JUNE 2023 – EDF ECONOMICS DISCUSSION PAPER SERIES – EDF EDP 23 – 02

Greenhouse Gas mitigation beyond the Nationally Determined Contributions in Chile:

an assessment of alternatives

José Miguel Valdés, Álvaro Lorca, Cristián Salas, Francisco Pinto, Rocío Herrera, Alejandro Bañados, Raúl Urtubia, Patricio Castillo, Lucas Maulén, and Diego González

Environmental Defense Fund

About Environmental Defense Fund

Guided by science and economics, Environmental Defense Fund (EDF) tackles our most urgent environmental challenges with practical solutions. EDF is one of the world's largest environmental organizations, with more than 2.5 million members and a staff of 700 scientists, economists, policy experts, and other professionals around the world.

EDF Economics Discussion Paper Series

EDF Economics Discussion Papers represent unrefereed works-in-progress by researchers who are solely responsible for the content and any views expressed therein. Any comments on these papers are welcome and should be sent to the author(s) by email. EDF's Office of the Chief Economist manages the series.

Sharing Our Discussion Papers

Our Discussion Papers (the "Materials") are available for sharing and adaptation under an Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) license (the "License"). You can copy and redistribute the Materials in any medium or format; provided, however: (i) you must give appropriate credit to us through recognition of our authorship of the Materials (generally by citing to the Materials); (ii) you must provide the link to the License as per the below; (iii) If you remix, transform, or build upon the Material, you may not distribute the modified Material without our prior written consent; (iv) you may not apply any additional restrictions to any third party that you distribute the Material to other then as specified herein, except that you may not permit any third party to remix, transform or build upon the Materials, without our prior written consent; and (v) you may not reproduce, duplicate, copy, distribute, transmit, sell, trade, resell or exploit for any commercial purpose any portion of the Materials. Images, trademarks, service marks, logos and icons used in the discussion papers are our property and may not be used without our prior written consent. License information can be found by visiting: https://creativecommons.org/licenses/by-nc-nd/4.0/

© 2023 Environmental Defense Fund. All rights reserved.

EDF Economics Discussion Paper 23 – 02

Greenhouse Gas mitigation beyond the Nationally Determined Contributions in Chile: an assessment of alternatives

José Miguel Valdés[a], Álvaro Lorca[b], Cristián Salas[c], Francisco Pinto[d], Rocío Herrera[e], Alejandro Bañados[f], Raúl Urtubia[g], Patricio Castillo[h], Lucas Maulén[i], and Diego González[j]

---

a GreenLab & Centro Cambio Global UC. jmvaldes@uc.cl
b Vinken and Pontifical Catholic University of Chile. alvarolorca@vinken.cl
c Centro Cambio Global UC. casalasp@uc.cl
d Climate Action Teams. fpinto@alumni.lse.ac.uk
e GreenLab. rdherrera1@uc.cl
f GreenLab. arbanados@uc.clg
g Vinken and Pontifical Catholic University of Chile. raulurtubia@vinken.cl
h Vinken and Pontifical Catholic University of Chile. pbcastillo@uc.cl
i Vinken and Pontifical Catholic University of Chile. lucasmaulen@vinken.cl
j Centro Cambio Global UC. dgonzalezt@uc.cl

Abstract

In support of the Climate Action Teams initiative, we evaluate Chile's potential for greenhouse gas (GHG) mitigation beyond its Nationally Determined Contributions (NDCs) through implementing ambitious actions. An open multisector model is used to project GHG emissions. The results indicate that additional efforts are required to meet Chile's NDC commitments. However, ambitious actions could yield a significant mitigation surplus at a reasonable cost, with a maximum potential of 75 (65–82) MtCO2e beyond the committed carbon budget. About one-third of this potential can be achieved at a mean abatement cost of less than 20 USD/tCO2e, and an additional 65% can be obtained with a mean abatement cost ranging between 20 and 50 USD/tCO2e. The estimated capital cost required for implementing these actions is 5.3 (4.9–5.3) billion USD from 2020 to 2030. In addition to mitigating GHG emissions, these actions also have significant health co-benefits, with an estimated avoidance of up to 2,250 (2,180–2,320) premature PM2.5-induced deaths between 2020 and 2030. The health co-benefit between 2020 and 2030 is estimated to be around 1.5 billion USD. The study also suggests that an early coal-power phase-out is not the most efficient mitigation action in the power sector. We estimate that a carbon tax between 40–45 USD/tCO2e could achieve the same level of emissions reduction as closing coal-fired power by 2025 but at a significantly lower cost.

Key Words

Climate Action Teams, Open-Access Model, Mitigation, Chile’s NDC, Marginal Carbon Costs

JEL Classification Numbers:

Q5, Q54

Acknowledgments:

This work relies on the work previously done by the professional team developed during phase 1, available at: http://dx.doi.org/10.2139/ssrn.4168343 . We thank Suzi Kerr (EDF), Matthias Fripp (EDF), Oleg Lugovoy (EDF), Luis Fernández (EDF), Patricia Hidalgo-Gonzalez (UCSD) and Rodrigo Bórquez (CAT) for their insightful comments.

INDEX

EXECUTIVE SUMMARY 7
MAIN INSIGHTS 11
1. INTRODUCTION 13
2. OBJECTIVES 15
3. MODEL DESCRIPTION 15
3.1 OVERVIEW 15
3.3 MITIGATION ACTIONS CONSIDERED 19
3.4. CO-BENEFIT ANALYSIS 22
4. RESULTS 23
4.1 EMISSIONS 23
4.2 COST ANALYSIS OF MITIGATION ACTIONS 31
4.2.1 Cost-effectiveness 32
4.2.2 Marginal abatement cost in the electricity generation sector 37
4.2.3 Capital cost 40
4.3 EMISSIONS CO-BENEFITS 41
5. CONCLUSIONS AND FURTHER WORK 42
5.2 COAL-POWER PHASE-OUT 45
5.2.1 Sensitivity on the level of ambition 45
5.2.2 Impact on the transmission grid 47
5.3 LIMITATIONS AND FURTHER WORK 47
REFERENCES 52
APPENDIXES 55
APPENDIX 1: DESCRIPTION OF THE MODELS 55
1.1 ENERGY: ELECTRICITY GENERATION 55
1.2 ENERGY: DEMAND SECTORS 101
1.3 TRANSPORT 103
1.4 INDUSTRY & MINING 106
1.5 BUILDINGS 111
1.6 IPPU 115
1.7 AGRICULTURE 118
1.8 LULUCF 121
1.9 WASTE 125
APPENDIX 2: DESCRIPTION OF THE MITIGATION ACTIONS 128
2.1 ELECTRICITY GENERATION ACTIONS 128
2.2 TRANSPORT ACTIONS 129
2.3 INDUSTRY & MINING ACTIONS 134
2.4 BUILDINGS ACTIONS 147
2.5 WASTE ACTIONS 155
2.6 IPPU ACTIONS 158
2.7 AGRICULTURE ACTIONS 159
2.8 LULUCF ACTIONS 168

APPENDIX 3: DETAILED RESULTS OVERFUTURES 176

3.1 EMISSIONS BY SECTOR OVERFUTURES 176
3.2 SENSITIVITY ANALYSIS OF 2020 AND 2030 EMISSIONS 179
3.3 GENERATION FOR THE ALTERNATIVES TO ACCELERATE MITIGATION ON THE ELECTRICITY SECTOR 182

APPENDIX 4: MACC CURVE FOR OTHER FUTURES 185

4.1 MACC CURVE FOR THE GREEN FUTURE 185
4.2 MACC CURVE FOR THE RED FUTURE 187

APPENDIX 5: OVERVIEW OF MODULES AND MODELS 189

5.1 SECTOR: ELECTRICITY 189
5.2 SECTOR: TRANSPORT 192
5.3 SECTOR: INDUSTRY & MINING 193
5.4 SECTOR: BUILDINGS 195
5.5 SECTOR: WASTE 197
5.6 SECTOR: IPPU 198
5.7 SECTOR: AGRICULTURE 199
5.8 SECTOR: LULUCF 201

REFERENCES OF APPENDIX 205

Executive summary

The Climate Action Teams initiative is a mechanism that supports international resource transfers for climate mitigation. Climate Action Teams operate through government-to-government agreements based on verified mitigation outcomes beyond Nationally Determined Contributions (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 modeling 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.

We developed a prospective emissions model that covers all sectors included in the National Greenhouse Gas (GHG) Inventory. These are the power generation and energy demand sectors—transportation, buildings, industry and mining, industrial processes and product use (IPPU), waste, agriculture, and forestry.

The modeling was carried out based on a combination of Mitigation Scenarios and Futures, where these two concepts are defined as follows:

Mitigation Scenarios: These represent different mitigation strategies implemented at a national level. Each scenario considers a set of mitigation actions and their specific level of implementation.

- Futures: These represent a trajectory of exogenous parameters that represent a possible set of conditions that could facilitate (or challenge) the mitigation strategies. We analyze two Mitigation Scenarios:
- NDC Mitigation Scenario (NDC): Considers the achievement of all the mitigation commitments for 2030 in Chile's last NDC.
- Beyond NDC Mitigation (NDC+): Considers enhanced mitigation actions to overachieve Chile's NDC commitments for 2030.

For each Mitigation Scenario, we consider three Futures: the first is the Reference Future, where all the drivers have their respective expected values. For the other two Futures, we developed a sensitivity analysis to explore the impact of uncertainty on the key drivers. We group these sensitivities into a 'Green' and a 'Red' Future.

For all the mitigation scenarios, we force the fulfilment of the NDC commitments[1] with an artificial constraint on the electric generation sector. In other words, if the set of mitigation actions is not enough to meet the commitments, the optimization of the electric sector will have active restrictions constraining GHG emissions. This is the case in the three futures of the NDC Mitigation Scenario. In cases when the set of mitigation actions is enough, these restrictions are not active, and the emissions are not artificially reduced. This is the situation for the three futures of the NDC+ Mitigation Scenario.

Although the results presented in this report consider only these Mitigation Scenarios, multiple intermediate scenarios could be generated. These new scenarios could differ in the criteria for defining the actions included. In the appendixes of this report, all the models, results, and further documentation of the models are included.

To estimate the potential reduction, we contrast the NDC+ Scenario with the NDC Scenario. In the first two columns of the table below we show the estimated emissions for the Reference Future for both Mitigation Scenarios for the period 2020–2030. Compared with the 'carbon budget' commitment established in Chile's NDC (1,100 MtCO$_2$e between 2020–2030), the NDC scenario oversatisfies the commitment by 11 MtCO$_2$e. In the last three columns, we show the emission reduction when comparing the emissions between NDC and NDC+. The emission reduction adds up to 64 MtCO$_2$e for the Reference Future, but considering the uncertainty of exogenous factors, it could be between 54 and 71 MtCO$_2$e between 2020 and 2030. Therefore, the NDC+ total mitigation potential in comparison with the committed carbon budget is 74 (65–81) MtCO$_2$e.

---

[1] The process is iterative; we allow a 1% deviation from the commitments. This means that we stop the iteration process when the emissions are [1,089–1,111] MtCO$_2$e between 2020 and 2030, and [94-96] MtCO$_2$e for the year 2030.

TABLE

GHG emission for each Mitigation Scenario and reductions beyond the carbon budget between 2020 and 2030(MtCO₂e)

Sector	NDC / Reference	NDC+ / Reference	Reduction / Reference	Reduction / Green	Reduction / Red
Power Generation	191	146	45	52	36
Energy	596	588	8	8	9
IPPU	93	88	6	6	6
Agriculture	129	124	5	5	4
Waste	79	80	0	0	0
Total	1,089	1,025	64	71	54

Source: Study Authors.

The health co-benefits increase with the ambition level of the Mitigation Scenario. By 2030, we estimate that the premature PM2.5-induced deaths avoided would amount to 10% of the expected deaths related to PM2.5 in the NDC+ scenario, in comparison with the NDC scenario. Moreover, the NDC+ scenario would result in an additional 2,250 (2,180–2,320) premature deaths avoided, in comparison with the NDC scenario, as a co-benefit because of the reduction in the PM2.5 emissions. This total is approximately 5% of the total PM2.5-induced premature deaths expected in 2020-2030.

In a more extended scope, between 2020 and 2050, a total net emission of 594 MtCO₂e is expected in the NDC scenario. The impact of the NDC+ actions could drive this total to 168 MtCO₂e, reducing the net emissions by 72%. The most significant contribution comes from the power generation sector (48% of the mitigation) and the energy demand sector (32%).

Although the definitive set of mitigation actions to fulfill the Chilean NDC is yet to be defined by the authorities, we propose a set of actions for the NDC scenario that we believe are most likely to be implemented in the following years. We complement this selection of actions with additional constraints in the electricity generation sector optimization model to guarantee the fulfillment of the carbon budget (1,100 MtCO₂e between 2020 and 2030) and the yearly emission (95 MtCO₂e by 2030) commitments. The result of the NDC scenario shows that both constraints are active in the optimization model, which means that our selection of mitigation actions was insufficient for achieving the commitments on their own. In other words, without these constraints, the projected emissions of the NDC scenario would not meet the NDC's commitments. Our estimates show that if we were to follow cost-effectiveness criteria to select the actions to include in the NDC scenario, the marginal cost would be in the proximity of 20 USD/tCO_2e. It is essential to highlight that in our analysis we are not including previous actions like the commitment to progressively decommission coal-fired power plants by 2040.

In the case of the NDC+ scenario, the proposed actions are enough to fulfill the commitments, and a 74 (65–81) MtCO_2e surplus can be achieved. The cost analysis shows that 30% of the surplus can be achieved with a mean abatement cost smaller than 20 USD/tCO_2e, and 95% can be achieved with an average cost smaller than 50 USD/tCO_2e. Among the different sectors, the electricity generation sector appears to be the more critical because it has the technical capability to achieve a crucial additional reduction: 45 (36–52) MtCO_2e available for mitigation at an average cost of 34 (34–38) USD/tCO_2e. At the same time, the decarbonization of the electric sector is relevant for the success of a series of electrification actions in the energy demand sector. In terms of marginal costs, the full mitigation potential of the NDC+ scenario has a marginal cost of over 700 USD/tCO_2e, but 96% of the potential can be achieved with a marginal cost of 60 USD/tCO_2e.

Given the relevance of the electricity generation sector, we carry out additional analysis to better comprehend the results. In particular, we generate two types of sensitivities: first, we run a sensitivity analysis on the final year of closure of coal-fired power plants, observing that, as expected, an early closure will yield many benefits for the 2020–2030 carbon budget. A second type of sensitivity explores the marginal cost: starting from the NDC scenario, we progressively increase the carbon tax to obtain a smooth marginal abatement cost curve. The carbon tax that yields comparable GHG reduction results for the NDC+ scenario is between 40 and 45 USD/tCO_2e; however, the tax does so at a much lower cost than the NDC+ scenario. Thus, it reveals that the accelerated coal-fired power plant closure included in the NDC+ scenario is not the most cost-efficient mitigation action. It is also important to remark here that the results for the electricity generation sector depend on the assumptions and data inputs employed, and the results obtained could change under different assumptions and/or data inputs; however, we believe that the analysis presented in this report is a relevant indicator for the importance of further assessing specific implementation mechanisms for mitigation actions, including but not limiting the analysis to strategies such as faster coal-power phase-out and carbon tax enforcement.

A total of 5.3 (4.9–5.3) billion USD is estimated to be necessary as additional capital between 2020 and 2030 to implement further actions from the NDC scenario to an NDC+ scenario. Around 83% of this additional capital is needed in the electricity generation sector and is mainly related to payments for early closure of coal-fired power plants (3.2 billion USD) and building additional renewable power capacity and transmission lines (1.2 billion USD). Transportation and LULUCF also represent another relevant fraction, together the two amounts to 11% of the additional capital cost estimated.

Main insights

The fulfillment of the commitments in Chile's NDC is not guaranteed. Although this is not the focus of the study, the results of the NDC scenario only achieve the commitments through additional restrictions of the electricity generation sector. This indicates that the mitigation actions selected for the NDC scenario are insufficient to fulfill all the commitments. We consider the current policies and discussions to decide which mitigation actions to include in the NDC. Given that three of the eleven years included in the carbon budget horizon have already passed, it is urgent that more actions (or increasing the ambitions of the current one) are implemented. Compared with previous studies, a worse economic projection has benefited the results through a reduced activity level. For example, the electricity demand for the reference scenario is close to the low electricity demand in previous studies. Nonetheless, according to our results, achieving the commitments needs additional effort.

Additional actions could yield a significant surplus of mitigation at a reasonable cost. Our results suggest that up to 75 (65–82) $MtCO_2e$ could be mitigated beyond the committed carbon budget. Almost one-third of the mitigation potential could be achieved at a mean abatement cost less than 20 USD/tCO_2e. An additional 65% could be obtained with a mean abatement cost between 20 and 50 USD/tCO_2e. We estimate that the capital cost needed for implementing these actions is 5.3 (4.9–5.3) billion USD from 2020 to 2030. For this period, the most relevant actions are reducing the carbon intensity in the electric sector, increasing environmental protection areas, and increasing the electrification of processes in the industry and mining sector. It is also important to note that the capital cost includes extra cost requirements regarding the early coal-power phase-out, such as the valuation of existing energy contracts or mechanisms that remunerate their retired capacity. We estimate a first approximation to this additional cost, as the remaining useful life of prematurely closed coal-fired power plants, which yields a total closure cost of 3.2 billion USD.

The early coal-power phase-out is not the most efficient mitigation action in the power sector. We generate new sensitivities in the electricity sector that showed how a carbon tax between 40–45 USD/tCO_2e could achieve a lower total cost to the year 2050 (38,199–38,770 million USD) at the same level of emissions mitigation to 2030 (35–49 MtCO_2e), in comparison with the early coal-power phase-out mitigation action, which presents a total cost of 42,935 MUSD to 2050 with 45 MtCO_2e of emissions reduction to 2030. Further studies should analyze in detail the implementation challenges associated to mitigation actions such as faster coal-power phase-out and carbon-tax enforcement, and the analysis presented in this report constitutes an important first step in this direction.

The additional mitigation has significant health co-benefits. We estimate that if the NDC+ mitigation actions are implemented, Chile could avoid up to 2,250 (2,180–2,320) premature PM2.5-induced deaths between 2020 and 2030. This represents nearly 5% of the total PM2.5-induced deaths expected in that period. By 2030, the annual avoided premature deaths amount to 460 (440–480); by 2050, this could amount to 2,110 (1,900–2,310) avoided death. These numbers represent a relevant benefit in health, considering that by 2019 the estimated annual PM2.5-induced premature deaths was close to 4,000 (MMA, 2019). Using the statistical valuation of life currently used by the Chilean environmental ministry, the health co-benefit between 2020 and 2030 is around 1.5 billion USD.

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, 2021).

The Climate Action Teams initiative operates through government-to-government agreements based on verified mitigation outcomes beyond Nationally Determined Contributions (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 Climate Team mechanism facilitates mitigation outcomes at lower abatement costs, but unlike a project-based mechanism, it does not require costly institutional infrastructure, thereby reducing transaction costs considerably. Currently the Climate Teams initiative is promoting an exploration process with Chile as a host country and New Zealand, Switzerland, and Canada as potential partner countries.

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

- A long-term vision of achieving Greenhouse Gas (GHG) Neutrality by 2050.
- The GHG emission budget does not exceed 1,100 $MtCO_2e$ between 2020 and 2030 (excluding LULUCF[2]), with a GHG emissions maximum (peak) by 2025 and a GHG emissions level of 95 $MtCO_2e$ by 2030.
- Reducing black carbon emissions by at least 25% by 2030, with respect to 2016 levels.
- Achieving a sustainable management and recovery of 200,000 hectares of native forests, which represent GHG captures of around 0.9 to 1.2 $MtCO_2e$ 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, which would result in captures between 3.0 and 3.4 $MtCO_2e$ annually by 2030.

---

[2] LULUCF. Land Use, Land Use Change and Forestry

- Reducing emissions in the LULUCF sector associated with degradation and deforestation of the native forest by 25% by 2030, with respect to the average emissions from 2001–2013.
- Others (not quantified or not directly related to mitigation).

The current study explores alternatives to go beyond the NDC commitments. In the first phase of this study (Pica-Téllez et al., 2022), a set of additional mitigation actions were identified that, if implemented, would allow an overachievement of the NDC commitments. In this study, around 40 $MtCO_2e$ of mitigation additional to the NDC commitments would be achievable with a marginal cost of less than 50 USD/tCO_2e.

For the present report, a modelling team from the Global Change Center of the Catholic University of Chile strengthened the previously developed model by integrating the different sectors, improving the economic analysis, attending to the shortcomings of the previous version, and including a new co-benefits module.

The detailed results and the open-access models are available for further analysis and understanding of the findings expressed in this report[3]. The previous report is a critical feature to increase the confidence of the parties interested in participating in the Climate Action Teams' schemes.

---

[3] available at: https://data.mendeley.com/datasets/jtp6dcyp78

2. Objectives

The main objectives of this report are to:

- Develop GHG emission models that cover all the sectors identified by the GHG National Inventories.
- Identify different Mitigation Scenarios, each with a set of GHG mitigation actions that achieve and go beyond the NDC commitments.
- Analyze the Mitigation Scenarios with respect to their economic impact, including a co-benefit analysis.

3. Model Description

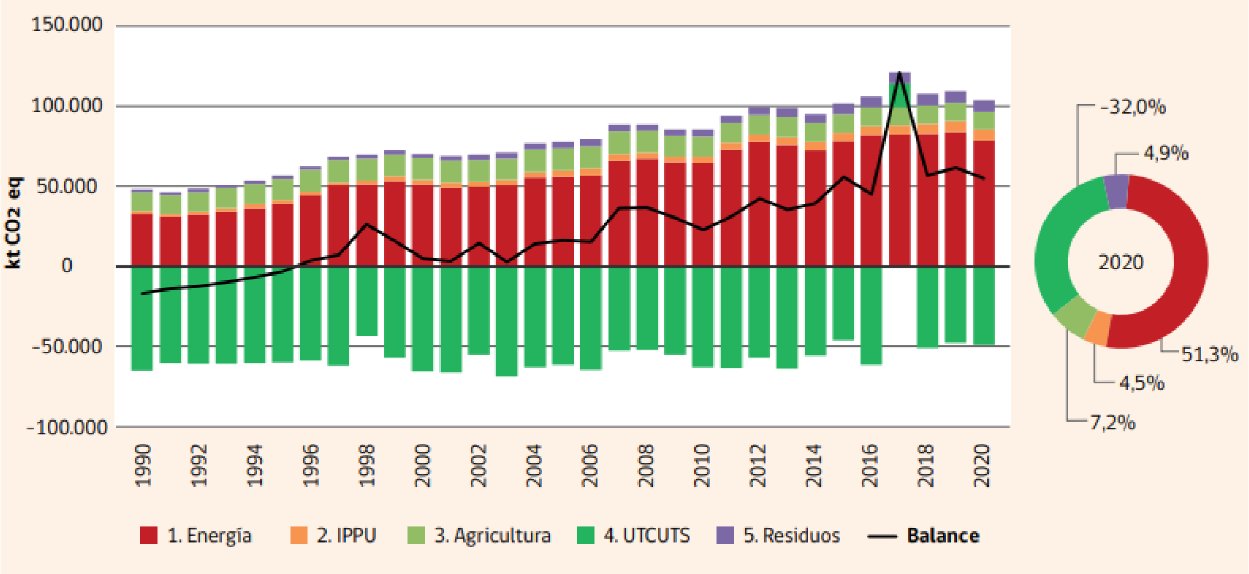
3.1 Overview

The model developed for this report represents Chile's GHG emissions from all the emission and sink sources included in the national inventory. This model is based on sectoral models, which are integrated via key parameters that impact more than one model (e.g., population, biomass burnt in households, or electricity prices).

The GHG's national inventories identify five 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. Figure 3-1 shows that LULUCF has significant net captures (-64MtCO$_2$e by 2018). Although the sector has shown some level of degradation related to forest fires and woodfire extraction, the forestry plantations and the native forest under conservation is still growing as of 1990. The other four sectors are net emitters (112.3 MtCO$_2$e by 2018); the main one being the Energy Sector (87MtCO$_2$e by 2018), followed by Agriculture (11.8 MtCO$_2$e), Waste (7 MtCO$_2$e by 2018), and IPPU (6.6 MtCO$_2$e by 2018).

FIGURE 3-1

Historical GHG Emissions of Chile by Sector



Source: (MMA, 2022).

From the net emitter sectors , the energy sector is the main contributor to GHG emissions in Chile because of the intensive use of fossil fuels to produce energy. This sector is distributed in subsectors: Electricity Generation (34.3% of the sector emissions), Transportation (32.7% of the sector emissions), Mining (9.5% of the sector emissions), and Buildings (8.3% of the sector emissions). The second sector in terms of emissions is Agriculture (10.6%), followed by Waste (7.3%) and Industrial Processes & Product Use (IPPU) (6.6%).

The following models were developed taking into account the relative importance of the different sectors and subsectors:

- Energy: electricity generation
- Energy: transportation
- Energy: industry and mining
- Energy: buildings
- IPPU
- Agriculture

- FOLU (forestry and other land uses)
- Waste.

Most of these models are simulations under mitigation actions and other factors (e.g., GDP, prices, demand) are exogenous. The exception is the electricity generation model, where an optimization process is used to simulate the private behavior of the actors. In this sense, there is an independent optimization process for each Mitigation Scenario/Future in the electric sector.

Considering the purposes of Climate Action Teams, transparency of the assumptions, methodology, and modelling is one of the goals during the modeling process. In this context, the models were developed in Python as open-source code and are available to whoever is interested[4]. In the appendixes of this report, more details are included about the modeling exercise in each sectoral model (Appendix 1) and the mitigation action considered (Appendix 2).

The models and their results were contrasted with the National GHG emission inventory (MMA, 2020) and previous efforts (Benavides et al., 2021; Palma Behnke et al., 2019) and relied on the best public information available to the team. To project a range of emissions trajectories, possible Futures and Mitigation Scenarios were defined. These Futures and Mitigation Scenarios, described in the following subsection, aim to complement the central estimations with insight into the impacts of external uncertainty.

3.2 Futures and Mitigation Scenarios developed

For this analysis, addressing the Future conditions driving GHG emissions is necessary. The different sources of variability in the emissions can be exogenous (generated at the international level or related to climate conditions) or endogenous (generated from the results of other parts of the model or by the level of implementation of the mitigation actions). To reflect this, this report developed two categories of pathways:

- **Futures** They represent a trajectory of exogenous parameters that define a possible set of conditions that could facilitate (or challenge) the mitigation strategies.
- **Mitigation Scenarios** They represent different mitigation strategies implemented at a national level. Each strategy considers a set of mitigation actions and their specific level of implementation.

---

[4] The models are available in: https://data.mendeley.com/datasets/jtp6dcyp78

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

- **Economic activity and commodity prices** Chinese GDP will affect national GDP, energy prices, copper prices, agricultural 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 the world level will impact the prices of the different clean technologies.
- **Climate action in Chile** The level of commitment to climate action and the government's efficiency will impact how quickly Chile will implement the planned mitigation measures.

Usually, a decision maker analyses one pathway of drivers and projects GHG emissions over these sets of conditions. In the current study, we consider three Futures; the first is the Reference Future, where all the drivers have their respective expected values. We developed a sensitivity analysis to explore the impact of uncertainty on the key drivers. We group these sensitivities in a Green and a Red Future. The following table (Table 3-1) presents the differences between the different Futures:

TABLE 3-1

Differences in the selected Futures

Group of variables	**Futures**		
	Red	**Reference**	**Green**
Chinese GDP growth, commodity prices, and national production levels	High: Chinese GDP, commodity prices, and National Production Level	Medium: Chinese GDP, commodity prices, and National Production Level	Low: Chinese GDP, commodity prices, and National Production Level

Group of variables	**Futures**		
	Red	**Reference**	**Green**
Climate Variables (representative decade)	Drought (2010–2019) [1]		
Green technology prices	High	Medium	Low
Climate Action	Delayed	Conventional	Early and active

[1] In the previous phase of this study (Pica-Téllez et al., 2022) different hydrologies were considered for the Futures. In response to the feedback of that study, which considered the assumption of a wet or medium hydrology to be too optimistic, in this phase we considered only a dry hydrology.

Source: Study Authors.

For the mitigation strategies, we define two Mitigation Scenarios[5]:

- NDC Mitigation Scenario (NDC): Considers the achievement of all the Chilean mitigation commitments for 2030 in its last NDC. In particular, it considers:
    - Carbon budget commitment: The total emissions from Chile between 2020 and 2030 will not surpass 1,100 MtCO$_2$e.
    - GHG emissions 2030: The GHG emissions of Chile in 2030 will not exceed 95 MtCO$_2$e.
- Beyond NDC Mitigation (NDC+): Considers enhanced mitigation actions to go beyond Chile's NDC commitments for 2030.

Multiple intermediate scenarios can be designed to consider different criteria in defining the actions included. These intermediate scenarios and different combinations were not analyzed by the team. The models are open-source and available for users to explore further scenarios of interest.

3.3 Mitigation actions considered

For this analysis, addressing the Future conditions driving GHG emissions is necessary. The different sources of variability in the emissions can be exogenous (generated at the international

---

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

level or related to climate conditions) or endogenous (generated from the results of other parts of the model or by the level of implementation of the mitigation actions).

For the two Mitigation Scenarios, we include different mitigation actions with a specific national level of implementation. A summary of these actions modeled in each sector is presented in the following table.

TABLE 3-2

Mitigation actions included in the model

Sector	Subsector	Mitigation action	Id
Transportation	On-road	Electromobility: Private cars	T1
		Hydrogen on freight trucks	T2
		New bus rapid transit corridors in Santiago	T3
		An incentive for new bicycle infrastructure	T4
	Air	Hydrogen on commercial flights	T5
Industry & Mining (I&M)	Copper	Solar thermal systems	I&M1
		Electrification in thermal processes	I&M2
		Electrification in motor processes	I&M3
		Hydrogen in motor processes, open pit mining	I&M4
		Hydrogen in motor processes, underground mining	I&M5
	Various industries	Solar thermal systems	I&M6
		Hydrogen in thermal processes	I&M7
		Hydrogen in motor processes	I&M8
		Electrification in motor processes	I&M9
	Various mines	Hydrogen in motor processes	I&M10
		Electrification in motor processes	I&M11
	Steel	Hydrogen in thermal processes	I&M12
		Biomass in thermal processes	I&M13
Buildings	Commercial	Electrification of end uses	B1
	Public	Solar water heaters in public hospitals	B2
		Electric heating in public hospitals	B3

Sector	Subsector	Mitigation action	Id
		Solar PV on public buildings	B4
	Residential	Electric residential heating	B5
		Electrification of residential cooking	B6
		Solar water heater	B7
		Retrofit of thermal insulation	B8
Waste	Solid waste disposal	Increased capture and burning of landfill gas	W1
		New composting plants	W2
	Wastewater treatment and discharge	New wastewater treatment plants for the most populated cities	W3
IPPU	Emissions of fluorinated substitutes for ozone-depleting substances	Recovery and regeneration of refrigerant plants	I1
Electricity Generation	Power	Phase-out acceleration to 2025	EG1
Agriculture	Enteric Fermentation	Change in bovine diet (lipidic additive)	A1
		Holistic Livestock Management – Regenerative Livestock	A6
	Manure Management	Biodigesters Pigs and Bovines	A2
		Meat Tax	A5
	Agricultural soils	Efficient use of fertilizers	A3
	C capture in soil	Application of organic amendments (poultry manure)	A4
	Agricultural burns	Reduction of agricultural burning	A7
	Biochar	Biochar utilization	A8
FOLU	Forest land	Native afforestation	L1
		Exotic afforestation	L2
		Increase in hectares of native forest management	L3
		Increase in protected areas	L5
		Native afforestation – increase in hectares	L7
		Increase in hectares of native forest management - increase in hectares	L8

Sector	Subsector	Mitigation action	Id
	Forest fires	Degradation reduction caused by forest fires	L4
	Other lands	Kelp forest management	L6

Source: Study Authors.

3.4. Co-benefit analysis

The mitigation of GHG impacts the emission of other substances co-emitted along the GHG. These other emissions significantly affect human health, with global estimates considering 3.1 million premature deaths due to air pollution, particularly due to PM2.5. In Chile, the official estimates account for around 4 thousand premature deaths related to exposure to high levels of PM2.5 (MMA, 2019). We include a module for estimating health co-benefits in this modelling version.

Climate actions, such as improvement of efficiency, electrification, and in general, any reduction of the level of fuel combustion, are also expected to reduce the levels of PM2.5 in the air. The design module considers the variation in the consumption of fuels produced by climate actions to estimate the variation in PM2.5 emissions. Although some variation is expected between the different sources due to technology, abatement options, quality of fuels, etc., emission factors that relates the level of activity to the level of emissions are commonly used for these estimates. For this purpose, we chose the tier 1 emission factor proposed by the European Environmental Agency (EMEP/EEA, 2019).

Changes in emissions have consequences on the concentration of pollutants in the air. This process is complex and is mediated by variables such as topology, local climate, and constructional characteristics of the sources, among others. Currently, the Chilean environmental ministry uses a simplification that directly links concentration with emissions, which was built at a communal level for 313 of the 346 communes in Chile. A population-weighted average was estimated to achieve a regional estimate of this parameter.

Regarding the impact on health, the endpoint considered was premature death due to exposure to high levels of PM2.5. There is consistent evidence of the effects of PM2.5 on human health, with a central estimation of the Hazard Ratio of 1.08 for long-term exposure to 10 μg/m3 (Pope et al., 2020). Along with the Hazard Ratio, the base incidence rate must be estimated to project the Future impacts of the changes in PM2.5. For this, health data published by the Chilean Health

Ministry were considered, and the base incidence rate was estimated by region, considering data from 2013–2017. Since 2018, high levels of immigration and the COVID-19 pandemic could affect the estimations so these years were not considered for the analysis.

4. Results

This chapter presents the aggregated results of the modelling exercise; the first part presents the GHGs emission results, while the second part presents an analysis of the mitigation costs. An estimation of the health co-benefits of the NDC+ scenario is included in the last section.

When interpreting these results, one must consider that we force the fulfilment of the NDC commitments[6] with an artificial constraint on the electric generation sector. In other words, if the set of mitigation actions is not enough to meet the commitments, the optimization of the electric sector will have active restrictions constraining GHG emissions. This is the case in the three futures of the NDC Mitigation Scenario. This is not necessary on the NDC+ Mitigation Scenarios.

4.1 Emissions

We estimated annual emissions for 2020–2050 for each Future (Reference, Red, Green) and Mitigation Scenarios (NDC, NDC+). In the following figures, we show the GHG emissions and CO_2 capture for the Reference Future for the NDC (Figure 4-1) and NDC+ (Figure 4-2) scenarios. Also, we present the distribution by modeling sector, where the relevance of the energy and forestry sector is noticeable. The net GHG emissions in the NDC scenario add up to 594 $MtCO_2e$, while the NDC+ scenario comes to 168 $MtCO_2e$. It is important to notices that at the moment of modeling we did not had official estimates for 2020–2022 GHG emissions, so all the numbers are the result of modelling.

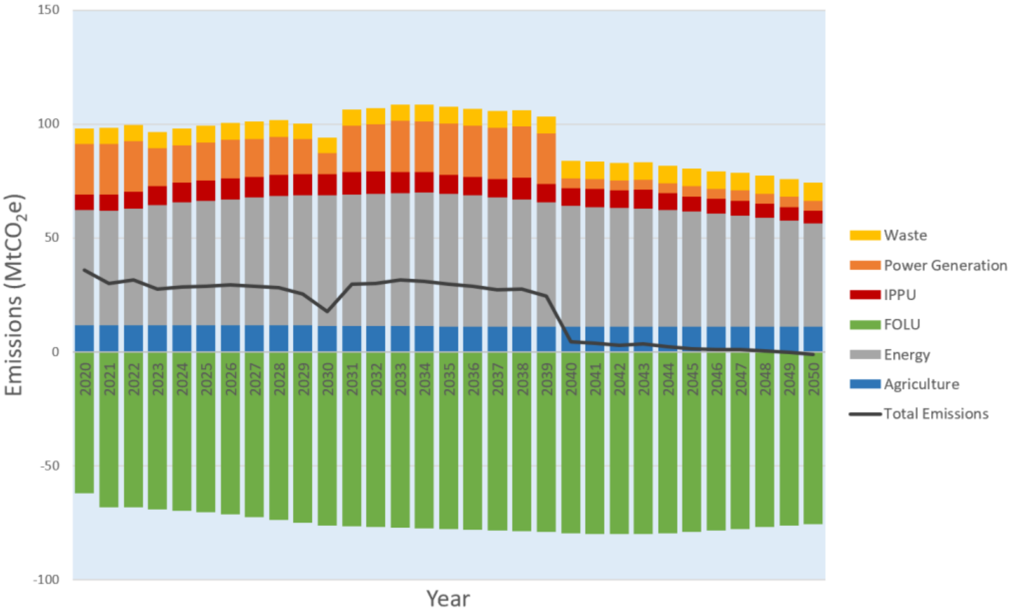
Table 4-1 helps to explain the difference in emissions by sector for the NDC and NDC+ scenarios. This difference is mostly driven by the Power Generation sector (48% difference between the scenarios) and by the energy demand sector (32% difference). The remaining 20% is distributed between Forestry (9% of difference), IPPU (7% difference), Agriculture (4% difference), and Waste (1% difference).

---

[6] The process is iterative, we allow a 1% deviation from the commitments. This means that we stop the iteration process when the emissions are in the [1089-1111] MtCO2e between 2020-2030, and between [94-96] MtCO2e for the year 2030.

FIGURE 4-1

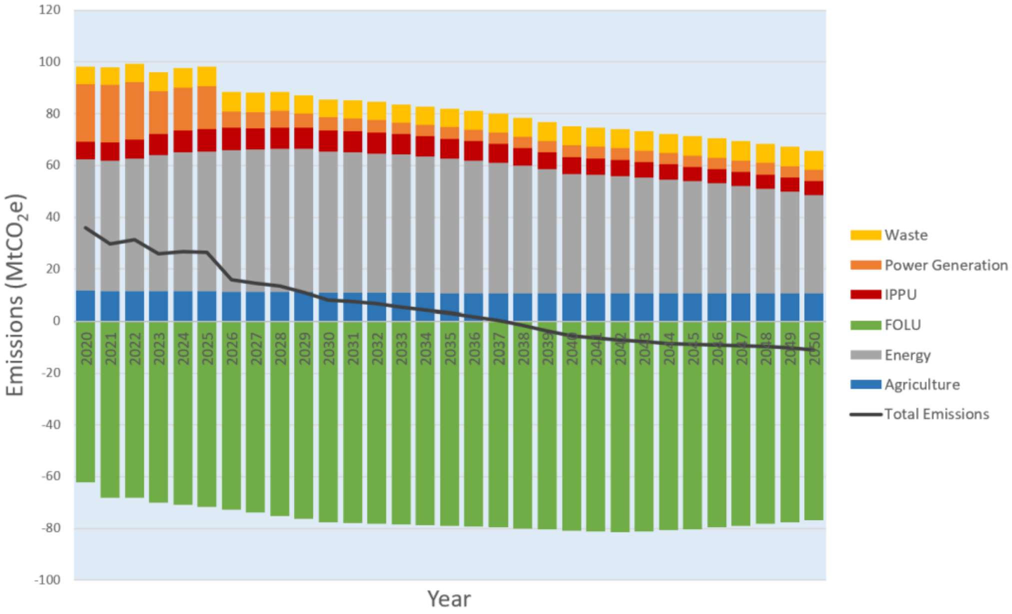
Emissions for the NDC Scenario in the Reference Future.



Source: Study Authors.

FIGURE 4-2

Emissions for the NDC+ Scenario in the Reference Future



Source: Study Authors.

TABLE 4-1

Net GHG emissions ($MtCO_2e$) by sector in 2020–2050

Sector	NDC	NDC+	Difference	% Total Difference
Power Generation	437	235	202	48%
Energy	1,661	1,525	136	32%
IPPU	250	220	31	7%
Agriculture	353	336	17	4%
FOLU	-2,336	-2,374	38	9%
Waste	229	227	2	1%
Total	594	168	426	100%

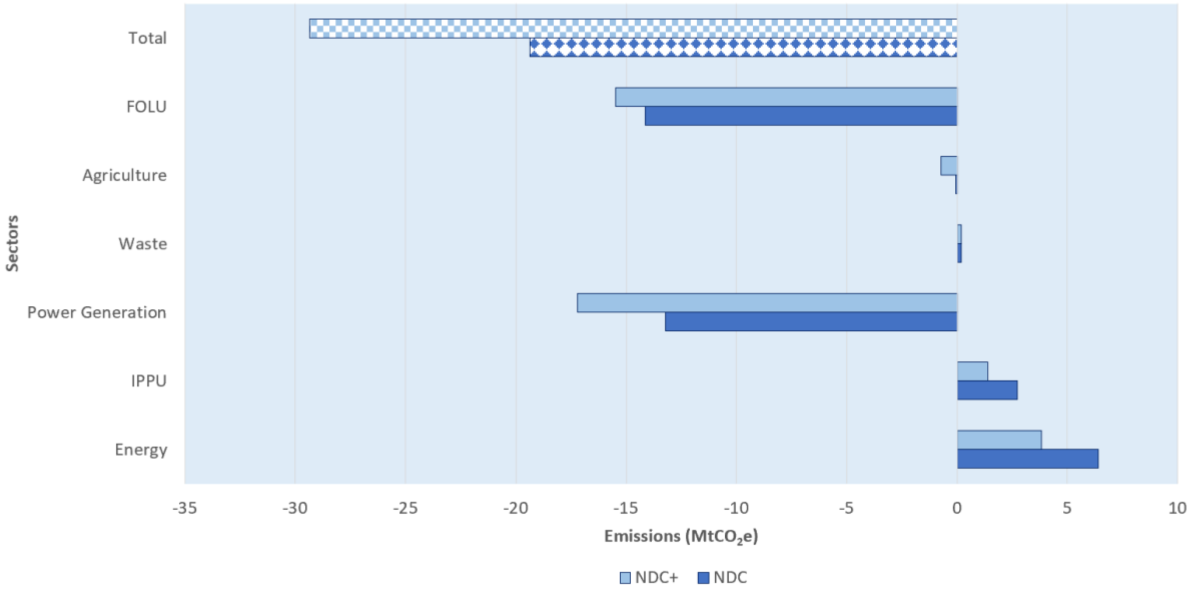
Note: IPPU: Industrial Processes and Product use; FOLU: Forestry and Other Land Uses

Source: Study Authors.

Specifically, for the period of interest 2020–2030, Figure 4-3 shows the difference between emissions in 2020 and 2030. We present this as a way to show the emission trajectories by sector within each Mitigation Scenario. We observe a reduction of emissions between the Mitigation Scenarios across all the sectors, with the more significant decreases observed in the power generation sector. We can also see that while the power generation, agriculture, and forestry sectors result in a net reduction of GHG emissions compared to 2020, this is not true for the waste, IPPU, and energy demand sectors. This last observation means that the mitigation actions considered were not enough to counter these sectors' increase in activity levels.

FIGURE 4-3

Difference between projected emissions by 2030 and 2020 (million tCO_2e) for each scenario in the Reference Future



Source: Study Authors.

4.1.1 Fulfillment of NDC commitments

The results show that the NDC scenario meets almost all of the Chilean NDC commitments. Table 4-2 presents a summary of the level of compliance with GHG mitigation commitments.

TABLE 4-2

Level of achievement of Chile's NDC commitments

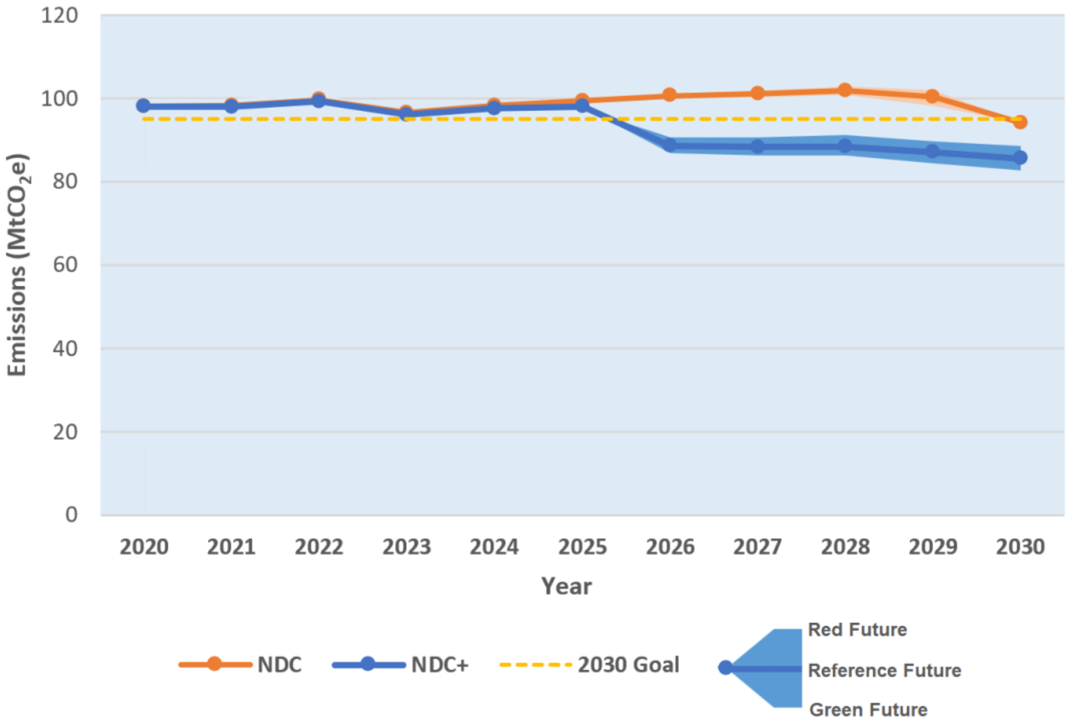
Commitment	**Detail**	**NDC**	**NDC+**
Carbon budget	1,100 $MtCO_2e$ between 2020–2030	Achieved (1,089 $MtCO_2e$)	Achieved (1,025 $MtCO_2e$)
Annual Emissions	95 $MtCO_2e$ by 2030	Achieved (94 $MtCO_2e$)	Achieved (86 $MtCO_2e$)
Peak of Emissions	By 2025	Not Achieved (2028)	Achieved (2022)
Carbon neutrality	Net zero emissions by 2050	Achieved (-1 $MtCO_2e$)	Achieved (-11 $MtCO_2e$)

Source: Study Authors.

The only commitment that is not achieved is the year of peak emission by 2025 in the NDC Mitigation Scenario. According to our projections, the peak (see Figure 4-4) would be achieved by 2028, three years later than the commitment. This peak year estimation also holds for the sensitivity Futures (Red and Green). It is relevant to notice that while the "carbon budget" and "annual emissions" are included as constraints in the modeling, the "peak emissions" and "carbon neutrality" were not included as constraints, as the focus of the project is on the identification of additional mitigation opportunities.

FIGURE 4-4

Total GHG emissions (not including captures) in Mitigation Scenarios in 2020–2030, intervals created by different modeled Futures.

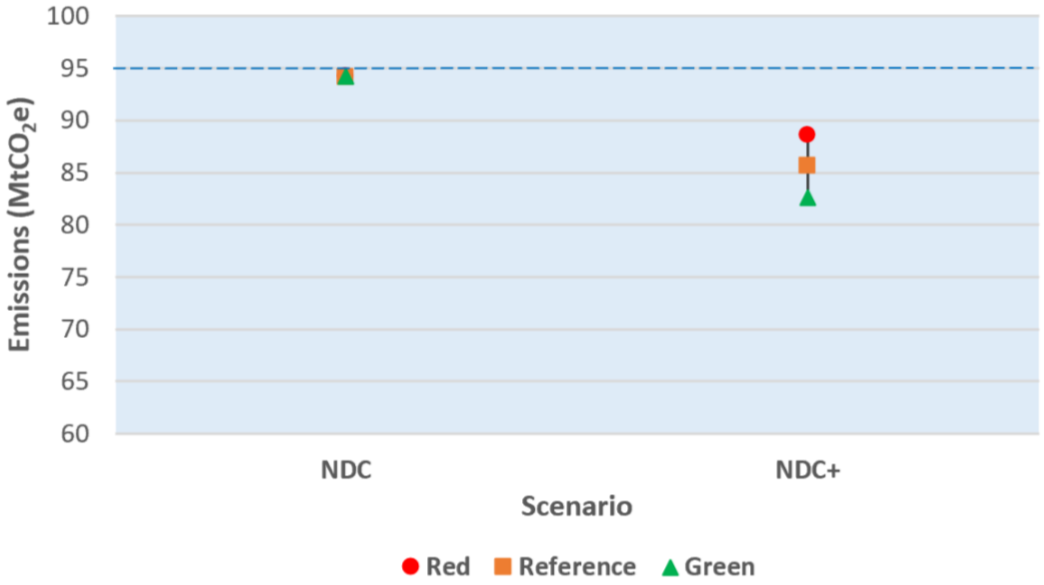


Source: Study Authors.

The "carbon budget" and "annual emissions" commitments are modeled as constraints on optimizing the electricity generation model. It is important to notice that in the NDC Mitigation Scenario, these constraints are active in the optimization, meaning that the electricity generation model has to reduce its GHG emissions output beyond what was economically optimal. For this reason, the commitments are fulfilled in the reference scenario and the sensitivity Futures (see Figure 4-5 and Figure 4-6).

FIGURE 4-5

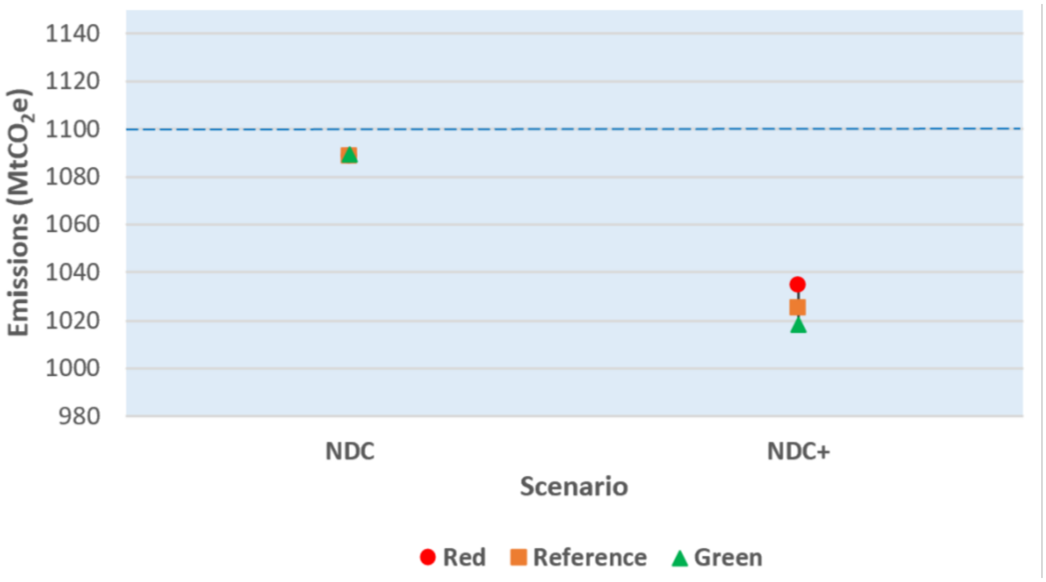
Projection of absolute emissions in the year 2030 for each scenario and for each Future.



Source: Study Authors.

FIGURE 4-6

Cumulative emissions emitted between 2020 and 2030 for each Mitigation Scenario and each Future.



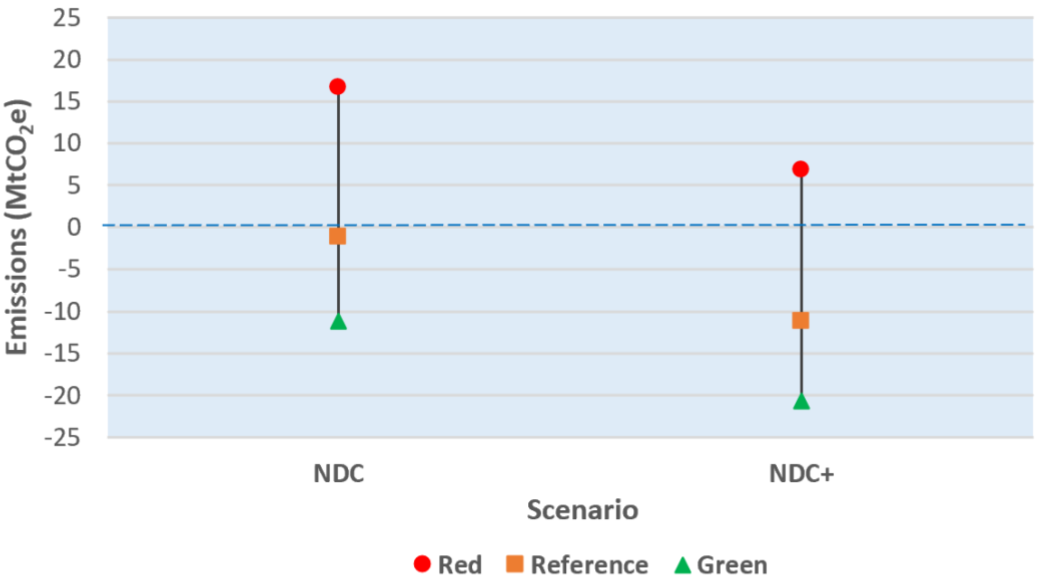
Source: Study Authors.

In the NDC+ scenario, the additional mitigation actions mitigate beyond the NDC commitment. In particular, a surplus of 75 (65–82) $MtCO_2e$ for the 2020–2030 period is observed. While for the 2030 GHG emission commitment, an excess of 9 (6–12) $MtCO_2e$ is estimated.

In terms of the long-term commitment to achieving carbon neutrality by 2050, in the NDC scenario, the Red Future does not comply with the commitment. This is true even in the NDC+ Mitigation Scenario (Figure 4-7). This result is consistent with previous studies (Benavides et al., 2021), which focus on identifying the factors that may lead to this unsatisfactory result in the long term.

FIGURE 4-7

Forecast of net emissions by 2050 for each Mitigation Scenario and each Future



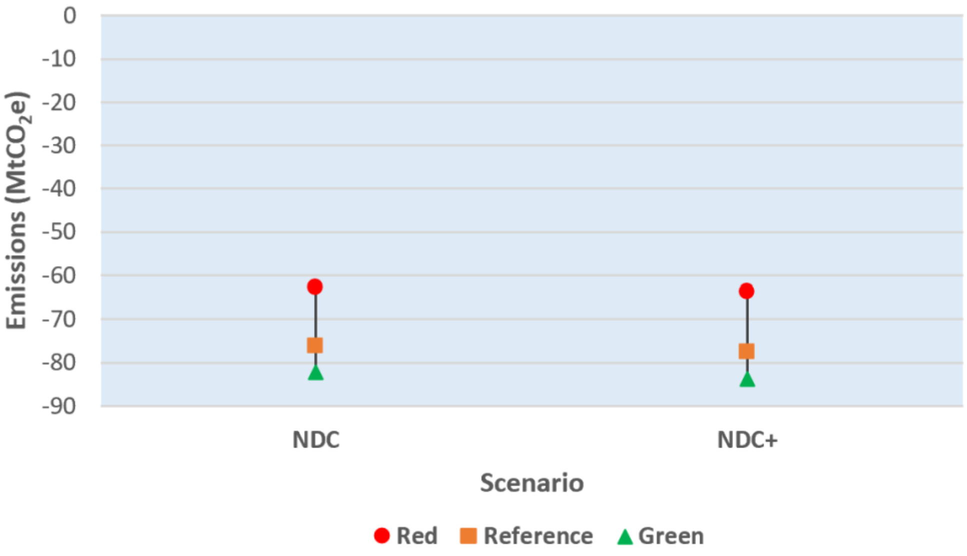
Source: Study Authors.

4.1.2 Carbon captures

Although most of the NDC commitments, except for carbon neutrality, do not consider the forestry capture, this sector has an essential contribution to the net balance of GHG emissions in Chile. Because of this relevance, Figures 4-8 through 4-10 replicate the same analysis shown in the previous section, especially for the forestry sector.

FIGURE 4-8

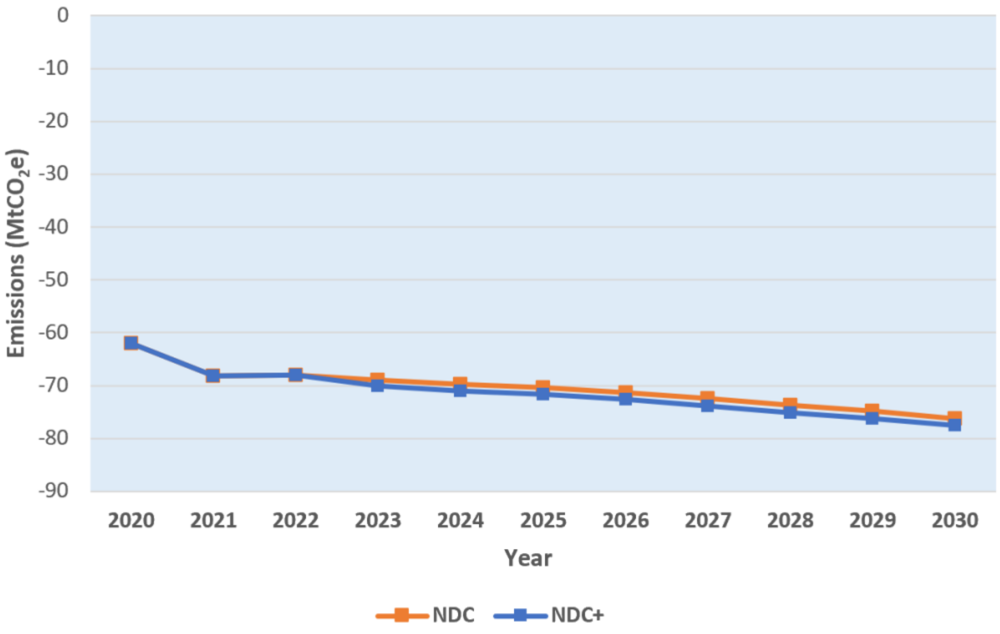
Emissions in 2030 of the LULUCF sector for each Mitigation Scenarios and each Future



Source: Study Authors.

FIGURE 4-9

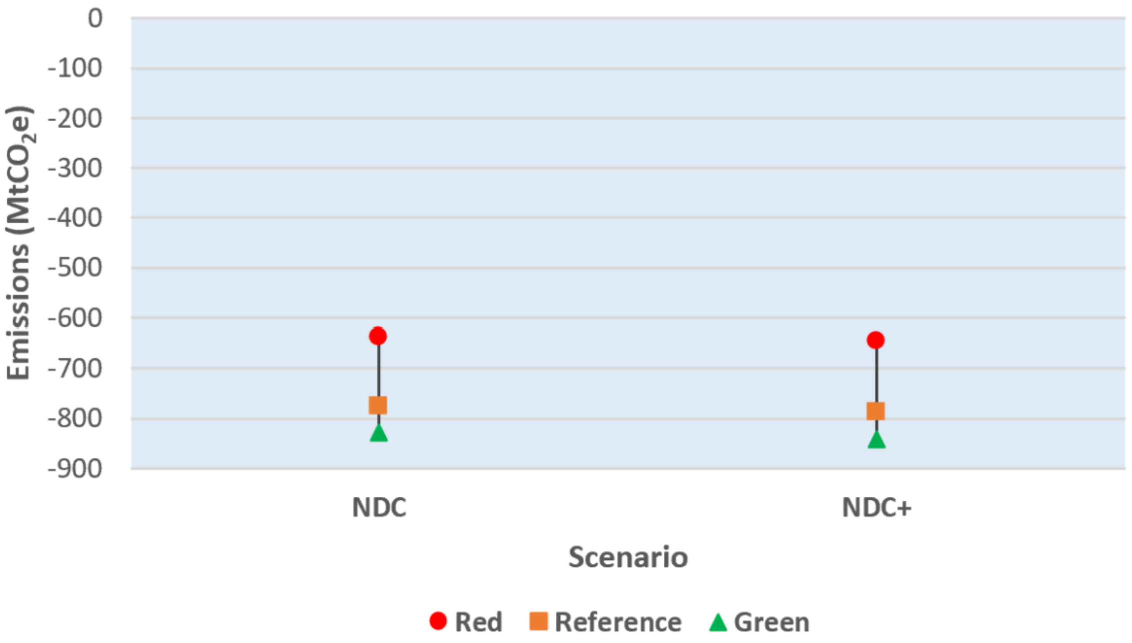
Total emissions of the LULUCF sector for Mitigation Scenarios in the period 2020–2030, Reference Future



Source: Study Authors.

FIGURE 4-10

Emissions of the LULUCF sector in each Mitigation Scenarios and each Future, in 2020–2030



Source: Study Authors.

4.2 Cost analysis of mitigation actions

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

- Mitigation potential: Corresponds to the difference of emissions between the 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 effect on emissions of other sectors (e.g., caused by changes on electricity or wood demand). This difference applies only to 2020–2030, which coincides with the NDC carbon budget commitment.

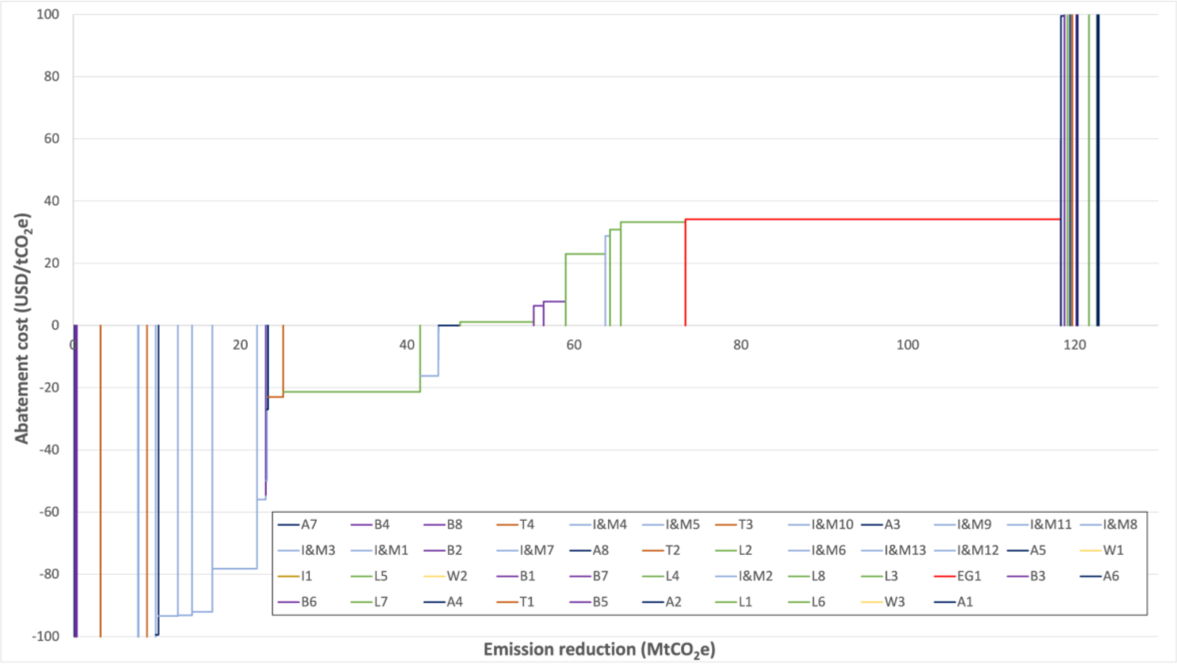
- The average cost of mitigation: Corresponds to the discounted costs of investments, operating costs, and savings in the long term (horizon 2020–2050), divided by the total mitigation potential for 2020–2050.

4.2.1 Cost-effectiveness

We use the Mean Abatement Cost Curve (MACC) to better understand the mitigation cost. In this MACC, 47 mitigation actions are included from the different sectors modeled. Figure 4-11 presents the resulting MAC of this exercise. The figure legend is described in Table 3-2.

FIGURE 4-11

Mean abatement cost for the 2020–2030 period for the Reference Future



Note: for purpose of better visualization, the range of the y-axis is cut between -100 and 100 USD/tCO$_2$e.

Source: Study Authors.

If every mitigation action were to be implemented, regardless of the cost, a total of 123 MtCO$_2$e could be mitigated between 2020–2030. The range of the mean mitigation cost for the actions goes from -344 USD/tCO$_2$e (reduction of agricultural burning) to 713 USD/tCO$_2$e (change in bovine diet). It is also noticeable that 44 MtCO$_2$e have a mitigation cost below 0 USD/tCO$_2$e. These are actions that, if implemented, would result in a net socio-economic benefit. Among these mitigations, the ones with the largest potential are electrification of processes in industry and mining, the use of green-hydrogen in mining, and increasing afforestation with exotic species.

Different reasons could explain why these actions might not be implemented in a baseline scenario:

- Different discount rates between the social analysis (6% according to the official recommendations in Chile) and the private analysis
- Coordination and commitment problems between the actors
- Lack of information and differences in the assumptions
- Negotiation costs and access to capital.

The mitigation action with the most significant mitigation potential (the large area under EG1 (red line) in Figure 4-11) is the accelerated coal phase-out (closure of coal-fired power plants by 2025) with 45 (36–52) $MtCO_2e$ available for mitigation at an average cost of 34 (34–38) USD/tCO_2e. This accelerated coal phase captures the full potential of mitigation of the accelerated closure of coal-fired power plants by 2025. This goal's political and technical feasibility is thin; in the Appendix of this study, we include sensibilities to closure by 2028 and 2030. Additionally, we provide more details about the marginal abatement cost in the electricity sector in Section 4.2.2.

Table 4-3 presents the mitigation potential between 2020-2030 distributed by their mean abatement cost, considering all possible mitigation actions that could be implemented and the Reference Future. The percentage from each mean abatement cost interval total mitigation potential is also detailed.

TABLE 4-3

Mitigation potential cost by level of mean abatement cost, for the Reference Future and all possible mitigation actions

Mean Abatement Cost (USD/tCO_2e)	**Total Mitigation Potential ($MtCO_2e$)**	**% from the Total Mitigation Potential**
<0	44	36%
[0–20]	15	12%
[20–50]	59	48%
>50	5	4%

Source: Study Authors.

To complement Table 4-3, Table 4-4 summarizes the distribution of mean abatement costs for each Future. The sensitivity analysis shows around 10% uncertainty in the total mitigation potential. The main contribution to this uncertainty is the electricity generation sector, which is highly sensitive to the exogenous parameters because of the optimization modeling. This effect directly impacts the distribution of the mitigation potential between the different intervals of mean abatement cost considered.

TABLE 4-4

Sensitivity analysis of mitigation potential ($MtCO_2e$) between 2020–2030, all possible mitigation actions

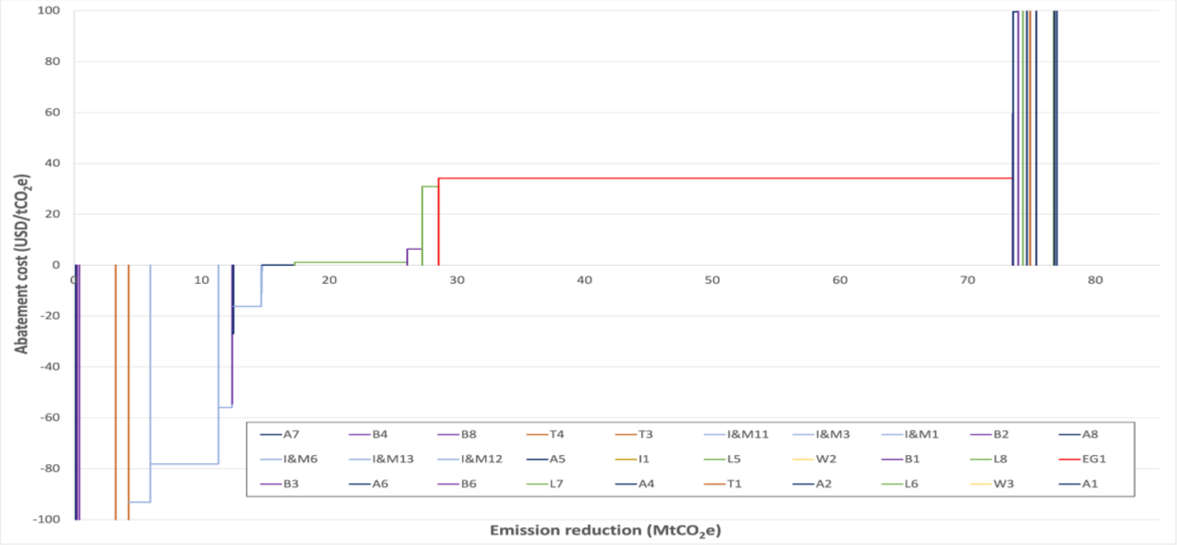
Mean Abatement Cost (USD/tCO_2e)	**Reference Future**	**Red Future**	**Green Future**
<0	44	44	44
[0–20]	15	28	23
[20–50]	59	44	64
>50	5	5	4
Total Potential	123	120	135

Source: Study Authors.

Figure 4-12 presents the MACC only for the additional actions considered between the NDC and NDC+ Mitigation Scenarios. It is necessary to notice that the NDC scenario modelling depended on a set of mitigation actions the team believe to be more plausible to implement in 2020–2030. Different combinations of mitigation actions could be considered in the NDC scenario, altering the MACC results that compare the NDC+ and NDC scenarios. Following cost-effectiveness criteria, the equivalent marginal cost for the NDC scenario is 19.7 USD/tCO_2e.

FIGURE 4-12

Mean abatement cost between the NDC and NDC+ Mitigation Scenarios for the 2020–2030 period for the Reference Future



Note: for purpose of better visualization, the range of the y-axis is cut between -100 and 100 USD/tCO$_2$e.

Source: Study Authors.

When we consider the implementation of the full potential of mitigation action, an additional total of 77 MtCO$_2$e could be mitigated between 2020–2030 beyond the fulfillment of the NDC's commitments. Among the actions included in the NDC+ Mitigation Scenario, some are the same actions considered in the NDC Scenario, but are more ambitious (e.g., a subsidy for electric vehicles or more subsidies for retrofit isolation in houses) while others are entirely new (e.g., meat tax or biodigesters for pig farming) In this case, 15 MtCO$_2$e have a mitigation cost below 0 USD/tCO$_2$e. This means that in the NDC scenario, we consider mainly actions that account for two-thirds of the mitigation potential (44 MtCO$_2$e) with a negative average cost. The other main mitigation action in the NDC scenario is the de-carbonization of the electricity generation sector but without the level of ambition that we estimate for the NDC+ scenario.

The distribution of the mitigation measures considered beyond the NDC is presented in Table 4-5. Additionally, Table 4-6 shows a summary of each sensitivity Future.

TABLE 4-5

Mitigation potential cost by bracket of mean abatement cost, for the Reference Future and additional mitigation actions

Mean Abatement Cost (USD/tCO_2e)	Total Mitigation Potential ($MtCO_2e$)	% from the total Mitigation Potential
<0	15	19%
[0–20]	13	16%
[20–50]	46	60%
>50	3	5%

Source: Study Authors.

TABLE 4-6

Sensitivity analysis of mitigation potential ($MtCO_2e$) between 2020–2030, additional mitigation actions

Mean Abatement Cost (USD/tCO_2e)	Reference Future	Red Future	Green Future
<0	15	16	15
[0–20]	13	11	13
[20–50]	46	37	54
>50	3	3	3
Total Potential	**77**	**67**	**86**

Source: Study Authors.

From Table 4-6, it is noticeable that of the additional actions, 28 $MtCO_2e$ have a cost below 20 USD/tCO_2e in the three Futures, although the Future impacts the mean costs. Most of the mitigation potential is in the 20–50 USD/tCO_2e interval, which is explained by the anticipated closure of coal-fired power plants by 2025. In terms of marginal cost, if we were to implement the full potential of mitigation, the marginal cost would rise over 700 USD/tCO_2e with actions that modify bovine diet. However, 96% of the potential is achievable with a marginal cost below 60 USD/tCO_2e.

4.2.2 Marginal abatement cost in the electricity generation sector

Most of the mitigation actions considered are incremental, meaning that an additional reduction would imply an extra action from a certain point for a certain mitigation level. For example, in electromobility, one extra electric car would yield in an additional reduction and cost[7], with an additional cost-effectiveness similar to the average cost of the previous action. In other words, the mean abatement cost would be the same as the marginal cost for most actions. The major exception is the actions related to the electricity generation sector. Each action in this sector is modeled as a constraint to the optimization sector that projects the Future's capacity and operation. Because of this modelling methodology, the optimized electricity generation system between two mitigation points can be completely different, and we can think of them as two competing alternatives. As a consequence, in this type of system, the mean mitigation cost estimated is not equivalent to the marginal abatement cost.

Since the previous results show the importance of the electricity sector in the GHG mitigation potential, we carried out additional experiments to analyze the effects on the total costs of the electricity sector by progressively reducing emissions between the NDC and NDC+ scenarios. To achieve this, we used a variable carbon tax, which penalizes the carbon emissions within the power system model, generating changes in the investment and operational decisions to avoid costly emissions. In particular, the experiments started from the NDC scenario and gradually increased the carbon tax to generate different points in the space of total costs versus total emissions. These cases were called NDC-t, where t indicates the tax (USD/tCO_2e) used in each case. From these additional simulations, it was possible to estimate an approximation of the marginal abatement cost of the electricity sector by comparing the total cost and total emissions between two consecutive simulations.

Figure 4-13 and Table 4-7 summarize the results obtained for each NDC-t case. We calculated the marginal abatement cost using the total cost of the electricity sector and the total emissions to 2050 of two consecutive NDC-t cases. Also, the costs presented here do not include the emission tax, which from a social evaluation perspective, is a transfer between actors and not a cost. From **Error! Reference source not found.**, it is possible to observe that a higher carbon tax yield lower GHG emissions and higher total systemic costs. However, this figure shows how the NDC+ scenario presents similar total emissions to 2050 (235 MtCO_2e) comparable to the NDC-40 and NDC-45 cases (256–224 MtCO_2e) but with a higher total cost (42,935 MUSD versus 38,119–

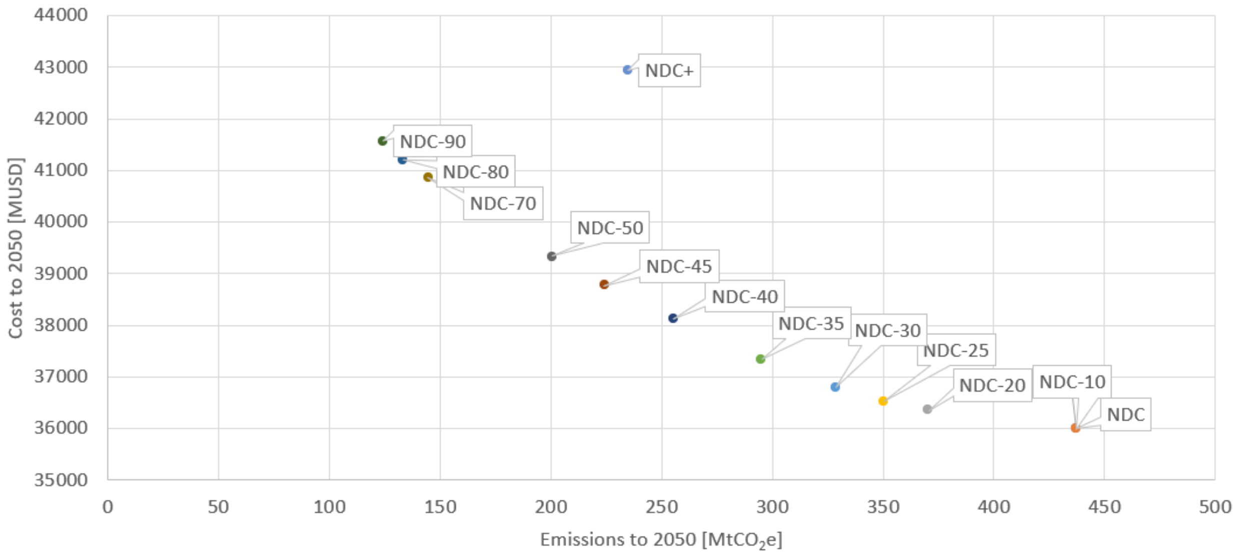
---

[7] The marginal cost of new infrastructure is included in the cost of investment estimated for each electric car.

38,770 MUSD). In other words, there are more cost-efficient policies than the accelerated closure of coal-fired power plants required in the NDC+ scenario.

FIGURE 4-13

Scatter plot of electricity total cost (million USD) vs electricity generation sector total emissions to 2050 (million tons of CO_2e).



Source: Study Authors.

TABLE 4-7

Summary of main results NDC-t cases: total costs (million USD), total emissions (million tons of CO_2e) and marginal abatement cost (USD/ton of CO_2e).

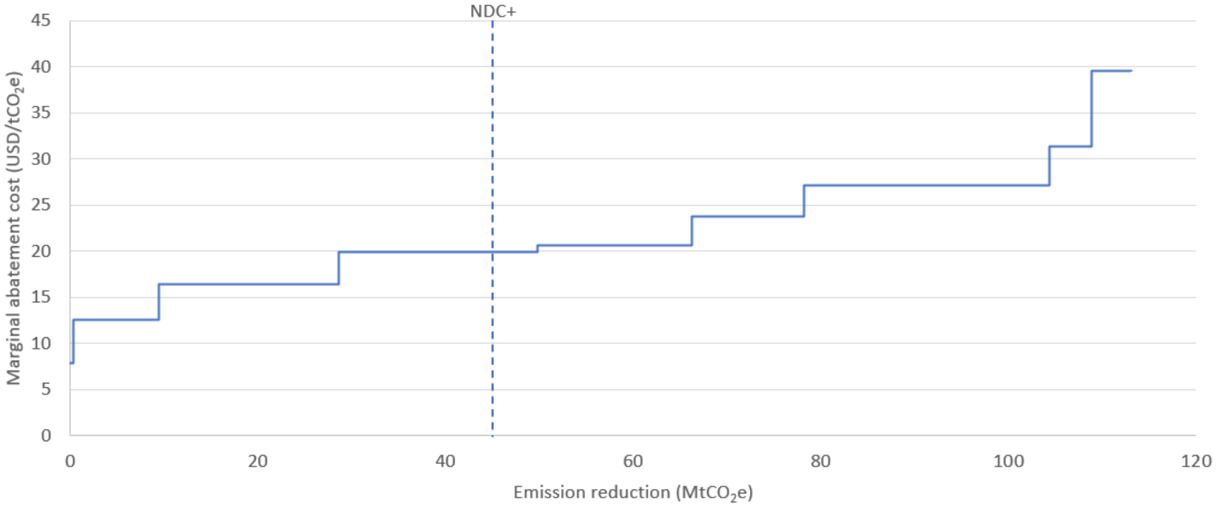
Cases	Emissions to 2030 [$MtCO_2e$]	Cost to 2050 [MUSD]	Emissions to 2050 [$MtCO_2e$]	Marginal abatement cost to 2050 [USD/tCO_2e]
NDC	191	36,004	437	$ -
NDC-10	191	36,004	437	$ -
NDC-20	191	36,354	370	$ 5.22
NDC-25	191	36,513	350	$ 7.87
NDC-30	182	36,784	329	$ 12.56
NDC-35	162	37,335	295	$ 16.46
NDC-40	141	38,119	256	$ 19.89
NDC-45	125	38,770	224	$ 20.62
NDC-50	113	39,333	200	$ 23.81
NDC-70	87	40,852	145	$ 27.16
NDC-80	82	41,209	133	$ 31.35
NDC-90	78	41,566	124	$ 39.59
NDC+	146	42,935	235	$ -

Source: Study Authors.

Although the NDC+ policy is suboptimal, an optimal policy to achieve a similar level of emissions would have a marginal abatement cost of 20 USD/tCO_2e, as can be seen in **Error! Reference source not found.**, where each NDC-t case is ordered in terms of emission reductions to 2030, and the marginal abatement cost is presented in the vertical axis.

FIGURE 4-14

MACC between the NDC and NDC-90 carbon tax scenarios for the 2020–2030 period for the Reference Future



Source: Study Authors.

4.2.3 Capital cost

Even though the mean abatement cost is relevant for comparing the different actions and designing mitigation strategies, it is also relevant to consider the capital cost needed to achieve these actions. This capital cost includes investment costs and payments for the early closure of coal-fired power plants. Additionally, it is important to note that the capital cost of the electricity sector considers the Net Present Value of annualized investment costs. We estimate that the capital cost required to implement the additional mitigation actions to go from an NDC to an NDC+ scenario is 5.3 (4.9–5.3) billion USD. From this total, 2.1 (1.7-2.1) billion USD is associated with investment costs, while 3.2 billion USD is associated with payments for the early closure of coal-fired power plants (see Table 4-8).

Most of the additional capital cost (~83%) is needed in the electricity generation sector and is mainly related to payments for early closure of coal-fired power plants (3.2 billion USD) and building additional renewable power capacity and transmission lines (1.2 billion USD). Payments for early closure of coal-fired power plants represent additional costs that are related to the implementation of specific mechanisms that make it possible to remunerate the coal-fired capacity retired from the electrical system. These mechanisms could recognize the remaining value of the infrastructure, value of existing energy contracts or payments to maintain reserve capacity. In the case of this study, we estimate this additional cost based on the remaining investment value of each coal-fired power plant, considering its date of installation, its years of useful life and the value of the initial investment. On the other hand, the additional wind and pump storage hydropower capacity between 2026 and 2030 increased from 8.9 GW to 10.5 GW and from 0 GW to 0.8 GW, respectively. In the case of transmission, the additional capacity between 2026 and 2030 increased from 5.8 GW to about 10 GW. Transportation and LULUCF also represent another relevant fraction; together, the two amount to 11% of the total additional capital cost estimated. Table 4-8 shows the difference between the Futures, around 10%, between the Reference Future and the sensitivity Futures.

TABLE 4-8

Additional capital cost (Million USD) between 2020–2030 to achieve NDC+ scenario

Sub Sector		Reference Future	Red Future	Green Future
Agriculture		9	8	10
Buildings		69	71	68
Electricity generation	Investment	1,166	1,253	835
	Coal payments	3,210	3,210	3,210
I&M		165	174	157
IPPU		1	1	1
LULUCF		227	205	250
Transportation		350	361	339
Waste		64	64	64
Total general		5,261	5,347	4,934

Source: Study Authors.

4.3 Emissions co-benefits

In addition to reducing GHG, we estimated the co-benefits of the actions included in the NDC+ scenarios for the energy sector. In this sector, between 2020–2030, an estimated 1,419 tMP2.5 were avoided by implementing all the mitigation actions. This reduction translates into 2,250 avoided premature deaths during those years—the sensitivity analysis with the Green and Red Futures estimates of between 2,180 and 2,320 premature deaths.

The estimate per year grows as the mitigation actions increase their ambition; for example, in the year 2030, the avoided premature deaths amount to 460 (440–480) between the NDC+ scenario and the NDC scenario. Following the same logic, the avoided premature deaths estimated for 2050 are 2,110 (1,900–2,310).

In comparison, the official estimate of deaths by PM2.5 in Chile was close to 4 thousand per year in 2018 (MMA, 2019). Assuming this level as the base level for Future years, it amounts to 40,000+ premature deaths during the eleven years considered in the budget. Another interpretation of the 2,250 premature deaths avoided is that the additional mitigation actions considered in the NDC+ Mitigation Scenario could reduce by more than 5% the PM2.5-induced deaths expected in that period. At the same time, in the year 2030, the 460 premature deaths avoided represent more than 10% of the expected PM2.5-induced deaths for that year. In the long term, by 2050, the mitigation action would account for nearly 50% of total PM2.5-induced premature deaths.

5. Conclusions and further work

This study is an extension of a previous effort to quantify the potential GHG mitigation beyond Chile's NDC in the context of the Climate Action Teams initiative (Pica-Téllez et al., 2022). Besides updating, refining, and adjusting the models, the current phase makes significant changes from the previous study. Among these, the main three differences are:

- To enhance transparency, we migrated all the models to Python (previously developed in LEAP and Analytica).
- The electricity generation sector was significantly improved by developing a better representation of the sector, including transmission constraints (26 buses or electricity zones instead of 1).
- We developed a module for the estimation of health co-benefits to complement the results.

Modeling is an exercise that tries to simplify a complex reality to gain valuable insights. There is a trade-off between the level of complexity of the modeling and the operational cost of developing and operating the models. Following this, we develop a more complex model, which we believe represents reality more precisely, for those activities expected to have more potential for mitigation. The electricity generation, copper industry, forestry, and the on-road transportation sector models, are some of the most complex models included, based on their current contribution to the GHG inventory and the projected mitigation of previous studies.

When interpreting these results, one must consider that we force the fulfilment of the NDC commitments[8] with an artificial constraint on the electric generation sector. In other words, if the set of mitigation actions is not enough to meet the commitments, the optimization of the electric sector has active restrictions constraining GHG emissions. This constraint has been used in the three futures of the NDC Mitigation Scenario. In those scenarios, when the set of mitigation actions is enough to meet the commitments, these restrictions are inactive; hence the emissions are not artificially reduced. This is the case in the three futures of the NDC+ Mitigation Scenario.

In Figure 5-1, we present a comparison of Chile's GHG emission projection among scenarios with different mitigation actions. The BAU scenario, which we developed in phase 1 of this studio (Pica-Téllez et al., 2022), consists of a scenario where no mitigation actions are taken to fulfill Chile's NDC commitment. In comparing this trajectory and the NDC's trajectory, we can assess the level of ambition of Chile's current NDC commitments. We can see that the commitments result in a substantive reduction of the emissions in the period 2020–2030, resulting in a decrease of 33 $MtCO_2e$ by 2030, representing 26% of the BAU's projected emissions. We can also observe a difference even from 2020, in response mainly to the fact that the BAU scenario does not include some preventive actions. We also highlight that the BAU scenario was developed in a previous version, which we improved during the development of the NDC and NDC+ trajectories.

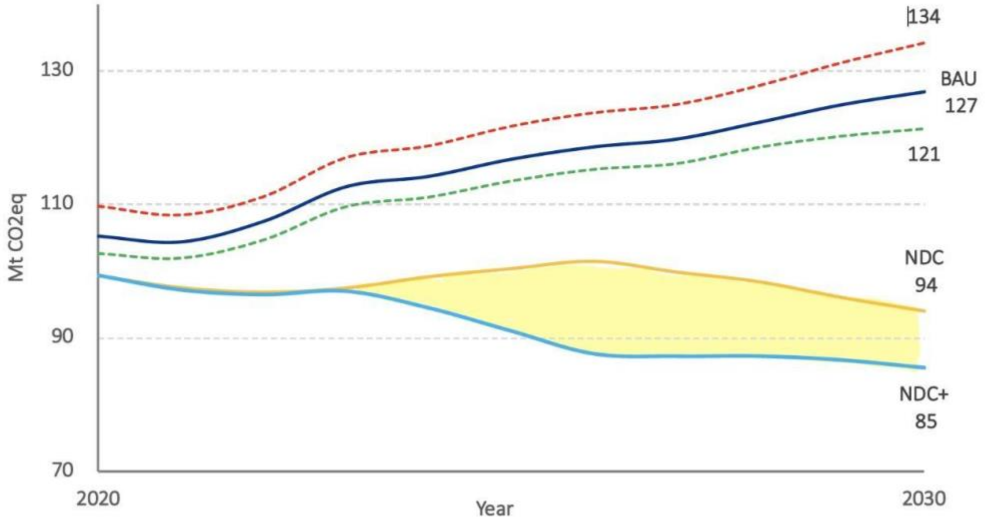
We can also conclude from our projections that there is space for further mitigation in Chile, going beyond the NDC commitments. This further mitigation is highlighted as the space in yellow between the NDC and NDC+ scenarios shown in Figure 5-1. To obtain these results, we had to generate a series of assumptions (e.g., which actions to include in the NDC scenario) which add uncertainty to the existing inherent uncertainty of the projection process (e.g., how much rain will fall in the following years). In this regard, these results do not pretend to be a prediction but hope to enlighten the discussion and design of policies. In this sense, we would like to offer the following insights.

---

[8] The process is iterative, we allow a 1% deviation from the commitments. This means that we stop the iteration process when the emissions are in the [1089-1111] MtCO2e between 2020-2030, and between [94-96] MtCO2e for the year 2030.

FIGURE 5-1

Comparison between the BAU projection (from phase 1) and the NDC and NDC+ scenario



Source: Study Authors using Business-As-Usual data from phase 1 (Pica-Téllez et al., 2022).

5.1 Main insights

The fulfillment of the commitments in Chile's NDC is not guaranteed. Although this is not the focus of the study, the results of the NDC scenario achieve the commitments only through additional restrictions of the electricity generation sector. This indicates that the mitigation actions selected for the NDC scenario are insufficient to fulfill all the commitments. We considered current policies and discussions to decide on which mitigation actions to include in the NDC. Given that three of the eleven years included in the carbon budget horizon have already passed, it is urgent that more actions (or increasing the ambitions of the current one) are implemented. Compared with previous studies, a worse economic projection has benefited the results with a reduced activity level. For example, the electricity demand for the reference scenario is close to the low electricity demand in previous studies. Nevertheless, according to our results, achieving the commitments needs additional effort.

Additional actions could yield a significant surplus of mitigation at a reasonable cost. Our results suggest that up to 75 (65–82) $MtCO_2e$ could be mitigated beyond the committed carbon budget. Almost one-third of the mitigation potential could be achieved at a mean abatement cost less than 20 USD/tCO_2e. An additional 65% could be obtained with a mean abatement cost between 20 and 50 USD/tCO_2e. We estimate that the capital cost needed for implementing these actions is 5.3 (4.9—5.3) billion USD from 2020 to 2030. For this period, the most relevant actions are reducing the carbon intensity in the electric sector, increasing environmental protection areas, and increasing the electrification of processes in industry and mining sector. It is also important to note that the capital cost includes extra cost requirements regarding the early coal-power phase-out, such as the valuation of existing energy contracts or mechanisms that remunerate their retired capacity. We estimate a first approximation to this additional cost, as the remaining useful life of prematurely closed coal-fired power plants, which yields a total closure cost of 3.2 billion USD.

The early coal-power phase-out is not the most efficient mitigation action in the power sector. We generate new sensitivities in the electricity sector that showed how a carbon tax of 40–45 USD/tCO_2e could achieve a lower total cost to 2050 (38,199–38,770 MUSD) at the same level of emissions mitigation to 2030 (35–49 $MtCO_2e$), in comparison with the early coal-power phase-out mitigation action, which presents a total cost of 42,935 MUSD to 2050 with 45 $MtCO_2e$ of emissions reduction to 2030. Further studies should analyze in detail the implementation challenges associated with mitigation actions such as faster coal-power phase-out and carbon-tax enforcement, and the analysis presented in this report constitutes an important first step in this direction.

The additional mitigation has significant health co-benefits. We estimate that if the NDC+ mitigation actions are implemented, Chile could avoid up to 2,250 (2,180–2,320) premature PM2.5-induced deaths between 2020 and 2030. This represents nearly 5% of the total PM2.5-induced death expected in that period. By 2030, the annual avoided premature deaths amount to 460 (440–480); by 2050, this could amount to 2,110 (1,900–2,310) avoided death. These numbers represent a relevant benefit in health, considering that by 2019 the estimated annual PM2.5-induced premature deaths was close to 4,000 (MMA, 2019). Using the statistical valuation of life currently used by the Chilean environmental ministry, the health co-benefit between 2020 and 2030 is around USD 1.5 billion.

5.2 Coal-power phase-out

5.2.1 Sensitivity on the level of ambition

We studied four coal phase-out schedules, which decommission coal-based generation entirely by 2025 (NDC+), 2028, 2030 and 2040 (NDC). The results are consistently similar for each Future:

- Accumulated emissions during the 2020–2030 decade:
    - Early phase-out has higher upfront investment, but it is associated with greater mitigated emissions and lower abatement costs in the short term. This effect is mainly due to the restricted timeframe of the measurement (that only takes into account emissions and costs up to 2030), as investments close to 2030 do not have large impacts on the reduction of emissions for the period.
    - The 2028 phase-out costs 9.5–11.5 USD less but mitigates 20.1-21.3% less emissions when compared to the NDC+. Thus, this alternative increases the average abatement costs by 49–85%. On the other hand, the 2030 phase-out does not reduce emissions when compared to the base NDC.
- Accumulated emissions until 2050:
    - Early phase-out still has higher upfront investment and emission mitigations. However, it no longer has the cheapest abatement costs. This is mainly due to coal decommission costs, which decrease quickly if the coal decommission is delayed a few years. Therefore, they negatively affect particularly hard earlier phase-out schedules.
    - The 2028 phase-out costs 3.9–5.8% less but mitigates 11.7–15.1% less emissions when compared to the NDC+, with an average abatement cost 16.6–17.8% lower. The 2030 phase-out follows the trend and costs 5.8–8.8% less but mitigates 15.6–22.6% less when compared to the NDC+, with an abatement cost 28.8–30.2% lower.

The model optimizes the long-term cost of the system. Therefore, it is natural that less constrained scenarios are cheaper than more constrained ones when looking at the systemic cost at the end of the simulation in 2050. However, the cost is not the only variable at stake here, as GHG mitigations and their timing are very relevant:

- The longer the coal phase-out is (i.e., closer to 2040), the cheaper the simulated abatement cost is in 2050.
- The earlier the coal phase-out is (i.e., closer to 2025), the cheaper the simulated abatement cost is in 2030.

- The earlier the coal phase-out is (i.e., closer to 2025), the greater the amount of mitigated tCO_2e.

Due to the high investment costs of the NDC+, the discussion should be opened to intermediate solutions, which generate emission reductions in the short term, but also have lower total costs when looking at their long-term effects. In this sense, an intermediate solution could be an early closure by 2030 in order to reduce emissions from 2030 onwards and establish mechanisms such as incentives for renewable investment or higher carbon taxes, to reduce emissions before 2030. As mentioned before, we would like to remark here that further studies should analyze in detail the implementation challenges associated to mitigation actions such as faster coal-power phase-out and carbon-tax enforcement, and the analysis presented in this report constitutes an important first step in this direction.

5.2.2 Impact on the transmission grid

A possible limitation to the increase of the share of renewables in the energy mix is the building of transmission lines because these projects are much slower to plan and build than many types of power plants. This limitation may constrain the transmission of electricity from the wind power plants in the south of the country to the capital (and main pole of consumption) in the center. This is particularly important because our simulations show that wind power plants may be one of the fastest, if not the fastest, growing technology in the coming years. Specifically, the NDC+ scenarios and the sensitivity phase-out in 2028 both show a significant increase in transmission up to 10 GW between 2026 and 2030, which is almost 30% of the initial transmission capacity.

5.3 Limitations and further work

The current modeling is part of a series of GHG projection exercises developed in Chile in the last ten years. Our understanding has benefited from these exercises, and we hope to contribute with the generation of helpful insight, both to public policy and future studies. In this understanding, we consider it valuable to explain what we think are the main limitations of our work. These limitations are stated not only as a proposition for further research but also as limitations that must be considered while analyzing our study's results.

- General
    - Based on the current policy discussions, we selected a set of mitigation actions for the NDC scenario. There might be other relevant discussions (e.g., in the private

sector) on further mitigation actions. These impact not only the NDC scenario results, but also the analysis of additional actions between the NDC and the NDC+ scenarios. It is expected that during 2023, most of the Chilean ministries will publish their Sectoral Mitigation Plans[9], reducing uncertainty about which actions will be implemented, with what level of ambition, and when.

  - The architecture of the models follows a two-tier structure, where some sectoral models are run before a second group of models. Although we have advanced significantly in the integration of the models, this two-tier structure is still in place, and full integration is yet to be achieved. This means that some iterations are needed in the process of designing the actions and evaluating their impact. The most notable example is the group of actions that imply electrification of activities/processes, where the net GHG emission impact and their cost will depend on the emissions of the electricity sector and the electricity price.
  - Another critical and ambitious line of future work is to consider a broader set of mitigation goals beyond NDC+. This set could be evaluated through an iterative mechanism considering a progressive emissions reduction. With this work, the set of mitigation actions would be obtained directly from the optimal solution of each model, allowing discrete packages of measures related to gradual changes in emission levels. For example, we could achieve this through mechanisms such as incremental emission taxes or decreasing maximum emission limits.
- Electricity sector
  - The Switch model improves over the previous LEAP model in the following areas:
    - The transmission grid is no longer represented by just one bus. Instead, it is characterized by 26 buses distributed throughout the country.
    - The transmission grid is a constraint to which the energy transmission is subjected. During some hours, the system decouples due to saturated lines.
    - The transmission grid expansion plan was incorporated into the model along with possible new investments the model could choose to build.
    - Three short-term storage technologies are modeled: BESS, PHS, and CAES.

---

[9] New instrument created by the recent Climate Change Framework Law

    - The temporal resolution was improved from two representative days a year (summer and winter) to 12 representative days a year (one per month).

- However, there are still areas that could be improved in future studies, leading to a more thorough understanding of the role of the power sector in GHG mitigation.

    - These results do not consider short-term operational safety aspects, such as inertia requirements or reserve requirements resulting from the inclusion of variable renewable generation. This can be seen in the results, where the model relies excessively on wind generation. A next step to validate the future power system proposed by the long-term planning model, would be to run a more detailed operational model that includes physical and spatial aspects such as AC power flow and better representation of the buses and electric transmission lines. Additionally, yearly weather variability of wind and solar is not considered. The hourly demand profile for each day was kept the same for the duration of the study. However, factors such as hydrogen production, electromobility, thermal processes electrification, and distributed generation are expected to shift the demand profile in the future. This shift may influence the peaks and valleys of generation and, therefore, the system behavior.

    - A critical line of future work is to study additional feasibility aspects of the early closure of coal power plants by e.g., 2030, with a greater level of operational detail and defining specific withdrawal mechanisms (including analyzing the contracts that each company currently owns for power delivery, and other market aspects) in order to estimate in a more precise and overall form the costs associated to early closure of coal-fired power plants.

    - Another aspect that could be considered in future studies is related to demand response. In particular, the adequate management of power consumption can significantly help the adoption of variable renewable energy sources, lowering the need for expensive energy storage devices.

    - Finally, hydrogen could play an important role in future energy (and specifically electric power) systems. A hydrogen network analysis can be incorporated in future studies. Hydrogen would imply power consumption from renewable energy sources, and could provide an important means for energy storage, with either direct uses or also for power generation. Such an analysis should also consider the use of synthetic fuels based on hydrogen.

- Energy demand sectors:
    - The transportation sector follows a bottom-up approach based on regional transportation demand. This approach makes it particularly difficult to model local mitigation actions (such as for urban solutions), since a series of assumptions are needed to include these actions.
    - The modeling of electricity penetration in households, industry, and transportation follows a logic based on historical data and comparative penetration rates from developed countries. The projected rates are not sensitive to the cost of this technology which could modify the actual penetration rates.
- IPPU:
    - 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 already installing abatement systems, actions in the industrial process subsectors were not considered. Additional actions 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 agricultural sector's emissions), an economic model was used, explained by national forecasts 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 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. We make the projections with emission factors derived from the historical calculation of GHG emissions of the subsectors due to the lack of complete regional data.
    - Wildfire emissions are still a significant source of uncertainty since the area burns yearly, and thus emissions come from a small number of fires that escape suppression and control. These few wildfire events are unpredictable.
    - The model does not consider uncertainties such as Future yield changes of native forests and plantations or changes in harvest frequencies due to climate change.
- Waste sector:
    - Recently, the government has published a strategy for organic waste; this strategy set ambitious goals, but there exists the question of the actual actions to fulfill the objectives. These goals are only partially considered in the modeling.

References

Benavides, C., Cifuentes, L., Díaz, M., Gilabert, H., Gonzales, L., González, D., Groves, D., Jaramillo, M., Marinkovic, C., Menares, L., Meza, F., Molina-Perez, E., Montedonico, M., Palma-Behnke, R., Pica-Téllez, A., Salas, C., Syme, J., Torres, R., Vicuña, S., … Vogt-Schilb, A. (2021a). Opciones para lograr la neutralidad en carbono para 2050 en Chile: Una evaluación en condiciones de incertidumbre. Banco Interamericano de Desarollo.

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/10.1080/13657305.2016.1177859V

CAT (2021). Climate Action Teams (CAT): mini-lateral cooperation to accelerate ambitious decarbonization

Comisión Nacional de Energía. (2021).

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

CONAF. (2020). DT N°239 Tabla de Valores 2020 Ley N°20.283 sobre recuperación del Bosque Nativo y Fomento Forestal. https://www.conaf.cl/cms/editorweb/chifo/DT239.pdf

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/

CONAF. (2021b). Estadísticas—Resumen Nacional Ocurrencia (Número) y Daño (Superficie Afectada) por Incendios Forestales 1964—2020. https://www.conaf.cl/incendios-forestales/incendios-forestales-en-chile/estadisticas-historicas/

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

Coordinador Eléctrico Nacional. (2020, septiembre). 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. (2021). Programa Diario de Generación. https://www.coordinador.cl/operacion/graficos/operacion-programada/programa-diario-de-generacion/

CORMA. (2021). (Comunicación personal) [Comunicación personal].

Fundación Chile. (2014). Proyección Escenario Línea Tendencial 2012 y Escenarios de Mitigación del Sector Comercial , Público y Residencial. MAPS Chile.

Gobierno de Chile. (2020). Contribución Determinada a Nivel Nacional (NDC) de Chile, Actualización 2020. https://mma.gob.cl/wp-content/uploads/2020/04/NDC_Chile_2020_espan%CC%83ol-1.pdf

INE. 2007. VII Censo Nacional Agropecuario y Forestal. Available at https://www.ine.cl/estadisticas/economia/agricultura-agroindustria-y-pesca/censos-agropecuarios.

INE. (2021). Calculadora IPC. https://calculadoraipc.ine.cl/

INFOR. (2021). Boletín N°176 Precios Forestales. https://bibliotecadigital.infor.cl/bitstream/handle/20.500.12220/30434/30434.pdf?sequence=1&isAllowed=y

IPCC. (2006). Directrices del IPCC de 2006 para los inventarios nacionales de gases de efecto invernadero, Volumen 4, Agricultura, silvicultura y otros usos de la tierra. https://www.ipcc-nggip.iges.or.jp/public/2006gl/spanish/vol4.html

MAPS Chile. (2014). Opciones de Mitigación para Enfrentar el Cambio Climático: Resultados Fase 2.

Ministerio de Energía. (2020, mayo). Plan de Retiro y/o Reconversión de Unidades a Carbón.

Ministerio de Energía. (2020, diciembre). Planificación Energética de Largo Plazo: Informe de Actualización de Antecedentes 2020.

Ministerio del Medio Ambiente de Chile. (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. Santiago, Chile.

MMA. (2021a). Informe del Inventario Nacional de Chile 2020: Inventario nacional de gases de efecto invernadero y otros contaminantes climáticos 1990-2018. Oficina de Cambio Climático. Santiago, Chile.

MMA. (2021b). Registro Nacional de Áreas Protegidas. http://bdrnap.mma.gob.cl/app-reportes/#/repAreasProtegidasXDecenio

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

ODEPA. (2003). Evaluación económica del Proyecto de Ley sobre Recuperación del Bosque Nativo y Fomento Forestal. ODEPA | Oficina de Estudios y Políticas Agrarias. https://www.odepa.gob.cl/publicaciones/articulos/evaluacion-economica-del-proyecto-de-ley-sobre-recuperacion-del-bosque-nativo-y-fomento-forestal

ODEPA & PUC. (2009). Valor de la tierra agrícola y sus factores determinantes. https://www.odepa.gob.cl/odepaweb/servicios-informacion/publica/Valor_tierra_agricola_y_sus_factores_determinantes.pdf

Palma Behnke R., C. Barría, K. Basoa, D. Benavente, C. Benavides, B. Campos, N. de la Maza, L. Farías, L. Gallardo, M. J. García, L. E. Gonzales Carrasco, F. Guarda, R. Guzmán, A. Jofré, J. Mager, R. Martínez, M. Montedonico, L. Morán, L. Muñoz, M. Osses, A. Pica, M. Rojas, A. Rudnick, J. P. San Martín, A. Santander, C. Silva, S. Tolvett, R. Torres, A. Urquiza, P. Valdivia, S. Vicuña (2019). Chilean NDC Mitigation Proposal: Methodological Approach and Supporting Ambition. Mitigation and Energy Working Group Report. Santiago: COP25 Scientific Committee; Ministry of Science, Technology, Knowledge and Innovation.

SII. (2021a). Dólar Observado. https://www.sii.cl/valores_y_fechas/dolar/dolar2020.htm

SII. (2021b). UTM - UTA - IPC. https://www.sii.cl/valores_y_fechas/utm/utm2021.htm

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

Ulibarry, P. G. (s. f.). Consumo y mercado de los fertilizantes. 5.

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

Zelada, A., & Maquire, P. (2005). Expediente Comunal. Estudio Modificación Plan Regulador Comunal de Coronel. https://www.ecoronel.cl/wp-content/uploads/2014/03/Capacidad-uso-de-suelo-coronel.pdf

MMA. (2019). Quinto Reporte del Estado del Medio Ambiente. Ministerio Del Medio Ambiente- Gobierno de Chile, 269. https://sinia.mma.gob.cl/wp-content/uploads/2019/12/REMA-2019-comprimido.pdf

Pica-Téllez, A., Lorca, Á., Urtubia, R., Cifuentes, L. A., Valdes, J. M., Cerda-Gho, V., Veloso, C., González, D., Gilabert, H., Meza, F., Jara, V., Marinkovic-De la Cruz, C., Vicuña, S., Pinto, F., & Montero, J. P. (2022). Potential Greenhouse Gas Reductions Beyond Chile's Nationally Determined Contribution to 2030: Preliminary Modelling Results. SSRN Electronic Journal, July. https://doi.org/10.2139/ssrn.4168343

MMA. (2022. Quinto informe bienal de actualización de Chile sobre Cambio Climático.

EMEP/EEA. (2019). EMEP/EEA air pollutant emission inventory guidebook 2019: Technical guidance to prepare national emission inventories. EEA Technical Report, 12/2019. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

Pope, C. A., Coleman, N., Pond, Z. A., & Burnett, R. T. (2020). Fine particulate air pollution and human mortality: 25+ years of cohort studies. Environmental Research, 183(October 2019), 108924. https://doi.org/10.1016/j.envres.2019.108924

Appendixes

Appendix 1: Description of the models

1.1 Energy: Electricity Generation

The electricity sector manages the electric grid generation and expansion needed to meet a specific electrical demand. In this context, the open source Switch Electricity Planning Model is used to optimize the grid's operation and investment costs given certain constraints. The modular nature of Switch allows us to create complex scenarios with a large and diverse number of inputs, such as fuel and investment costs, electricity demand, emission thresholds, scheduled decommission, carbon taxes, capacity factors and energy conversion efficiency.

Switch designs and simulates future scenarios of electric systems as a portfolio of conventional generation, renewable energy and storage methods. It optimizes investment and dispatch decisions for complex generation and transmission systems. These systems may include co-existing hydro systems and other possible assets. The optimization identifies a least-cost system design using hourly simulation of representative samples of time data, subject to restrictions, which makes it ideal for analyzing decarbonization scenarios using emissions budget and carbon taxes.

A Chilean electric system was generated using publicly available data from the energy ministry of Chile. Thus creating a simplified version of the transmission lines with 26 buses used for generation and demand, as well as 1539 generation and storage projects distributed in different buses and timepoints.

The simulations were performed under 6 different scenarios (Table E1) of carbon policies, fossil fuel costs, investment costs and scheduled phase-out of coal power plants, which are classified based on future conditions (red, reference green) and mitigation scenarios (NDC, NDC+).

The NDC+ scenario, which is coal free by the end of 2025, is very ambitious and not very likely to be implemented. However, the NDC coal free goal by 2040 is the opposite, as it is certainly within the capacities of the country, but possibly too lenient considering the urgency of climate action.

This dichotomy is analyzed specifically for the electricity sector through the proposal of two new coal phase-out schedules, which aim to remove coal by 2028 and 2030 (Table E2). The goal of this analysis is to gain more insight into the most cost effective period to decarbonize the electric grid.

TABLE 1

Scenarios for the electricity generation sector

Sector: Electricity Generation		
Case	**NDC Coal Phase-Out by 2040**	**NDC+ Phase-Out acceleration to 2025**
Red High investment costs for renewables High fuel prices	Max of 170 $MtCO_{2eq}$ accumulated (2020-2030) Max of 6 $MtCO_{2eq}$ in 2030.	Max of 170 $MtCO_{2eq}$ accumulated (2020-2030) Max of 6 $MtCO_{2eq}$ in 2030.
Reference Medium investment costs for renewables Medium fuel prices	Max of 191 $MtCO_{2eq}$ accumulated (2020-2030) Max of 9 $MtCO_{2eq}$ in 2030.	Max of 191 $MtCO_{2eq}$ accumulated (2020-2030) Max of 9 $MtCO_{2eq}$ in 2030.
Green Low investment costs for renewables Low fuel prices	Max of 211 $MtCO_{2eq}$ accumulated (2020-2030) Max of 12 $MtCO_{2eq}$ in 2030.	Max of 211 $MtCO_{2eq}$ accumulated (2020-2030) Max of 12 $MtCO_{2eq}$ in 2030.

TABLE 2

Additional sensitivity scenarios for the electricity generation sector

Sector: Electricity Generation		
Case	**Coal Phase-Out acceleration to 2030**	**Phase-Out acceleration to 2028**
Red High investment costs for renewables High fuel prices	Max of 170 $MtCO_{2eq}$ accumulated (2020-2030) Max of 6 $MtCO_{2eq}$ in 2030.	Max of 170 $MtCO_{2eq}$ accumulated (2020-2030) Max of 6 $MtCO_{2eq}$ in 2030.
Reference Medium investment costs for renewables Medium fuel prices	Max of 191 $MtCO_{2eq}$ accumulated (2020-2030) Max of 9 $MtCO_{2eq}$ in 2030.	Max of 191 $MtCO_{2eq}$ accumulated (2020-2030) Max of 9 $MtCO_{2eq}$ in 2030.
Green Low investment costs for renewables Low fuel prices	Max of 211 $MtCO_{2eq}$ accumulated (2020-2030) Max of 12 $MtCO_{2eq}$ in 2030.	Max of 211 $MtCO_{2eq}$ accumulated (2020-2030) Max of 12 $MtCO_{2eq}$ in 2030.

Data sources:

Capacity factors (PELP 2022):

- Switch is not able to model CSP with its base modules. Therefore we approximate it with a capacity factor that fluctuates during the day.
- Hydroelectric plants were assigned a capacity factor, since they are not 100% available due to drought.

- Capacity factor is the ratio of actual power output to maximum capacity for a given plant. For hydro and CSP, the ratio for each hour was obtained from historical data publicly available. The capacity factors, by hour, were calculated by comparing the plant power output to its maximum capacity. The hourly dispatch outputs of the PELP and the installed capacity were used to calculate this factor.
- Other renewables such as PV or wind power plants have their capacity factor set by the PELP.

Installed Capacity (GEN 2022):

- Installed capacity in 2020: Generators that are available from the initial timepoint. There is no investment cost associated with these generators.
- Number of potential plants in 2050: Maximum number of generators that may, or may not, be installed in 2050. Their installation is subject to the optimization decisions of the model.
- Potential installed capacity in 2050: Maximum capacity installed by 2050 if every potential generator is built.

TABLE 3

Installed and potential capacity

Technology Capacity			
Technology	**Installed capacity in 2020 (MW)**	**Number of potential plants in 2050**	**Potential installed capacity in 2050 (MW)**
PV	3479	481	669406
CSP	99	178	173663
Wind	2493	181	60595
Coal	4902	28	5326
Diesel	4151	146	44180
LNG	3820	60	29561
Cogeneration	129	6	129
Geothermal	81	17	1763
Biomass	445	26	846
Biogas	26	10	26

Technology Capacity			
Technology	**Installed capacity in 2020 (MW)**	**Number of potential plants in 2050**	**Potential installed capacity in 2050 (MW)**
Hydro	7068	248	14108
Pumped Hydroelectric Storage (PHS)	0	46	42277
Battery Energy Storage System (BESS)	0	81	255000
Compressed Air Energy Storage (CAES)	0	26	52000

Electrical Network (PELP 2022):

TABLE 4

Distribution of buses

Buses by region	
Region	**Number of Buses**
Arica y Parinacota	1
Tarapacá	1
Antofagasta	6
Atacama	3
Coquimbo	1
Valparaiso	1
Metropolitana de Santiago	2
Libertador General Bernardo O’Higgins	2
Maule	1
Ñuble	0
Biobío	3
La Araucanía	1
Los Ríos	2
Los Lagos	2

Carbon tax (PELP 2022):

TABLE 5

Carbon tax schedule

Carbon Tax Schedule	
Years	**Carbon Tax (USD/tCO$_{2eq}$)**
2020 – 2022	0
2023 – 2029	5
2030 – 2050	10

Coal phase-out schedule (MEN 2020):

TABLE 6

Coal Phase-Out schedule for both mitigation scenarios

Year	Coal Phase-Out Schedule			
	Coal Installed Capacity NDC (MW)	**Coal Installed Capacity NDC+ (MW)**	**Coal Installed Capacity Sensitivity 2028 (MW)**	**Coal Installed Capacity Sensitivity 2030 (MW)**
2020	4902	4902	4902	4902
2021	4902	4634	4634	4634
2022	4902	4634	4634	4634
2023	4214	2984	3945	3945
2024	4214	2421	3945	3945
2025	3945	1789	3662	3945
2026	3945	-	2984	3662
2027	3945	-	2420	3496
2028	3662	-	1789	2984
2029	3363	-	-	2420
2030	3227	-	-	1789
2031	3083	-	-	-
2032	3083	-	-	-
2033	3083	-	-	-

Year	Coal Phase-Out Schedule			
	Coal Installed Capacity NDC (MW)	Coal Installed Capacity NDC+ (MW)	Coal Installed Capacity Sensitivity 2028 (MW)	Coal Installed Capacity Sensitivity 2030 (MW)
2034	2941	-	-	-
2035	2544	-	-	-
2036	2091	-	-	-
2037	1632	-	-	-
2038	1253	-	-	-
2039	389	-	-	-

TABLE 7

Coal Phase-Out schedule for every mitigation scenario by year

Coal-fired Power Plant	Coal Phase-Out Schedule				
	Year of entry into service	Closure 2040	Closure 2025	Closure 2028	Closure 2030
Ventanas 1	1964	-	-	-	-
CTTOCOPILLA U12	1983	-	-	-	-
CTTOCOPILLA U13	1985	-	-	-	-
CTTARAPACA CTTAR	1998	-	-	-	-
CTTOCOPILLA U14	1987	2024	2020	2020	2020
CTTOCOPILLA U15	1990	2024	2020	2020	2020
Bocamina	1970	2022	2022	2022	2022
Ventanas 2	1977	2022	2022	2022	2022
CTNORGENER NTO1	1995	2027	2022	2024	2025
Guacolda U1	1995	2027	2022	2024	2025
CTMEJILLONES CTM1	1996	2028	2022	2025	2026
Guacolda U2	1996	2028	2022	2025	2027
Bocamina II	2012	2022	2022	2022	2022
Santa María	2012	2037	2022	2025	2027
CTNORGENER NTO2	1997	2029	2023	2026	2028
CTMEJILLONES CTM2	1998	2030	2023	2026	2028
Guacolda U3	2009	2033	2023	2026	2028
Guacolda U4	2010	2034	2023	2026	2028
CTANDINA CTA	2011	2035	2024	2027	2029
CTANGAMOS1 ANG1	2011	2035	2024	2027	2029

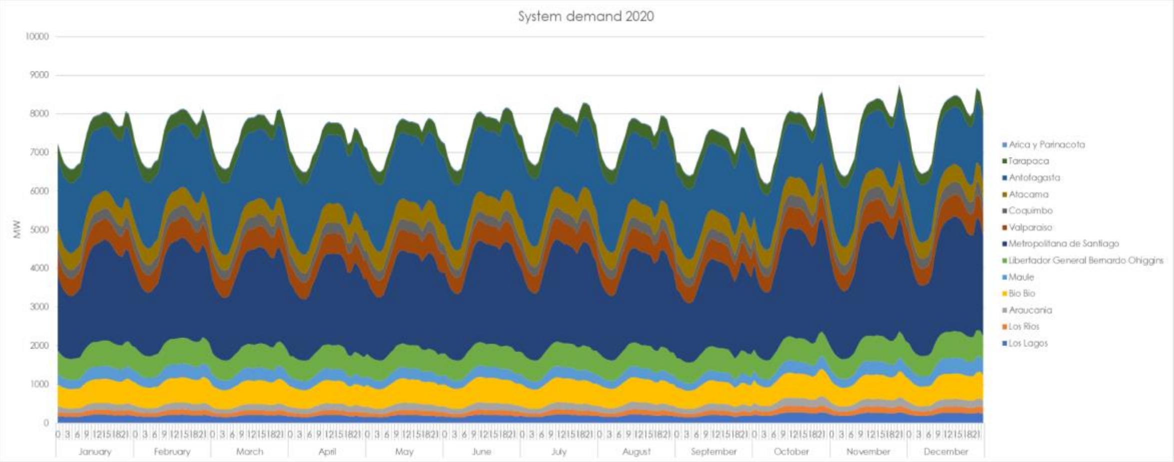
Coal-fired Power Plant	Coal Phase-Out Schedule				
	Year of entry into service	Closure 2040	Closure 2025	Closure 2028	Closure 2030
CTHORNITOS CTH	2011	2036	2024	2027	2029
Nueva Ventanas	2010	2034	2025	2028	2030
CTANGAMOS2 ANG2	2011	2036	2025	2028	2030
Campiche	2013	2038	2025	2028	2030
GuacoldaU5	2015	2038	2025	2028	2030
COCHRANE CCH1	2016	2038	2025	2028	2030
COCHRANE CCH2	2016	2038	2025	2028	2030
IEM	2019	2039	2025	2028	2030

Electricity demand profile (PELP 2022):

- The demand profile from the PELP was used as a base to distribute the projected demand modeled by the Energy: Demand sector.

FIGURE 2

Electricity demand profile as a representative day for each month



Investment, operative and fuel costs (PELP 2022):

- High, medium and low costs for every technology and fuel.

Power plant thermal efficiency (PELP 2022):

- Each power plant has its own thermal efficiency implicit on its heat rate.

Coal decommission costs:

The forced decommission of coal power plants, either done through direct or indirect means, translates to an additional cost to the system. However, not every decommissioned plant costs the same amount: older power plants that have already fulfilled their lifecycle cost less than newer ones that have been operating for only a few years due to depreciation. Thus, the coal decommission costs were added to each scenario based on their phase-out schedule, the useful life remaining of plants at decommission (we estimated a 20 years lifecycle), and their original investment.

It is important to note that the payment of these costs is heavily negotiated between the government and coal plant stakeholders. A fraction of these costs could very well be aimed towards investment on new renewable power plants owned by them or the purchase of renewable energy to fulfill ongoing power purchase agreements. In which case these costs would not really be additional, but the necessary investment costs in disguise.

As it stands now in this model, these costs are added to the abatement costs. Thus greatly increasing the 2020 decade abatement costs by 62 USD/TonCO2eq. Their impact is not as big for the 2020-2050 abatement costs, only accounting for around 14 USD/TonCO2eq.

Results:

- Abatement costs tables

TABLE 8

CO2 Abatement Cost with Coal Decommission Cost 2020 -2030

	Cost to 2030 (MUSD)	Emissions to 2030 (MtCO2)	USD/TonCO2
Reference NDC	14746	191	
Reference NDC+	18833	146	90,90
R. Sensitivity 2028	16785	177	147,55
R. Sensitivity 2030	15789	191	-
Red NDC	17961	170	
Red NDC+	22095	134	116,00
Red Sensitivity 2028	19995	161	214,77
Red Sensitivity 2030	19019	170	
Green NDC	12730	211	
Green NDC+	16627	159	74,47
Green Sensitivity 2028	14703	193	111,44
Green Sensitivity 2030	13759	211	-

TABLE 9

CO2 Abatement Cost with Coal Decommission Cost 2020 -2050

	Cost to 2050 (MUSD)	Emissions to 2050 (MtCO2)	USD/TonCO2
Reference NDC	36004	437	
Reference NDC+	42935	235	34,17
R. Sensitivity 2028	40809	266	28,07
R. Sensitivity 2030	39760	280	23,84
Red NDC	45828	424	
Red NDC+	53241	230	38,32
Red Senstiivity 2028	51120	257	31,71
Red Sensitivity 2030	50129	266	27,27
Green NDC	28794	412	
Green NDC+	34772	238	34,37
Green Sensitivity 2028	32750	274	28,64
Green Sensitivity 2030	31699	292	24,24

TABLE 10

CO2 Abatement Cost 2020 -2030

	Cost to 2030 (MUSD)	Emissions to 2030 (MtCO2)	USD/TonCO2
Reference NDC	14345	191	
Reference NDC+	15636	146	28,71
R. Sensitivity 2028	14882	177	38,88
R. Sensitivity 2030	14571	191	-
Red NDC	17560	170	
Red NDC+	18898	134	37,53
Red Sensitivity 2028	18091	161	56,12
Red Sensitivity 2030	17801	170	-
Green NDC	12328	211	
Green NDC+	13429	159	21,03
Green Sensitivity 2028	12800	193	26,62
Green Sensitivity 2030	12541	211	-

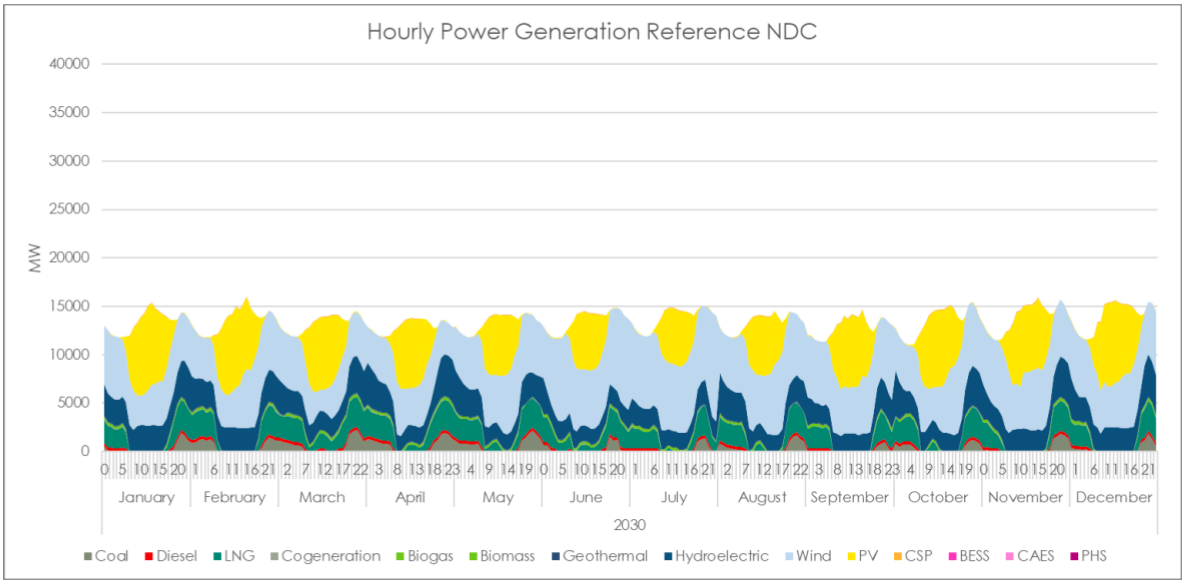
TABLE 11

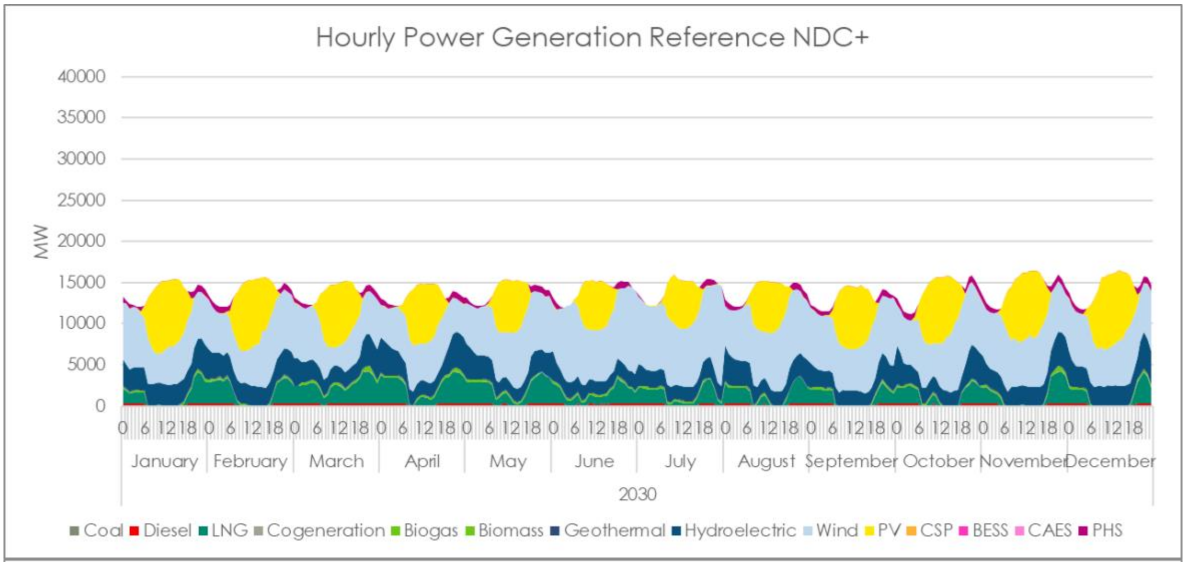
CO2 Abatement Cost 2020 -2050

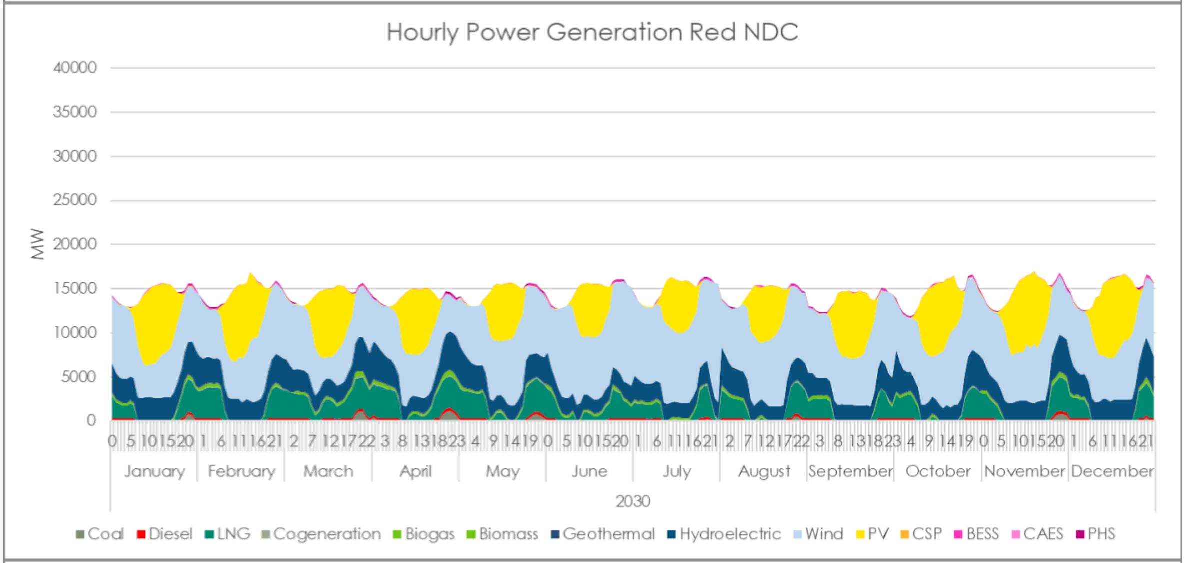
	Cost to 2050 (MUSD)	Emissions to 2050 (MtCO2)	USD/TonCO2
Reference NDC	35603	437	
Reference NDC+	39737	235	20,38
R. Sensitivity 2028	38906	266	19,30
R. Sensitivity 2030	38542	280	18,66
Red NDC	45426	424	
Red NDC+	50043	230	23,86
Red Sensitivity 2028	49217	257	22,71
Red Sensitivity 2030	48911	266	22,10
Green NDC	28393	412	
Green NDC+	31574	238	18,29
Green Sensitivity 2028	30846	274	17,77
Green Sensitivity 2030	30481	292	17,42

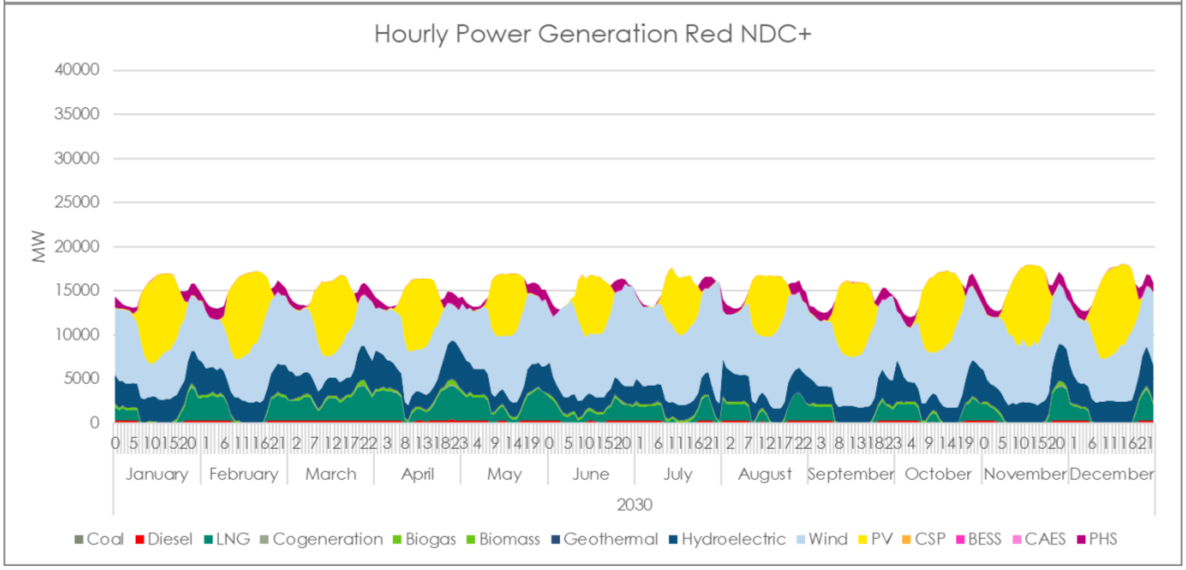
FIGURE 3

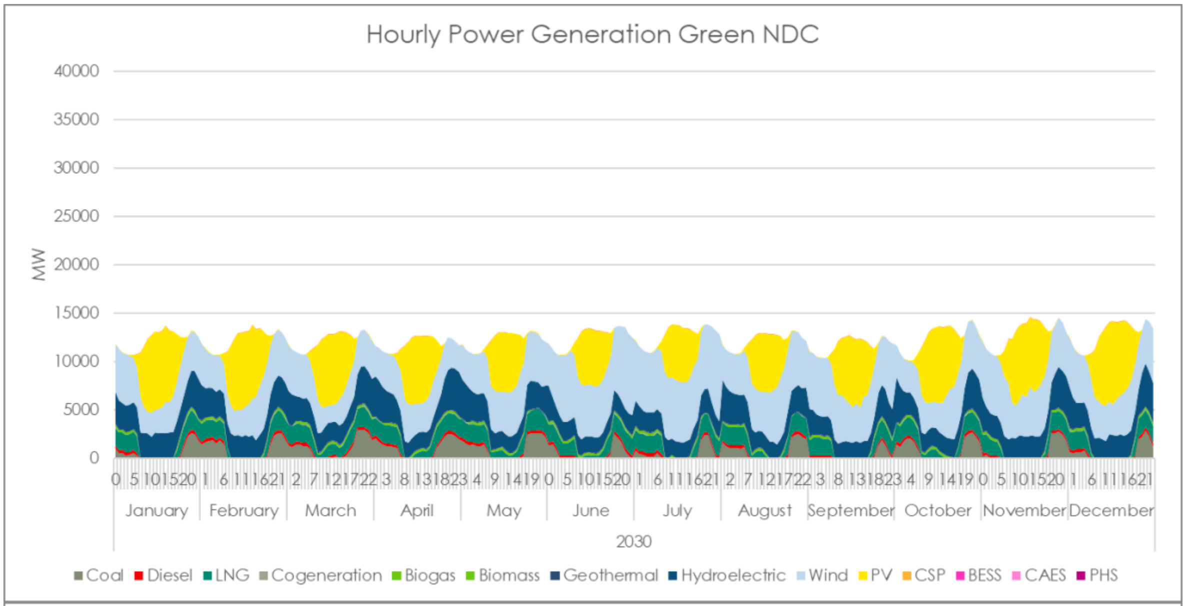
Hourly power generation 2030 by futures and mitigation scenarios




Hourly Power Generation Reference NDC+
MW
40000
35000
30000
25000
20000
15000
10000
5000
0
0 6 12 18
January
February
March
April
May
June
July
August
September
October
November
December
2030
■ Coal ■ Diesel ■ LNG ■ Cogeneration ■ Biogas ■ Biomass ■ Geothermal ■ Hydroelectric ■ Wind ■ PV ■ CSP ■ BESS ■ CAES ■ PHS


Hourly Power Generation Red NDC
MW
40000
35000
30000
25000
20000
15000
10000
5000
0
0 5 10 15 20
January
February
March
April
May
June
July
August
September
October
November
December
2030
■ Coal ■ Diesel ■ LNG ■ Cogeneration ■ Biogas ■ Biomass ■ Geothermal ■ Hydroelectric ■ Wind ■ PV ■ CSP ■ BESS ■ CAES ■ PHS


Hourly Power Generation Red NDC+
MW
40000
35000
30000
25000
20000
15000
10000
5000
0
0 5 10 15 20
January
February
March
April
May
June
July
August
September
October
November
December
2030
■ Coal ■ Diesel ■ LNG ■ Cogeneration ■ Biogas ■ Biomass ■ Geothermal ■ Hydroelectric ■ Wind ■ PV ■ CSP ■ BESS ■ CAES ■ PHS


Hourly Power Generation Green NDC
40000
35000
30000
25000
20000
15000
10000
5000
0
MW
January
February
March
April
May
June
July
August
September
October
November
December
2030
Coal
Diesel
LNG
Cogeneration
Biogas
Biomass
Geothermal
Hydroelectric
Wind
PV
CSP
BESS
CAES
PHS

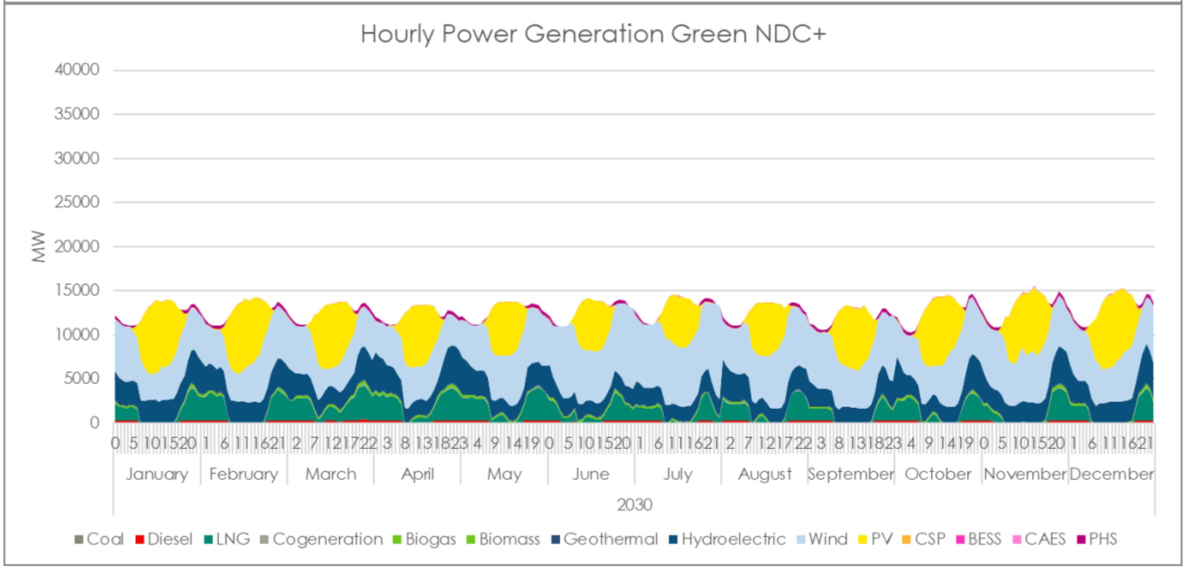
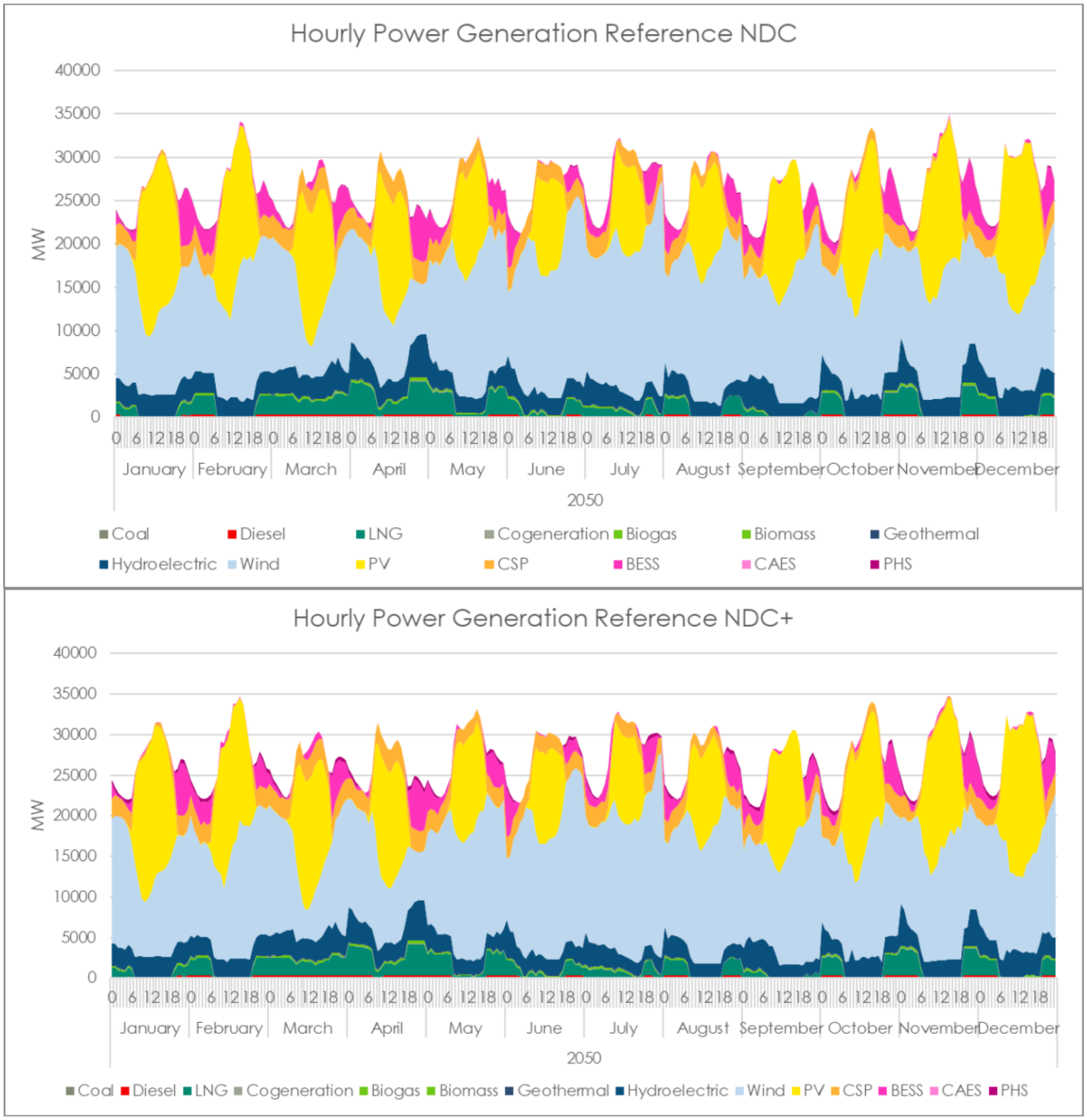
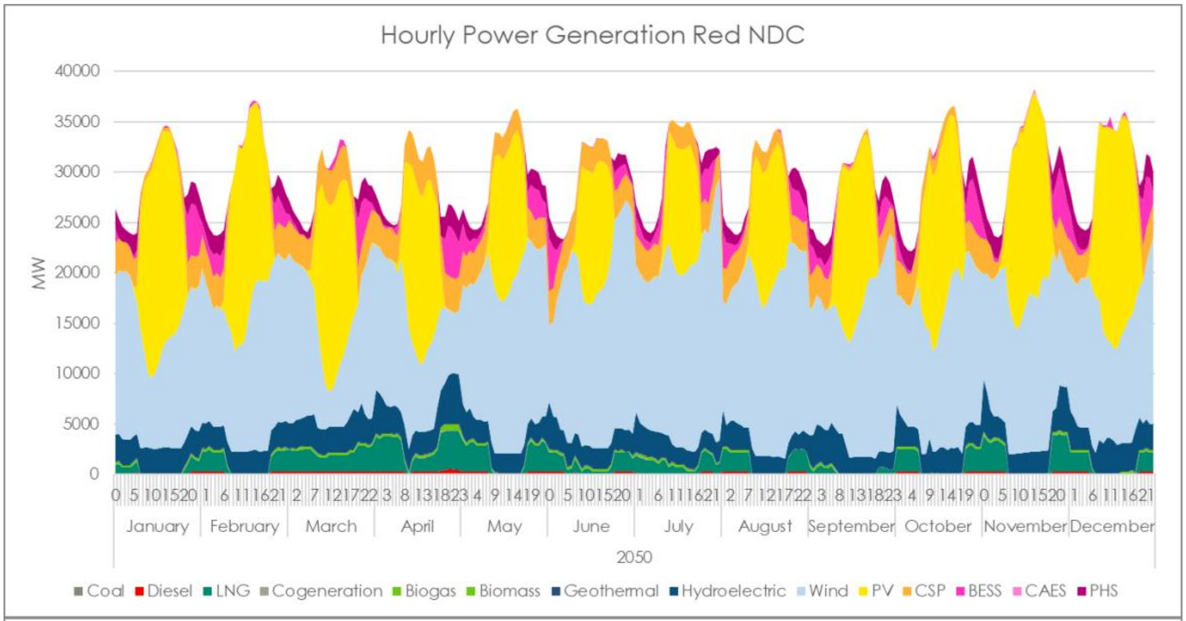
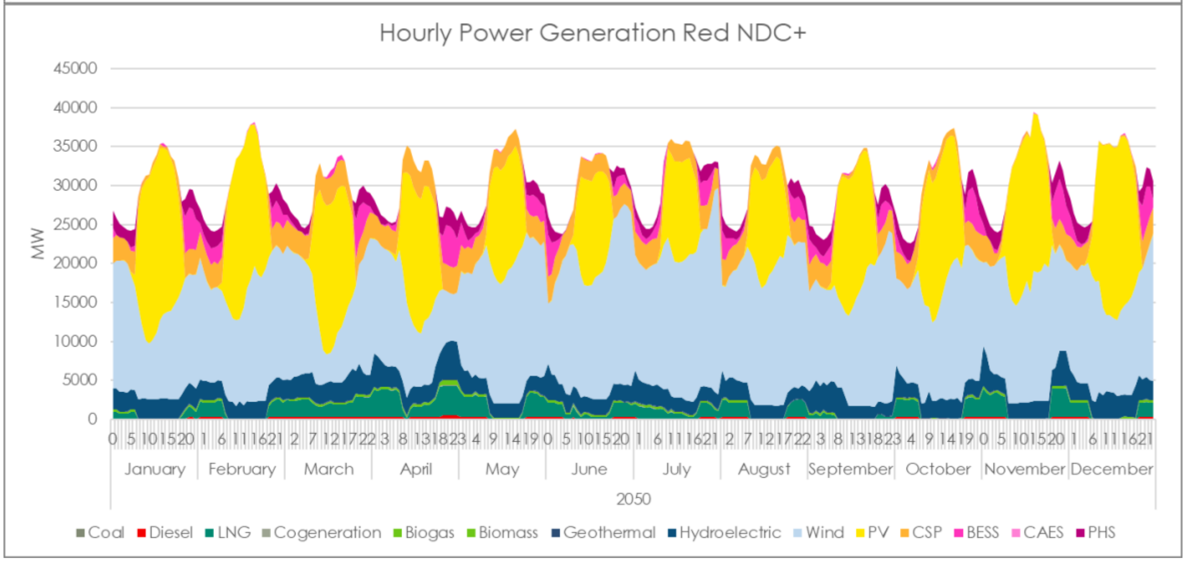

Hourly Power Generation Green NDC+
40000
35000
30000
25000
20000
15000
10000
5000
0
MW
January
February
March
April
May
June
July
August
September
October
November
December
2030
Coal
Diesel
LNG
Cogeneration
Biogas
Biomass
Geothermal
Hydroelectric
Wind
PV
CSP
BESS
CAES
PHS

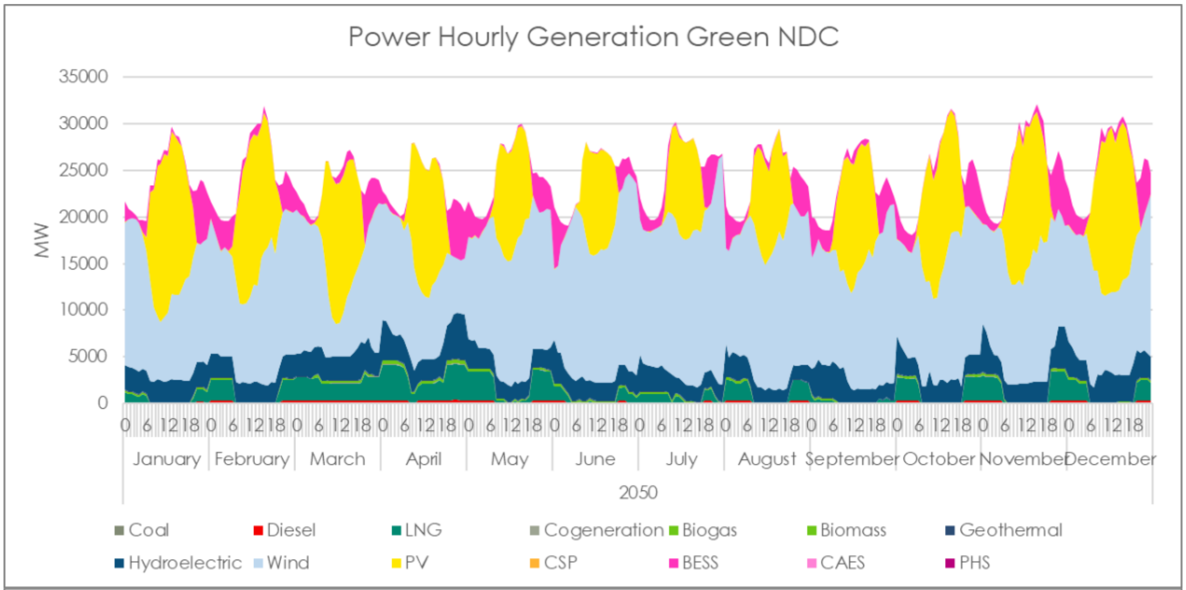
FIGURE 4

Hourly power generation 2050 by futures and mitigation scenarios

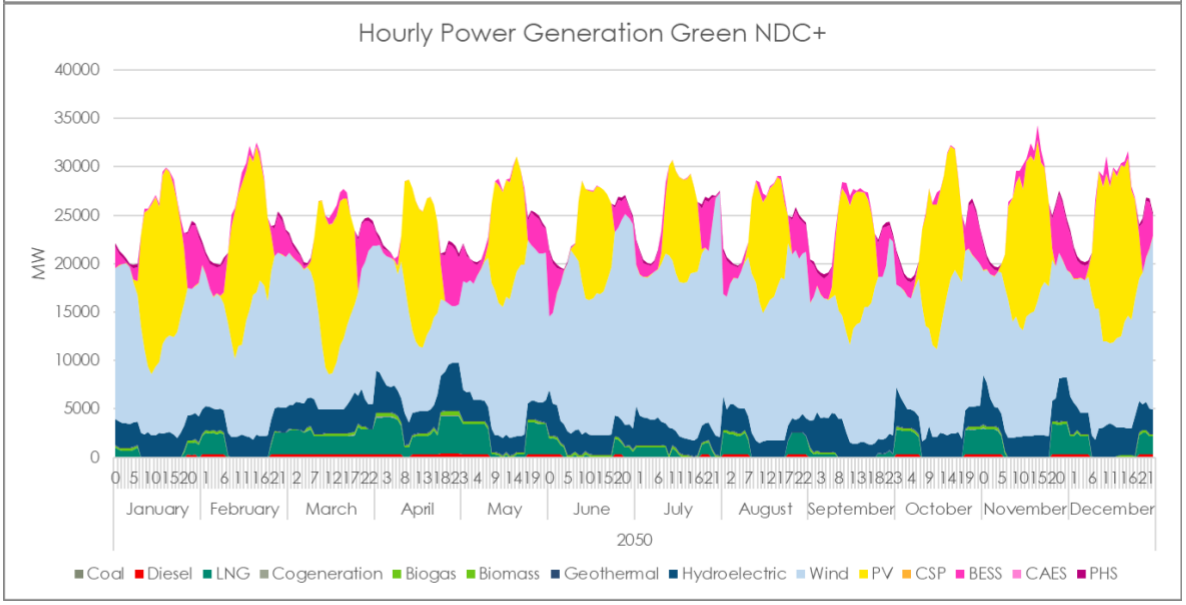



Hourly Power Generation Red NDC
MW
40000
35000
30000
25000
20000
15000
10000
5000
0
0 5 10 15 20 1 6 11 16 21 2 7 12 17 22 3 8 13 18 23 4 9 14 19 0 5 10 15 20 1 6 11 16 21 2 7 12 17 22 3 8 13 18 23 4 9 14 19 0 5 10 15 20 1 6 11 16 21
January
February
March
April
May
June
July
August
September
October
November
December
2050
Coal
Diesel
LNG
Cogeneration
Biogas
Biomass
Geothermal
Hydroelectric
Wind
PV
CSP
BESS
CAES
PHS


Hourly Power Generation Red NDC+
MW
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0 5 10 15 20 1 6 11 16 21 2 7 12 17 22 3 8 13 18 23 4 9 14 19 0 5 10 15 20 1 6 11 16 21 2 7 12 17 22 3 8 13 18 23 4 9 14 19 0 5 10 15 20 1 6 11 16 21
January
February
March
April
May
June
July
August
September
October
November
December
2050
Coal
Diesel
LNG
Cogeneration
Biogas
Biomass
Geothermal
Hydroelectric
Wind
PV
CSP
BESS
CAES
PHS



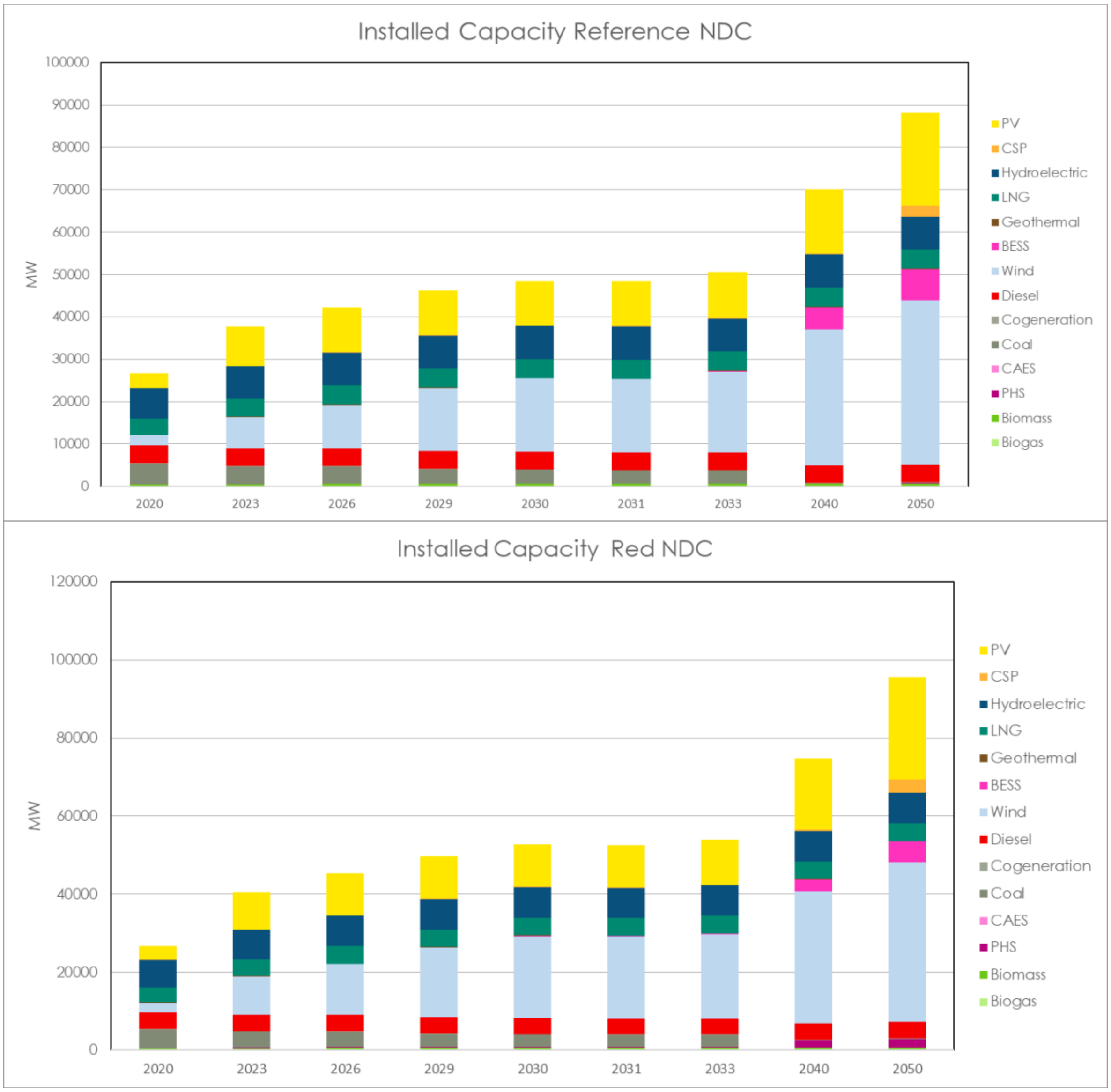
Power Hourly Generation Green NDC

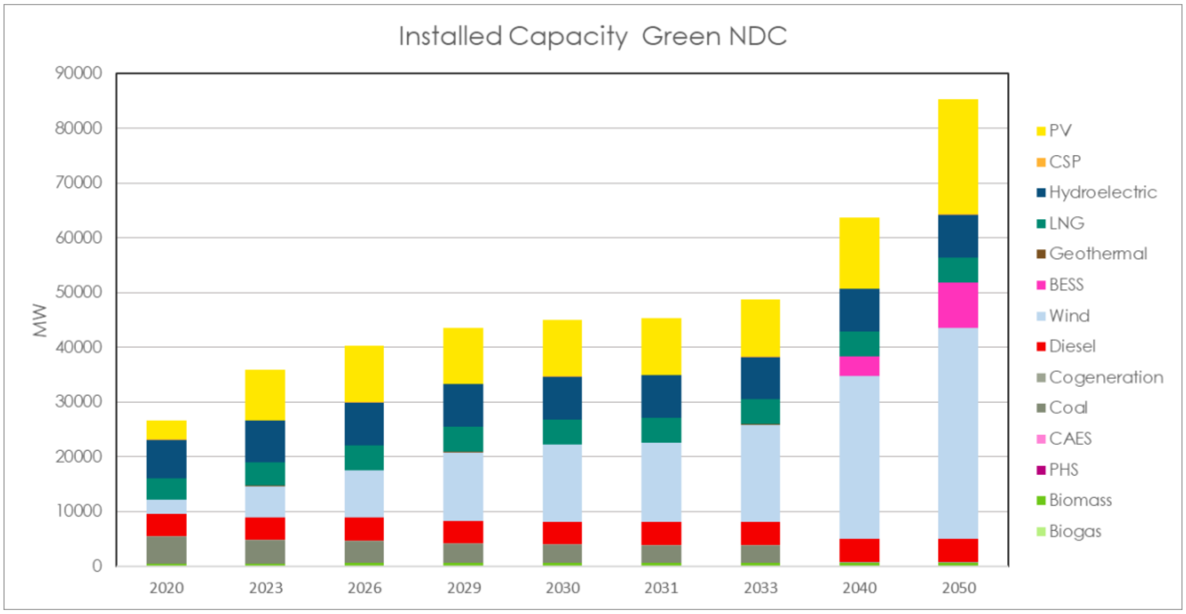


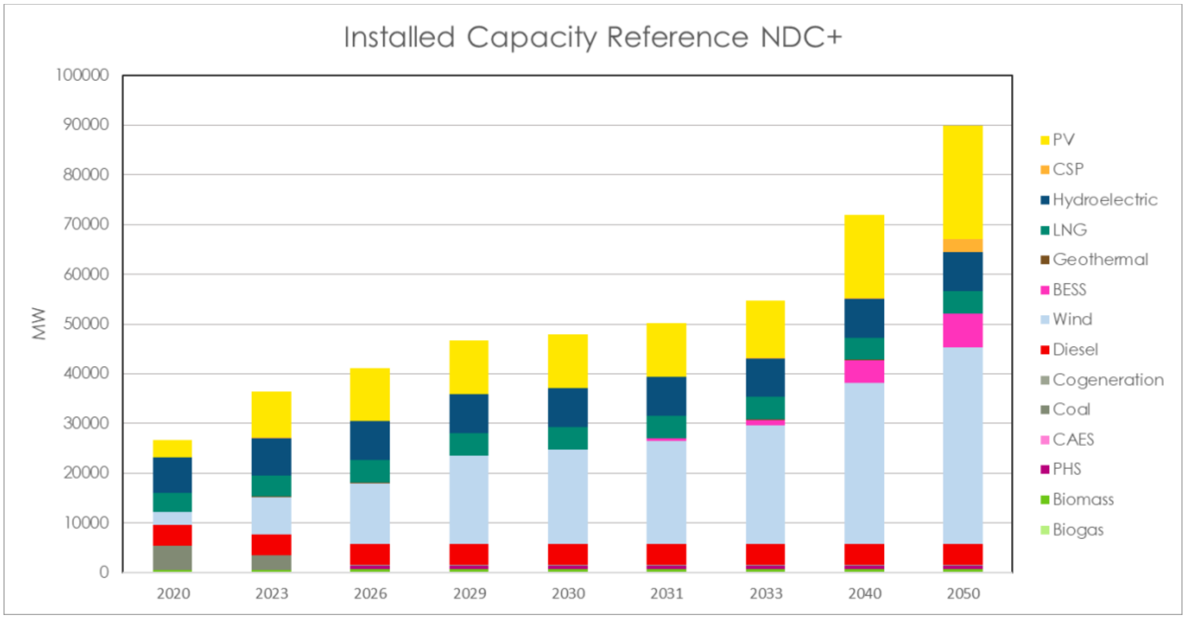
Hourly Power Generation Green NDC+

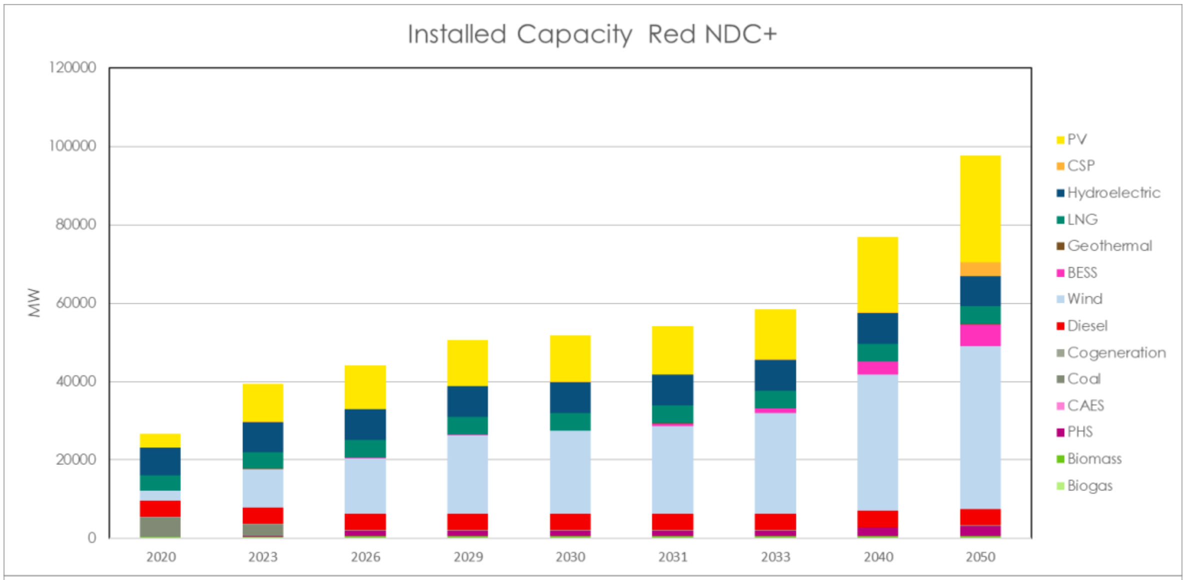
FIGURE 5

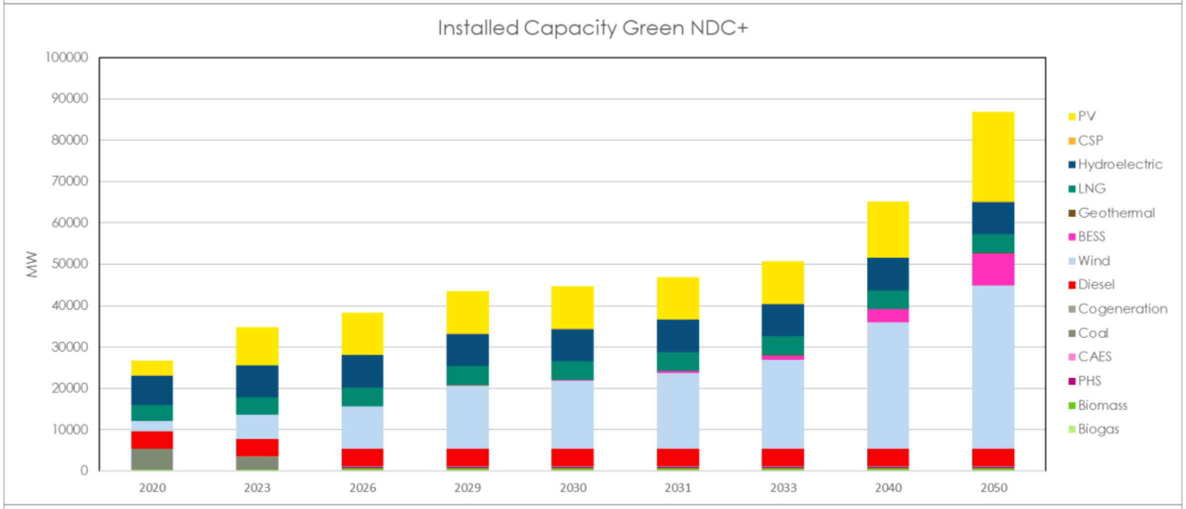
Installed capacity by futures and mitigation scenarios

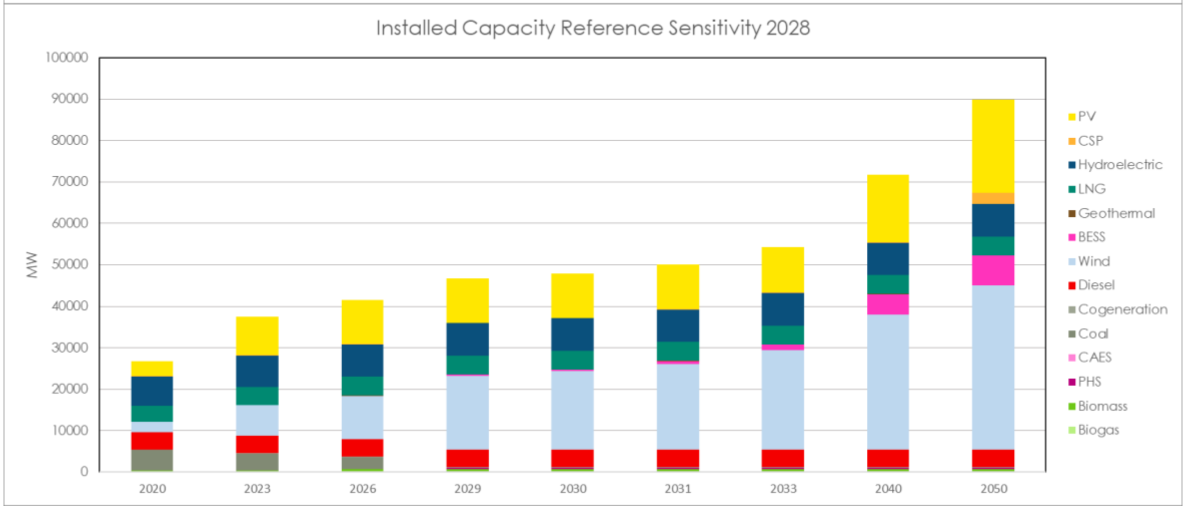


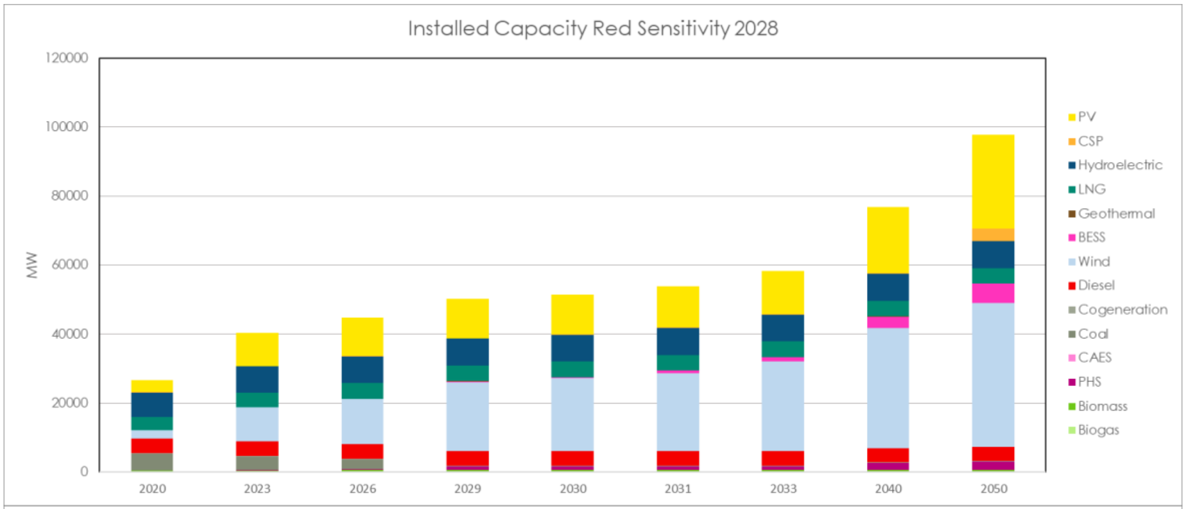

Installed Capacity Green NDC
MW
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

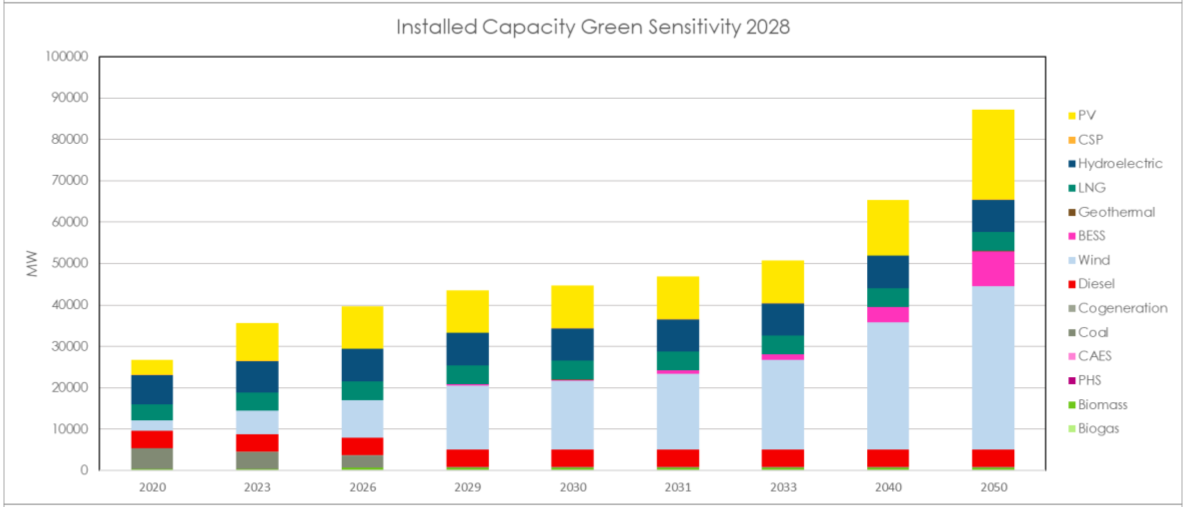

Installed Capacity Reference NDC+
MW
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

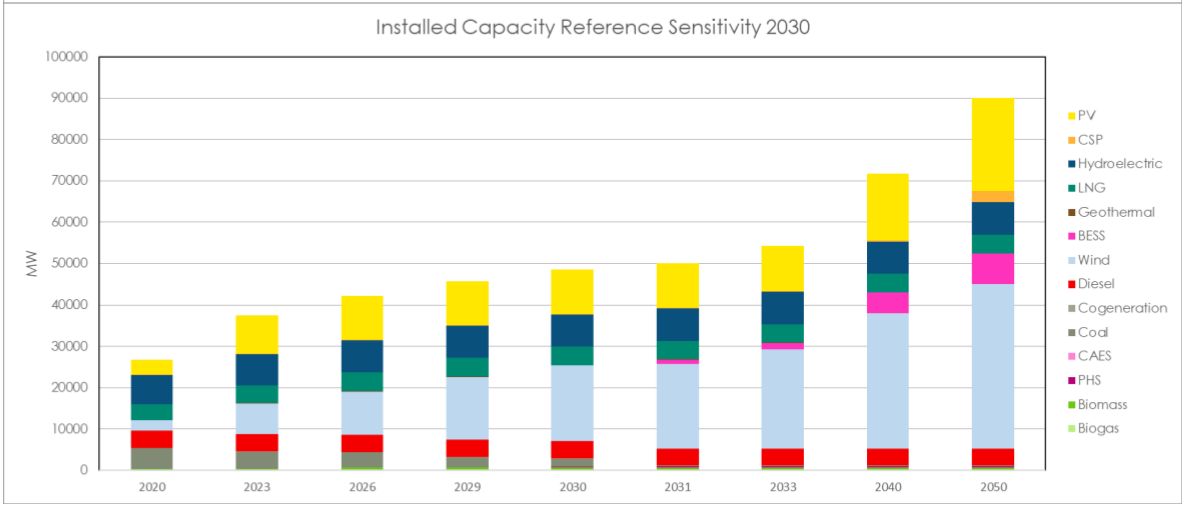

Installed Capacity Red NDC+
MW
120000
100000
80000
60000
40000
20000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

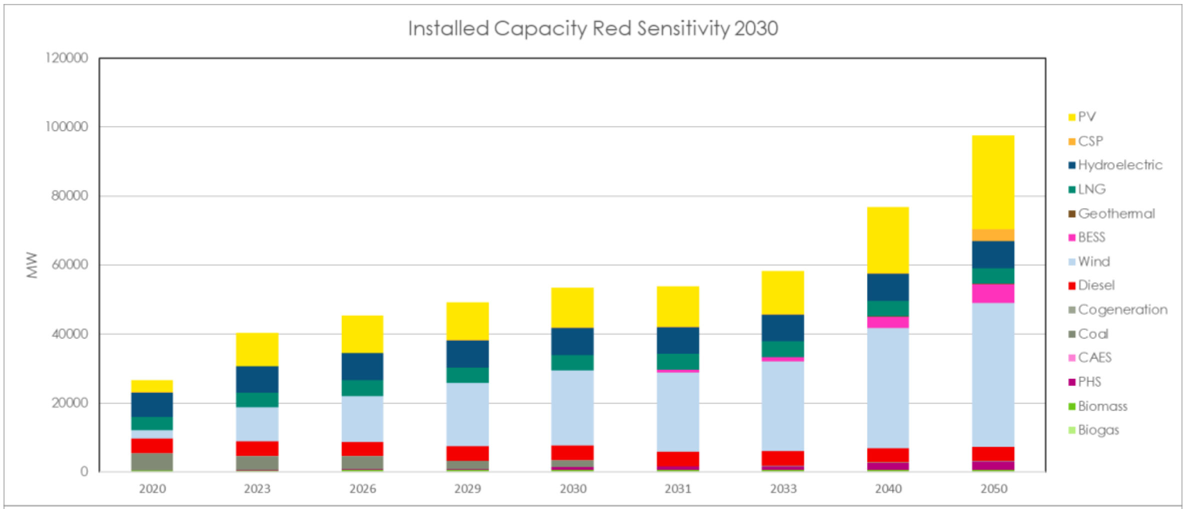

Installed Capacity Green NDC+
MW
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Installed Capacity Reference Sensitivity 2028
MW
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Installed Capacity Red Sensitivity 2028
MW
0
20000
40000
60000
80000
100000
120000
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Installed Capacity Green Sensitivity 2028
MW
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Installed Capacity Reference Sensitivity 2030
MW
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Installed Capacity Red Sensitivity 2030
MW
120000
100000
80000
60000
40000
20000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

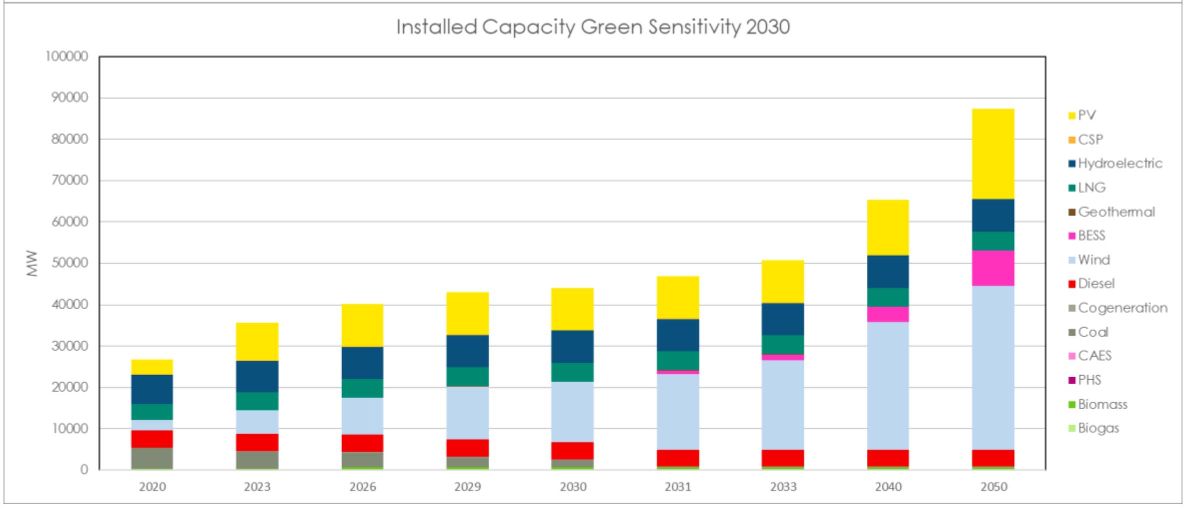
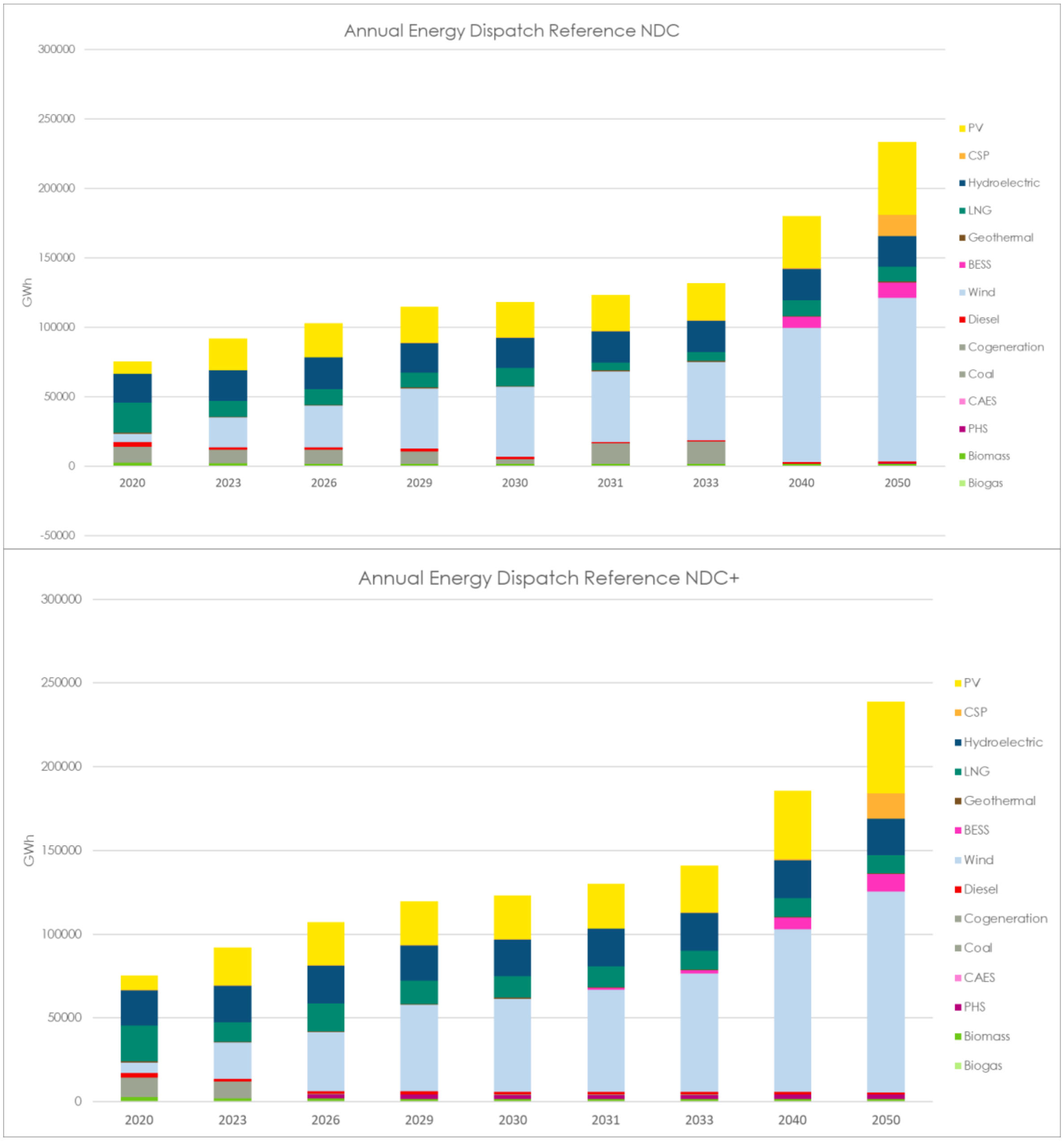
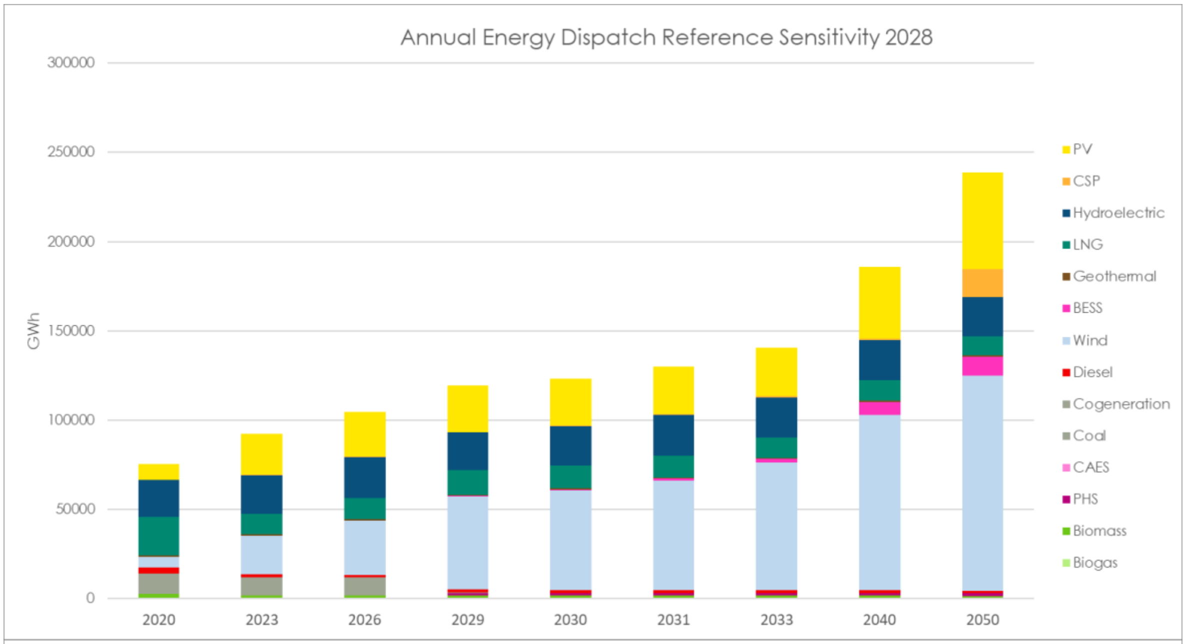
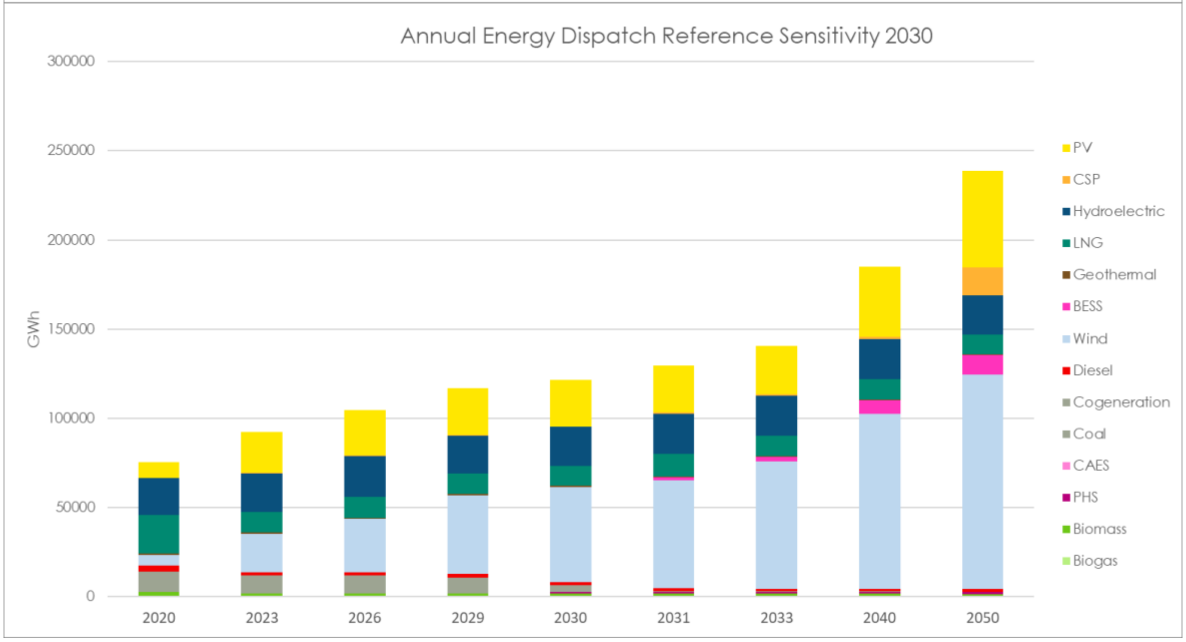

Installed Capacity Green Sensitivity 2030
MW
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

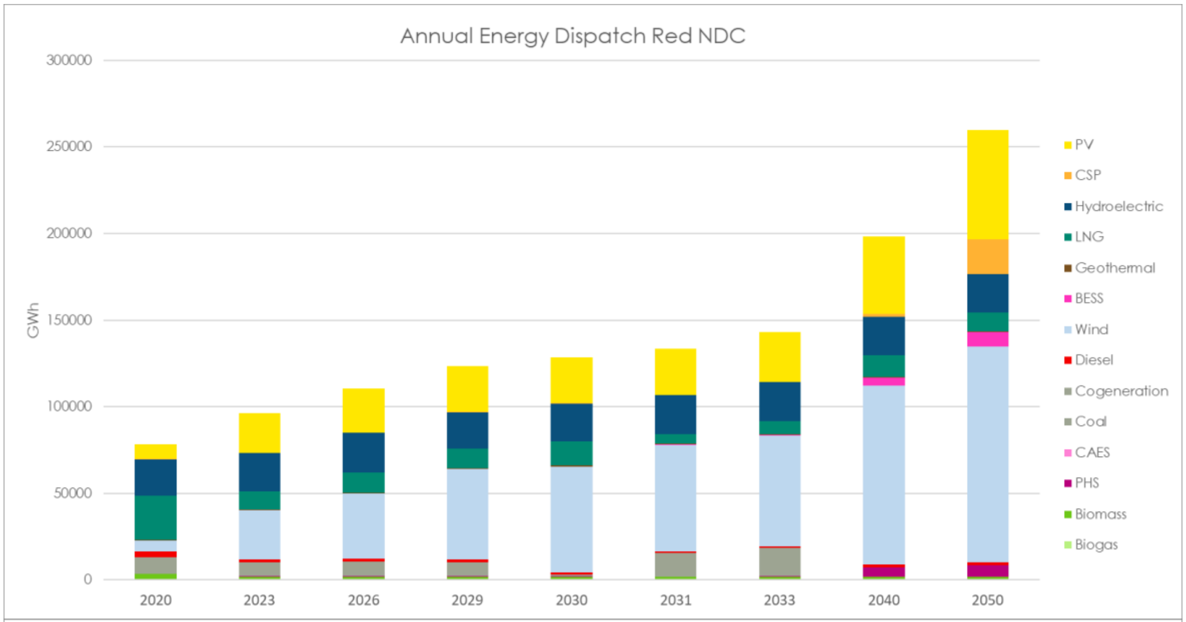
FIGURE 6

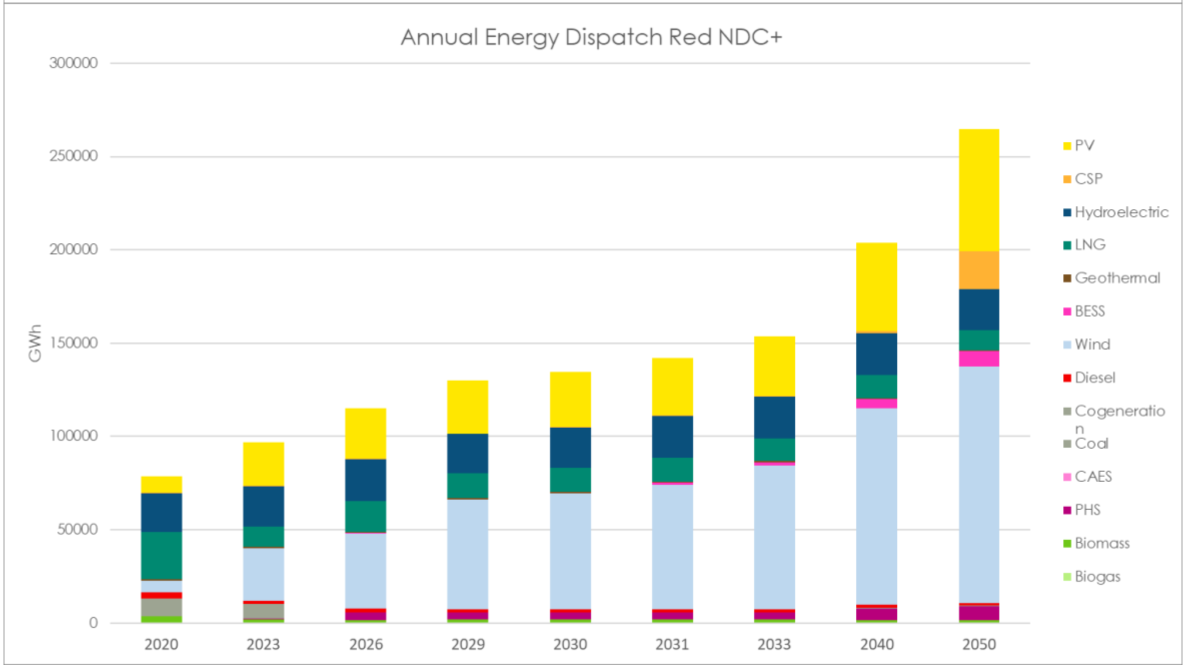
Annual energy dispatch by futures and mitigation scenarios

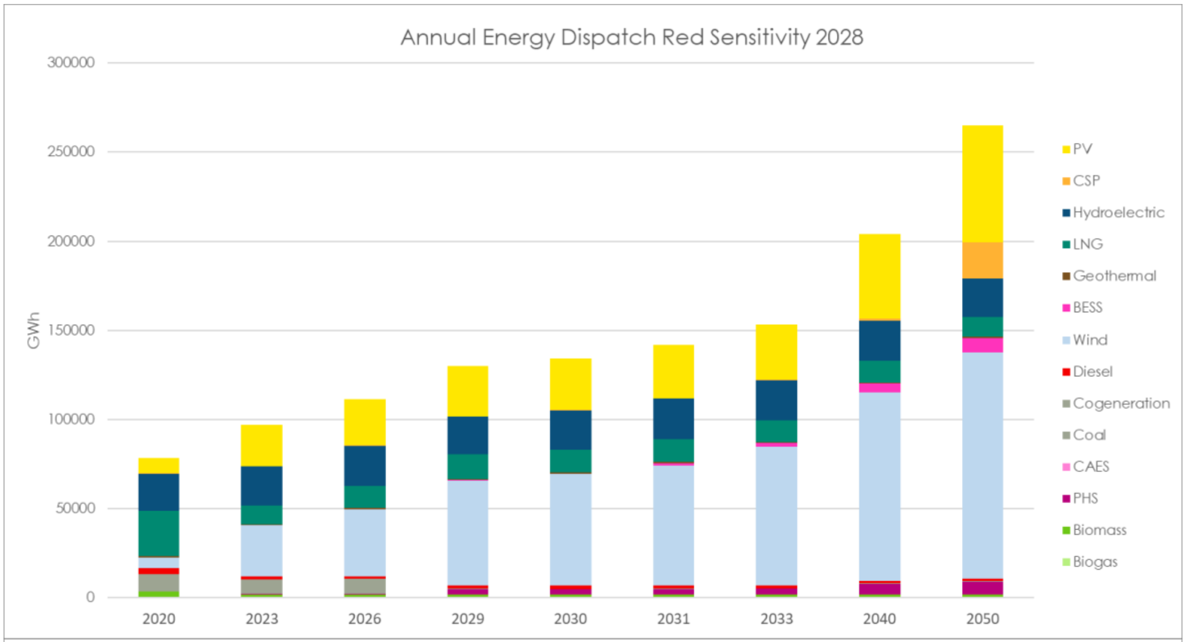



Annual Energy Dispatch Reference Sensitivity 2028
GWh
300000
250000
200000
150000
100000
50000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

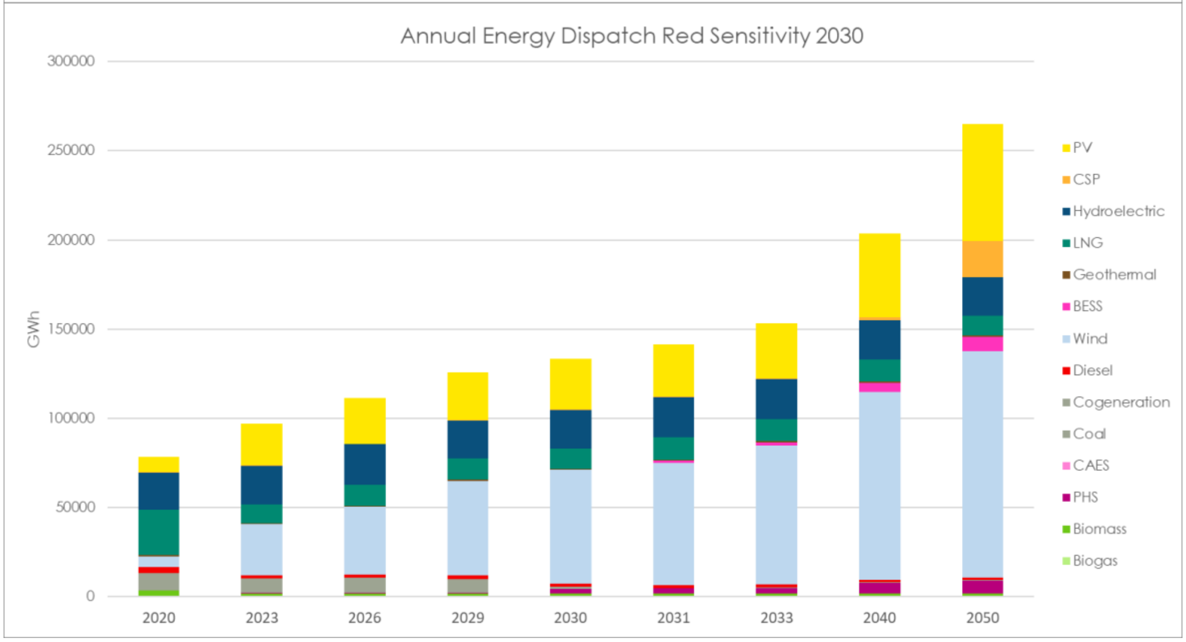

Annual Energy Dispatch Reference Sensitivity 2030
GWh
300000
250000
200000
150000
100000
50000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Annual Energy Dispatch Red NDC

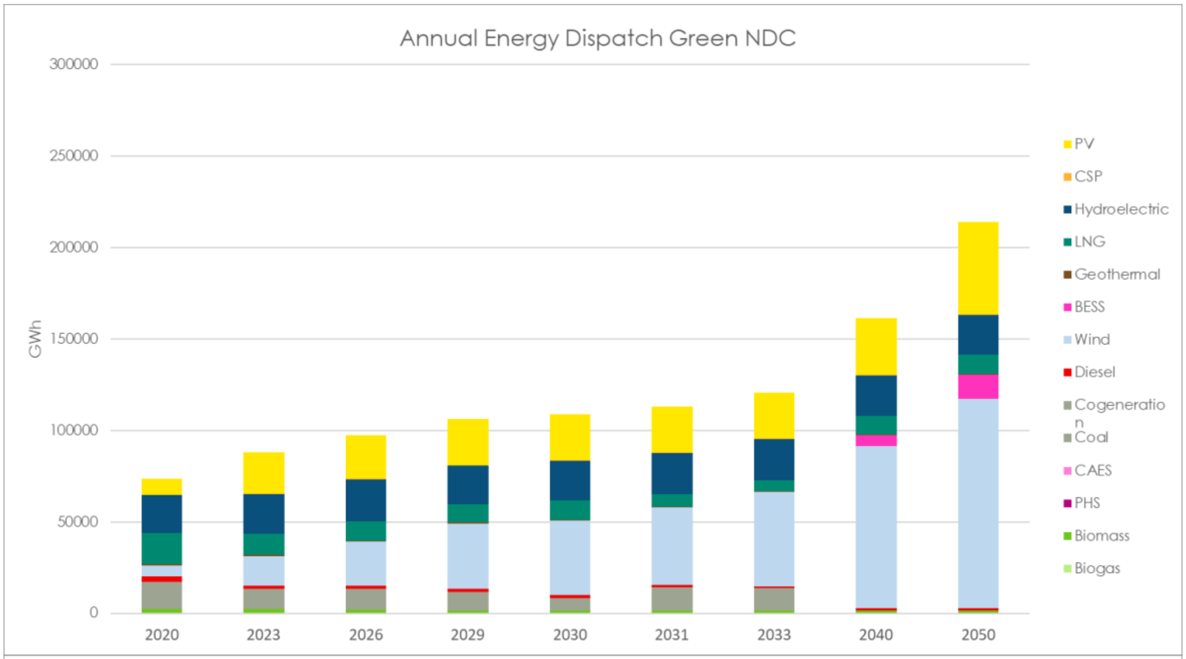

Annual Energy Dispatch Red NDC+

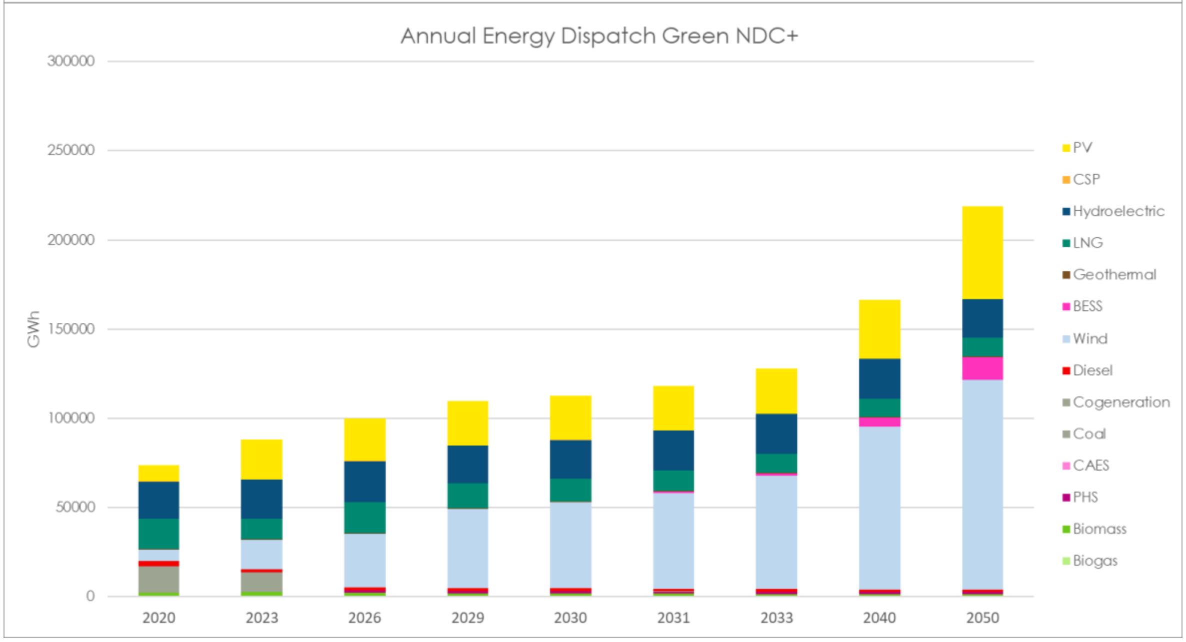


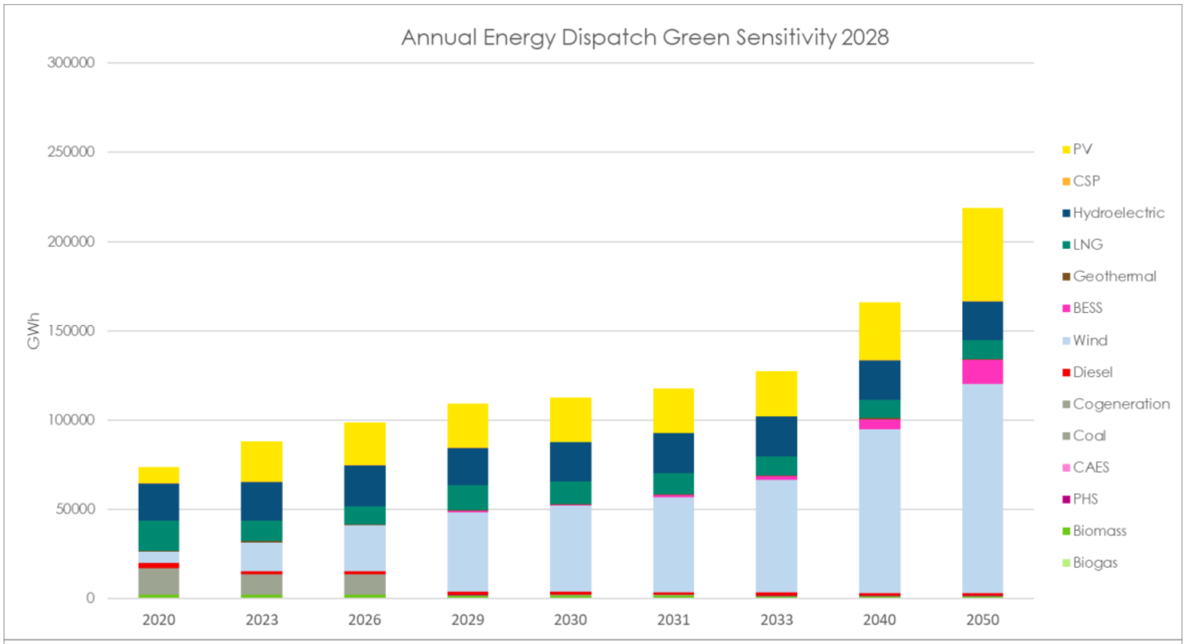
Annual Energy Dispatch Red Sensitivity 2028



Annual Energy Dispatch Red Sensitivity 2030


Annual Energy Dispatch Green NDC
GWh
300000
250000
200000
150000
100000
50000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Annual Energy Dispatch Green NDC+
GWh
300000
250000
200000
150000
100000
50000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Annual Energy Dispatch Green Sensitivity 2028
GWh
300000
250000
200000
150000
100000
50000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

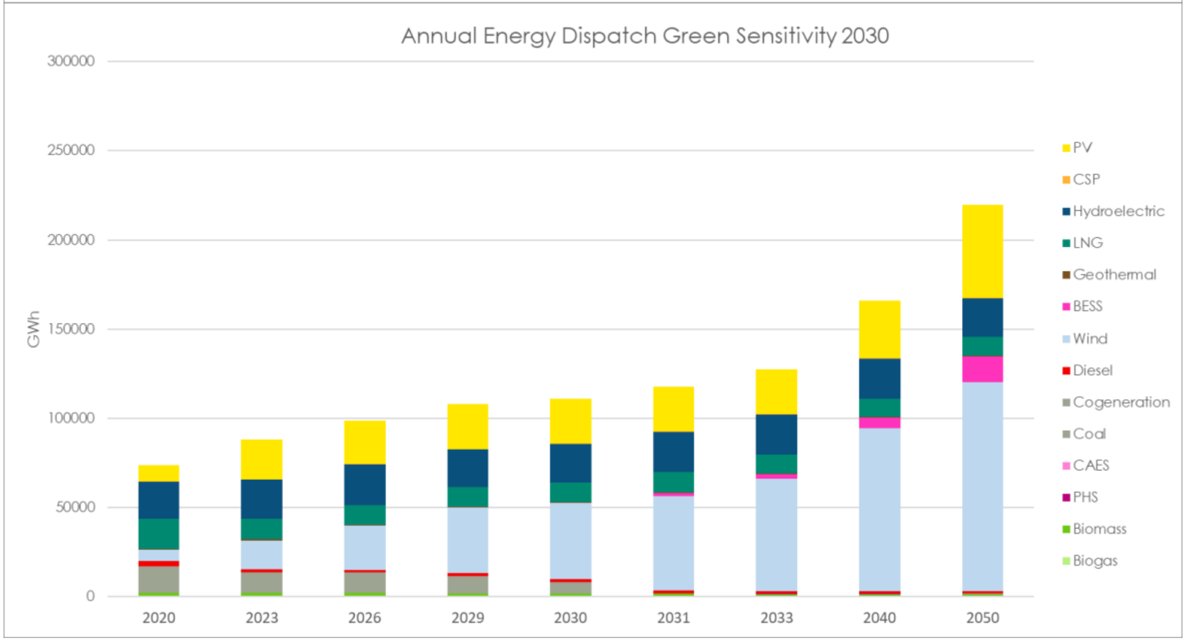
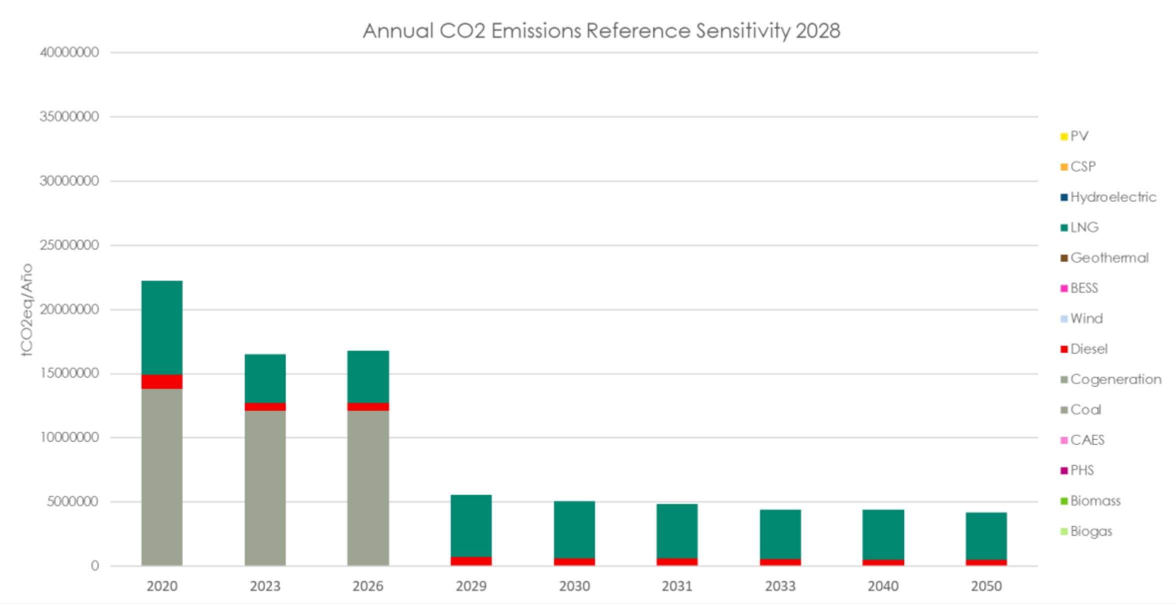
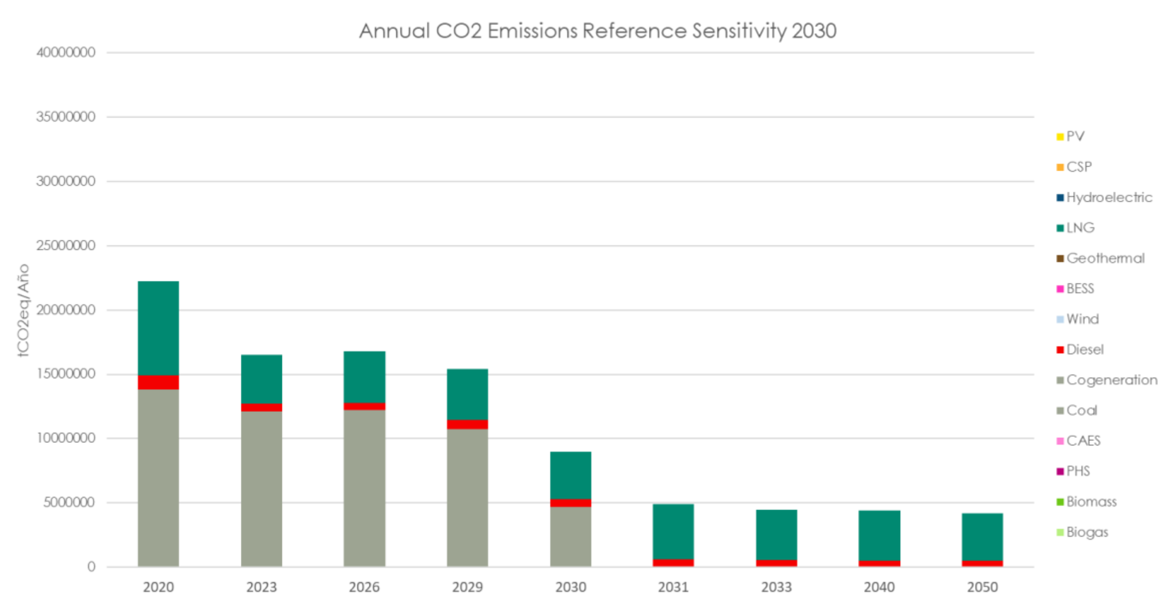
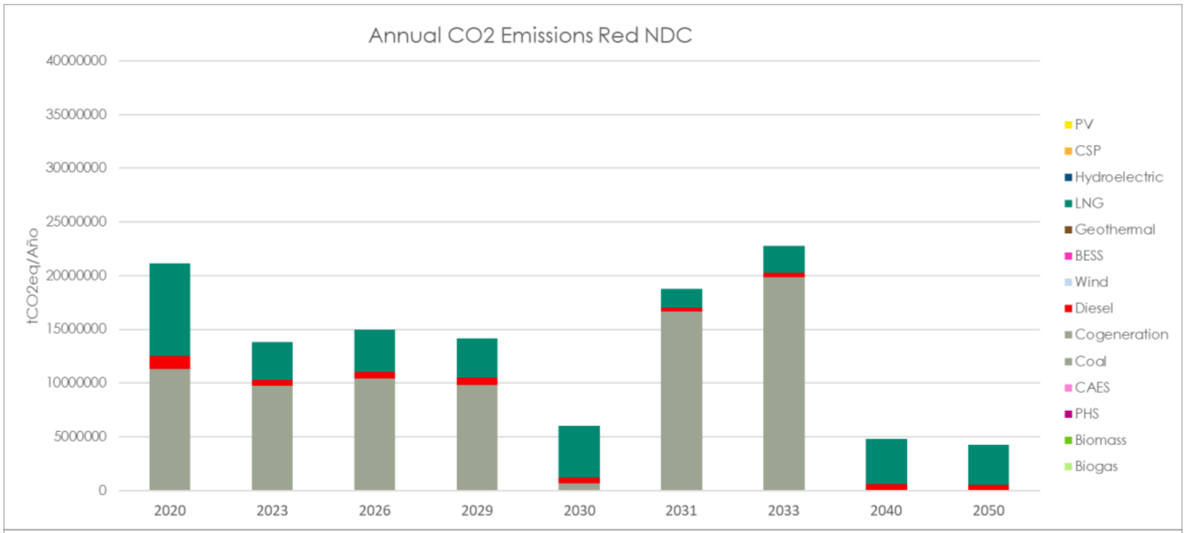

Annual Energy Dispatch Green Sensitivity 2030
GWh
300000
250000
200000
150000
100000
50000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

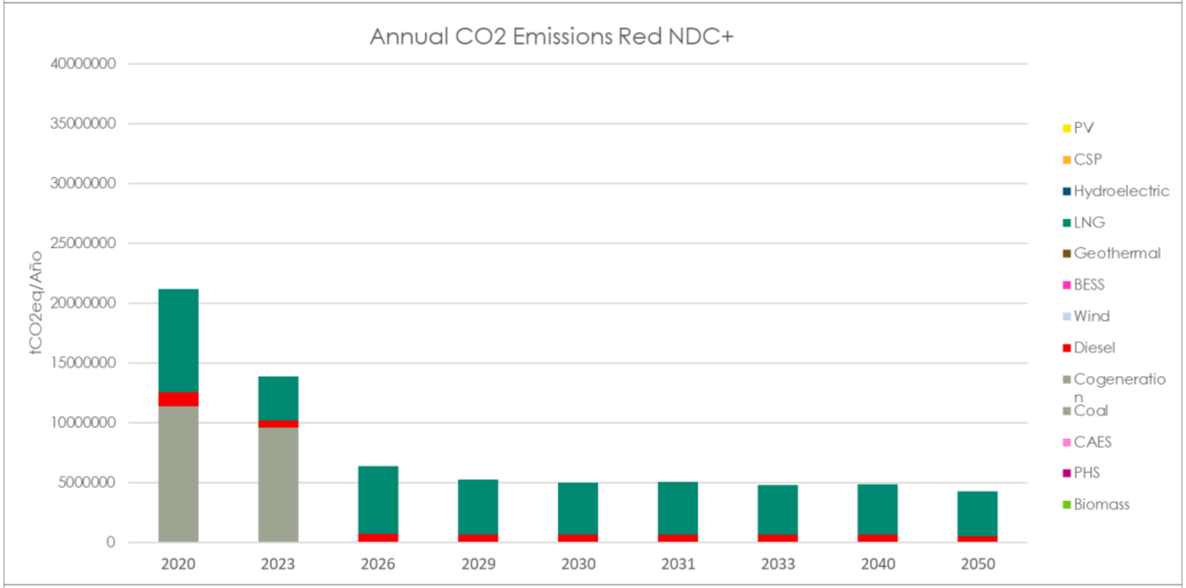
FIGURE 7

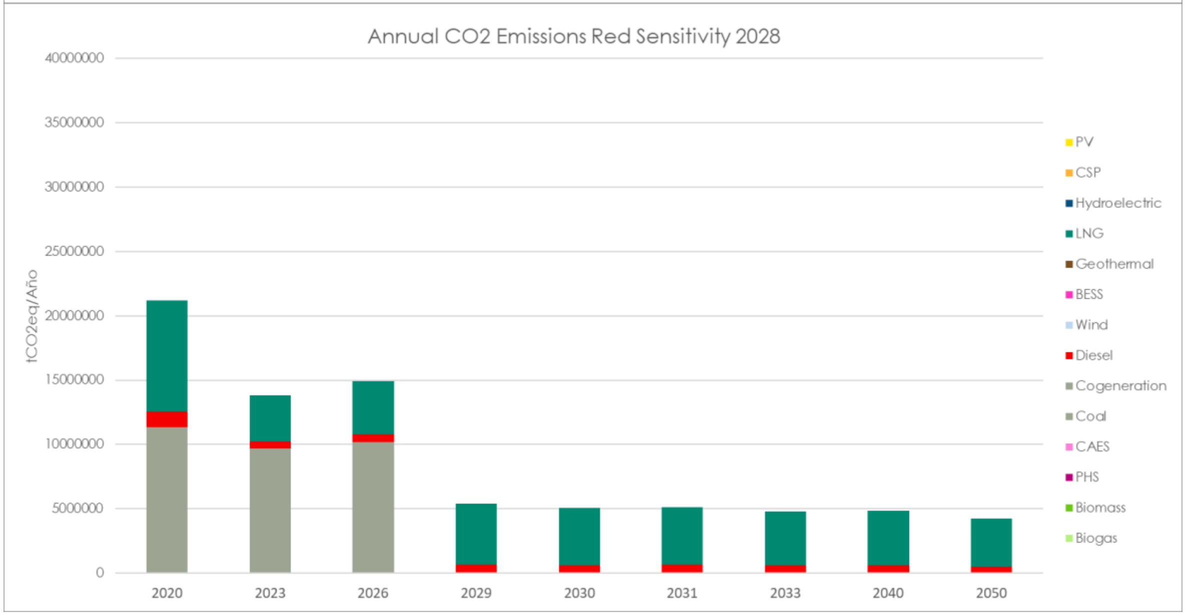
Annual CO2 emissions by futures and mitigation scenarios

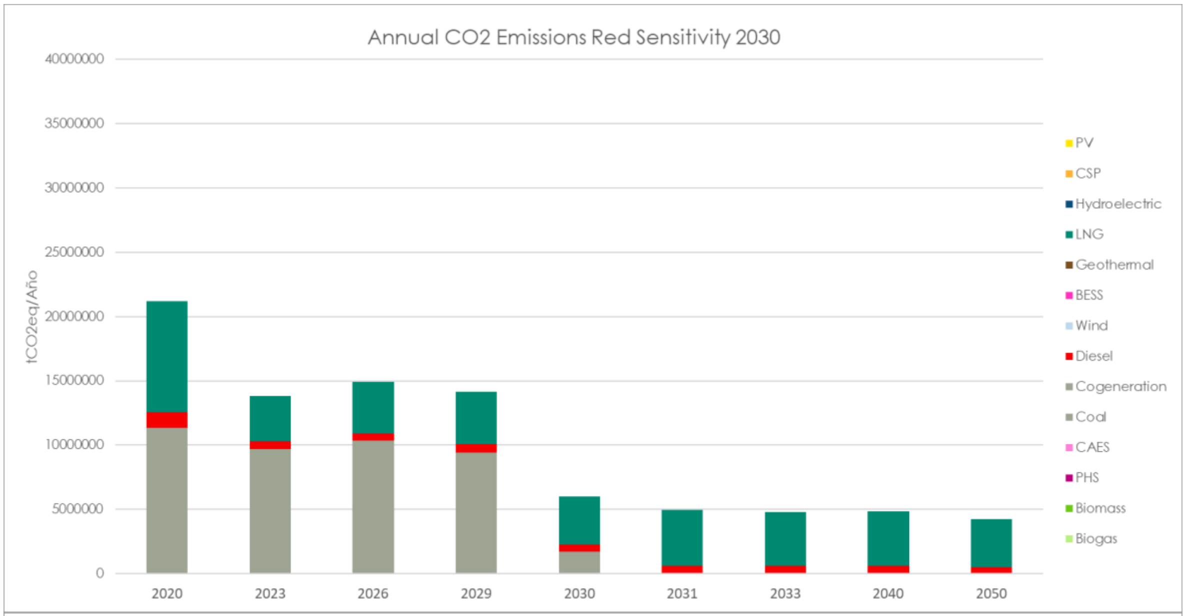

Annual CO2 Emissions Reference Sensitivity 2028
tCO2eq/Año
40000000
35000000
30000000
25000000
20000000
15000000
10000000
5000000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Annual CO2 Emissions Reference Sensitivity 2030
tCO2eq/Año
40000000
35000000
30000000
25000000
20000000
15000000
10000000
5000000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

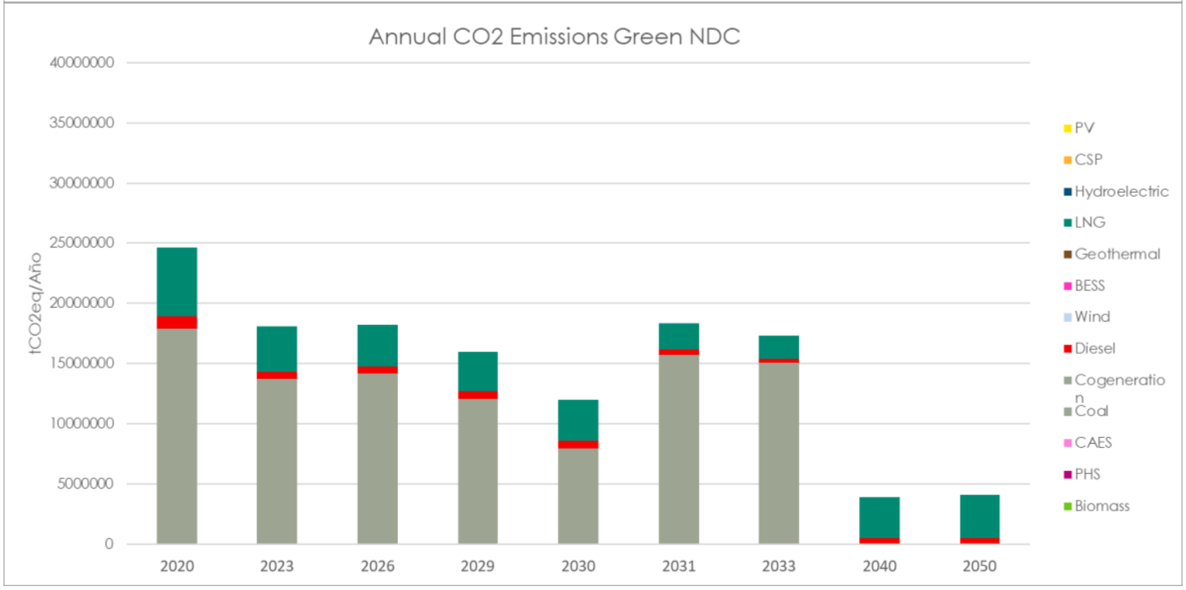

Annual CO2 Emissions Red NDC
tCO2eq/Año
40000000
35000000
30000000
25000000
20000000
15000000
10000000
5000000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Annual CO2 Emissions Red NDC+
tCO2eq/Año
40000000
35000000
30000000
25000000
20000000
15000000
10000000
5000000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass

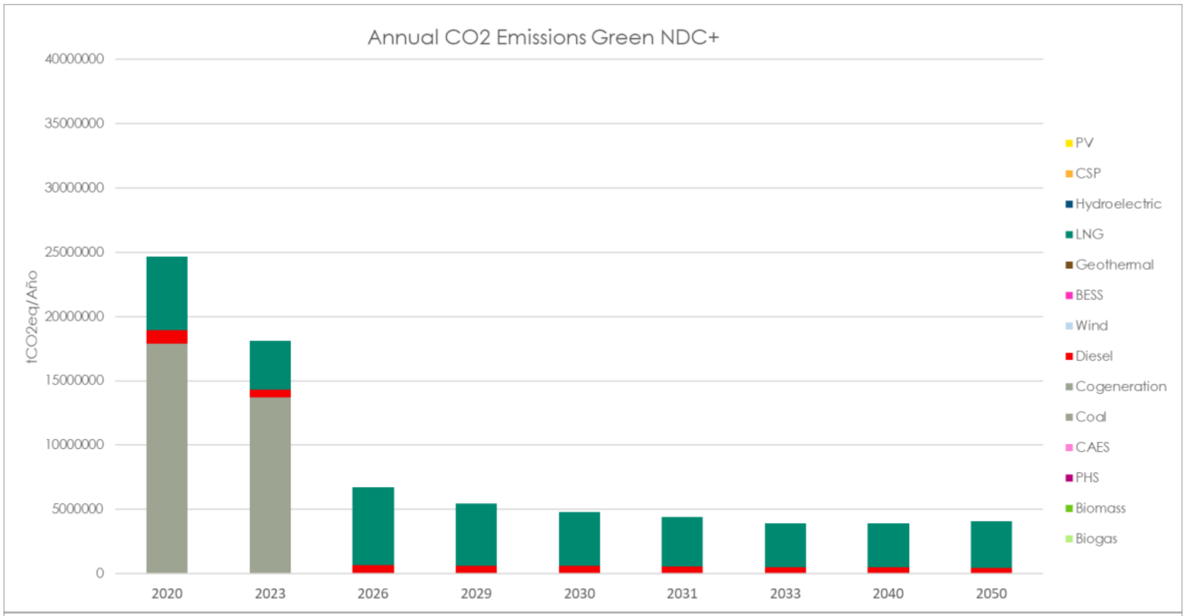

Annual CO2 Emissions Red Sensitivity 2028
tCO2eq/Año
40000000
35000000
30000000
25000000
20000000
15000000
10000000
5000000
0
2020
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

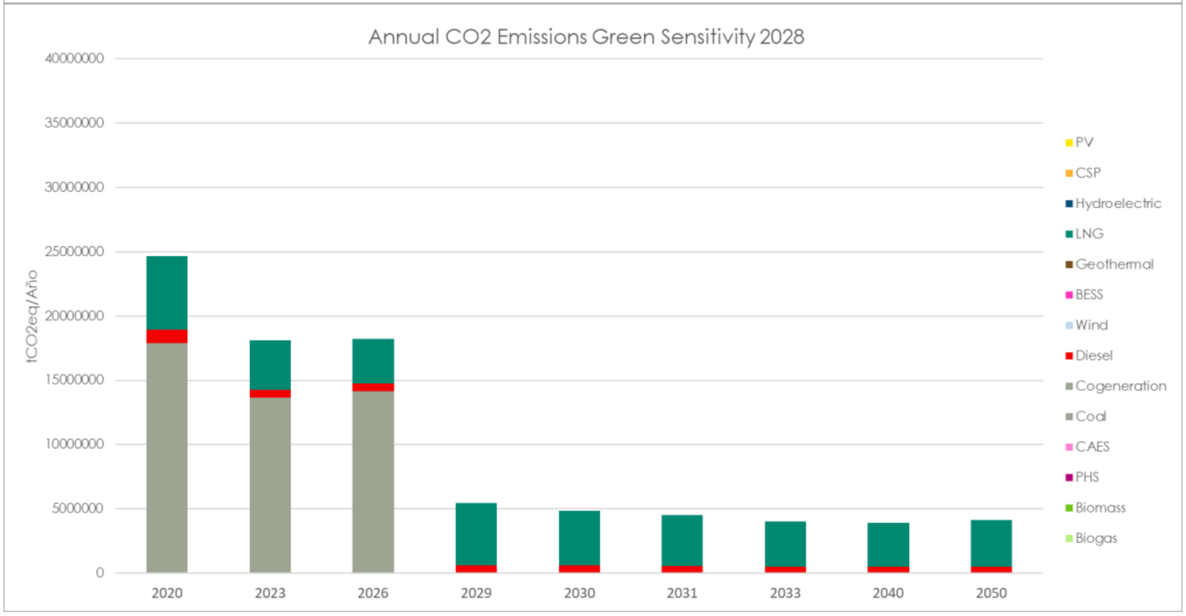


Annual CO2 Emissions Red Sensitivity 2030



Annual CO2 Emissions Green NDC


Annual CO2 Emissions Green NDC+


Annual CO2 Emissions Green Sensitivity 2028

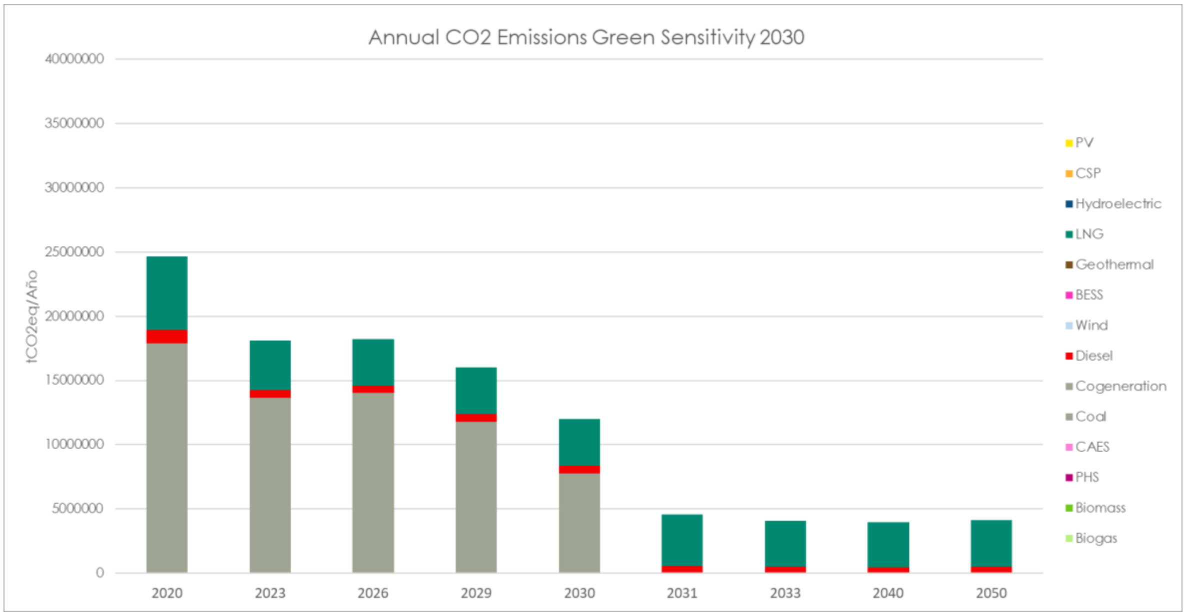
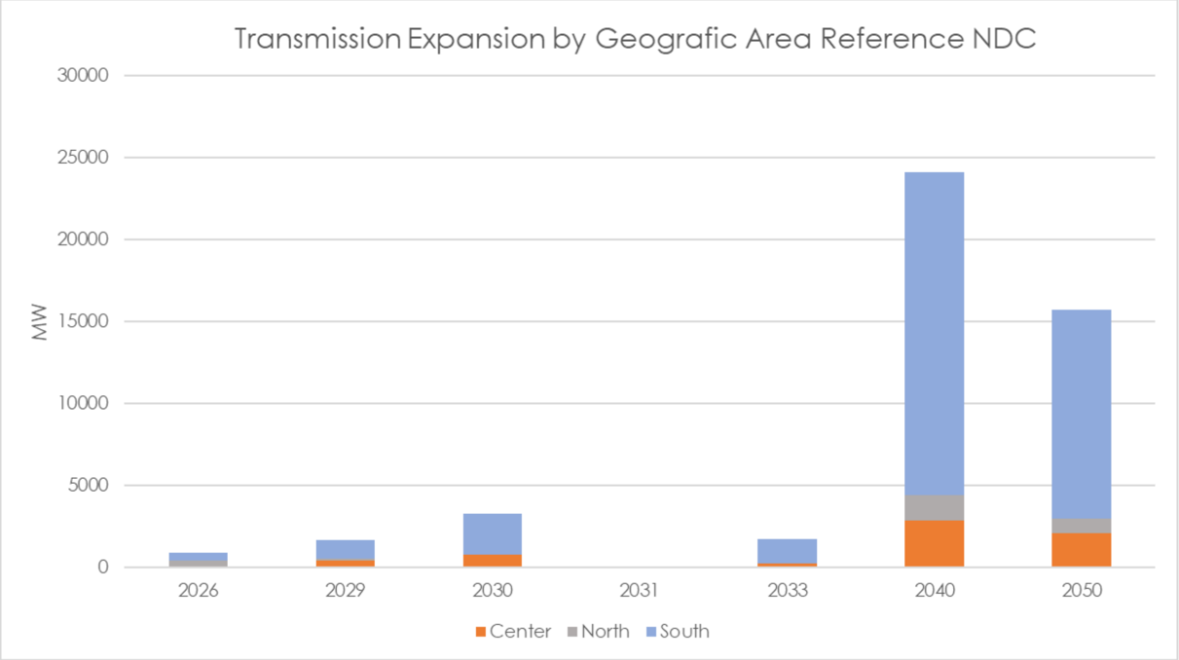
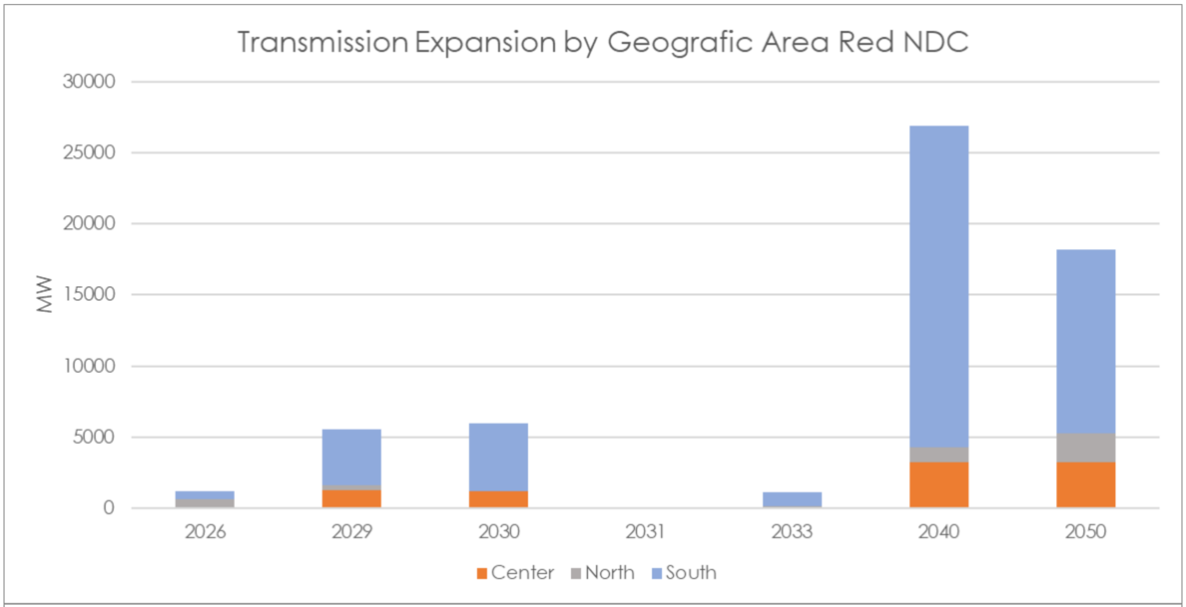
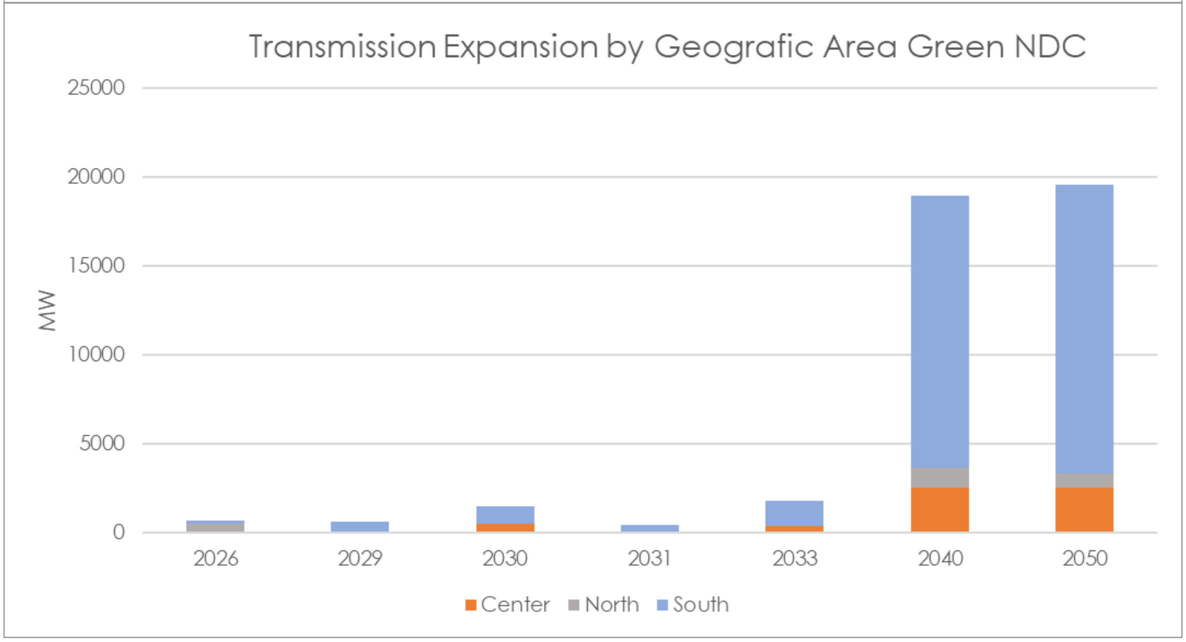


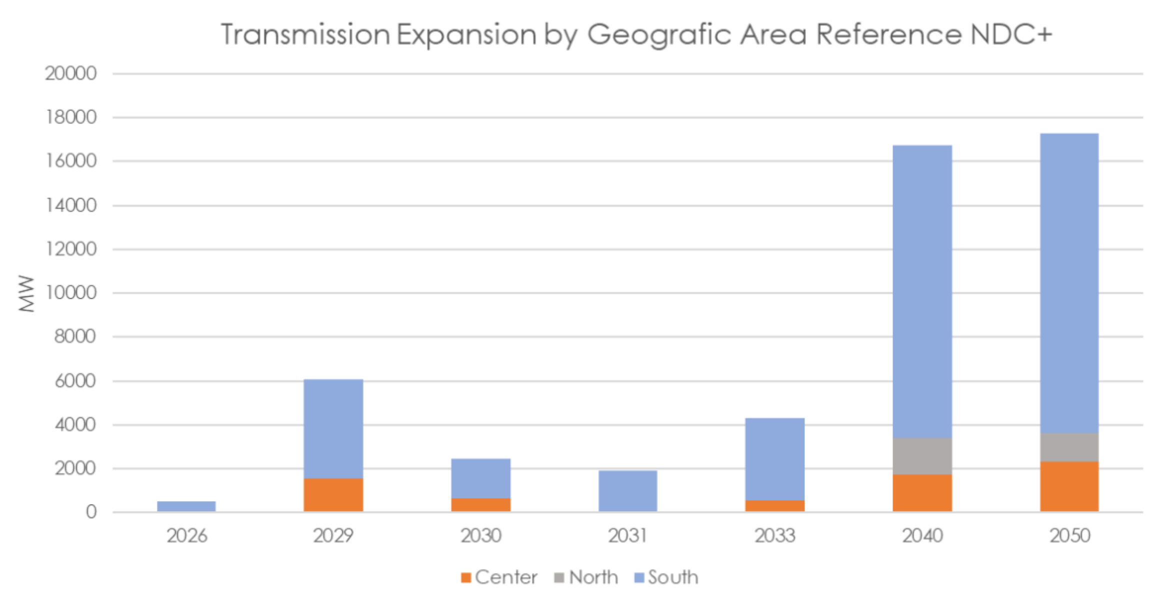
FIGURE 8

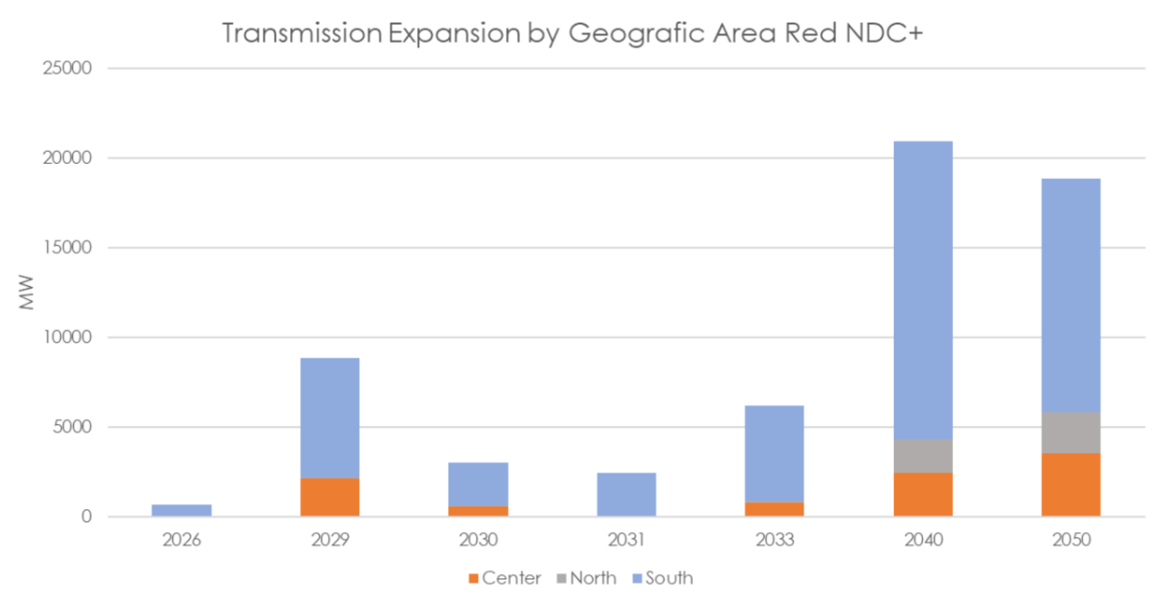
Transmission expansion by futures and mitigation scenarios

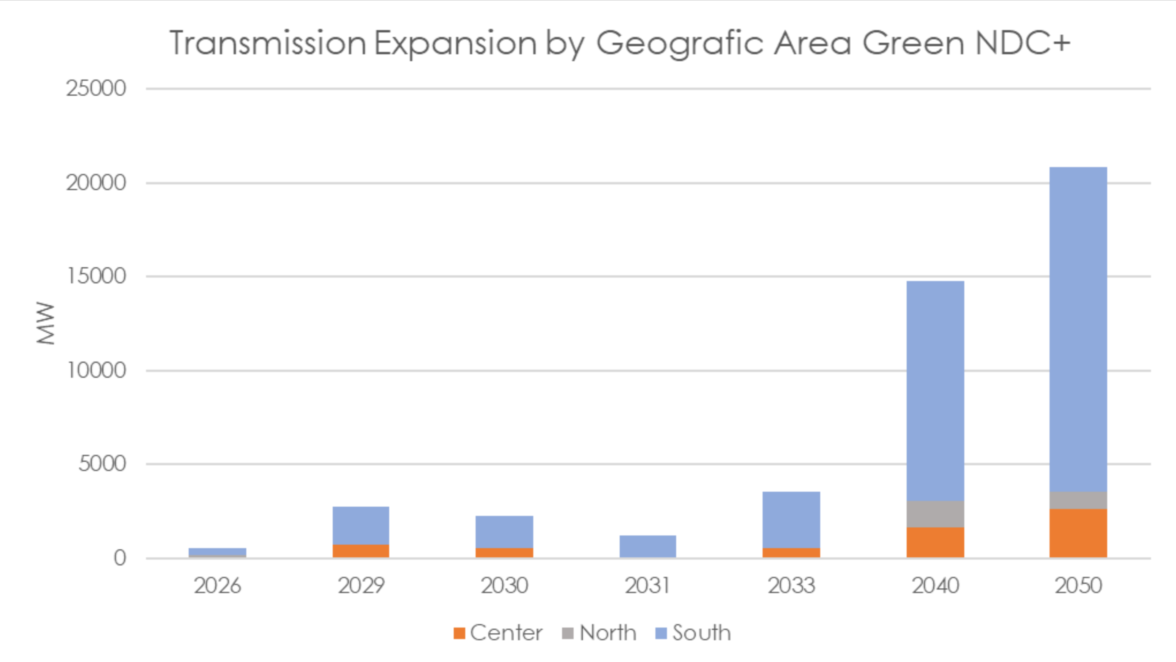


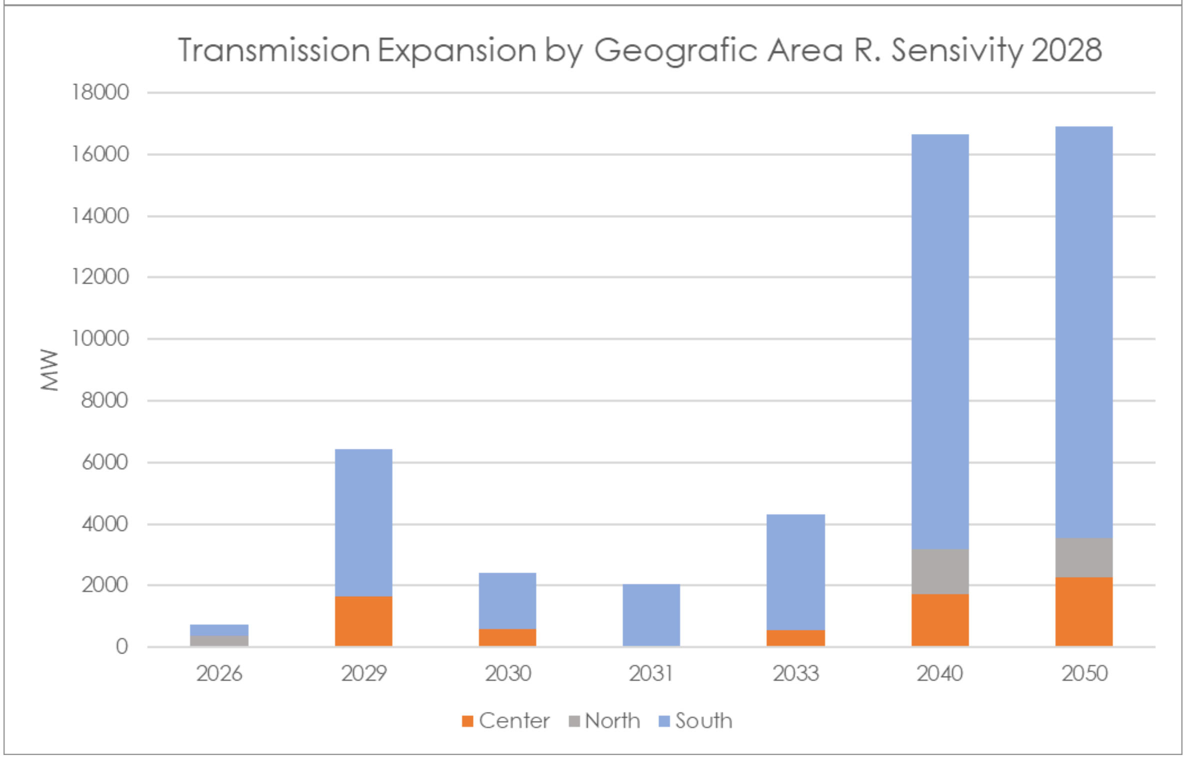

Transmission Expansion by Geografic Area Red NDC
MW
30000
25000
20000
15000
10000
5000
0
2026
2029
2030
2031
2033
2040
2050
Center
North
South

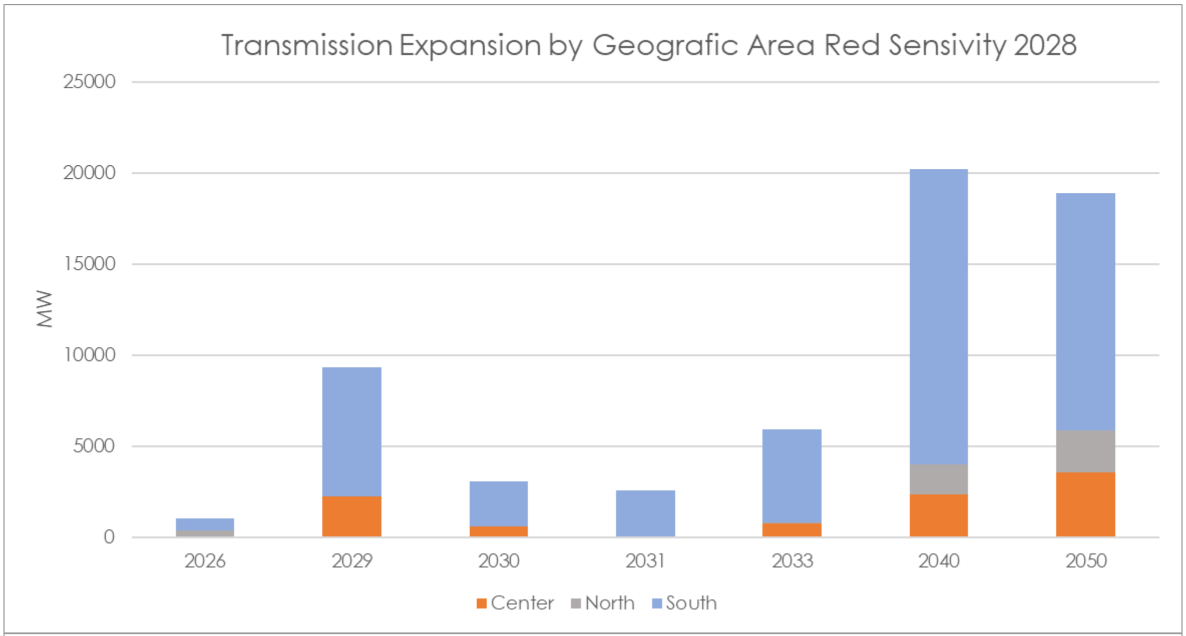

Transmission Expansion by Geografic Area Green NDC
MW
25000
20000
15000
10000
5000
0
2026
2029
2030
2031
2033
2040
2050
Center
North
South

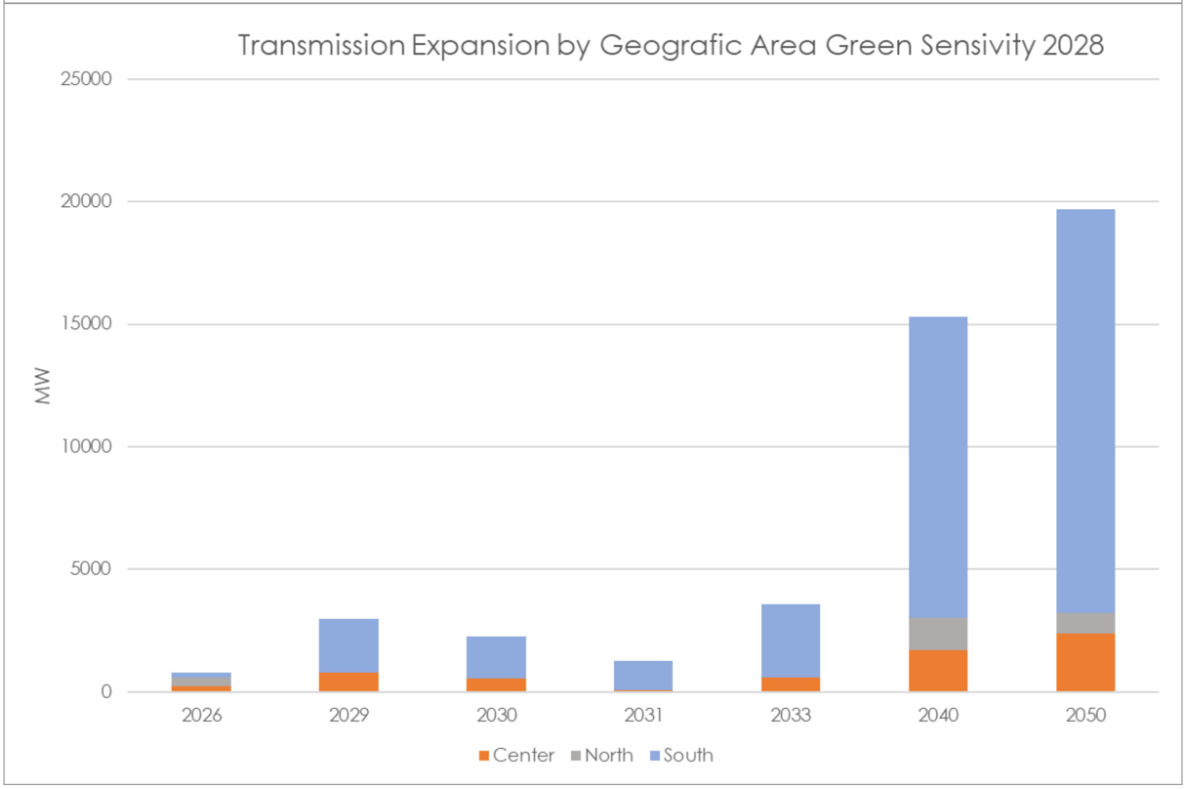

Transmission Expansion by Geografic Area Reference NDC+
MW
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
2026
2029
2030
2031
2033
2040
2050
■ Center ■ North ■ South

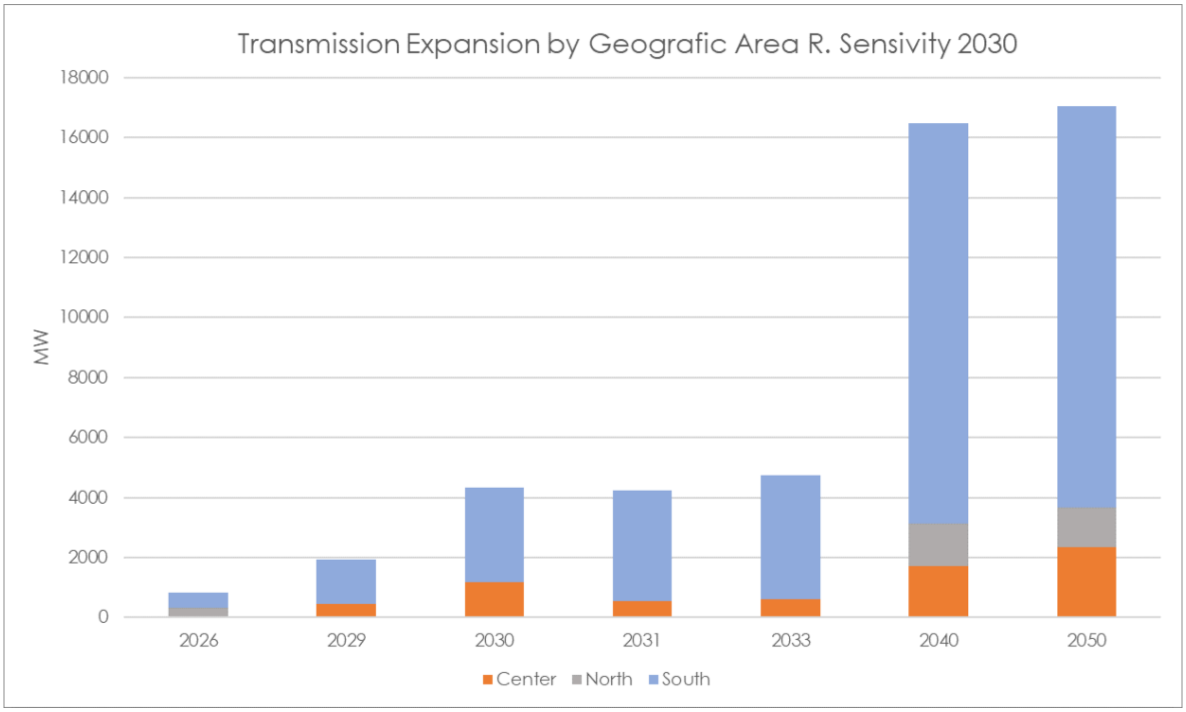

Transmission Expansion by Geografic Area Red NDC+
MW
25000
20000
15000
10000
5000
0
2026
2029
2030
2031
2033
2040
2050
■ Center ■ North ■ South

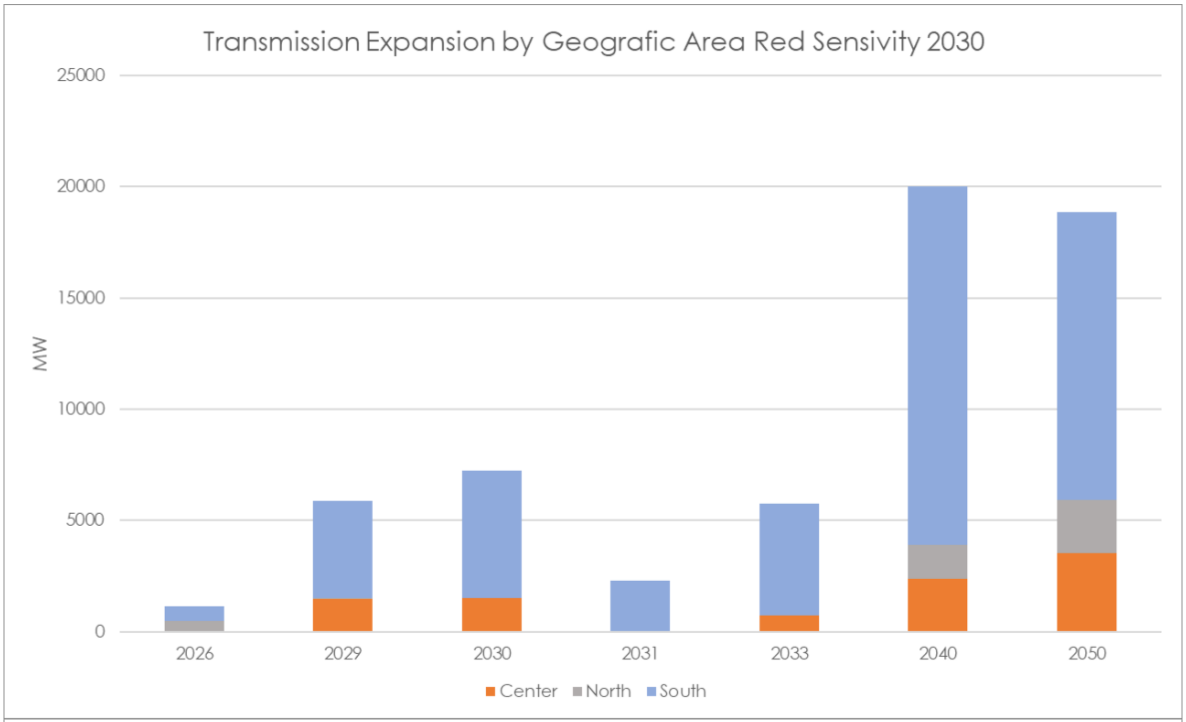

Transmission Expansion by Geografic Area Green NDC+


Transmission Expansion by Geografic Area R. Sensivity 2028


Transmission Expansion by Geografic Area Red Sensivity 2028
MW
25000
20000
15000
10000
5000
0
2026
2029
2030
2031
2033
2040
2050
Center
North
South


Transmission Expansion by Geografic Area Green Sensivity 2028
MW
25000
20000
15000
10000
5000
0
2026
2029
2030
2031
2033
2040
2050
Center
North
South


Transmission Expansion by Geografic Area R. Sensivity 2030
MW
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
2026
2029
2030
2031
2033
2040
2050
Center
North
South


Transmission Expansion by Geografic Area Red Sensivity 2030
MW
25000
20000
15000
10000
5000
0
2026
2029
2030
2031
2033
2040
2050
■ Center ■ North ■ South

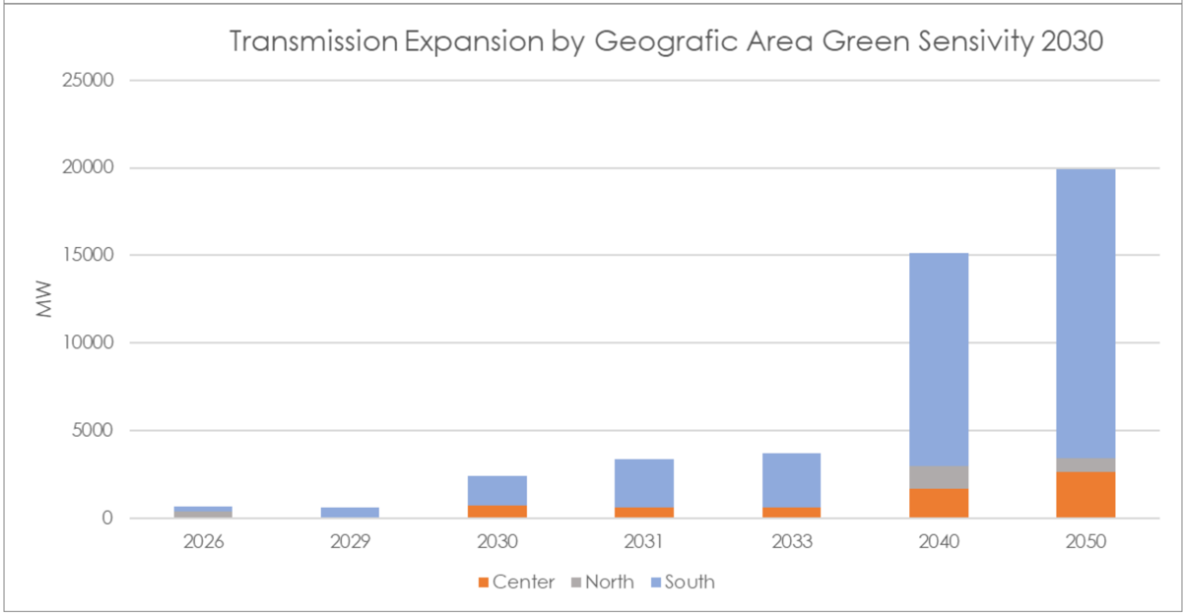
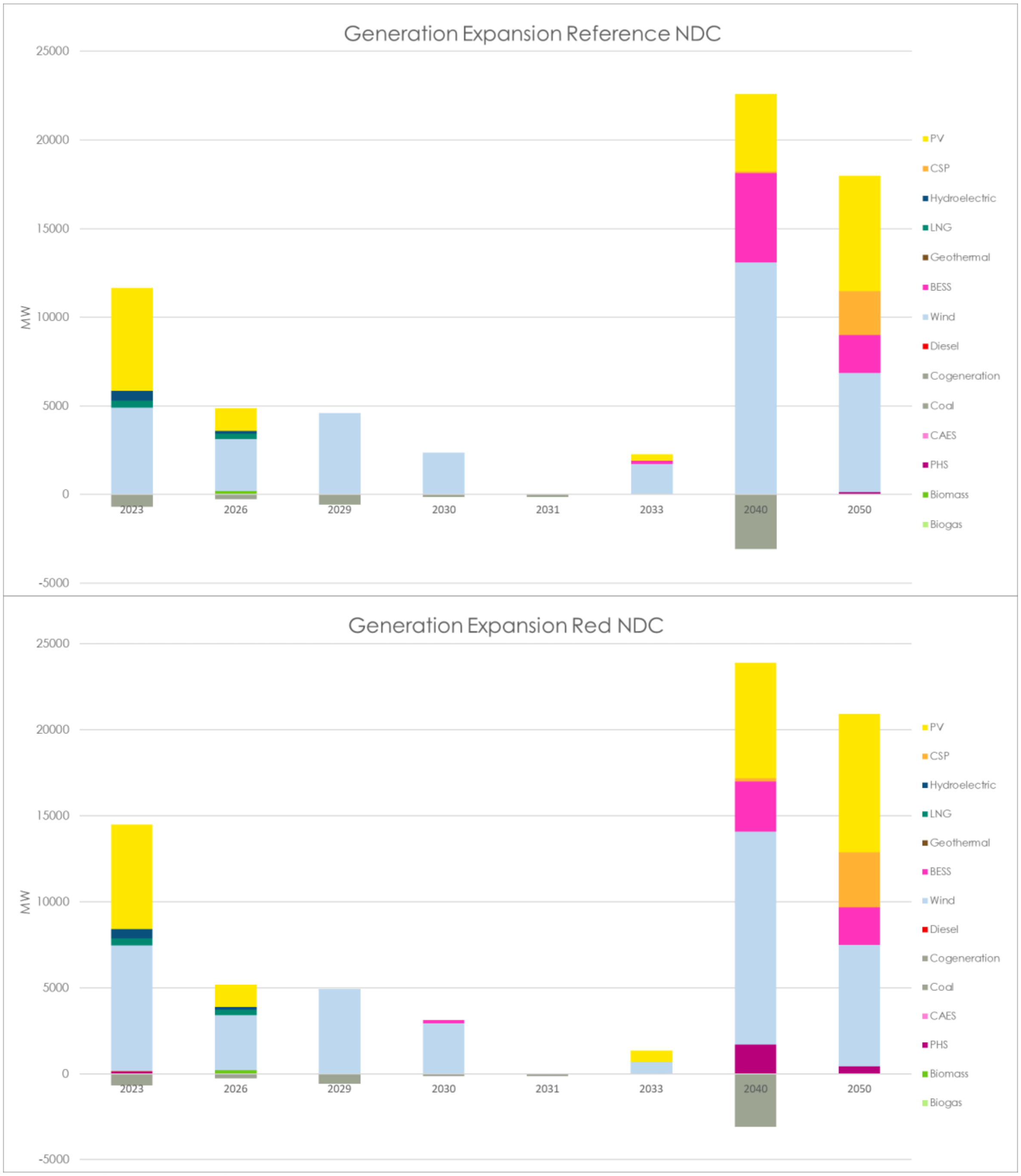
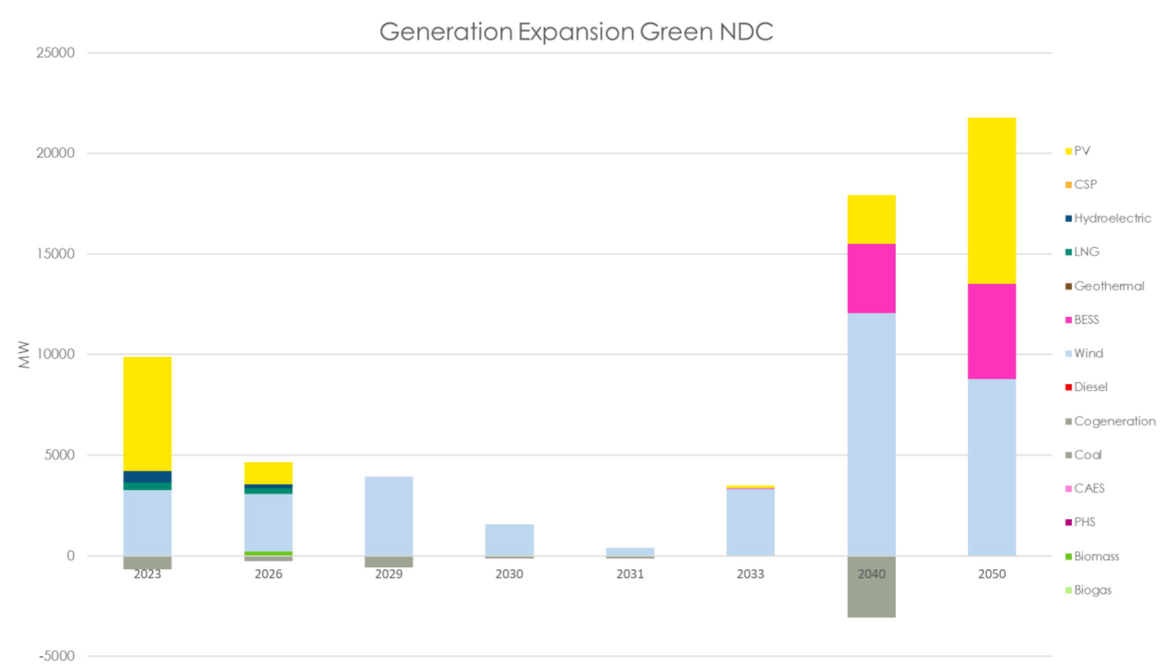

Transmission Expansion by Geografic Area Green Sensivity 2030
MW
25000
20000
15000
10000
5000
0
2026
2029
2030
2031
2033
2040
2050
■ Center ■ North ■ South

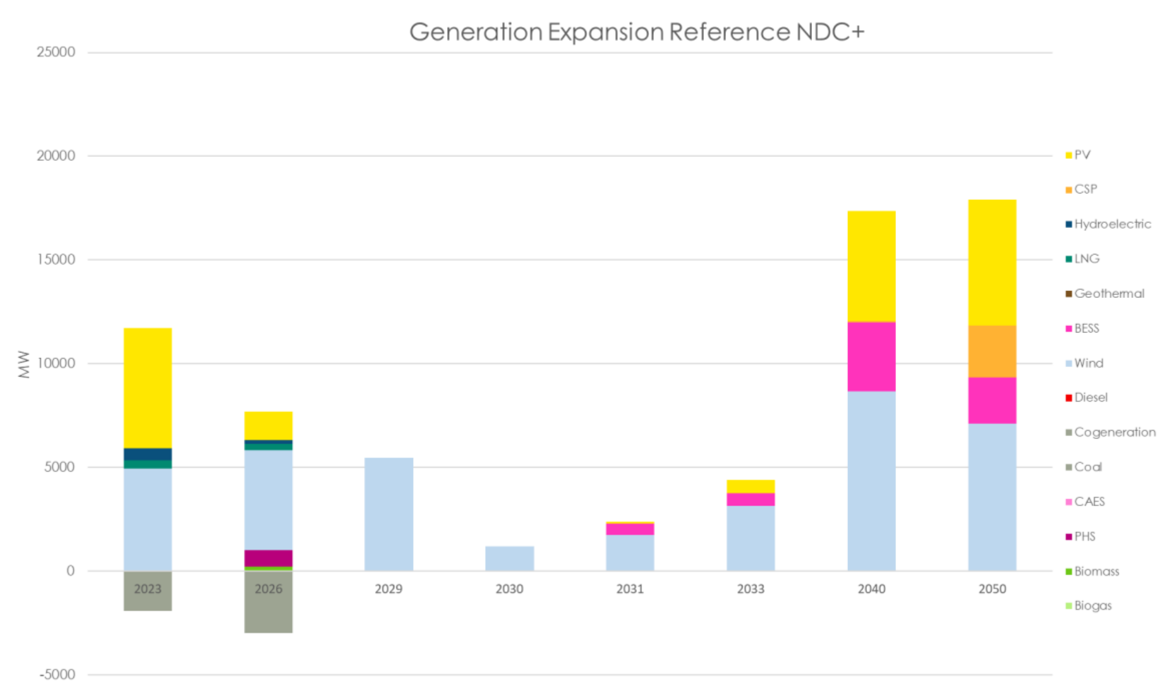
FIGURE 9

Generation expansion by futures and mitigation scenarios

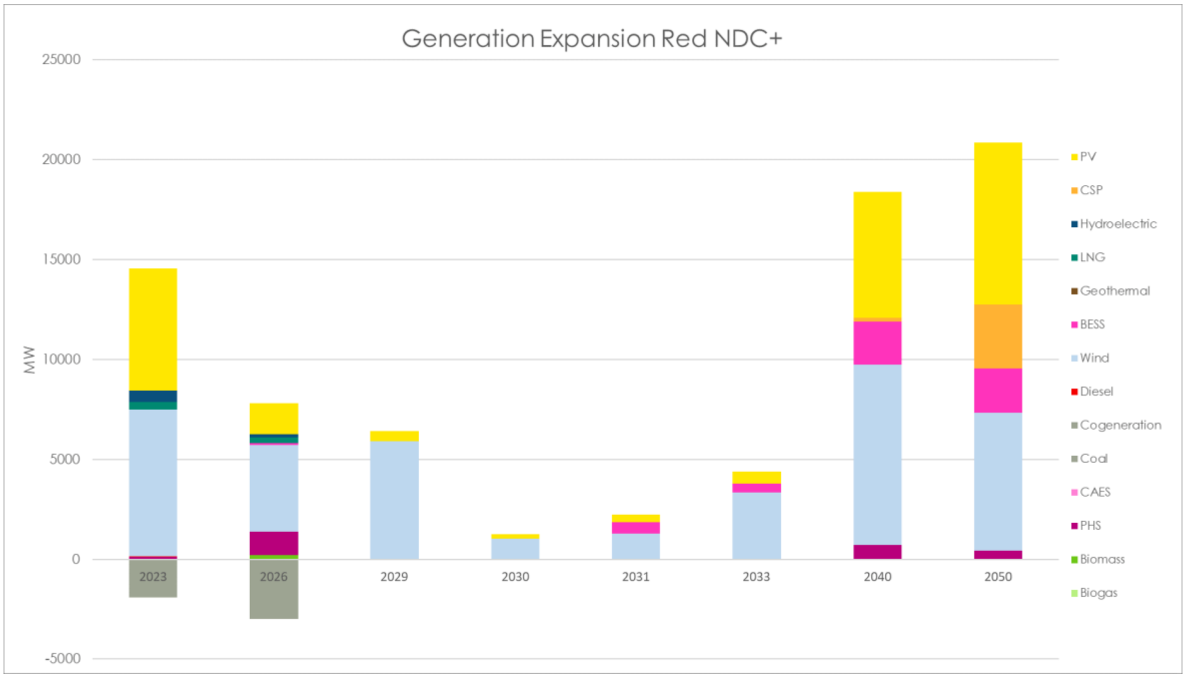


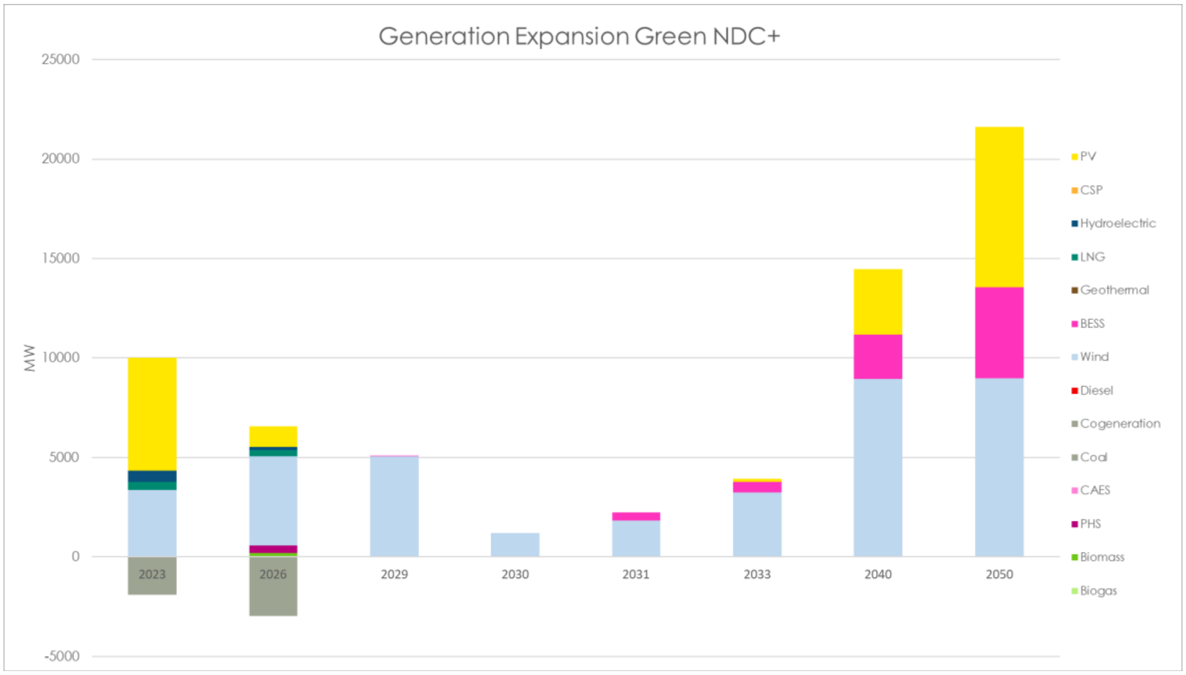


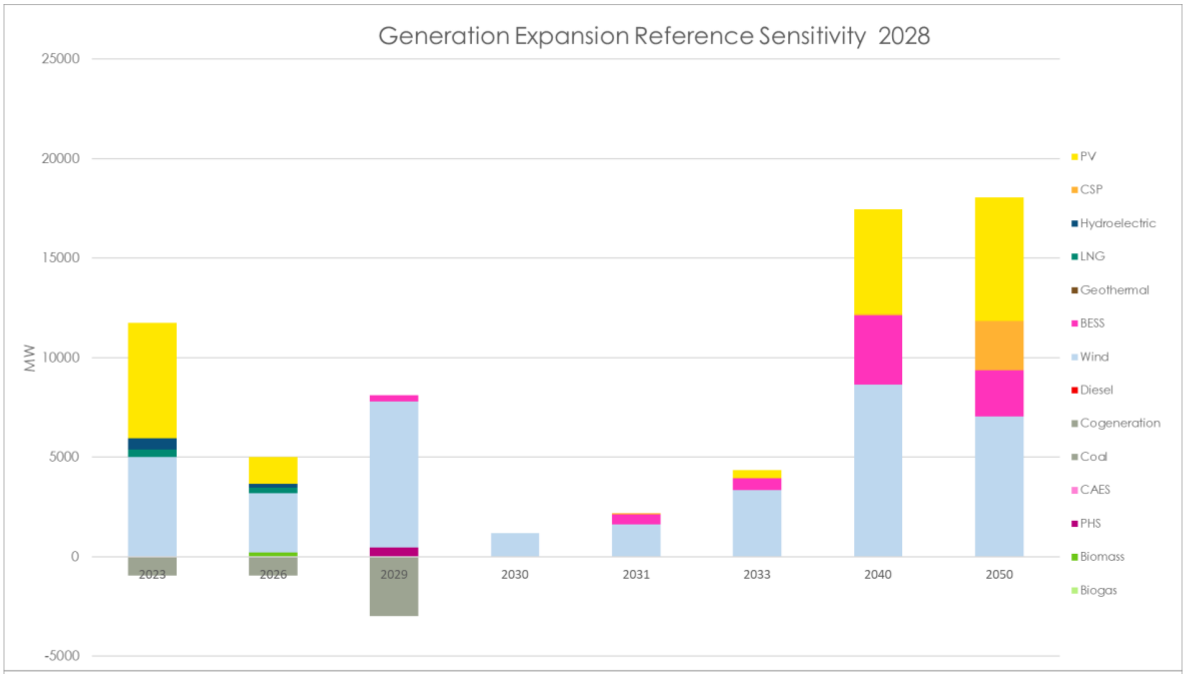
Generation Expansion Green NDC



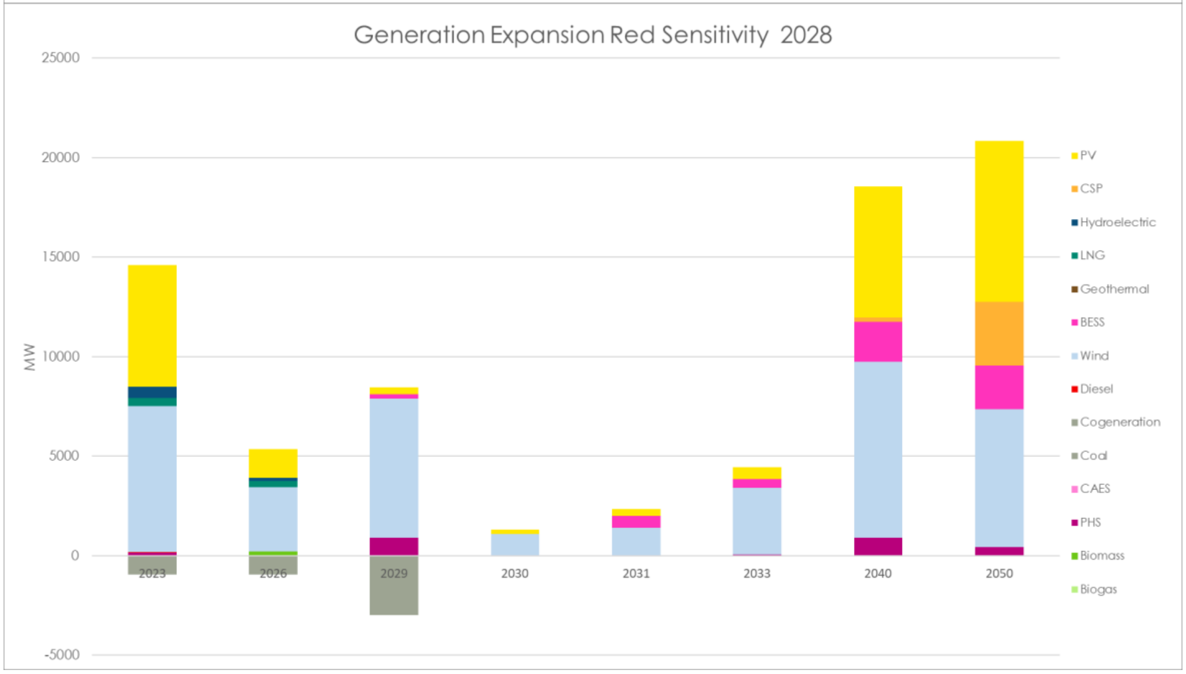
Generation Expansion Reference NDC+


Generation Expansion Red NDC+
MW
25000
20000
15000
10000
5000
0
-5000
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

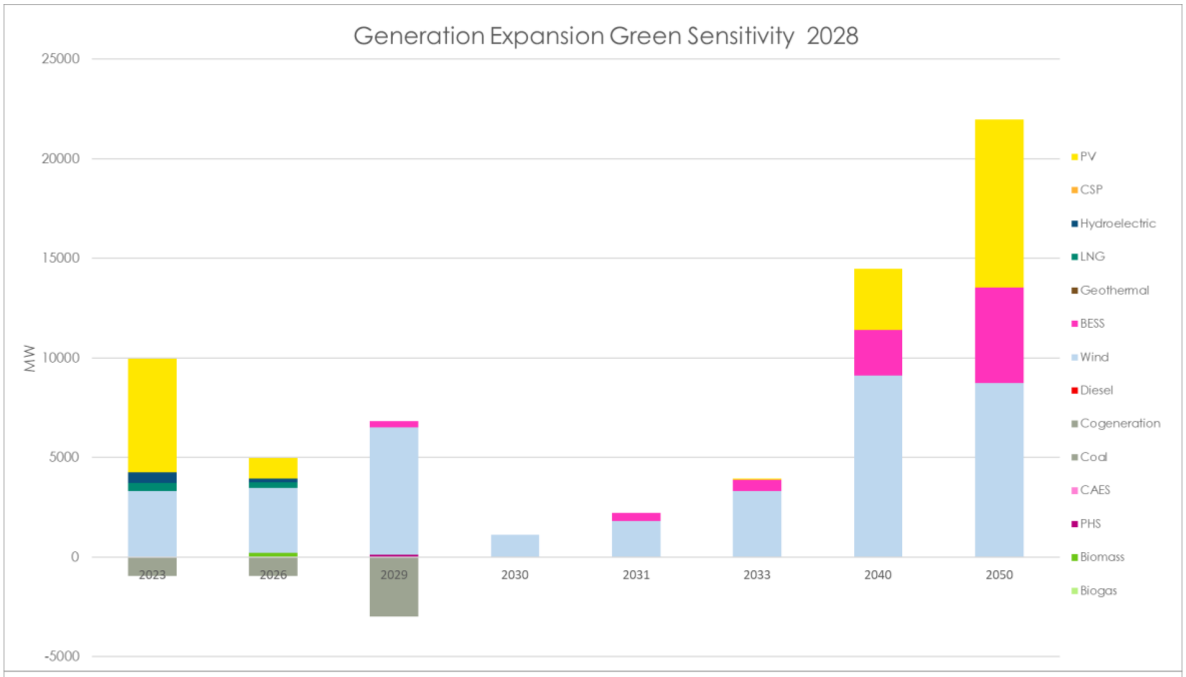

Generation Expansion Green NDC+
MW
25000
20000
15000
10000
5000
0
-5000
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas

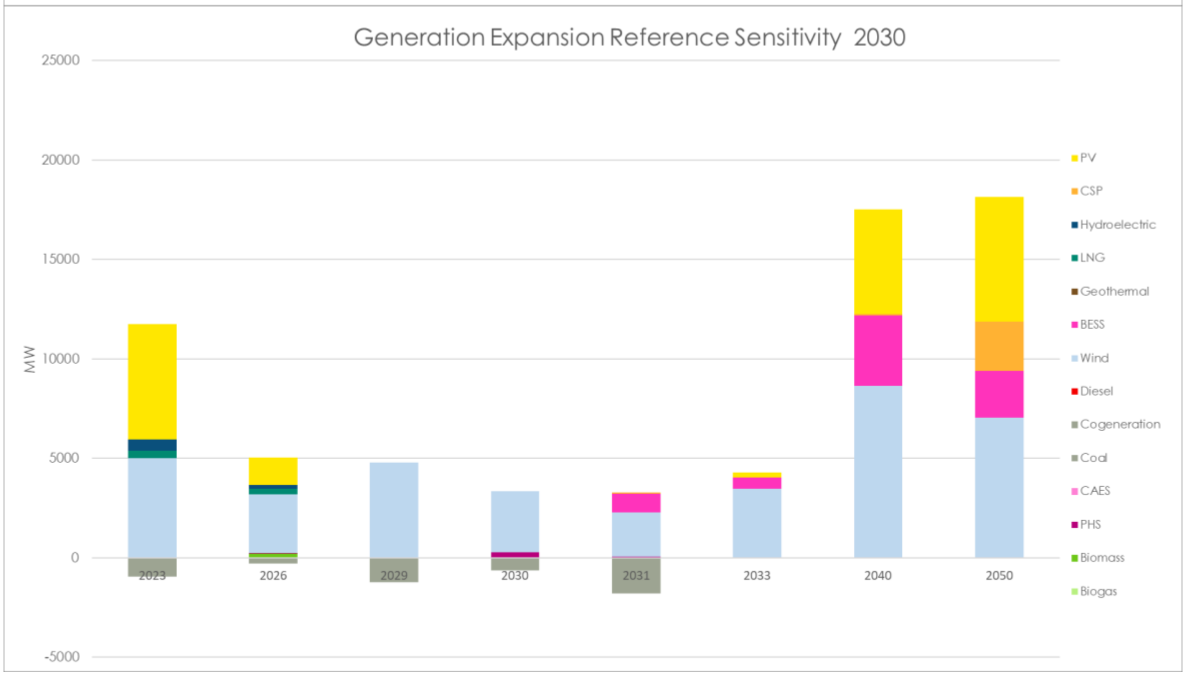


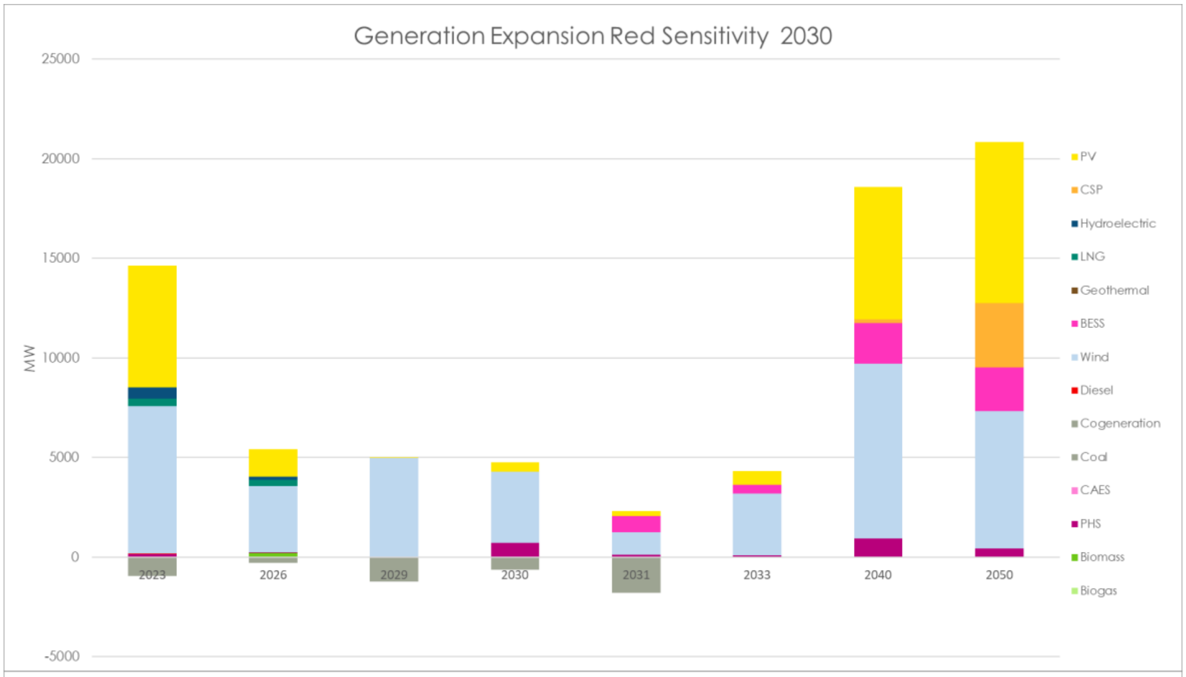
Generation Expansion Reference Sensitivity 2028

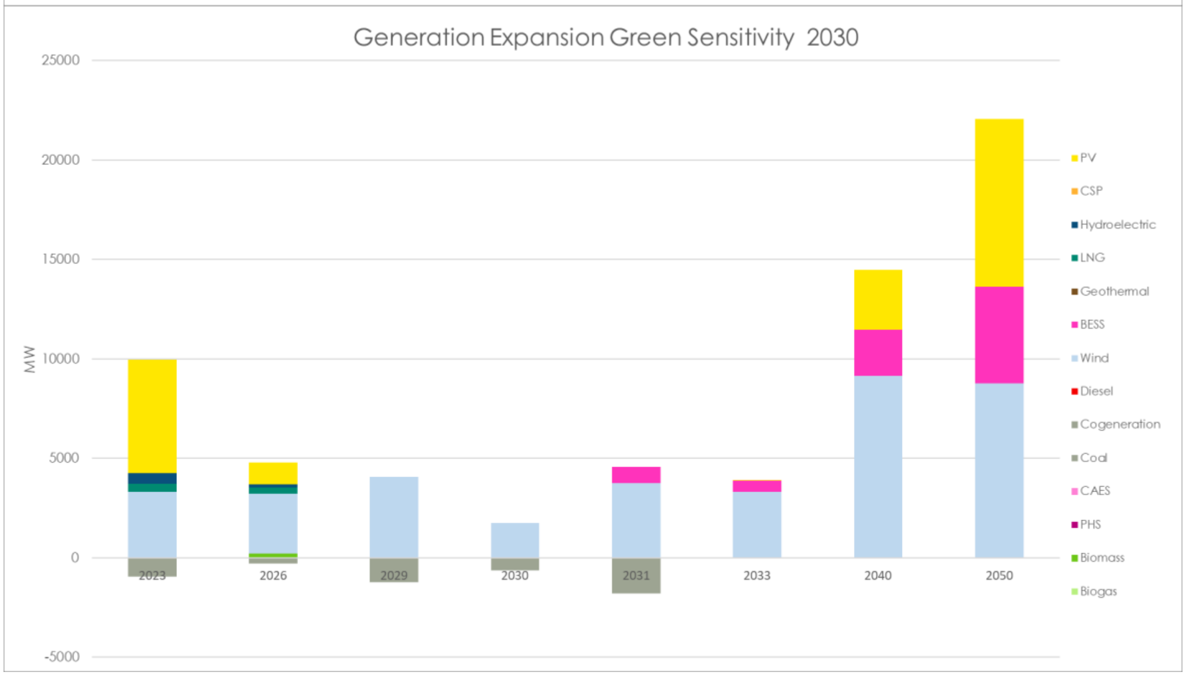


Generation Expansion Red Sensitivity 2028


Generation Expansion Green Sensitivity 2028
MW
25000
20000
15000
10000
5000
0
-5000
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas


Generation Expansion Reference Sensitivity 2030
MW
25000
20000
15000
10000
5000
0
-5000
2023
2026
2029
2030
2031
2033
2040
2050
PV
CSP
Hydroelectric
LNG
Geothermal
BESS
Wind
Diesel
Cogeneration
Coal
CAES
PHS
Biomass
Biogas





Approximation to the marginal abatement curve:

In order to calculate an approximation to the marginal abatement cost, additional sensitivities were carried out using Switch, starting from the NDC scenario (in its reference case) and progressively increasing the carbon tax to generate a scatter plot in the space of total costs versus total emissions. With this data, an approximation of marginal abatement cost could be calculated from the slope of two consecutive points. These additional sensitivities, were called NDC-t, where t represents the carbon tax in USD/tCO2 used in each case. The results of these sensitivities are shown in the figures and tables presented below. It is important to highlight that the costs presented here do not consider emission costs.

FIGURE 10

Scatter plot of electricity sector total cost vs total emissions to 2050 (with coal decommission cost)

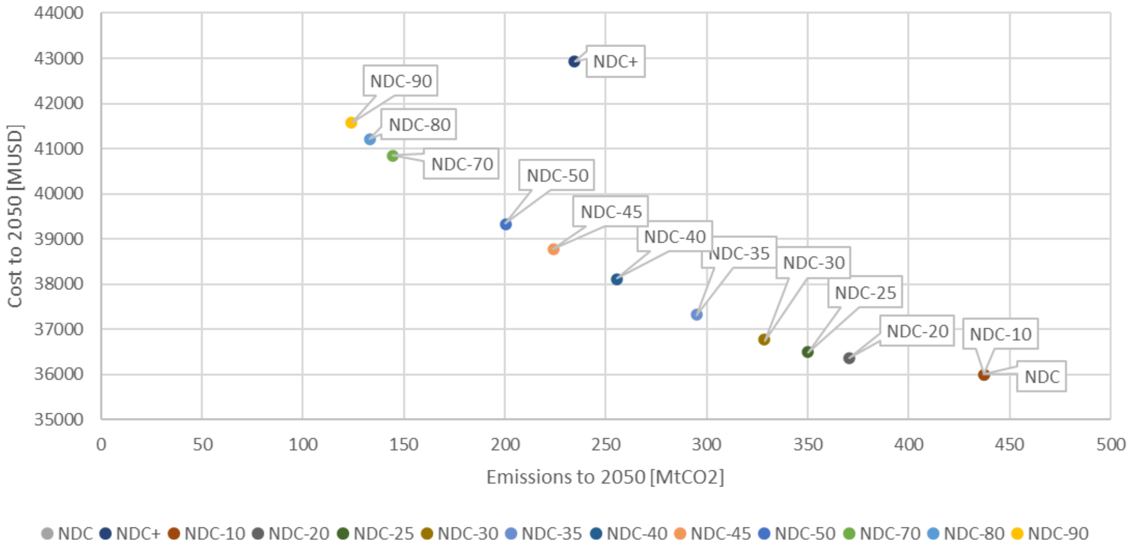


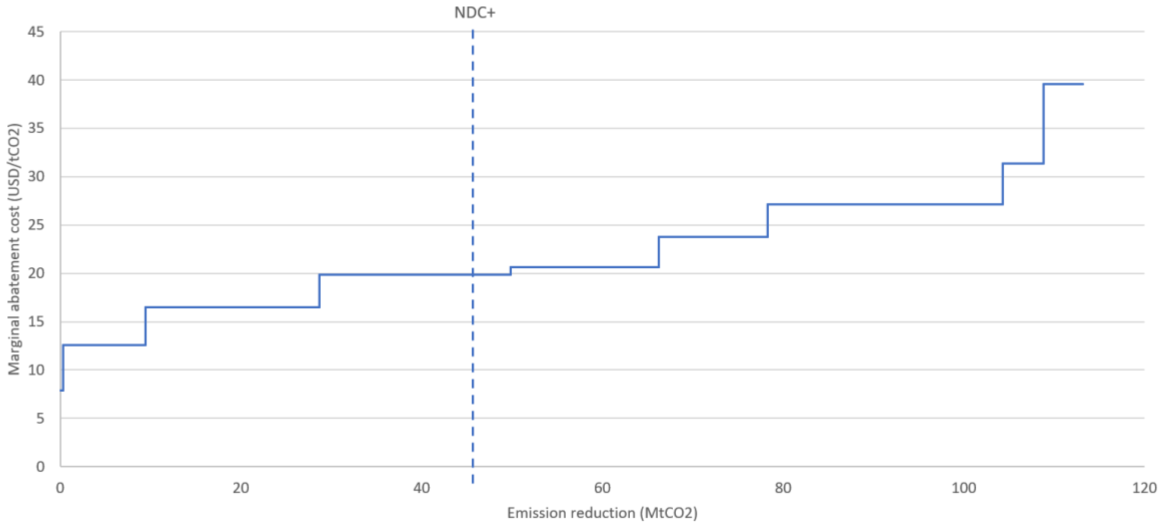
TABLE 12

CO2 Marginal Abatement Cost with Coal Decommission Cost

	Emissions to 2030 [MtCO2]	Cost to 2050 [MUSD]	Emissions to 2050 [MtCO2]	Marginal abatement cost to 2050 [USD/tCO2]
NDC	191	36004	437	$ -
NDC -10	191	36004	437	$ -
NDC -20	191	36354	370	$ 5,22
NDC-25	191	36513	350	$ 7,87
NDC -30	182	36784	329	$12,56
NDC-35	162	37335	295	$ 16,46
NDC -40	141	38119	256	$19,89
NDC-45	125	38,770	224	$ 20,62
NDC -50	113	39333	200	$23,81
NDC -70	87	40852	145	$27,16
NDC -80	82	41209	133	$31,35
NDC -90	78	41566	124	$39,59
NDC+	146	42935	235	-

FIGURE 11

MACC between the NDC and NDC-90 carbon tax scenarios for the 2020-2030 period for the reference future



Although the methodology to include the coal decommission cost makes it possible to improve the approximation of the average mitigation cost that the early closure of coal-fired plants would have, on the other hand it makes it difficult to calculate a marginal abatement cost, because the cost of early closure generates a significant cost overrun in the NDC+ case, which cannot be directly translated into the NDC-t sensitivities mentioned above, since these do not imply the early closure of coal power plants. Because of this, when considering this extra cost, the emissions and total costs of the NDC+ case differs from the behavior of the other NDC-t scenarios, which can be seen in the scatter plot with coal decommission cost. In particular, if we compare the cost of NDC-45 with the cost of NDC+, we can observe a difference of 4165 MUSD. If we divide that cost difference by the emissions mitigation to 2050 between NDC+ and NDC we get a cost of 20,53 USD/tCO2. This means that the cost associated with the inefficiencies of NDC+ compared to NDC-45 is around 20,53 USD/tCO2, or in other words, the mean abatement cost of NDC+ without inefficiencies is 13,64 USD/tCO2 (34,17 - 20,53). On the other hand, if we calculate this number with the average of the marginal abatement costs obtained with NDC-t cases between NDC-20 and NDC-45, we obtain a mean abatement cost of 13.77 USD/tCO2, which is in the order of the 13,64 USD/tCO2 obtained with the previous analysis.

In this context, two important lines of future work emerge to guide further analyses:

- Defining an exogenous mitigation policy (such as early closure in the NDC+ scenario) may not be the most efficient strategy to achieve emission targets and also makes it difficult to calculate a marginal mitigation cost. A better option is to gradually define emission goals in such a way that the system directly determines the optimal way to achieve the required emission goals based on an optimization approach, rather than externally selecting a pre-defined emission reduction strategy. Some modeling aspects can also improve in the model, to more precisely account for operational aspects regarding the massive inclusion of variable renewable energy and storage.

- The implementation mechanisms that allow the mitigation policies to materialize, must be endogenously represented in the Switch optimization model and related analysis. With this, all the relevant costs associated with each mitigation policy could be more precisely analyzed. In the particular case of this study, the early closure of coal power plants must consider some mechanism to resolve market issues such as the existing power purchase agreements of the companies owning coal power plants, for example.

Further, it is also important to remark that the obtained results presented above depend on the assumptions and data inputs employed. Different assumptions and/or data inputs could lead to different results. In particular, some of the scenarios show a decrease in power sector emissions in 2030, and a subsequent increase in emissions after such year (see Figure 6 above). This is only due to the specific constraints employed in the presented analysis, which did not enforce a subsequent emissions reducion year by year. However, future studies will analyze that type of scenarios, among other aspects.

1.2 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[10] (2020). This model is developed in Pyplan, where the activity level projections and the estimation of the emissions for each of the demand sectors are organized in different modules. 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[11] for fifteen Chilean regions, for each fuel and electricity consumed. The energy balances are published by the energy ministry. The information from activity

---

[10] Acronym for the spanish traduction of the Long Term Energetic Planification.
[11] The most updated energy balance corresponds to 2019.

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 emissions generated by each sector are estimated, disaggregated by the corresponding subsectors, the fifteen administrative regions, 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.

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:

1.3 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 organized in different modules in Pyplan: (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 13

Dissagregations of the road transport sector

Demand	Sub demand	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: Study 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[12] 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 14

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.	100% electrified sales in the private car market from 2035. Proportional exit of gasoline and diesel cars.	100% electrified sales in the private car market from 2035. Proportional exit of gasoline and diesel cars.
	Electromobility: Taxis	100% of the taxis in 2040. Exponential penetration with an estimation of	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

---

[12] 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**
		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 2024 with a 0.4% of trucks. By 2030, it is estimated that 19.9% of freight trucks could use hydrogen.	85% of the freight trucks in 2050. Linear growths starting in 2024 with a 0.4% of trucks. By 2030, it 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: Study Authors.

1.4 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 modelled 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 15

Energy-Industry & Mining subsector description

Sector: Energy-Industry & Mining	
Subsector	Subsector description
Copper	Exploitation, extraction and metallurgical processes associated with copper mining. Modelled following the projection of the Chilean Copper Commission (2020). It is modelled 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. Modelled 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. Modelled based on projected Asia Pacific GDP growth.
Saltpeter	Exploitation, extraction and metallurgical processes associated with saltpeter mining. Modelled based on projected Asia Pacific GDP growth.
Paper & pulp	Paper and pulp production; does not include printing. Modelled based on a national projection of the sector.
Fishing	Stationary and mobile fishing, modelled based on a national projection of the sector.

Sector: Energy-Industry & Mining	
Petrochemical Industry	Methanol and ethylene production, modelled based on a national projection of the sector.
Sugar	Beet sugar production. Modelled according to the projection of beet production.
Concrete	Concrete industry. Modelled according to the projected growth of the national GDP.

Source: Study 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 was adjusted.

The different modelled futures are generated by different demand projections that are related to macroeconomic parameters such as national, Asian[13], 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[14]. The actual actions considered in the models are presented in the following table:

---

[13] 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.

[14] Modelled hydrogen is assumed to be "green hydrogen" produced by solar energy, as was the case with modelled hydrogen in the transport energy demand.

TABLE 16

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 92.7%)	Additional 25%, when possible. Linear growth starting in 2021, with an estimated penetration that varies for each process and region, from 45.5% to 88.9%[15] in 2030.	Additional 25%, when possible. Linear growth starting in 2021, with an estimated penetration that varies for each process and region, from 45.5% to 88.9% in 2030.
	Electrification in motor processes	Same as 2019 (varies for each region, from 3.5% to 21.2%)	57% in open pit mining by 2050. Linear growth starting in 2021, with an estimated penetration that varies for each region, from 21.3% to 33.1% in 2030.	63% in open pit mining by 2050. Linear growth starting in 2021, with an estimated penetration that varies for each region, from 23.3% to 35.1% in 2030.
	Hydrogen in motor processes	Same as 2019 (0%)	37% in open pit mining by 2050. Linear growth starting in 2021, with an estimated penetration of 12.3% in 2030.	37% in open pit mining by 2050. Linear growth starting in 2021, with an estimated penetration of 12.3% in 2030.
	Electrification in thermal processes	Same as 2019 (0%)	8% in underground mining by 2050. Linear growth starting in 2021, with an estimated	8% in underground mining by 2050. Linear growth starting in 2021, with an estimated

---

[15] 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**
			penetration of 2.7% in 2030.	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.
	Electrification in motor processes	Same as 2019 (varies for each region, from 18.6% to 88.6%).	88% by 2050. Linear growth starting in 2021, with an estimated penetration that varies for each region, from 41.8% to 88.4% in 2030.	88% by 2050. Linear growth starting in 2021, with an estimated penetration that varies for each region, from 41.8% to 88.4% in 2030.
Various Mines	Hydrogen in motor processes	Same as 2019 (0%).	21% by 2050. Linear growth starting in 2021, with an estimated penetration of 7.0% in 2030.	21% by 2050. Linear growth starting in 2021, with an estimated penetration of 7.0% in 2030.
	Electrification in motor processes	Same as 2019 (varies for each region, from 0% to 94.4%).	74% by 2050. Linear growth starting in 2021, with an estimated penetration that varies for each region, from 24.7% to 87.6% in 2030.	79% by 2050. Linear growth starting in 2021, with an estimated penetration that varies for each region, from 26.3% to 89.2% in 2030.

Sector: Energy-Industry & Mining				
Subsector	**Action**	**Action level CP**	**Action level IM**	**Action level AM**
Steel Industry	Hydrogen in thermal processes	Same as 2019 (0%).	Same as 2019 (0%).	10% by 2050. Linear growth starting in 2021, with an estimated penetration of 3.3% in 2030.
	Biomass in thermal processes	Same as 2019 (0%).	Same as 2019 (0%).	10% by 2050. Linear growth starting in 2021, with an estimated penetration of 3.3% in 2030.

Source: Study Authors

1.5 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 17

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 Heating and Climatization Offices Equipment

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

Source: Study 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 ktCO2eq. 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[16] technologies, and (2) reduction of the energy demand, with better thermal insulation on buildings. The following table presents the mitigation actions considered:

---

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

TABLE 18

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 80% of the final demand is electricity by 2050, considering an exponential growth from 2022 (52.4%). In 2030 electricity represents 59.2% 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-
	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 Region 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: Study Authors.

1.6 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 Pyplan, based on a previous model developed in Benavides et al. (2021).

Since the original development of the model, a new official 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 SF6 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 modelling 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:

- 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.

- 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.
- 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.
- 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}):

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

- 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 19

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: Study Authors.

1.7 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 (N_2O) 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[17], 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 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 (N_2O), 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

---

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

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 modelled:

TABLE 20

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%

Sector: Agriculture			
Action	**Action level CP**	**Action level IM**	**Action level AM**
			of national cereal surface to 2030, starting in 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
Meat tax	No additional adoption	No additional adoption	A 10% tax on consumer prices, reducing the national meat production.

Source: Study Authors.

1.8 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 modelling of a category of the LULUCF sector and are organized as follows:

- 4.A Forest land:

  - **Forest Land Remaining Forest Land:** This module modelled 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 €, 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 € and Other Lands (F) remaining as such.

For the projection of the sector to 2030, we used the methodology and modelling 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 21

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
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

Sector: LULUCF			
Action	**Action level CP**	**Action level IM**	**Action level AM**
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
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: Study Authors.

1.9 Waste

The waste sector is modelled in Pyplan, based on 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.

---

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

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 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 ktCH4 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

---

[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 would emit non-biogenic CO_2 and other GHG.

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 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 modelled:

TABLE 22

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: Study Authors.

Appendix 2: Description of the mitigation actions

2.1 Electricity generation actions

Name	**Phase-Out acceleration to 2025**	
General Overview	Speeds up the decarbonization originally scheduled to 2040 by moving the phase-out deadline sooner to 2025.	
Modeling		
Main Assumptions	• The hydroelectric capacity factor will remain relatively low compared to prior decades. • Renewable sources are assumed to be non-stochastic. Although their capacity factor profile embeds part of their stochastic behavior. • Inertia requirements are not modeled. • Shutdown and startup ramps are not modeled. • Transmission efficiency is modeled at 96% for every line. • Distribution losses are considered negligible. • Chile's electrical grid can sustain a radical shift in energy generation and management. • Public policies can be enforced quickly enough.	
Cost Elements	• Investment costs • Fixed costs • Variable costs • Fuel costs • Carbon tax costs • Transmission costs	
References	Plan de Retiro y/o Reconversión de Unidades a Carbón. (Ministerio de Energía, 2020). Planificación Energética de Largo Plazo 2023-2027. (Ministerio de Energía, 2022). Generación Eléctrica en Chile. (Generadoras de Chile, 2022, http://generadoras.cl/generacion-electrica-en-chile)	
Emission Reduction		
	Year 2030 NDC	**Year 2030 NDC+**
Emission reduction (MM tCO_{2eq})	Red: - Ref: - Green: -	Red: 1.02 Ref: 3.97 Green: 7.21
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	Red: - Ref: - Green: -	Red: 35.64 Ref: 44.96 Green: 52.33
Cost Evaluation (period 2020-2050)		
	6% Discount rate	
Total Cost (MM USD)	Red: 7413 Ref: 6930 Green: 5978	
Abatement cost (USD/t CO_2eq)	Red: 38.32 Ref: 34.17 Green: 34.37	

2.2 Transport actions

Name	**Electromobility: Private cars: 100% electrified sales from 2035, NDC+ 100% from 2030**
Source	Chilean NDC
General Description	Incentives to accelerate the transition to private electric cars and to achieve the goals defined in the electromobility strategy.
Modelling	
Main Assumptions	Same objective as the one established on the electromobility strategy
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	Gobierno de Chile (2021) National Electromobility Strategy.

Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission Reduction (MM tCO_{2eq})	**0.0**	**0.46** 0.43 ~ 0.49
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0**	**0.46** 0.43 ~ 0.49

Cost Evaluation (period 2020 - 2050)	
	Discount rate 6%
Total Investment Cost (MM USD)	**19,557.08** 18,333.87 ~ 20,824.66
Total Cost (MM USD)	**17,412.39** 16,326.17 ~ 18,538.43
Abatement cost (USD/t CO_2eq)	**166.25**

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.	
Modelling		
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})	**0.53** 0.51 ~ 0.56	**0.53** 0.51 ~ 0.56
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**1.85** 1.76 ~ 1.94	**1.85** 1.76 ~ 1.94
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Investment Cost (MM USD)	**2,485.24** 2,338.87 ~ 2,637.89	
Total Cost (MM USD)	**-855.77** -962.73 ~ -749.83	
Abatement cost (USD/t CO_2eq)	**-23.00**	

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**	**0.43** 0.42 ~ 0.44
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0**	**1.02** 1.00 ~ 1.05
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Investment Cost (MM USD)	**944.91**	
Total Cost (MM USD)	**-2,048.91** -2,228.94 ~ -1,870.09	
Abatement cost (USD/t CO_2eq)	**-103.81**	

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.
Modelling	
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**	**0.86** 0.84 ~ 0.89
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0**	**2.84** 2.77 ~ 2.90

Cost Evaluation (period 2020 - 2050)	
	Discount rate 6%
Total Investment Cost (MM USD)	**191.33**
Total Cost (MM USD)	**-6,276.38** -6,657.16 ~ -5,898.63
Abatement cost (USD/t CO_2eq)	**-142.50**

<table>
<tr><td>Name</td><td colspan="2">Hydrogen on commercial flights: 10% of flights with hydrogen in 2050, linear increase from 2035.</td></tr>
<tr><td>Source</td><td colspan="2">Expert opinion of the authors and the reference cited bellow.</td></tr>
<tr><td>General Description</td><td colspan="2">Replace of aviation kerosene with hydrogen for 10% of the flights in 2050.</td></tr>
<tr><td colspan="3">Modelling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">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.</td></tr>
<tr><td>Costs Elements</td><td colspan="2">As this action is modelled from 2035, no details on the modelled costs are presented here.</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.</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>0.0</td><td>0.0</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>0.0</td><td>0.0</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 Investment Cost (MM USD)</td><td colspan="2">0.0</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">0.0</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">0.0</td></tr>
</table>

2.3 Industry & Mining Actions

<table>
<tr><td>Name</td><td colspan="3">Copper-Solar thermal systems: 16% by 2050, NDC+ 30% by 2050</td></tr>
<tr><td>Source</td><td colspan="3">Chilean NDC.</td></tr>
<tr><td>General Overview</td><td colspan="3">Incentives to accelerated transition from fossil fuel combustion in thermal processes to solar thermal systems.</td></tr>
<tr><td colspan="4">Modeling</td></tr>
<tr><td>Main Assumptions</td><td colspan="3">Same penetration rate as assumed on the design of the NDC on the IM Scenario, 14% more penetration for AM Scenario.</td></tr>
<tr><td>Cost Elements</td><td colspan="3">Considers the investment in solar thermal systems, and the reduction in fossil fuels consumption.</td></tr>
<tr><td>References</td><td colspan="3">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="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>0.07
0.06 ~ 0.08</td><td>0.13
0.10 ~ 0.15</td></tr>
<tr><td colspan="2">Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>0.57
0.50 ~ 0.65</td><td>1.06
0.92 ~ 1.20</td></tr>
<tr><td colspan="4">Cost Evaluation (period 2020-2050)</td></tr>
<tr><td colspan="2"></td><td colspan="2">Discount rate 6%</td></tr>
<tr><td colspan="2">Total Investment Cost (MM USD)</td><td colspan="2">292.86
247.10 ~ 336.15</td></tr>
<tr><td colspan="2">Total Cost (MM USD)</td><td colspan="2">-273.50
-314.02 ~ -230.90</td></tr>
<tr><td colspan="2">Abatement cost (USD/t CO_2eq)</td><td colspan="2">-55.96</td></tr>
</table>

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.	
Modelling		
Main Assumptions	Same penetration rate as assumed on the design of the NDC.	
Cost Elements	Considers the investment in electric motors, the reduction in fossil fuels consumption, and the increase in electricity use.	
References	Gobierno de Chile (2020) NDC.	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.08** 0.06 ~ 0.10	**0.09** 0.07 ~ 0.10
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.45** 0.32 ~ 0.59	**0.57** 0.45 ~ 0.70
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Investment Cost (MM USD)	**33.34** 28.20 ~ 38.19	
Total Cost (MM USD)	**97.24** 55.66 ~160.60	
Abatement cost (USD/t CO_2eq)	**28.84**	

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})	**0.81** 0.64 ~ 0.98	**0.97** 0.81 ~1.13
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**4.25** 3.50~ 5.09	**5.34** 4.51 ~ 6.23
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Investment Cost (MM USD)	**4.72** 3.95~ 5.43	
Total Cost (MM USD)	**-4,109.15** -4,464.35 ~ -3,581.60	
Abatement cost (USD/t CO_2eq)	**-78.16**	

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.
Modelling	
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})	**0.80** 0.67 ~ 0.93	**0.80** 0.67 ~ 0.93
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**4.48** 3.86 ~ 5.12	**4.48** 3.86 ~ 5.12

Cost Evaluation (period 2020-2050)	
	Discount rate 6%
Total Investment Cost (MM USD)	**399.32** 337.22 ~ 458.44
Total Cost (MM USD)	**-4,623.84** -5,332.36 ~ -3,857.99
Abatement cost (USD/t CO_2eq)	**-105.32**

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** 0.051 ~ 0.068	**0.059** 0.051 ~ 0.068
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Investment Cost (MM USD)	**5.92** 4.99 ~ 6.80	
Total Cost (MM USD)	**-71.93** -82.99 ~ -59.94	
Abatement cost (USD/t CO_2eq)	**-104.21**	

<table>
<tr><td>Name</td><td colspan="2">Various Industries-Solar thermal systems: 33% by 2050, NDC+ 46% by 2050</td></tr>
<tr><td>Source</td><td colspan="2">Chilean NDC</td></tr>
<tr><td>General Overview</td><td colspan="2">Incentives to accelerated transition from fossil fuel combustion and electricity use in motor processes to solar thermal systems.</td></tr>
<tr><td colspan="3">Modelling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">Same penetration rate as assumed on the design of the NDC on IM Scenario, 13% more penetration for AM Scenario.</td></tr>
<tr><td>Cost Elements</td><td colspan="2">Considers the investment in solar thermal systems, and the reduction in fossil fuels consumption.</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>0.33
0.32 ~ 0.34</td><td>0.46
0.45 ~ 0.48</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>1.68
1.64 ~ 1.72</td><td>2.18
2.13 ~ 2.23</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 Investment Cost (MM USD)</td><td colspan="2">2,337.01
2,192.57 ~ 2,481.45</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">-331.15
-351.75 ~ -310.55</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">-16.21</td></tr>
</table>

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 fossil fuels consumption.	
References	Gobierno de Chile (2020) NDC.	
Emission Reduction		
	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO_{2eq})	**0.030** 0.029 ~ 0.031	**0.030** 0.029 ~ 0.031
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.142** 0.139 ~ 0.145	**0.142** 0.139 ~ 0.145
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Investment Cost (MM USD)	**92.08** 86.39 ~ 97.77	
Total Cost (MM USD)	**-92.53** -98.26 ~ -86.80	
Abatement cost (USD/t CO_2eq)	**-49.83**	

<table>
<tr><td>Name</td><td colspan="2">Various Industries-Hydrogen in motor processes: 12% by 2050</td></tr>
<tr><td>Source</td><td colspan="2">Chilean NDC.</td></tr>
<tr><td>General Overview</td><td colspan="2">Incentives to accelerated transition from fossil fuel combustion in motor processes to green hydrogen use.</td></tr>
<tr><td colspan="3">Modelling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">Same penetration rate as assumed on the design of the NDC. The hydrogen is assumed to come from solar power.</td></tr>
<tr><td>Cost Elements</td><td colspan="2">Considers the investment in hydrogen motors and the reduction in diesel consumption. In the CP scenario the purchase of diesel engines is accounted for.</td></tr>
<tr><td>References</td><td colspan="2">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>0.48
0.47 ~ 0.50</td><td>0.48
0.47 ~ 0.50</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>2.43
2.37 ~ 2.49</td><td>2.43
2.37 ~ 2.49</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 Investment Cost (MM USD)</td><td colspan="2">246.39
234.44 ~ 258.34</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">-2,724.74
-2,903.31 ~ -2,546.17</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">-92.05</td></tr>
</table>

<table>
<tr><td>Name</td><td colspan="2">Various Industries-Electrification in motor processes: 88% by 2050</td></tr>
<tr><td>Source</td><td colspan="2">Chilean NDC.</td></tr>
<tr><td>General Overview</td><td colspan="2">Incentives to accelerated transition from fossil fuel in motor processes to electricity use.</td></tr>
<tr><td colspan="3">Modeling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">Same penetration rate as assumed on the design of the NDC.</td></tr>
<tr><td>Cost Elements</td><td colspan="2">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.</td></tr>
<tr><td>References</td><td colspan="2">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>0.47
0.43 ~ 0.51</td><td>0.49
0.48 ~ 0.51</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>2.10
1.95 ~ 2.25</td><td>2.33
2.23 ~ 2.43</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 Investment Cost (MM USD)</td><td colspan="2">1.57
1.47 ~ 1.67</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">-2,869.56
-2,910.08 ~ -2,779.82</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">-93.39</td></tr>
</table>

<table>
<tr><td>Name</td><td colspan="2">Various Mines-Hydrogen in motor processes: 21% by 2050</td></tr>
<tr><td>Source</td><td colspan="2">Chilean NDC.</td></tr>
<tr><td>General Overview</td><td colspan="2">Incentives to accelerated transition from fossil fuel combustion in motor processes to green hydrogen use.</td></tr>
<tr><td colspan="3">Modelling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">Same penetration rate as assumed on the design of the NDC.
The hydrogen is assumed to come from solar power.</td></tr>
<tr><td>Cost Elements</td><td colspan="2">Considers the investment in hydrogen motors and the reduction in diesel consumption.
In the CP scenario the purchase of diesel engines is accounted for.</td></tr>
<tr><td>References</td><td colspan="2">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>0.21
0.19 ~ 0.22</td><td>0.21
0.19 ~ 0.22</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>1.04
0.98 ~ 1.11</td><td>1.04
0.98 ~ 1.11</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 Investment Cost (MM USD)</td><td colspan="2">104.74
94.32 ~ 116.44</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">-1,287.90
-1,473.57 ~ -1,126.42</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">-101.75</td></tr>
</table>

<table>
<tr><td>Name</td><td colspan="2">Various Mines-Electrification in motor processes: 74% by 2050</td></tr>
<tr><td>Source</td><td colspan="2">Chilean NDC and expert opinion of the authors for the AM Scenario.</td></tr>
<tr><td>General Overview</td><td colspan="2">Incentives to accelerated transition from fossil fuel in motor processes to electricity use.</td></tr>
<tr><td colspan="3">Modeling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">Same penetration rate as assumed on the design of the NDC on IM Scenario, 5% more penetration for AM Scenario.</td></tr>
<tr><td>Cost Elements</td><td colspan="2">Consider 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.</td></tr>
<tr><td>References</td><td colspan="2">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>0.29
0.26 ~ 0.33</td><td>0.36
0.33 ~ 0.39</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>1.33
1.19 ~ 1.48</td><td>1.69
1.56 ~ 1.84</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 Investment Cost (MM USD)</td><td colspan="2">0.38
0.34 ~ 0.44</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">-2,071.18
-2,254.46 ~ -1,878.20</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">-93.16</td></tr>
</table>

<table>
<tr><td>Name</td><td colspan="2">Steel Industry-Hydrogen in thermal processes: 10% by 2050</td></tr>
<tr><td>Source</td><td colspan="2">Benavides et al. (2021)</td></tr>
<tr><td>General Overview</td><td colspan="2">Incentives to accelerated transition from fossil fuel combustion in thermal processes to hydrogen use.</td></tr>
<tr><td colspan="3">Modelling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">10% more penetration rate than BAU (and of the NDC without associated measures). The hydrogen is assumed to come from solar power.</td></tr>
<tr><td>Cost Elements</td><td colspan="2">Considers the investment in hydrogen thermal systems and the reduction in fossil fuels consumption.</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.</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>0.0</td><td>0.0062
0.0061 ~ 0.0063</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>0.0</td><td>0.034
0.033 ~ 0.035</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 Investment Cost (MM USD)</td><td colspan="2">4.20
4.15 ~ 4.25</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">-0.61
-0.62 ~ -0.60</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">-2.07</td></tr>
</table>

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 fossil fuels consumption.	
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**	**0.0058** 0.0057 ~ 0.0058
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.0**	**0.032** 0.031 ~ 0.033
Cost Evaluation (period 2020-2050)		
	Discount rate 6%	
Total Investment Cost (MM USD)	**1.76** 1.74 ~ 1.78	
Total Cost (MM USD)	**-3.05** -3.09 ~ -3.02	
Abatement cost (USD/t CO_2eq)	**-11.03**	

2.4 Buildings Actions

Name	**Commercial: Electrification of end uses**	
Source	Chilean NDC.	
General Overview	Incentives to an accelerated electrification of the commerce sector	
Modelling		
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})	**0.00**	**0.31** 0.30 ~ 0.32
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})	**0.00**	**1.18** 1.11 ~ 1.25
Cost Evaluation (period 2020 - 2050)		
	Discount rate 6%	
Total Investment Cost (MM USD)	**78.96** 72.77 ~ 85.15	
Total Cost (MM USD)	**160.56** -84.23 ~ 543.59	
Abatement cost (USD/t CO_2eq)	**6.32**	

<table>
<tr><td>Name</td><td colspan="3">Public: Solar water heaters on public hospitals</td></tr>
<tr><td>Source</td><td colspan="3">Chilean NDC.</td></tr>
<tr><td>General Overview</td><td colspan="3">Installation of solar colleting energy on hospital roofs for the use on hot sanitary water.</td></tr>
<tr><td colspan="4">Modeling</td></tr>
<tr><td>Main Assumptions</td><td colspan="3">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%</td></tr>
<tr><td>Costs Elements</td><td colspan="3">Considers the investment in solar thermal systems, and the reduction in fossil fuels consumption.</td></tr>
<tr><td>References</td><td colspan="3">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="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>0.00088
0.00084 ~ 0.00092</td><td>0.0044
0.0042 ~ 0.0046</td></tr>
<tr><td colspan="2">Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>0.0043
0.0041 ~ 0.0044</td><td>0.021
0.021 ~ 0.022</td></tr>
<tr><td colspan="4">Cost Evaluation (period 2020 - 2050)</td></tr>
<tr><td colspan="2"></td><td colspan="2">Discount rate 6%</td></tr>
<tr><td colspan="2">Total Investment Cost (MM USD)</td><td colspan="2">12.25
11.23 ~ 13.28</td></tr>
<tr><td colspan="2">Total Cost (MM USD)</td><td colspan="2">-16.09
-17.36 ~ -14.83</td></tr>
<tr><td colspan="2">Abatement cost (USD/t CO_2eq)</td><td colspan="2">-54.46</td></tr>
</table>

<table>
<tr><td>Name</td><td colspan="2">Public: Electric heating on public hospitals</td></tr>
<tr><td>Source</td><td colspan="2">Chilean NDC.</td></tr>
<tr><td>General Overview</td><td colspan="2">Incentives to an accelerated electrification of the heating in public hospitals.</td></tr>
<tr><td colspan="3">Modelling</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 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%.</td></tr>
<tr><td>Costs Elements</td><td colspan="2">Considers the investment in electric heating, the reduction in fossil fuels consumption, and the increase in electricity use.</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>0.0037
0.0025 ~ 0.0049</td><td>0.010
0.0097 ~ 0.011</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO$_{2eq}$)</td><td>0.0093
0.005 ~ 0.014</td><td>0.037
0.034 ~ 0.040</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 Investment Cost (MM USD)</td><td colspan="2">1.91
1.75 ~ 2.08</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">49.64
34.44 ~ 71.19</td></tr>
<tr><td>Abatement cost (USD/t CO$_2$eq)</td><td colspan="2">59.53</td></tr>
</table>

<table>
<tr><td>Name</td><td colspan="2">Public: Solar PV on public buildings</td></tr>
<tr><td>Source</td><td colspan="2">Expert opinion of the authors.</td></tr>
<tr><td>General Overview</td><td colspan="2">Incentives to the installation of PV on public buildings on the center and north of Chile.</td></tr>
<tr><td colspan="3">Modeling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">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.</td></tr>
<tr><td>Costs Elements</td><td colspan="2">Considers the investment in solar PV panels, and the reduction in electricity consumption.</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>0.0</td><td>0.0102
0.010 ~ 0.0103</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>0.0</td><td>0.098
0.086 ~ 0.011</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 Investment Cost (MM USD)</td><td colspan="2">303.82
286.12 ~ 321.43</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">-125.15
-176.84 ~ -85.34</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">-317.88</td></tr>
</table>

Name	**Residential: Electric heating**		
Source	Chilean NDC.		
General Overview	Program to replace combustion heaters for electric heaters.		
Modelling			
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 heating, 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})		**0.08** -0.02 ~ 0.18	**0.18** 0.16 ~ 0.20
Reduction of cumulative emissions from 2020 (MM tCO_{2eq})		**-0.83**[20] -1.18 ~ -0.40	**0.17** -0.05 ~ 0.43
Cost Evaluation (period 2020 - 2050)			
		Discount rate 6%	
Total Investment Cost (MM USD)		**67.28** 63.32 ~ 71.01	
Total Cost (MM USD)		**2,297.55** 1,832.36 ~ 2,942.86	
Abatement cost (USD/t CO_2eq)		**167.06**	

Name	**Residential: Electrification of residential cooking**
Source	Chilean NDC.
General Overview	Program to replace combustion stoves for electric stoves.
Modelling	

---

[20] In the short term it is negative because the first years after 2020 electricity has a higher emission factor, which makes it worse to switch to electric heating. In the long term the cumulative reduction emissions is positive.

<table>
<tr><td>Main Assumptions</td><td colspan="3">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.</td></tr>
<tr><td>Costs Elements</td><td colspan="3">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.</td></tr>
<tr><td>References</td><td colspan="3">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="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>0.020
0.014 ~ 0.025</td><td>0.010
0.099 ~ 0.101</td></tr>
<tr><td colspan="2">Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>0.034
0.007 ~ 0.062</td><td>0.36
0.32 ~ 0.42</td></tr>
<tr><td colspan="4">Cost Evaluation (period 2020 - 2050)</td></tr>
<tr><td colspan="2"></td><td colspan="2">Discount rate 6%</td></tr>
<tr><td colspan="2">Total Investment Cost (MM USD)</td><td colspan="2">15.20
15.11 ~ 15.27</td></tr>
<tr><td colspan="2">Total Cost (MM USD)</td><td colspan="2">560.36
475.76 ~670.53</td></tr>
<tr><td colspan="2">Abatement cost (USD/t CO_2eq)</td><td colspan="2">110.66</td></tr>
</table>

<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">Modelling</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 fossil fuels 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>1.10
1.08 ~ 1.12</td><td>1.10
1.08 ~ 1.12</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>2.66
2.55 ~ 2.77</td><td>2.66
2.55 ~ 2.77</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">203.76
200.64 ~ 209.08</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.	
Modelling		
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)	**-170.39** -179.41 ~ -167.15	
Abatement cost (USD/t CO_2eq)	**-172.90**	

2.5 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.	
Modelling		
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 Investment Cost (MM USD)	**5.57** 5.51 ~ 5.63	
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 Investment Cost (MM USD)	**315.96**	
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.	
Modelling		
Main Assumptions	The capacity of treatment needed for each of the wastewater is estimated with the estimation of the demand in 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 Investment Cost (MM USD)	**108.41**	
Total Cost (MM USD)	**493.8**	
Abatement cost (USD/t CO_2eq)	**344.61**	

2.6 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).
Modelling	
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 Investment Cost (MM USD)	**1.097**
Total Cost (MM USD)	**5.57** 5.58 ~ 5.61
Abatement cost (USD/t CO$_2$eq)	**0.18**

2.7 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$_2$eq)	**0.0015** 0.013 ~ 0.017	**0.051** 0.045 ~ 0.059
Reduction of cumulative emissions from 2020 (MM tCO$_2$eq)	**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$_2$eq)	**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.	
Modelling		
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 tCO2eq)	**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 CO2eq)	**-123** -122 ~ 123.8	

<table>
<tr><td>Name</td><td colspan="2">Biodigesters Pigs</td></tr>
<tr><td>General Overview</td><td colspan="2">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><td colspan="3">Modeling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">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="2">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="2">Caroca, F. G. (2015). Planta fe Biogás para Autoabastecimiento Energético: Una Estrategia para Diferentes Contextos. Universidad de Chile.</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>0.29
0.28 ~ 0.29</td><td>0.29
0.28 ~ 0.29</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_2eq)</td><td>1.286</td><td>1.286</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 accumulated (MM USD)</td><td colspan="2">49.09
15.2 ~ 95.7</td></tr>
<tr><td>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.
Modelling	
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 considered.
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 an 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.

Modelling

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

<table>
<tr><th>Name</th><th colspan="2">Meat Tax</th></tr>
<tr><td>General Overview</td><td colspan="2">Application of a 10% tax to the consumer based on the producer price, affecting national production.</td></tr>
<tr><td colspan="3">Modelling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">Chile is the fifth country with the highest per capita consumption of beef in the world[21] 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.</td></tr>
<tr><td>Cost Elements</td><td colspan="2">Costs were not considered given its high complexity in distribution.</td></tr>
<tr><td>References</td><td colspan="2">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 alimentario. Centro de Microdatos - Facultad de Economía y Negocios, 1–102.</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</td><td>0.25
0.22 ~ 0.29</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_2eq)</td><td>0</td><td>2.55
2.27 ~ 2.83</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">N/A</td></tr>
<tr><td>Abatement Cost (USD/t CO_2eq)</td><td colspan="2">N/A</td></tr>
</table>

---

[21] 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).
Modelling	
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	

2.8 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).

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$_2$eq)	**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)

Modelling

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$_2$eq)	**-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

<table>
<tr><td>Name</td><td colspan="2">Degradation reduction caused by forest fires</td></tr>
<tr><td>Source</td><td colspan="2">Chilean NDC.</td></tr>
<tr><td>General Overview</td><td colspan="2">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)"</td></tr>
<tr><td colspan="3">Modelling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">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.</td></tr>
<tr><td>Cost Elements</td><td colspan="2">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.</td></tr>
<tr><td>References</td><td colspan="2">CONAF. (2020). DT N°239 Tabla de Valores 2020 Ley N°20.283 sobre recuperación del Bosque Nativ y Fomento Forestal. https://www.conaf.cl/cms/editorweb/chifo/DT239.pdf
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/
CONAF. (2021b). Estadísticas—Resumen Nacional Ocurrencia (Número) y Daño (Superficie Afectada por Incendios Forestales 1964—2020. https://www.conaf.cl/incendios-forestales/incendios-forestales-en-chile/estadisticas-historicas/- Valor de la tierra agrícola y sus factores determinantes (ODEPA & PUC, 2009)
Zelada, A., & Maquire, P. (2005). Expediente Comunal. Estudio Modificación Plan Regulador Comuna de Coronel. https://www.ecoronel.cl/wp-content/uploads/2014/03/Capacidad-uso-de-suelo-coronel.pdf</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>0.95
0.95 ~ 2.868</td><td>0.95
0.95 ~ 2.868</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO$_{2eq}$)</td><td>4.75
4.75 ~ 14.34</td><td>4.75
4.75 ~ 14.34</td></tr>
<tr><td colspan="3">Cost Evaluation (period 2020-2050)</td></tr>
<tr><td></td><td colspan="2">6% Discount rate</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">3.46
3.46 ~ 3.46</td></tr>
<tr><td>Abatement cost (USD/t CO$_2$eq)</td><td colspan="2">23.03
13.7 ~ 23.03</td></tr>
</table>

Name	**Increase in protected areas**
Source	Benavides et al. 2021
General Overview	This measure considers the creation of new National Parks and Reserves, which, on one hand, increase the area of forest under management, and on the other, contribute to the conservation of native forests and terrestrial ecosystems. The measure begins in 2023, the year in which 100,000 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.
Modelling	
Main Assumptions	100% of the measure is implemented in 2023. The emissions corresponding to the extraction of biomass for the construction of trails or other human interventions are not considered. For costs, income begins to be received one year after the creation of the parks and reserves.
Cost Elements	The investment costs of the measure to increase protected areas were calculated based on the average of the values per hectare of private investments, and the operating costs and income are derived based on economic data from the current protected areas.
References	MMA, 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

Emission Reduction

	Year 2030 IM	**Year 2030 AM**
Emission reduction (MM tCO$_{2eq}$)	**0** 0 ~ 0	**1.1** 0.89 ~ 1.33
Reduction of cumulative emissions from 2020 (MM tCO$_{2eq}$)	**0** 0 ~ 0	**8.81** 7.14 ~ 10.66

Cost Evaluation (period 2020-2050)

	6% Discount rate
Total Cost (MM USD)	**41.28** 37.15 ~ 45.41
Abatement cost (USD/t CO$_2$eq)	**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.	
Modelling		
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).	
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	

<table>
<tr><th>Name</th><th colspan="2">Increase in hectares of native forest management - increase in hectares</th></tr>
<tr><td>Source</td><td colspan="2">Raise in the commitment of Chilean NDC.</td></tr>
<tr><td>General Overview</td><td colspan="2">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)</td></tr>
<tr><td colspan="3">Modeling</td></tr>
<tr><td>Main Assumptions</td><td colspan="2">The goal is met in 2026, starting the increase in hectares under forest management in 2023 with 5,000 hectares each year.</td></tr>
<tr><td>Cost Elements</td><td colspan="2">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</td></tr>
<tr><td>References</td><td colspan="2">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].</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
0 ~ 0</td><td>0.196
0.16 ~ 0.24</td></tr>
<tr><td>Reduction of cumulative emissions from 2020 (MM tCO_{2eq})</td><td>0
0 ~ 0</td><td>1.28
1.03 ~ 1.55</td></tr>
<tr><td colspan="3">Cost Evaluation (period 2020-2050)</td></tr>
<tr><td></td><td colspan="2">6% Discount rate</td></tr>
<tr><td>Total Cost (MM USD)</td><td colspan="2">187.95
166.5 ~ 203.5</td></tr>
<tr><td>Abatement cost (USD/t CO_2eq)</td><td colspan="2">30.87
28.06 ~ 34.3</td></tr>
</table>

Appendix 3: Detailed results overfutures

3.1 Emissions by sector overfutures

FIGURE 12

Emissions for the CP - Green Future Scenario

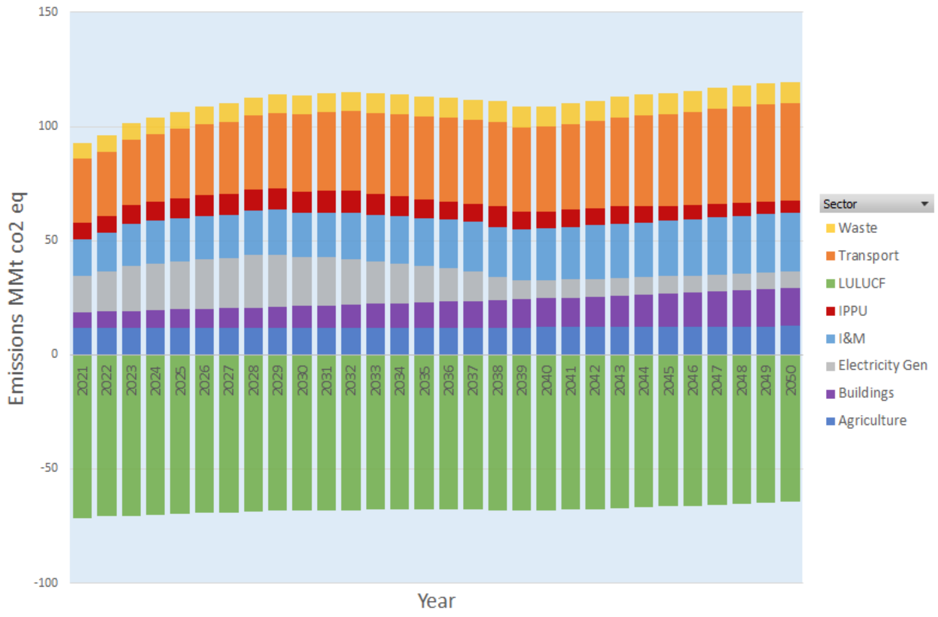


FIGURE 13

Emissions for the CP-Red Future Scenario

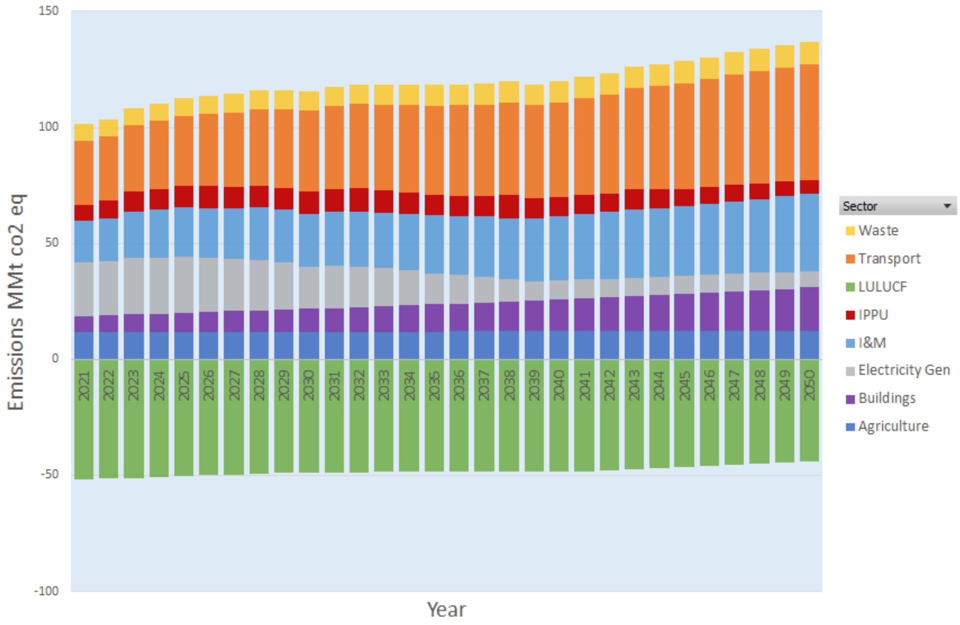


FIGURE 14

Emissions for the IM-Green Scenario

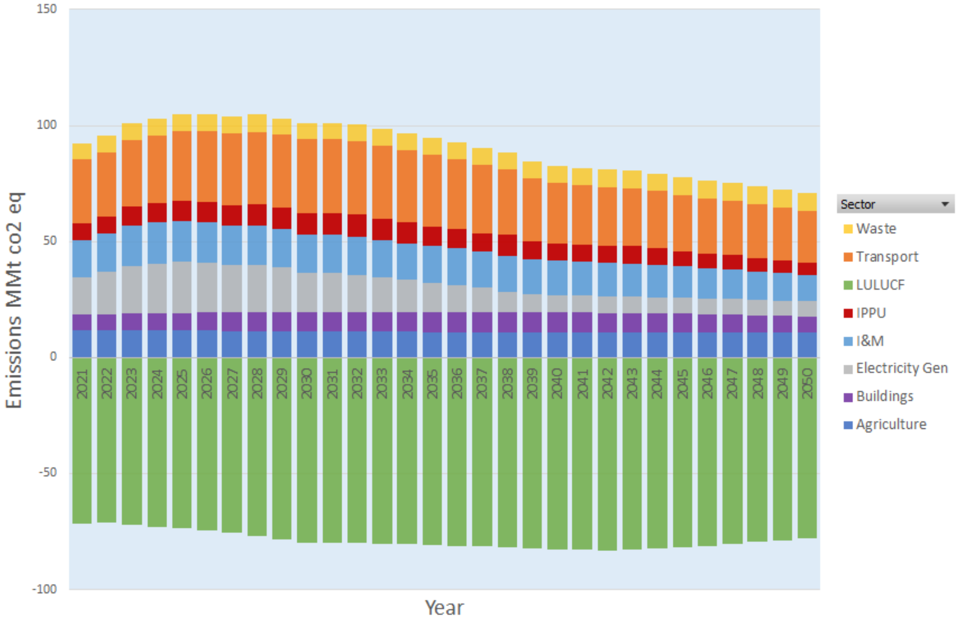


FIGURE 15

Emissions for the IM-Red Future Scenario

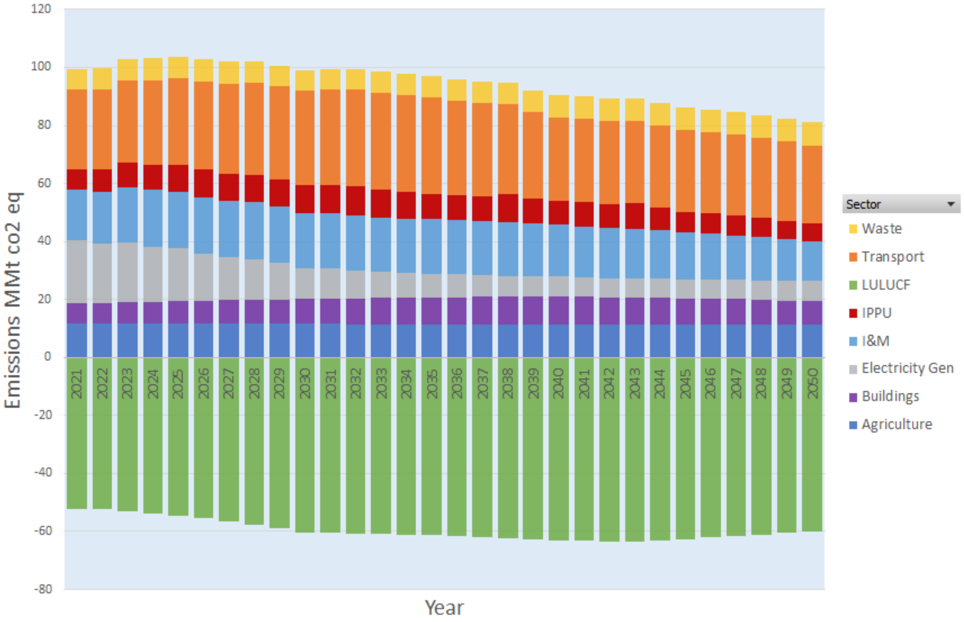


FIGURE 16

Emissions for the AM-Green Future Scenario

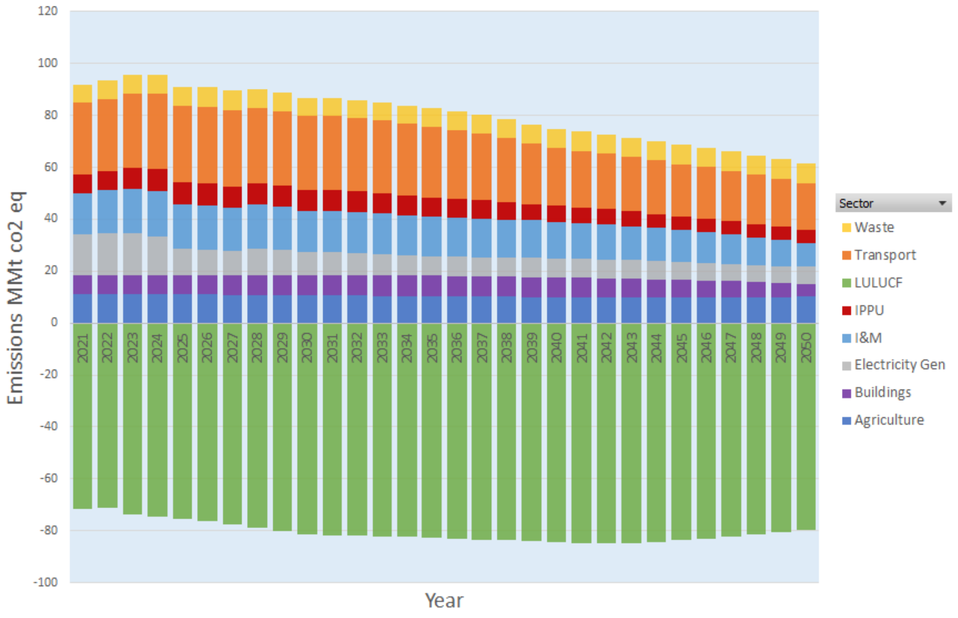
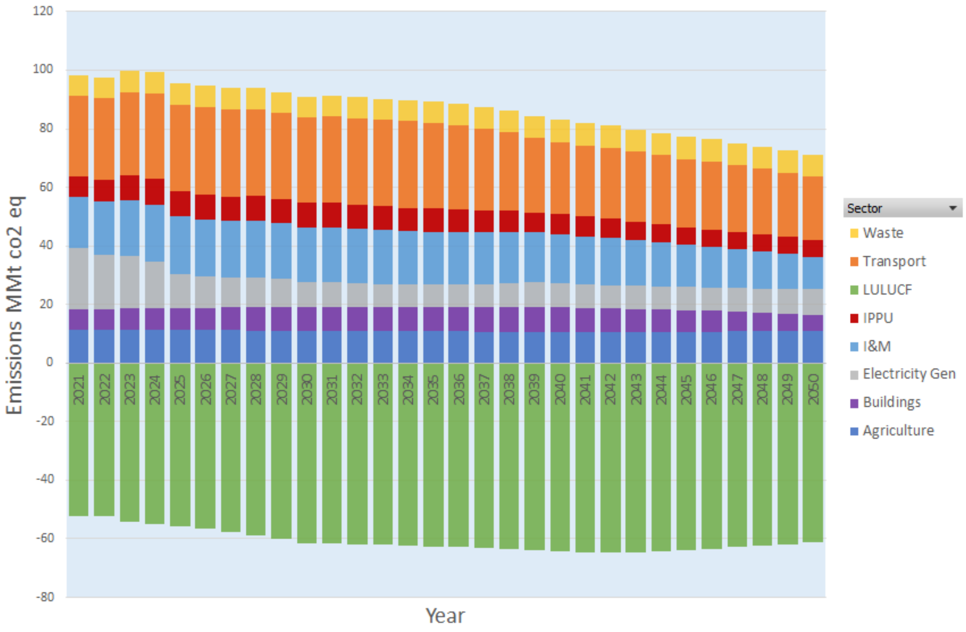


FIGURE 17

Emissions for the AM-Red Future Scenario



3.2 Sensitivity analysis of 2020 and 2030 emissions

TABLE 23

Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO2eq) 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 24

Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO2eq) 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 25

Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO2eq) 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 26

Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO2eq) 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 27

Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO2eq) 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 28

Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO2eq) 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 29

Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO2eq) 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 30

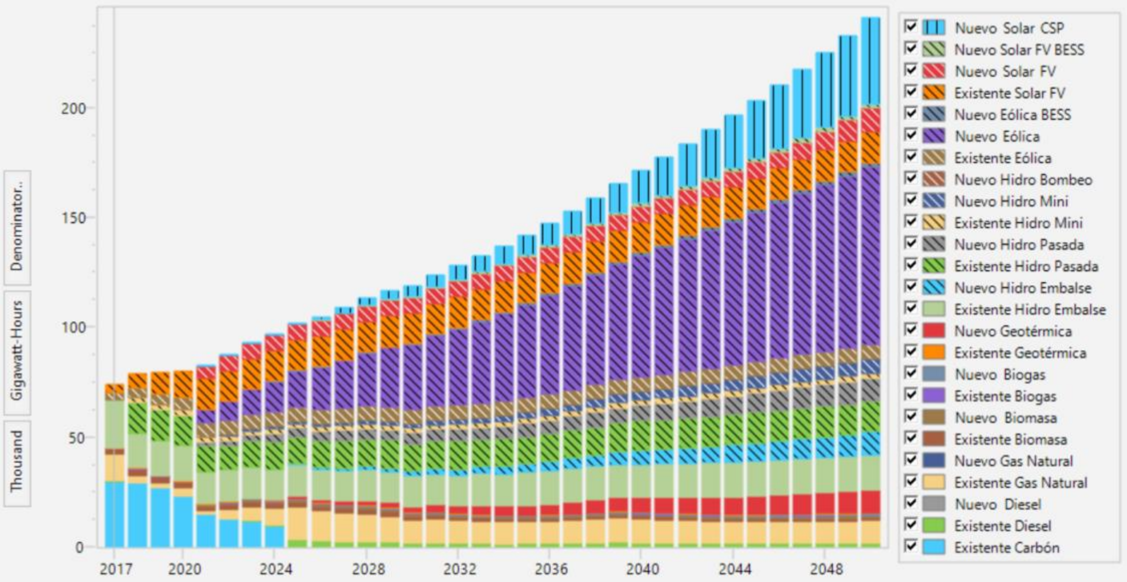
Shows the difference between projected 2030 emissions less 2020 emissions (MM tons of CO2eq) for each scenario and all the futures for the LULUCF sector.

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

3.3 Generation for the alternatives to accelerate mitigation on the electricity sector

FIGURE 18

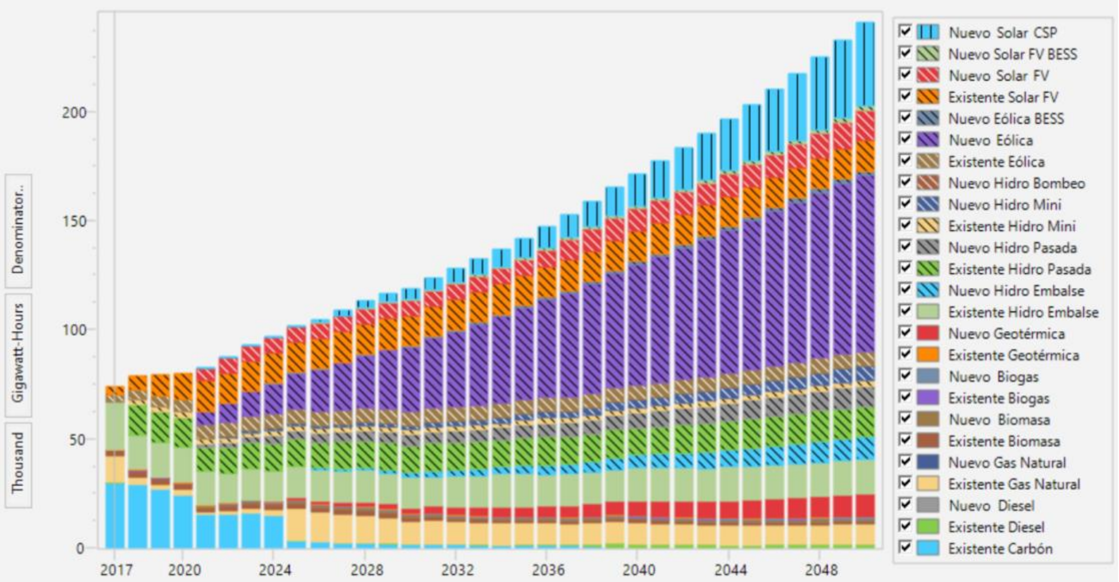
Generation output Reference future AM 2025



Source: Selfmade

FIGURE 19

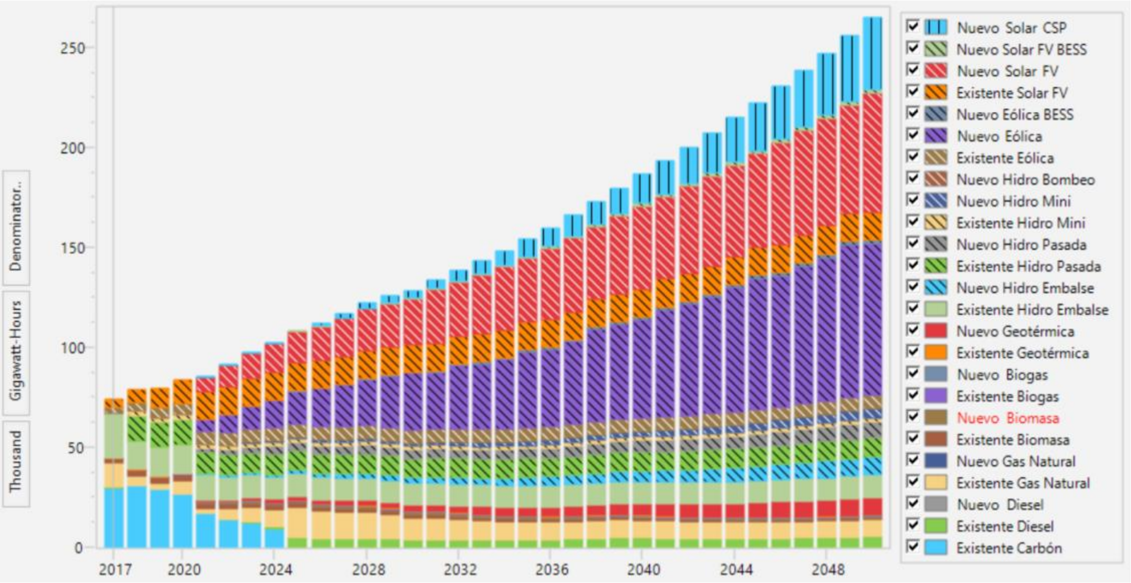
Generation output Reference future AMHT



Source: Selfmade

FIGURE 20

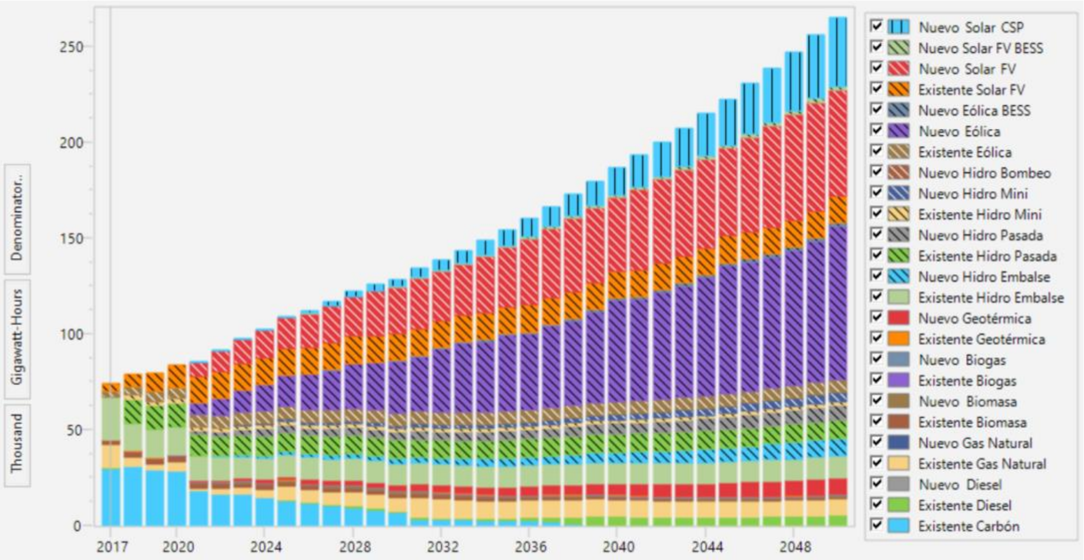
Generation output Red future AM 2025



Source: Selfmade

FIGURE 21

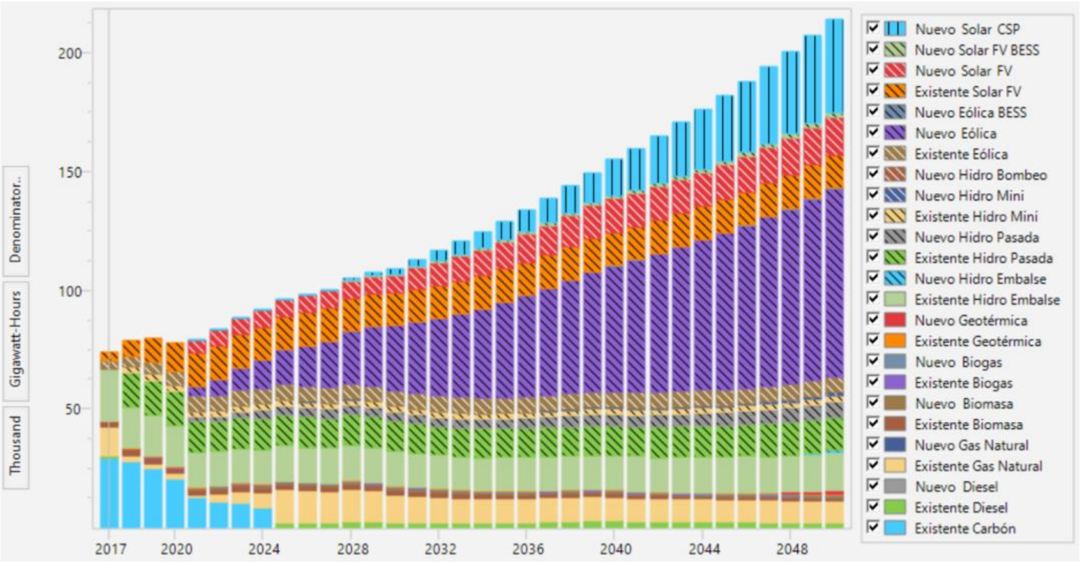
Generation output Red future AMHT



Source: Selfmade

FIGURE 22

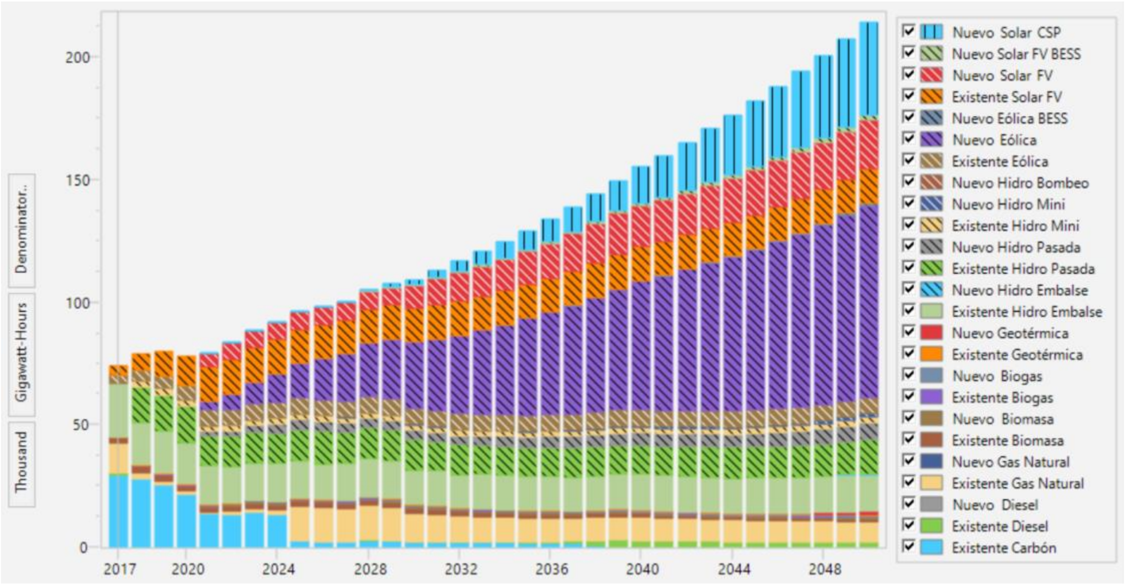
Generation output Green future AM 2025



Source: Selfmade.

FIGURE 23

Generation output Green future AMHT



Source: Selfmade.

Appendix 4: MACC Curve for other futures

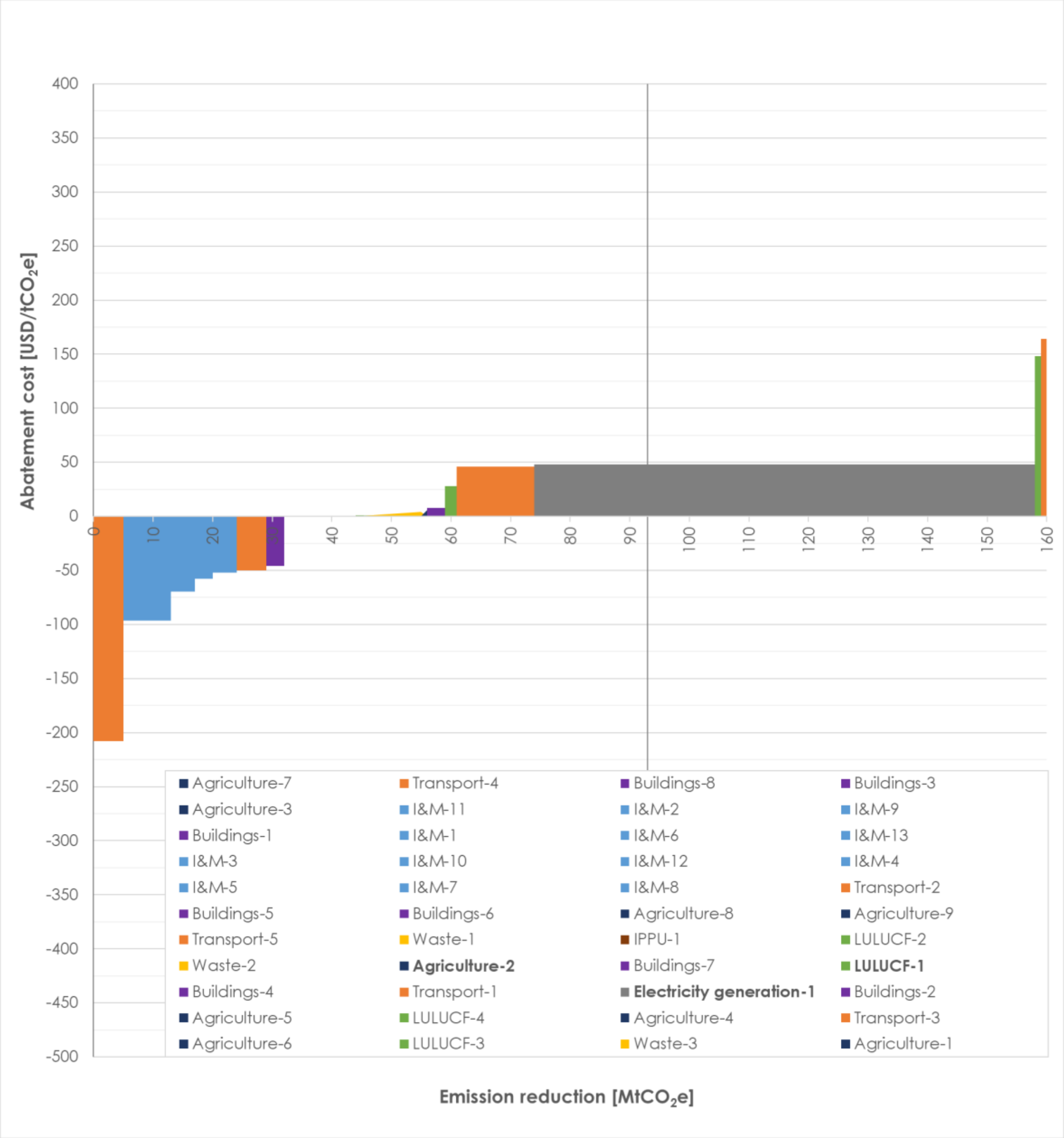
The curves presented in this Annex follow the same legend presented in Table 4-1.

4.1 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/tCO2eq, 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 24

MACC curve for the 2020-2030 period for the green future



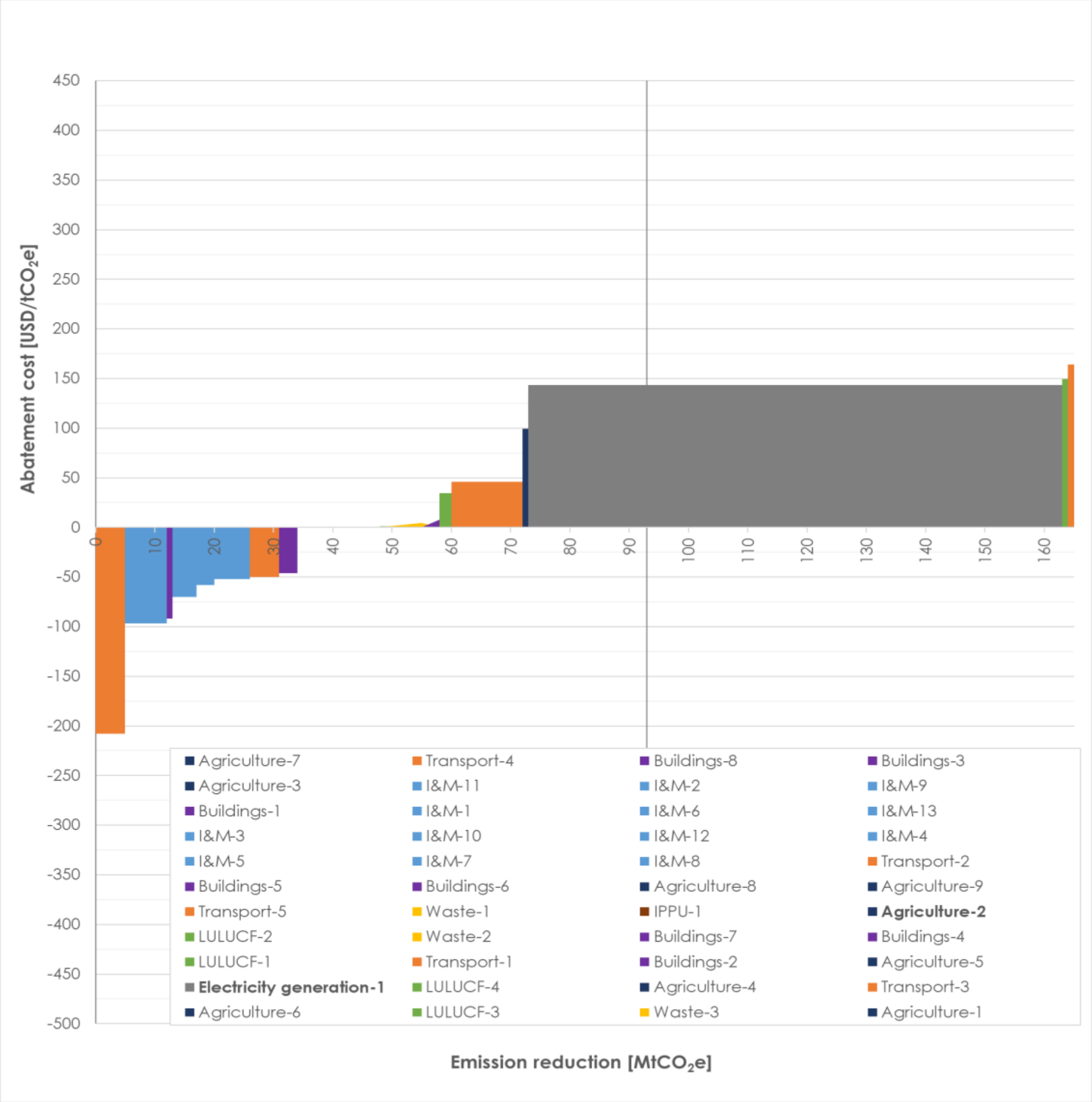
Source: Study Authors.

4.2 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/tCO2eq, 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/tCO2eq in the reference future to 0.7 USD/tCO2eq 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 25

MACC curve for the 2020-2030 period for the red future



Source: Study Authors.

Appendix 5: Overview of modules and models

The models that were used for the development of this study are available at the repository https://data.mendeley.com/datasets/jtp6dcyp78. This section presents a summary of each of these modules, which ranges from its input parameters to the main outputs of each model. With this, and together with the codes available in the repository, we hope to facilitate the reproduction of the results.

5.1 Sector: Electricity

5.1.1 Inputs

Variable	Brief description	Unit	SWITCH ref
Candidate projects	Candidate projects considered for study such as power plants and storage technologies.	-	GENERATION_PROJECT, generation_projects_info.csv
Predetermined projects	Installed and in planning projects considered for study.	-	GENERATION_PROJECT, gen_built_predetermined.csv
Maximum capacity	Maximum capacity for each available project.	MW	gen_capacity_limit_mw, generation_projects_info.csv
Predetermined project capability	Capacity of projects installed and in planning considered prior to the study.	MW	gen_predetermined_cap, gen_built_predetermined.csv
Maximum project year	Age limit for each project.	Year	gen_max_age, generation_projects_info.csv
Heat Rate	Heat rate for the thermal power plant	MMBtu/MWh	gen_full_load_heat_rate, generation_projects_info.csv
Variable project cost	Operational and maintenance cost for each available project.	USD/MWh	gen_variable_om, generation_projects_info.csv
Generation forced outage rate	Means the hours a generating unit is removed from service.	.	gen_forced_outage_rate, generation_projects_info.csv
Investment project cost	Investment cost considered for each new project to be constructed.	USD/MW	gen_overnight_cost, gen_built_cost.csv
Variable capacity factor	Measure of the amount of energy produced by a plant compared to its maximum production.	-	gen_max_capacity_factor, variable_capacity_factor.csv

Variable	Brief description	Unit	SWITCH ref
Fuel cost	Fuel cost of the thermal power plants under consideration.	USD/MMBtu	fuel_cost, fuel_cost.csv
CO_2 Intensity	Intensity factor of each fossil fuel.	t CO_2/MMBtu	co2_intensity, fuels.csv
Nodes or load zones	Areas to which generators and transmission lines are connected.	-	LOAD_ZONE, load_zones.csv
Carbon Cap	Carbon cap considered per year	t CO_2	carbon_cap_tco2_per_yr, carbon_policies.csv
Carbon Tax	Carbon tax considered per period.	USD/t CO_2	carbon_cost_dollar_per_tco2, carbon_policies.csv
Transmission Lines	Transmission lines that make up the electric power transmission network.	-	TRANSMISSION_LINE, transmission_lines.csv
Transmission efficiency	Efficiency of each transmission line.	-	trans_efficiency, transmission_lines.csv
Transmission capacity	Capacity of each transmission line connected between nodes	MW	existing_trans_cap, transmission_lines.csv
Length of transmission lines	Maximum length of each transmission line under consideration.	km	trans_length_km, transmission_lines.csv
Electricity demand	Demand for each timepoint	MW	zone_demand_mw, loads.csv
Time scale	In this case, we consider the representation by representative days, organized in timepoints and periods of years.	-	Timeseries, timepoints.csv; ts_scale_to_period, timeseries.csv
Discount and interest rate	A discount rate 6% and interest rate of 10% have been considered.	%	discount_rate and interest_rate, financials.csv

5.1.2 Brief explanation of the projection of the activity level

For the representation of the power system in a long-term planning study, the open-source tool SWITCH was used. Were considered 826 existing and 714 candidate projects including thermal, solar, wind, biomass, geothermal, hydro, CSP and battery generators, with 26 nodes and 29 transmission lines and three economic scenarios Reference, Red and Green were simulated with investment periods between 2020 – 2050, to finally obtain the costs of infrastructure investments, total CO2 emissions, as well as the capacity and dispatch of each project. For the correct representation of the behaviour of the projects, the methodology of representative days was used for each year considered in the study and all data was obtained from Long-Term Energy Planning (PELP) conducted by the Chilean Ministry of Energy.

5.1.3 Outputs

Variable	Brief description	Unit	SWITCH ref
Total costs	Includes costs for infrastructure, operational (fuels and non-fuels) emissions of CO_2 and storage.	USD	AnnualCost_NPV, costs_itemized.csv
Energy dispatch	Maximum energy dispatch for each project and at each timepoint.	MWh	Energy_GWh_typical_yr, dispatch.csv
Installed capacity	Maximum installed capacity of each project and in each investment period.	MW	GenCapacity, gen_cap.csv
Installed transmission capacity	Maximum installed capacity of the transmission lines considered in the study.	MW	BuildTx, BuildTx.csv
Transmission energy dispatch	Maximum energy dispatch over transmission lines	MW	BuildTx, DispatchTx.csv
Emissions dispatch	Maximum CO_2 emissions per project for each timepoint.	t CO_2/h	DispatchEmissions_tCO2_per_typical_yr, dispatch.csv
Load balance	All injections and withdrawals of power at the transmission node of each zone during each timepoint.	MW	ZoneTotalCentralDispatch - TXPowerNet – WithdrawFromCentralGrid, load_balance.csv

5.1.4 Brief tutorial for running the electric model

To run the model, you must consider the pre-tutorial and tutorial documents present in SWITCH web page[22]. You must compose the inputs folder hosted in the link[23], in the folder Electricity Generation – Reference_NDC with the last model run and together with the modules.txt file that indicates which modules will be used in SWITCH. Once the address of the input file is specified, the command "switch solve" is written so that the model starts solving. When the model finishes solving, an output file will be created which will contain the results detailed above.

---

[22] Switch Power System Planning Model (switch-model.org)

[23] GHG Mitigation beyond the NDC in Chile: An assessment of alternatives - Pyplan Models - Mendeley Data

5.2 Sector: Transport

5.2.1 Inputs

Variable	Brief description	Unit
Historical demand for passenger transportation	Obtained from the Transport Ministry for each region between 1998 and 2013.	passenger-km (pkm)
Historical demand for freight transportation	Obtained from the Transport Ministry for each region between 1998 and 2013.	t-km (tkm)
Coefficients	Coefficients of the econometric model for demand projection developed for the long-term energy planning process.	-
Chilean GDP	Chile's GDP at the national and regional level for each year and future.	USD/year
Chilean GDP per capita	Chile's GDP per capita at the national and regional level for each year and future.	USD/year- person
National copper production	Projected in the copper subsector of Industry & Mining for each future.	t/year
Modal split of transport	Percentage of use of a mode of transport.	%
Occupancy rate	For each mode of transport for passenger and freight transportation.	t/vehicle or passenger/vehicle
Fuel efficiency	Estimated efficiency for each fuel used, disaggregated for each mode of transport.	km/liter
Fuel emission factor	Emission factor of each GHG for the energy consumption of each fuel.	kg GHG/TJ

5.2.2 Brief explanation of the projection of the activity level

The main emitting subsector corresponds to Road transport, whose demand is projected over time using a specific econometric model for each region and type of demand (passengers and freight) developed by the Energy Ministry for its long-term strategy. Depending on the region (15 regions), transport demand is projected based on national or regional GDP, demand from previous years, and/or key production (e.g., copper production). With these results, the distances travelled by each mode of transport are estimated based on the percentage of use of the mode and its occupancy rate (in this case: private car, taxi, motorcycle and bus).

For other modes of transportation, including trains, airplanes, and boats, a similar approach is used based on historical information.

5.2.3 Outputs

Variable	Brief description	Unit
GHG emissions from Transport	Projected GHG emissions to 2050, generated by road transportation, railway, maritime transport, and air transportation for each region and future.	kt GHG/year
CO_{2eq} emissions from Transport	Projected emissions to 2050, generated by road transportation, railway, maritime transport, and air transportation for each region and future.	kt CO_{2eq} /year
Mitigation potential of transport mitigation actions	Reduction in GHG emissions between 2020-2030, due to the implementation of transport mitigation actions for each mitigation scenario.	t CO_{2eq}
Capital costs of transport mitigation actions	Net present value of total cost of implementing the mitigation actions in the long term, including investments, operating costs, and savings.	USD
Abatement costs of transport mitigation actions	Corresponds to the present value of the total cost of the action in the 2020-2050 horizon, divided by the total mitigation potential for 2020-2050.	USD/t CO_{2eq}

5.3 Sector: Industry & Mining

5.3.1 Inputs

Variable	Brief description	Unit
Historical production of the subsectors	Obtained from annual reports of each industry.	t/year
Coefficients	Coefficients of the econometric models to project the production of some industries developed for the long-term energy planning process.	-
Annual production variation	Used as proxy to project the national production of smaller industries.	%
Projected copper production	Regional projection of the Chilean Copper Commission.	t/year
Historical energy consumption of the subsectors	Obtained from the national energy balances published by the Energy Ministry.	Tcal/year

Variable	Brief description	Unit
Chilean GDP	Projected Chile's GDP at the national and regional level for each year and future, used to project production from certain industries.	USD/year
Global GDP	Projected World's GDP for each year and future, used to project production from certain industries.	USD/year
Asia Pacific GDP	Projected Asia Pacific GDP for each year and future, used to project production from certain industries.	USD/year
Fuel efficiency	Estimated energy efficiency of each fuel consumed for production in each industry.	%
Fuel emission factor	Emission factor of each GHG for the energy consumption of each fuel.	kg GHG/TJ

5.3.2 Brief explanation of the projection of the activity level

For each subsector, the industrial production is projected following an econometrical approach based on the demands model of the long-term energy strategy of Chile. Specific energy-consumption factors are estimated based on historical data.

A notorious exception is the copper industry, whose production is projected following the regional projection of the Chilean Copper Commission (2020) to year 2031. Given the relevance of copper to Chile, the Commission has better models and its information is more reliable. The mass of material processed by type of copper is estimated for each region, year, and future, based on the projected copper production, the percentage of annual participation of each type of copper in the region's production, the law of each type of copper and the percentage recovery of the material. On the other hand, the percentage of the annual participation by type of mine (open pit and underground) is estimated, which is projected to 2031 based on the projection of production by type of mine developed by COCHILCO (2020) and keeping it constant until 2050.

5.3.3 Outputs

Variable	Brief description	Unit
GHG emissions from Industry & Mining	Projected GHG emissions to 2050, generated by each industry for each region and future.	kt GHG/year
CO_{2eq} emissions from Industry & Mining	Projected emissions to 2050, generated by each industry for each region and future.	kt CO_{2eq} /year

Variable	Brief description	Unit
Mitigation potential of mitigation actions	Reduction in GHG emissions between 2020-2030, due to the implementation of mitigation actions in the sector for each mitigation scenario.	t CO_{2eq}
Capital costs of mitigation actions	Net present value of total cost of implementing the mitigation actions in the long term, including investments, operating costs, and savings.	USD
Abatement costs of mitigation actions	Corresponds to the present value of the total cost of the action in the 2020-2050 horizon, divided by the total mitigation potential for 2020-2050.	USD/t CO_{2eq}

5.4 Sector: Buildings

5.4.1 Inputs

Variable	Brief description	Unit
Segment units in 2014	Number of units of each segment (type of building) per region in 2014.	units
Segment index of the United States	Number of units of each segment per functional unit of inhabitants, of the reference developed country selected (US).	units/FU
Chilean GDP per capita	Chile's GDP per capita at the national and regional level for each year and future.	USD/year-person
US GDP per capita	United States's GDP per capita for each year.	USD/year- person
Projected regional population	Amount of inhabitants of each region in Chile per year.	people/year
Percentage of new buildings	Percentage of new residential buildings (houses and apartments) each year.	%
Size of a segment unit	Average size of a unit of each segment.	m^2/unit
Percentage participation of fuels	Percentage participation of each fuel in the total energy consumption of each final use of the energy in a segment.	%
Specific energy consumption	Annual specific energy consumption per unit area of each segment.	kWh/m^2
Historical energy consumption of the subsectors	Obtained from the energy balances published by the Energy Ministry.	Tcal/year
Fuel emission factor	Emission factor of each GHG for the energy consumption of each fuel.	kg GHG/TJ

5.4.2 Brief explanation of the projection of the activity level

The number of segment units of each subsector (residential, commercial and public buildings) per region is projected to the year 2050 based on the available data from 2012. This projection is based on the Saturation Theory, which assumes that as Chile's GDP per capita increases, it will be closer to a developed reference country (in this case, the United States).

For example, for the residential sector (the main sub-sector), the segment index of the United States is used as reference, indicating the number of segment units per functional unit of inhabitants. Therefore, the segment development index is determined as the higher value between the one from the United States and the regional index for Chile in 2014, calculated from the segment units in 2014 and the regional population of the same year. The segment index for Chile is projected assuming linear growth over time as a function of the national per capita GDP for each future. Finally, the number of units per segment is projected based on the projected Chilean index, the projected regional population, and the functional unit of inhabitants of the index.

5.4.3 Outputs

Variable	Brief description	Unit
GHG emissions from Buildings	Projected GHG emissions to 2050, generated by residential, commercial and public buildings, for each region and future.	kt GHG/year
CO_{2eq} emissions from Buildings	Projected emissions to 2050, generated by residential, commercial and public buildings for each region and future.	kt CO_{2eq} /year
Mitigation potential of mitigation actions in buildings	Reduction in GHG emissions between 2020-2030, due to the implementation of mitigation actions in the sector for each mitigation scenario.	t CO_{2eq}
Capital costs of mitigation actions in buildings	Net present value of total cost of implementing the mitigation actions in the long term, including investments, operating costs, and savings.	USD
Abatement costs of mitigation actions in buildings	Corresponds to the present value of the total cost of the action in the 2020-2050 horizon, divided by the total mitigation potential for 2020-2050.	USD/t CO_{2eq}

5.5 Sector: Waste

5.5.1 Inputs

Variable	Brief description	Unit
Historical waste generation	Series of waste generation from 1990 onwards, reconstructed by the Environmental Ministry.	Gg/year
Historical waste deposition	Data of the accumulated waste in the different landfills.	Gg/year
DOC by type of waste	Degradable Organic Carbon of food waste, paper, wood, textiles, sludge, plastics, and other non-organic waste.	%
Chilean GDP	Chile's GDP at the national and regional level for each year and future.	USD/year
Chilean GDP per capita	Chile's GDP per capita at the national and regional level for each year and future.	USD/year-person
Projected regional population	Amount of inhabitants of each region in Chile per year.	people/year
Projected protein content	Developed by the Environmental Ministry to estimate N2O emissions from domestic water treatment.	g/day-person

5.5.2 Brief explanation of the projection of the activity level

Solid waste disposal has historically represented the primary source of emissions of the Waste sector, because of the methane generated from the decomposition of the organic fraction of the waste. To project waste disposal, an econometric model was used, which relates per capita waste disposal to per capita GDP. Then, the waste was disaggregated into its different components (food waste, paper and cardboard, wood, textiles, and others), considering that the composition currently considered in the National GHG Inventory varies linearly towards the composition of middle-high income countries by 2030 and high-income countries by 2050.

5.5.3 Outputs

Variable	Brief description	Unit
GHG emissions from Waste	Projected GHG emissions to 2050, generated by solid waste disposal, biological treatment of solid waste, incineration and open burning of waste, and wastewater treatment, for each region and future.	kt GHG/year
CO_{2eq} emissions from Waste	Projected emissions to 2050, generated by each subsector, for each region and future.	kt CO_{2eq} /year
Mitigation potential of Waste mitigation actions	Reduction in GHG emissions between 2020-2030, due to the implementation of mitigation actions in the sector for each mitigation scenario.	t CO_{2eq}
Capital costs of Waste mitigation actions	Net present value of total cost of implementing the mitigation actions in the long term, including investments, operating costs, and savings.	USD
Abatement costs of Waste mitigation actions	Corresponds to the present value of the total cost of the action in the 2020-2050 horizon, divided by the total mitigation potential for 2020-2050.	USD/t CO_{2eq}

5.6 Sector: IPPU

5.6.1 Inputs

Variable	Brief description	Unit
Historical industry production	Data of the annual level of production of each industry considered as a subsector.	t/year
Historical clinker production	Data of the annual level of production of clinker. Used in mineral cement industry.	t/year
Historical clinker importation	Data of the annual level of importation of clinker. Used in mineral cement industry.	t/year
Projected cement production	Projected in the cement subsector of Industry & Mining for each future. Used in mineral cement industry.	t/year
Chilean GDP	Projected Chile's GDP at the national and regional level for each year and future.	USD/year
Projected regional population	Amount of inhabitants of each region in Chile per year.	people/year

5.6.2 Brief explanation of the projection of the activity level

The main subsectors in terms of emissions correspond to alternative products for ozone-depleting substances and the mineral industry. The activity data corresponds to the production of the industries, or to the quantities of products whose use generates GHG emissions. Activity levels are projected based on econometric relationships that depend on historical trends and GDP. In specific subcategories such as domestic refrigeration and vehicle air conditioning, the population is incorporated to estimate consumption. In the particular case of cement, CO_2 emissions are generated during the production of cement due to the production of clinker. Clinker production is estimated based on the non-imported fraction and the demand, which is determined by the estimated cement production variable in the industry and mining sector.

5.6.3 Outputs

Variable	Brief description	Unit
GHG emissions from IPPU	Projected GHG emissions to 2050, generated by each subsector, for each region and future.	kt GHG/year
CO_{2eq} emissions from IPPU	Projected emissions to 2050, generated by each subsector, for each region and future.	kt CO_{2eq} /year
Mitigation potential of IPPU mitigation actions	Reduction in GHG emissions between 2020-2030, due to the implementation of mitigation actions in the sector for each mitigation scenario.	t CO_{2eq}
Capital costs of IPPU mitigation actions	Net present value of total cost of implementing the mitigation actions in the long term, including investments, operating costs, and savings.	USD
Abatement costs of IPPU mitigation actions	Corresponds to the present value of the total cost of the action in the 2020-2050 horizon, divided by the total mitigation potential for 2020-2050.	USD/t CO_{2eq}

5.7 Sector: Agriculture

5.7.1 Inputs

Variable	Brief description	Unit
Historical number of livestock heads by type	The populations of animal species, measured in animal-years, were obtained from the Agricultural and Forestry Censuses of 1997 and 2007, as well as from the annual and biennial statistics published by the Oficina de Estudios y Políticas Agrarias (ODEPA), the Instituto Nacional de	N° livestock heads /year

Variable	Brief description	Unit
	Estadística (INE), and the Asociación de Productores de Cerdo (ASPROCER), in the case of the pig population.	
Emission factor for livestock types	Emission factors used correspond to Tier 1 and Tier 2	kg GHG/N° livestock heads
Cultivated rice area	Hectares of rice Crop, using national rice harvest area data from ODEPA	ha
Synthetic fertilizer use in agriculture for historical periods	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	t N
Total biomass burned from cereals and other crops	Data from 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.	kg dry biomass per ha
Historical national consumption of amendments	Data provided by the private sector on production and sales estimates, combined with import data from the Customs.	t/year
Urea consumption estimation	The data used for Urea use in agriculture for historical periods was obtained from ODEPA, based on fertilizer import data provided by the National Customs Service	t Urea/year
Urea Emission Factor	Emission factor used in equation 11.13	t C/ t urea
Beef producer price	prices obtained from OECD Stats	CLP
Corn producer price	prices obtained from OECD Stats	CLP
Producer price of Soy	prices obtained from OECD Stats	CLP
Producer price of Poultry Meat	prices obtained from OECD Stats	CLP

5.7.2 Brief explanation of the projection of the activity level

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 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.

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.

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 (kg N/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.

5.7.3 Outputs

Variable	Brief description	Unit
CO_{2eq} emissions from Agriculture sector	Projected CO_{2eq} emissions to 2050, generated by each categories and future.	MMt CO_{2eq}
Mitigation potential of mitigation actions	Reduction in GHG emissions between 2020-2030, due to the implementation of mitigation actions in the sector for each mitigation scenario.	MMt CO_{2eq}
Capital costs of mitigation actions	Net present value of total cost of implementing the mitigation actions in the long term, including investments, operating costs, and savings.	USD
Abatement costs of mitigation actions	Corresponds to the present value of the total cost of the action in the 2020-2050 horizon, divided by the total mitigation potential for 2020-2050.	USD/t CO_{2eq}
CO_{2eq} emissions from LULUCF	Projected CO_{2eq} emissions to 2050, generated by each category and future, including forest fires and HWPs.	MMt CO_{2eq}

5.8 Sector: LULUCF

5.8.1 Inputs

Variable	Brief description	Unit
Native and exotic forest areas	"Historical values of surface areas at a general level, considering the total area of plantations and native forests. Source: INFOR Yearbook for plantations up to 2018, and Chilean INGEI Report for native forests.	ha

Variable	Brief description	Unit
	For the latter, values for the years 2017 and 2018 were estimated using simple regression based on the last 5 years of information	
VAR Model Coefficient	coefficients for VAR model adjustment for projecting forest land area. Adjusted based on historical values. Method based on projections made by INFOR.	s/u
Historical emissions: Biomass Increase	Historical emissions of the Biomass Increase category, for each type of management. Source: INGEI.	kt CO_2
Forest management percentages	Percentages associated with each type of management, for native forests. The percentages were calculated as an average of the 5 most recent years of historical information.	%
Harvest Volume	Historical harvest values separated only by wood harvested from native and exotic species.	m^3
Harvested wood Percentage	Percentage of harvested wood for each type of origin. Estimated based on the average of the last 5 years of historical information	%
Historical firewood consumption	Historical firewood consumption, by region, year, and firewood origin	m^3
Forest fire emissions	Greenhouse gas emissions per year due to fires, separated by vegetation origin, historical period 1990-2018. Information from 1990-2016 based on INGEI, and 2017-2018 estimated based on previews burned hectares."	kt CO_{2eq}
Historical GHG emissions from forest waste burning	Historical values of GHG emissions from forest waste burning. Source: INGEI	Kt GHG (CO2, CH4, N2O)
Historical emissions associated with forested land with vegetation change.	Historical emissions associated with forested land with vegetation change. INGEI, 2017 and 2018 as an average of the last 5 years.	kt CO_{2eq}
Historical emissions associated with land converted to forested land.	Historical emissions associated with land converted to forested land, period 1990-2018. For 2017 and 2018, the average of the last 5 years is considered.	kt CO_2
Area of land converted to another land use	Area of land converted to X, where X is Cropland, Grassland, Wetland, Settlements, and Other lands	ha
Area of grassland and cropland burned.	Area of grassland and cropland burned, extracted from the CONAF inventory.	ha

Variable	Brief description	Unit
Emission factors	Emission factors for aboveground biomass in the forestry sector (biomass increase, biomass loss, vegetation change)	kt CO_2/ha
Firewood demand from the CPR sector	Firewood demand used by the CPR sector, delivered by the sector model.	Millions of GJ
Volume of Wood for harvested wood products	Cubic meters of wood produced by the forestry sector used for harvested wood products, sawnwood, wood pulp, chips, industrial wood waste, among others. Source: INFOR Yearbooks	m^3

5.8.2 Brief explanation of the projection of the activity level

For the projection of the sector to 2030, we used the methodology and modelling 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.

5.8.3 Outputs

Variable	Brief description	Unit
CO_{2eq} emissions from LULUCF	Projected CO_{2eq} emissions to 2050, generated by each category and future, including forest fires and HWPs.	MMt CO_{2eq}
Mitigation potential of mitigation actions	Reduction in GHG emissions between 2020-2030, due to the implementation of mitigation actions in the sector for each mitigation scenario.	MMt CO_{2eq}
Capital costs of mitigation actions	Net present value of total cost of implementing the mitigation actions in the long term, including investments, operating costs, and savings.	USD
Abatement costs of mitigation actions	Corresponds to the present value of the total cost of the action in the 2020-2050 horizon, divided by the total mitigation potential for 2020-2050.	USD/t CO_{2eq}

References of Appendix

Generación Eléctrica en Chile. (Generadoras de Chile, 2022, http://generadoras.cl/generacion-electrica-en-chile)

Plan de Retiro y/o Reconversión de Unidades a Carbón. (Ministerio de Energía, 2020)

Planificación Energética de Largo Plazo 2023-2027. (Ministerio de Energía, 2022)

Environmental Defense
Fund
257 Park Avenue South
New York, NY 10010

T 212 505 2100
EDF.ORG

New York, NY / Austin, TX / Bentonville, AR / Boston, MA / Boulder, CO / Raleigh, NC /
Sacramento, CA San Francisco, CA / Washington, DC / Beijing, China / La Paz, Mexico /
London, UK