ha each year.
Cost elements	For the investment costs of the measure, the mean values of ecological enrichment, infiltration ditch, direct seeding, control and elimination of exotic species, firebreaks, fuelbreaks and surveillance trails are used. In turn, for operating costs two types of cost are used: costs counted only one year after the application of the management plan, which includes the control values of exotic species and sanitary cutting costs; and a set of silvicultural interventions and harvest activities that occur every year. Also used were the income values from the timber harvest
References	CONAF (2021a), CORMA (personal communication, 2021), ODEPA (2003)

Emission reduction

	Year 2030 IM	**Year 2030 AM**
Emission reduction ($MtCO_2e$)	**0** 0 ~ 0	**0.196** 0.16 ~ 0.24
Reduction of cumulative emissions from 2020 ($MtCO_2e$)	**0** 0 ~ 0	**1.28** 1.03 ~ 1.55
Cost evaluation (period 2020–50)		
	6% Discount rate	
Total cost (MM US$)	**187.95** 166.5 ~ 203.5	
Abatement cost (US$/$tCO_2e$)	**30.87** 28.06 ~ 34.3	

Appendix 2: Detailed results over future scenarios

Emissions by sector over future scenarios

FIGURE A1

Emissions for the CP Green future scenario

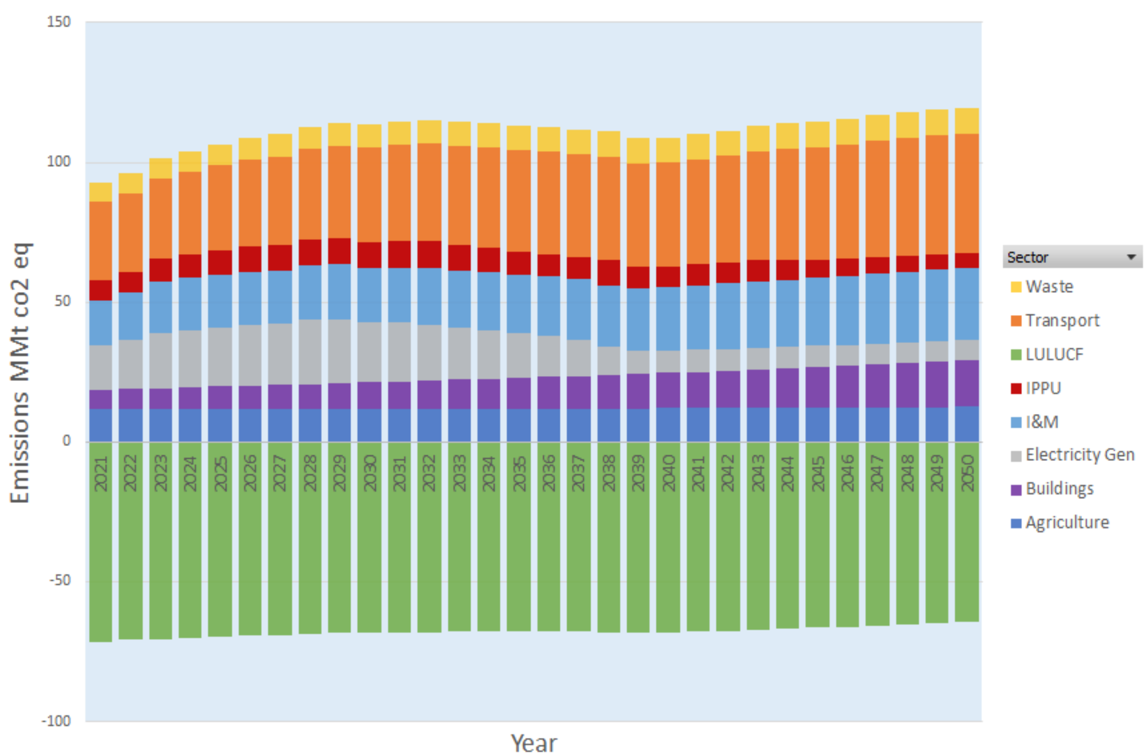


FIGURE A2

Emissions for the CP Red future scenario

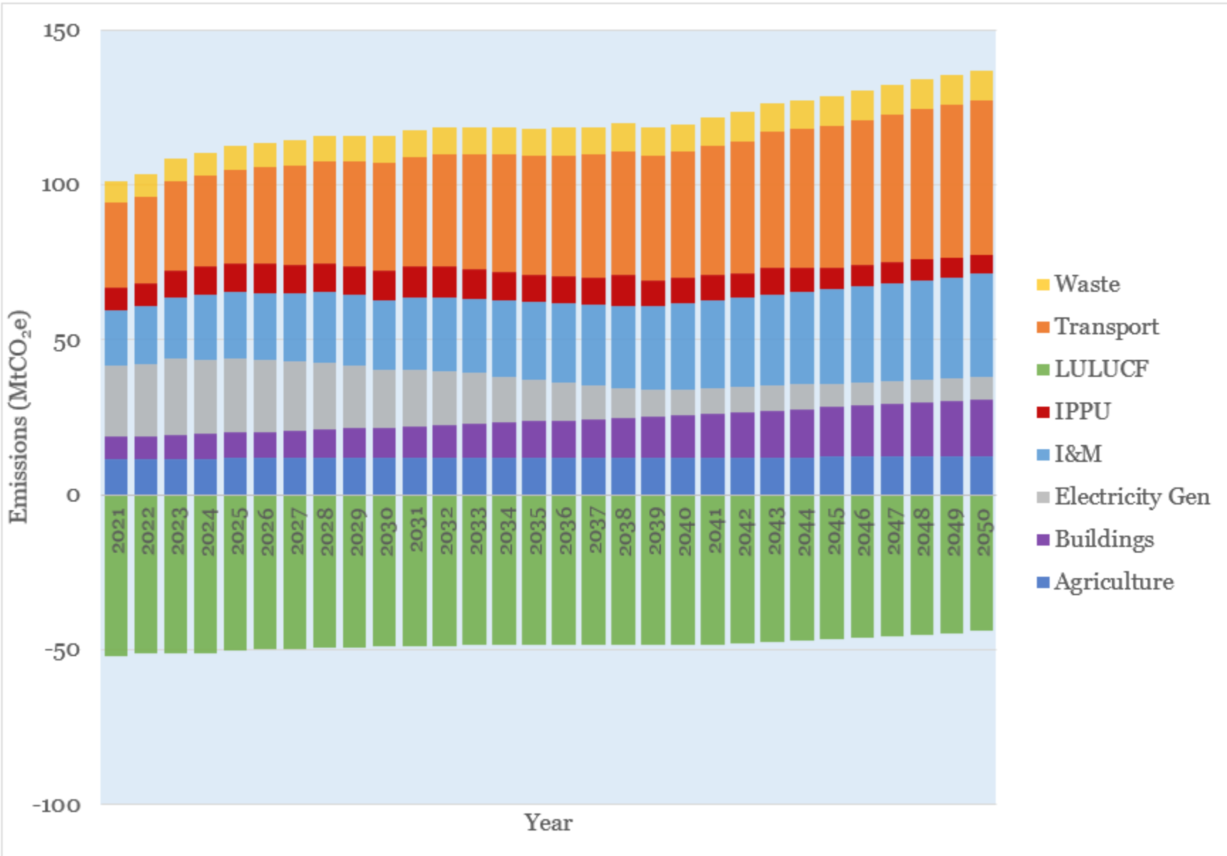


FIGURE A2

Emissions for the IM Green future scenario

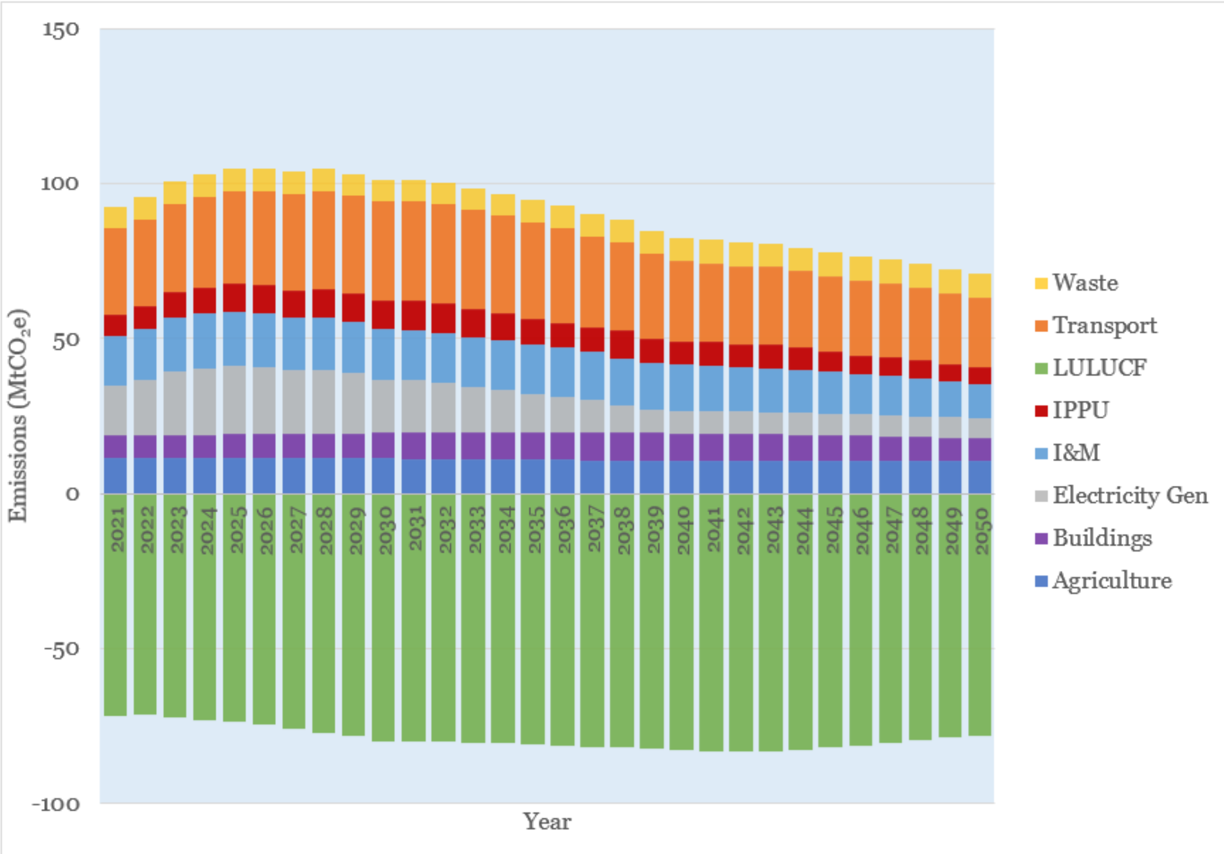


FIGURE A3

Emissions for the IM Red future scenario

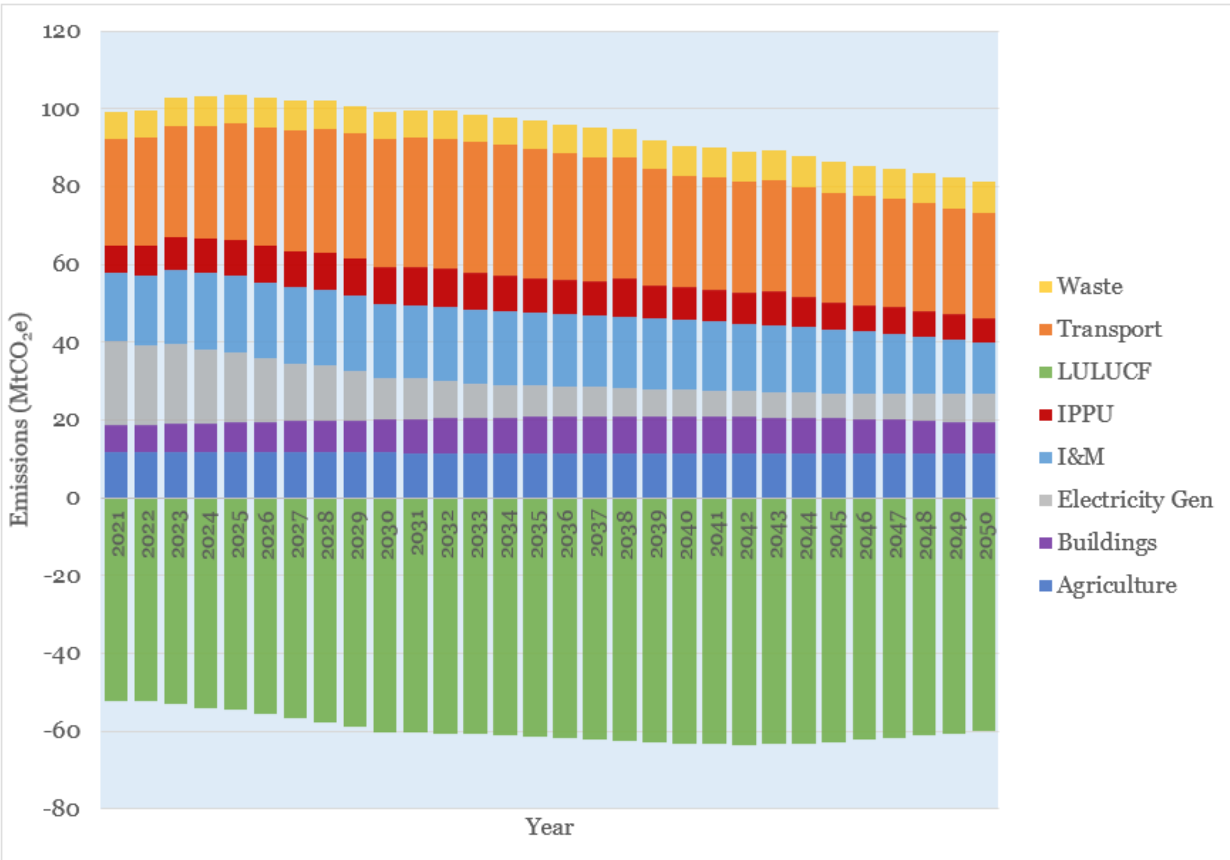


FIGURE A4

Emissions for the AM Green future scenario

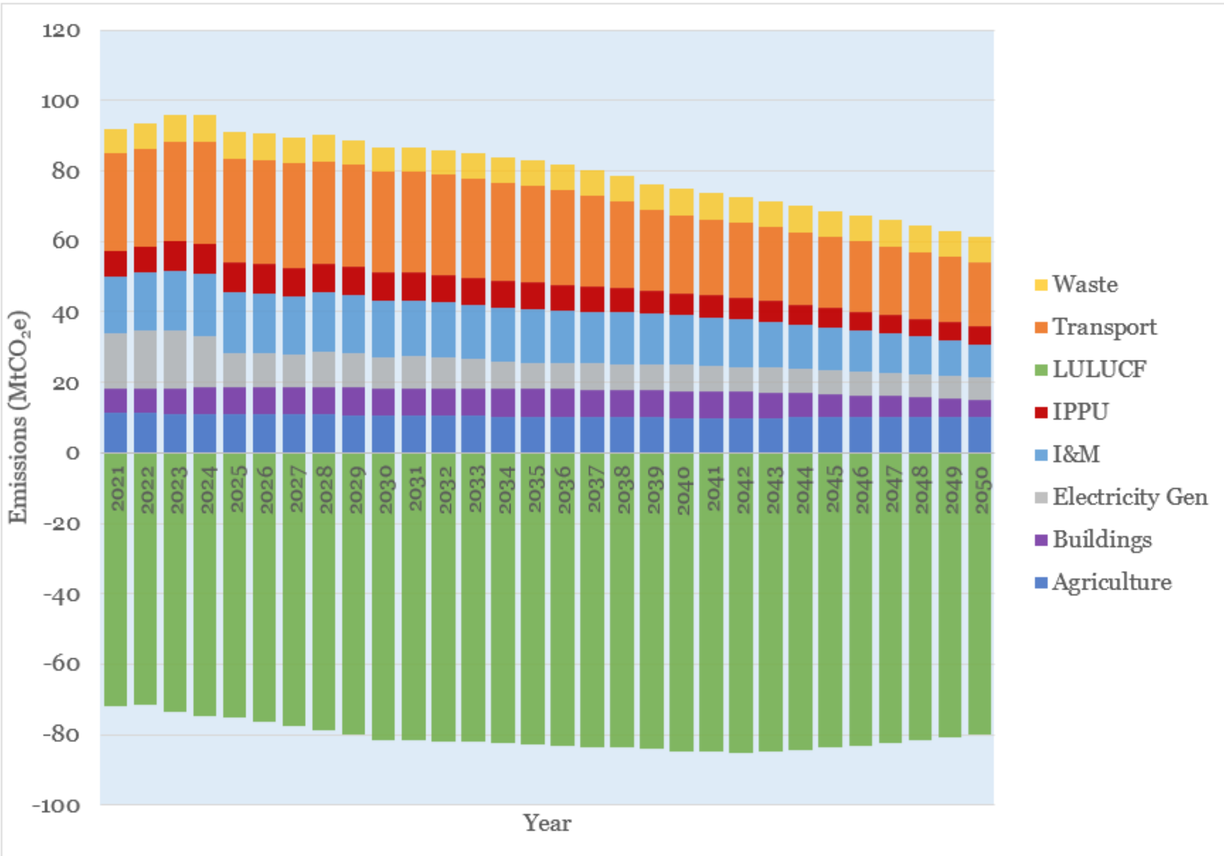
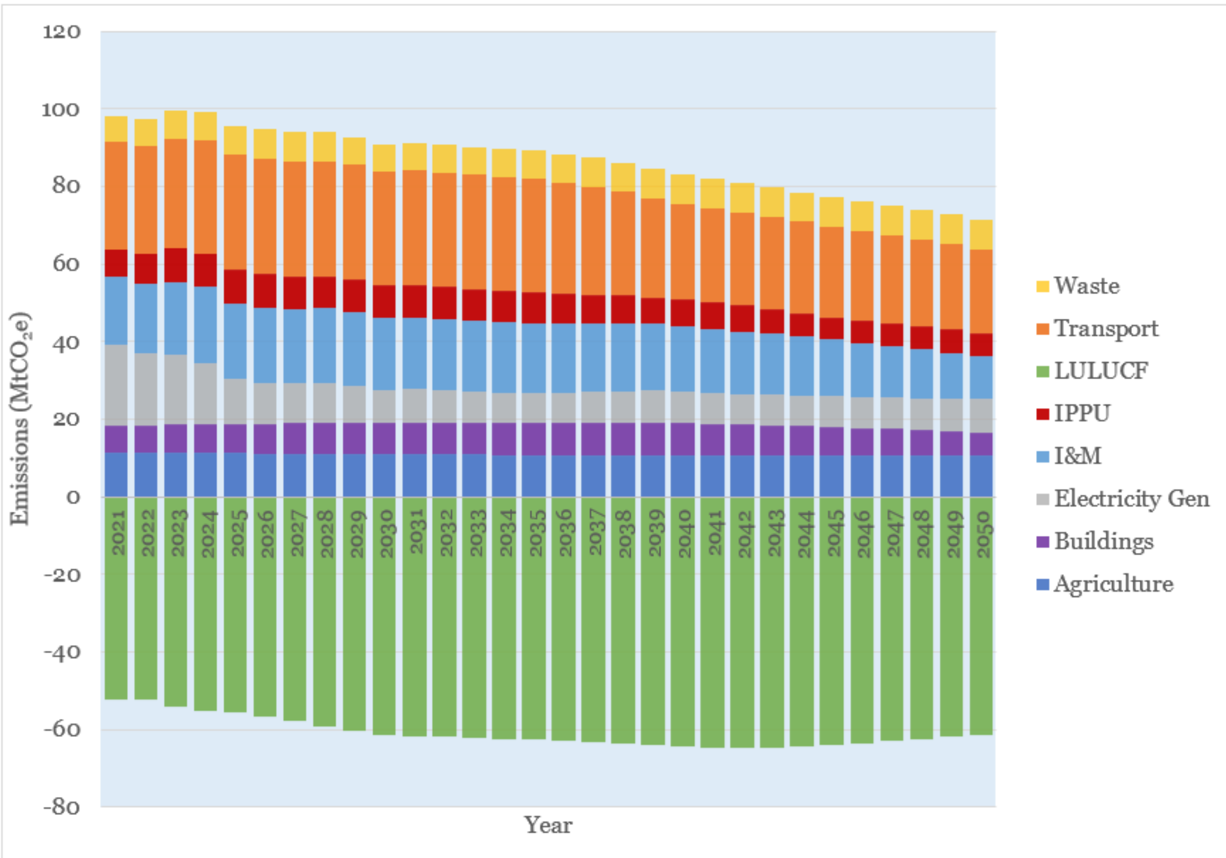


FIGURE A5

Emissions for the AM Red future scenario



Sensitivity analysis of 2020 and 2030 emissions

TABLE A13

The difference between projected 2030 emissions less 2020 emissions ($MtCO_2e$) for each scenario and all futures for the electricity sector

Sector	Future/scenario	CP	IM	AM
Electricity	Green future	-17	-22	-30
	Red future	-20	-28	-30
	Reference future	-20	-25	-32

TABLE A14

The difference between projected 2030 emissions less 2020 emissions (Mt CO_2e) for each scenario and all futures for the transport sector

Sector	Future/scenario	CP	IM	AM
Transport	Green future	6	4	1
	Red future	7	5	1
	Reference future	6	4	1

TABLE A15

The difference between projected 2030 emissions less 2020 emissions (Mt CO_2e) for each scenario and all futures for the buildings sector

Sector	Future/scenario	CP	IM	AM
Buildings	Green future	3	1	1
	Red future	3	2	1
	Reference future	3	1	1

TABLE A16

The difference between projected 2030 emissions less 2020 emissions (Mt CO_2e) for each scenario and all futures for the industry and mining sector

Sector	Future/scenario	CP	IM	AM
Industry & Mining	Green future	3	0	-1
	Red future	6	2	2
	Reference future	4	1	1

TABLE A17

The difference between projected 2030 emissions less 2020 emissions ($MtCO_2e$) for each scenario and all futures for the IPPU sector

Sector	Future/scenario	CP	IM	AM
IPPU	Green future	3	3	1
	Red future	3	3	2
	Reference future	3	3	1

TABLE A18

The difference between projected 2030 emissions less 2020 emissions (MtCO2e) for each scenario and all futures for the agriculture sector

Sector	Future/scenario	CP	IM	AM
Agriculture	Green future	0.1	-0.3	-1.0
	Red future	0.2	-0.1	-0.7
	Reference future	0.1	-0.2	-0.9

TABLE A19

The difference between projected 2030 emissions less 2020 emissions ($MtCO_2e$) for each scenario and all futures for the waste sector

Sector	Future/scenario	CP	IM	AM
Waste	Green future	1.6	0.2	0.2
	Red future	1.7	0.2	0.2
	Reference future	1.6	0.2	0.2

TABLE A20

The difference between projected 2030 emissions less 2020 emissions ($MtCO_2e$) for each scenario and all futures for the LULUCF sector

Sector	Future/scenario	CP	IM	AM
LULUCF	Green future	-7.6	-19.0	-20.8
	Red future	11.8	0.4	-0.8
	Reference future	-2.8	-13.1	-14.6

Generation for the alternatives to accelerate mitigation in the electricity sector

FIGURE A6

Generation output: Reference future AM 2025

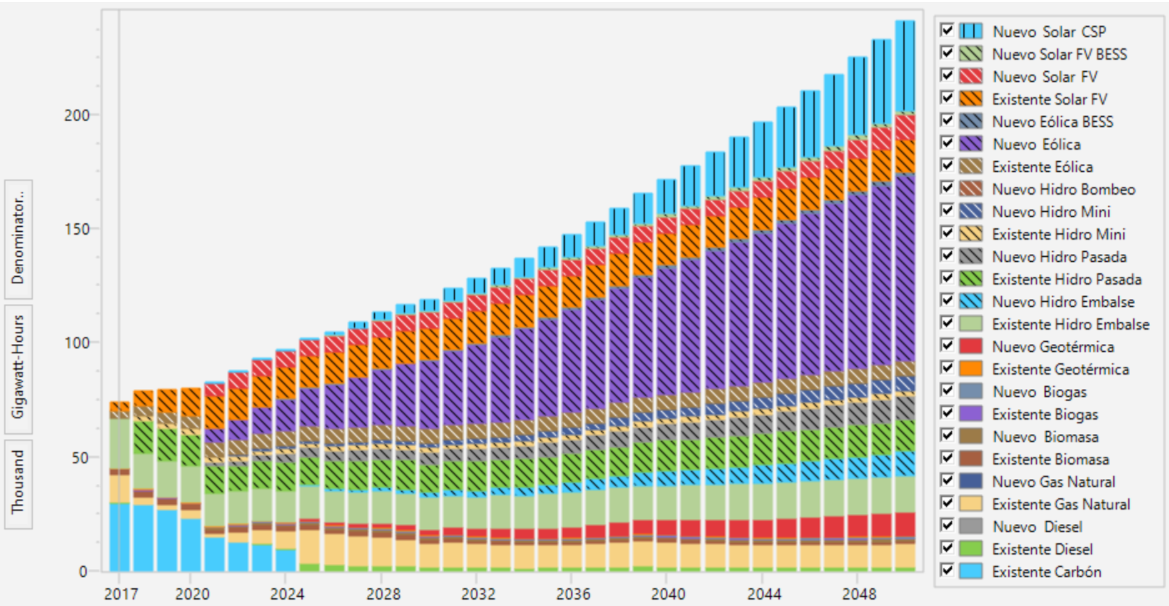


FIGURE A7

Generation output: Reference future AM Heavy Tax

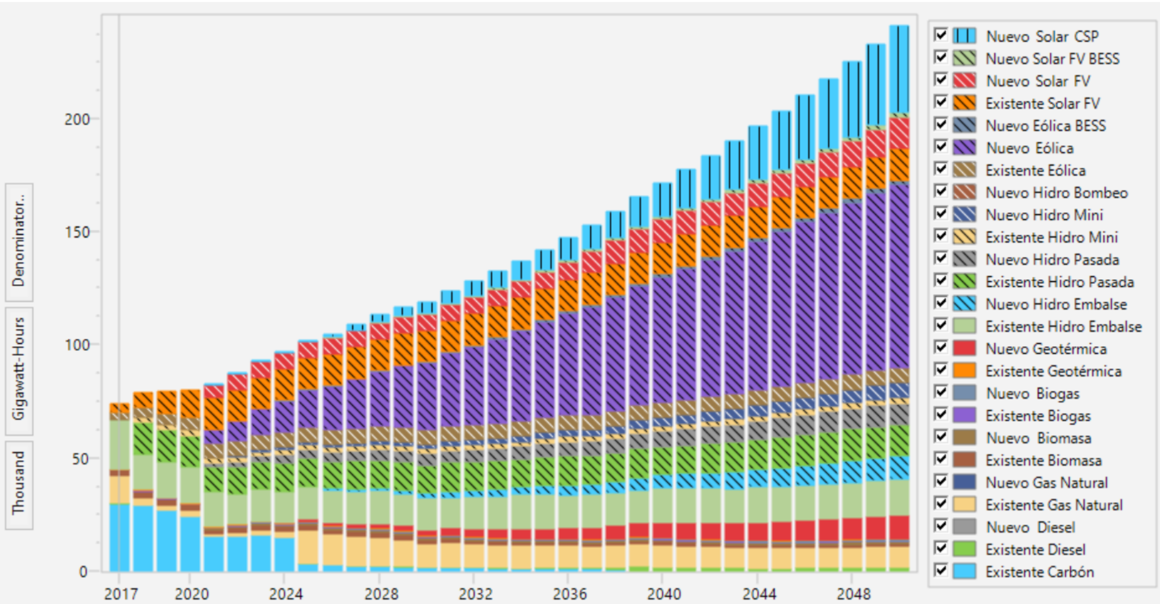


FIGURE A8

Generation output: Red future AM 2025

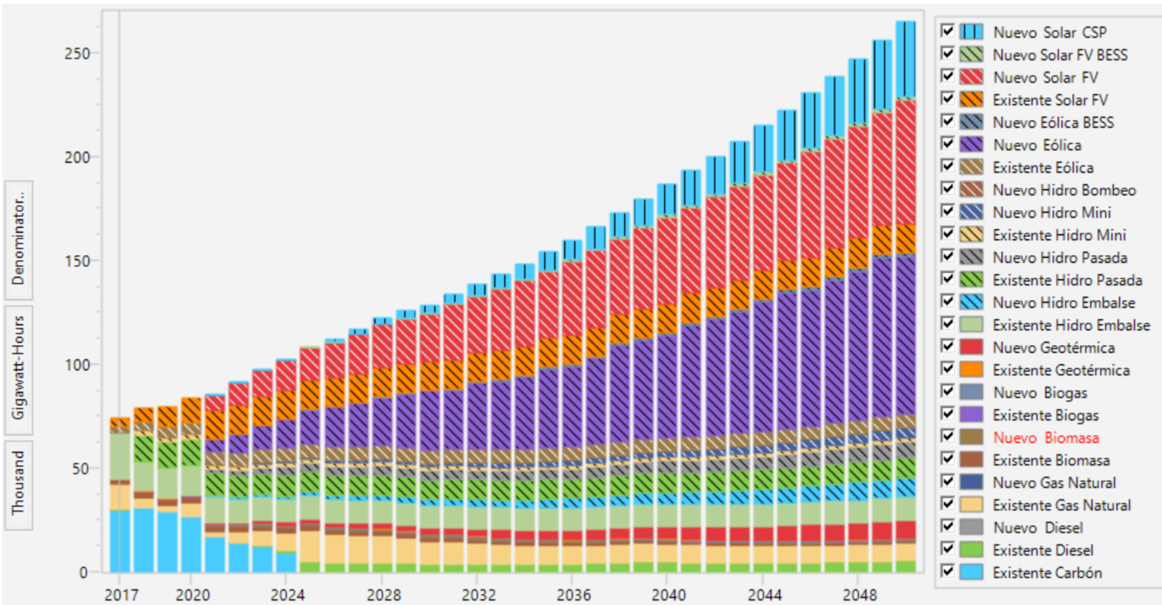


FIGURE A9

Generation output: Red future AM Heavy Tax

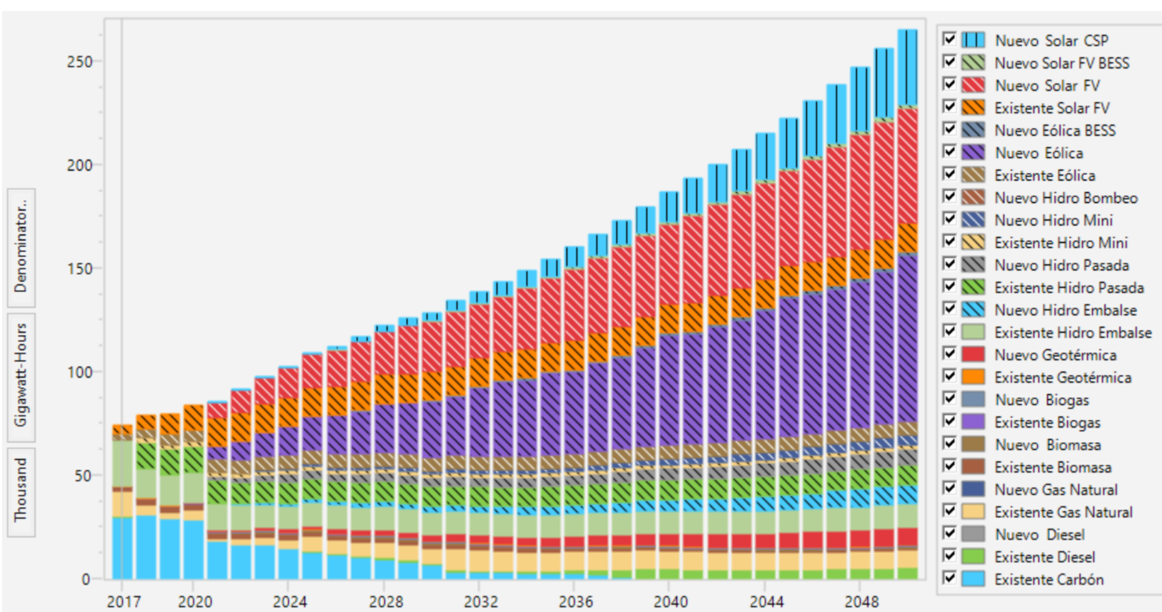


FIGURE A10

Generation output: Green future AM 2025

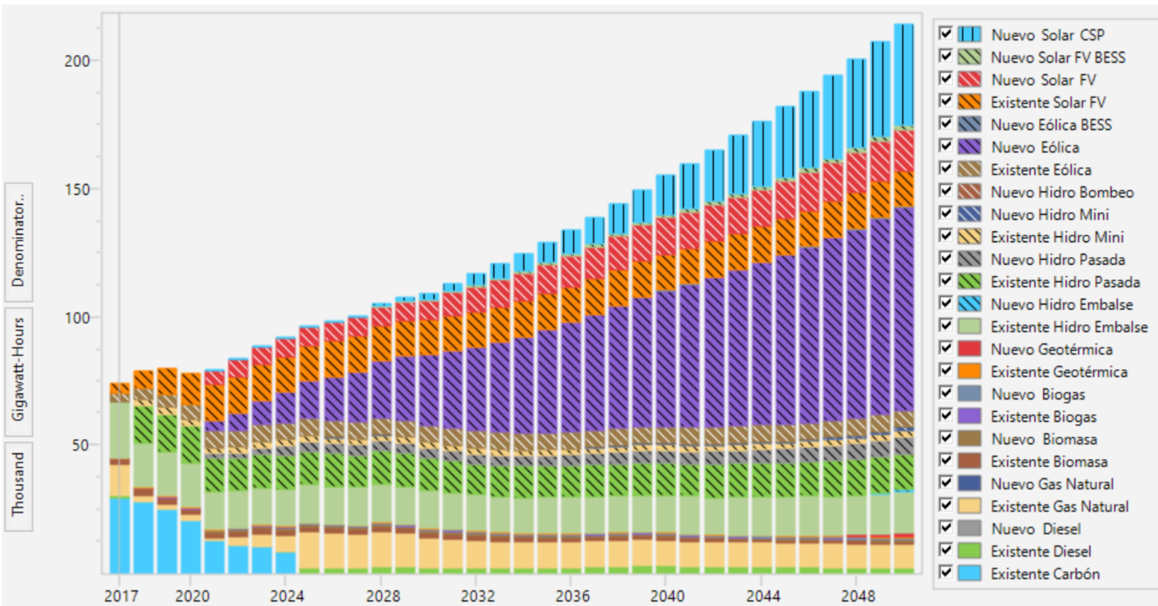
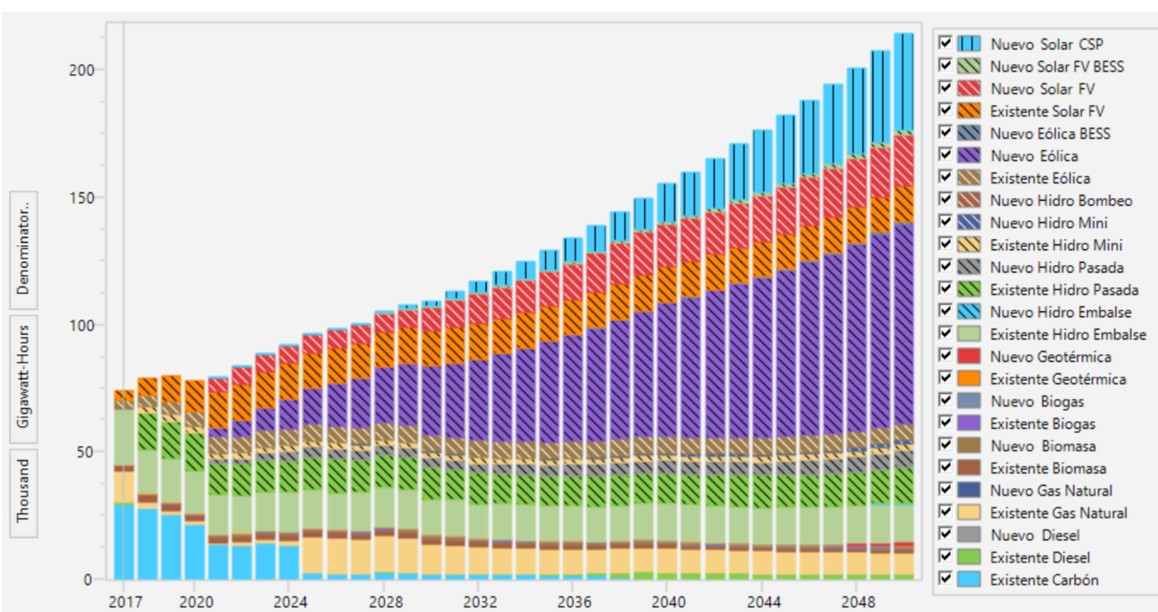


FIGURE A11

Generation output: Green future AM Heavy Tax



Appendix 3: Marginal abatement cost curves for other futures

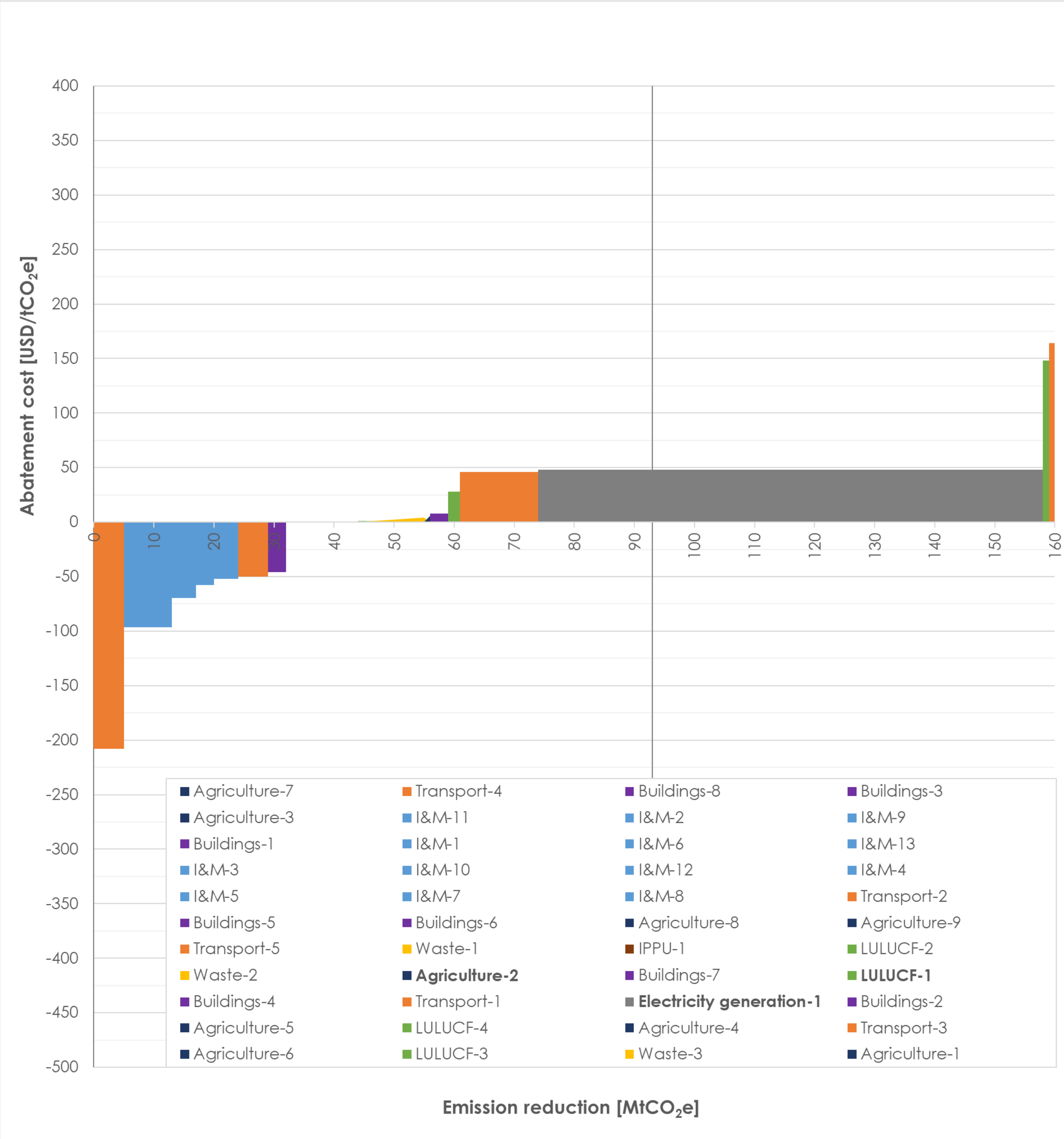
The MACCs presented in this appendix follow the same legend presented in Table 15.

MACC for the Green future

In the following figure the MACC for the Green future is presented in Figure A13. The main difference observed with the Reference future is that the decommissioning of coal power plants in this case, at US$48/t$CO_2$e, has a lower cost in comparison with the implementation of solar water heaters on public hospitals (Buildings-2 measure), where in the Reference future this latter measure was cheaper than the decommissioning of coal power plants. Likewise, in the Green future the implementation of porcine biodigesters (Agriculture-2) is more expensive than composting plants (Waste-2), and native forest management—increase in hectares—is more economical than the implementation of solar PV on public buildings (Buildings-4), which moves these last two measures earlier on the curve by one stage each.

FIGURE A12

MACC for the 2020–30 period for the Green future



MACC for the Red future

A MACC for the Red future is presented in Figure A14. In this case the main difference with the Reference future is the change in cost of the decommissioning of coal power plants, at US$143/t$CO_2$e, which moves this measure behind the holistic management of cattle (Agriculture-5) on the curve. Similarly, the implementation of porcine biodigesters (Agriculture-2) changes from US$3.6/t$CO_2$e in the Reference future to US$0.7/t$CO_2$e in the Red future, which makes this measure more economical than the increase in protected areas (LULUCF-2) and advances it one stage on the curve.

FIGURE A13

MACC for the 2020–30 period for the Red future