Climate Action Teams
International Greenhouse Gas Mitigation

MODELLING EXERCISE FOR CHILE
PROGRESS REPORT[1]

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Executive summary

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 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 Team'. The mitigation outcomes are 'credited' to the partner countries and can potentially contribute to their NDC commitments.

As part of the technical work in Chile a modelling team from the Global Change Center of the Catholic University of Chile has built open-access models to explore mitigation opportunities beyond Chile's NDC. This report presents the results of the developed models and the analyzed mitigation scenarios.

A prospective emissions model was developed that covers all sectors included in the National GHG Inventory (Energy, including electricity generation and the energy demand sectors - transport, industry and mining, and buildings-; waste; IPPU; agriculture and LULUCF)

The modeling was carried out based on the combination of scenarios and futures, where these two concepts are defined as follows:

- Futures: They represent a trajectory of exogenous parameters that represent a possible set of conditions that could facilitate (or hinder) the mitigation strategies.
- Mitigation scenarios: They represent different mitigation strategies implemented at a national level, each strategy considers a set of mitigation measures and their specific level of implementation.

Three futures and three mitigation scenarios were analyzed, as described in the next tables:

Table 0-1: Differences in the futures selected

Group of variables	Futures		
	Red	Reference	Green
Global GDP growth, commodities prices and National Production Level	High Global GDP, commodities prices and National Production Level	Medium Global GDP, commodities prices and National Production Level	Low Global GDP, commodities prices and National Production Level
Climate Variables (representative decade)	Drought (2010-2019)	Medium (1990-1999)	Wet (1980-1989)
Green technology prices	High	Medium	Low
Climate Action	Delayed	Conventional	Early and active

SOURCE: AUTHORS

Table 0-2: Differences in the mitigation scenarios selected

Mitigation scenarios		
Current Policies (CP)	Intermediate Mitigation (IM)	Accelerated Mitigation (AM)
Expected emissions under current regulation and incentives (12 Measures)	Considers the implementation of all mitigation measures analyzed to develop the NDC commitment (41 measures)	Considers enhanced mitigation measures in order to overachieve the Carbon Budget (60 measures)

SOURCE: AUTHORS

Figure 0-1 shows the total aggregated emissions for the Agriculture, Energy, IPPU, Transport and Waste sectors for the three mitigation scenarios for the reference future, where the CP and IM scenarios shows an increase on the emissions by 2030, and the only scenario that achieves an absolute decrease on the emissions is the AM Scenario, also is the only scenario that has its peak of emissions before 2025[2].

[2] Chile's NDC includes a goal of emissions peak in 2025.

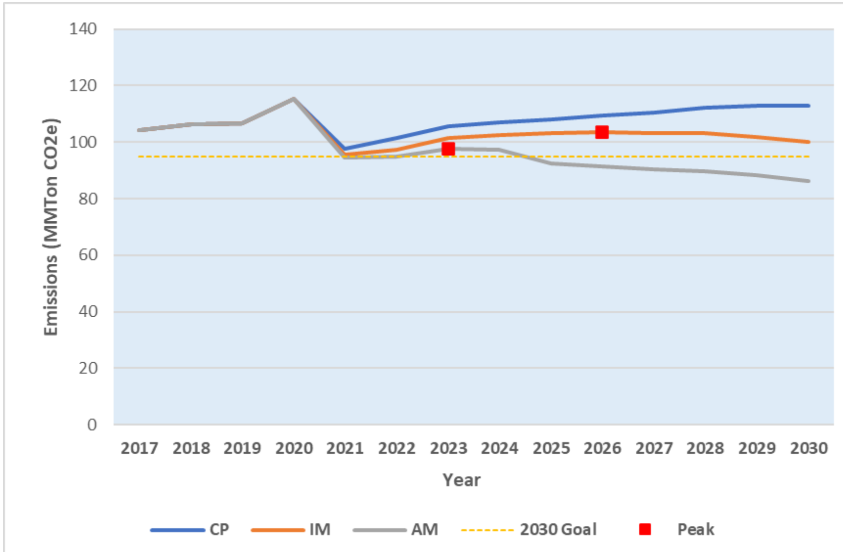

Figure 0-1 Total aggregated emissions of the carbon budget sectors in three different scenarios in the period 2020-2030

SOURCE: AUTHORS

Complementary in the Figure 0-2 the trajectories of the cumulated emissions during the 2020-2030 are shown. In this Figure, it is shown that the IM scenario goes over, for a small margin, over the goal budget, while the AM scenario overachieve the goal by some margin.

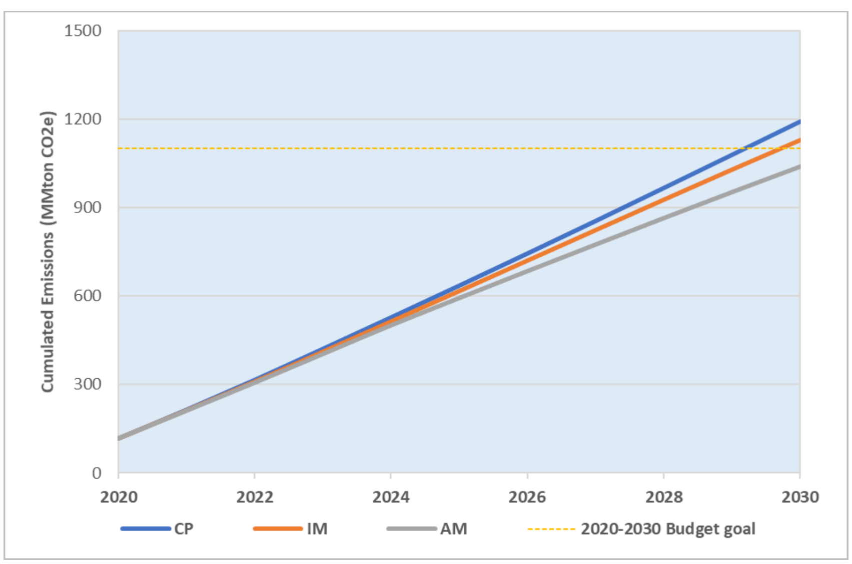

Figure 0-2 Cumulated emissions in three different scenarios for the period 2020-2030, and comparison with budget goal

SOURCE: AUTHORS

Figure 0-3 shows the emissions of LULUCF for the different scenarios for the reference future, because LULUCF has net captures and independent goals on the NDC. This result show that for the 2021-2030 period the actions defined in the NDC leaves little room for further captures on the LULUCF sector in Chile.

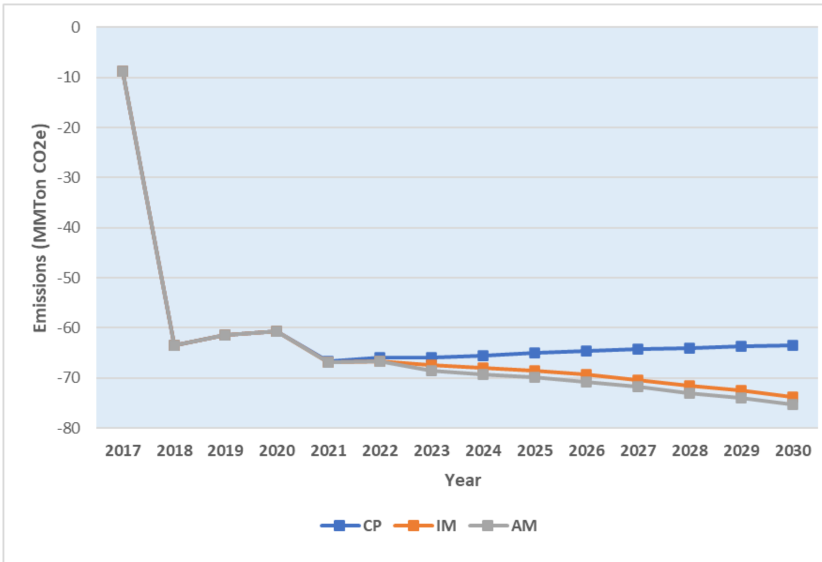

Figure 0-3 Total emissions of the LULUCF sector in three different scenarios in the period 2020-2030.
SOURCE: AUTHORS

In the NDC Chile commits to a GHG emission budget not exceeding 1,100 MMton CO_2eq between 2020 and 2030, with a GHG emissions maximum (peak) by 2025, and a GHG emissions level of 95 MMton CO_2eq by 2030 (Gobierno de Chile, 2020). From Figure 0-4 it can be observed that only in the AM, that is, where additional measures to the Chilean NDC are considered, the commitment to emit below 1,100 MMTon CO_{2eq} between 2020 and 2030 is fulfilled. An analysis of GHG emissions in 2030 (Figure 0-5) shows something very similar where only in the AM scenario and under the three different futures the target of emitting 95 MM tons CO_{2eq} in 2030 is achieved.

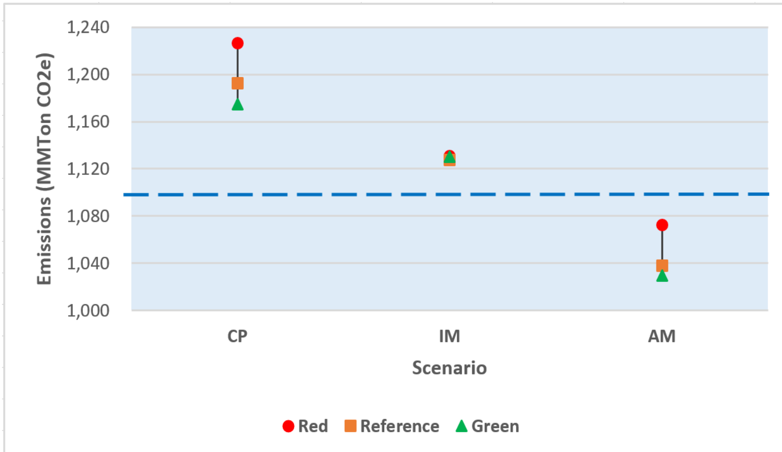

Figure 0-4 Total absolute comulative emissions emitted between 2020 and 2030 for each scenario and each future

SOURCE: AUTHORS

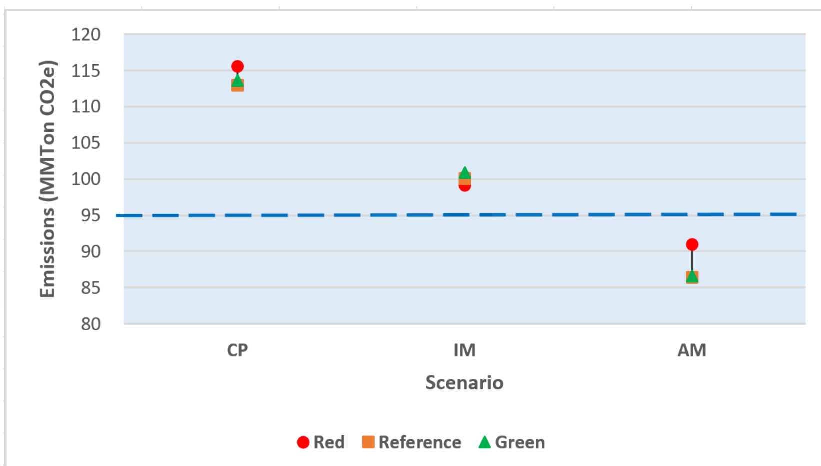

Figure 0-5 Forecast of absolute emissions in the year 2030 for each scenario and for each future

SOURCE: AUTHORS

For the study of mitigation costs, each of the mitigation actions was characterized by its abatement potential and the average cost of mitigation of one tCO_{2eq}. The following definitions were 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 in emissions of other sectors (e.g., caused by changes on electricity or wood demand). This difference applies only to the period 2020-2030 which coincides with the NDC carbon budget commitment.

- Average cost of mitigation: Correspond to the discounted costs of investments, operating costs, and savings, divided by the total mitigation potential on the period 2020-2050. It is important to notice 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 don't occur at the same time. For example, this helps a better evaluation of an action with an important investment and mitigation that occurs in the future.

The following table shows the mitigation abatement for the 2020-2030 period by sector for the reference future.

Table 0-3 Mitigation abatement for the 2020-2030 by sector for the Reference Future

Sector	Abatement potential IM vs CP [MMtCO_{2eq}]	Abatement potential AM vs IM [MMtCO_{2eq}]	Total abatement potential for 2020-2030 [MMtCO_{2eq}]
Electricity generation	28	65	92
Transport	8	16	24
I&M	16	3	20
Buildings	5	2	7
Waste	4	-0,03	4
IPPU	-	6	6
Agriculture	2	4	5
LULUCF	-	11	11
TOTAL	**63**	**106**	**169**

SOURCE: AUTHORS

Figure 0-6 shows the MACC Curve associated with the AM scenario in the reference future. It is observed that 169 M tCO_{2eq} could be mitigated in the period 2020-2030 if every mitigation action is implemented, and that 34 M tCO_{2eq} has a mitigation cost below 0 USD/tCO_{2eq}, and 61 M tCO_{2eq} could be mitigated with a cost under 40 USD/tCO_{2eq}.

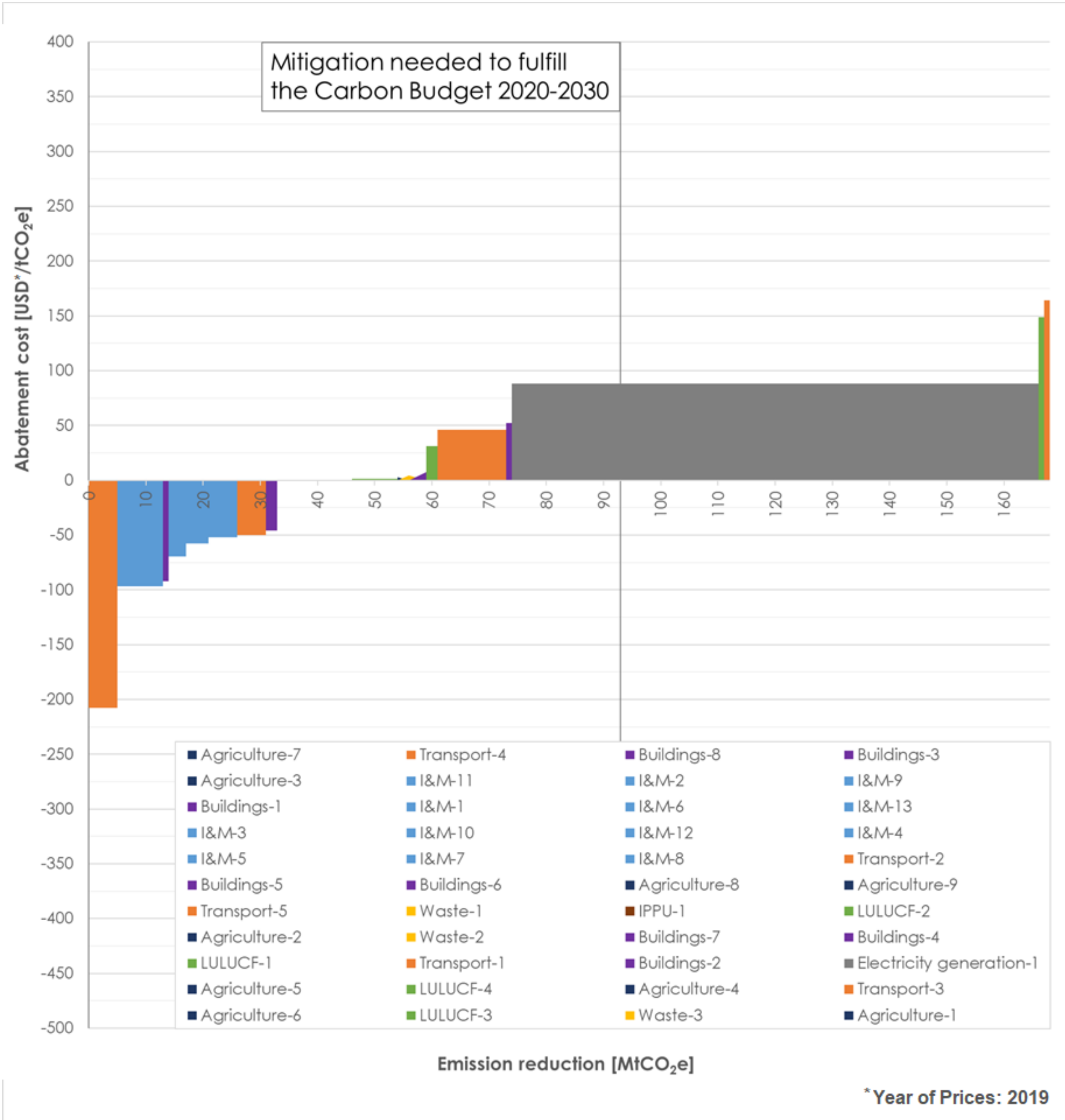

Figure 0-6 MACC curve for the 2020-2030 period for the reference future

SOURCE: AUTHORS

The current work and results represent a first step which was ambitious to develop and integrate a prospective model for the GHG emissions in Chile, which focus on the near-term emissions, but which extends with projections to the midcentury. Further work is needed in this model to analyse other paths of actions considering both new actions and new level of ambitious in the current actions, also the level of integration of the models can be improved aswell as the generation of new mitigation scenarios which could combine diferente actions packages. During the presentations of the results of the current work to Climate Action Teams partners and stakeholders in Chile some comments were made that could enable better results.

Finally, it is relevant to consider these results as a preliminary 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 baseline scenario, 62 MtCO2e 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 MtCO2e could be obtained at a marginal cost of less than USD 50/tCO2e. In addition, estimates of the capital cost required to achieve this 70% is about USD 2.8 billion.

Resumen Ejecutivo

La iniciativa Climate Action Teams (CAT) es un mecanismo que apoya las transferencias internacionales de recursos para la mitigación del clima. CAT funciona a través de acuerdos de gobierno a gobierno basados en resultados de mitigación verificados más allá de los compromisos de la NDC de un país (el anfitrión) a cambio de apoyo financiero y tecnológico de uno o más países (los socios) que forman parte del "Climate Action Team". Los resultados de mitigación se "acreditan" a los países socios y pueden contribuir a sus compromisos de NDC.

Como parte del trabajo técnico en Chile, un equipo de modelización del Centro de Cambio Global de la Universidad Católica de Chile ha construido modelos de libre acceso para explorar las oportunidades de mitigación más allá de la NDC de Chile. Este informe presenta los resultados de los modelos desarrollados y los escenarios de mitigación analizados.

Se ha desarrollado un modelo prospectivo de emisiones que cubre todos los sectores incluidos en el Inventario Nacional de GEI (Energía, incluyendo la generación de electricidad y los sectores de demanda energética -transporte, industria y minería, y edificios-; residuos; IPPU; agricultura y LULUCF).

La modelización se realizó a partir de la combinación de escenarios y futuros, donde estos dos conceptos se definen como sigue:

- Futuros: Representan una trayectoria de parámetros exógenos que representan un posible conjunto de condiciones que podrían facilitar (o dificultar) las estrategias de mitigación.
- Escenarios de mitigación: Representan diferentes estrategias de mitigación implementadas a nivel nacional, cada estrategia considera un conjunto de medidas de mitigación y su nivel específico de implementación.

Se analizaron tres futuros y tres escenarios de mitigación, como se describe en las siguientes tablas:

Tabla 0-1: Diferencias en los futuros seleccionados

Grupo de variables	Futures		
	Rojo	Referencia	Verde
Crecimiento del PIB mundial, precios de las materias primas y nivel de producción nacional	PIB mundial, precios de las materias primas y nivel de producción nacional alto	PIB mundial, precios de las materias primas y nivel de producción nacional medio	PIB mundial, precios de las materias primas y nivel de producción nacional bajo
Variables climáticas (década representativa)	Sequía (2010-2019)	Medio (1990-1999)	Húmedo (1980-1989)
Precios de tecnologías verdes	Alto	Medium	Low
Acción Climática	Retrasada	Convencional	Temprana y activa

SOURCE: AUTHORS

Tabla 0-2: Diferencias en lose scenarios de mitigación seleccionados

Escenarios de Mitifación		
Políticas Actuales (CP)	Mitigación Intermedia (IM)	Mitigación Acelerada (AM)
Emisiones esperadas con la normativa y los incentivos actuales (12 medidas)	Considera la aplicación de todas las medidas de mitigación analizadas para llevar a cabo el compromiso NDC (41 medidas)	Considera medidas de mitigación reforzadas para sobre cumplir el Presupuesto de Carbono (60 medidas)

SOURCE: AUTHORS

La Figura 0-1 muestra las emisiones totales agregadas de los sectores de Agricultura, Energía, IPPU, Transporte y Residuos para los tres escenarios de mitigación en el futuro de referencia, donde los escenarios CP e IM muestran un aumento de las emisiones para 2030, y el único escenario que logra una disminución absoluta de las emisiones es el escenario AM, el que además es el único escenario que tiene su peak de emisiones antes de 2025[3].

[3] La NDC de Chile incluye un peak objetivo de emisiones en 2025.

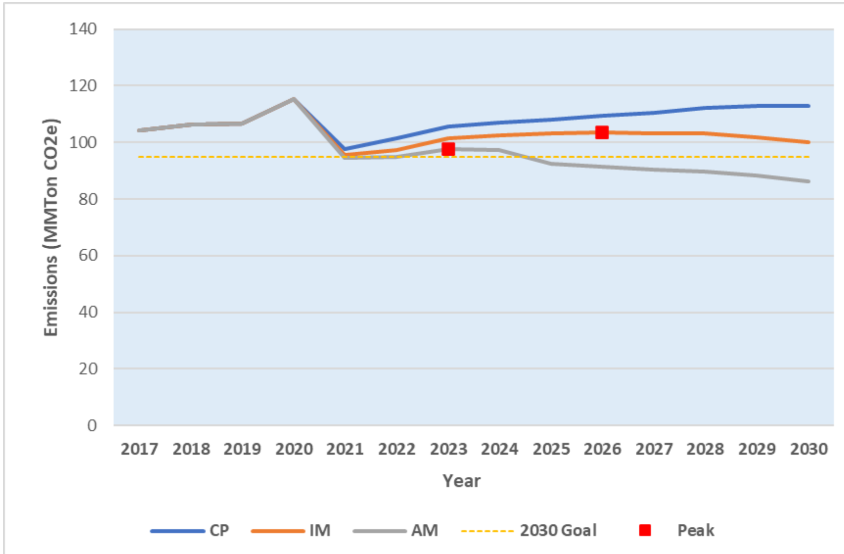

Figura 0-1 Emisiones totales agregadas de los sectores del presupuesto de carbono para tres escenarios diferentes en el periodo 2020-2030

SOURCE: AUTHORS

De manera complementaria, en la Figura 0-2 se muestran las trayectorias de las emisiones acumuladas durante el periodo 2020-2030. En esta figura, se muestra que el escenario IM sobrepasa, por un pequeño margen, el presupuesto objetivo, mientras que el escenario AM sobrepasa el objetivo por cierto margen.

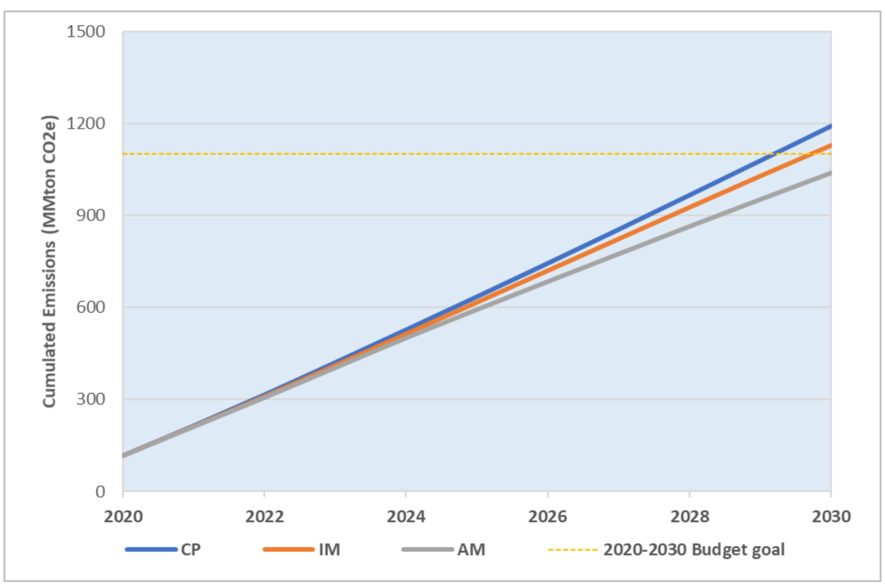

Figure 0-2 Emisiones acumuladas en tres escenarios diferentes para el periodo 2020-2030, y comparación con el objetivo presupuestario.
SOURCE: AUTHORS

La Figura 0-3 muestra las emisiones del sector LULUCF para los diferentes escenarios en el futuro de referencia, dado que el sector LULUCF tiene capturas netas y objetivos independientes de la NDC. Este resultado muestra que para el periodo 2021-2030 las acciones definidas en la NDC dejan poco margen para nuevas capturas en este sector en Chile.

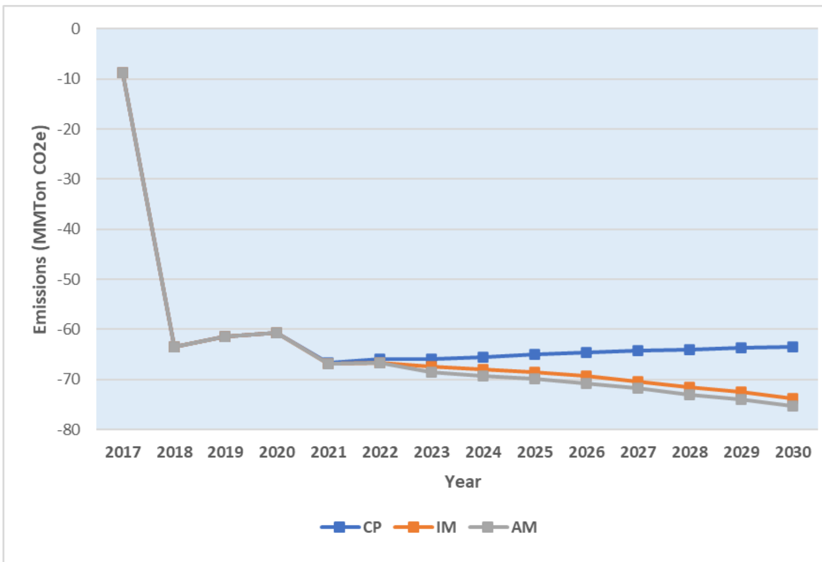

Figura 0-3 Emisiones totales del sector LULUCF en tres escenarios diferentes en el periodo 2020-2030.
SOURCE: AUTHORS

En su NDC, Chile se compromete a un presupuesto de emisiones de GEI que no supere los 1.100 MMton CO2eq entre 2020 y 2030, con un máximo de emisiones de GEI (peack) para 2025, y un nivel de emisiones de GEI de 95 MMton CO2eq para 2030 (Gobierno de Chile, 2020). En la Figura 0-4 se observa que sólo en el AM, es decir, donde se consideran medidas adicionales a la NDC chilena, se cumple el compromiso de emitir por debajo de 1.100 MMTon CO2eq entre 2020 y 2030. Un análisis de las emisiones de GEI en 2030 (Figura 0-5) muestra algo muy similar, donde sólo en el escenario AM y bajo los tres futuros diferentes se logra el objetivo de emitir 95 MM tonsde CO2eq en 2030.

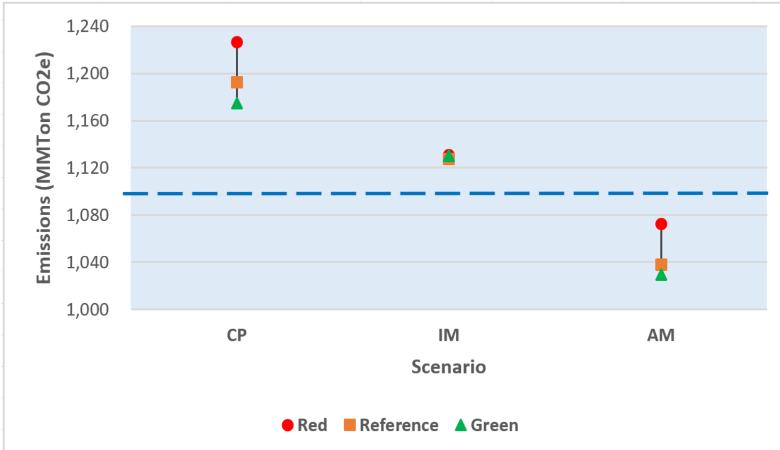

Figura 0-4 Emisiones acumuladas totales emitidas entre 2020 y 2030 para cada escenario y cada futuro

SOURCE: AUTHORS

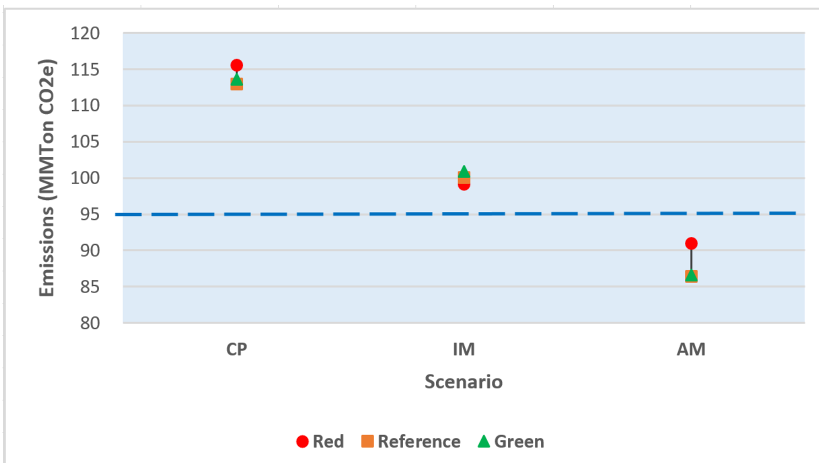

Figura 0-5 Pronóstico de emisiones absolutas en el año 2030 para cada escenario y para cada futuro

SOURCE: AUTHORS

Para el estudio de los costos de mitigación, cada una de las acciones se caracterizó por su potencial de reducción y el costo medio de mitigación de una tCO2eq. Se utilizaron las siguientes definiciones:

- Potencial de mitigación: Corresponde a la diferencia de emisiones entre el escenario CP y un escenario con sólo la acción de mitigación, considerando el impacto directo en las emisiones (en el mismo sector en el que se aplica la acción de mitigación) y el impacto indirecto en las emisiones de otros sectores (por ejemplo, causado por los cambios en la demanda de electricidad o madera). Esta diferencia se aplica únicamente al periodo 2020-2030, que coincide con el compromiso del presupuesto de carbono de la NDC.

- Costo medio de mitigación: Corresponde a los costos descontados de las inversiones, los costes operativos y los ahorros, divididos por el potencial total de mitigación en el periodo 2020-2050. Es importante señalar que el costo medio tiene un horizonte diferente para su cálculo que el potencial de reducción. Esto corresponde a una decisión metodológica para representar mejor los costos medios reales de las acciones de mitigación cuando el costo y las reducciones de GEI no se producen al mismo tiempo. Por ejemplo, esto ayuda a una mejor evaluación de una acción con una importante inversión y mitigación que se produce en el futuro.

La siguiente tabla muestra la mitigación para el período 2020-2030 por sector para el futuro de referencia.

Tabla 0-3 Mitigación por sector para el Futuro de Referencia (2020-2030)

Sector	Potencial de reducción IM vs CP [MMtCO2eq]	Potencial de reducción AM vs IM [MMtCO2eq]	Potencial de reducción total para 2020-2030 [MMtCO2eq].
Generación de electricidad	28	65	92
Transporte	8	16	24
I&M	16	3	20
Construcción	5	2	7
Residuos	4	-0,03	4
IPPU	-	6	6
Agricultura	2	4	5
LULUCF	-	11	11
TOTAL	**63**	**106**	**169**

SOURCE: AUTHORS

La Figura 0-6 muestra la curva MACC asociada al escenario AM en el futuro de referencia. Se observa que podrían mitigarse 169 M tCO2eq en el periodo 2020-2030 si se aplican todas las medidas de mitigación, y que 34 M tCO2eq tienen un costo de mitigación inferior a 0 USD/tCO2eq, y 61 M tCO2eq que podrían mitigarse con un coste inferior a 40 USD/tCO2eq.

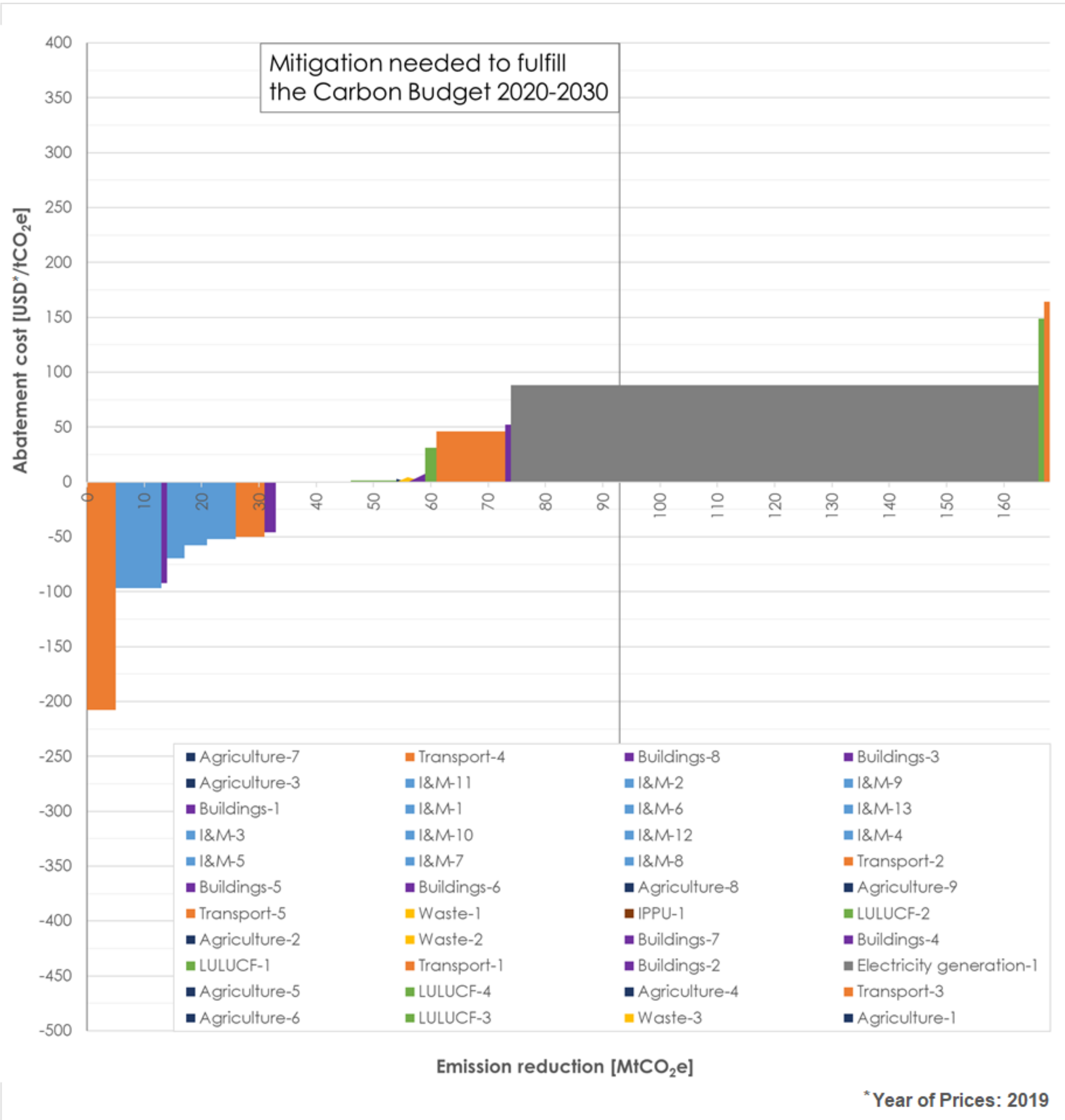

Figura 0-6 Curva MACC periodo 2020-2030 para el futuro de referencia

SOURCE: AUTHORS

El presente trabajo y sus resultados representan un primer paso que tuvo la ambición de desarrollar e integrar un modelo prospectivo para las emisiones de GEI en Chile, el cual se enfoca en las emisiones de corto plazo, pero que se extiende con proyecciones hasta mediados de siglo. Es necesario seguir trabajando en este modelo para analizar otras vías de acción considerando tanto nuevas acciones como nuevos niveles de ambición en las acciones actuals. También se puede mejorar el nivel de integración de los modelos, así como la generación de nuevos escenarios de mitigación que puedan combinar diferentes paquetes de acciones. Durante las presentaciones de los resultados del trabajo actual a los partners de la iniciativa Climate Action Teams y a las partes interesadas en Chile, se hicieron algunos comentarios que podrían permitir mejorar los resultados.

Finalmente, es relevante considerar estos resultados como una aproximación preliminar del potencial de mitigación y sus costos, ya que la implementación de cualquiera de las acciones presentadas podría necesitar todo un conjunto de análisis para determinar una estimación más precisa. No obstante, algunos de los resultados son de especial interés y la estructura del modelo puede utilizarse para algunas investigaciones preliminares. Por ejemplo, en el escenario de referencia, se estima que hay 62 MtCO2e disponibles más allá del compromiso presupuestario. Los resultados preliminares de nuevas ejecuciones basadas en diferentes precios del carbono, sugieren que el 70% de los 62 MtCO2e se podrían obtener a un costo marginal inferior a 50 USD/tCO2e. Además, las estimaciones del costo de capital necesario para alcanzar este 70% es de unos 2.800 millones de dólares.

1. Introduction

The Climate Action Teams 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 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 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 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 GHG Neutrality by 2050
- GHG emission budget not exceeding 1,100 $MtCO_{2eq}$ between 2020 and 2030 (excluding LULUCF), with a GHG emissions maximum (peak) by 2025, and a GHG emissions level of 95 $MtCO_{2eq}$ by 2030.
- Reduce total black carbon emissions by at least 25% by 2030, with respect to 2016 levels.
- Achieving the sustainable management and recovery of 200,000 hectares of native forests, representing GHG captures of around 0.9 to 1.2 $MtCO_{2eq}$ annually by 2030.
- Afforesting 200,000 hectares, of which at least 100,000 hectares will comprise permanent forest cover, with at least 70,000 hectares of native species, representing captures of between 3.0 and 3.4 $MtCO_{2eq}$ annually by 2030.

- Reduce 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 2001-2013.
- Others (not quantified or not directly related with mitigation)

As part of the technical work in Chile a modelling team from the Global Change Center of the Catholic University of Chile has built open-access models to explore mitigation opportunities beyond the NDC in more depth. 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.

2. Objectives

The main objectives of this report are:

- Develop GHG emission models that cover all the sectors identified at the GHG National Inventories.
- Analyze mitigation actions considering the ones evaluated for the Chilean NDC and additional.
- 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.

3. Model Description

This initial effort has focused on developing a set of sectoral GHGs emission models, that represent all the national emission of GHG inclluded on the GHG´s national inventories. For the modelling, 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 their analysis on the changes that should occur in order to reduce emissions (technologies and behaviors), rather than the specific policies needed to get those changes, the only exception are the policies that are currently in place (for example, the carbon tax on electricity generation).

The GHG´s national inventories identify 5 emission sectors: 1. Energy, 2. Industrial Processes and Product Use (IPPU), 3. Agriculture, 4. Land Use Land-Use Change and Forestry (LULUCF or UTCUTS in spanish) and 5. Waste. As it can be seen in the Figure 3-1, LULUCF has significant net captures (-64MtonCO_{2eq} by 2018), this is because despite that the sector has shown some level of degradation related to forest fires and woodfire extraction, the forestry plantations and the native forest under conservation are still growing with respect to the year 1990. The other 4 sectors are net emitters (112.3 MtonCO_{2eq} by 2018), the main one is the Energy Sector (87MtonCO2_{eq} by 2018), followed by Agriculture (11.8 MtonCO_{2eq}), Waste (7 MtonCO_{2eq} by 2018) and IPPU (6.6 MtonCO_{2eq} by 2018).

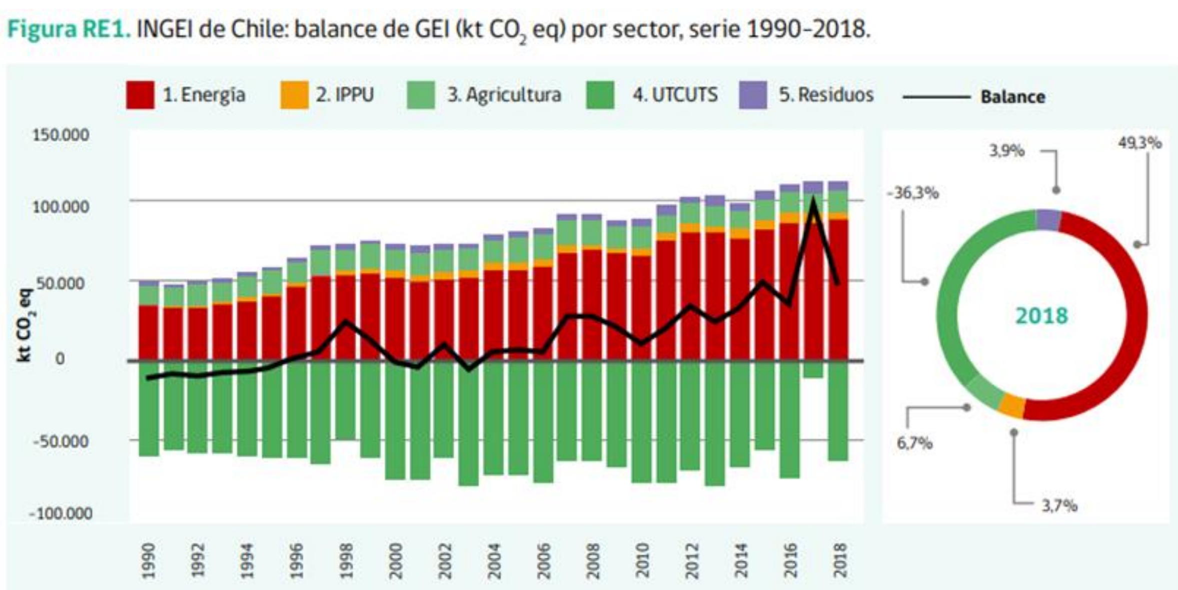

Figure 3-1 Historical GHG's Emissions of Chile by Sector

SOURCE: (MINISTERIO DEL MEDIO AMBIENTE DE CHILE, 2021)

From the net emitter sectors (112.3 $MtonCO_{2eq}$ by 2018), the energy sector is the main contributor to GHGs emissions in Chile due to the intensive use of fossil fuels to produce energy, this sector can be distributed in sub-sectors: Electricity Generation (29% of the sector emissions), Transport (25% of the sector emissions), Industry & Mining (14% of the sector emissions) and Buildings (7% of the sector emissions). The second sector in terms of emissions is Agriculture (10.5%), followed by Waste (6.2%) and Industrial Processes & Product Use (IPPU) (5.9%).

Taking into account the relative importance of the different sectors and sub-sector were developed the following models:

- Energy: Electricity Generation
- Energy: Transport
- Energy: Industry & Mining
- Energy: Buildings
- IPPU
- Agriculture
- LULUCF
- Waste

The energy models were built in LEAP[4] and the other sectors were developed in Analytica[5], with both software it is possible to explore and run the models with free accounts. The models were developed considering the same information used by the government in 2019 (Palma Behnke R., C. Barría, K. Basoa, D. Benavente, C. Benavides, B. et al., 2020), but updating some parameters, in order to use the best current public information available, also the analysis considers a different methodology to address the futures and scenarios, that is described in the following subsection in contrast with the work of the government that considered only one mitigation scenario without addressing uncertainty.

3.1. Futures and Scenarios developed

For the purpose of this analysis, it is necessary to address the future conditions that would drive GHG´s emissions. The different sources of variability on the emissions can be exogenous (generated at international level or related with climate conditions) or endogenous (generated from the results of other parts of the model or by the level of implementations of the mitigation actions). Acknowledging this documents

[4] https://leap.sei.org/
[5] https://lumina.com/

developed 2 categories of pathways:

- Futures: They represent a trajectory of exogenous parameters that represent a possible set of conditions that could facilitate (or difficultate) the mitigation strategies.
- Scenarios: They represent different mitigation strategies implemented at a national level, each strategy considers a set of mitigation measures and their specific level of implementation.

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

- 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 the electricity generation and the intensity of the forest wildfires.
- Clean technologies costs: The level of mitigation at world level will impact on the prices of the different clean technologies.
- Climate action in Chile: The level of commitment with climate action and efficiency of the government, 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 set of conditions project GHG's emissions. For the current analysis 3 futures were considered, the first one is the Reference, that considers that all drivers will show their respective expected value, but in order to have a sensitivity analysis, were developed a Green and Red futures, the following table (Table 3-1) presents the differences:

Table 3-1: Differences in the futures selected.

Group of variables	Futures		
	Red	Reference	Green
Chinese GDP growth, commodities prices and National Production Level	High: Chinese GDP, commodities prices and National Production Level	Medium Chinese GDP, commodities prices and National Production Level	Low Chinese GDP, commodities prices and National Production Level
Climate Variables (representative decade)	Drought (2010-2019)	Medium (1990-1999)	Wet (1980-1989)
Green technology prices	High	Medium	Low
Climate Action	Delayed	Conventional	Early and active

SOURCE: SELFMADE

For the mitigation strategies, 3 scenarios were analyzed[6]:

- Current Policies (CP): Expected emissions under current regulation and incentives. (12 Measures)
- Intermediate Mitigation (IM)[7] : Considers the implementation of all mitigation measures analyzed to develop the NDC commitment. (41 measures)

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[6] The detail of the mitigation measures considered in each sector and scenario is presented in the following sections.

[7] The Current Policies is different from the Intermediate Mitigation, because even if Chile analyzed a set of possible mitigation policies in order to achieve the NDC commitment, not all of these policies are currently in place.

- Accelerated Mitigation (AM): Considers enhanced mitigation measures in order to overachieve the Carbon Budget. (60 measures)

The following sections present a brief explanation of the different models developed, also the models are available to be explored in depth by anyone.

3.2. Energy: Electricity Generation

The Electricity Generation covers power plants and the electric grid including the expansion needed to meet a specified electrical demand. Therefore, modelling this sector simulates the operation of the already existing power plants and the planning of installation of new plants. These questions are answered by the Low Emissions Analysis Platform (LEAP) model, which minimizes the cost of the system given the constraints of the decarbonization policies.

The Electric Generation and Electric Distribution modules from the LEAP platform are used to calculate this sector's emissions. These modules let LEAP act as an optimization tool focused on the determination of 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 that links all the generation and demand of the system, where the 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 LEAP limitations, 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, when they are expected to play an important role beyond 2030. Instead, the value of these simulations resides in allowing our team to analyze the differences of costs and benefits associated to different policies, therefore linking actions and policies to CO_2 mitigations in the future.

The scope of this model requires a huge amount of data from different sources to simulate it accurately. Such inputs and sources are as followsThe scope of this model requires a huge amount of data from different sources to simulate it accurately. Such inputs and sources are as follows:

- Installed capacity (CNE[8]).
- Investment, operative and fuel costs projections (PELP[9]).
- Electric demand daily shape (CEN[10]).
- Wind and solar daily capacity factor shape (CEN).
- Capacity factor for each technology (PELP).
- Thermal efficiency for thermal power plants (PELP).

[8] Acronym for the spanish traduction of the National Energy Commission
[9] Acronym for the spanish traduction of the Long Term Energetic Planification
[10] Acronym for the spanish traduction of the National Electrical Coordinator

- Threshold for new capacity added (PELP).
- Coal phase out schedule (CEN).
- Carbon tax (PELP).
- Electric demand projection.
- Transmission loss factor.
- Discount rate.
- Power plant lifetime.

The LEAP model was calibrated and tested with data from the Ministry of Energy and their Long-Term Energetic Planning 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 annexes.

The Chilean approach to address CO_2 emissions in the electricity sector is to phase out coal powered power plants. The Current Policies (CP) and Intermediate Mitigation (IM) scenarios correspond to a full decarbonization of the grid by 2040. Two Accelerated Mitigation scenarios (AM) were analyzed, the first corresponds to the full phase-out of coal power plants by 2025 (AM 2025) and the second to the 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 base load previously provided by coal, in the CP and IM scenarios, is replaced mainly by a mix of CSP, new hydropower and geothermal power plants. On the other hand, the loss of base load in the AM 2025 scenario is too quick to be immediately replaced by renewable energy. Therefore, the already existing gas power plants need to temporarily increase their share of generation while the system adjusts. Something similar happens in the AM Heavy Tax scenario, but this one 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 fossil fuel cost.

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

It is important to remark that the technologies that replace coal are not fixed scenario by scenario, instead they 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 each other and therefore directly affect the nature of the decisions made by the model.

Table 3-2 Mitigation actions for the electricity generation sector

Sector: Electricity Generation			
Action	CP / IM	AM 2025	AM Heavy Tax
Coal Phase-Out	44% of the coal power plants by 2025 60% of the coal power plants by 2030 100% of the coal power plants by 2040	100% of the coal power plants by 2025	44% of the coal power plants by 2025 60% of the coal power plants by 2030 100% of the coal power plants by 2040
Carbon Tax	5 USD/TonCO_2 until 2030 From 5 to 32,5 USD/TonCO_2 between 2030 and 2050	5 USD/TonCO_2 until 2030 From 5 to 32,5 USD/TonCO_2 between 2030 and 2050	5 USD/TonCO_2 until 2025 From 50 to 100 USD/TonCO_2 between 2025 and 2050

SOURCE: AUTHORS

3.3. Energy: Demand Sectors

The energy demand sectors modelling considers the development of three models that covers the main demand sectors: transport, industry and mining, and buildings. These models follow the same steps for the projection, based on the models used by the energy ministry for the development of the PELP[11] (2020). This model is developed in a mix between Excel Spreadsheets and the software LEAP, where the activity level projections for each of the different sub-sectors are developed on Excel and then fed into LEAP. In general, the modelling process consist of the following steps:

1. Data updating: the data considered in the Ministry of Energy is updated with the energy balance for 2014-2019[12] for fifteen Chilean regions, for each fuel and electricity consumed. The energy balances are published by the energy ministry. The information from activity data (i.e. the sectors' production, distances traveled, etc.) is also updated from public available information, with the specific source of information depending on the different activities considered.
2. Energy intensity calculations: with both the total energy consumption and the activity level, energy intensities for the different activities are estimated. These results are compared with previous data and differentiated by the final use of energy.
3. Projection of activity level: Based on the historical data econometric relationships are calculated which allows the projection of activity data based on macroeconomic parameters considered for the different futures.
4. Results estimation: The information is fed into a LEAP model, for calculation of 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. Most 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 fed into the IPPU models as well.

[11] Acronym for the spanish traduction of the Long Term Energetic Planification

[12] The most updated energy balance corresponds to 2019.

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

- MAPS Chile Initiative, see MAPS Chile (2014)
- The 2020 Chilean NDC mitigation process, Palma et al. (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 main sectors are presented in the following subsections:

3.3.1. Transport

The transport modelling follows a demand-based focus, where the demand for transportation is satisfied by a mix of modes, each of them having different characteristics such as occupation rate and energy intensity. The original demand projection comes from the energy ministry and is based on the studies of the transport ministry which constructed a series from 1997 to 2013. The modelling considers four subsectors: (1) Road transportation, (2) railway, (3) maritime transport, and (4) air transportation. Also, there are two types of demand of transportation considered: demand for passenger transportation (expressed as passenger-kilometer, pkm) and freight transportation (expressed as tonne-kilometer, tkm), each of this demand is estimated for the four subsectors.

According to the last GHG inventory (series 1990-2018) most of the GHG emissions comes from the subsector road transportation. The modelling of this subsector is complex, as it considers a detailed disaggregation of the sector as it is shown in the following table:

Table 3-3 Dissagregations of the road transport sector

Demand	Subdemand	Modes	Fuels
Passengers	Urban	Private cars Taxi Motorcycle Bus	Gasoline Hybrid Gasoline Diesel Hybrid Diesel Electric GLP CNG Hydrogen
	Interurban	Private cars Bus	
Freight	Urban	Light trucks Medium trucks Heavy trucks	Diesel Hybrid Diesel Hydrogen
	Interurban	Heavy trucks	

SOURCE: AUTHORS

The result in terms of fuel consumption projected by the original energy ministry model is compared with the actual fuel consumption for the 2014-2019 period, where an underestimation of the demand of around 20% for the year 2018 is observed, difference that is concentrated in the less populated regions. Because of this difference the demand was adjusted for the period 2014-2019 and the projection is corrected considering this new demand estimation.

The different futures modelled are applying different demand projections which are related to the macroeconomic parameters such as GDP, population, and some secondary projections from the industry & 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 registered for the 2014-2019 period. This enables a projection of the GHG emissions that is closer to the actual GHG emission reported on the GHG emission inventory.

The mitigation scenarios consider three kinds of mitigation action: (1) change from fossil-fuels to zero-emission[13] vehicles, (2) change in the mode of transportation from a GHG emission-intensive mode to a less intensive mode (for example from private car to bus), and (3) reduction from the total demand with actions that incentive active transport (e.g. walking, bicycle) or a reduction from transport demand (e.g. remote working). The actual actions considered in the models are presented in the following table:

Table 3-4 Mitigation actions for the Transport Sector

Sector: Energy-Transport				
Subsector	Action	Action level CP	Action level IM	Action level AM
Road transportation	Electromobility: Private cars	33% of the private car market in 2050. Exponential penetration with an estimation of 2.6% of private cars in 2030.	58% of the private car market in 2050. Exponential penetration with an estimation of 3.2% of private cars in 2030.	68% of the private car market in 2050. Exponential base penetration plus a subsidy for electric cars equivalent in the period 2025-2030, to a fifth of all new cars in 2025, a fourth in 2026, and a third in the period 2027 to 2030. This results in 13.5% of

[13] At least in terms of emissions on the exhaust pipe, they certainly mean a demand for electricity and hydrogen that could need fossil fuels to satisfy. As an assumption the hydrogen modelled is considered as "green-hydrogen" produced using solar energy. In the case of electric vehicles, the additional electricity demand is considered in the electricity generation projections.

Sector: Energy-Transport				
Subsector	Action	Action level CP	Action level IM	Action level AM
				private cars in 2030.
	Electromobility: Taxis	100% of the taxis in 2040. Exponential penetration with an estimation of 24.0% of Taxis in 2030.	100% of the taxis in 2040. Exponential penetration with an estimation of 24.0% of Taxis in 2030	100% of the taxis in 2040. Exponential penetration with an estimation of 24.0% of Taxis in 2030
	Electromobility: Buses	100% of the buses in 2040. Exponential penetration with an estimation of 21.0% of public buses in 2030.	100% of the buses in 2040. Exponential penetration with an estimation of 21.0% of public buses in 2030.	100% of the 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 the freight trucks in 2050. Linear growths starting in	85% of the freight trucks in 2050. Linear growths starting in 2024 with a 0.4% of trucks. By 2030, it

Sector: Energy-Transport				
Subsector	Action	Action level CP	Action level IM	Action level AM
			2024 with a 0.4% of trucks. By 2030, it is estimated that 19.9% of freight trucks could use hydrogen.	is estimated that 19.9% of freight trucks could use hydrogen.
	New bus rapid transit 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 leave private cars.

Sector: Energy-Transport				
Subsector	Action	Action level CP	Action level IM	Action level AM
	Incentive to new bicycle infrastructure	Normal increase of bicycle infrastructure from historical tendency.	Normal increase of bicycle infrastructure from historical tendency.	3000 km of new bikeway installed between 2025 and 2030. Estimated impact of a reduction of 10% from urban passenger demand.
Air transportation	Hydrogen on commercial flights	No hydrogen on commercial flights	No hydrogen on commercial flights	10% of flights with hydrogen in 2050, linear increase from 2035.

SOURCE: AUTHORS

3.3.2. Industry & Mining

The Industry and Mining energy demand sector (I&M) covers the GHG emissions associated with the energy use of fossil fuels in industrial processes. For the I&M modelling, the demand is estimated from the final use of energy, with detailed characterization for each of the fifteen administrative regions. This model is an updated version of the model originally used by the Energy Ministry for the development of the PELP (2020), where both the data from 2014-2019 from the energy balance and the production of each region was updated. The model is disaggregated by sub-sectors associated with each main industry, where some categories are specific to mining, since this is a major economic activity in the country, especially copper mining. Also, for each of this 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, concentrate, leaching, smelting, refining, and associated services), while all the other subsectors are modelled with detail on process type: (1) motor processes, (2) thermal processes and (3) other electric uses. This categorization is described in more detail in the following table:

Table 3-5 Energy-Industry & Mining subsector description

Sector: Energy-Industry & Mining	
Subsector	Subsector description
Copper	Exploitation, extraction and metallurgical processes associated with copper mining. Modeled following the projection of the Chilean Copper Commission (2020). It is 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	It includes 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 non-metallic 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.

Sector: Energy-Industry & Mining	
Paper & 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.
Concrete	Concrete industry. Modeled according to the projected growth of the national GDP.

SOURCE: AUTHORS

The comparison between the projected fuel consumption by model and the fuel consumption recorded for the 2014-2019 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 modelled futures are generated by different demand projections that are related to macroeconomic parameters such as national, Asian[14], 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 2014-2019.

The scenarios modelled consider two kinds of mitigation actions: (1) change from the use of fossil-fuels to the use of electricity, (2) change from fossil-fuels and electricity use to energy sources without GHG-emissions, such as biomass, solar energy and hydrogen[15]. The actual actions considered in the models are presented

[14] In this case the Asian GDP was used as a parameter, without prejudice to the fact that the Chinese GDP was used as a parameter in other sectors.

[15] Modeled hydrogen is assumed to be "green hydrogen" produced by solar energy, as was the case with modeled hydrogen in the transport energy demand.

in the following table:

Table 3-6 Mitigation actions for the Energy-Industry & Mining Sector

Sector: Energy-Industry & Mining				
Subsector	Action	Action level CP	Action level IM	Action level 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.
	Electrification in thermal processes	Same as 2019 (varies for each process and region, from 37.2% to	Additional 25%, when possible. Linear growth starting in 2021, with an estimated penetration that varies for each	Additional 25%, when possible. Linear growth starting in 2021, with an estimated penetration that varies for each process and region,

Sector: Energy-Industry & Mining				
Subsector	Action	Action level CP	Action level IM	Action level AM
		92.7%)	process and region, from 45.5% to 88.9%[16] in 2030.	from 45.5% to 88.9% in 2030.
	Electrificati on 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.
	Electrificati on in thermal processes	Same as 2019 (0%)	8% in underground mining by 2050. Linear growth starting in 2021, with	8% in underground mining by 2050. Linear growth starting in 2021, with an

[16] This value is lower than the starting point because, if necessary, compliance with the solar thermal systems action was prioritized over this electrification action.

Sector: Energy-Industry & Mining				
Subsector	Action	Action level CP	Action level IM	Action level AM
			an estimated penetration of 2.7% in 2030.	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 estimated penetration of 1.0% in 2030.	3% by 2050. Linear growth starting in 2021, with an 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.
	Electrificati on in motor processes	Same as 2019 (varies for each	88% by 2050. Linear growth starting in 2021, with	88% by 2050. Linear growth starting in 2021, with an

Sector: Energy-Industry & Mining				
Subsector	Action	Action level CP	Action level IM	Action level AM
		region, from 18.6% to 88.6%).	an estimated penetration that varies for each region, from 41.8% to 88.4% in 2030.	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.
	Electrificati on 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.

Sector: Energy-Industry & Mining				
Subsector	Action	Action level CP	Action level IM	Action level AM
	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.

SOURCE: AUTHORS

3.3.3. Buildings

Just as the other demand sectors, building modelling follows a demand-based focus, where the demand is estimated according to the final use of the energy. This model originally is an updated and improved version of the model originally used by the Energy Ministry to develop the PELP (2020). The model is divided into 3 sub-sectors: (1) residential, (2) commercial and (3) public, and for each of them the characterization is detailed by fifteen administrative regions. Also, for each of these models some level of detail is characterized according to the next table:

Table 3-7 Buildings Sector subsector description

Sub-sector	Sub-division	Final use
Residential	Houses	Heating Hot sanitary water Cooking Appliances
	Apartments	
Commercial	Banks	Hot Sanitary Water Pump and ventilation

Sub-sector	Sub-division	Final use
		Heating and Climatization Offices Equipment Lighting Others uses
	Supermarkets	Hot Sanitary Water Cooking Heating and Climatization Refrigeration Lighting Others 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
Public	Public Hospitals	

Sub-sector	Sub-division	Final use
		Lighting Laundry Others uses
	Schools	Hot Sanitary Water Cooking Computers Lighting Other uses
	Universities	
	Other public buildings	General uses

SOURCE: AUTHORS

The model developed by the energy ministry was updated considering the data from 2014-2019 from the energy balance for each of the regions, and with complimentary information about the different activities, such as number of new buildings from the different categories. The original results of the ministry energy model overestimated the GHG emissions by 7% in comparison with the GHG emissions inventory, which is equivalent to 0.5 ktCO_{2eq}. It is important to highlight the information recollected from the newest Census that allowed us to have 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 projections of the energy, and as a result we have an updated projection that in comparison to the original is higher for the public sector and lower for the residential and commercial sector.

These projections are based on econometric models that correlate the different variables with macroeconomic models such as population and GDP. As for the saturation of electric equipment in the homes, data from the US is used and it is assumed that for similar levels of GDP per capita the penetration of this equipment will be the same. This approach has been used in previous experiences in Chile, most notably in Fundación Chile, (2014).

The different futures modelled are differentiated by buildings areas and penetration rates of the different appliances in those buildings, all of this estimated from macroeconomic parameters such as GDP and population.

The scenarios represent different mitigation actions which can be summarized as (1) change from fossil-fuel to zero-emission[17] technologies, and (2) reduction of the energy demand, with better thermal insulation on buildings. The following table presents the mitigation actions considered:

Table 3-8 Mitigation actions for the Energy-Buildings Sector

Sector: Energy-Buildings				
Subsector	Action	Action level CP	Action level IM	Action level 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 on public hospitals	Same as 2018 (0%)	10% in hospitals by 2050, starting from 2020 and linear growth. By 2030, 3.3% of hot sanitary water comes from solar roofs-	50% in hospitals by 2050, starting from 2020 and linear growth. By 2030, 16.7% of hot sanitary water comes from solar roofs-

[17] Although the changes to electric appliance result in an increase electric demand

Sector: Energy-Buildings				
Subsector	Action	Action level CP	Action level IM	Action level AM
	Electric heating in public hospitals	Same as 2018 (0%)	48% in hospitals by 2050, starting from 2022 and linear growth	100% in hospitals by 2050, starting from 2022 and linear growth
	Solar PV on public buildings	Same as 2018 (0%)	Same as 2018 (0%)	50% of the electric demand cover by solar PhV on non-specific public buildings for the northern regions (down to the Región VII) by 2050. Linear growth starting in 2021. By 2030, 16.7%.
Residential	Electric residential heating	20% of houses by 2050 40% of apartment by 2050	72% of houses by 2050 89% of apartments by 2050 Growing linearly from 2021. By 2030, around 35% houses, and around 55% apartments.	72% of houses by 2050 89% of apartments by 2050 Growing linearly from 2021. By 2030, around 35% houses, and around 55% apartments

Sector: Energy-Buildings				
Subsector	Action	Action level CP	Action level IM	Action level AM
	Electrification of residential cooking	20% of houses and apartments by 2040. Linear growth from 2018. By 2030, 11%.	36% of houses by 2050 35% of apartments by2050. Linear growth from 2018. By 2030, 14%	72% of houses by 2050 89% of apartments by2050. Linear growth from 2018. By 2030, 32%
	Solar water heater	Same as 2018 (0%)	63% hot sanitary water of houses by 2050 57% hot sanitary water of apartments by 2050 Linear growth from 2021. By 2030, 22% of houses and 19% of apartments	63% hot sanitary water of houses by 2050 57% hot sanitary water of apartments by2050 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 yea	20.000 new houses with retrofit of thermal insulation by year	40.000 new houses with retrofit of thermal insulation by yea

SOURCE: AUTHORS

3.4. Waste

The waste sector is represented in an Analytica model, which has been used previously by the modelling 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[18] (MMA, 2020),

The model is developed considering four modules for each one of the categories: solid waste disposal, biological treatment of solid waste, incineration and open burning of waste, and wastewater treatment and discharge. It is important to consider the connections between the four models, as they not only use the same key inputs such as population and GDP, but also there are some interconnections, for example the fraction of organic waste that is destined to compost affects both the 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 on landfills.

Of the four categories included in the waste model, solid waste disposal has historically represented the main category of emissions. This module follows the IPCC Guidelines (2006), modelling the emissions following a first decay order modelling, which estimates the generation of methane from the decomposition of the organic fraction of waste. This method is intense in the use of historical data, estimating for each year the emissions of the accumulated waste in the differente landfills. For this, ther model considers a series of waste generation from 1950 onwards, the series that was reconstructed by the environmental ministry and the same one that is used to create the national GHG inventory. The projection of the generation is based on the econometric relationship between waste generation and GDP per capita founded by the World Bank (2018). The data of waste generation is disaggregated by the fifteen administrative regions of the country.

The composition of the generated waste is divided into 9 categories: food waste and similars, 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 methane, while the remaining don't produce GHG emissions on landfills[19]. The final disposal sites of the waste changes

[18] Base year 2018. Includes the 1990-2018 series.

[19] They are modelled with this detail in order to model some policies and co-benefits of potential mitigation actions. Also, it is worth notice that if incinerated, the plastic fraction

both in time and by region, based on the historical data and the projected new landfill sites. The model distinguishes between four different types of final disposal sites, considering the physical characteristics and usual operation of them. This as well as the climate affect the decomposition rate considered for each of the waste fractions.

Finally, the model considers some options that affect the estimation of the methane emissions, considering technologies such as capture and burning of the biogas generated. This is based on the historical registers, it is noted that in Chile there has been some capturing and burning of biogas since 2004, growing fast until 2010 from where it has stabilized on 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: Considers historical data from industrial composting. It could be underestimating the emissions as it does not consider small-scale composting, and only rely on a database of register composting projects.
- Incineration and open burning: consider incineration of hospital waste and cremation, and industrial waste incineration. The data comes from health stats (hospital waste and cremation) and the declaration from the industry on the account of the registry for waste generation, transfer, and disposition. It is relevant to consider that the data from the industry has been available only from 2014.
- Wastewater treatment and discharge: considers methane from residential wastewater, nitrous oxide from wastewater and industrial wastewater. The data comes from official data related to the sanitaries report. The residential wastewater method distinguishes between rural and urban wastewater as the mix of treatment varies significantly between them.

As with any estimating model, the analysis from the results have to consider the uncertainty of the modelling process, as the estimation can vary in time as the assumptions, methodologies and data are refined. In this aspect some of the uncertainties of the projections are captured by the futures developed. This model is especially sensitive to the population projections and, in second place, the GDP projections. These parameters affect the residential solid waste generation, the

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would emi non-biogenic CO_2 and other GHG.

industrial generation of waste, the wastewater generation, the amount of protein on wastewater, and the activity level of incinerations and hospital waste incinerated, among others.

In particular for each of the scenarios considered in this exercise the following actions were modeled:

Table 3-9 Mitigation actions for the Waste Sector

Sector: Waste				
Subsector	Action	Action level CP	Action level IM	Action level AM
Solid waste disposal	Increased capture and burning of landfill gas	Same as 2018. New project in Tarapaca 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)

SOURCE: AUTHORS

3.5. IPPU

The Industrial Processes and Product Use (IPPU) GHG emissions is a sector that covers emissions from industrial processes, from the use of GHG in products, and from non-energy use of fossil fuel carbon (Harnisch and, Kojo, 2006). For the purpose of this study these emissions are modelled in Analytica, based on a previous model developed in Benavides et al. (2021).

Since the original development of the model, a new oficial GHG inventory was published by the Chilean Government, which in the IPPU sector applied some new methodologies for some subsector, for example a tier 3 methodology is applied for the production of nitric acid and a tier 2 methodology for refrigeration and air conditioner, when on previous inventory a lower tier methodology was used. These methodological changes and updated data were included in the new version of the model, which means the resulting estimation is closer to the official GHG inventory series (1990-2018).

The model consist of six modules which represents the six categories of GHG sources included in the inventory, this are: (1) mineral industry, which includes cement, lime and glass industries, (2) chemical industry, which includes nitric acid and petrochemical industries, (3) metallic industry, which includes iron, steel and lead industries, (4) Non-energy products from fuels and solvents use (5) emissions of fluorinated substitutes for ozone depleting substances, which includes different applications of this substances, and (6) Other product manufacture and use, which includes mainly the SF_6 emissions from the manufacture of electric 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 the cement production or the projections of transportation. This information is complemented with industry level information and historical data to find 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, 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 to project, and on the relevance of each category in terms of total emissions. For those categories with more emissions a more detailed modeling is conducted in order to get more sensitive estimations to the multiple factors that could impact in 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.

The emissions of fluorinated substitutes for ozone depleting substances consist mainly of HFC emissions due to the installation, fugitive emissions and end-of-life emissions of Refrigeration and Air Conditioning equipment and systems. Also, there is a contribution of the use of HFCs regarding products such as Metered-Dose Inhaler and solvents. This category has an additional complexity because it's affected by the Kigali Amendment of the Montreal Protocol, which regulates the consumption of HFC. This means that the use of historical data to represent the future might not be enough. For this reason, a five step method is used:

1. HFC consumption base-projection: this projection doesn't consider the impact of the Kigali Amendment, and it depends on the relationship between the banks of HFC on the different applications and macroeconomic variables.
2. Determination of the HFC consumption limit: The Kigali amendment establishes a chronogram of reduction, which depends on the base consumption determined from the actual consumptions between the years 2020-2022, plus a margin related to the HCFC consumption in the past. For Chile, the Kigali Amendment means a freeze of the HFC consumption between the years 2024-2028, a 10% reduction from 2029, a 30% form 2035, a 50% from 2040, and 80% 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 (2017) and Hoglund-Isaksson (2017). The prioritization means that when the total consumption of the base-projections is greater than the limit, the sub-applications with less technological substitution cost will reduce their consumption until the limit is reached. The model will reduce consumption in as many sub-applications as it 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 equipments, 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 bank that finish their lifespan (N_{t-ls}):

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

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

The results of the projections represent the best estimation, but they have to be carefully considered, as they have uncertainties. These uncertainties have different origins, and some are collected by the use of different futures as explained at the beginning of this chapter. Some of the parameters that vary between the different sectors are both primary projections such as GDP and population, and secondary projections that came fundamentally from the energy demand sectors 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 highlight 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 scenario. In the next table, the mitigation actions for each of the scenarios are presented:

Table 3-10 Mitigation actions for the IPPU Sector

Sector: IPPU				
Subsector	Action	Action level CP	Action level IM	Action level AM
Emissions of fluorinated substitutes for ozone depleting substances	HFC consumption restriction	Kigali Amendment	Kigali Amendment	Kigali Amendment
	Recovery and regeneration of refrigerants 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 al 2030

SOURCE: AUTHORS

3.6. Agriculture

The agriculture sector model has been developed in Lumina's Analytica software, based on the model developed for the study "Options for achieving carbon neutrality in Chile by 2050 under uncertainty"(Benavides et al., 2021). The methodology for estimating emissions based on the National Inventory of Greenhouse Gases (Ministerio del Medio Ambiente de Chile, 2021), based on the methodological guidelines of the IPCC 2006, was used for this category. The current model considers the updates of the last inventory report (INGEI) 1990-2018 for the sector to date.

The emissions that are considered from the agriculture sector are subdivided into 7 categories, (1) Enteric fermentation, (2) Manure management, (3) Rice cultivation, (4) Agricultural soils, (5) Urea application, (6) Agricultural burn and (7) Liming. Within this sector, 82% of the emissions come from the Enteric Fermentation and Agricultural Soils categories (based on last 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 with 12% of the sector emissions; these 3 categories add up to 94.7% of the total emissions of the sector (Ministerio del Medio Ambiente, 2021).

The category **Enteric Fermentation (1)** considers those emissions of methane (CH_4) that are produced in the digestive systems of livestock, mainly by cattle and sheep, representing 93.9% of the emissions of the category, followed by pigs and other species. The emissions corresponding to the **Manure Management (2)** category, includes those emissions of Methane (CH_4) and Nitrous Oxide (N2O) generated by the manure storage in livestock production systems, mainly pigs and cattle. It also includes emissions from other species, such as poultry, camelid horses and goats.

The historical series was estimated in the model, data at the regional level are used for No. of heads of cattle by type of cattle, based on official information generated by ODEPA[20], mainly based on the 2007 Agricultural and Forestry Census (INE, 2007), in addition to annual reports. Emission factors used, correspond to Tier 1 and Tier 2.

For the projection of cattle heads, an econometric model was developed based on the beef producer price and the corn producer price. The projected number of Pig heads is based on the projections of the corn producer price, and the projection

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

of the number of heads of Poultry was based on the projection of the price to the producer of Corn and producer price of Soy. The price projections were obtained from OECD world statistics, updated to 2020, corresponding to the period 2020-2029, for the year 2030, the growth rate of each of the prices obtained from OECD Stats was maintained.

The emissions corresponding to the **Rice Crop (3)** category include Methane (CH_4) emissions, produced by the anaerobic decomposition of organic material in flooded rice fields, using IPCC methodological level 1, using national rice harvest area data from ODEPA. For the rice surface 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 (4)** correspond to those emissions of Nitrous Oxide (N2O), generated from the soil surface as a result of microbial processes associated with the application of nitrogen in its different forms, including inorganic fertilizer, organic fertilizer (livestock manure), nitrogen from urine and manure from grassland grazing animals, and nitrogen available in crop residues.

The data used 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 level intensity use of nitrogen by crop was used (Ulibarry, 2019). The future area by different crop typeswas estimated based on their historical trend (1990-2018) and projected up to 2030, to estimate the future consumption of fertilizer, a conventional dose of N application was used by type of crop (KgN/ha). For the estimation of organic fertilizer applied to soils, it was estimated based on the available manure in confined productive systems (integrated variable with projection of livestock), also for the emissions of nitrogen from urine and manure from grazing animals.

The results of the projections were compared with “MAPS initiative 2012” and National estimations from the Ministry of Environment, differing mainly in the number of cattle and pigs.

Three different futures were considered in the analysis for different parameters. Green Future considers low prices of bovine meat, maize, and soy, and, for actions, considers an early implementation of one year. 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.

In particular, for each of the mitigation scenarios considered in this exercise the following actions were modeled:

Table 3-11 Mitigation actions for the Agriculture Sector

Sector: Agriculture			
Action	Action level CP	Action level IM	Action level AM
Change in bovine Diet (lipids)	No additional adoption	70% of the dairy cattle in 2037, starting the implementation in 2030	Implementation starts in 2025
Porcine Biodigesters	27% of total porcine heads purines managed their purines with biodigesters to 2030	Additional 17% of the total of porcine heads managed their purines with Biodigeters, 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 on 2026	No additional adoption
Application of organic amendments	No additional adoption	No additional adoption	Application of organic amendments to the 10% of national cereal surface to 2030, starting in

Sector: Agriculture			
Action	Action level CP	Action level IM	Action level AM
			2025.
Holistic management of cattle	No additional adoption	No additional adoption	20% of the bovine grazing grassland of the X Region (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 the heads 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 biochart production plant starting in 2024

Sector: Agriculture			
Action	Action level CP	Action level IM	Action level AM
Meat tax	No additional adoption	No additional adoption	A 10% tax on consumer prices, reducing the national meat production.

SOURCE: AUTHORS

3.7. LULUCF

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

- **4.A Forest land:**
    - **Forest Land Remaining Forest Land**: This module modeled emissions and captures associated with the following categories: 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.
- **4.X.1**: **Land converted into 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)

- **4.X.2.X: X that remain as X (Where X = BCDEF)**: In this module are considered 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 used the methodology and modeling approach used by Benavides et al. (2021). The approach calibrated an autoregressive vector model (VAR) for the subcategories of increases in biomass, harvests, Land converted to Forest Lands, croplands, grasslands, wetlands, and other lands. For burning of forest residues, change in vegetation and HWP the approach used the corresponding average of the last 5 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 1980-1989 was used, the Reference scenario used the period 1990-1999 and the period 2000-2009 for the Red Future scenario. This projection starts in 2021, for the years 2019 and 2020 official data of areas affected by wildfires provided by CONAF (2021b) were used. Projection of the biomass loss by firewood extraction follows the trend of demand energy sector of residential wood consumption.

The projection method for native and exotic afforestation measures (and the afforestation measure - increase in hectares in the AM scenario) is the same as the approach used by Benavides et al. (2021), which use emission factors derived from the historical calculation of GHG emissions from the Land converted into Forest lands subcategory (native forest and plantations). For increases in hectares of native forest under forest management measure (and the measure that increases the hectares managed in the AM scenario) and the increase in protected areas measure, 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 in Biomass" subcategory, derived from the IPCC equations (2006) used by the National Inventory Report of Chile 2020 (MMA, 2021); Similarly, the same approach (Benavides et al., 2021) was used for the projection of fire degradation control measures, using IPCC equations (2006) used by the National Inventory Report of Chile 2020 (MMA, 2021) for the subcategory of Biomass Loss.

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 were provided by CONAF (2012) where the investment cost were calculated using an average of the values of macro zones within Chile with a density of 1100 plants per hectare, considering manual plantation per plant, subsoiling at 40 cm and protection against lagomorphs. Another source of data of plantation establishment was provided by 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, technical advice in degraded soils, pruning and commercial thinnings, plus technical advice, CONAF (2012) values were used. CORMA (2021) also provides operating cost data, which includes land lease and marginal administration cost. The mean of the total operation cost for exotic afforestation was used.

For the incomes, mean of yield given by Corvalán & Hernández (2012) were used, prices of harvested wood were given by INFOR (2021).

For the values of the investments in afforestation with native species, the same sources were used (CONAF, 2012; CORMA, 2021), but also were 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) used for the exotic forestation measure.

For the investment costs of the increase of hectares under forest management measure, 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 (2021) also gives values of management establishment. the mean between both sources of data were used. For operating costs, these 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, other costs of operation considered, corresponding to the set of silvicultural interventions and harvesting activities that allow meeting the objectives established for the use of a forest, as well as the income values for the harvest of native wood were taken from ODEPA (2003), which made 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 were provided by CORMA (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 of MMA, PNUD, & GEF (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 (2021b).

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

For costs of activities in native forest degradation reduction 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 value of income the average costs of the land of class V, VI, VII and VIII as a function of soil distributions using information from Zelada & Maquire (2005) as a reference, considering the probability of forest fire using data of CONAF (2021a).

All values were brought to current values using the variation of the CPI provided by INE (2021), the values of the dollar and UTM were converted using the monthly average data provided by the 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.

Table 3-12 Mitigation actions for the LULUCF Sector

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

Sector: LULUCF			
Action	Action level CP	Action level IM	Action level AM
Exotic afforestation	No additional adoption	Forestation of 100,000 hectares with exotic species in 2030	Forestation of 100,000 hectares with exotic species in 2030
Native forest management	No additional adoption	increase the managed native forest land in 200,000 hectares in 2030	increase the managed native forest land in 200,000 hectares 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 hectares of protected areas in 2030
Kelp forest management	No additional adoption	No additional adoption	1,000 hectares of managed kelp forest in 2030

Sector: LULUCF			
Action	Action level CP	Action level IM	Action level AM
Native afforestation – increase in hectares	No additional adoption	No additional adoption	20,000 hectares of permanent forest cover with native species in 2030
Native forest management – increase in hectares	No additional adoption	No additional adoption	increase the managed native forest land in 20,000 hectares in 2030

SOURCE: AUTHORS

4. Results

This section presents the aggregated results of the modelling exercise, the first part presents the GHGs emission results, the second part presents an analysis of the fulfillment of the Carbon Budget defined on the Chilean NDC and the last part presents the mitigation costs results.

4.1. Emissions

This section presents the GHGs emission results for all the sectors. Figure 4-1 shows the total aggregated emissions for the Agriculture, Energy, IPPU, Transport and Waste sectors for the 3 scenarios for the reference future, the CP and IM scenarios shows an increase on the emissions by 2030, the only scenario that achieves an absolute decrease on the emissions is the AM Scenario, also is the only scenario that has their peak of emissions before 2025.

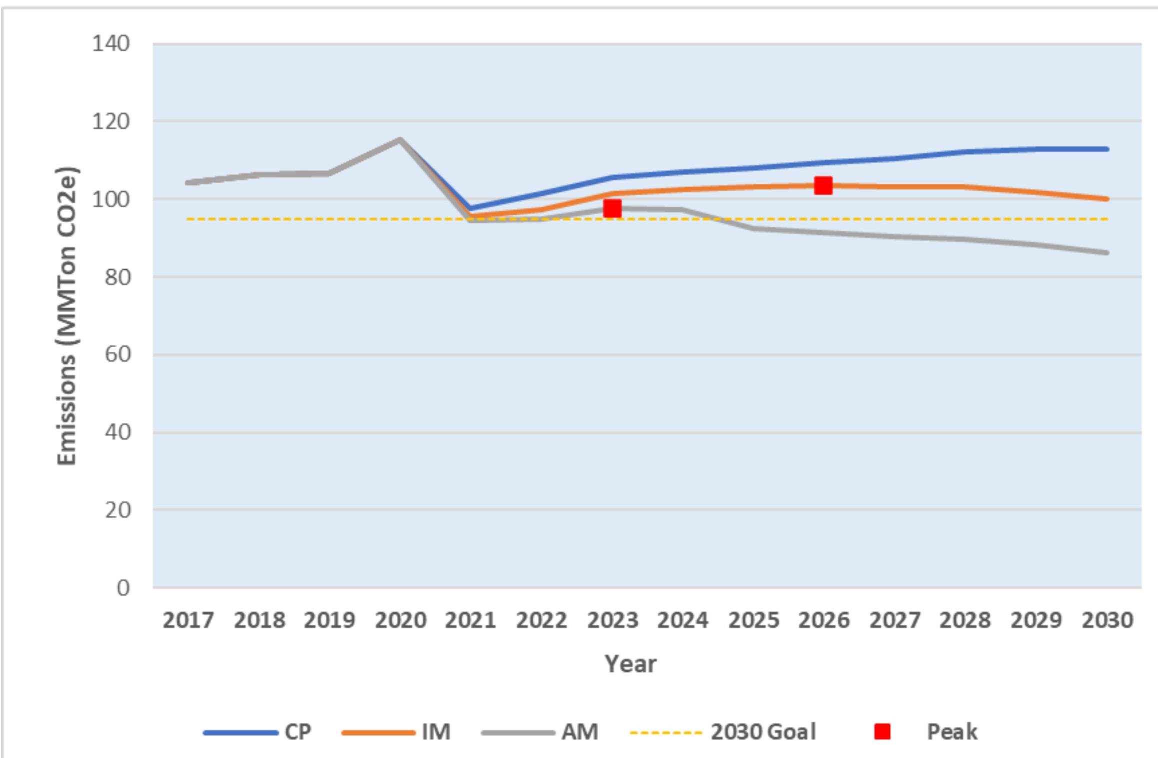

Figure 4-1 Total aggregated emissions of the carbon budget sector in three different scenarios in the period 2020-2030.

SOURCE: SELFMADE

LULUCF sector has net captures and independent goals on the NDC, so the results are presented separately, Figure 4-2 shows the emissions of LULUCF for the different scenarios for the reference future, for all the pathways the sectors remains capturing more GHGs than it emits, but the IM and the AM scenarios increases the net captures of the sector by 2030.

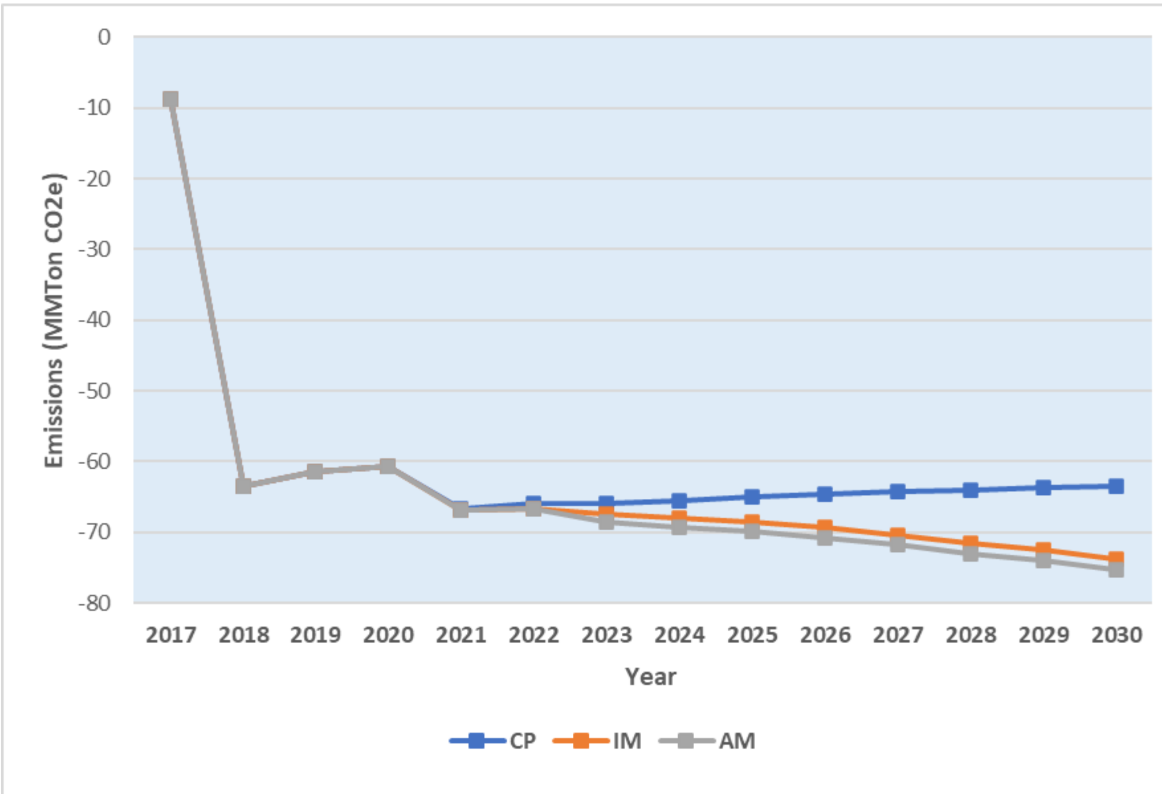

Figure 4-2 Total emissions of the LULUCF sector in three different scenarios in the period 2020-2030.
SOURCE: SELFMADE

More detailed results are presented in Figure 4-3, Figure 4-4 and Figure 4-5 where the projected emissions for all the sectors can be analyzed with a 2050 perspective with more detail for each scenario, as an illustrative way. For the Current Policies scenario (Figure 4-3), we can appreciate a steady increase of emissions related to Transport, Buildings and I&M, and a decrease in the net captures of the LULUCF sector, these heavily increase the emissions by 2050, despite the reductions of the Electricity Generation Sub-Sector.

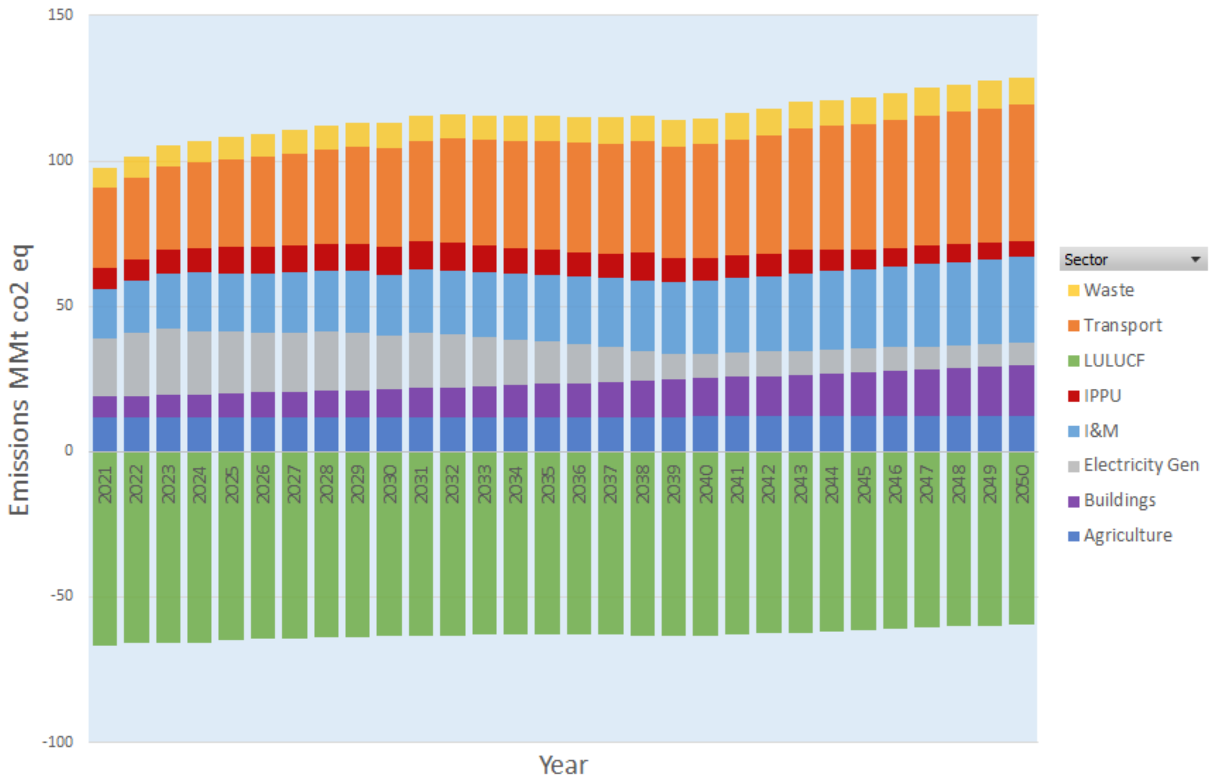

Figure 4-3 Emisions for the CP Scenario in the reference future.
SOURCE: SELFMADE

For the IM scenario (Figure 4-4), the absolute emissions peak around 2030, but decline by 2050, this is related to a decrease in the emissions of most of the sectors and an increase of the levels of capture of the LULUCF sector. The electricity sub-sector contributes heavily with the mitigation by 2040, but afterwards starts to increase their level of emissions again.

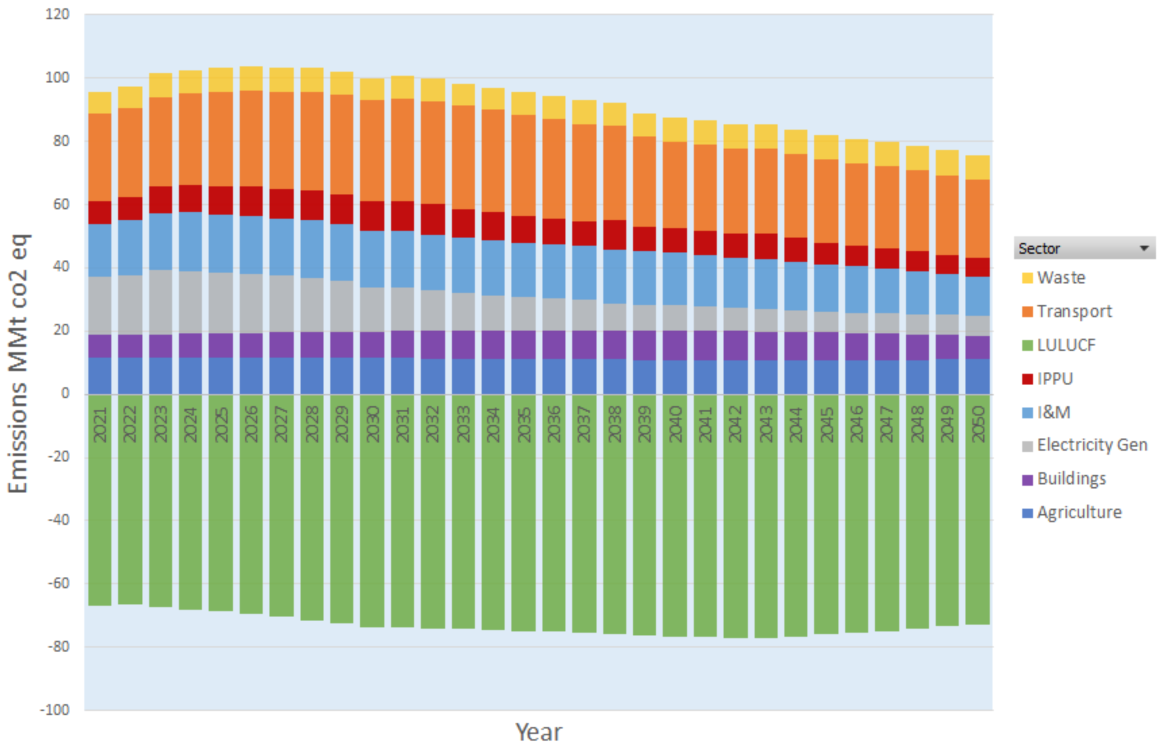

Figure 4-4 Emissions for the IM Scenario-Reference Future
SOURCE: SELFMADE

For the AM scenario (Figure 4-5), the absolute emissions peak by 2023 and decline steadily until 2050, this is related to a decrease in the emissions of all the sectors and an increase of the levels of capture of the LULUCF sector.

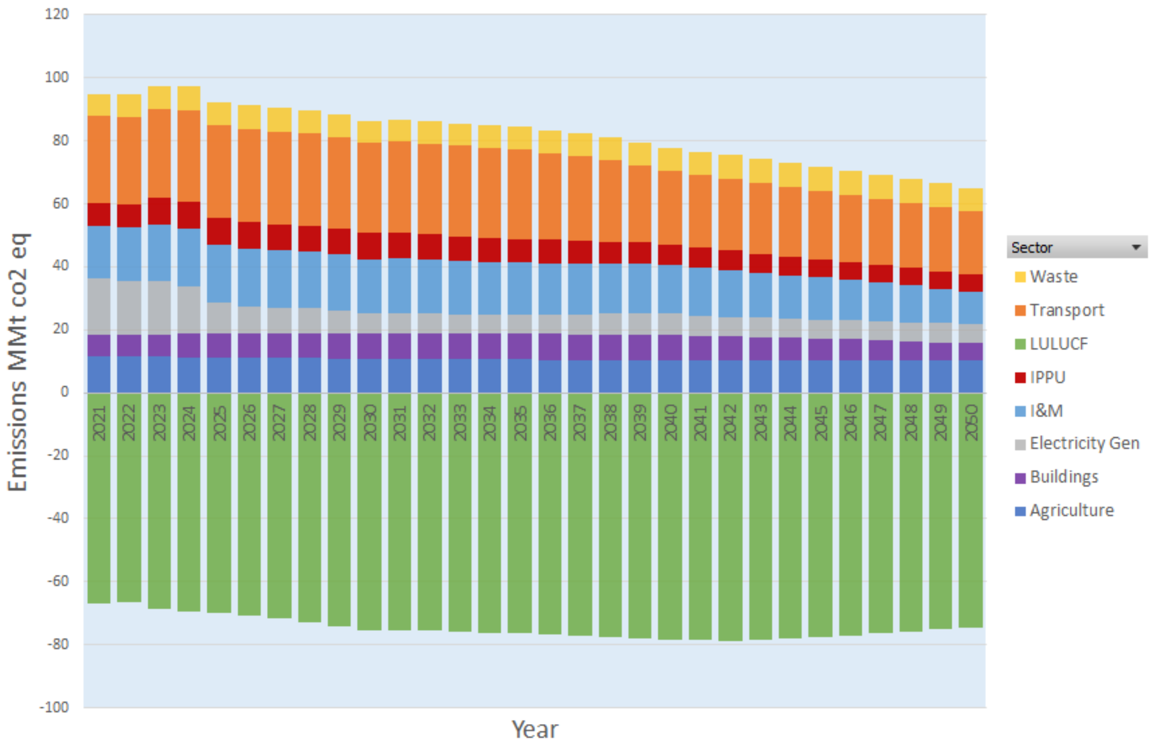

Figure 4-5 Emissions for the AM Scenario-Reference Future
SOURCE: SELFMADE

4.2. Emission overfutures: Sensitivity Analysis

As was explained before, this modelling exercise developed different futures that address theexgenous uncertainties, this sub-section presents a sensitivity analysis of the GHG emissions on the different scenarios. Figure 4-6 shows the aggregated total emissions[21]; intervals represent different futures for the three simulated scenarios. The results show that the AM has significantly lower emissions than the other scenarios, but also is more sensitive to be deviated to higher levels of emissions than lower.

[21] All net emitter Sectors.

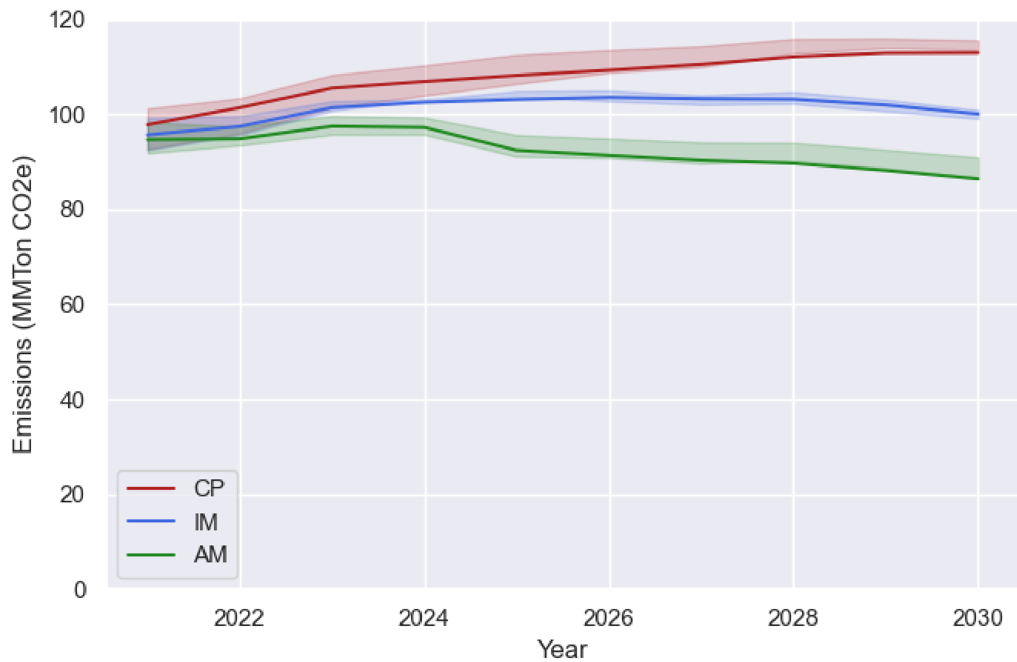

Figure 4-6 Total aggregated emissions of the carbon budget sectors in three different scenarios in the period 2020-2030, intervals created by different modelated futures.

SOURCE: AUTHORS

Figure 4-7 and Figure 4-8 shows the sensitivity analysis for LULUCF sector net captures on the different scenarios, the intervals showing different simulated futures. LULUCF sector is highly sensitive to climate conditions, because affects the incidence and severity of forest fires, this fact explains the wide interval for all the scenarios at the beginning of the period, afterwards, by 2030, the IM and AM scenarios reduce their interval, this is related with the NDC commitment of reducing the forest fires.

Figure 4-7 Emissions at 2030 of the LULUCF sector in three different scenarios
SOURCE: AUTHORS

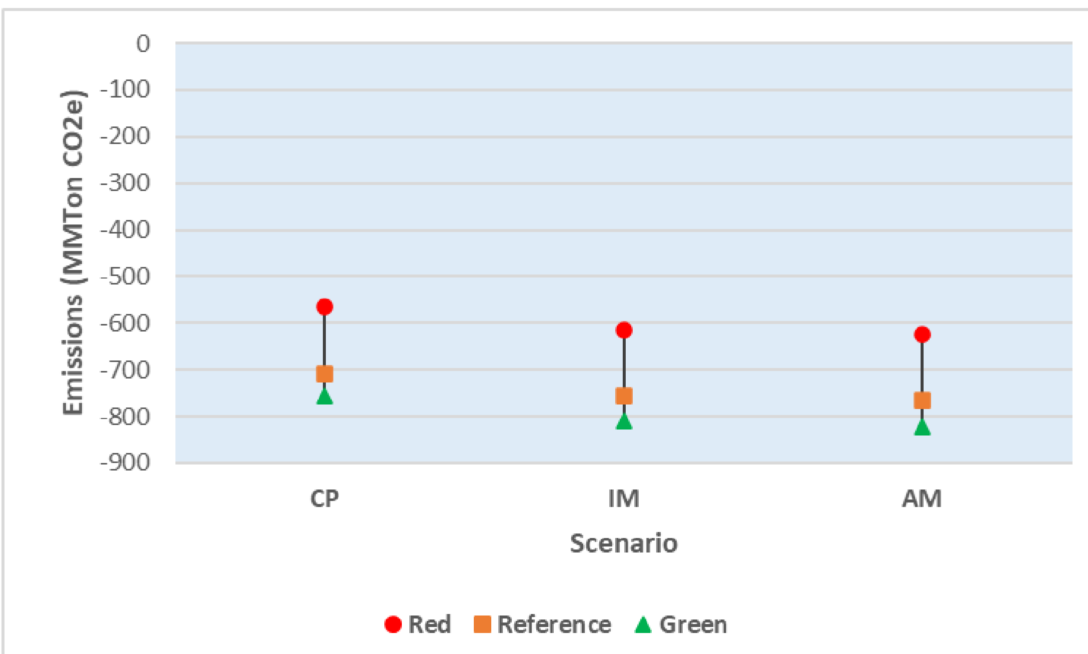

Figure 4-8 Aggregated emissions of the LULUCF sector in three different scenarios in the period 2020-2030
SOURCE: AUTHORS

In ANNEX 2 there are more detailed results of the sensitivity analysis, presenting the sectoral emissions for each scenario and future.

4.3. Alternatives to accelerate mitigation on the electricity sector

Currently in Chile, there is a lot of political pressure to accelerate the closure of coal power plants, specifically, congress is currently discussing a law to force the decommission of all coal power plants by 2025. It is interesting to evaluate the performance of another form of accelerated mitigation, because forced phase-out does not inherently follow an optimal economic path necessarily. For this comparison the phase-out by 2040 will be maintained, but the carbon tax will be increased to a level equivalent to the externality that CO_2 emissions produces (50 USD/tCO_{2eq} by 2025 and 100 USD/tCO_{2eq} by 2050), thus sending an economic signal to every power plant that depends on fossil fuels.

As it can be seen from the results in The results presented above present a dilemma: setting a higher carbon tax is expected to achieve lower overall emission reductions at lower mitigation costs, but higher uncertainty on the reductions. On the other hand, a forced phase-out by 2025 has lower uncertainty on the mitigation goal, but with higher costs.

Table 4-1 the GHG mitigation of the AMHT scenario is lower, although similar, than the AM2025 for the red and reference futures (Figure 4-9, Figure 4-10, Figure 4-11 and Figure 4-12). However, the lower fuel prices present in the green future disincentivize it to transition to cleaner technologies, therefore it does not reduce the coal generation as quickly and its GHG mitigation is underwhelming (Figure 4-13 and Figure 4-14). The Table 4-2 shows that for each future the AMHT has lower costs than the AM2025, this cost reduction is achieved at the expense of GHG mitigation.

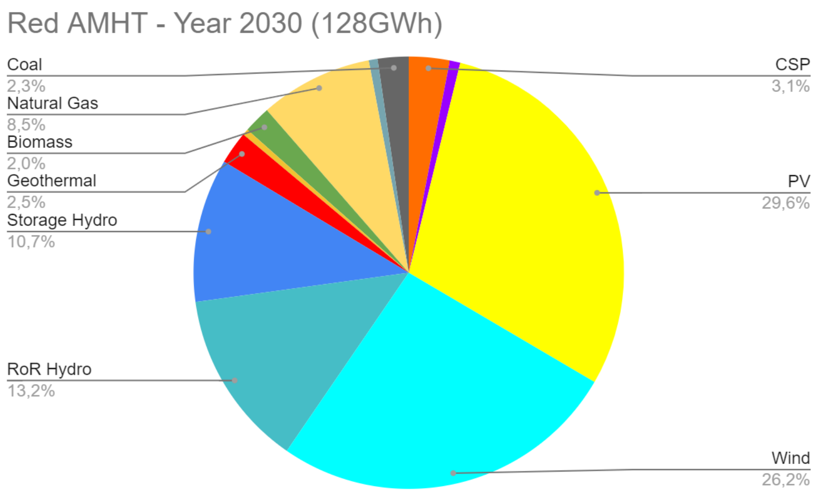

Figure 4-9 Red Future, AMHT Scenario for Year 2030

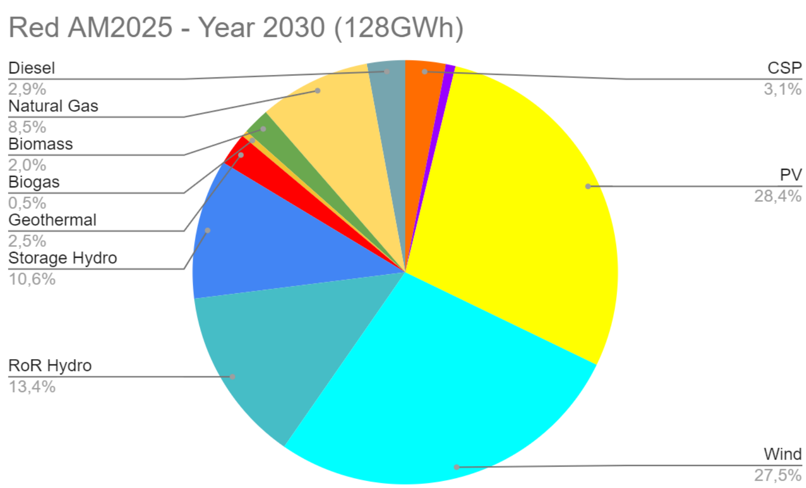

Figure 4-10 Red Future, AM2025 Scenario for Year 2030

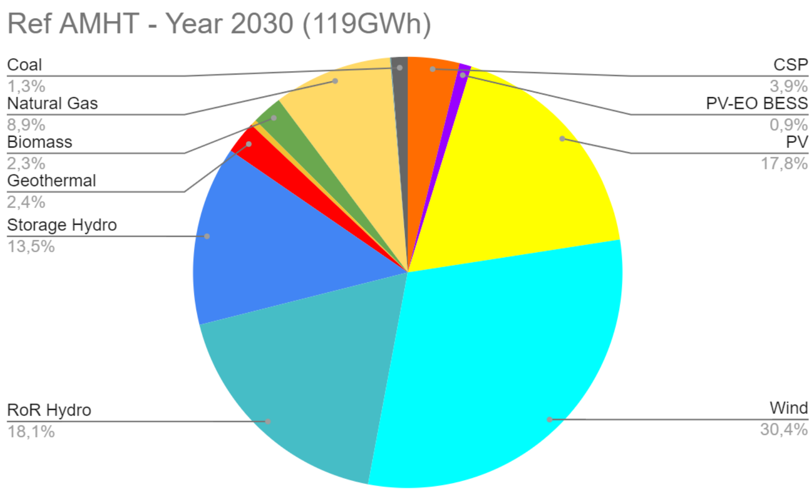

Figure 4-11 Reference future, AMHT Scenario for Year 2030

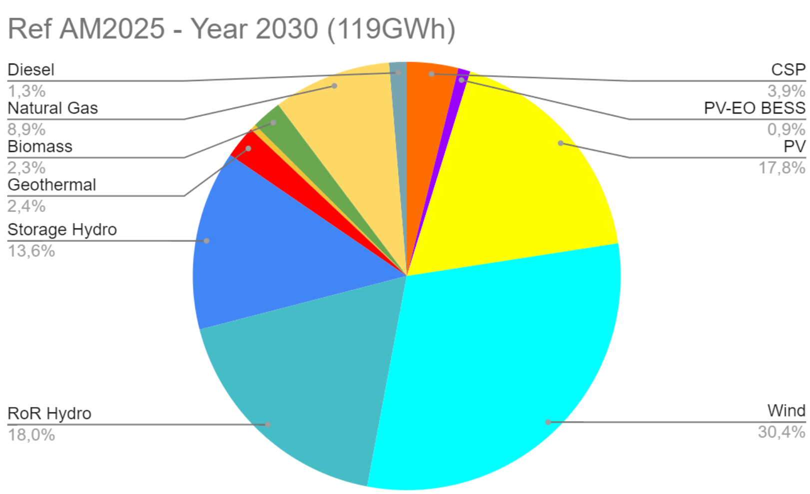

Figure 4-12 Reference Future, AMHT Scenario for Year 2030

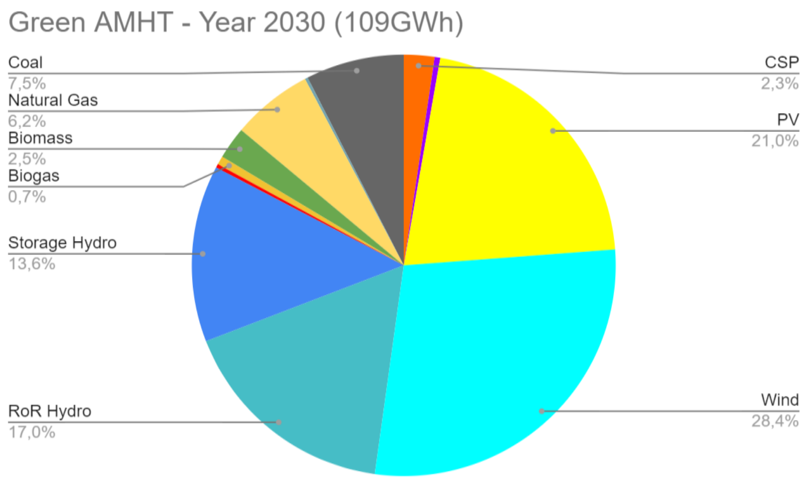

Figure 4-13 Green Future, AMHT Scenario for Year 2030

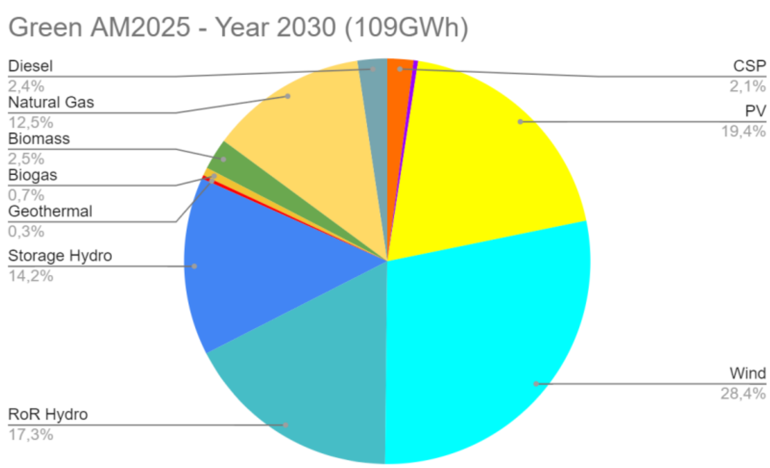

Figure 4-14 Green Future, AM2025 Scenario for Year 2030

The results presented above present a dilemma: setting a higher carbon tax is expected to achieve lower overall emission reductions at lower mitigation costs, but higher uncertainty on the reductions. On the other hand, a forced phase-out by 2025 has lower uncertainty on the mitigation goal, but with higher costs.

Table 4-1 Mitigation Cumulate emission reduction 2020-2030 per Scenario and future

Emissions (MMTon CO_2)	IM	AM 2025	AM HT

Red Future	56.88	90.57	76.33
Reference Future	**27.51**	**92.37**	**81.1**
Green Future	7.91	83.85	38.39

SOURCE: AUTHORS

Table 4-2 Mitigation cost per Scenario and future

Cost (USD/ Ton CO_2)	IM	AM 2025	AM HT
Red Future	154.05	143.26	140.09
Reference Future	**83.09**	**88.33**	**85.48**
Green Future	53.45	47.95	44.6

SOURCE: AUTHORS

4.4. Fulfillment of the Carbon Budget

In the Nationally Determined Contribution (NDC) Chile commits to a GHG emission budget not exceeding 1,100 MMton CO_{2eq} between 2020 and 2030, with a GHG emissions maximum (peak) by 2025, and a GHG emissions level of 95 MMton CO_{2eq} by 2030 (Gobierno de Chile, 2020).

In order to determine if with the mitigation measures proposed by each sector will achieve the carbon budget by 2030 and carbon neutrality by 2050 (zero net emissions) as established in the NDC, an analysis was made considering 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").

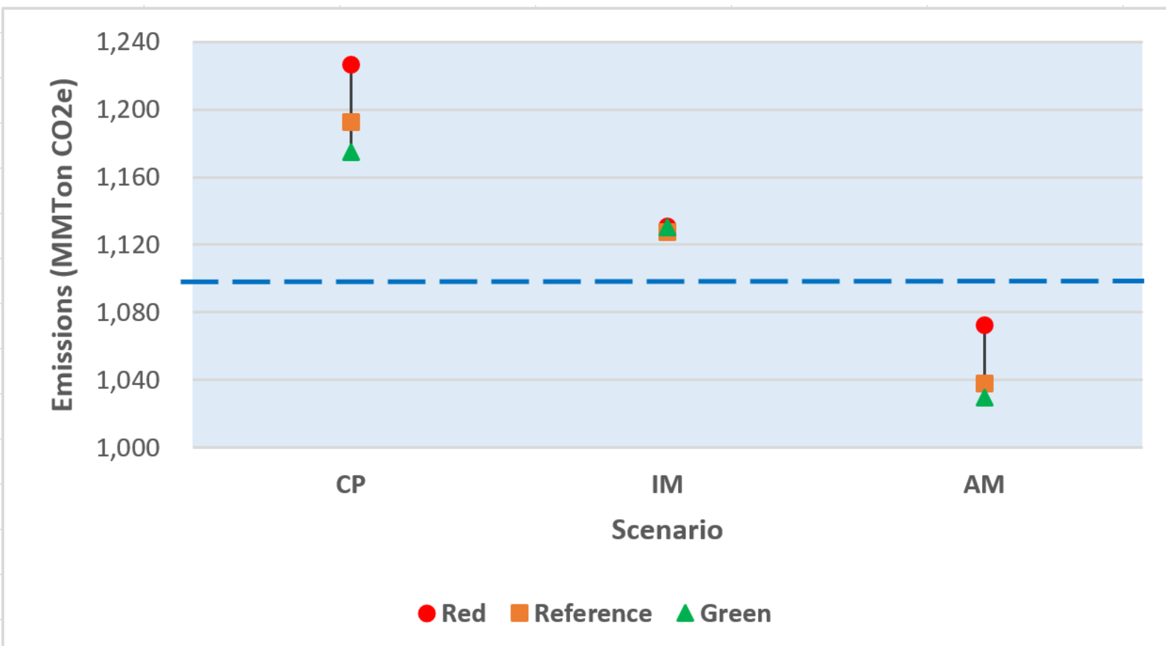

Figure 4-15 Total absolute comulative emissions emitted between 2020 and 2030 for each scenario and each future

SOURCE: SELFMADE

From Figure 4-15 it can be observed that only in the AM, that is, where additional measures to the Chilean NDC are considered, the commitment to emit below 1,100 MMTon CO_{2eq} between 2020 and 2030 is fulfilled. For the other hand, the IM scenario shows a close approach to meeting the commitment, although it does not reach 1,100 MMTon of $CO2_{2eq}$, the three futures are very close to reaching the goal, especially the "Reference Future" (1,128 MM ton CO_{2eq}). The differences between the futures in the IM scenario are very similar because the NDC mitigation mesures are projected to reach arbon neutrality to 2050, therefore the NDC establishes that many mitigation measures begin around 2030, that's way we can´t see big captures for the period 2020-2030. In view of the above, only if additional measures to those established in the current NDC are taken, Chile could meet the carbon budget established between 2020 and 2030.

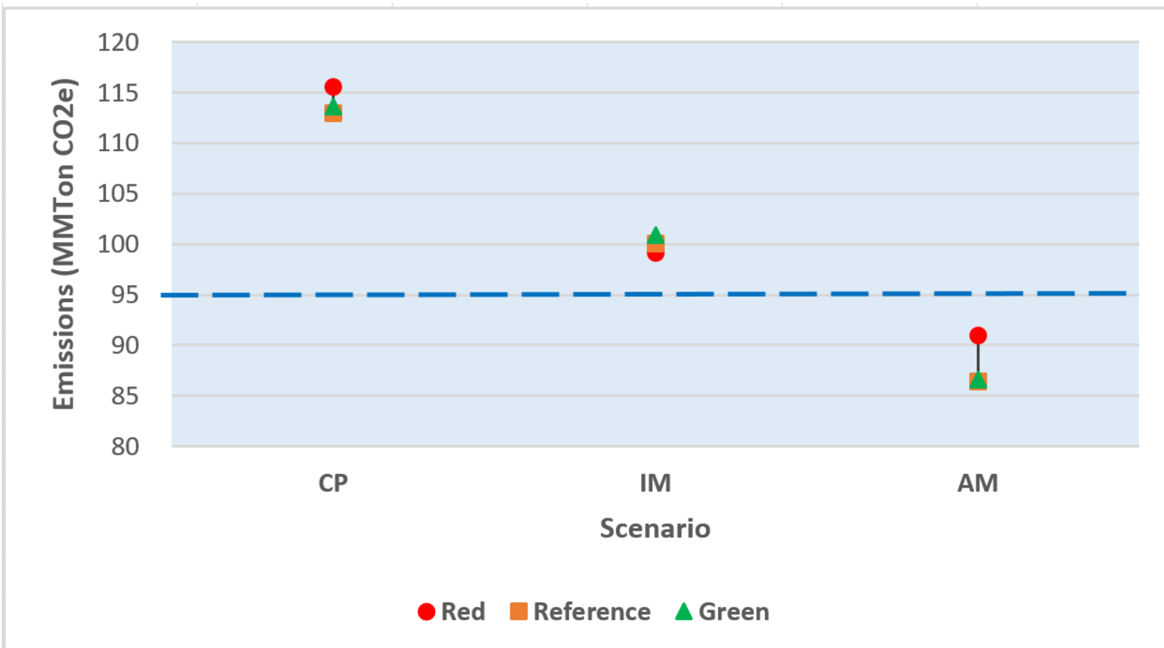

Figure 4-16 Forecast of absolute emissions in the year 2030 for each scenario and for each future
SOURCE: SELFMADE

An analysis of GHG emissions in 2030 (Figure 4-16) shows something very similar to the previous case. Only in the AM scenario and under the three different futures, the target of emitting 95 MM tons CO_{2eq} in 2030 is achieved. On the other side, the IM scenario is close to meeting the NDC target.

In the IM scenario it can be seen a difference in comparison with the other scenarios, where the emissions in the "Red future" are slightly lower than the other futures. This can be explained by the expected emissions from the electricity sector, the optimization model, seeks to minimize the cost of the system on the overal period, like the "Red Future" has a greater energy demand in relationship with the "Green and Reference future", together with a high electrification of the energy uses and the earlier Coal Phase Out of the IM scenario, leads to an early significant increase of the renewable capacity, action that happen a few years after in the other futures, because the electricity demand is not high enough to justify a higher investment yet, prefering to use existing Natural Gas capacity to produce the electricity, which is reflected with a slightly higher GHG emissions for those futures.

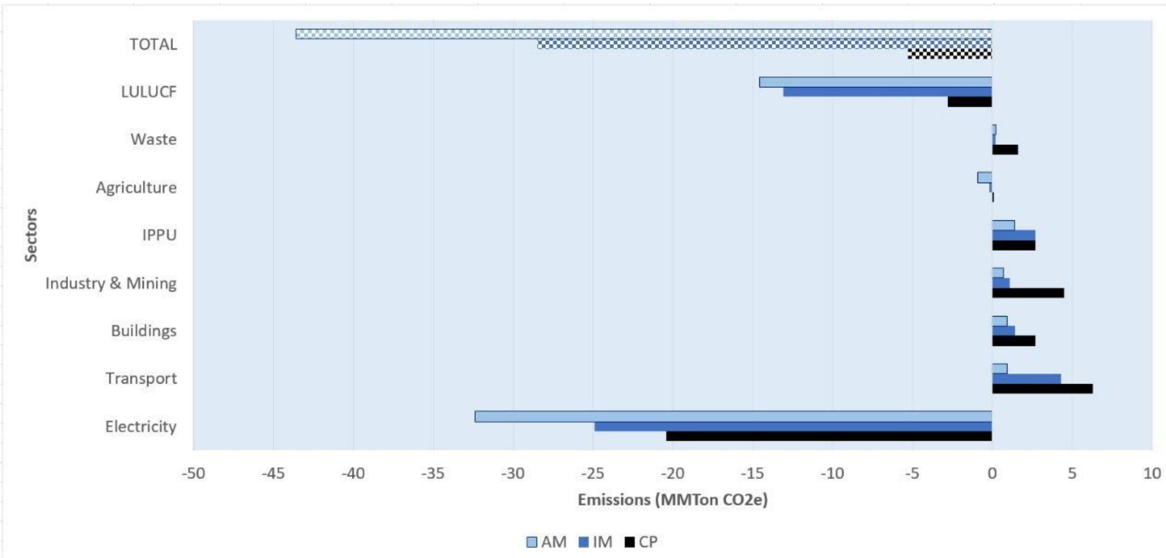

Figure 4-17 Difference between projected emissions by 2030 compared with 2020 (MM tons of CO_{2eq}) for each scenario in the reference future.
SOURCE: SELFMADE

More detailed results of the changes on the emissions between 2020 and 2030 can be seen in Figure 4-17n where it is noticed that the Electricity Generation which represent 29% of Chile's total emissions in 2018 (Ministerio del Medio Ambiente de Chile, 2021) shows a decrease in emissions from 2020 to 2030 under all scenarios and futures analyzed. Being such a representative sector, it allows that despite the fact that emissions in the other sectors (except Agriculture) increase slightly by 2030, total emissions decrease, and even more, with the addition of the LULUCF sector captures, though they are small for 2030. This allows that at least under the AM scenario, the target of achieving 1,100 MMton CO_{2eq} between 2020 and 2030 could be fulfilled, as well as the emission target of 95 MMton CO_{2eq} for 2030. Finally, Figure 4-17 shows that despite the fact that the aggregation of the differences of all sectors is 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 Secction 7.2.2).

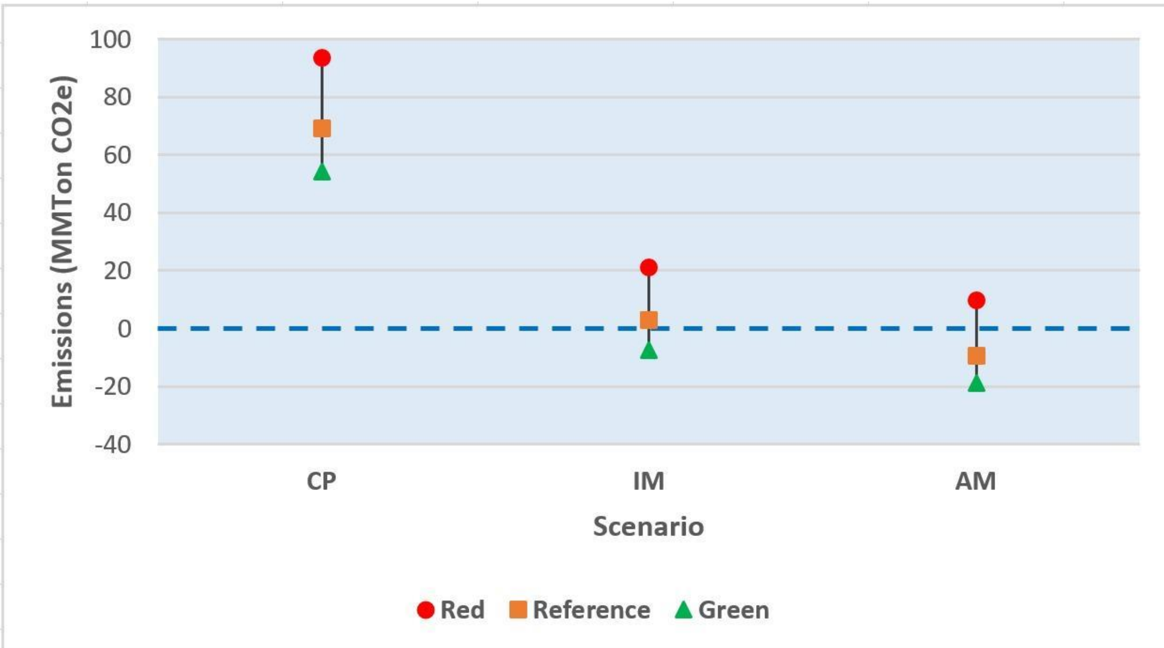

Figure 4-18 Forecast of net emissions (MM tons of CO_{2eq}) in the year 2050 for each scenario and for each future
SOURCE: SELFMADE

Figure 4-18 shows that under the IM scenario, carbon neutrality is only achieved in the Green Future (-7.4 MM tons CO_{2eq}), in the rest of the futures the 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 MMton CO_{2eq}), and under the Reference Future (-9.4 MMton CO_{2eq}) but no under the Red Future.

The results shows that the NDC measures (in Reference Future) allow to get closer to the commitments (2.9 MM tons CO_{2eq} to 2050) but are not enough to meet the goals established in the NDC. On the other hand, the AM scenario shows that under all the futures the targets set for 2030 could be overachieved, and only for the Red Future the carbon neutrality wouldn´t be reached by 2050. In conclusion, it would be necessary to include more additional measures to the IM scenario, to achieve the NDC goals and to be able to sell credits on the climate teams inititative.

4.5. Mitigation Costs: MACC

For the study of mitigation costs, each of the mitigation actions was characterized by its abatement potential and the average cost of mitigation of one tCO_{2eq}. This is presented in the annexes of the present 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 Current Policies 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 in emissions of other sectors (e.g., caused by changes on electricity or wood demand). This difference applies only to the period 2020-2030 which coincides with the NDC carbon budget commitment.
- Average cost of mitigation: Correspond to the discounted costs of investments, operating costs, and savings, divided by the total mitigation potential on the period 2020-2050. It is important to notice 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 don't occur at the same time. For example, this helps a better evaluation of an action with an important investment and mitigation that occurs in the future.

To better understand the mitigation cost a MAC Curve is presented, the legend of which is described in Table 4-1. The values of abatement cost and emission reduction associated with this MAC curve are presented in Table 4-2, for each action. In this curve 44 mitigation actions are included from the different sectors modelled. The abatement potential is considered to be the mitigation estimated between the Current Policies and Accelerated Mitigation scenarios for each of the actions included in the Accelerated Mitigation scenario. The following figure presents the resulting MAC of this exercise. In order to fulfill its Carbon Budget 2020-2030, Chile needs to mitigate an additional 93 M tCO_{2eq}, any mitigation beyond which could be sold.

Table 4-3 Mitigation actions legend for the MACC Curve presented in Figure 4-14

Sector	id	Full name of the mitigation action
Electricity generation	1	Decarbonization by the Phase out of Coal Power Plants
Transport	1	Electromobility: Private cars: 58% of the private car on 2050
	2	Hydrogen on freight trucks: 85% of the freight trucks on 2050
	3	New bus rapid transit corridors in Santiago: Installation of 150 km of new BRT corridors (total of 245 km) between 2027 and 2032
	4	Incentive to new bicycle infrastructure: 3000 km of new bikeway installed between 2025 and 2030. Estimated impact of a reduction on 10% from urban passenger demand.
	5	Hydrogen on commercial flights: 10% of flights with hydrogen on 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 on public hospitals

Sector	id	Full name of the mitigation action
	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 heater
	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 refrigerants plants: New installed capacity for 2.800 t/year al 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

SOURCE: AUTHORS

Table 4-4 Abatement cost and emission reduction of the mitigation actions included in the MACC Curve associated with the reference future, presented in Figure 4-19

Mitigation action	Abatement cost [USD/tCO_{2eq}]	Emission reduction [$MtCO_{2eq}$]
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-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
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
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

Mitigation action	Abatement cost [USD/tCO_{2eq}]	Emission reduction [$MtCO_{2eq}$]
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

SOURCE: AUTHORS

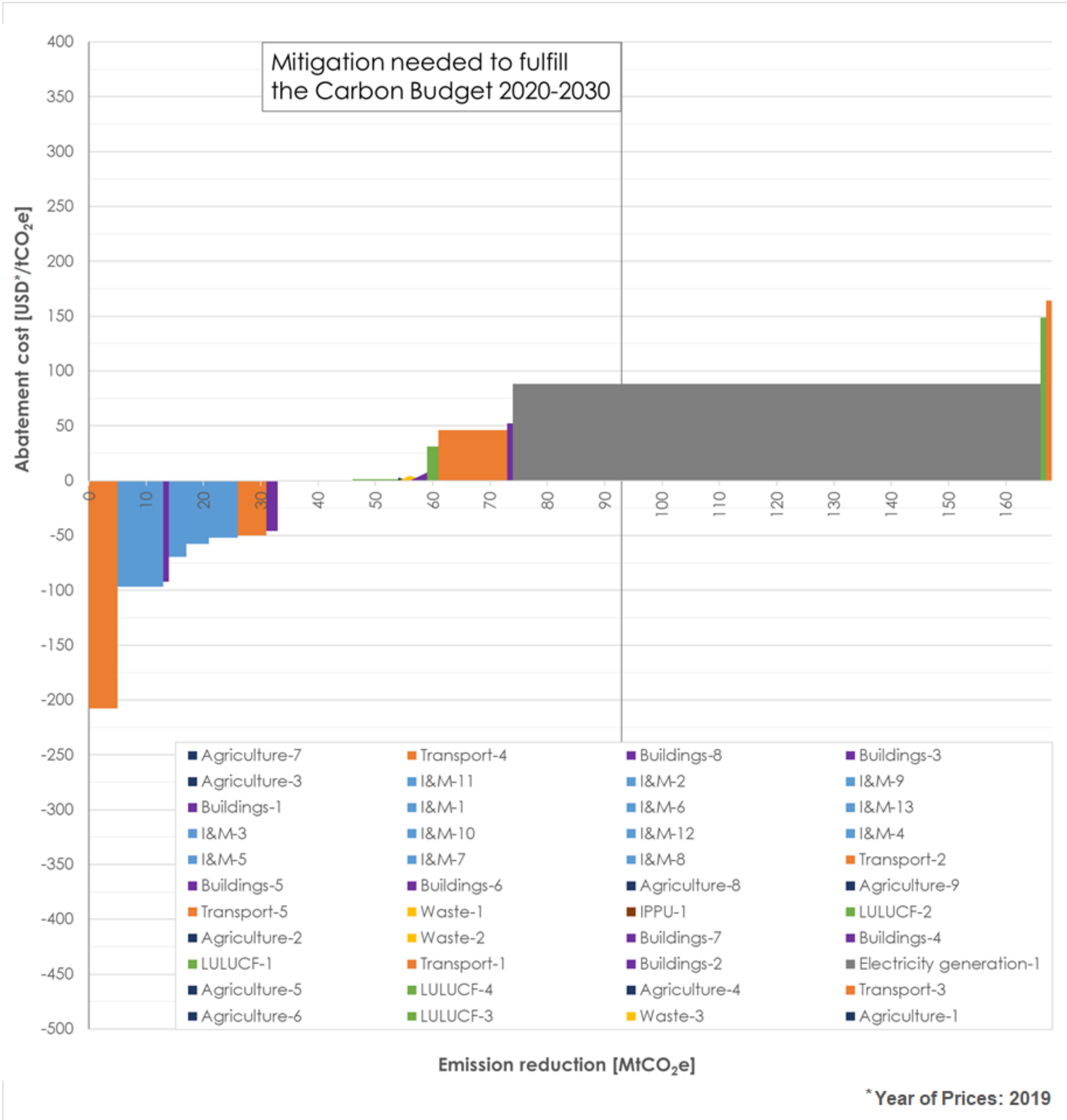

Figure 4-19 MACC curve for the 2020-2030 period for the reference future

SOURCE: AUTHORS

It is observed that 169 M tCO_{2eq} could be mitigated in the period 2020-2030 if every mitigation action is implemented. The mitigation cost goes from -344 USD/tCO_{2eq} (reduction of agricultural burning) to 360 USD/tCO_{2eq} (change in bovine diet). It is also noticeable that 34 M tCO_{2eq} has a mitigation cost below 0 USD/tCO_{2eq}, and 61 M tCO_{2eq} could be mitigated with a cost under 40 USD/tCO_{2eq}. The mitigation action with the larger mitigation abatement (the big grey area in the horizontal axis) is the accelerated Coal phase out (no coal electricity generation after 2025) with 92 M tCO_{2eq} of mitigation potential (with an average cost of 88 USD/tCO_{2eq}), followed by the electromobility in private cars with 13 M tCO_{2eq} available for mitigation at a cost of 46 USD/tCO_{2eq}).

It´s important to notice that there is a high political pressure to accelerate the decommissioning of coal power plants, so it's very likely that Chile will implement this action even if is not the cheapest one, this leaves around 60 M tCO_{2eq} that could be sold at around 40 USD/ tCO_{2eq}. For comparison, the following figure presents a MAC Curve considering that decommissioning of Coal Power plants will occur. In this case, if all measures with cost bellow cero where implemented, this would we associated with a potential reduction of 126 M tCO_{2eq}, which leaves 33 M tCO_{2eq} above Chile's Carbon Budget.

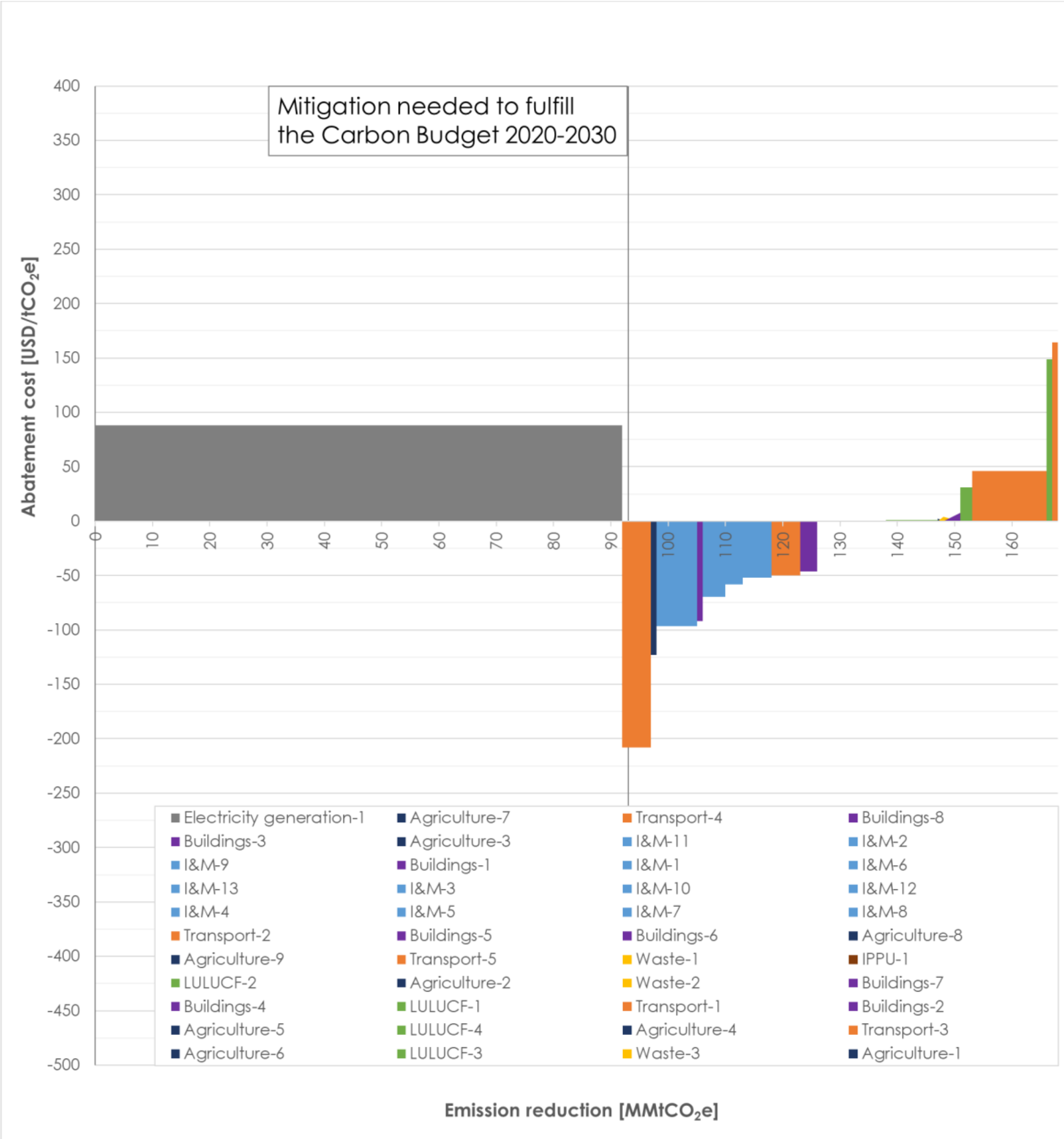

Figure 4-20 MACC curve for the 2020-2030 period for the reference future, forcing the decommission of Coal Power plants as certain
SOURCE: AUTHORS

The following table shows the mitigation abatement for the 2020-2030 period by sector for the reference future. It shows the relevance of the electricity generation sector, followed by the transportation and I&M sectors with a contribution of around 22 M tCO_2e each. In a second level Transportation and LULUCF appears with around

11 $MtCO_{2eq}$ of mitigation potential. The remaining sectors (agriculture, buildings, IPPU, and waste) contribute close to 6 $MtCO_{2eq}$ each.

Table 4-5 Mitigation abatement for the 2020-2030 by sector for the Reference Future

Sector	Abatement potential IM vs CP [$MMtCO_{2eq}$]	Abatement potential AM vs IM [$MMtCO_{2eq}$]	Total abatement potential for 2020-2030 [$MMtCO_{2eq}$]
Electricity generation	28	65	92
Transport	8	16	24
I&M	16	3	20
Buildings	5	2	7
Waste	4	-0,03[22]	4
IPPU	-	6	6
Agriculture	2	4	5
LULUCF	-	11	11
TOTAL	**63**	**106**	**169**

SOURCE: AUTHORS

[22] The result is negative because of the composting mitigation action. This action. which has some GHG emissions in the form of CH_4 emissions during the compost process (in the same year), avoids larger future emissions of CH_4 because of the decomposition of organic waste in landfills, which would happen in a larger period of time. This imbalance between the period of emissions of composting and landfills, results in a small emission in the first years of the compost, but in GHG reduction in the long term.

It is relevant to consider these results as a preliminary approach of the mitigation potential and costs, as the implementation of any of the actions presented could need a whole set of studies to determine a more precise estimation, nevertheless the current results represent the best estimation given the resources available for the modelling team. Is important to consider that more mitigation action could be included in future exercises, this will modify the results, changing the MACC and the conclusions derived from it.

The MACC Curves associated with the Green and Red Futures are presented in ANNEX 3: MACC Curve for other futures.

4.6. Analysis of measures with negative mitigation costs

In the previous section were presented several mitigation actions that had negative mitigation costs, this should mean that this action should happen by their own, because is profitable to do it, even without considering the environmental benefits. There are many reasons that explains why a mitigation action that has a negative mitigation costs from a social perspective, it isn´t happening:

- 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 isn´t the one that gets the benefits:
- Imperfect information

5. Conclusions and further work

The current work and results represent a first step which was ambitious to develop and integrate a prospective model for the GHG emissions in Chile, which focus on the near-term emissions, but which extends with projections to the midcentury. The results should be interpreted as the "current" results, as the prospective modelling has been understood as an iterative process. Under this conception the main results of the efforts 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 the ambitious NDC of Chile. Moreover, these additional reductions are costly, which should be considered when analysing any mechanism that supports international resource transfers for climate mitigation.

The modelling process took advantages from previous experience, calibrating previously developed models to better represent the situation observed in the last few years, which implies considering impacts suchs as the COVID pandemic and the social unrest that Chile experienced in the last months of 2019. At the same time, recent actions are also included, which are expected to impact Chile's GHG emissions in the short term, such as the acceleration of the closure of part of the coal-fired power plants, the promotion of the electrification of public transport or the application of the law to encourage recyclability.

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.
    - A model such as LEAP does not consider the effect of saturated transmission lines, which arises from certain technologies such as PV being placed very close to one another.
    - Pure energy storage processes were not represented, when they are expected to become important beyond 2030.

- This model did not use a refined temporal resolution, meaning that it had a scenario for winter and another for summer, and 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 sectors:
  - The transport sector follows a bottom-up approach that is based on a regional transportation demand. This approach makes it actions particularly difficult to model territorial mitigation actions, since a series of assumptions are needed in order to include this kind of actions.
  - The modeling of electricity penetration in households, industry and transportation follows a logic based on historic data and comparative penetration rates from developed countries. 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 the GDP and the population, the distribution of the different kinds of waste is based on data from developed countries and is not sensible to the GDP.
  - Recently the government has published a strategy for organic waste, this strategy set ambitious goals, but there exists the question on the actual actions to fulfill the goals. These goals are only partially considered in the modeling.
- IPPU:
  - There is room to better connect the IPPU model with the other sectorial models. The lack of data, specially in the industrial refrigeration sector is one of the main difficulties to achieve 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

  - For the projection of cattle and pigs (responsible for 68% of the emissions of the agricultural sector) an economic model was used, explained by national projections of commodity prices, presenting high variability for the different futures to consider, and possibly improving it.

  - 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 Greenhouse Gases, 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 have the information that allows their accounting.

- LULUCF

  - This model is a national approach to the sector, and the projectios are made with emission factors derived from the historical calculation of GHG emissions of the subsectors due to the lack of complete regional data.

  - Wildfire emissions is still a big source of uncertainty since the area that is burned every year, and thus emissions, comes from a small part of fires that escapes suppression and control. These few wildfires events are unpredictable.

  - The model does not consider uncertainties such as future yield change of native forest and plantations or changes in harvest frequencies due to climate change.

- Kelp forest management cost were determined using data based on implementations from developed countries.

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

1. Implement modifications based on comments and suggestions received during the diffusion phase of the modelling process and its results. This includes:
    a. Revisit definitions used in the architecture of models to be sure they are in line with the definitions used in other climate teams initiatives.
    b. Increase the ambition in measures thay 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[23]. This may be done by modeling earlier penetration, as well as changing the level of penetration itself. Notice that this is not a complex task.
    d. Asses if there are other factors to be considered in the projections, for example, the GDP of Southeast Asia.
    e. Evaluate possible modifications of the assumptions of the model, for example, the projected hidrology for each future could be modified for drier scenarios, which could be more likely 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 in the creation of front-end for the prospective models that allows the user to explore different combinations of actions and level of ambitions.

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

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

As a general conclusion, the first results of this modelling exercise shows that Chile needs to implement additional mitigation efforts in order to fulfill their NDC in relationship with the Carbon Budget. The main difference with the results developed by the Government of Chile (Palma et al, 2019) is related with the contribution of the electricity sector.

There is a set of additional mitigation action that would allow Chile to fullfill the 2020-2030 Carbon Budget and even overachieved. The mitigation cost of overachieving the NDC is costly but is possible that the decommission of Coal Power plants will happen earlier (2025).

In the case of the agriculture sector, which represents around 10.6% of national emissions for the year 2018, it presents a relatively low future mitigation potential, mainly due to the additional cost efforts that must be made, which are relatively high, with high uncertainty, in addition to 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 emissions (2018), however, a slight decrease in national production is projected by 2030. Projections for pigs show an increase for 2030, that represent around a 12% of the sector's emissions, without However, this differs from the projections for pigs made by FAO 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, to reduce it emissions.

In the case of the LULUCF sector, the mitigation options assessed were mainly those associated with Chile's NDC; forestation, natural forests management and forest degradation reductions through wildfires prevention. Additional measures were assessed for an accelerated mitigation scenario (AM); Kelp forests management and increases in protected natural areas. The outcomes from the implementation of each of these mitigation options show that by far, and only from the mitigation standpoint, forestation with exotics 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 about exotic forestation, mainly related to water usage and wildfire proneness of these plantations. When compared to forestation with native species, the abatement cost is very high because of the lower growth rates of native species, is almost 18 times smaller and the costs are 4 times higher and does not consider any income. Natural forest management is also a reasonable option, not only because it has a high mitigation potential with costs per tCO_2eq much smaller than plantation with native species, but also is linked to multiple co-benefits; such as biodiversity, water and soil conservation; landscape connectivity and recreation among other. Measures aimed to decrease native forests degradation by wildfires is 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 wildfires management (in this case using firebreaks) is subject to great uncertainty, because large wildfires occurrence is highly uncertain, and investing in wildfire prevention (not suppression) is probably a risk-proof option and in general more efficient than investing in fire suppression. Considering all these results (total costs, cost per ton of CO2 and mitigation potential) the NDC scenario must be considered a bottom line for the LULUCF sector, a minimum that Chile must aim to improve.

The additional measures (Kelp management and more natural protected areas) are overall marginal on the big picture for LULUCF. The differences between mitigation scenarios IM and AM are in the range of 1.24-1.77 MM, which seems marginal for an expected (IM scenario, Reference future) mitigation of -73.8 MM tCO_2eq.

It is relevant to consider these results as a preliminary approach of the mitigation potential and costs, as the implementation of any of the actions presented could need 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 scenario, 62 MtCO2e are estimated to be available in excces of the budget commitment. Preliminary results of new runs based on different carbon prices, suggests that 70% of the 62 MtCO2e are available with a marginal cost of less than 50 USD/tCO2e. Furthermore, the central estimations of the capital cost needed to achieve this 70% is around 2.8 billion of USD.

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7. ANNEXES

7.1. ANNEX 1: Description of the mitigation measures

7.1.1. 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 5 USD/tCO_2 and goes up linearly between 2030 and 2050 reaching a cap of 32.5 USD/tCO_2 according to the PELP (2020). ● The phase out of the coal power plants follows the decarbonization plan proposed by the MEN (2020) and the 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	Energía Abierta. (Comisión Nacional de Energía, 2021) Análisis de la Operación y Abastecimiento del Sistema Eléctrico Nacional de Chile en un escenario de retiro total de centrales a carbón al año 2025. (Coordinador Eléctrico Nacional, 2020) Programa Diario de Generación. (Coordinador Eléctrico Nacional, 2021) Plan de Retiro y/o Reconversión de Unidades a Carbón. (Ministerio de Energía, 2020) Planificación Energética de Largo Plazo. (Ministerio de Energía, 2020)

Emission Reduction

	Year 2030 IM	Year 2030 AM
Emission reduction (MM tCO_{2eq})	Red: 28.29 Ref: 24.85 Green: 21.77	Red: 30.26 Ref: 32.44 Green: 30.08
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	Red: 56.88 Ref: 27.51 Green: 7.91	Red: 90.57 Ref: 92.37 Green: 83.85
Cost Evaluation (period 2020-2050)		
	6% Discount rate	
Total Cost (MM USD)	Red: 30451.57 Ref: 22971.71 Green: 11337.55	
Abatement cost (USD/t CO_2eq)	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 100 USD/tCO_2 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 5 USD/tCO_2. For the IM scenario it goes up linearly between 2030 and 2050 reaching a cap of 32.5 USD/tCO_2 according to the PELP (2020). However, for the AM scenario, the carbon tax changes to 50 USD/tCO_2 in 2025 and goes up linearly until it reaches 100 USD/tCO_2 in 2050. • The phase out of the coal power plants follows the decarbonization 2040 plan proposed by the MEN (2020) and the 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	Energía Abierta. (Comisión Nacional de Energía, 2021) Análisis de la Operación y Abastecimiento del Sistema Eléctrico Nacional de Chile en un escenario de retiro total de centrales a carbón al año 2025. (Coordinador Eléctrico Nacional, 2020) Programa Diario de Generación. (Coordinador Eléctrico Nacional, 2021) Plan de Retiro y/o Reconversión de Unidades a Carbón. (Ministerio de Energía, 2020) Planificación Energética de Largo Plazo. (Ministerio de Energía, 2020)

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	Red: 28.29 Ref: 24.85 Green: 21.77	Red: 29.52 Ref: 32.12 Green: 25.93
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	Red: 56.88 Ref: 27.51 Green: 7.91	Red: 76.33 Ref: 81.1 Green: 38.39
Cost Evaluation (period 2020-2050)		
	6% Discount rate	
Total Cost (MM USD)	Red: 26978.51 Ref: 21684.87 Green: 8827.52	
Abatement cost (USD/t CO_2eq)	Red: 140.09 Ref: 85.48 Green: 44.6	

7.1.2. Transport actions

Name	**Electromobility: Private cars: 58% of the private car on 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.56** 0.54 ~ 0.59	**3.80** 3.86 ~ 3.72
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**2.65** 2.53 ~ 2.84	**12.91** 12.78 ~ 13.02
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Cost (MM USD)	**592.8** 586.5 ~ 597.5	
Abatement cost (USD/t CO_2eq)	**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.	
Costs Elements	The investment in hydrogen trucks and their operating cost were accounted for, as well as the reduction in the use of diesel and the investment avoided in trucks with a diesel engine.	
References	Benavides et al. (2021) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**1.43** 1.40 ~ 1.46	**1.43** 1.40 ~ 1.46
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**4.97** 4.86 ~ 5.09	**4.97** 4.86 ~ 5.09
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-248.4** -243.0 ~ -254.7	
Abatement cost (USD/t CO_2eq)	**-50.00**	

Name	**New bus rapid transit 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 bellow.
General Description	Investment on new corridors specially for buses (150 km), as a way to incentive the 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 on bus usage of 7%. It is assumed that all this increase comes from private cars.
Costs Elements	The investment cost associated with the new bus rapid transit corridors in Santiago were considered, as well as the associated reduction in the use of private cars powered by fossil fuels.
References	Sistemas sustentables (2014) MAPS initiative - Baseline scenario 2013 projection and mitigation scenarios of the transportation sector

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.0**	**0.36** 0.31 ~ 0.41
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0**	**0.76** 0.74 ~ 0.78

Cost Evaluation (period 2020 - 2050)	
	Discount rate 6%
Total Cost (MM USD)	**125.1** 128.3 ~ 122.0
Abatement cost (USD/t CO_2eq)	**164.10**

Name	**Incentive to new bicycle infrastructure: 3000 km of new bikeway installed between 2025 and 2030. Estimated impact of a reduction on 10% from urban passenger demand.**
Source	Expert opinion of the authors and the reference cited bellow.
General Description	Investment on new infrastructure for bicycles: a total of 3000 km of new bikeways
Modeling	
Main Assumptions	The new infrastructure impacts only on private cars. The impact is a reduction of 10% of the emissions on the urban area, based on previous studies.
Costs Elements	The investment costs associated with the new bicycle infrastructure were taken into account, as well as the reduction in the use of private cars powered by fossil fuels.
References	Sistemas sustentables (2014) MAPS initiative - Baseline scenario 2013 projection and mitigation scenarios of the transportation sector

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.0**	**1.52** 1.48 ~ 1.56
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0**	**5.00** 4.89 ~ 5.12

Cost Evaluation (period 2020 - 2050)	
	Discount rate 6%
Total Cost (MM USD)	**-2,103.0** -2151.1 ~ -2055.0
Abatement cost (USD/t CO_2eq)	**-420.30**

Name	**Hydrogen on commercial flights: 10% of flights with hydrogen in 2050, linear increase from 2035.**
Source	Expert opinion of the authors and the reference cited bellow.
General Description	Replace of aviation kerosene with hydrogen for 10% of the flights in 2050
Modeling	
Main Assumptions	The action is modelled as starting on 2035, and the rate of participation of hydrogen grows linearly between 2035 and 2050. It's 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.0**	**0.0**
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0**	**0.0**

Cost Evaluation (period 2020 - 2050)	
	Discount rate 6%
Total Cost (MM USD)	**0.0**
Abatement cost (USD/t CO_2eq)	**0.0**

7.1.3. Industry & Mining Actions

Name	**Copper-Solar thermal systems: 16% by 2050, NDC+ 30% by 2050**	
Source	Chilean NDC.	
General Overview	Incentives to accelerated 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.052** 0.048 ~ 0.056	**0.108** 0.101 ~ 0.115
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.43** 0.39 ~ 0.47	**0.88** 0.80 ~ 0.95
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-61.11** -55.99 ~ -65.99	
Abatement cost (USD/t CO_2eq)	**-69.80**	

Name	Copper-Electrification in thermal processes: Additional 25%	
Source	Chilean NDC.	
General Overview	Incentives to accelerated transition from fossil fuel combustion in thermal processes to electricity use.	
Modeling		
Main Assumptions	Same penetration rate as assumed on 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) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.16** 0.15 ~ 0.17	**0.18** 0.17 ~ 0.19
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.88** 0.75 ~ 1.04	**1.20** 1.10 ~ 1.28
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-116.10** -106.6 ~ -123.93	
Abatement cost (USD/t CO_2eq)	**-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 accelerated transition from fossil fuel in motor processes to electricity use.		
Modeling			
Main Assumptions	Same penetration rate as assumed on the design of the NDC on 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) NDC		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})		**0.66** 0.56 ~ 0.77	**0.77** 0.64 ~ 0.89
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**2.80** 2.31 ~ 3.36	**3.31** 2.83 ~ 3.69
Cost Evaluation (period 2020-2050)			
		Discount rate 6%	
Total Cost (MM USD)		**-191.7** -164.3 ~ -214.2	
Abatement cost (USD/t CO_2eq)		**-58.00**	

Name	**Copper-Hydrogen in motor processes: 37% in open pit mining by 2050**
Source	Chilean NDC.
General Overview	Incentives to accelerated transition from fossil fuel combustion in motor processes to green hydrogen use.
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	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) NDC

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.43** 0.36 ~ 0.50	**0.43** 0.36 ~ 0.50
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**2.30** 1.98 ~ 2.63	**2.30** 1.98 ~ 2.63

Cost Evaluation (period 2020-2050)	
	Discount rate 6%
Total Cost (MM USD)	**-119.7** -103.2 ~ -136.9
Abatement cost (USD/t CO_2eq)	**-52.00**

Name	**Copper-Hydrogen in motor processes: 8% in underground mining by 2050**		
Source	Chilean NDC.		
General Overview	Incentives to accelerated transition from diesel trucks to green hydrogen use.		
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	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) NDC		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})		**0.012** 0.010 ~ 0.014	**0.012** 0.010 ~ 0.014
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**0.059** 0.050 ~ 0.067	**0.059** 0.051 ~ 0.067
Cost Evaluation (period 2020-2050)			
		Discount rate 6%	
Total Cost (MM USD)		**-3.07** -2.64 ~ -3.50	
Abatement cost (USD/t CO_2eq)		**-52.00**	

Name	**Various Industries-Solar thermal systems: 33% by 2050, NDC+ 46% by 2050**
Source	Chilean NDC
General Overview	Incentives to accelerated transition from fossil fuel combustion and electricity use in motor processes to solar thermal systems.
Modeling	
Main Assumptions	Same penetration rate as assumed on the design of the NDC on 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.36** 0.34 ~ 0.37	**0.50** 0.48 ~ 0.51
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**2.11** 2.10 ~ 2.11	**2.84** 3.03 ~ 2.97

Cost Evaluation (period 2020-2050)	
	Discount rate 6%
Total Cost (MM USD)	**198.4** 207.0 ~ 211.2
Abatement cost (USD/t CO_2eq)	**69.80**

Name	**Various Industries-Hydrogen in thermal processes: 3% by 2050**	
Source	Chilean NDC.	
General Overview	Incentives to accelerated transition from fossil fuel combustion and electricity use in thermal processes to green hydrogen use.	
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	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) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.032** 0.031 ~ 0.033	**0.032** 0.031 ~ 0.033
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.163** 0.159 ~ 0.167	**0.163** 0.159 ~ 0.167
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-8.47** -8.27 ~ -8.68	
Abatement cost (USD/t CO_2eq)	**-52.00**	

Name	**Various Industries-Hydrogen in motor processes: 12% by 2050**
Source	Chilean NDC.
General Overview	Incentives to accelerated transition from fossil fuel combustion in motor processes to green hydrogen use.

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	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) NDC

Emission Reduction	**Year 2030 IM**	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.34** 0.33 ~ 0.35	**0.34** 0.33 ~ 0.35
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**1.70** 1.66 ~ 1.74	**1.70** 1.66 ~ 1.74

Cost Evaluation (period 2020-2050)	**Discount rate 6%**
Total Cost (MM USD)	**-88.5** -86.4 ~ -90.6
Abatement cost (USD/t CO_2eq)	**-52.00**

Name	**Various Industries-Electrification in motor processes: 88% by 2050**
Source	Chilean NDC.
General Overview	Incentives to accelerated transition from fossil fuel in motor processes to electricity use.
Modeling	
Main Assumptions	Same penetration rate as assumed on 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) NDC

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.73** 0.71 ~ 0.76	**0.73** 0.71 ~ 0.76
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**3.27** 3.13 ~ 3.42	**3.35** 3.26 ~ 3.40

Cost Evaluation (period 2020-2050)	
	Discount rate 6%
Total Cost (MM USD)	**-324.0** -315.7 ~ -328.5
Abatement cost (USD/t CO_2eq)	**-96.70**

Name	**Various Mines-Hydrogen in motor processes: 21% by 2050**	
Source	Chilean NDC.	
General Overview	Incentives to accelerated transition from fossil fuel combustion in motor processes to green hydrogen use.	
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	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) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.14** 0.13 ~ 0.16	**0.14** 0.13 ~ 0.16
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.73** 0.68 ~ 0.78	**0.73** 0.68 ~ 0.78
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-38.0** -35.6 ~ -40.5	
Abatement cost (USD/t CO_2eq)	**-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 accelerated transition from fossil fuel in motor processes to electricity use.	
Modeling		
Main Assumptions	Same penetration rate as assumed on the design of the NDC on 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) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.41** 0.38 ~ 0.45	**0.47** 0.43 ~ 0.50
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**1.83** 1.68 ~ 2.01	**3.11** 2.25 ~ 3.11
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-301.0** -217.5 ~ -283.6	
Abatement cost (USD/t CO_2eq)	**-96.70**	

Name	**Steel Industry-Hydrogen in thermal processes: 10% by 2050**	
Source	Benavides et al. (2021)	
General Overview	Incentives to accelerated 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.0**	**0.0065** 0.0061 ~ 0.0068
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0**	**0.035** 0.034 ~ 0.037
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-1.8** -1.7 ~ -1.9	
Abatement cost (USD/t CO_2eq)	**-52.00**	

Name	**Steel Industry-Biomass in thermal processes: 10% by 2050**		
Source	Benavides et al. (2021)		
General Overview	Incentives to accelerated 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})		**0.0**	**0.0088** 0.0084 ~ 0.0092
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**0.0**	**0.048** 0.046 ~ 0.051
Cost Evaluation (period 2020-2050)			
		Discount rate 6%	
Total Cost (MM USD)		**-2.8** -2.7 ~ -2.9	
Abatement cost (USD/t CO_2eq)		**-58.00**	

7.1.4. Buildings Actions

Name	**Commercial: Electrification of end uses**	
Source	Chilean NDC	
General Overview	Incentives to an accelerated electrification of the commerce sector	
Modeling		
Main Assumptions	Same penetration rate as the one assumed on the design of the NDC: by 2050 the electrification is around 70% of the consumption of energy. On the base line 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.000**	**0.188** 0.187 ~ 0.172
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.033** 0.02 ~ 0.04	**0.661** 0.67 ~ 0.61
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-60.8** -61.3 ~ -55.8	
Abatement cost (USD/t CO_2eq)	**-92.08**	

Name	**Public: Solar water heaters on public hospitals**
Source	Chilean NDC
General Overview	Installation of solar colleting energy on hospital roofs for the use on hot sanitary water.
Modeling	
Main Assumptions	Same penetration rate as the one assumed on the design of the NDC: by 2050 the recollected 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 base line 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.00107** 0.00111 ~ 0.00102	**0.0053** 0.0056 ~ 0.0051
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0052** 0.0050 ~ 0.0054	**0.026** **0.025 ~ 0.027**

Cost Evaluation (period 2020 - 2050)	
	Discount rate 6%
Total Cost (MM USD)	**1.36** 1.31 ~ 1.41
Abatement cost (USD/t CO_2eq)	**52.30**

Name	**Public: Electric heating on public hospitals**
Source	Chilean NDC
General Overview	Incentives to an accelerated electrification of the heating in public hospitals
Modeling	
Main Assumptions	Same penetration rate as the one assumed on 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 base line 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.0024** 0.0021 ~ 0.0029	**0.0072** 0.0067 ~ 0.0070
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.009** 0.007 ~ 0.011	**0.030** 0.028 ~ 0.031

Cost Evaluation (period 2020 - 2050)	
	Discount rate 6%
Total Cost (MM USD)	**-3.96** -3.66 ~ -4.03
Abatement cost (USD/t CO_2eq)	**-130.20**

Name	Public: Solar PV on public buildings		
Source	Expert opinion of the authors.		
General Overview	Incentives to the installation of PV on public buildings on the center and north of Chile		
Modeling			
Main Assumptions	Installation of Photo-Voltaic solar panels on public installations from the eight regions to the north. Enough panels to supply 50% of the electric demand on 2050. It considers a linear penetration starting from 2021.		
Costs 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})		**0.0**	**0.038** 0.039 ~ 0.042
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**0.0**	**0.238** 0.244 ~ 0.246
Cost Evaluation (period 2020 - 2050)			
		Discount rate 6%	
Total Cost (MM USD)		**6.90** 7.09 ~ 7.13	
Abatement cost (USD/t CO_2eq)		**29.00**	

Name	**Residential: Electric heating**	
Source	Chilean NDC	
General Overview	Program to replace combustion heaters for electric heaters	
Modeling		
Main Assumptions	Same penetration rate as the one assumed on the design of the NDC: by 2050 the heating electrification is around 72% of the houses and 89% of apartments The base line considers. by 2050. around 20% of houses and 40% of apartments with electric heating. The heaters replaced are distributed as the distribution on 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 on the LULUCF model.	
Costs 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.45** 0.42 ~ 0.51	**0.45** 0.42 ~ 0.51
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**1.73** 1.56 ~ 1.97	**1.73** 1.56 ~ 1.97
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-79.7** -71.8 ~ -90.7	
Abatement cost (USD/t CO_2eq)	**-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 on the design of the NDC: by 2050 the stove electrification is around 36% of the houses and 35% of apartments The NDC+ scenario considered 72% of houses and 89% of apartments with electric stoves The base line considers 0 penetration of electricity on stoves. The stoves replaced are distributed as the distribution on 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.	
Costs Elements	Considers the investment in electric motors, the reduction in fossil fuels 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) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.072** 0.068 ~ 0.252	**0.219** 0.211 ~ 0.219
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.379** 0.354 ~ 0.412	**1.051** 1.013 ~ 1.047
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-48.5** -48.3 ~ -46.7	
Abatement cost (USD/t CO_2eq)	**-46.13**	

<table>
<tr><td>Name</td><td colspan="2">Residential: Solar water heaters</td></tr>
<tr><td>Source</td><td colspan="2">Chilean NDC</td></tr>
<tr><td>General Overview</td><td colspan="2">Installation of solar thermal roofs on residential houses to supply hot sanitary water</td></tr>
<tr><td colspan="3">Modeling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">Same penetration rate as the one assumed on the design of the NDC: by 2050 the heating electrification is around 63% of the houses and 57% of apartments
The base line consider. by 2050. 0 solar thermal roofs.
The impact on the reduction of wood is not included on the quantified reduction. although it is included on the LULUCF model.</td></tr>
<tr><td>Costs Elements</td><td colspan="2">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.</td></tr>
<tr><td>References</td><td colspan="2">Benavides et al. (2021) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty
Gobierno de Chile (2020) NDC</td></tr>
<tr><td colspan="3">Emission Reduction</td></tr>
<tr><td></td><td>Year 2030 IM</td><td>Year 2030 AM</td></tr>
<tr><td>Emission Reduction (MM tCO_{2eq})</td><td>0.584
0.578 ~ 0.582</td><td>0.564
0.561 ~ 0.572</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>3.18
3.15 ~ 3.19</td><td>3.07
3.05 ~ 3.11</td></tr>
<tr><td colspan="3">Cost Evaluation (period 2020 - 2050)</td></tr>
<tr><td></td><td colspan="2">Discount rate 6%</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">23.6
23.5 ~ 23.9</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">7.70</td></tr>
</table>

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 on the design of the NDC: 20k houses intervened by year. For the NDC+ scenario a level of 40k houses retrofitted by year is considered On the base line 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 on the quantification reduction. although it is included on the LULUCF model.	
Costs Elements	Considers the investment in thermal insulation, and the reduction in fossil fuels and electricity consumption.	
References	Benavides et al. (2021) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.0157** 0.0154 ~ 0.0160	**0.0377** 0.0372 ~ 0.0387
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.093** **0.092 ~ 0.095**	**0.186** 0.189 ~ 0.184
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Cost (MM USD)	**-32.1** -31.8 ~ -32.7	
Abatement cost (USD/t CO_2eq)	**-172.90**	

7.1.5. 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 landfills operation by 2030	
Modeling		
Main Assumptions	The installation of torches on landfills starts in 2024 and grows linearly until 2030 when all the landfills do have torches. A 45% of capture efficiency is considered	
Costs Elements	Considers the investment in new torches, and the costs in operation and maintenance of them.	
References	GreenLab (2014) MAPS initiative - Baseline scenario 2013 projection and mitigation scenarios of the anthropic waste sector Benavides et al. (2021) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty Gobierno de Chile (2020) NDC	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**1.59** 1.58 ~ 1.60	**1.59** 1.58 ~ 1.60
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**4.17** 4.14 ~ 4.20	**4.17** 4.14 ~ 4.20
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Cost (MM USD)	**5.80** 5.76 ~ 5.84	
Abatement cost (USD/t CO_2eq)	**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 recollect and compost 50% of the organic residential waste		
Modeling			
Main Assumptions	Starting from 2025, a chronogram is proposed for each region considering plants with a capacity of 30k and 50 k t of organic waste/y. The total capacity (t of organic waste/year) installed is: 2025- 240k; 2030 - 570k; 2035 - 980k; 2040-1.65M; 2045-2,14M; 2050-2,14M An 80% average plant factor is considered.		
Costs 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	GreenLab (2014) MAPS initiative - Baseline scenario 2013 projection and mitigation scenarios of the anthropic waste sector Benavides et al. (2021) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})		**0.0**	**-0.08**
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**0.0**	**-0.09**
Cost Evaluation (period 2020 - 2050)			
		Discount rate 6%	
Total Cost (MM USD)		**179.7**	
Abatement cost (USD/t CO_2eq)		**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 its urban surroundings: Great Concepcion; Great Valparaiso; La Serena-Coquimbo and Antofagasta
Modeling	
Main Assumptions	The capacity of treatment needed for each of the wastewater is estimated with the estimation of the demand on 2050. The operations of the plants begin in the year the plants are installed. This varies from city and scenario. On the NDC scenario the installation is expected to occur on 2030-Gran Concepcion; 2035 Gran Valparaíso; 2038-La Serena/Coquimbo and Antofagasta On the NDC+ scenario the installation is expected to occur two years before.
Costs Elements	Considers the investment and operational costs, relative to the different flows for each city.
References	GreenLab (2014) MAPS initiative - Baseline scenario 2013 projection and mitigation scenarios of the anthropic waste sector Benavides et al. (2021) Options for the achievement of carbon neutrality in Chile by 2050 under uncertainty

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.03**	**0.03**
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.03**	**0.09**

Cost Evaluation (period 2020 - 2050)	
	Discount rate 6%
Total Cost (MM USD)	**493.8**
Abatement cost (USD/t CO_2eq)	**344.61**

7.1.6. IPPU Actions

Name	**Recovery and regeneration of refrigerants plants: New installed capacity for 2.800 t/year al 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 modelled as business as usual.	
General Overview	Subsidized installation of new regeneration sites of HFC, increasing from 350 t/y (actual capacity) to 3150 t/year by 2030 (increase of 2800 t/y capacity)	
Modeling		
Main Assumptions	2 plants, each of 350 t/y, 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% on 2030 and 80% on 2050.	
Costs Elements	Considers the investment associated with the implementation of the two refrigerant regeneration plants and their cost of operation.	
References	GISMA (2014) Proyecto diseño del programa de regeneración. Hoglund-Isaksson et al. (2017) Cost estimates of the Kigali Amendment to phase-down hydrofluorocarbons. Global emissions of fluorinated greenhouse gases 2005-2050 with abatement potentials and costs	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.0**	**1.317** 1.318 ~ 1.327
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0**	**5.53** 5.54 ~ 5.57
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Cost (MM USD)	**5.57** 5.58 ~ 5.61	
Abatement cost (USD/t CO_2eq)	**0.18**	

7.1.7. Agriculture actions

Name	Change in bovine diet (lipidic additive)
General Overview	This measure considers an additional component in the diet in cattle from 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 the improvement of the diet of 70% of 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 the dairy-producing cattle by 2030. It was considered that a dairy cow lives 7 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, McGinn, & Petit, 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	Sunflower seed oil Price: https://bibliotecadigital.odepa.gob.cl/handle/20.500.12650/70638 Beauchemin, K. A., McGinn, S. M., & Petit, H. V. (2007). Methane abatement strategies for cattle: Lipid supplementation of diets. Canadian Journal of Animal Science, 87(3), 431–440. https://doi.org/10.4141/CJAS07011

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction in 2030 (MM tCO_2eq)	**0.0015** 0.013 ~ 0.017	**0.051** 0.045 ~ 0.059
Reduction of cumulative emissions from 2020 (MM tCO_2eq)	**0.0015** 0.013 ~ 0.017	**0.189** 0.16 ~ 0. 21

Cost Evaluation (period 2020-2050)	
	Discount rate 6%
Total Cost (including accelerated scenario) (MM USD)	**703** 597.25 ~ 840.5
Abatement cost (USD/t CO_2eq)	**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, specifically urea, potassium saltpeter, sodium saltpeter and ammonium phosphate, which correspond to nitrogen fertilizers provided by ODEPA as inputs of producers. By 2035, the application of 20% less nitrogen fertilizers without inhibitors in cereal crops and cereal seedbeds, and 15% less nitrogen fertilizers without inhibitors for industrial and forage crops, product of the technical assistance measures applied in rainfed soils and non-mechanized irrigation(leaching/runoff) or subjected to volatilization, was considered. No accelerated scenario was considered. The weight of each of these fertilizers was weighed by the average amount of imports between 2015-2017 provided by FAO. It was considered as the start date of linear implementation of the measure from the year 2026 to 2035.		
Cost Elements	This measure does not require investment costs. To calculate the savings of the measure, a weighted mineral nitrogen price of 537USD/ton was considered. .		
References	http://www.fao.org/faostat/es/#data/RFN		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction in 2030 (MM tCO_2eq)		**0.112** 0.10 ~ 0.12	**0.12** 0.10 ~ 0.12
Reduction of cumulative emissions from 2020 (MM tCO_2eq)		**0.34** 0.30 ~ 0.37	**0.34** 0.30 ~ 0.37
Cost Evaluation (period 2020-2050)			
		Discount rate 6%	
Total cost accumulated (MM USD)		**-555** **-494.7 ~ -615.2**	
Abatement Cost (USD/t CO_2eq)		**-123** -122 ~ 123.8	

<table>
<tr><th>Name</th><th colspan="3">Biodigesters Pigs</th></tr>
<tr><td>General Overview</td><td colspan="3">This measure considers the implementation of biodigesters at the property level to transform methane emissions (CH4) generated in wells or lagoons for the accumulation of organic waste (slurry and/or manure), into carbon dioxide (CO2), reducing the emission factor associated with gas generation.</td></tr>
<tr><th colspan="4">Modeling</th></tr>
<tr><td>Main Assumptions</td><td colspan="3">This measure considered the implementation of biodigesters and a biogas plant for power generation, with an average slurry processing capacity of 31,102m3.
An annual manure generation of 2.02 m3 / 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 pig heads.</td></tr>
<tr><td>Cost Elements</td><td colspan="3">A unit CAPEX of $ 1,555,024 USD per plant + plant is considered and an OPEX annual of $198.976 per plant unit, and an additional saving in the thermal and electrical energy produced by the biogas plant.</td></tr>
<tr><td>References</td><td colspan="3">Caroca, F. G. (2015). PLANTA DE BIOGÁS PARA AUTOABASTECIMIENTO ENERGÉTICO: UNA ESTRATEGIA PARA DIFERENTES CONTEXTOS. Universidad de Chile.</td></tr>
<tr><th colspan="4">Emission Reduction</th></tr>
<tr><td colspan="2"></td><th>Year 2030
IM</th><th>Year 2030
AM</th></tr>
<tr><td colspan="2">Emission reduction (MM tCO_2eq)</td><td>0.29
0.28 ~ 0.29</td><td>0.29
0.28 ~ 0.29</td></tr>
<tr><td colspan="2">Reduction of cumulative emissions from 2020 (MM tCO_2eq)</td><td>1.286</td><td>1.286</td></tr>
<tr><th colspan="4">Cost Evaluation (period 2020-2050)</th></tr>
<tr><td colspan="2"></td><th colspan="2">Discount rate 6%</th></tr>
<tr><td colspan="2">Total Cost accumulated (MM USD)</td><td colspan="2">49.09
15.2 ~ 95.7</td></tr>
<tr><td colspan="2">Abatement Cost (USD/t CO2eq)</td><td colspan="2">2.62
0.72 ~ 5.62</td></tr>
</table>

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) applied to soils of annual crops. Implementation starting in 2025, reaching 10% of the surface by 2030, and remaining constant until 2050.	
Modeling		
Main Assumptions	Using the Tier 1 Methodology of IPCC 2006 (Vol 4, Chapter 2, Equation 2.25 Vol), different management 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 temperate thermic regime. It is assumed that 12% of carbon inputs of poultry manure is retained as SOC in soils, (Maillard & Angers, 2014). Nitrogen emissions were consider	
Cost Elements	The Cost estimation considers the average price delivered for 3 quotations of m3 bird guano (Average ($ 11,000CLP/m3 (farmer reference price) + $ 6,000CLP/m3 (reference case study quinoa) + $ 2000CLP/m3 (Vial enterprise) / 3 = $ 7000 CLP/ m3) + plus the unit cost of transportation (CLP $ 250,000 transportation cost to transport 22m3), so the unit is $ 11,364 per m3 and also data on unit labor (30m3 = CLP ha / year = $ 13,000.- unit $ 433 m3) = $ CLP18,979 / 792 (average 2020 dollar) = 39,601 the value per m3 of manure. Also, it considers a additional yield increase of 30Kg/ha * 0.5tonCO2eq/ha.	
References	FAO. 2017. Carbono Orgánico del Suelo: el potencial oculto. Organización de las Naciones Unidas para la Alimentación y Agricultura Roma, Italia	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_2eq)	0	**0.069** 0.07 ~ 0.061
Reduction of cumulative emissions from 2020 (MM tCO_2eq)	0	**0.26** 0.23 ~ 0.29
Cost Evaluation (period 2020-2050)		
	6% Discount rate	
Total Cost accumulated to 2030 (MM USD)	**226.4** 203.7 ~ 249.	
Abatement Cost (USD/t CO_2eq)	**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 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, 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 12254 KgMS/ ha year, increasing the organic matter content in soils. An average annual catch of -0.2tonCO2eq/ha per 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 v / s Traditional for the period of 5 years (2014-2018).
Cost Elements	An increase in kgMS/ha and grazing measurement planning HH was considered, considering a value of $30,000 man day, considering a required amount per ha/year of 0.48, with an annual cost of $14,400CLP/year. It was also considered Labor separation properties / maintenance of fences at a value of $20.000 Man day, considering an amount required per ha / year of 4. 8, with an annual cost of $96,000CLP /year. This generates an extra annual operating cost of $110,400. A power savings per kgMS/ha year increase of $51,784 CLP/year is considered. The total cost of the measure per ha is $73.99USD/year, considering the average price of the value of the dollar in the year 2020(792CLP/USD).
References	The Carbon Underground. (2017). ¿ Qué es Agricultura Regenerativa ?, 1–2. https://thecarbonunderground.org/our-initiative/definition/

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_2eq)	0	**0.11** 0.09 ~ 0.12
Reduction of cumulative emissions from 2020 (MM tCO_2eq)	0	**0.415** 0.37 ~ 0.45

Cost Evaluation (period 2020-2050)	
	6% discount rate
Total Cost (MM USD)	**267.5** 240.7 ~ 294.2
Abatement Cost (USD/t CO_2eq)	**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 is the fifth country with the highest per capita consumption of beef in the world[24] An average consumption of 149 gr/meat per day was considered, of which 44grm/day is beef(Universidad de Chile, 2011). The consumption of reef meat was projected based on the Population (INE 2019) and the elasticity of demand (Nadia, 2020), and the projection of the producer price used to project the head of cattle(OECD Stats). 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, nor increase in other types of livestock considered as a replacement for this feed.	
Cost Elements	Costs were not considered given its high complexity in distribution.	
References	Nadia, B. Q. (2020). EVALUACIÓN DE INSTRUMENTOS ECONÓMICOS PARA LA MITIGACIÓN DE EMISIONES DE GEI PROVENIENTES DE LA GANADERÍA BOVINA EN CHILE. Tesis MSc En Economía Agraria y Ambiental. Universidad de Chile. (2011). Informe Final: ENCUESTA NACIONAL DE CONSUMO AL IMENTARIO. Centro de Microdatos - Facultad de Economía y Negocios, 1–102.	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_2eq)	0	**0.25** 0.22 ~ 0.29
Reduction of cumulative emissions from 2020 (MM tCO_2eq)	0	**2.55** 2.27 ~ 2.83
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Cost (MM USD)	N/A	
Abatement Cost (USD/t CO_2eq)	N/A	

[24] 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, methane (CH_4) and nitrous oxide (N_2O), (Ministerio de Medio Ambiente, 2021) 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 purposes, the nutrients present in the wheat stubble were considered) (Acevedo, 2003; Araya et al., 2009).
References	Acevedo, E. (2003). Sustentabilidad en cultivos anuales: Cero labranza manejo de rastrojos: Vol. No8. Universidad de Chile, Departamento de Producción Agrícola. http://cultivatuhuerto.cl/sitio/wp-content/uploads/2018/09/Sustentibilidad_en_cultivos_anuales-1-no-borrar.pdf Araya, J., Duprat, C., & Parra, M. (2009). Alternativas de Reemplazo a las Quemas de Residuos Agrícolas y Forestales. Corporación Nacional Forestal (CONAF). https://www.prevencionincendiosforestales.cl/documento/alternativas-de-reemplazo-a-las-quemas-de-residuos-agricolas-y-forestales/ Ministerio de Medio Ambiente. (2021). Informe del Inventario Nacional de Chile 2020: Inventario nacional de gases de efecto invernadero y otros contaminantes climáticos 1990-2018. Oficina de Cambio Climático. ODEPA. (2017). Series Quinquenales. Oficina de Estudios y Políticas Agrarias. https://www.odepa.gob.cl/precios/avance-por-productos

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	0	**0.024** 0.021 ~ 0.026
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	0	**0.13** 0.12 ~ 0.15
Cost Evaluation (period 2020-2050)		
	6% Discount rate	
Total Cost (MM USD)	**-213.6** -192.3 ~ -235	
Abatement cost (USD/t CO_2eq)	**-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 & 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 od ton/year (Bridgwater, 2009, obtenido de 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. On the other hand, it is assumed an application of 30 ton/ha of biochar versus applying 20 ton of compost per hectare per year (Qambrani et al., 2017; Shackley et al., 2011; Servicio Agrícola y Ganadero [SAG], 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 biooil from priolysis as fuels for the same plant (Rebolledo, et al., 2016; Qambrani et al., 2017). As well, the market price of compost (Vuelta Verde, s. f.; Lizama, 2018; Gordillo & Chávez, 2010) 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, F., & Chávez, E. (2010). Evaluación comparativa de la calidad del compost producido a partir de diferentes combinaciones de desechos agroinductriales azucareros. https://www.dspace.espol.edu.ec/bitstream/123456789/9112/1/Evaluaci%C3%B3n%20Comparativa%20de%20la%20calidad%20del%20compost.pdf Lizama, M. (2018). Mercado de Meteria Orgánica en Chile [Memoeria título pregrado, Federico Santa María - Departamento de Ingeniería Comercial]. https://repositorio.usm.cl/bitstream/handle/11673/47136/3560903501040UTFSM.pdf?sequence=1&isAllowed=y Oldfield, T. L., Sikirica, N., Mondini, C., López, G., Kuikman, P. J., & Holden, N. M. (2018). Biochar, compost and biochar-compost blend as options to recover nutrients and sequester carbon. Journal of Environmental Management, 218, 465–476. https://doi.org/10.1016/j.jenvman.2018.04.061 Qambrani, N. A., Rahman, Md. M., Won, S., Shim, S., & Ra, C. (2017). Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review. Renewable and Sustainable Energy Reviews, 79, 255–273. https://doi.org/10.1016/j.rser.2017.05.057 Servicio Agrícola y Ganadero [SAG]. (2017). Pauta Tecnica para la Aplicación de Compost. http://www.sag.cl/sites/default/files/pauta-tecnica-aplicacion-de-compost-conc.1-2-3_region_atacama.pdf Shackley, S., Hammond, J., Gaunt, J., & Ibarrola, R. (2011). The feasibility and costs of biochar deployment in the UK. Carbon Management, 2(3), 335–356. https://doi.org/10.4155/cmt.11.22 Singh, J. S., & Singh, C. (Eds.). (2020). Biochar Applications in Agriculture and Environment Management. Springer International Publishing. https://doi.org/10.1007/978-3-030-40997-5 Vuelta Verde. (s. f.). Retiro y Reciclaje de Desechos Vegetales [Precio productos]. Recuperado 1 de junio de 2021, de https://www.vueltaverde.cl/precios Escalante Rebolledo, A., G. Pérez López, C. Hidalgo Moreno, J. López Collado, J. Campo Alves, E. Valtierra Pacheco y J. D. Etchevers Barra. (2016). Biocarbón (biochar) I: Naturaleza, historia, fabricación y uso en el suelo. Terra Latinoamericana 34: 367-382

Emission Reduction

	Year 2030 IM	Year 2030 AM
Emission reduction (MM tCO_{2eq})	0	0.013 0.013 ~ 0.013
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	0	0.09 0.07 ~ 0.1

Cost Evaluation (period 2020 - 2050)	
	6% Discount rate
Total Cost accumulated (MM USD)	-9.752
Abatement cost (USD/t CO_{2eq})	-26.94

7.1.8. 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 hectares by 2030, of which 100,000 correspond to permanent forest cover of native forest, and the other 100,000 to forest plantations. This measure is part of the NDC of Chile, and is called "Contribution in Integration - LULUCF - Forests N ° 5 (I5)"		
Modeling			
Main Assumptions	It contemplates the 100,000 hectares of permanent forest cover are made with native forest. The goal is fulfilled in 2030, starting the afforestation in 2023 with 6,500 hectares, which increase progressively until 2027, for the period 2028-2030 15,500 hectares are planted per year.		
Cost Elements	The investment costs consider a number of 1100 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 were considered.		
References	CONAF. (2012). Fija costos de forestación, recuperación de suelos degradados, estabilización de dunas, poda y raleo, por hectárea, y establecimiento de cortinas cortavientos por kilómetro, al 31 de julio de 2011, para los efectos del Decreto Ley No 701 de 1974 y sus modificaciones posteriores. https://www.conaf.cl/wp-content/files_mf/1368117546TablaCostos_2012.pdf CORMA. (2021). (Comunicación personal) [Comunicación personal].		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})		**0.2357** 0.21 ~ 0.26	**0.2357** 0.21 ~ 0.26
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**0.93** 0.84 ~ 1.02	**0.93** 0.84 ~ 1.02
Cost Evaluation (period 2020-2050)			
		6% Discount rate	
Total Cost (MM USD)		**1361.7** 1.226 ~ 1.498	
Abatement cost (USD/t CO_2eq)		**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 hectares by 2030, of which 100,000 correspond to permanent forest cover of native forest, and the other 100,000 to forest plantations. This measure is part of Chile's NDC, and is called "Contribution in Integration - LULUCF - Forests N ° 5 (I5)"(Gobierno de Chile, 2020)		
Modeling			
Main Assumptions	It contemplates the 100,000 hectares made with forest plantations. The goal is fulfilled in 2030, starting the afforestation in 2023 with 6,500 hectares, which increase progressively until 2027, for the period 2028-2030 15,500 hectares are planted per year.		
Cost Elements	the investment costs consider a number of 1100 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 the ground were considered.		
References	CONAF. (2012). Fija costos de forestación, recuperación de suelos degradados, estabilización de dunas, poda y raleo, por hectárea, y establecimiento de cortinas cortavientos por kilómetro, al 31 de julio de 2011, para los efectos del Decreto Ley No 701 de 1974 y sus modificaciones posteriores. https://www.conaf.cl/wp-content/files_mf/1368117546TablaCostos_2012.pdf CORMA. (2021). (Comunicación personal) [Comunicación personal]. Corvalán, P., & Hernández, J. (2012). Tablas de rendimiento en biomasa aérea en pie para plantaciones de Eucalyptus globulus en Chile. http://www.gep.uchile.cl/Publicaciones/Tabla%20de%20rendimiento%20en%20biomasa%20a%C3%A9rea%20en%20pie%20para%20plantaciones%20de%20Eucalyptus%20globulus%20en%20Chile.pdf INFOR. (2021). Boletín N°176 Precios Forestales. https://bibliotecadigital.infor.cl/bitstream/handle/20.500.12220/30434/30434.pdf?sequence=1&isAllowed=y		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})		**4.15** 3.735 ~ 4.57	**4.15** 3.735 ~ 4.57
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**16.39** 14.75 ~ 18.03	**16.39** 14.75 ~ 18.03

Cost Evaluation (period 2020-2050)	
	6% Discount rate
Total Cost (MM USD)	**-1014** -912.9 ~ -1116
Abatement cost (USD/t CO_2eq)	**-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 hectares by 2030. This measure is part of Chile's NDC, and is called "Contribution in Integration - LULUCF Bosques N ° 4 (I4) "
Modeling	
Main Assumptions	The goal is fulfilled in 2030, starting the increase in hectares under forest management in 2023 with 13,000 hectares, which increase progressively until 2027, for the period 2028-2030, 31,000 hectares 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, were use two types of cost: a) costs counted only one year after the application of the management plan, which includes the control values of exotic species, sanitary cutting costs, and b) set of silvicultural interventions and harvest activities that occur every year, as well as the income values from the timber harvest
References	CONAF. (2021a). Estadísticas—Ocurrencia y Daño por Incendios Forestales según Incendios de Magnitud 1985—2020. https://www.conaf.cl/incendios-forestales/incendios-forestales-en-chile/estadisticas-historicas/ ODEPA. (2003). Evaluación económica del Proyecto de Ley sobre Recuperación del Bosque Nativo y Fomento Forestal. ODEPA | Oficina de Estudios y Políticas Agrarias CORMA. (2021). (Comunicación personal) [Comunicación personal].

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**1.96** 1.59 ~ 2.38	**1.96** 1.59 ~ 2.38
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**7.76** 6.28 ~ 9.39	**7.76** 6.28 ~ 9.39

Cost Evaluation (period 2020-2050)	
	6% Discount rate
Total Cost (MM USD)	**1783.8** 1605.4 ~ 1962.2
Abatement cost (USD/t CO_2eq)	**33.29** 30.26 ~ 36.99

Name	**Degradation reduction caused by forest fires**
Source	Chilean NDC
General Overview	In this measure, they are considered one of the three elements of native forest degradation, which gradually decrease until reaching 25% less loss of native forest by 2030, corresponding to the decrease in forest fires. This measure is part of Chile's NDC, and is called "Contribution in Integration - LULUCF - Forests N ° 6 (I6)"
Modeling	
Main Assumptions	To determine the reduction of fires caused by the firebreaks, an analysis was carried out with the information on fires for the period 1985-2020, truncating all fires greater than 100 hectares, under the assumption of implementing firebreaks around the perimeter each 100 hectares of forest or forest plantation. To determine how many kilometers of firebreaks are required to protect one hectare of forest, the application of firebreaks in stands with an area of 100 hectares on a homogeneous plot of 400,000 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 the land of class V, VI, VII and VIII as a function of soil distributions using reference to Zelada & Maquire (2005), and taking into consideration the probability of forest fires measured by data provided by CONAF.
References	CONAF. (2020). DT N°239 Tabla de Valores 2020 Ley N°20.283 sobre recuperación d Bosque Nativo y Fomento Forestal. https://www.conaf.cl/cms/editorweb/chifo/DT239.pd CONAF. (2021a). Estadísticas—Ocurrencia y Daño por Incendios Forestales segú Incendios de Magnitud 1985—2020. https://www.conaf.cl/incendios-forestales/incendio forestales-en-chile/estadisticas-historicas/ CONAF. (2021b). Estadísticas—Resumen Nacional Ocurrencia (Número) y Daño (Superfic Afectada) por Incendios Forestales 1964—2020. https://www.conaf.cl/incendio forestales/incendios-forestales-en-chile/estadisticas-historicas/- Valor de la tierra agríco y sus factores determinantes (ODEPA & PUC, 2009) Zelada, A., & Maquire, P. (2005). Expediente Comunal. Estudio Modificación Pla Regulador Comunal de Coronel. https://www.ecoronel.cl/wp content/uploads/2014/03/Capacidad-uso-de-suelo-coronel.pdf

Emission Reduction

	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.95** 0.95 ~ 2.868	**0.95** 0.95 ~ 2.868
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**4.75** 4.75 ~ 14.34	**4.75** 4.75 ~ 14.34

Cost Evaluation (period 2020-2050)	
	6% Discount rate
Total Cost (MM USD)	**3.46** 3.46 ~ 3.46
Abatement cost (USD/t CO_2eq)	**23.03** 13.7 ~ 23.03

<table>
<tr><td>Name</td><td colspan="3">Increase in protected areas</td></tr>
<tr><td>Source</td><td colspan="3">Benavides et al. 2021</td></tr>
<tr><td>General Overview</td><td colspan="3">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 hectares of forest are added to the estimate of carbon sequestration in the GHG National Inventory (INGEI) subcategory of Parks and Reserves, where those hectares corresponding to renewals and forest in equilibrium are excluded.</td></tr>
<tr><td colspan="4">Modeling</td></tr>
<tr><td>Main Assumptions</td><td colspan="3">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 begins to be received one year after the creation of the parks and reserves.</td></tr>
<tr><td>Cost Elements</td><td colspan="3">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.</td></tr>
<tr><td>References</td><td colspan="3">MMA, PNUD, & GEF. (2010). Valoración económica detallada de las áreas protegidas de Chile—Creación de un sistema nacional integral de áreas protegidas para Chile. http://bdrnap.mma.gob.cl/recursos/privados/Recursos/CNAP/GEF-SNAP/Figueroa_2010.pdf

Toledo, C. (2017). “Análisis económico de los ingresos y egresos del Sistema Nacional de Áreas Silvestres Protegidas del Estado (SNASPE)”.

MMA. (2021b). Registro Nacional de Áreas Protegidas. http://bdrnap.mma.gob.cl/app-reportes/#/repAreasProtegidasXDecenio</td></tr>
<tr><td colspan="4">Emission Reduction</td></tr>
<tr><td colspan="2"></td><td>Year 2030 IM</td><td>Year 2030 AM</td></tr>
<tr><td colspan="2">Emission reduction (MM tCO_{2eq})</td><td>0
0 ~ 0</td><td>1.1
0.89 ~ 1.33</td></tr>
<tr><td colspan="2">Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>0
0 ~ 0</td><td>8.81
7.14 ~ 10.66</td></tr>
</table>

Cost Evaluation (period 2020-2050)	
	6% Discount rate
Total Cost (MM USD)	**41.28** 37.15 ~ 45.41
Abatement cost (USD/t CO_2eq)	**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 due to 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). On the other hand, the measure contributes to the conservation of these marine ecosystems.
Modeling	
Main Assumptions	The measure contemplates 1,000 hectares, which are 66 of Lessonia nigrescens, 841 of Lessonia trabeculata and 93 of Macrocystis spp., Distribution 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	Vásquez, J. A., Zuñiga, S., Tala, F., Piaget, N., Rodríguez, D. C., & Vega, J. M. A. (2014). Economic valuation of kelp forests in northern Chile: Values of goods and services of the ecosystem. Journal of Applied Phycology, 26(2), 1081-1088. https://doi.org/10.1007/s10811-013-0173-6 Burg, S. W. K. van den, Duijn, A. P. van, Bartelings, H., Krimpen, M. M. van, & Poelman, M. (2016). The economic feasibility of seaweed production in the North Sea. Aquaculture Economics & Management, 20(3), 235-252. https://doi.org/10.1080/13657305.2016.1177859

Emission Reduction

	Year 2030 IM	Year 2030 AM
Emission reduction (MM tCO_{2eq})	**0** 0 ~ 0	**0.012** 0.011 ~ 0.013
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0** 0 ~ 0	**0.07** 0.064 ~ 0.078

Cost Evaluation (period 2020-2050)

	6% Discount rate
Total Cost (MM USD)	**125.9** 113.4 ~ 138.6
Abatement cost (USD/t CO_2eq)	**330.2** 330.2 ~ 330.2

Name	**Native afforestation - increase in hectares**		
Source	Raise in the commitment of Chilean NDC		
General Overview	This measure corresponds to an increase in forested hectares with native vegetation, is oriented towards increasing forest area, and considers the afforestation of 20,000 hectares by 2030, of which 100% corresponds to permanent forest cover of native forest.		
Modeling			
Main Assumptions	The goal is met in 2026, starting to increase the forested area in 2023, implementing 5,000 hectares each year.		
Cost Elements	The investment costs consider a number of 1100 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 were considered.		
References	CONAF. (2012). Fija costos de forestación, recuperación de suelos degradados, estabilización de dunas, poda y raleo, por hectárea, y establecimiento de cortinas cortavientos por kilómetro, al 31 de julio de 2011, para los efectos del Decreto Ley No 701 de 1974 y sus modificaciones posteriores. https://www.conaf.cl/wp-content/files_mf/1368117546TablaCostos_2012.pdf CORMA. (2021). (Comunicación personal) [Comunicación personal].		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})		**0** 0 ~ 0	**0.047** 0.042 ~ 0.052
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**0** 0 ~ 0	**0.31** 0.27 ~ 0.34
Cost Evaluation (period 2020-2050)			
		6% Discount rate	
Total Cost (MM USD)		**281.6** 196.7 ~ 240.5	
Abatement cost (USD/t CO_2eq)		**148.8** 148.4 ~ 149.4	

Name	**Increase in hectares of native forest management - increase in hectares**		
Source	Raise in the commitment of 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 hectares by 2030. This measure is part of Chile's NDC, and is called "Contribution in Integration - LULUCF Bosques N ° 4 (I4) "(Gobierno de Chile, 2020)		
Modeling			
Main Assumptions	The goal is met in 2026, starting the increase in hectares under forest management in 2023 with 5,000 hectares 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 were used. In turn, for operating costs, were use two types of cost: a) costs counted only one year after the application of the management plan, which includes the control values of exotic species, sanitary cutting costs, and b) set of silvicultural interventions and harvest activities that occur every year, as well as the income values from the timber harvest		
References	CONAF. (2021a). Estadísticas—Ocurrencia y Daño por Incendios Forestales según Incendios de Magnitud 1985—2020. https://www.conaf.cl/incendios-forestales/incendios-forestales-en-chile/estadisticas-historicas/ ODEPA. (2003). Evaluación económica del Proyecto de Ley sobre Recuperación del Bosque Nativo y Fomento Forestal. ODEPA | Oficina de Estudios y Políticas Agrarias CORMA. (2021). (Comunicación personal) [Comunicación personal].		
Emission Reduction			
		Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})		**0** 0 ~ 0	**0.196** 0.16 ~ 0.24
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**0** 0 ~ 0	**1.28** 1.03 ~ 1.55

Cost Evaluation (period 2020-2050)	
	6% Discount rate
Total Cost (MM USD)	**187.95** 166.5 ~ 203.5
Abatement cost (USD/t CO_2eq)	**30.87** 28.06 ~ 34.3

7.2. ANNEX 2: Detailed results overfutures

7.2.1. Emissions by sector overfutures

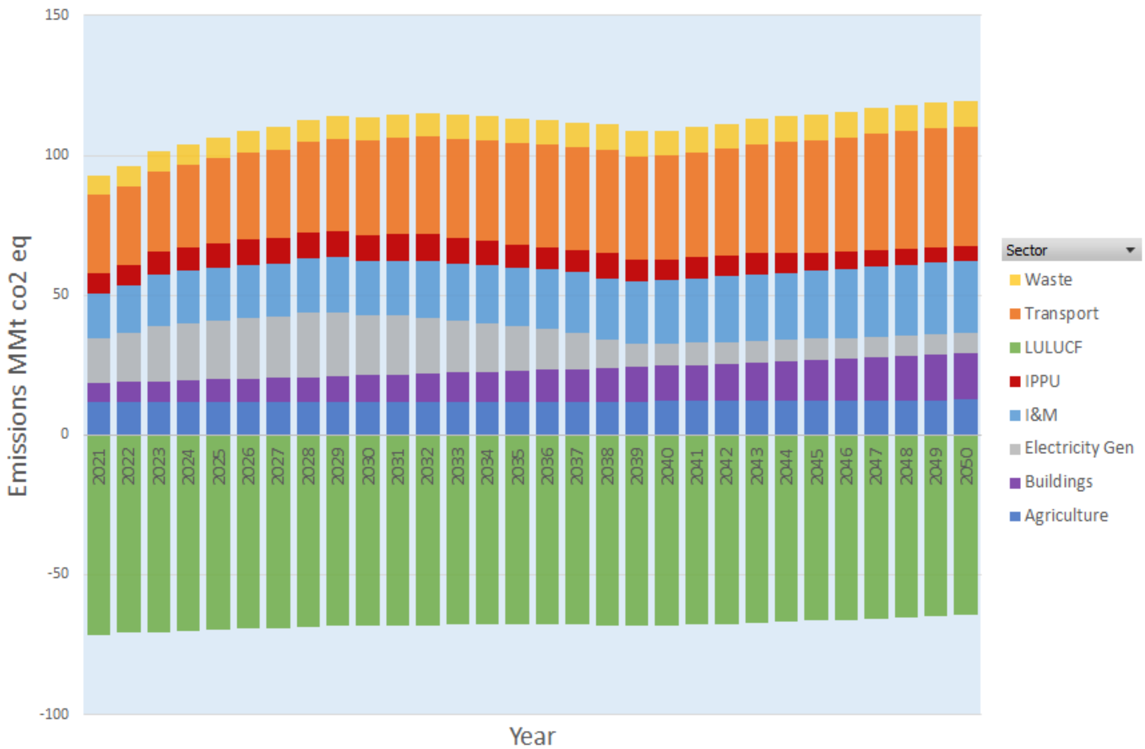

Figure 7-1 Emissions for the CP - Green Future Scenario

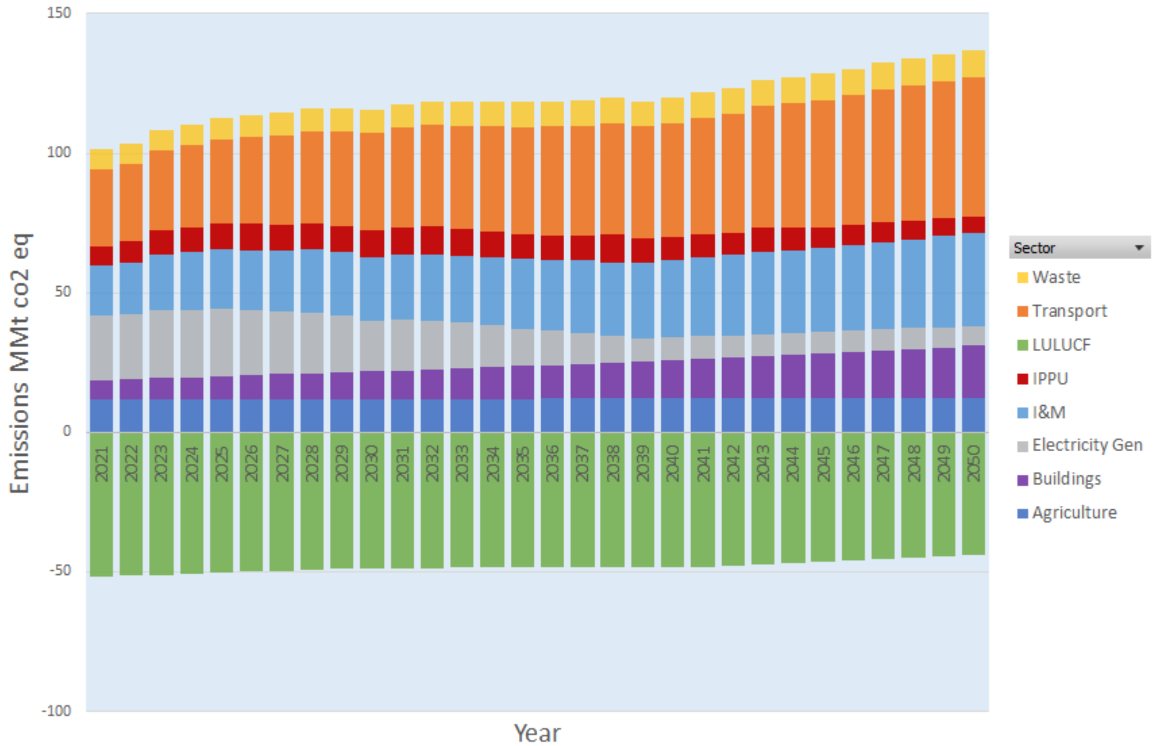

Figure 7-2 Emissions for the CP-Red Future Scenario

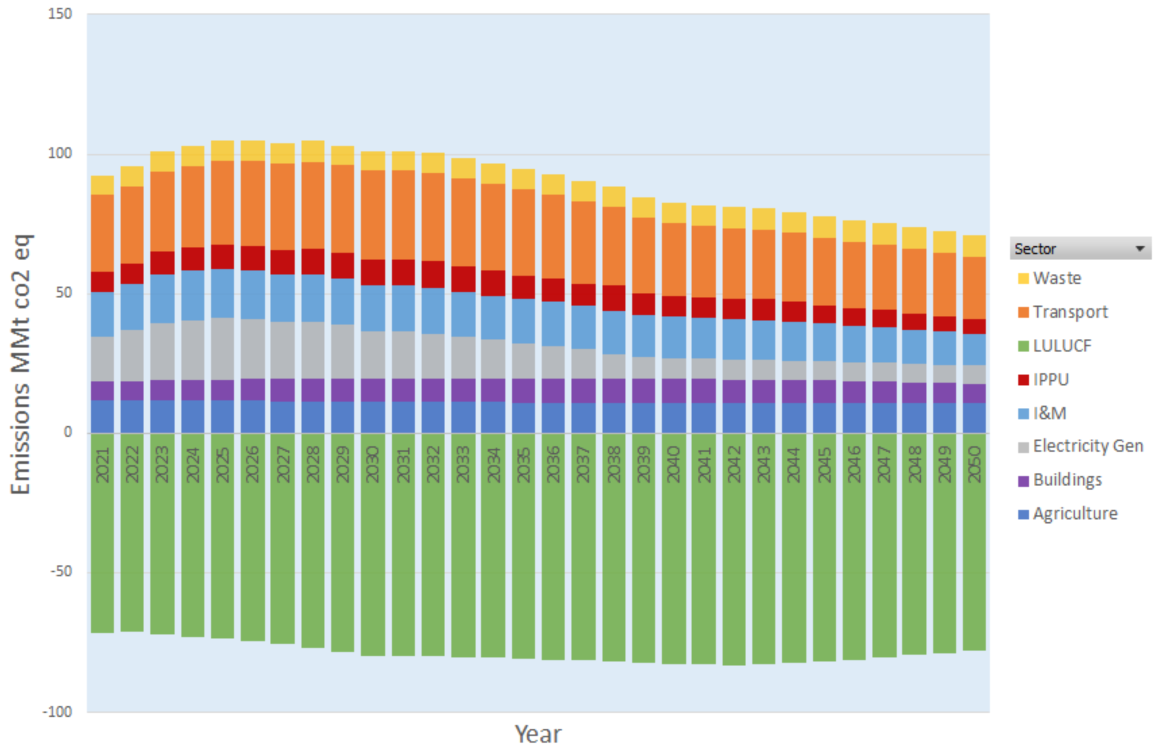

Figure 7-3 Emissions for the IM-Green Scenario

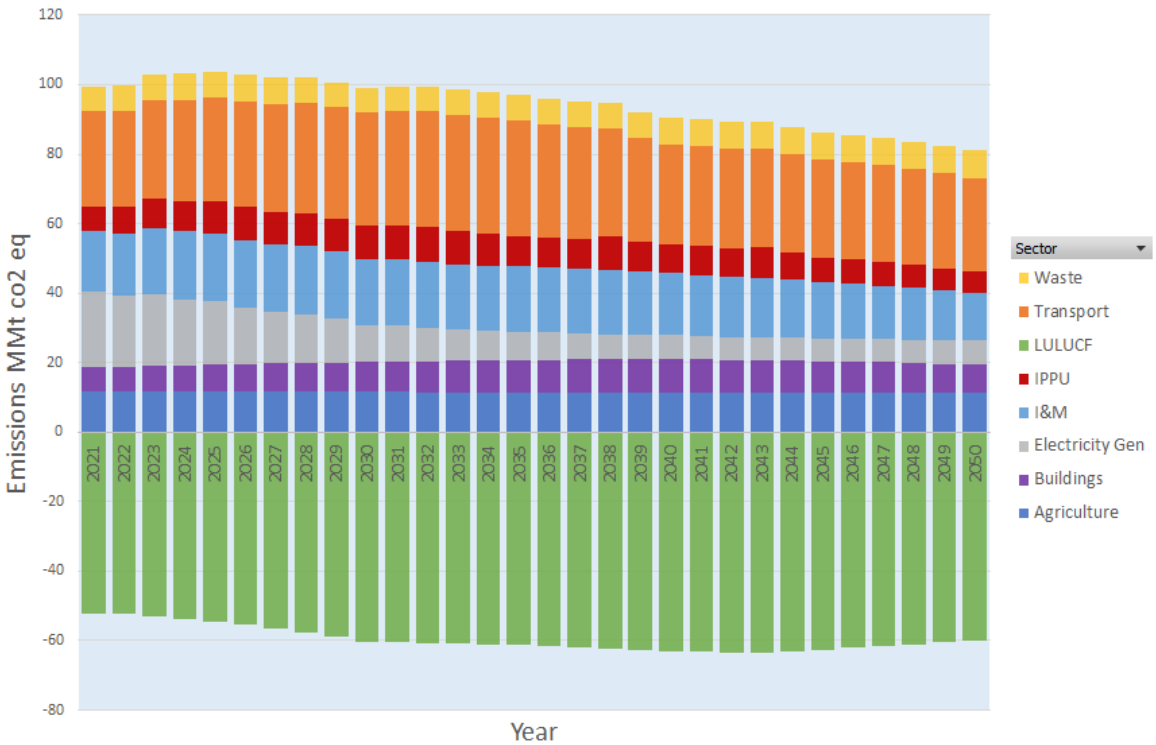

Figure 7-4 Emissions for the IM-Red Future Scenario

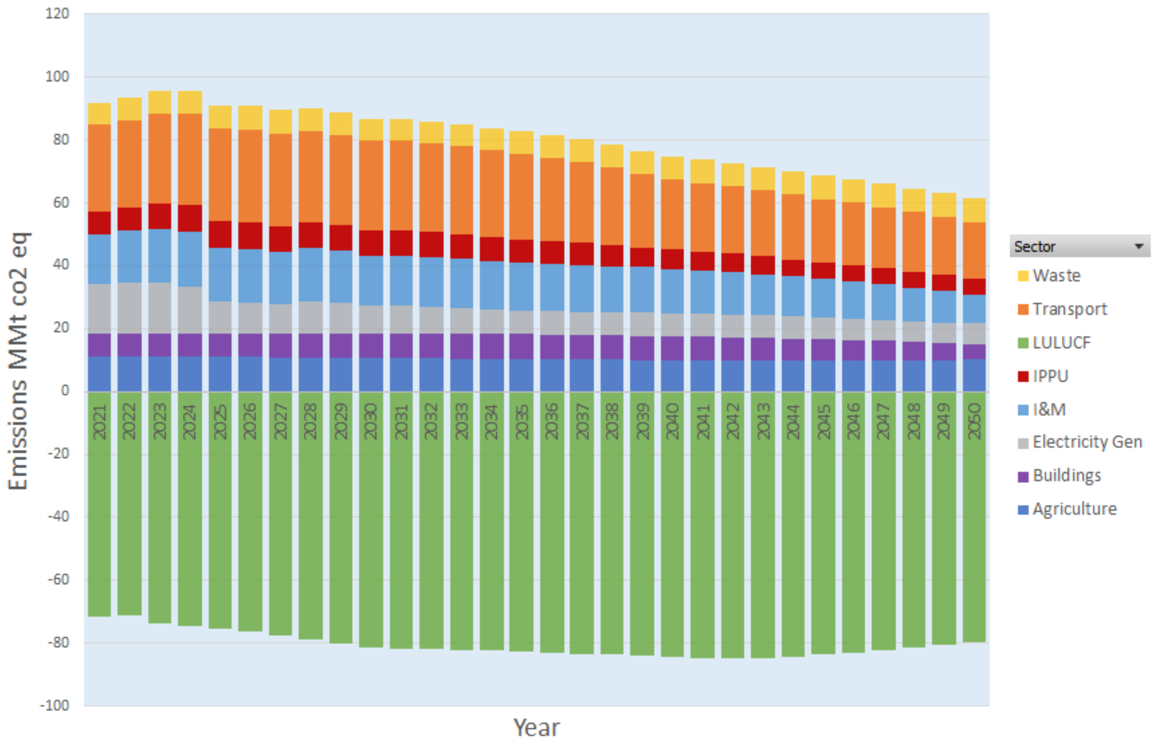

Figure 7-5 Emissions for the AM-Green Future Scenario

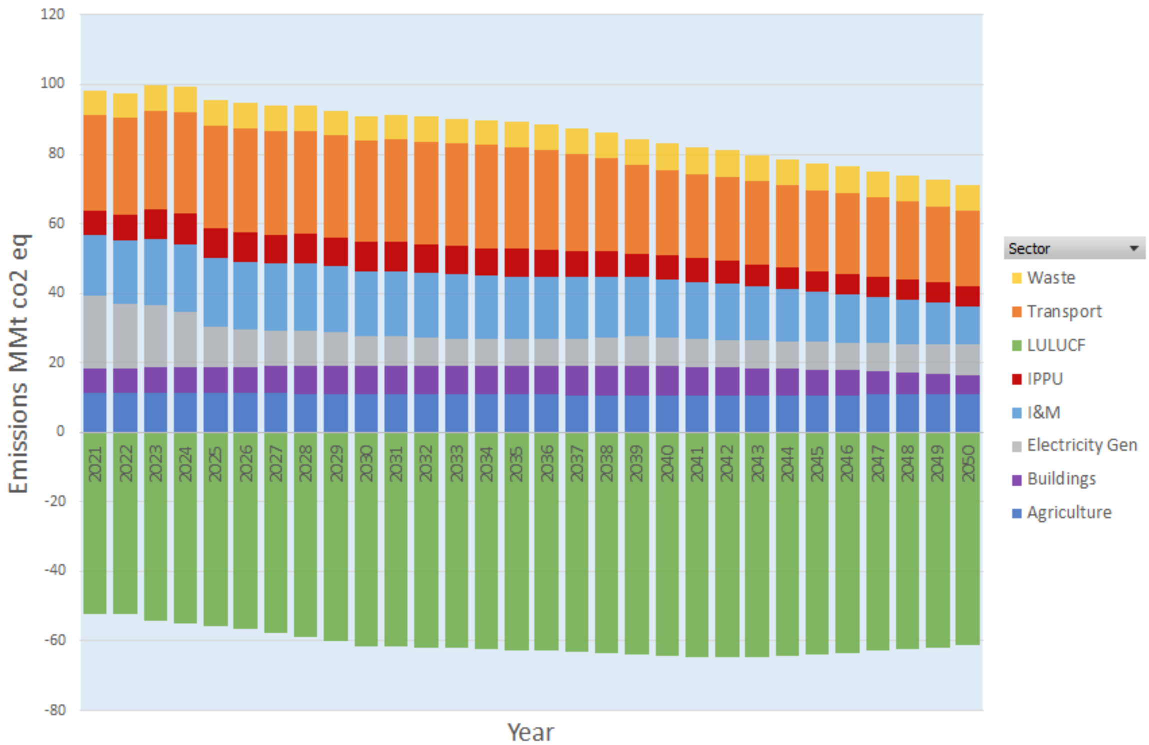

Figure 7-6 Emissions for the AM-Red Future Scenario

7.2.2. Sensitivity analysis of 2020 and 2030 emissions

Table 7-1 Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO_{2eq}) for each scenario and all the 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 7-2 Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO_{2eq}) for each scenario and all the 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 7-3 Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO_{2eq}) for each scenario and all the 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 7-4 Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO_{2eq}) for each scenario and all the futures for the Industry & 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 7-5 Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO_{2eq}) for each scenario and all the 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 7-6 Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO_{2eq}) for each scenario and all the 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 7-7 Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO_{2eq}) for each scenario and all the 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 7-8 Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO_{2eq}) for each scenario and all the 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

7.2.3. Generation for the alternatives to accelerate mitigation on the electricity sector

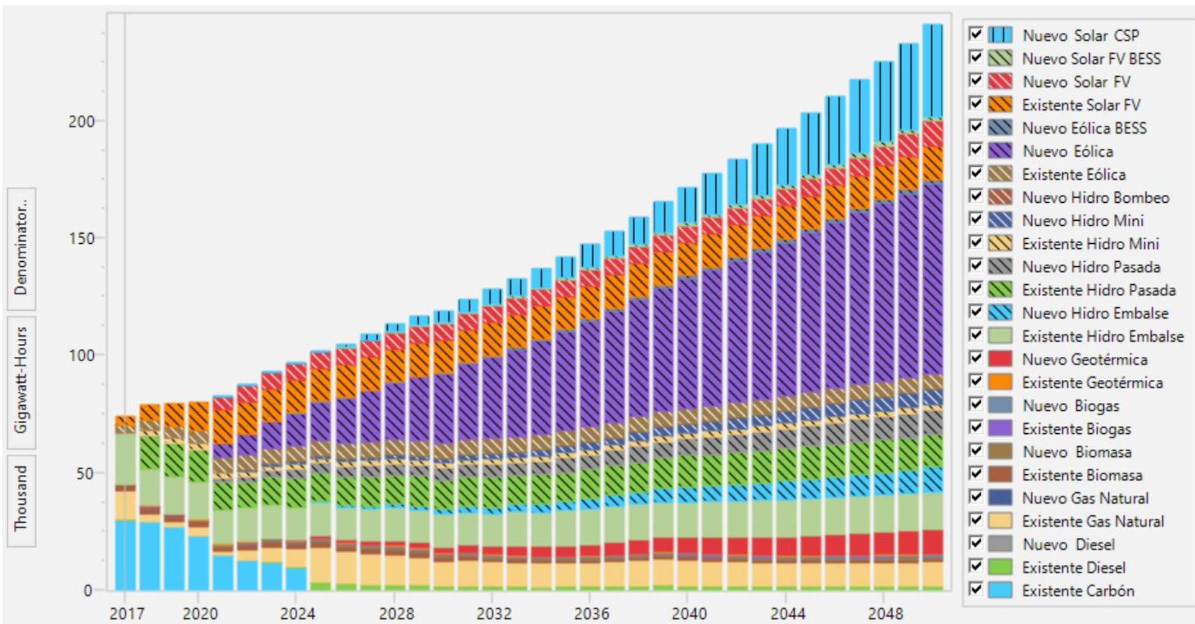

Figure 7-7 Generation output Reference future AM 2025

SOURCE: SELFMADE

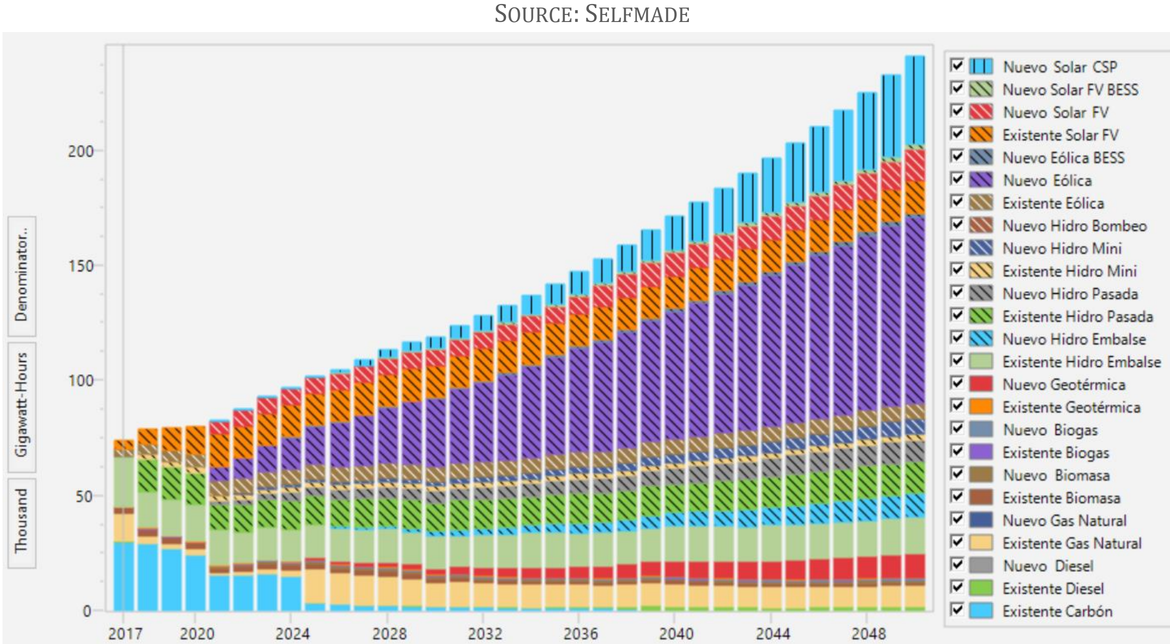

Figure 7-8 Generation output Reference future AMHT

SOURCE: SELFMADE

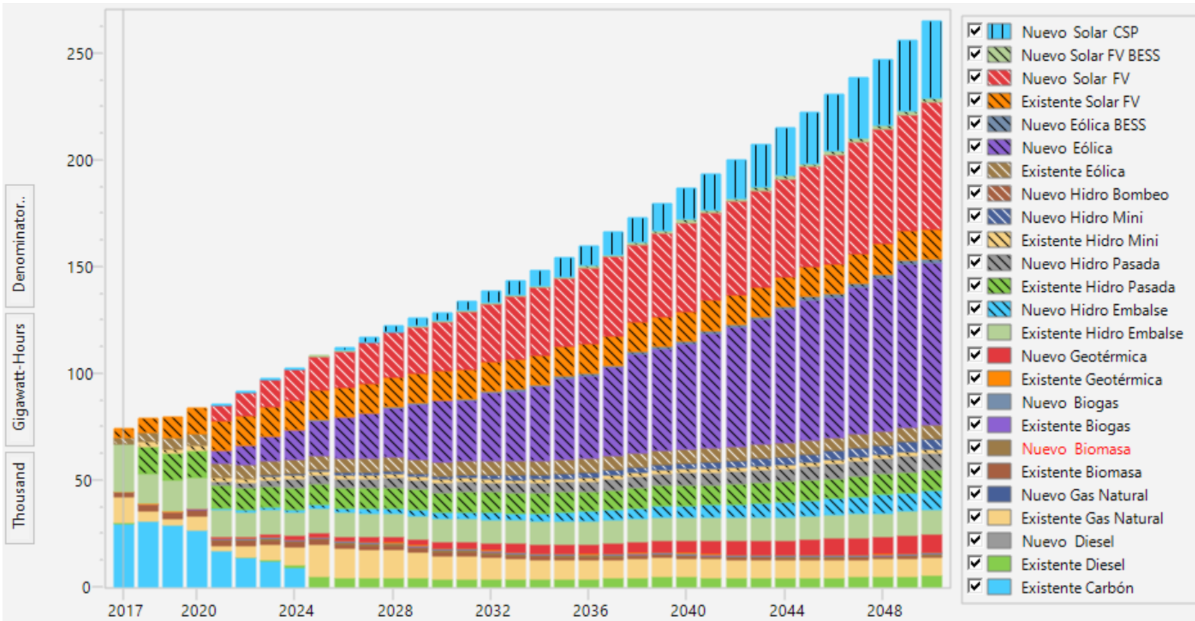

Figure 7-9 Generation output Red future AM 2025

SOURCE: SELFMADE

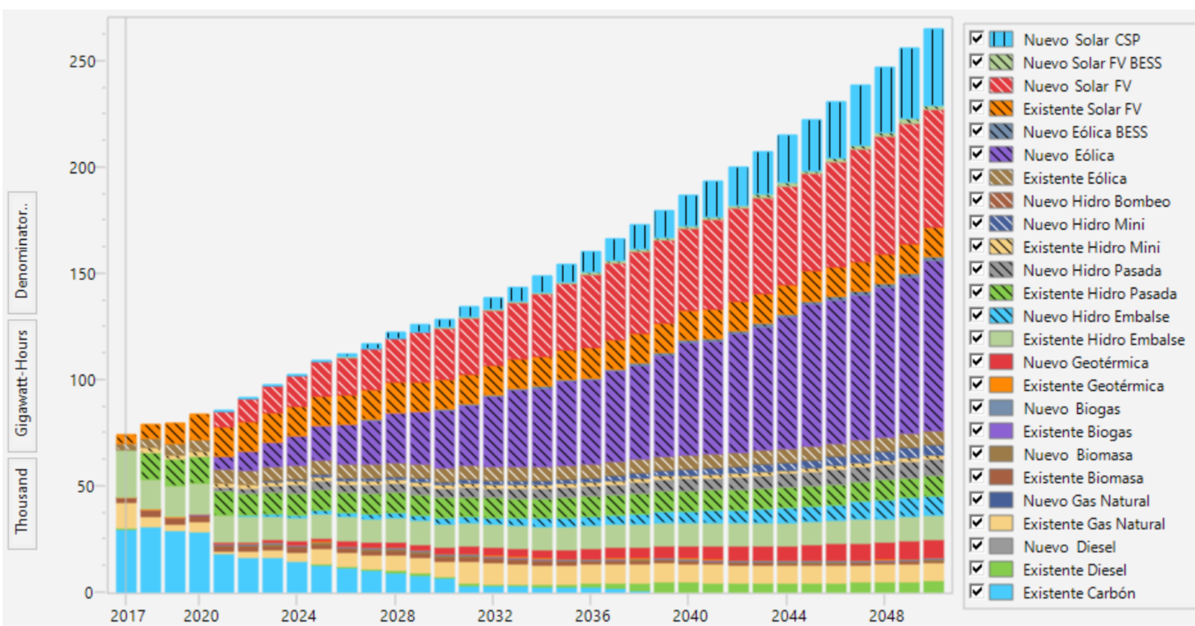

Figure 7-10 Generation output Red future AMHT

SOURCE: SELFMADE

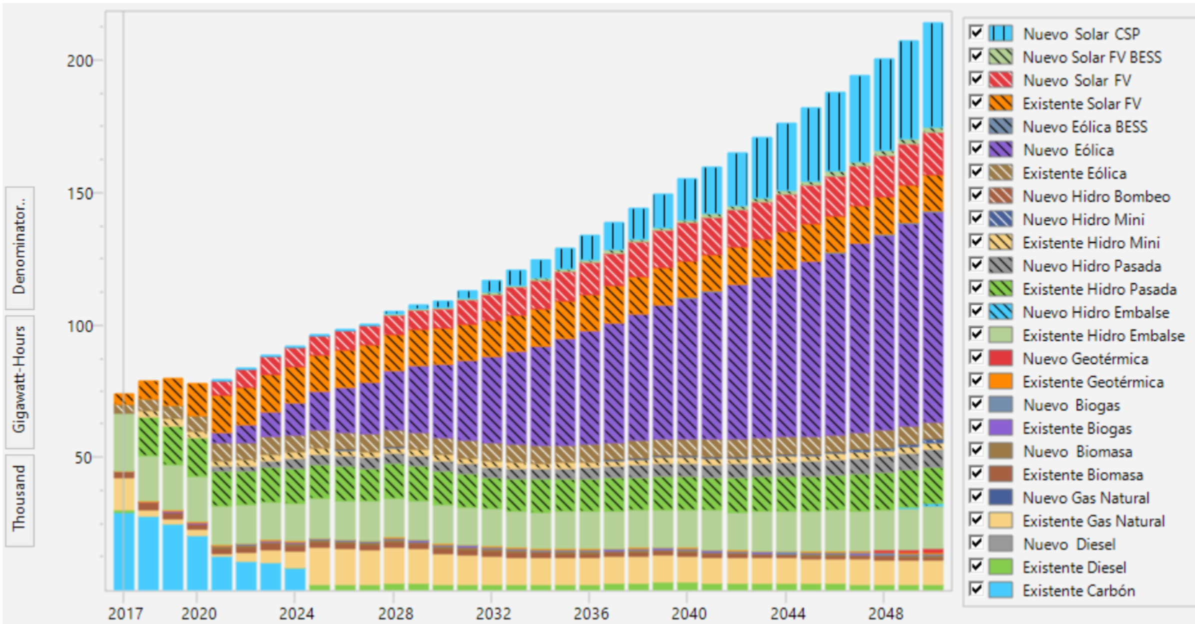

Figure 7-11 Generation output Green future AM 2025

SOURCE: SELFMADE

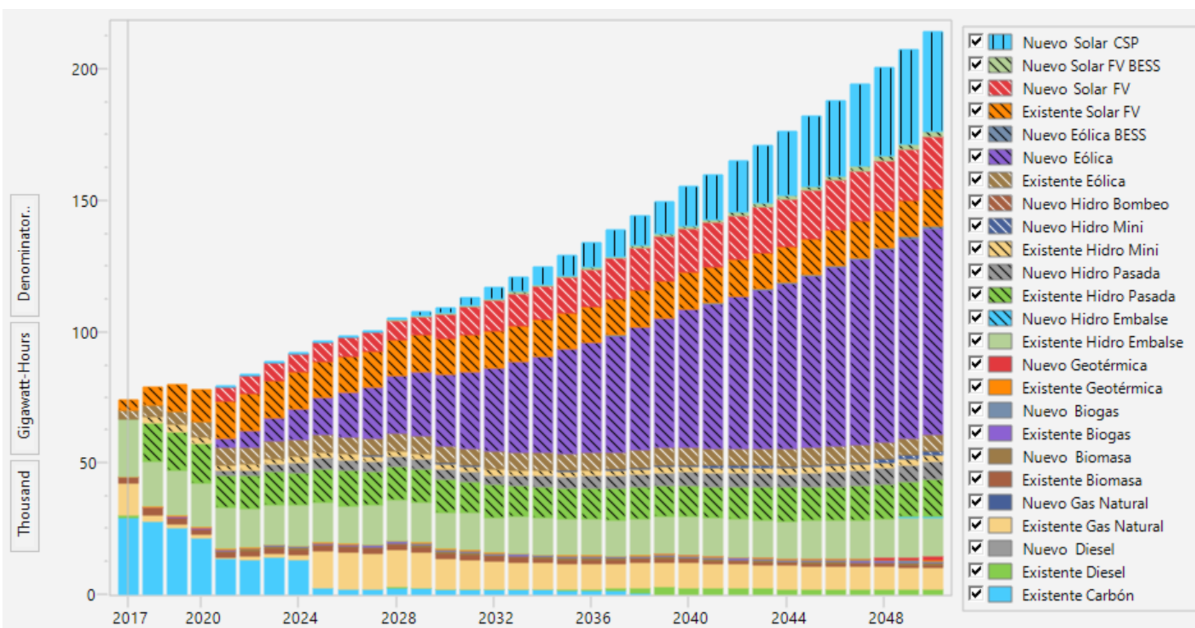

Figure 7-12 Generation output Green future AMHT

SOURCE: SELFMADE

7.3. ANNEX 3: MACC Curve for other futures

The curves presented in this Annex follow the same legend presented in Table 4-1.

7.3.1. MACC Curve for the Green future

In the following figure the MAC Curve for the green future is presented. The main difference observed with the reference future is that the decommissioning of coal power plants in this case, with 48 USD/tCO_{2eq}, 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 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 that the composting plants (Waste-2), and the 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, one stage each.

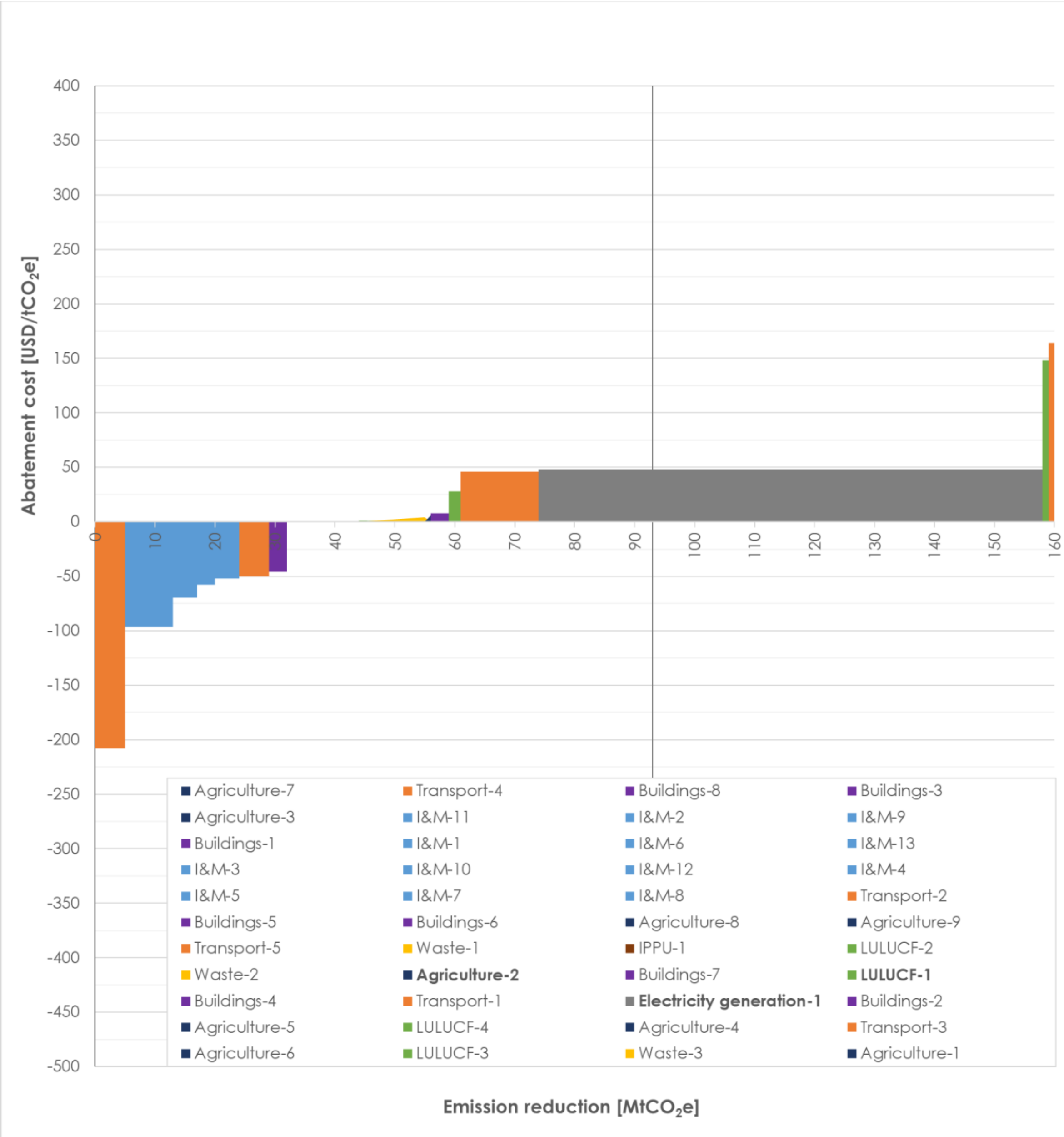

Figure 7-13 MACC curve for the 2020-2030 period for the green future
SOURCE: AUTHORS

7.3.1. MACC Curve for the Red future

A MAC Curve for the red future is presented in the following figure. In this case the main difference with the reference future is the change in cost of the decommissioning of coal power plants, 143 USD/tCO_{2eq}, which moves this measure behind the holistic management of cattle (Agriculture-5) on the curve. Similarly, the implementation of porcine biodigesters (Agriculture-2) turns from 3.6 USD/tCO_{2eq} in the reference future to 0.7 USD/tCO_{2eq} in the red scenario, which makes this measure more economical than the increase in protected areas (LULUCF-2) and advances this measure one stage on the curve.

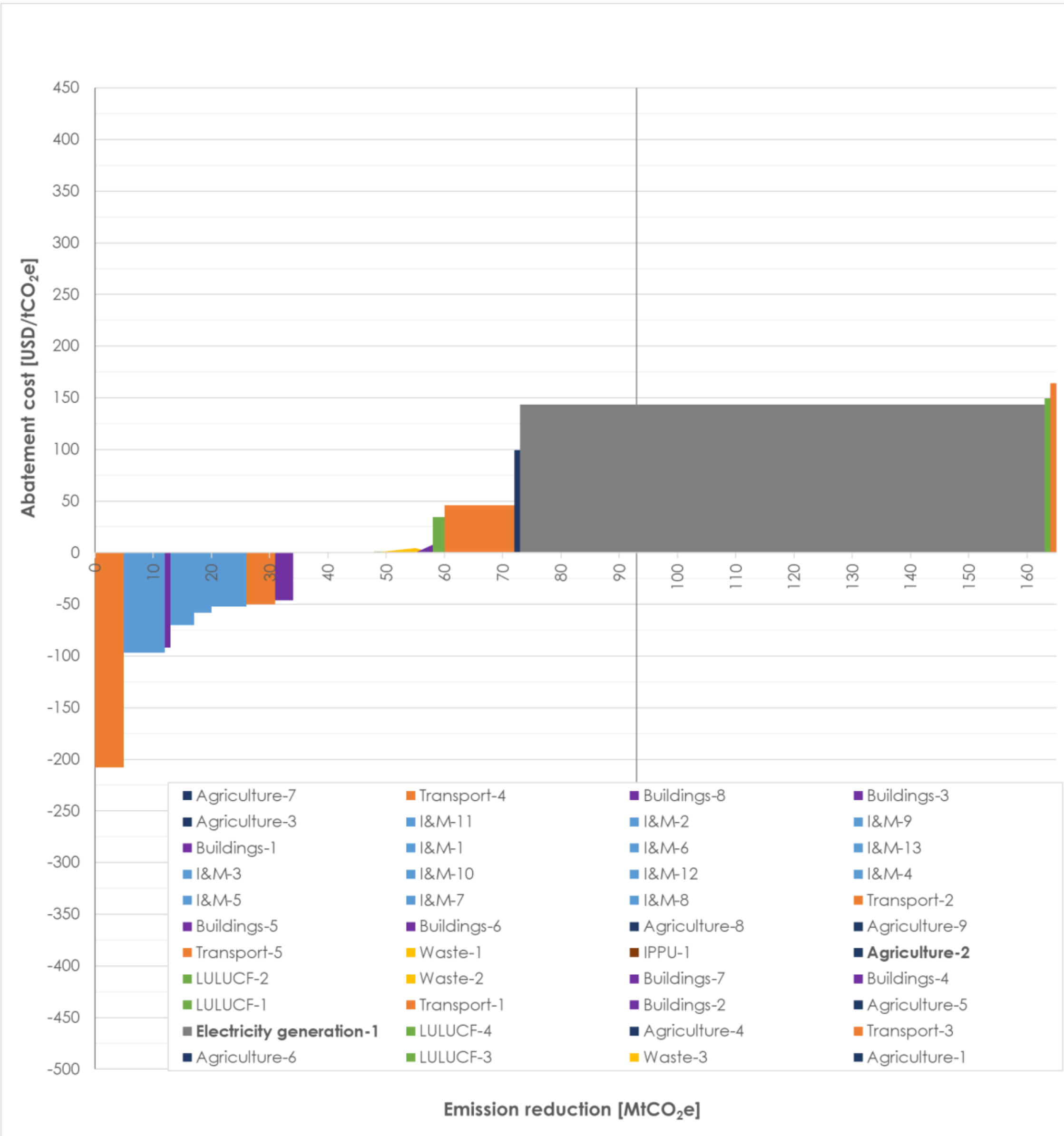

Figure 7-14 MACC curve for the 2020-2030 period for the red future

SOURCE: AUTHORS