MITIGATION AND ENERGY
WORKING GROUP

Chilean NDC mitigation proposal: Methodological approach and supporting ambition

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SCIENTIFIC COMMITTEE ON CLIMATE CHANGE

Chilean NDC mitigation proposal: Methodological approach and supporting ambition

MITIGATION AND ENERGY WORKING GROUP

CIENTIFIC COMMITTE ON CLIMATE CHANGE

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PROCESS

The COP25 Scientific Committee was appointed by the Ministry of Science, Technology, Knowledge and Innovation in April 2019 to coordinate the contributions of the scientific community towards the 2019 United Nations Conference on Climate Change. The Committee includes seven working groups: two transversal - Mitigation and energy and Adaptation - and five sectorial - Water, Biodiversity, Cities, Cryosphere and Oceans.

The Committee's work consists on identifying, compiling and reporting the scientific evidence on the evolution and impacts of climate change in Chile, with inputs from a network of more than 600 scientists from academic and public and private research centers.

The mandate is to deliver recommendations that can support the design of public policies, negotiations in international forums such as the COP25, the United Nations Climate Action Summit, and the Intergovernmental Panel on Climate Change, and the linkages of the scientific community with the Ministry of Science, Technology, Knowledge and Innovation.

At the national level, the climate change agenda included a discussion of the draft Framework Law for Climate Change, the NDC update and the elaboration of a Long-Term Strategy for Greenhouse Gas Emissions Reduction. A guiding milestone of the Committee's work has been Chile's ambitious commitment to achieve GHG-neutrality by 2050.

The Mitigation and energy working group developed the following activities:

- Two online surveys for the collection of evidence in the field, research studies, assessment of mitigation actions, proposal of new mitigation actions, and analysis of the proposed Framework Law for Climate Change.
- Creation of a first repository with collected information as a basic database for future developments in the mitigation sector (Chilean COP25 Scientific Committee, 2019).
- One extended workshop to share existing evidence and identify mitigation actions.
- Four plenary workshops, several meetings, and coordination via e-mail for developing the present White Paper.

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Note: This report is the responsibility of the authors and does not necessarily represent the opinion of their affiliated institutions.

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Abstract

This paper analyses the Chilean Nationally Determined Contributions (NDC) proposal for the mitigation component. The methodological approach and the supporting ambition of a process carried out by the Chilean Government are assessed based on the scientific evidence available and local context. The analysis is developed by representatives of four ministries and a group of 21 researchers from six universities and research centers throughout the country. This exchange experience between the Government and the scientific community enables the identification of future challenges and opportunities for the Chilean transition in terms of mitigation. This process emerges from a bridging approach led by the recently assumed Minister of Science, Technology, Knowledge and Innovation under the presidency of the Government of Chile in the Conference of the Parties (COP25) for the United Nations Framework Convention on Climate Change (UNFCCC). After a description of the methodological approach, key topics that have an impact on the NDC definition are identified and analyzed. These topics include technical, economical, and socio-environmental issues along with a description of the current socio-political context in the country. Additionally, the major uncertainties that would have the highest potential to modify the results and conclusions of this work are identified. Finally, a summary with the main conclusions and recommendations is presented. The analysis framework and key aspects identified in this exercise may be of value for other countries with similar institutional contexts.

Keywords: *Mitigation; NDC; Climate change; Climate policy.*

1 Introduction

Nationally Determined Contributions (NDCs) are a core element for achieving the Paris Agreement (PA) goal, namely "limiting the global mean temperature to much below 2 °C and pursuing ...". For this, the PA (Article 4, paragraph 2) requires each Party to prepare, communicate and maintain successive increasingly ambitious NDCs, in what is called a "ratchet mechanism" for increasing ambition over time. Every five years, the parties shall plan and implement domestic measures for mitigating, adapting, and implementing means, which include capacity building, technology transfer, financing and transparency. The process started in 2015 when all parties submitted their Intended Nationally Determined Contributions (INDCs) for COP21, which then became the first NDC as a result of the ratification of the PA. According to the established timeline, the updated NDC shall have to be submitted before COP26, during 2020.

Chile submitted its INDC to the UNFCCC secretariat in September 2015 (Chilean COP25 Scientific Committee, 2019). The commitments of the country are divided into five pillars: i) mitigation, ii) adaptation, iii) capacity building, iv) development and transfer of technologies; and v) financing. For the mitigation pillar, Chile chose to submit its contribution employing an emission intensity format (CO_2 equivalent tons per unit of gross domestic product in million CLP$ 2011). Methodologically speaking, the sector comprising land use, land-use change and forestry (LULUCF) was separated from the national mitigation commitment due to the high annual variability of their carbon capture and emissions, and for being less dependent on economic growth.

Chile is one of the first countries to propose an updated and more ambitious Paris Agreement pledge (NDC) (Ministry of the Environment, 2019). This development took place during the Climate Conference in December 2019 (Madrid) when Chile held the presidency of the COP. At that moment, under the Paris Agreement and its enabling decisions, all countries were requested to improve their NDCs by 2020 to bridge the existing emission gap in order to achieve PA temperature goal.

This paper analyses the mitigation component of the Chilean NDC proposal from an interdisciplinary point of view.

1.1 BRIEF DESCRIPTION OF THE CHILEAN PROCESS SINCE 2010

The latest Chilean National Greenhouse Gas Inventory (NGGI) was prepared according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. It covers the entire national territory and includes emissions and removals of carbon dioxide (CO_2) and methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) in a time series from 1990 to 2016.

In 2016, the balance of Chile's greenhouse gas (GHG) emissions and removals accounted for 46.1 MtCO_2eq, while total GHG emissions (excluding LULUCF) in the country accounted for 111.6 MtCO_2eq, an increase since 1990 of 115%, and since 2013 of 7% (Table 1). The main reasons of this trend are the Energy and LULUCF sectors. The values outside the trend in the balance (Figure 1) are mainly a result of forest fires accounted for in the LULUCF sector.

Sector	1990	2000	2010	2013	2014	2015	2016
1. Energy	33.6	52.5	68.6	79.9	77.4	83.7	87.1
2. IPPU	3.6	6.2	5.4	6.1	6.2	6.5	6.9
3. Agriculture	12.1	14.0	13.2	12.8	12.4	12.2	11.8
4. LULUCF	-50.1	-62.6	-71.9	-71.8	-55.7	-44.9	-65.4
5. Waste	2.9	3.8	4.5	5.3	5.4	5.7	5.8
Balance	1.9	13.9	19.9	32.4	45.7	63.2	46.1
Total	**52.0**	**76.5**	**91.8**	**104.3**	**101.4**	**108.2**	**111.6**

Table 1: Chile's NGGI: balance and total GHG emissions ($MtCO_2eq$) by sector, 1990-2016 series.
Source: Ministry of the Environment.

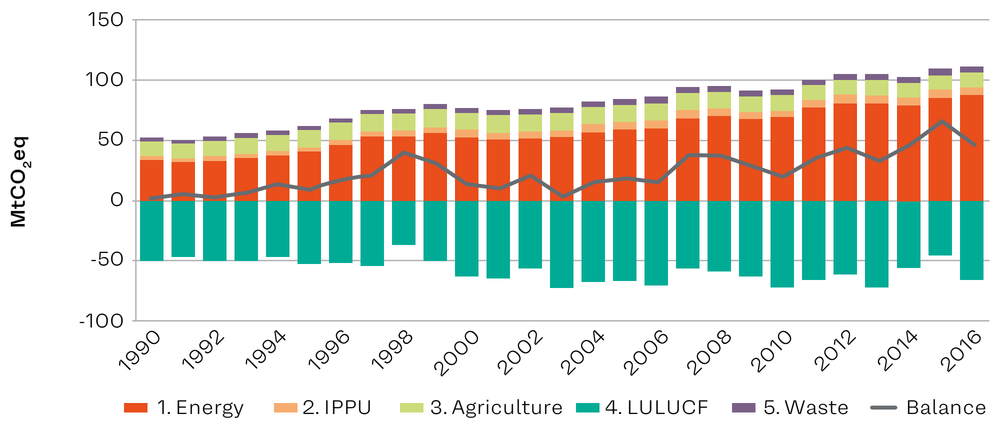

Figure 1: Chile's NGGI: balance of GHG emissions ($MtCO_2eq$) by sector, 1990-2016.
Source: Ministry of the Environment.

The Energy sector is the main GHG national emitter, with 78% of the total GHG emissions in 2016. In the same year, GHG emissions in the sector accounted for 87.1 $MtCO_2eq$, which represents an increase since 1990 of 138%, and since 2013 of 17%. In general, the main cause for this growth is the increase in country's energy consumption, including the consumption of coal and natural gas for power generation, as well as liquid fuels for land transportation, mostly diesel and gasoline. As for these classifications, Fuel Combustion Activities in 2016 accounted for 99% of the sectoral emissions, while the remaining 1% was associated to Fugitive Emissions from fuels. Within the Fuel Combustion Activities classification, the Electricity Generation subclass is the most important with 32%, followed by 21% of Land Transportation, 14% of Manufacturing Industries and Construction and finally, 7% of Residential activities (Figure 2).

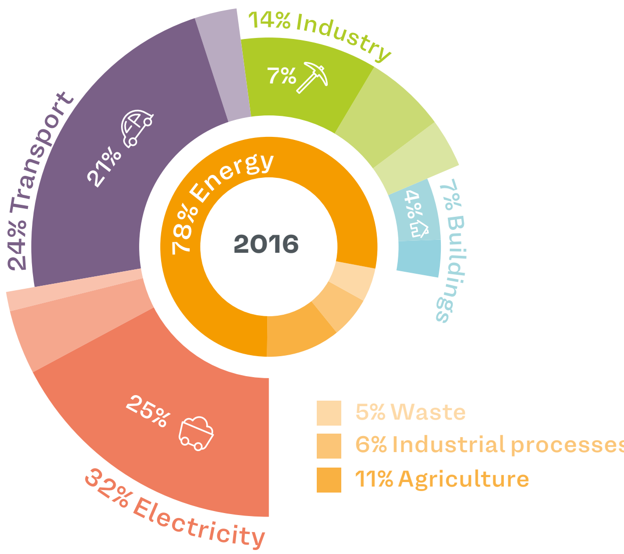

Figure 2: GHG emissions by sector.
Source: Ministry of Energy.

Currently, most of the energy supply comes from fossil sources. According to the National Energy Balance of 2018, 58% of final energy consumption corresponded to oil products, which added to the consumption of natural gas and coal, reaches a fossil fuel participation of 65%, relegating electricity to 22%, and biomass, whose consumption was 13%.

Over the last decades, the most significant structural change of the Chilean energy matrix was observed in the electricity sector. This sector has undergone major changes in its composition and prices. Traditionally, electricity generation in the Chilean interconnected system was mostly hydraulic (over 60%), supplemented with thermal generation, mainly based on coal. During the 1990s, the composition of the energy matrix changed due to the import of natural gas from Argentina and the reduced availability of water resources, transforming natural gas into a primary low-cost source of abundant energy. Once the availability of natural gas was exhausted in 2004, there was a change towards thermal generation with an intense use of coal and oil, which increased prices significantly and made long-term supply contracts difficult to subscribe due to the volatility in the marginal cost value of kWh.

Strong citizen support is required for changing this uncertain scenario in order to define a road map that would enable the composition of an energy matrix to be projected over a long-term horizon by the year 2050, with a larger incorporation of renewable energy, while fulfilling the commitments made to become a carbon neutral country. Additionally, in 2010 this was not a straightforward change in a recently established Ministry of Energy, with scarce history of citizen participation in its processes, as these are issues of high technical contents. In this context, a series of studies and initiatives carried out in different organizations (NGOs, Government, Universities, International organizations) built a diagnosis and a common understanding about energy, social, and environmental challenges (Figure 3).

Figure 3: Initiatives in the field of energy scenarios and climate change.

In order to build a roadmap building for energy development in Chile – in compliance with the OECD standards for the participatory preparation of energy policies and the commitments acquired as a country to mitigate the effects of climate change – participatory processes were defined, giving space for the technical and citizen worlds. In this way, a scenario that would be accepted by the citizenry was defined, which would facilitate investments in this important sector.

The Mitigation Action Plans and Scenarios (MAPS) Program that started in 2012 is an example of a participatory process. The MAPS grew out of the experience of the long-term mitigation scenarios mandated by the South African government that took place between 2005 and 2008. The main objectives of MAPS Chile were:

- To increase the knowledge and general awareness related to climate change among the various relevant stakeholders. This achievement was intended by building broad grounds of support among domestic stakeholders, developing sound scientific evidence to support climate mitigation.
- To contribute with information and possible courses of action to mitigate GHG emissions that both internationally enhances Chile's competitiveness and increases its development opportunities.
- To facilitate the compliance with the voluntary commitment made by Chile and announced in Copenhagen.

It was a participatory process mandated by the government, which engaged stakeholders across the sectors and partnered them with the best indigenous and international researches. Central to MAPS was the combination of researches and stakeholder interests, along with the policy making processes.

Another key initiative, Energy 2050, was developed within the framework of a work prepared by a group of academics who developed a technical proposal later validated by the citizenry. The Energy 2050 initiative included the participating bodies considered in its development, i.e. an Advisory Council composed of 28 people, convened and chaired by the Minister of Energy, including the Ministers of the Environment, Transportation and Communications, National Property, Housing and Urban Planning, and Mining, along with the Vice President of Corfo, responsible for providing strategic guidance throughout the process to build a long-term vision for the sector and give feedback about the development of the year 2050 energy policy.

Jointly with the Advisory Board, teams of experts grouped according to subject, who oversaw the technical discussions in order to provide answers to relevant issues and questions. These groups had representation from different stakeholders in the key issues addressed, and regional representation in previously selected issues. Finally, a citizen space was created through a virtual citizen platform, with relevant information of the process, with a schedule of workshops and meetings, and in control of receiving comments and observations from citizens. Pilot deliberative surveys were also conducted inside this citizen space, seeking to obtain an informed opinion from citizens regarding the future of the energy sector. This work was carried out in four stages over a period of 20 months. Stage 1, definition of the energy agenda; Stage 2, development of the vision and roadmap to 2050; Stage 3, development of a long-term energy policy, which was eventually submitted to the President of the Republic of Chile; and Stage 4, dissemination of this long-term energy policy, whose objective was to communicate and spread both the technical aspects of the proposal and the participatory process implemented.

This work – unprecedented in Chile – enabled a radical change in the composition of the energy matrix with a spectacular development of wind and solar power plants, taking up more than 10% of the matrix, without a government subsidy, and with a significant fall in electricity prices.

Finally, for an ongoing support of the energy analysis, in 2017, a long-term energy planning process (PELP) was created inside the Ministry of Energy. This new institutional framework is the basic tool for energy and environmental analyses that can be used for the development of public policies in the country.

The compilation of all these initiatives in one single repository is part of the results and process carried during the year 2019 and the creation of this white paper (Chilean COP25 Scientific Committee, 2019).

1.2 SUMMARY OF THE CHILEAN NDC MITIGATION PROPOSAL

During 2017, the Ministry of the Environment coordinated a Working Group from the Public Sector focused on discussing the NDC update (WGPS-NDC) in 2020, as required by the Paris Agreement. The ultimate purpose of this group was to develop a shared diagnosis on which elements should be updated, along with identifying the possible institutional arrangements that contribute to NDC management, and proposing the guidelines and next steps to move forward in this matter.

Chile has released its new NDC draft for consultation (Ministry of the Environment, 2019), which refers to economy-wide emissions excluding the Land Use, Land Use Change and Forestry (LULUCF) sector. It provides targets in terms of absolute emissions (97 $MtCO_2eq$ in 2030), includes a carbon budget between 2020 and 2030 (1110 and 1175 $MtCO_2eq$ between 2020 and 2030) and a peak in emissions by 2027 (Figure 4).

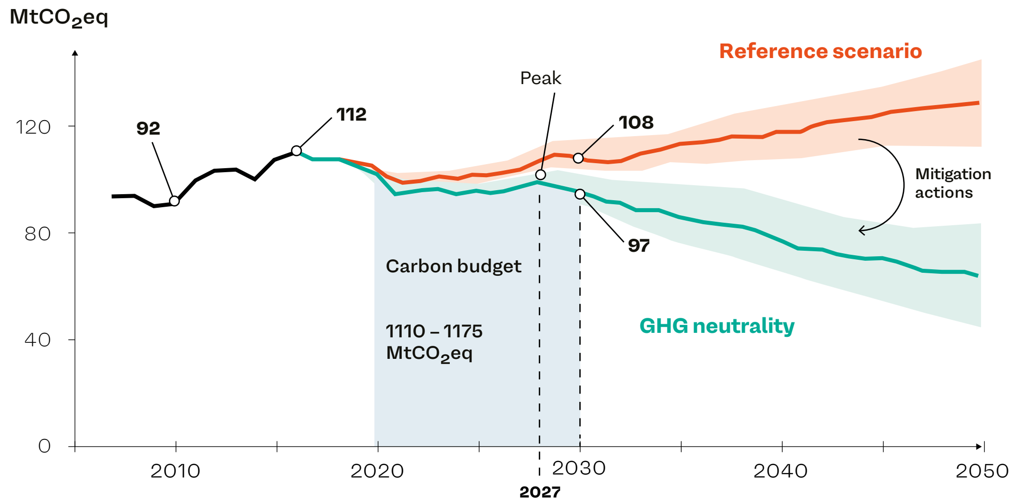

Figure 4: Paths of GHG emissions between 2005 and 2050.
Note: Figure does not include land use sector, land use change and forestry (LULUCF).

In this new NDC draft update, Chile also acknowledges its 2030 target as a medium-term goal towards achieving its long-term goal to GHG-neutrality by 2050. Additionally, this draft proposal also mentions planning processes involving governance, as well as the existing and future strategies including the "Long-term Climate Strategy 2050."

Data between 2005 and 2016 come from the National GHG Inventory, 2017 to 2018 are estimates, and those from 2019 to 2050 are the projections of two scenarios. The green and red areas have been shaded for illustration purposes, representing the commonly expected uncertainties associated with the projections, which grow as time horizon increases. This topic is covered in Section 4.

1.3 SOCIO-POLITICAL BACKGROUND IN CHILE

The Chilean NDC proposal and its public consultation during 2019, experienced a highly changing and complex socio-political scenario in the country, characterized by:

- Proposal of a Framework Law for Climate Change, 2018-2019.
- Chile took the presidency after Brazil declined to host the COP25, December 2018.
- NDC updating process started, April 2019.
- GHG-neutrality commitment by 2050, April 2019.
- Coal Phase Out Coal-Fired Power Generation by 2040 Agreement, June 2019.
- Chile faced a socio-political crisis since October 18th, 2019 when mass protests against severe social and economic inequalities broke out nationwide.
- Due to the social crisis, the APEC was cancelled and the COP25 summit changed its location, October 2019.
- COP25 was moved to Madrid, but Chile retained the COP presidency until the next version in Glasgow 2020, November 2019.

In this context, the COP presidency offers a unique opportunity to influence the international and national debates, by drawing the attention to the urgency of facing the challenges regarding climate change, and considering the conditions of inequality and its relationship with social crises. In a first approximation, the link between social crises and climate change is not evident; however, an in-depth analysis allows us to understand the deep articulation between these social and environmental phenomena, as discussed below.

There is growing evidence that climate change contributes to generate or radicalize social crises and that this will deepen in the future. Researches over the last decade show that deviations from the "normal" temperature and precipitation patterns for a given geographical context are systematically associated with an increased interpersonal violence, criminality and various forms of political instability, institutional crisis and conflict, as can be observed in protests and even civil wars, ethnic violence and hotbeds of war between countries (Burke *et al.*, 2009; Burke, Hsiang and Miguel, 2015; Hsiang, Burke and Miguel, 2013; Gleick, 2014; Hsiang and Burke, 2013; O'Loughlin *et al.*, 2012, Werrell *et al.*, 2013). These effects may be related to food insecurity, water scarcity, the occurrence of disasters, price increases or even measures implemented to respond to the impacts of climate change (National Research Council, 2013; von Uexkull *et al.*, 2016).

The IPCC's 5th Assessment Report reflects these concerns as part of its Chapter 12 (justifiably entitled "Human Security"). There is evidence that relates climate change to different dimensions of human security, from the ability to maintain one's own way of life to cultural tensions, migration and situations of social conflict. While recognizing the complexity and multi-scale nature of these phenomena, it also affirms the importance of recognizing the interdependencies between these different processes, and that climate change represents one of the most important factors of human uncertainty in the future.

One issue that could help to illustrate these challenges for Chile from now and in the near future has to do with water conflicts and its system of tradable water rights.

From a primary point of view of the authors, the privatization of water rights in Chile, along with a lack of prioritization among competing water uses (Arnold, Troost and Berger, 2014; Bauer, 2015) has led to a progressive process of accumulation and speculative hoarding of water volumes by powerful actors (Arnold, Troost and Berger, 2014; Prieto Montero, 2016), while gradually dispossessing subsistence farmers (Delgado *et al.*, 2015) and producing an increased vulnerability of rural potable water users (Fundación Chile, 2018). As a consequence, increased conflicts around water (Costumero *et al.*, 2017; Rivera *et al.*, 2016) arise, and even a progressive increase in water stress in some parts of the country (Meza *et al.*, 2019; Urquiza and Billi, 2018) (nearly ten years of persistent dry years in most regions across the country). These effects combined with land dispossession and deforestation, tend to increase inequality and environmental vulnerability, resulting in a double exposure of local communities to the combined effect of climate change and socioeconomic forces they have little control upon (Montaña, Diaz and Hurlbert, 2016). This example also shows deep and intertwined bonds between Chile's development model and the environmental inequalities and injustices.

From a second point of view of the authors, a tradable water rights system has had several benefits relative to the efficiency of water use and the economic development (Donoso, 2015). However, analyses have warned about a lack of institutionalized prioritization among competing water uses (Bauer, 2015) and of a progressive accumulation process as well as a speculative hoarding of water volumes in some sectors (Arnold, Troost and Berger, 2014; Prieto Montero, 2016). A reform in year 2005 upgraded the system by penalizing unused water rights and by introducing additional requirements for granting new water rights, but there are several challenges that still remain (Delgado *et al.*, 2015; Donoso, 2015). Persistent dry years in most regions of the country may increase vulnerability of subsistence farmers (Delgado *et al.*, 2015) and of rural potable water users (Fundación Chile, 2018) along with conflicts related to water (Costumero *et al.*, 2017; Rivera *et al.*, 2016), and even a progressive increase in water stress in some parts of the country (Meza *et al.*, 2019; Montaña, Diaz and Hurlbert, 2016; Urquiza and Billi, 2018).

Although the relationship between the social conflict and climate is highly complex, and the processes that link different types of climate hazards with the different phenomena of violence, instability and socio-political crisis are yet to be defined (Brzoska and Fröhlich, 2016; Buhaug, 2015; Salehyan, 2016), it is already evident that these risks are lower in countries with institutional and social abilities that allow them to respond and adapt to these threats National Research Council (2013).

It is essential to understand climate change as a complex and multidimensional risk that works as a "threat multiplier" that worsens social, economic and environmental pressures, leads to social protests and triggers violent conflicts. If we fail to reduce greenhouse gas emissions and build the ability to manage the impacts of this phenomenon, we will face more tensions, instability, and crisis in the long term. The world will become less stable and less secure.[1]

Based on the Chilean current socio-political scenario, the NDC update and future climate change commitments will be part of the main structural changes that will have an impact on priorities and focuses.

The discussion about the Chilean constitution has been planned as the main political activity for the year 2020, in parallel with the update of the Chilean NDC.

To deal with the social and economic inequities existing in the country, an economic and social agenda involves, among other changes, a guaranteed minimum income, pensions, taxes, and the educational system.

1 "Climate Change Poses Increasing Risks to Global Stability," United Nations Climate Change, 21 February 2017, https://unfccc.int/news/climate-change-poses-increasing-risks-to-global-stability.

In this context, quick, far-reaching and unprecedented transformations are required to reach the warming goal of 1.5°C. The IPCC Special Report SR1.5 sets out that the feasibility of those transitions includes social/cultural feasibility and institutional feasibility (Figure 5).

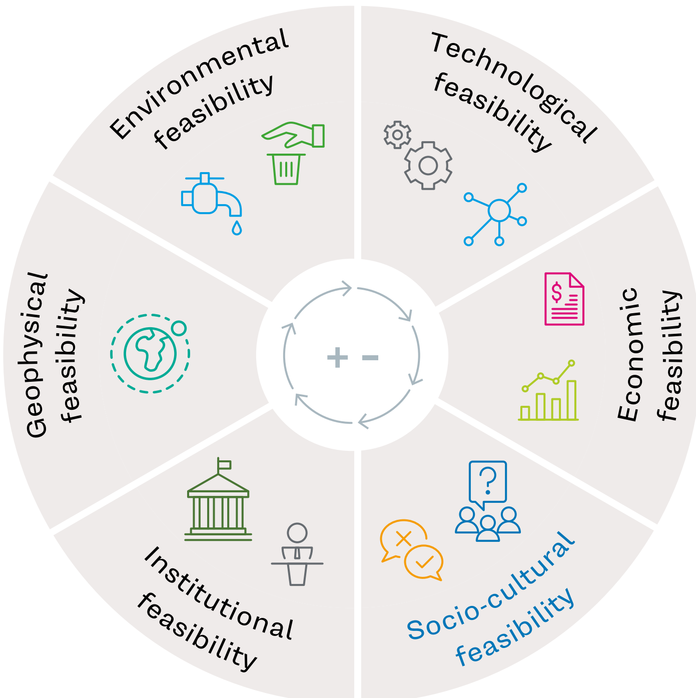

Figure 5: Feasibility dimensions towards limiting warming to 1.5°C.
Source: based on Masson-Delmotte *et al*. (2007).

1.4 SCOPE OF WORK AND PAPER STRUCTURE

As in its 2015 NDC, Chile's NDC 2019 draft proposal includes separate unconditional targets for the forestry sector. Chile has now doubled these targets from 100,000 hectares to 200,000 hectares, proposed for a sustainable management and other 200,000 hectares to be reforested. Another LULUCF target in the updated NDC is a 25% reduction in emissions related to forest land degradation and deforestation of the primary forest, compared to a reference value of the average annual emissions between 2001 and 2013.

The analysis of this topic is out of the scope of the paper. Nevertheless, a specific working group was created in the Chilean COP25 Scientific Committee. The detailed results of this working group can be found in reference (Rojas *et al.*, 2019). It is worth noting that a comprehensive assessment of the Chilean NDC mitigation requires information from both the LULUCF and non-LULUCF targets.

Additionally, specific aspects regarding nature-based solutions and black carbon are included due to the importance of these topics in the current discussion in the field of mitigation.

This paper is a joint work among Government representatives and researchers from Chilean research institutions. The result represents a consensus among the different visions and perspectives. Open discussion issues are highlighted for future analysis.

After a general description of the Chilean NDC process, local context, and historical evolution (Section 1), Section 2 describes the methodological approach followed by the Chilean Government. This description includes the development of a common understanding and critical analysis along with the scientific mitigation and the energy working group. Section 3 is aimed at a more detailed analysis of the key topics closely related with methodology, simulations, results, and the NDC proposal. Section 4 analyses the main uncertainties that may have an impact on the final results and decisions. Finally, Section 5 summarizes the main conclusions and recommendations.

2 Methodological approach

The vision of the country about the management of climate change guided the work of scenario forecasts, which were defined under two timelines:

Medium-term (in line with NDC): Year 2030

> *"Each Party shall prepare, communicate and maintain successive national determined contributions (NDCs) that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions". (Article 4.2 of the Paris Agreement)*

The medium-term vision is defined as part of the modernization stage of the NDC, under the coordination of the Ministry of the Environment, and with the collaboration of stakeholders from the public and private sectors, the academia and civil society.

Long-term: Year 2050

> *"All Parties should strive to formulate and communicate long-term low greenhouse gas emission development strategies" (Article 4.19 of the Paris Agreement).*

The long-term vision for the country is to be outlined through a collaborative process that will be executed during 2020, within the framework of the design of a Climate Strategy for low GHG emissions and sustainable development by 2050 for Chile.

This modeling considered all five sectors of Chile's last National GHG Inventory: Energy, Industrial Processes and Product Use (IPPU), Agriculture, LULUCF and Waste. For each sector, the activity data used for the GHG estimate was projected according to the guidelines of the National GHG Inventory System of Chile (SNICHILE). Subsequently, estimating methodologies were applied to this data, in compliance with the 2006 IPCC Guidelines.

As for the Energy sector, this forecasting was carried out with the tools available at the Ministry of Energy to assess energy demand and supply scenarios. These are the main instruments with which the Ministry prepares scenarios for their Long-Term Energy Planning (PELP). This Model includes insight from other ministries as well as from other key actors, such as NGOs and the private sector.

As for IPPU, Agriculture, LULUCF and Waste sectors, the fundamental indicators of each classification or sector were forecasted, such as: GDP, production, population, heads of livestock, hectares of expected forestation, etc.

Definition of the mitigation measures to be considered in each scenario
In order to define the specific mitigation measures to be modeled under each scenario, two methodologies were used.

Specific information published regarding policies, strategies and plans to reduce GHG emissions has been collected for the current scenario, therefore modeling is produced while considering these mitigation measures under an active use. The spirit of this scenario attempts to project what we already know or what we believe will happen, while reducing the uncertainty of the forecast.

Meanwhile, in the case of long-term exploratory scenarios, such as scenarios that seek to present a national emissions structure with a balance of neutrality by 2050, deeper reflection and debate is required to discuss potential future policies, strategies and plans, along with a long-term country vision to define desired standards, such as energy efficiency, technological changes, fuel changes, or other areas of climate change mitigation, and their related uncertainties.

2.1 NDC PROCESS

Since 2018, the Climate Change Office (CCO) of the Ministry of the Environment has been working on the revision of the current NDC in order to enable its update. Consequently, the CCO arranged a public sector committee, composed of different representatives of the public sector, to submit a diagnosis of the contribution in 2015. This diagnosis was based on transparency and the possibilities of an increasing ambition.

During 2019, in the context of the COP25 led by Chile and the new announcement of GHG-neutrality included in the preliminary draft of the "Framework Law for Climate Change", the CCO began the process of updating and incorporating new content into the NDC.

For the update on mitigation elements, the CCO has been given the task of integrating the 2050 vision to the medium-term goal of 2030. To give rise to this national vision reflected in different paths or scenarios by 2030 and 2050, the CCO has arranged a series of meetings with multiple public and private actors in order to exchange and combine ideas to achieve GHG-neutrality and increase goal ambition by 2030. The general work scheme is summarized in Figure 6.

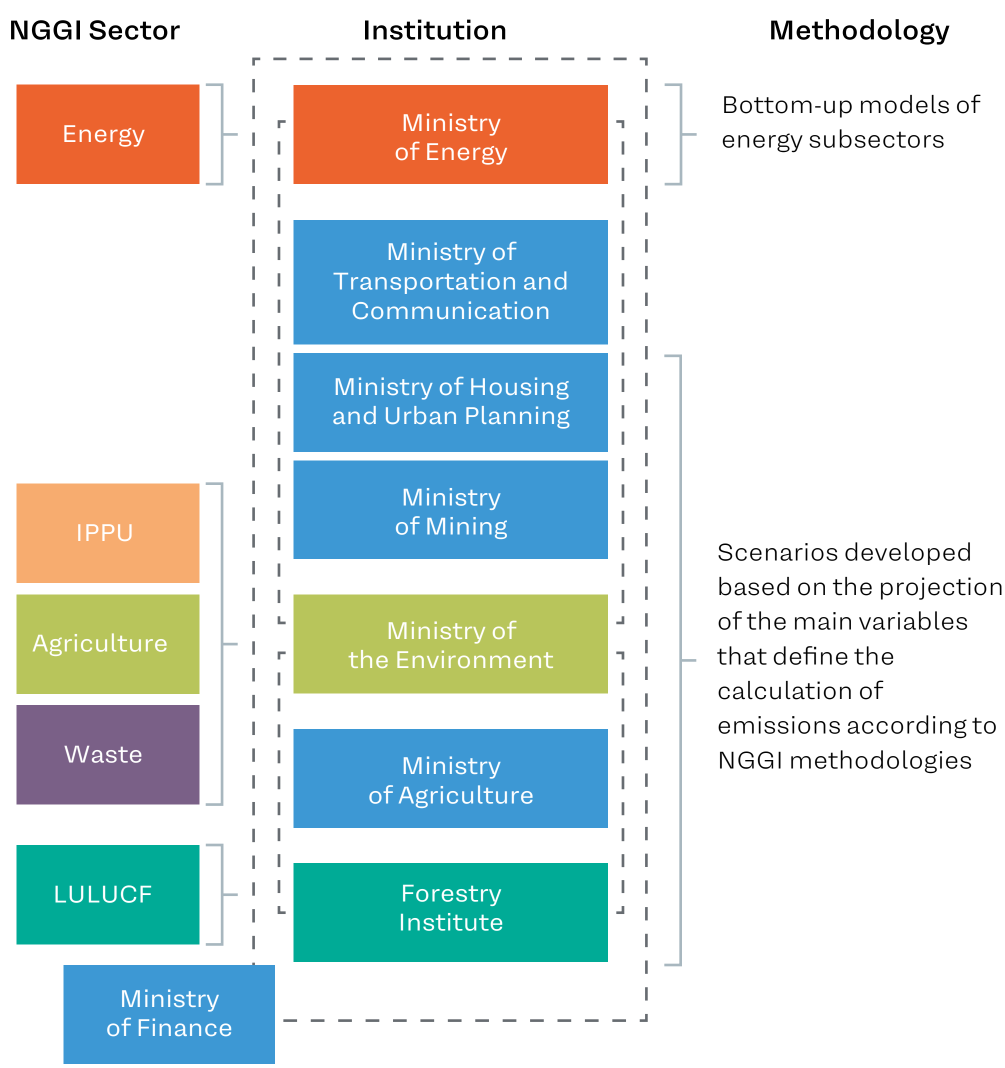

Figure 6: General work scheme.

The purpose of these meetings was agreeing on different matters, and assessing how these could be represented in each scenario, i.e. increased efforts in actions and plans already in progress; addition of other measures; interpretation of macroeconomic variables; revision of indicators and transparency; incorporation of climate justice for the definition of the final goal; amongst other topics.

As for GHG emissions and absorption projection of each scenario, five sectors currently present in Chile's latest NGGI were considered. These are the 1990-2016 series, included in the third biennial update report (BUR). The scenarios project the influence of different variables (economic growth, population, current policies and new measures) on the main activity indicators of each sector, such as energy demand, production, livestock, generation of waste or changes in land use. Subsequently, emissions and absorptions are estimated in accordance with the guidelines of SNICHILE and the 2006 IPCC Guidelines for the elaboration of national GHG inventories.

Thus, emissions from the Energy sector are estimated by the Ministry of Energy based on their experience in the PELP process, supported by the insights of the Ministries of Transportation and Communications, Housing and Urbanism, and Mining. Remaining emission and absorption rates are projected by the CCO, supported by the Ministry of Agriculture and the Forestry Institute. In addition, the Ministry of Finance also participates in the process, by reviewing the consistency of the macroeconomic variables used in the different processes.

2.2 MODELLING FRAMEWORK

2.2.1 Overview

The flowchart in Figure 7 shows the general framework used in the process of energy analysis, including its main components. The flowchart is divided into sections A - G depicting the logical stages of the methodological approach. Complementarily, each block represents a specific model, a common assumption of forecasted variables, and the criterion used alongside the process. Section A includes base forecasted variables (upper left), including demand for services (bottom left), and reference emissions (on the right). Section B comprises the synthesis of mitigation option proposal and assessment through the sectorial models in section C. In section D, abatement cost curves are calculated on the basis of reference cost/emissions. Calculated emissions in section C plus other emissions, completes the national GHG emissions estimated in section E. Finally, in section F, the estimated GHG emissions are confronted with the general goal of the process. Once achieved the complying mitigation options characterized in section G, constitute and support a relevant portion of the new NDC proposal.

In section A of the process, main macro and microeconomics forecasting are stated, based on future estimates from local authorities and international references. Local and supplementary variables such as socio-economic variables were also forecasted to feed modules for the projections of national demand for services energy. These demands for services are converted into energy needs using specific models by economy sector, and more recent national energy inventories as a starting point. The current national mitigation policies scenario for emission projections is calculated accordingly and used as a base reference to compare emissions and cost levels obtained for trial mitigation policies, or mitigation scenarios (section B), in the assessment period from the current year to 2050.

In section C, while the electricity sector is directly modelled as a centralized and deterministic least-cost, remaining sectors are simulated by supplying the demand through predetermined trial technologies, and the costs are estimated by C(t) x D(t). In the second case, cost effectiveness needs to be found upon considering the options available for technology adoption and cost assumptions.

From a calculation point of view, the process depends on several interconnected modules to form an iterative heuristic approach to search for a combination of mitigation options, under a least-cost objective in order to reach a GHG emission goal. The loop goes back and forth from the bottom of section A through section F until the condition is reached.

Mitigation option alternatives include diverse technology adoption, intensities, timing, demand management and reallocation of demand for energy among sectors. These alternatives are proposed, compiled, and assessed in section B, following either one of these opposite directives: increase of the mitigation ambition or continue the search for further cost reduction.

As a start, and as reference scenario, the iterative process begins with the calculation of GHG emission and costs under current national policies regarding technology adoption, and costs under the forecasted base-variables scenario. When entering section D, this result allows the calculation of marginal abatement costs used to guide the assembling of new mitigation action trials to be assessed in each module. Its output, in turn, feeds back refined marginal costs and emission calculation. The emission forecast of this new mitigation scenario proposal, plus the emissions of other non-energy sources, are confronted to comply with the main goal of the process, targeted as the accomplishment of national GHG-neutrality by 2050. This neutrality target assumes a predetermined LULUCF curve that reaches 65 $MtCO_2eq$ capture by 2050. Failing to comply with this target establishes an increase in mitigation action ambitions (either by adding new actions or increasing the intensity of the existing ones) to be introduced in the loop in the next iteration. On the other hand, if the target is met, costs are revisited for further cost reduction. The interactive process ends when both target neutrality and no possible cost reduction criteria are met.

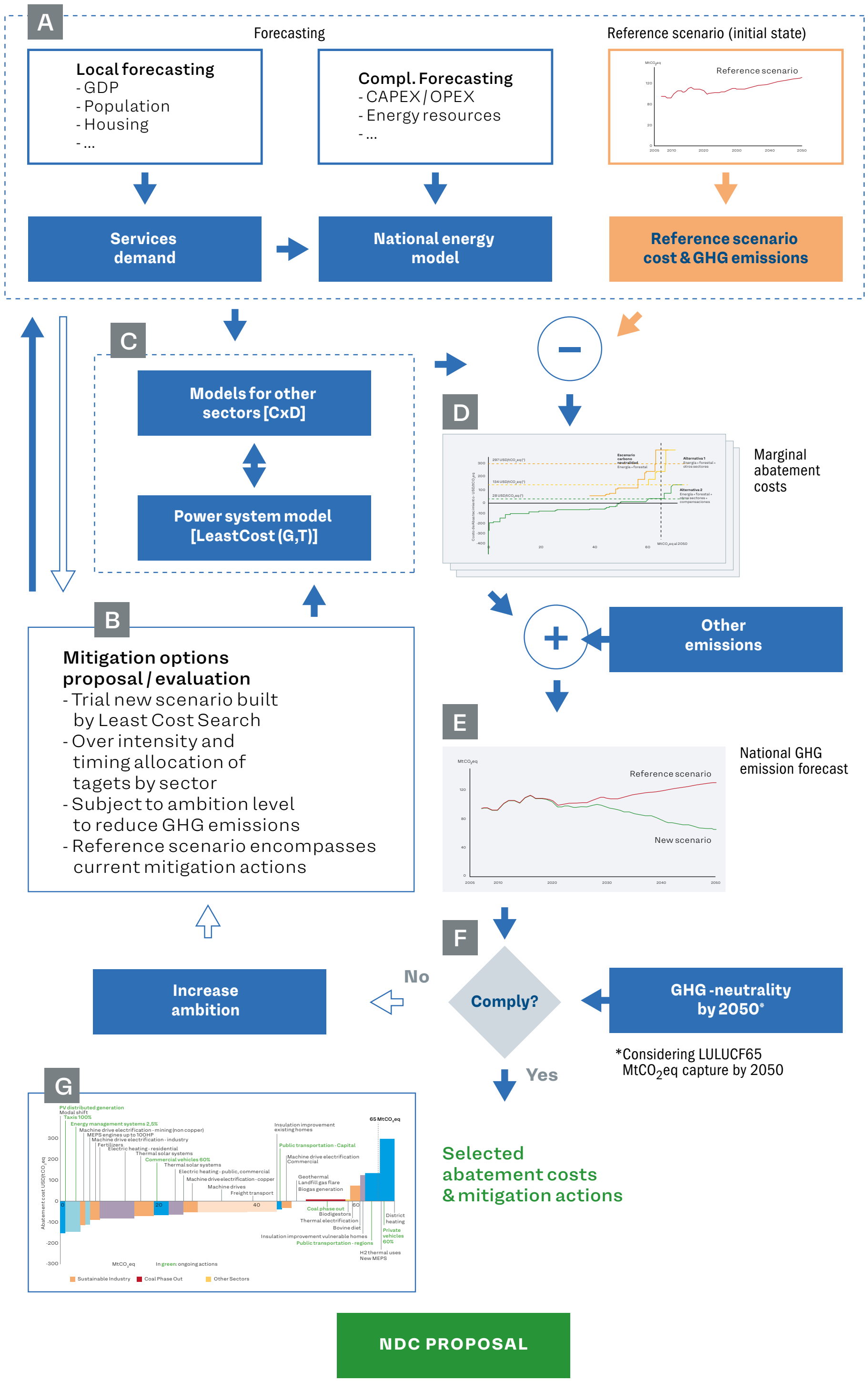

Figure 7: Modelling framework for the NDC mitigation proposal, energy sector.
CAPEX: Capital Expenditures.
OPEX: Operational Expenditures.

Table 2 summarizes the resulting mitigation options modelled and selected as a result of the process for the reference and GHG-neutrality scenario.

Table 2: Mitigation measures per scenario.
MEPS: Minimum Energy Performance Standards
Note: All measures for the Energy sector were analyzed by the Ministry of Energy.

Description			Reference Scenario	GHG-Neutrality Scenario
Action	**Policy**	**Sector**		
Coal Phase Out	Renewable energy in replacement of coal	Energy	Decommission of 2,500 MW by 2050	Decommission of 5,500 MW by 2040
Sustainable Buildings	Insulation improvement and electric heating	Energy	General Ordinance of Urban Planning and Construction (OGUC)	OGUC & 57% of houses (70% of apartments) use electric heating by 2050
	Thermal solar systems	Energy	No actual measures	52% and 10% for hot water uses in houses and hospitals respectively, by 2050
	PV distributed generation	Energy	1,278 GWh Residential and 3,633 GWh commercial by 2050	1,800 GWh residential and 5,657 GWh commercial by 2050
	Insulation improvement of vulnerable homes	Energy	No actual measures	20.000 homes per year
	New MEPS	Energy	No actual measures	MEPS on TVs, dishwashers, tumble dryers, electric ovens and microwaves
	Electric heating in the public and commercial sector	Energy	No actual measures	Supermarkets, retail, private clinics use: 84%,76% and 48% by 2050
	Geothermal heat pumps	Energy	No actual measures	35 GWh nationally by 2050
	District heating	Energy	No actual measures	0.2% of the energy matrix for heating
Electromobility and modal shift	Electric taxis	Energy	21% of taxis by 2050	100% of taxis by 2050
	Public transportation - capital	Energy	20% urban public transportation in Santiago by 2050	100% urban public transportation in Santiago by 2040
	Public transportation - regions	Energy	0% urban public transportation in regions by 2050	100% urban public transportation in regions by 2040
	Private vehicles	Energy	21% private vehicles by 2050	58% private vehicles by 2050
	Commercial vehicles	Energy	21% commercial vehicles by 2050	58% commercial vehicles by 2050
	Modal shift	Energy	No actual measures	Replacement of private motor transportation for buses and bicycles
Hydrogen	Freight transport	Energy	No actual measures	71% of freight transport by 2050
	Machine drives	Energy	No actual measures	12% of machine drives in industry and mining by 2050
	Thermal uses	Energy	No actual measures	Replacing natural gas for thermal use: 7% of housing and 2% of industrial by 2050
Sustainable Industry	Thermal solar systems	Energy	No actual measures	10% thermal use in industry and 16% in copper mining
	Electrification of machine drives - mining (non-copper)	Energy	No actual measures	52% in mining (non-copper) by 2050
	Electrification of machine drives - industry	Energy	No actual measures	67% in miscellaneous industries by 2050
	Electrification of machine drives - commercial	Energy	No actual measures	56% in the trade sector by 2050
	Electrification of machine drives - copper mining	Energy	No actual measures	57% in open pit mines by 2050 and 74% in underground mines by 2050
	Biogas generation	Energy	No actual measures	New landfill sites with electricity-powered centrals
	Thermal electrification	Energy	No actual measures	Additional thermal use of 25% in industrial and mining sectors
	Energy Management Systems	Energy	Annual savings of 0.6%	Annual savings start at 0.6 % and increase up to 2.5%
	MEPS engines up to 100HP	Energy	No actual measures	Full replacement by 2030
Non Energy	Capture or use of landfill gases	Waste	Current projects only	100% of urban domestic waste deposited at landfills with gas capture or use by 2035
	Sludge from wastewater treatment plants as a forest bio-stabilizer	Waste	No actual measures	New treatment plants in the Gran Concepción and Gran Valparaíso, with methane management and sludge use, by 2035
	Anaerobic bio-digestion of pig manure	Agriculture	No additional projects	71% of pig heads manure destined to biodigesters
	Technical assistance for efficient use of fertilizers	Agriculture	No actual measures	Program applied for industrial, forage and cereal crops by 2035
	Bovine diet change	Agriculture	Trend	Digestibility levels of 79% reached by 2050
	Afforestation, forest management and avoiding degradation	LULUCF	Trend, no incremental programs or land use changes	300,000 hectares of sustainable management, 250,000 hectares of permanent afforestation, 250,000 hectares of commercial plantations, and a 25% decrease in degradation and deforestation

2.2.2 Models, parameters and forecasting

Simulation tools

The following models are used as simulation modules in the framework:

Energy Demand: Long-range Energy Alternatives Planning (LEAP) System. Simulation software of energy systems used for the analysis of energy policies in the medium and long term, through an integrated representation of the energy demand using a bottom-up methodology for each of the economic activities of the country according to the structure of the National Energy Balance, considering the multiple final uses of energy in each sector. It incorporates information at a regional level. The model allows the representation of all energy sources in the country, in accordance to the BNE with regional disaggregation. The modeling allows the estimate of future energy demand through the projection of the main activity data and socioeconomic variables. Its functionalities include the accounting of sources and sinks of greenhouse gas emissions from the energy sector.

Power System: Central planning for the national generation and transmission interconnected system. Approach based on a deterministic least-cost, implemented in a platform named AMEBA.

AMEBA is an analysis tool for energy systems, capable addressing decision-making of electricity markets. It allows the study of short-term phenomena (economic dispatch and unit-commitment), medium-long term (hydrothermal coordination) and long term (investment planning in generation and transmission). Generation expansion planning and transmission reinforcements described throughout this report were determined with the support of the AMEBA platform. It determines the future expansion in order to jointly minimize the expected value of operating costs (fuel and failure costs) and investment costs (capital and maintenance) of the electrical system for a given time horizon.

Other sectoral model accounts for supplying a forecasted demand for services, prepared by each related ministry, based on common socioeconomic projections.

More details about sectoral models are presented in section 3.

Main forecast scenario and sources

The following table summarizes the sources of the main forecasted variables and sub-scenarios selected that define the forecasting set of exogenous input variables in the simulation process.

Main forecast Variable	Main National Reference Source	Sub Scenario		
		Low	Med (trend)	High
GDP	Ministry of Finance, 2019		√	
Population	National Statistics Institute, 2017		√	
Fossil fuels costs	Ministry of Energy, PELP 2019*			√
Renewable costs (CAPEX OPEX)	Ministry of Energy, PELP 2019*	√		
Other tech (CAPEX OPEX)	Ministry of Energy, PELP 2019*		√	

Table 3: Main forecasted variables, sub-scenarios and sources.
(*) National Long-Term Energy Planning exercise, built from multiple international sources.

For other forecasted variables not mentioned in the table above, the sub-scenarios selected and used in the process are those in the medium trend of their respective outlooks. Finally, some methodological guidance and parameters used in the present work are shown in the Table 4.

Parameter	Source	Web Reference
Methodology	2006 IPCC "Guidelines for National Greenhouse Gas Inventories" (Vol2)	https://www.ipcc-nggip.iges.or.jp/public/2006gl/spanish/vol2.html
Emission factors	2006 IPCC "Guidelines for National Greenhouse Gas Inventories" (Vol 2, Ch 2)	https://www.ipcc-nggip.iges.or.jp/public/2006gl/spanish/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf
Global Warming Potential (GWP)	IPCC 2018, "Fourth Assessment Report of the Intergovernmental Panel on Climate Change" (AR4)	https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-ts-1.pdf
Energy densities, calorific value	Ministry of Energy, National Energy Balance	http://datos.energiaabierta.cl/dataviews/238711/balance-nacional-de-energia/

Table 4: Other parameters and sources.

3 Analysis of key topics

Based on the previous context and methodological approach, key topics are selected by the authors for further analysis and discussion. This analysis sets the grounds for the recommendations and conclusions of this work.

3.1 INFORMATION TO FACILITATE NDC CLARITY, TRANSPARENCY AND UNDERSTANDING

In accordance with the provisions of the Katowice Rulebook (United Nations, 2019) regarding the information to facilitate NDC clarity, transparency and understanding (Annex I, Decision 4 / CMA.1), the following is recommended to the 2019 NDC proposal:

1. **Regarding reference point information**: The unconditional mitigation goal without LULUCF consists of an emission budget for a defined period between 2020-2030, therefore a reference point is not required. However, the goal conditional on additional international financial flows commits up to 45% of net emission reduction based on 2016's. In that case, it is recommended that a line of argument regarding the change of the base year from 2007 to 2016 is presented along with providing information about the change of the goal type, enabling the assessment of whether the conditional goal of NDC 2019 is more ambitious than the conditional goal presented in NDC 2015. The inclusion of absolute and net emissions of 2016 is also recommended, expressed numerically along with the source of information. Finally, it is suggested to establish whether there will be circumstances under which the country may update the reference year 2016, or clarify that the year 2016 will not be modified under any circumstances.
2. **Regarding time frame and implementation period**: The unconditional mitigation goal without LULUCF consists of an emission budget for a defined period between 2020-2030, where the time frame and implementation period are clear. However, the year of maximum emissions is also committed for 2027. Chapter 6 of the proposed update of the NDC 2019 establishes that the goal by 2027 is indicative. It is very relevant to clarify whether the year of maximum emissions will be no later than 2027 or that it may be after 2027. It is necessary to establish the time frame of the conditioned goal for a full understanding of the emission reduction committed.
3. **Regarding scope and coverage**: On the one hand, there is a transversal goal to the economy that includes the sectors of energy, industrial processes and use of products, agriculture and waste, and on the other hand there is an exclusive goal of LULUCF sector. Additionally, a goal of 45% of net emission reduction is established based on 2016, which includes all sectors of the national greenhouse gas inventory (including LULUCF). It is very important to provide information that ensures the methodological consistency between the three goals, including the projection of emissions of each sector and the reasons why the LULUCF sector is excluded from the emission budget. Finally, it is recommended to include co-benefits of the mitigation that result from the reduction of black carbon, in addition to other mitigation co-benefits that may result from specific projects and economic diversification.
4. **Regarding planning processes:** It is recommended to include an analysis of how economic and social consequences of response measures were considered in the NDC update proposed.

5. **Regarding methodological approaches and assumptions for emission estimates:** This section has substantial room for improvement since the 2019 NDC proposal only mentions the use of the IPCC guidelines for emission estimate inventories. For clarity, transparency and understanding of the contribution, it is necessary to know the following: GDP projections by 2030; 2030 emission projections; assumptions used for the projection of emissions; emission reduction scenarios by 2030; policies and measures considered in emission reduction scenarios; methodological considerations on the mega-wildfires of 2017 and the loss of their emission absorption; information on how climate forcers were estimated. It would also be relevant to include how voluntary cooperation will be considered in the absence of Article 6 of the Paris Agreement.

Based on these recommendations and also on the criteria and background of the authors, a further analysis for key topics is presented in the following sections, where most of the recommendations to better understand the 2019 NDC proposal are solved.

3.2 SCENARIO ACCURACY BASED ON PREVIOUS EXPERIENCES

As described in Section 1.1, several initiatives on energy forecasting and the estimate of GHG emissions at national level have been carried out. These exercises have enabled the establishment of permanent capacities for the training of human capital in this field.

Previous experiences have shown that it is hard to foresight the future, especially for models that are very sensitive to some key parameters such as GDP growth (main driver of the energy demand in most sectors), technology costs (e.g. PV investment costs and wind power), etc. On the other hand, they have shown how the results derived from the projection of scenarios can be very different from actuals in short/medium term (5 years) time horizons.

In the context of the Scientific Committee's support for updating the NDC, a comparative exercise was carried out between past prospective scenarios and the latest available values (Comité Científico COP25, 2019). The results of the initiatives "Energy Scenarios 2030" (Dufey *et al.*, 2013) and "MAPS Chile Phase 2" (SEIA and "MAPS Chile Phase 2" (MAPS Chile, 2014) were assessed against actual 2018 values for electricity generation, as well as greenhouse gas emissions projections of the MAPS Chile initiative with respect to the latest projections in this area.

As a summary, the main reasons that explain the differences observed between projections and actuals are:

- Differences in the projection of technology prices.
- Differences in resource availability estimates.
- Differences in the estimate of the penetration of mitigation measures (due to delays in the application of public policy instruments).
- Differences in the projection of input drivers (e.g. GDP) models are sensitive about. These elements should be considered when assessing current NDC by incorporating these elements as part of the uncertainty. It should be noted that prospective exercises were more conservative than actuals in terms of renewables penetration and GHG emission levels.

It is important to emphasize that these differences should not be understood as modeling errors, but as differences caused by the uncertainty of projection models. Because of this, it is critical to develop a sensitive and uncertainty analysis to conduct periodical reviews and updates on the scenarios developed.

3.3 DEMAND AND SECTORAL MODELS

In general terms, demand models used correspond to simple quantity projection schemes on the horizon using macro information related to country's development, cautioning the interrelations between the different sectors and the effects mitigation measures have between them.

Methodologically, the demands are directly input into a general cost accounting scheme [C(t)xQ(t)], where C represents the cost of satisfying (Q) demand with the available technological options, searching the most economical means among them in the evaluation horizon. In each sector, the effects related to price response, typical of equilibrium models [C(t)xQ(C(t), t)], are discarded.

3.3.1 Common base projections

The projections of common base variables encompass the following methodologies and sources:

The National Energy Balance is used to establish the base line in terms of energy consumption for each of the sectors of the economy: industry, mining, transportation, commercial, public and residential, using regional disaggregation and separated energy sources: electricity, oil derivatives, natural gas, firewood, among others.

Country projections of growth of socioeconomic variables and productive activities: population, housing, public and private transportation, industrial mining production (cellulose, copper, iron), among others. Sources: INE, CASEN, SEC, other ministries.

The methodology for calculating the transportation sector in Chile includes land vehicles, ships, airplanes and off-road machinery. Bottom-up schemes are used to estimate activity, together with emission factors reported abroad and adapted to the reality of the existing fleet in Chile. Transportation demand estimates are divided into urban and interurban trips, for passengers and cargo in tons. In addition to estimating CO_2, criteria pollutants and black carbon are included.

The simulation of long-term energy scenarios presents a projection of national economic growth for the period 2018-2050 provided by the Ministry of Finance.

Economic growth forecast

Long-term energy scenario simulations used national economic growth forecasts carried out by the Ministry of Finance for the 2018-2050 period.

The estimate strategy distinguishes three periods: i) Long-term growth expected by 2050, ii) Medium-term or transition period, and iii) Short-term, period between 2019-2024, which incorporates the information available by the time of trajectory designing.

The GDP growth of 2018 considers the data observed in national accounts published by the Central Bank (Figure 8). For the short-term period between 2019 and 2024, the following sources of information were considered:

The GDP trend results report of the consultative committee of August 2018.

The monetary policy report of the Central Bank available by March 2019 and the public Q1 Budget Directorate finance report.

Economic expectation surveys and the update of the Consensus Forecast survey that includes the perception of the market and some study centers.

Complementarily, a product growth function was taken to be reconciled with information from other sources.

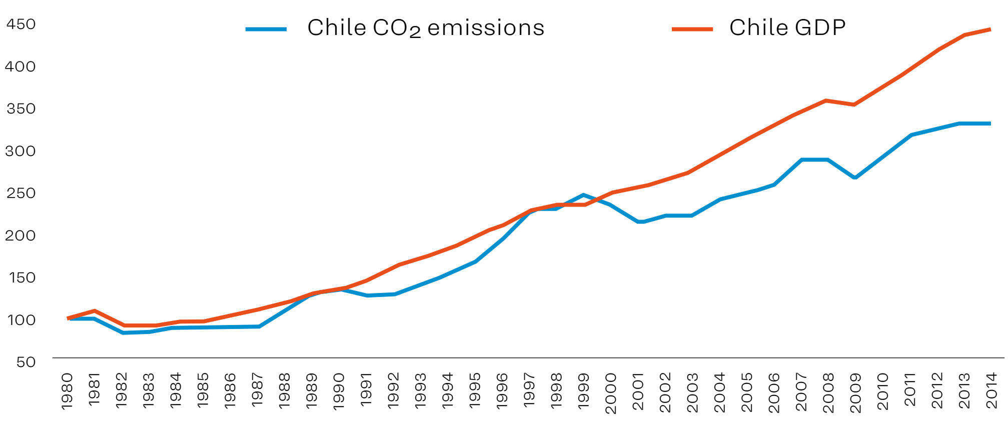

Figure 8: GHG emission projection MAPS Chile and current scenarios (reference year 1980).

The long-term growth rate of 2% for Chile was estimated to be reached in 2049 and 2050 from a per capita GDP convergence exercise in the OECD group of countries, taking Australia and New Zealand as a reference, given their productive matrix (Figure 9). As for the interim period, a geometric extrapolation was made from short-term information with long-term convergence. In addition, the scenario was corroborated with the information available from the World Economic Outlook of the International Monetary Fund, OECD and the medium-term information collected by the Consensus Forecast.

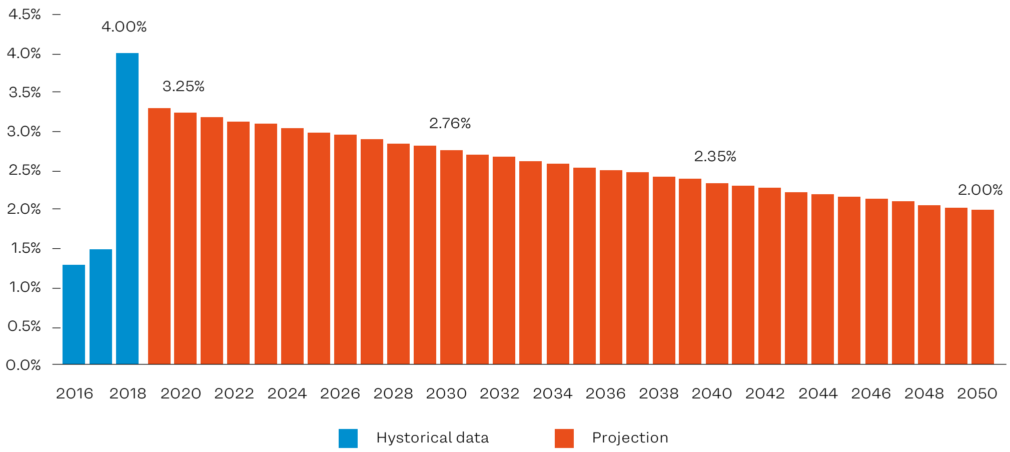

Figure 9: GDP growth rate projection.

Population projections

Population is one of the main determinants of the evolution of energy projections. The statistics of the National Institute of Statistics compiled from the last census have been considered. Between 2019-2050, the average population growth rate is 0.4% per year. Table 5 summarizes the projections for year 2030 and 2050.

Table 5: Population projections.

Year	2017	2030	2050
Population	18,419,192	20,735,289	21,626,079
Variation with respect to 2017	-	+13%	+17%

Fuel price projections

Price projections for the different fuels considered are shown. These are obtained from the price trajectories used by the Long-Term Energy Planning Process (PELP).

Table 6: Fuel price projections.

Prices	Diesel (USD/m3)	GN (USD/MMBtu)	Gasoline (USD/lt)	Kerosene (USD/lt)	GLP (USD/kg)
2016	571.62	8.03	1.00	0.83	1.88
2020	600.71	8.37	1.21	1.03	1.88
2030	808.18	9.72	1.46	1.41	1.88
2040	923.90	10.61	1.64	1.74	1.88
2050	965.67	11.94	1.72	1.94	1.88

3.3.2 Methodology of the electricity sector

The methodology of the electricity sector is depicted in Figure 10. Based on the "reference scenario", a first variant that considers the decommission of all coal-fired power plants by 2040 was elaborated according to the schedule established in the Voluntary Agreement between the Government and the industry (for 2024), and according to a trajectory defined based on the criteria regarding the useful life and economic assessment (between 2025 and 2040). This scenario was simulated and the costs of investment in electricity generation, operating costs of the electric system and equivalent CO_2 emissions were accounted for, which were then compared with the levels of the "reference scenario" to estimate the abatement cost of this measure (Figure 11).

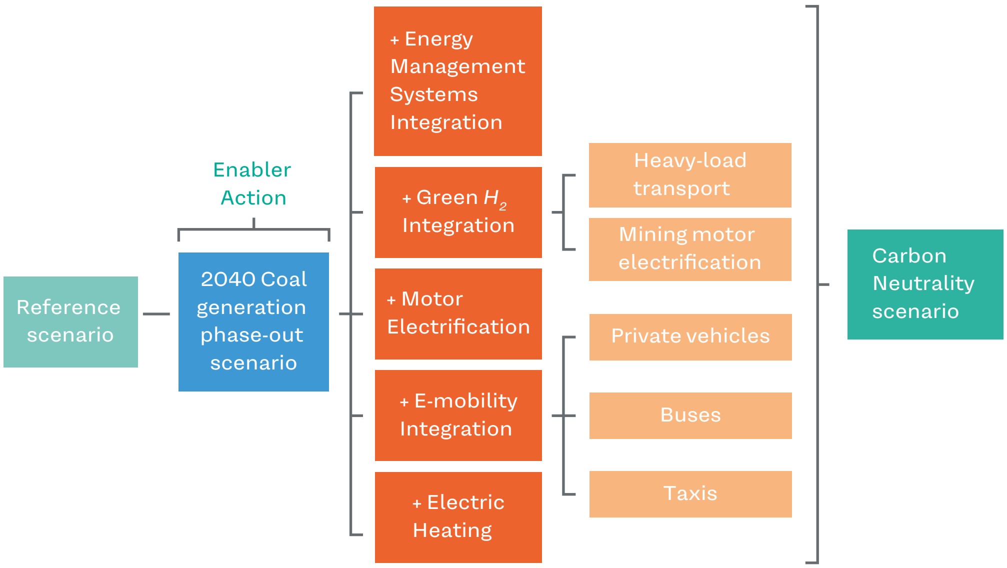

Figure 10: Methodology for the electricity sector.

In the GHG emission neutral scenario, coal phase-out by 2040 implies an electricity generation matrix with 85% of its installed capacity based on renewable energy, which makes it a propitious scenario for consumption electrification in different sectors of the economy, without practically increasing GHG emissions. In this sense, coal phase-out is considered an "enabling measure" for the adoption of those that increase electricity demand (hydrogen, electrification of machine drives, electromobility and electric heating). When analyzing generation at the end of the period, results are even better, reaching up to 95% of renewable energy generation.

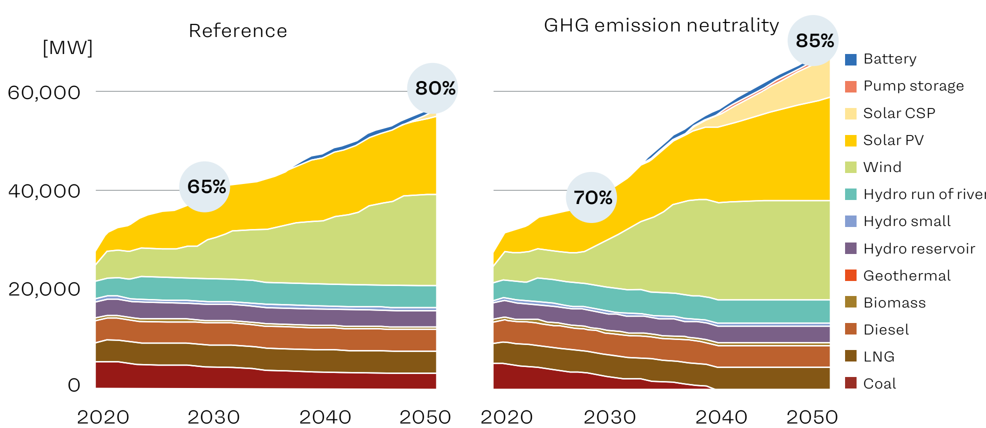

Figure 11: Installed capacity evolution under the reference and GHG-neutrality scenarios. Note: CSP (concentrated solar power), LNG (Liquefied natural gas), PV (photovoltaic)

Taking this into account, and in order to estimate the abatement cost of each measure, the effect on electricity demand related to electrification measures was simulated, considering the retirement of coal-fired power plants by 2040. For each simulation, investment costs in electricity generation, electric system operating costs and equivalent CO_2 emissions were accounted for and compared against the levels of the "2040 retirement scenario".

Finally, a "GHG-neutrality scenario" was simulated, considering the addition of the electrification measures described above, as well as others of energy efficiency or distributed generation (which were not individualized given the lower impact they have). Analogous to the individual measures, the investment costs in electricity generation, the operating costs of the electric system and equivalent CO_2 emissions were accounted for and compared against the levels of the "reference scenario", in order to quantify the cost of GHG-neutrality.

Additional considerations:

a) Infrastructure of the electricity generation sector. With respect to generation projects under construction, which should come into operation in the 2020-2024 period, that was published in the Short-Term Nodal Price Report in March 2019 by the National Energy Commission is considered. Additionally, the projects committed on the basis of the award of supply bids from regulated clients in recent years were considered, particularly the bids of 2015.

b) Potentials and profiles of renewable generation. The definition of areas with potential for electricity generation based on renewable energy resources is based on geo-referencing and characterization of resources usable for renewable energy, considering technical, territorial and environmental restrictions, through a combined use of geospatial information. The generation profiles of the solar photovoltaic (PV) and wind power plants are obtained from the information of the Wind and Solar Explorers. In the case of Concentrated Solar Power (CSP) plants, a fixed generation profile is used as a complement to photovoltaic production.

Major investment cost information used for this analysis is summarized in the following Figure 12.

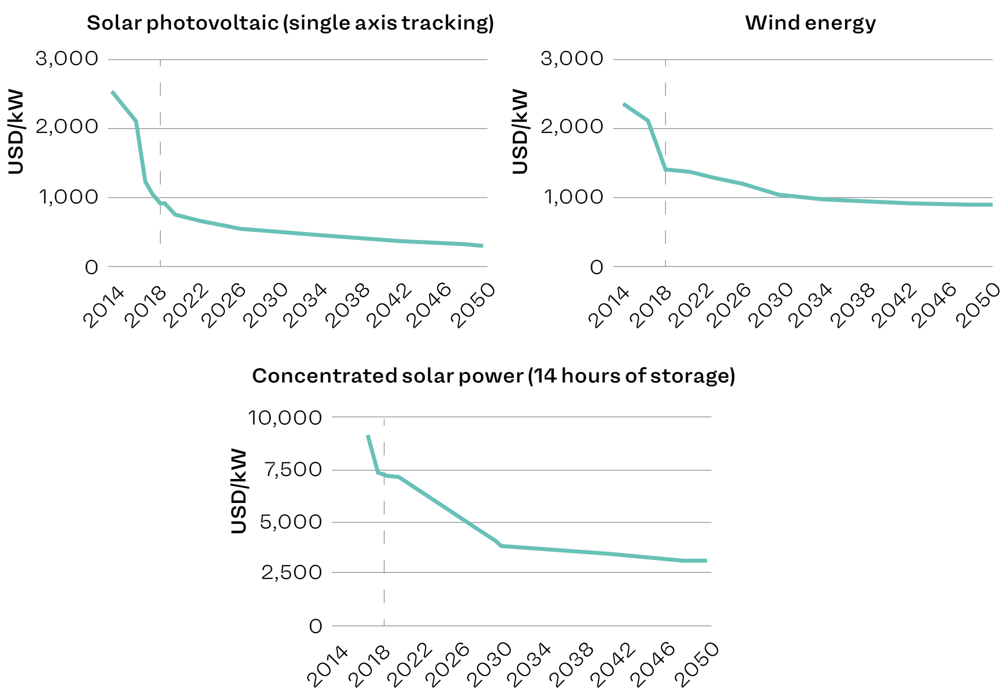

Figure 12: Renewable technology costs.
Sources: CNE, NREL, BNEF, IRENA.
CAPEX: Capital Expenditures.
OPEX: Operational Expenditures.

These cost projections constitute a key parameter for the overall assessment of the NDC scenarios. High levels of cost reductions in the future are considered for each technology. A sensitivity analysis for these projections is highly recommended to ensure the robustness of the proposed results.

3.3.3 Hydrogen

Hydrogen can help tackle various critical energy challenges. It offers ways to decarbonize a range of sectors where it is proving difficult to meaningfully reduce emissions. It can also help improve air quality and strengthen energy security.

The use of green hydrogen (H_2) was analyzed in the following cases:

Diesel replacement in national land freight transport (85% of vehicles with capacity U5 ton).

Replacement of diesel engines in mining and domestic industry (37%, 12% and 8% of the energy used for motor purposes in the Pit Copper, Miscellaneous Industries and Underground Copper sectors respectively).

Gas replacement for residential and industrial uses (7% of the energy used for domestic hot water). Combined LNG-H_2 for power generation.

Methodology

First, the energy demand per sector is projected for the base scenario and for the H2 scenario.

Next, the costs of investment and operation of electricity generation and transmission infrastructure are calculated.

Next, the investment and operation costs of other infrastructure and machinery are calculated: (i) electroplating plants, (ii) diesel machinery, (iii) hydrogen machinery, (iv) gas pipelines.

Finally, the difference in total costs and emissions is estimated to calculate the abatement cost of the measure.

Key scenarios and assumptions

The H_2 penetration scenario described is analyzed and then a more aggressive adoption scenario.

Optimistic projection of investment costs in hydrogen and renewable generation technologies.

Projection of high fuel prices (diesel, coal and natural gas).

Electroplating plants connect to SEN and have electricity supply contracts.

The measure is robustly cost-efficient for several other scenarios preliminarily analyzed. However, it heavily depends on technological advances, human capital formation and the ability to effectively deploy the necessary electrical and non-electrical investments.

3.3.4 Electrification in motor uses

The measure of motor electrification is presented as a real alternative to achieve GHG-neutrality given its low abatement cost, mainly driven by savings in fuel consumption by the greater efficiency of electric motors compared to diesel. While more intensive electricity penetration offers an even better abatement cost, the effective reduction in emissions by 2050 only increases by 38%.

The increase in the share of electricity in motor use was analyzed in the following cases:

- Increase in the share of electricity in the Copper Mining sector, reaching 65% of total energy consumption for motor uses.
- Increase in the share of electricity in the whole Mining Sector, reaching 44% of total energy consumption for motor uses.
- Increase in the share of electricity in the Miscellaneous Industries sector, reaching 54% of total energy consumption for motor uses.

Methodology

Energy demand by sector is projected for the IBA3+ and Motor Electrification scenarios.

With the projected demands, the difference in electricity between the two scenarios is obtained, associated with the new electrical machinery, as well as the differences in diesel consumption, which represent the economic savings of the measure.

Subsequently, investment and operating costs are calculated for the generation and transmission infrastructure due to the increase in electricity demand.

Finally, the difference in total costs and emissions is estimated to calculate the abatement cost of the measure.

3.3.5 Electromobility

For the Reference scenario, the following penetrations per vehicle type were considered:

- Penetration of 21% of private vehicles and electric taxis by 2050 (15% battery vehicles and 6% plug-in hybrid vehicles), given a constant annual removal rate of 2% for older vehicles.
- Penetration of 20% of electric buses in the Metropolitan Region and 0% in other regions by 2050.

In the GHG-neutrality scenario, the following penetrations per vehicle type were considered:

- Penetration of 58% of electric vehicles by 2050 (41% of battery vehicles and 17% of plug-in hybrid vehicles). The objective is to reach a penetration of electric vehicles of 45% by 2045, considering that external sources estimate this penetration level for Europe.
- Penetration of 100% in electric taxis by 2050.
- Penetration of 100% of electric buses by 2040.

Existing vehicle fleet by year 2017 has been extracted from INE statistics.

Methodology applied to each vehicle park

Private and commercial park

First, the country's total private vehicle fleet is estimated over the long term, based on a model that relates GDP per capita and income distribution to the country's motorization rate, using data from 122 countries between 1970 and 2003.

A vehicle fleet of approximately 3.34 million and 1.18 million private and commercial vehicles, respectively, has been taken as a reference value.

Then, the proportion of sales of electric vehicles is determined from external sources for the reference case; for the GHG-neutrality scenario, a distribution of sales by technology has been established with growth rates that allow the goals described above to be reached.

Based on vehicle fleet growth, the retirement rate of old vehicles and sales distribution, the sale of new cars is estimated by type of technology, thus determining the investment made in particular vehicles by type of technology. External sources have been considered for the price of vehicles by technology.

Based on the number of electric vehicles in circulation, the number of slow- and fast-charging stations required to be built and their costs are determined.

Public park

For the Metropolitan Region:

The number of existing buses and the retirement of machines is determined according to the expiration dates of the current contracts.

Then, the final necessary bus fleet is determined, estimated following the growth of the PKM (passenger-kilometre) increases parameterized in the energy demand model of the Ministry of Energy.The entry of new machines is established considering a useful life of 10 years for diesel buses and 14 years for electric buses.Annual purchase distribution is considered between diesel/electric buses with an exponential penetration rate, which allows reaching the goals defined in the Electromobility Strategy, approaching 100% of electric vehicles within a minimum period near 2040. Finally, the investment made in new buses is determined by type of technology.

For other regions:

An initial stock was defined (by 2017) based on the number of buses for public transportation managed by the INE, subtracting those present in the Metropolitan Region.Then, the necessary fleet is projected according to the growth of the PKM parameterized in the energy model.After that, a distribution of electric buses penetration against the total fleet is assumed in order to reach the goal of the Electromobility Strategy and to have 100% of electric buses by 2040, considering an exponential growth.

Finally, the investment made in new buses by type of technology is determined.

Key assumptions

- An annual retirement rate for private and commercial vehicles of 2% is considered for the whole period for all scenarios.
- An optimistic projection of investment costs in hydrogen and renewable generation technologies is considered.
- Projected reference fuel prices (diesel, coal and natural gas).
- Costs for fixed charging stations: 3,100 USD for slow-charging and 40,000 USD for fast-charging stations.

As a base, by 2018 accumulated sales between 2011 and 2018 of battery vehicles and plug-in hybrids reached 299 and 122 units respectively.

In general terms, demand models used correspond to simple schemes of quantity projection on the horizon using macro information related to country's development, cautioning the interrelations between the different sectors and the effects mitigation measures have between them. Figure 13 summarizes the forecast of electricity consumption by type.

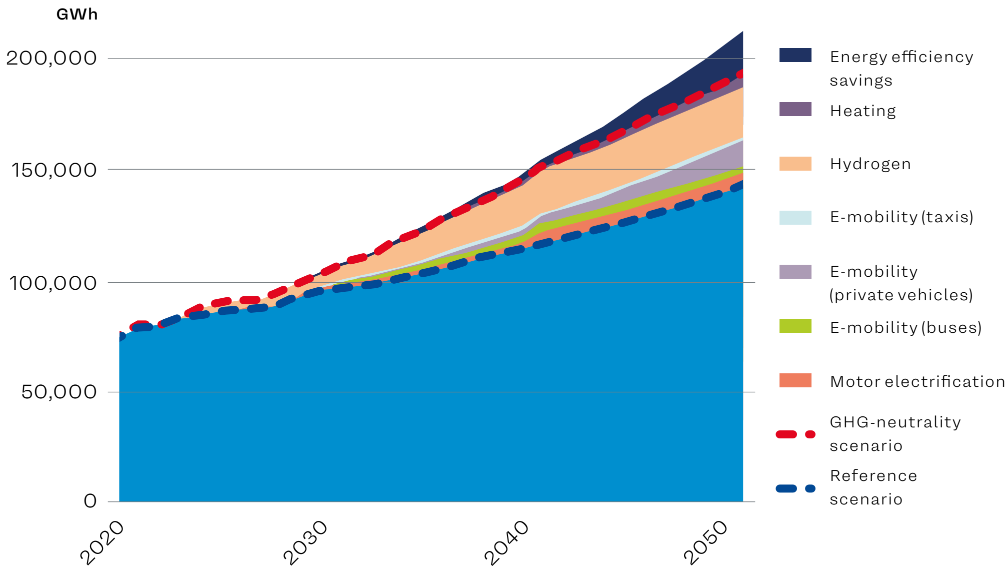

Figure 13: Energy consumption projection for the GHG-neutrality scenario.

3.4 SECTORAL CONSISTENCY

The following assumptions were made to guarantee the consistency between the different models used to project greenhouse gas emissions and to assess the impact of different mitigation actions. In order to define future trajectories, it was necessary to make assumptions on the expected evolution of many key variables: GDP growth, population growth, demand for export, fuel prices and many others. All sectors used the same GDP and population growth. The increase in fuel prices was the same for all sectors. The discount rate used to assess the abatement cost for all sectors is the same.

Energy demand is estimated on a yearly basis for all sectors represented in the National Energy Balance: commercial, public and residential; transportation; and industry and mining. Electricity demand from each of these sectors is then input into an electricity generator sector model from which energy requirements to satisfy this demand are estimated.

The introduction of renewable energies in residential, commercial and industrial sectors was assessed as a mitigation action. This renewable energy is discounted from the electricity demand, prior to assessing the impact in the electricity generation sector. A similar assumption was made when the electrification measures of energy end-use in residential, commercial and industry sectors were assessed. Electricity increase is added to the electricity demand, prior to assessing the impact in the electricity generation sector.

The use of biomass for heating in the residential sector is one of the main sources of energy in some regions in the south of Chile. In addition, the pulp and paper industry is one of most important in Chile. In this industry sector, the biomass has also a high participation in the end-use of energy. Different models were used to project the use of biomass in these sectors. On the other hand, the removals from the LULUCF sector were obtained using other models. For this paper, the consistency between the removals for energy use in the LULUCF, and the biomass used in the residential and industry sector was not assessed. Also, the relationship between the use of biogas for electricity generation in the waste sector, and the biogas power plant projection of the electricity generation sector was not analyzed either. These activities are part of future works in Chile. Table 7 summarizes the main sectoral consistencies analyzed by the authors.

Table 7: Sectoral consistency check list.

Parameter/assumptions	Description
IPCC guidelines	All sectors use the 2006 IPCC guidelines to estimate GHG emissions.
Emission factors	The emission factors were obtained from 2006 IPCC guidelines.
Global warming potential (GWP) factors	All sectors use the same GWP factors.
Density and calorific values for fuels	All sectors use the same density and calorific values for the same fuels.
GDP	All sectors use the same GDP growth.
Population	All sectors use the same population growth.
Fuel prices	All sectors use the same fuel prices growth.
Discount rate	All sectors use the same discount rate to assess the abatement cost.
Demand-generation balance	The electricity generator sector model uses as input the electric demand projected by sectoral demand models.
Electrification measures	The increase in electricity is added to the electricity demand, prior to assessing the impact in the electricity generation sector.
Renewable energy measures in energy demand sectors	Renewable energy is discounted from the electricity demand, prior to assessing the impact in the electricity generation sector.
Use of biomass	The consistency between the removals for energy use in the LULUCF and the biomass used in the residential and industry sector was not assessed.
Use of biogas	The consistency between the use of biogas for electricity generation in the waste sector and the biogas projection in the electricity generation model was not assessed.

3.5 MAC CURVES AND SECTORAL MODELS

Thirty-three mitigation actions (MAs) were assessed for the Chilean NDC. Different quantitative indicators were assessed for each mitigation action: CAPEX (present value of the additional capital expenditure to implement the MA), OPEX (present value of the operation expenditure to implement the MA, accumulated GHG emission reduction, annual GHG emission reduction, and abatement cost (USD/tCO_2eq). The abatement cost (AC) is calculated as the present value of the total costs divided by the total GHG emission reduction. This is one of the most common cost indicators used to compare mitigation actions. The abatement cost is represented in the following equation:

$$AC = \sum_{t=ti}^{T} \left(\frac{\Delta CAPEX_t}{(1+r)^{t-ti}} + \frac{\Delta OPEX_t}{(1+r)^{t-ti}} \right) / \sum_{t=ti}^{T} \Delta E_t$$

Where $\Delta CAPEX_t$ is the additional capital expenditure located with respect to the baseline scenario in the year t, $\Delta OPEX_t$ is the additional operational expenditure in t, ΔE_t is the GHG emission reduction in t, r is the discount rate, and ti is the start year (2019). The AC was evaluated using a discount rate equals to 6%. The main assumptions to evaluate the AC are available in the NDC proposal web page2.

Marginal abatement cost (MAC) curves are used to analyze emission abatement potential and associated abatement costs for different mitigation actions. Economy-wide MAC curves are a preferred tool for policy makers to assess the economics associated with carbon abatement as they are an easily understandable concept that convey relevant information in one graph. The following figure shows the MAC curve considering the necessary measures to achieve GHG-neutrality by 2050.

Most measures would have a negative abatement cost by 2050. Some of the measures considered are energy efficiency actions in industrial processes of large energy industries. For instance, mobile electrification uses in industry and mining have a reduction potential of 3.3 MtCO_2eq by 2050 and a negative AC. However, this measure faces relevant economic barriers.

Electrification measures for private vehicles, commercial vehicles, taxis and electric buses will play an important role in achieving GHG-neutrality. An emission reduction of 10.2 MtCO_2eq is projected for these meas-

2 http://consultasciudadanas.mma.gob.cl/mma-epac/app/home_ciudadano?execution=e1s2

ures and their ACs would be negative by 2050 due to the reduction in the prices of these vehicles. The use of hydrogen produced based on renewable energy sources for freight transport will also have an important role in achieving GHG-neutrality and would be economically convenient. Nevertheless, this technology is in full development and it is expected to be commercially competitive as of 2030 (Corfo, 2018; Yáñez *et al.*, 2019).

Decommission of all coal-fired power plants by 2040 would reduce 7.5 $MtCO_2eq$ by 2050, and although it represents a positive abatement cost of 8 USD/tCO_2eq, it may be the most relevant measure in the analysis, since coal phase-out cleans the energy grid, giving space to other macro and cost-efficient measures in the sustainable industry (electrification of machine drives), electromobility (electric public transportation and commercial vehicles), hydrogen (heavy duty vehicles and machine drives), and sustainable buildings (electric space heating). Other measures with positive abatement cost are thermal refurbishment of housing, electrification of boilers and furnaces of the industrial sector, promotion of public transportation and use of district heating (Figure 14).

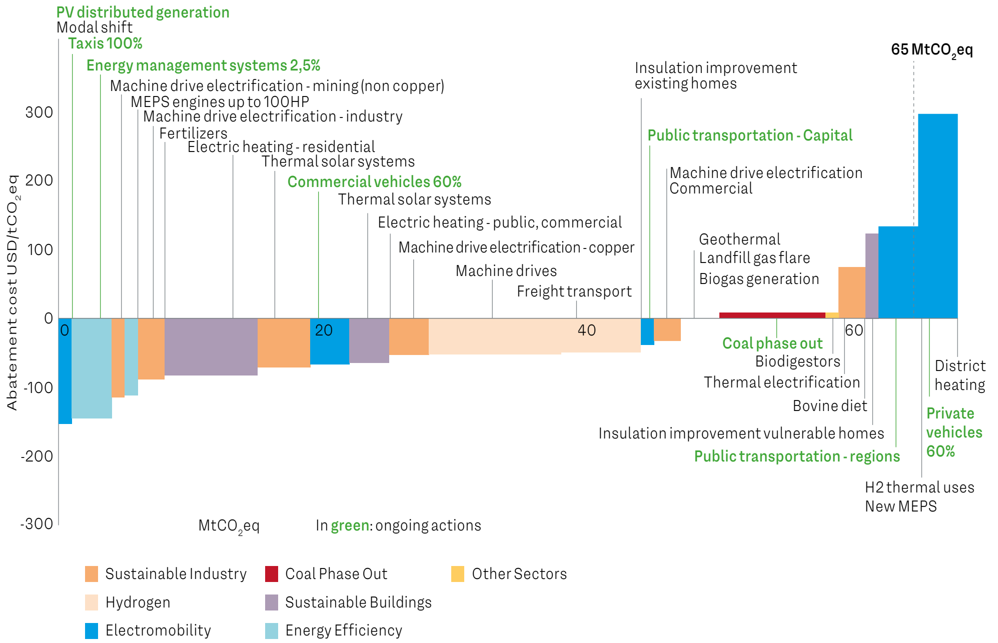

Figure 14: MAC curve for year 2050.
Source: Environment and Climate Change Division.
Source: Environment and Climate Change Division, Ministry of Energy (2019)

The analysis of the results related with the abatement costs revealed several measures having negative abatement costs, meaning they should be "free for implementation". This situation raises the question: If decision makers are rational, why were these measures not implemented in the reference scenario? Given the present analysis is developed from a social assessment perspective, some of the reasons these mitigation measures were not implemented are:

- Imperfect information: In the real world, most market information is not perfect, so decision makers could have decided not to invest in some measures because they did not have all the relevant information (e.g. without an Energy Rating Label, consumers will not know which is the best solution).
- Different discount rates: For measures with a high CAPEX and a negative OPEX (e.g. residential PV rooftop), decision makers using higher discount rates will obtain higher mitigation abatement costs for the same measures. This situation is related to budget restraints, as people and small companies need support in order to implement many of these mitigation measures.
- Social, cultural or political considerations: some measures that could make economic sense, could be ignoring important social, cultural or political considerations (e.g. preference for an older technology based on tradition).

Therefore, it is crucial to analyze the reasons behind the failure to implement a measure with negative abatement costs, in order to properly design the necessary public policies and correct this situation, thus, obtaining the corresponding economic, social and environmental benefits.

3.6 ADDITIONAL TOPICS

The authors identified additional topics which were partially or not considered in the previous analysis but which are also relevant for the Chilean NDC definition.

3.6.1 Long-term analysis

Assessments of climate change impacts using conventional Integrated Assessment Models (IAMs) present essential challenges for our society. Indeed, to integrate causes and effects over long horizon periods (four or more decades ahead) in which discount rates and intergenerational time consistency are still under discussions; the modeling aspect of uncertainties, sensitivity analysis and tail risks coming from extreme events or combined hazard effects are part of the current research agenda today; a more precise estimation of regional impacts coming from global models are also complex to integrate; finally supplies and demands are also affected by the climate change creating complex endogenous behavior, as it has been pointed out in (Cronin, Anandarajah and Dessens, 2018; Pindyck, 2017). One of the consequences of these difficulties are the generation market investing decisions. In the sense that, company boards not always integrate long-horizon impacts in the equation, and then some of them are neglected or underestimated such as the cases of ecosystem damage, long-term reliability, climate change resiliency and financial sustainability. In the same vein, we remark that in the standard economic model, there is no "ecological interest rate". However, the literature is growing fast towards the incorporation of these variables in the assessment of climate change impacts and consequences over the macroeconomics and financial markets like is presented on (Barnett, Brock and Hansen, 2019). Therefore, an active regulator for the energy market is required for implementing policies and plans at all levels. In the case of Chile, long-term planning models have been generated and applied by the regulator to the transmission expansion integrating some of these long-term effects through scenarios for a 20- to 30-year horizon. These optimization models are subject to continuous improvements to integrate better the difficulties mentioned above. In the setting of generation investment decisions, which are more "pure" market dependent, the integration of the above-mentioned difficulties produced by the climate change are more complex, and the regulator actions are based most often on incentives, policies as decarbonization and caps. Thus, we have a mix of central planning and market decision energy system, which will require fine-tuning to integrate all the new knowledge on better climate change models, uncertainty quantification, discount rates, technology innovation, tail risk models.

3.6.2 Non-energy emissions

The prospective non-energy assessment of emissions: Waste, Agriculture and IPPU sectors arises from the development of a trend-type reference line, using the methodologies defined in the IPCC guidelines and considering the scopes defined for the preparation of Chile's NGGI.

The projection of the variables determining emissions – which evolve and are subject to variability on an annual basis – are developed without considering structural deviations or mitigation actions that are not official in terms of public or private projects or objectives, until May 2019. In this sense, the projections considered to seek in order to reflect, in each sector, an advance towards the stability of the levels of activity that determine most of the emissions of each sector. According to this definition, the impacts of the Kigali Amendment on hydrofluorocarbon emissions associated with the use of substitute products for ozone-depleting substances, subscribed in 2016, are considered referential in the IPPU sector, but with an action schedule for Chile that starts in 2024.

Mitigation actions considered in the neutrality simulation of the national emissions balance are collected based on the criteria of potential impact and cost-effectiveness of these actions. The foregoing does not imply they should be excluded from an action agenda, but that in this assessment those having impacts of higher relevance are favored. These are mainly an integral technical assistance for an efficient use of nitrogen fertilizers, mechanisms for the expansion of the swine population covered by anaerobic bio digesters, and incentives for the use of foods that reduce bovine methanogenesis. As for the Waste sector, the generalization in the use or burning of biogas produced in sanitary landfills is considered, as well as the management and use of sludge from sanitary plants.

The actions of the Waste sector imply a reduction of 17.4% of sector's emissions by 2030; if we consider the whole 2020-2030 period, the reduction reaches only 6.5%. By 2050, emissions are reduced by 24%. The actions of the Agriculture sector lead to a reduction of 2.8% of emissions of the sector in 2030; if we consider the whole period 2020-2030, the reduction reaches only 1.1%. By 2050 emissions are reduced by 8.1%. Although the IPPU neutral scenario does not differ from the reference scenario, it is important to mention that the Kigali Amendment means a reduction of 21.6% of sector's total emissions by 2030, and 66.2% by 2050.

The relative importance of these specific sectors will increase with respect to national emissions. By 2016, the 3 classifications represent 21% of the emissions; by 2050 their participation reaches 36%. The results in the neutrality scenario imply significant impacts in IPPU and Waste sectors with respect to a BAU scenario without the Kigali Amendment, this while not considering an important behavior change in waste generation, produced by an increasing awareness and education about the climate crisis.

Efforts are more modest in the agriculture sector. Such impacts on mitigation practices are often subject to a significant level of uncertainty, cultural aspects and local characteristics of the soil, while climate exacerbates the uncertainty and makes the implementation of mitigation policies more difficult in the sector. The capacity to implement these measures usually has a low impact and its application is usually complex, in part because of the atomicity of sector stakeholders. Despite this, management options in the sector provide alternatives to reduce the magnitude of emissions and improve carbon absorption. These options improve crop productivity, soil nutrient status, organic waste, microclimate or biodiversity management and therefore support adaptation to climate change (Shukla *et al.*, 2019).

In Agriculture, interventions on the demand side were not considered, such as modifications of food choices, reduction of food loss and waste which reduce GHG emissions and improve food systems resilience. These measures, in combination with mitigation measures in the supply side, may allow the implementation of large-scale adaptation and mitigation strategies, without threatening food security as a result of an increased competition for land for food production, and higher prices (Shukla *et al.*, 2019).

In general, the mitigation options of the non-energy sectors are neither associated to technological changes nor to high costs, their difficulty lies both in organizational and paradigm changes, and in proposing new regulations and rules that face traditional methods and establish standards where they did not exist before, enforcing and educating towards more sustainable behaviors. In this scenario, the mitigation actions could be rushed, however the atomicity of the actors, the entrenched cultural difficulty, or regulation changes in some services, can be complex barriers to overcome.

3.6.3 Black carbon

Urban areas are the scenario where long-reaching, profound transformations shall occur if we are to achieve the Sustainable Development Goals (SDGs) and honor the Paris Agreement, avoiding the adverse impacts of an unsustainable and fast warming world (Acuto, 2016; Allen *et al.*, 2018; Anenberg *et al.*, 2019; Gallardo *et al.*, 2018; Government of Chile, 2015; Haines *et al.*, 2017; INE, 2018; Jorquera *et al.*, 2018; Lamb *et al.*, 2019).
The avoidance of a global warming exceeding 1.5 °C above pre-industrial levels, entails GHG- neutrality by 2050, as well as the mitigation of short-lived climate forcers (SLCF), methane (CH_4) and black carbon (BC) in particular (Allen *et al.*, 2018). This stresses the need to address the mitigation of SLCF in a consistent manner with carbon dioxide (CO_2) and other long-lived climate forcers. Also, there is evidence suggesting that mitigating SLCF can facilitate the achievement of the SDGs, mainly through technological and energy matrix changes and their implications on air quality (Haines *et al.*, 2017; Shindell *et al.*, 2017). In this context, by adopting these actions, mortality associated with poor air quality is reduced, particularly through measures to curb aerosol levels (Anenberg *et al.*, 2019; Lelieveld, 2017; Silva, R. A. *et al.*, 2017).

The statements indicated above apply to the world at large but specially to Chile where urbanization has reached nearly 90% (INE, 2018), and air quality problems remain a major issue of concern despite long-standing attainment efforts (Gallardo *et al.*, 2018; Jorquera *et al.*, 2018). This was recognized by Chile in its NDC from 2015 (Government of Chile, 2015). No quantitative goal was established then, but a first emission inventory for BC was developed shortly after (Ministry of the Environment, 2017) and presented in Chile's National Communication in 2018 (Ministry of the Environment, 2018). In its current version, a quantitative goal of an emission reduction from 10 to 25% with respect to 2016 to be achieved by 2030 is stated. In the current NDC process, the Ministry of the Environment, through the United Nations' Environmental Program, is collaborating with the Center for Climate and Resilience Research (http://www.cr2.cl/) to establish a mitigation goal for BC consistent with the overall mitigation effort to be carried out by the country. In this work, mitigation measures considered for long-lived greenhouse gases (LLGG), have been assessed in terms of their potential for reducing BC over the period 2010-2050 using the analysis framework of the Long-range Energy Alternatives Planning System - Integrated Benefits Calculator (LEAP-IBC) (https://www.energycommunity.org/). In addition to mitigation options for LLGG, specific measures regarding air quality achievement plans have been assessed. These measures refer to residential and industrial wood burning by means of a better housing by having new building standards and enhanced insulation for already existing houses, leading to less energy demand. Other measures refer to off-road machinery emission standards, and overall technological and modal changes in transport. Figure 15 shows BC emission reduction scenarios. According to the available estimates, the "carbon-neutrality scenario" implies a reduction from 10.1 kt BC in 2016 to 8.7 k by 2030, and 6.6 k by 2050, i.e. 13% reduction by 2030 compared to 2016 and 49% less compared to the current policies scenario by 2050. In addition, an ambitious scenario was proposed with measures specifically focused on reducing black carbon, including district heating and strict off-road machinery standards. This scenario called "carbon-neutrality +" implies a reductions from 10.1 k BC in 2016 to 6.3 k BC by 2030, and 3.2 k by 2050 i.e. ca. 37% reduction by 2030 compared to 2016 and 75% less compared to the current policies scenario by 2050.

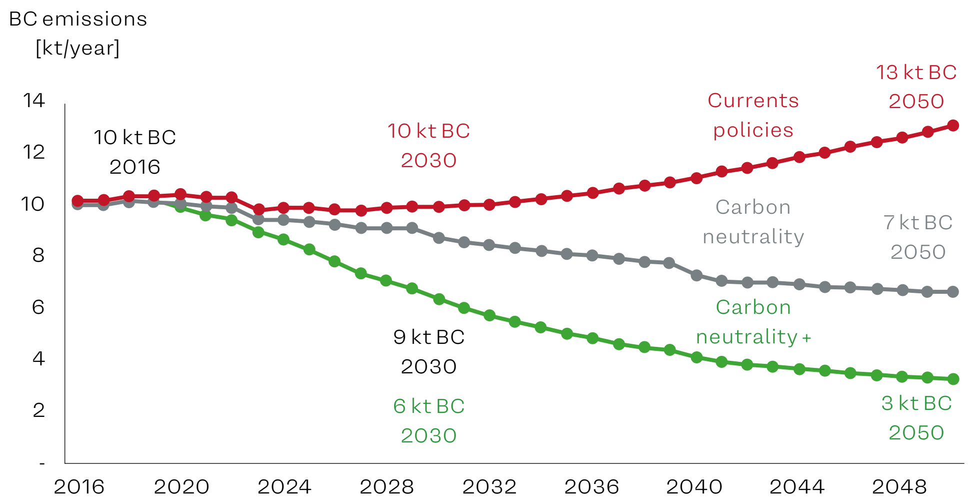

Figure 15: Evolution of black carbon (BC) emissions according to current policies, carbon neutrality and carbon neutrality + scenarios.

The previous estimates are based on a non-regional national level, which would be necessary to fully appreciate the co-benefits of BC mitigation, particularly regarding impacts on human health, agriculture and ecosystems, where a spatially distributed but nationally integrated approach is required to address the spatial and temporal heterogeneity of BC. This in turn will require systematic monitoring of BC and other aerosol components and gaseous precursors, as well as higher-resolution inventories (~1 km2), and an improved characterization of activity levels and emission factors.

Even though GHG-neutrality scenarios result in substantial reductions of BC at a national level, such reductions are probably not enough to achieve air quality standards, and thus it is imperative to strengthen air quality attainment plans and improve urban life at large for nearly 90% of Chileans. This, in turn, will require medium- and long-term planning in urban areas in terms of mobility, housing construction (insulation), green areas, etc. Better governances are also needed to reduce fragmentation in large cities and amplify the role and resources of local governments (Hölzl and Nuissl, 2014).

An appropriate assessment of BC mitigation options will require improved emission inventories, as well as urban area monitoring. This may open an opportunity for collaboration between the government and the academia, by means of joint ventures to allow the broadening of current measurements (Gallardo *et al.*, 2018). This will also be functional to increase the detail of CO_2 inventories and monitoring (Mitchell *et al.*, 2018).

3.6.4 Specific nature-based solutions

This far, climate change mitigation strategies have been based on actions to prevent the loss of carbon storage by conserving terrestrial sinks, e.g., tropical forests. However, studies indicate that coastal habitats are among the most effective carbon sinks in the biosphere, that have led to the development of the so-called "blue carbon strategies" (Pendleton *et al.*, 2012). Since 2016, the IUCN has promoted "nature-based solutions" as measures towards climate change mitigation and adaptation in UNFCCC negotiations. This approach is justified due to the various ecosystem services provided by the creation and protection of climate sanctuaries, which strengthen adaptation capacities, especially in areas where the ocean acts as a carbon sink (thus mitigating the effects of climate change).

The term blue carbon is used to define the carbon that is stored naturally by marine and coastal ecosystems (Duarte *et al.*, 2013). In general, it includes four types of coastal ecosystems: mangroves, seagrasses, salt marshes and kelp forests. These vegetated coastal habitats within the biosphere, characterized by the presence of both submerged (seagrass and macroalgae) and partially emerged (mangroves and saltmarshes) macrophytes, occupy a narrow fringe from the upper intertidal zone to about 40m depth. However, they play an important role in carbon burial, a process by which Carbon is preserved for an extended period of time within a coastal reservoir (Duarte *et al.*, 2013; Krause-Jensen and Duarte, 2016). In fact, these ecosystems are able to bury up to 20 times more carbon per acre compared to terrestrial forests (Figure 16). Their immense capacity for carbon storage and burial make the conservation of these carbon blue habitats a critical component in climate change solutions. Coastal blue carbon can contribute to various national Climate Change mitigation strategies, but its global reach is limited (offsetting <3% of current emissions). However, they do have several associated effects (or co-benefits) on some Climate Change impacts in the ocean (Pörtner *et al.*, 2019). Specifically in Chile, co-benefits may be strengthened due to several comparative advantages: 1) Chile has one of the largest coastal marine surface areas, given its extensive coastline and the extension of its exclusive economic zone (EEZ); estimates of the ratio of the area of EEZ vs. continental area ranges between 0.65-0.86 (Avelar, van der Voort and Eglinton, 2017), making it one of the largest global ratios (compared to that of Mexico, Greenland, Norway, and the United Kingdom), 2) Chile has organic carbon reserves accumulated and buried in continental shelves and epicontinental seas and fjords, due to the high primary production of these systems; in fact, Southern Chile encompasses one of the most extensive fjord regions in the world (Iriarte, González and Nahuelhual, 2010); 3) there are important carbon reservoirs stored in halophyte (saline resistant) vascular plants in salt marches and in macroalgae (kelp forests). Carbon burial rate in the Chilean EEZ and continental shelf, indicates that sediments preserve an important amount of organic carbon over long time scales. As a result, sediment disturbance, from activities such as underwater mining, must consider the relevant amount of buried carbon within these systems and the benefits of preserving these carbon stores.

Chile has a high presence of salt marshes in coastal zones (Arellano *et al.*, 2013), with dense reserves of dense brown macroalgae (Buschmann *et al.*, 2014). Although these systems are yet to be fully assessed in Chile and are not considered in the scope of the current NDC proposal, many studies already indicate the high carbon burial potential of these systems, as well as their numerous ecosystem services (Pendleton *et al.*, 2012). It can be extrapolated to Chilean habitats; therefore, these ecosystems should be considered within the national carbon budget as they have a significant economic value due to the provision of various economic services.

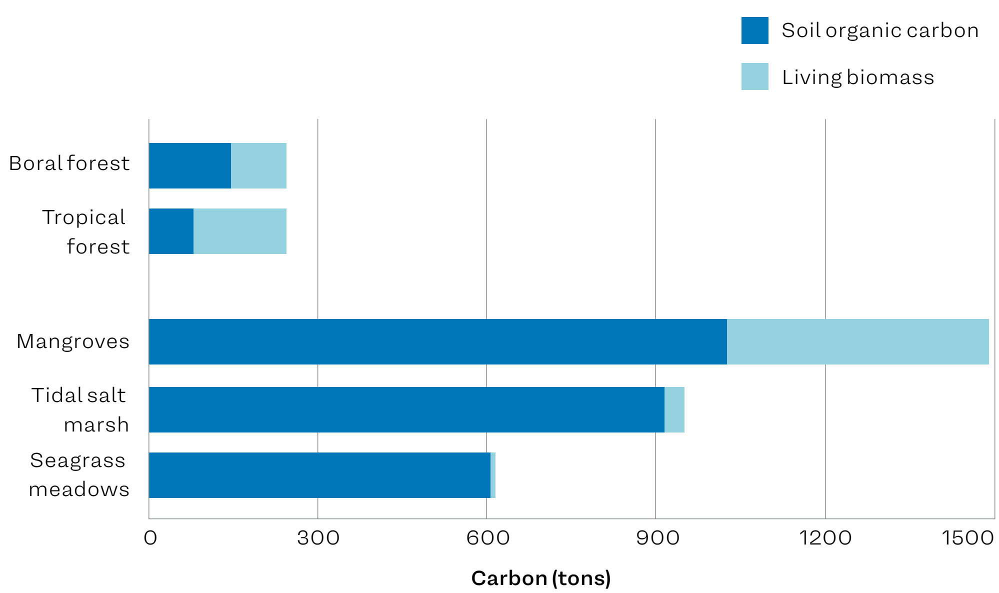

Figure 16: Carbon storage in different reservoirs: biosphere (as biomass) and lithosphere (sediments and soils) in ecosystems called blue carbon.
Note: Much of the carbon is stored in soils / sediments associated with these systems and far exceeds the carbon stored in terrestrial ecosystems (reproduced from Pendleton et al., 2012).

3.6.5 Socio-environmental challenges

As per NDCs, the vulnerability associated with specific geographical, climatic, economic and socio-cultural characteristics of a country's territory is considered a relevant aspect. However, the traditional approach is mainly deployed in terms of adaptation and the addressing of comprehensive measures that allow visualizing this complex problem from a multidimensional approach (Ministry of the Environment, 2019).

NDC mitigation is mainly approached from a technical-economic (microeconomic) point of view where efficiency indicators and scale economies predominate as the basis for analyzing the measures proposed (Ministry of the Environment, 2018, 2019).

As the NDC of Chile indicates, "neutrality is a country vision", i.e. it should not only refer to mitigation, but also to its economic, social and environmental implications.

Moreover, when the impacts of climate change interact with other pressures, it can prompt social conflicts, even violent ones. Other risks may emerge when climate change interacts with social, environmental or economic tension, e.g. food security, competition of local resources, human uncertainty of people who depend on natural resources for their livelihood (Rüttinger *et al.*, 2015).

This statement gives rise to the challenge to approach the mitigation analysis from a socio-ecological point of view, therefore enabling the consideration of system complexity in order to identify its effects.

This multidimensional and transdisciplinary approach considers society – with its social, cultural and economic characteristics – as a part of the biosphere. It recognizes the role of humanity in shaping ecosystems and vice versa, along with its dependence on the availability of natural resources for its development (Folke, 2016). Under this view, socio-ecological systems have thresholds, change agents and feedback (Levin *et al.*, 2013)that should be understood in order to face the challenges adjacent to sustainable development.

To successfully and sustainably move towards a carbon neutral scenario and implement mitigation measures, a profound system transformation is required, which will generate positive and negative effects. The identification of these trade-offs and feedbacks as a result from the development of mitigation measures are essential to face the risks adjacent to the implementation of technical innovations, adverse effects on other SDGs and on the different elements of a socio-ecological system (McCollum *et al.*, 2018).

Some of these identified trade-offs refer, for instance, to public resistance to decarbonization (and promotion of non-conventional renewable energy) that could result in an unequal access to energy in the most vulnerable sectors. Another example is a possible increase in energy demand, as a result of a rebound effect upon the addition of renewable energies and higher energy efficiency (IEA, 2016). On the other hand, there are potential impacts associated with the change in land use and the decrease in biodiversity, as a result of the promotion of renewable energies under a scenario where the costs associated to its implementation suffer a substantial fall (Van den Bergh *et al.*, 2015), or environmental and social impacts related to the exploitation of rare-earth elements and the intensification of productive activities such as agriculture and mining (Sachs *et al.*, 2019).

In Chile, we have some experiences that have integrated the analysis of interactions and the positive and negative effects of mitigation measures. For instance, measures related to short-lived pollutants that have clear associated co-benefits: decreased air pollution or improved air quality, and decreased costs associated with health impacts (respiratory diseases), are some of the aspects covered in this analysis. In line with this, the MAPS Chile project explores the adverse effects and benefits of each mitigation measure proposed (Ministry of the Environment, 2016).

Although these initiatives have contributed to a multidimensional analysis, it is necessary to deepen the study on the co-impacts of mitigation measures, so they can be incorporated into the analysis in a way that allows making the necessary decisions to achieve sustainable development. This type of analysis requires the integration of power dynamics and the most vulnerable groups, by changing consumption and production patterns, decoupling the social welfare of environmental degradation and adopting a circular economy (Sachs *et al.*, 2019). In this sense, mitigation actions can be presented as a great opportunity to integrate groups such as indigenous communities, women, small-scale producers among others into the analysis and participation in order to promote the empowerment of country's communities through social innovation tools.

Furthermore, it is necessary to incorporate the political feasibility of measures, particularly in the light of social demands within the framework of the current socio-political crisis in the country. Among the demands, environmental equity should be considered, specifically for disempowered segments that suffer most from both local and global environmental impacts. In this sense, as Chile's energy matrix decarbonizes, there may be a positive impact on the current slaughter areas, in particular localities such as Quintero-Puchuncavi, Huasco and Coronel, where its inhabitants have historically suffered and continue to suffer environmental impacts to health, caused by emissions of gases and particulate matter.[3]

3 Website of Programa de Recuperación Ambiental y Social (PRAS), Ministry of the Environment, available at https://pras.mma.gob.cl/.

In addition, environmental and territorial aspects consistent with the reality and changes the country is facing, should be taken into consideration. For instance and in accordance with the way in which the country is trying to face the current social crisis, climate change policies should be conceived to propose how to include citizens in a binding way to define the commitments of our country in this matter, especially to those segments that have been historically postponed, such as native people. Only through this it will be possible to implement a transformation processes to face climate change.

3.6.6 Macroeconomic analysis

The dynamics of climate change consequences are a matter of study not only for the natural sciences but also for social and economic branches. In particular, macroeconomic assessments of the effects of climate change have been conducted using different tools during the last decades, and several institutional supervisors and central banks, along with the IMF, have encouraged to proceed with a quantitative analysis of its effects (IMFFA, 2019; Krogstrup and Oman, 2019; NGFS, 2019). The risks posed by climate change itself can have significant macroeconomic and financial repercussions (NGFS, 2019). Furthermore, the transition towards low-carbon economies also involves risks for financial systems stability (Campiglio *et al.*, 2018; NGFS, 2019). Thus, we propose that a macroeconomic assessment of scenarios with and without mitigations measures should be a key element of the methodology that supports the nationally determined contributions of Chile as is presented in (Antosiewicz *et al.*, 2020). In that regard, we propose an assessment of the policies in the process of determining Chile's NDC in the loop shown in Figure 17.

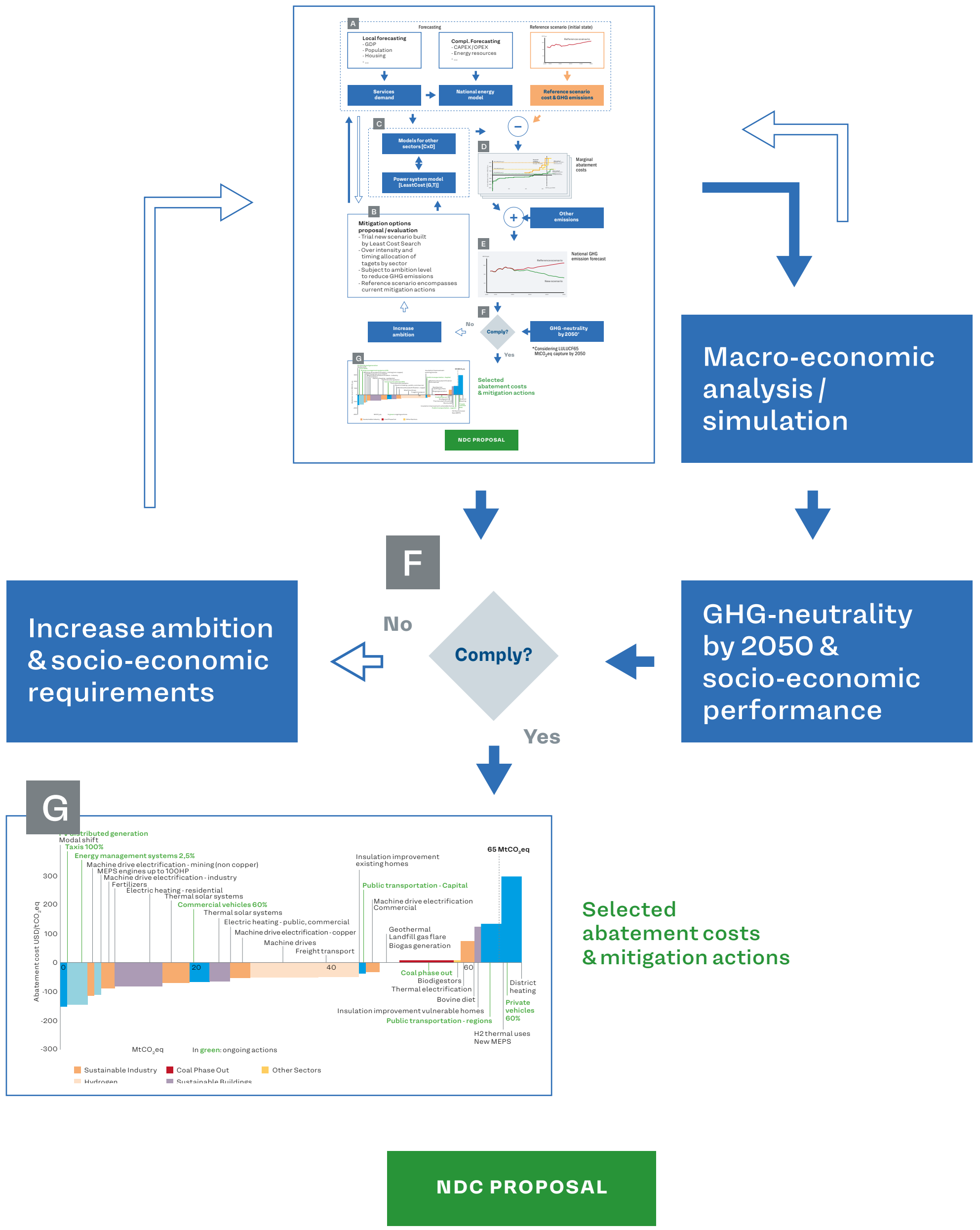

Figure 17: Proposed macroeconomic loop.

Over the last decades, price stability and fiscal responsibility have proven necessary conditions for development and economic growth (Corbo and Fischer, 1995). In turn, economic growth seems to be an important factor to help mitigate and adapt to climate change (Bowen, Cochrane, and Fankhauser, 2012). Thus, fiscal instruments that strengthen macroeconomic conditions, such as credible fiscal rules, and preventive investment or fiscal buffers can help support climate change adaptation (Pigato, 2019). The current socio-political situation in Chile has forced fiscal rules to the limit and threatens to stagnate or even bring down the GDP.

In this context, it is imperative to assess the macroeconomic impacts of the different measures proposed to reduce CO_2 emissions. It is worth mentioning these measures do not consider increasing current carbon tax from 5 USD/tCO_2eq to more effective rates which – according to OECD and IMF – should be way above 25 USD/tCO_2eq to represent the actual damage caused (IMF, 2019; OECD, 2019).

In order to estimate the potential macroeconomic effects of the different measures, there are some issues that the methodology should consider. Firstly, the set of measures should be economically and financially feasible. Although this set of measures seems to be financially profitable, it is not clear where the funding will come from and whether public infrastructure serves well for private investment that may not come along due to market frictions. Some fiscal funding might be necessary, which may imply an increasing debt, the creation of concessions or public-private partnerships, depending on what share of the capital expenditures could be borne by the government. This will be restricted through fiscal revenue, rules and debt. Secondly, governmental measure funding might compete with other social needs, such as investments in education, health or pensions. Finally, as we discuss below, there is uncertainty around technology upgrades that would enable some of these measures.

A macroeconomic assessment should shed light over these issues and help understand whether these measures support economic growth, boost development, or somehow threaten the economy, worsening the pain they were supposed to relieve.

4 Main uncertainties and modelling challenges

> *"The policy debate with respect to anthropogenic climate change typically revolves around the accuracy of models. Those who contend that models make accurate predictions argue for specific policies to stem the foreseen damaging effects; those who doubt their accuracy cite a lack of reliable evidence of harm to warrant policy action. These two alternatives are not exhaustive. One can sidestep the "skepticism" of those who question existing climate models, by framing risk in the most straightforward possible terms, at the global scale. That is, we should ask "what would the correct policy be if we had no reliable models?"* (Norman *et al.,* 2015).

In this context, it is important to note that the results shown in this document depend on exogenous variables, which may cause conclusions to vary. The research team chose the values of these variables in order to obtain the most representative results, which best reflect the current level of knowledge about the future trends for each of the variables included in the analysis. Likewise, the team believes it is worth noting the list of the most relevant variables, which would have a true potential to modify the results and conclusions of this work:

a) Availability of the water resource. Climate change is influencing the availability of water resources for its different uses, particularly for electricity generation. Its projection may affect the performance of different mitigation measures.

b) Retirement speed of coal-fired power plants. This point is the result of negotiations between the public and private sectors and does not involve additional costs for the State. The study considers two retirement scenarios (base and accelerated), but both faster and slower coal-fired retirement scenarios may be considered. It is relevant to establish that the retirement of coal-fired power plants is a key and enabling measure for the objectives proposed. Therefore, a more robust and legal binding process is envisioned.

c) Fuel costs. The study assumes that fuel costs will be predominantly rising during the period of analysis. This may not be the case, because scenarios of low demand as a result of diminishing fossil fuel consumption could lead to lower increases or fluctuations in fossil fuel prices. Scenarios where fossil fuel consumption decreases due to a drop in demand and not due to supply restrictions can be considered, hence not leading to a price increase.

d) Hydrogen development. Although disruptive technological developments cannot be predicted, fuel storage and production technologies are now being developed with the potential to produce disruptive changes. Thus, it can be argued that while solar hydrogen (H2) is being commercially developed, alternative technologies could drive the storage area and energy-to-fuel, such as molten salts, solar fuels and dual combustion based on liquefied natural gas, among others.

e) Technology costs. Technological costs are often unpredictable over time, especially over long-term horizons. In this way, it is interesting to consider scenarios with different cost variations. In fact, scenarios where the costs of renewables drop significantly, and conventional technologies rise in the same way (due to higher fuel prices) lead to conclusions that should be assessed in alternative scenarios.

f) Penetration level of electrification and electromobility. The analysis shows an auspicious vision for electrification and electromobility, but it has its nuances either through a faster or a slower development.

g) Electricity demand. Increasing electricity demand with high energy efficiency standards and low co-impacts (electrification) is important for the introduction of new technologies. If demand does not grow rapidly, technological changes may be delayed and will have to be assessed again. In this way, it is interesting to know the robustness of the results in the face of variations in demand.

The analyses utilized the available estimates and visions of the different variables that affect the conclusions of the work. However, the research team understands that these results are sensitive to several of the assumptions considered, which should be permanently re-assessed based on the evidence available.

4.1 CLIMATE CHANGE IMPACT ON CHILEAN HYDROLOGY

The links between climate change and hydroelectricity are many and reflect the many and complex mechanisms that affect this problem. Of special concern is the sensitivity of hydroelectricity to potential impacts of climate change on the water cycle and hence in the availability of water for electricity generation. In Chile, this relation is evident as shown in Figure 18 where we compare recent (1996-2018) hydropower generation (as a fraction of installed capacity, i.e. plant factor) and recent trends in precipitation patterns (Garreaud *et al.*, 2019). Although this is not a statistically strong relationship among both variables (expected in a short-time series and with the effect of reservoirs storage) there is some patterns that explain that under consistently reduced precipitation levels, plant factor (capacity factor) tends to diminish as it has been the case for the last 10 years.

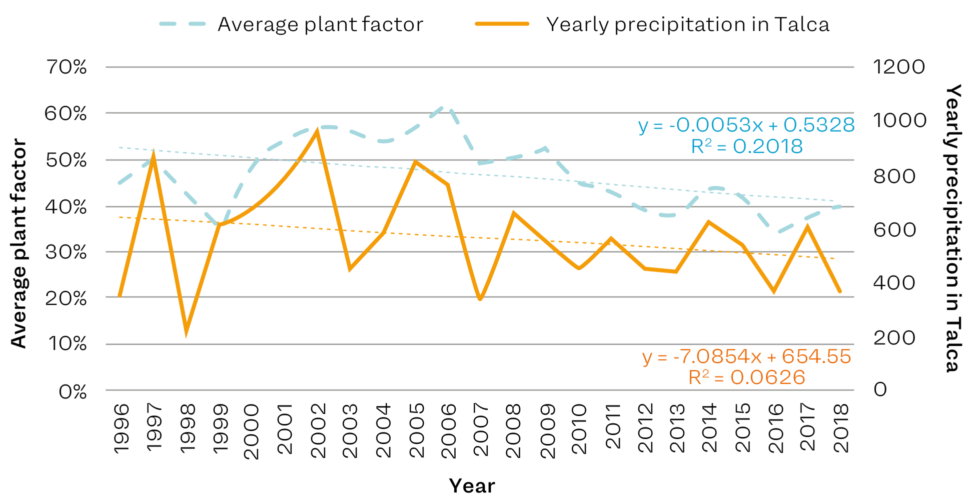

Figure 18: Comparison between the hydroelectrical generation plant factor and precipitations shown at the weather station in Talca. Source: Generation: http://generadoras.cl/generacion-electrica-en-chile; Precipitation: http://explorador.cr2.cl/; Installed capacity: http://energiaabierta.cl/

A series of studies have analyzed the potential impacts of climate change on hydroelectric generation in Chile (ECLAC, 2012a, 2012b, 2019; McPhee *et al.*, 2011; Ministry of Energy, 2015, 2016). Some of these have done detailed analyses on some key basins such as Maule, Laja and Biobio, while others have covered many basins at once. In all of them, the main findings are that the expected climate change-related reduction in average rainfall and increase in temperature imply a reduction in the hydroelectric generation capacity of the central area of the country. For example, Figure 19 shows the impacts expected in terms of the future hydroelectric development potential for a series of GHG emission scenarios (RCP scenarios).

Figure 19: Potential for future hydroelectric generation in the Maule, Biobio and Tolten basins.
Source: Ministry of Energy (2016).

The connection between this reduced hydropower generation capacity and the implications in terms of GHG emissions was studied at MAPS using an interconnected water resources and energy planning model. The results show (Figure 20) that future scenarios in emissions face considerable uncertainty (based on Montecarlo simulations) due to climate change impacts.

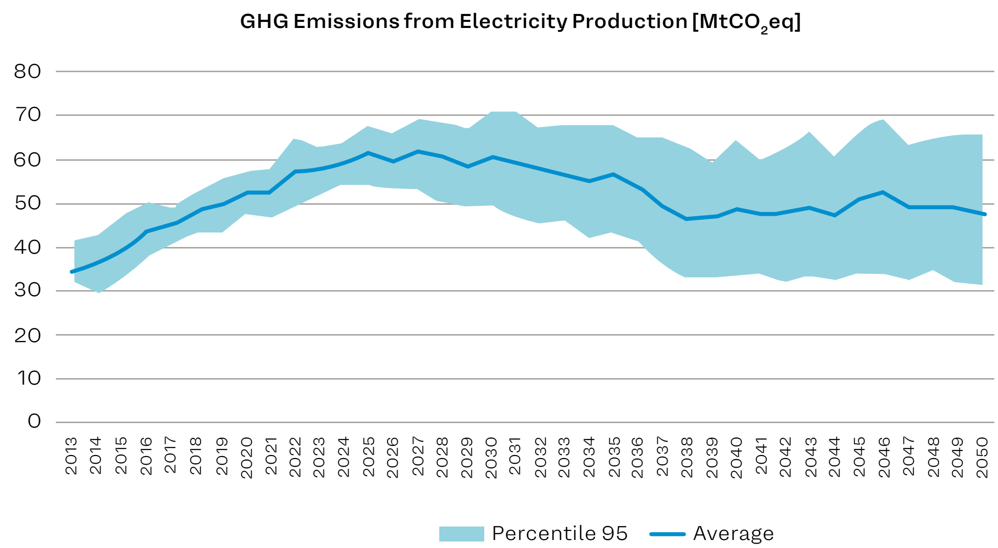

Figure 20: Uncertainty ranges of GHG emissions for the electricity sector based on climate change scenarios. Source: Centro de Cambio Global UC (2018).

4.2 MACROECONOMIC ANALYSIS

The challenge of designing climate mitigation policies packages entails many dimensions and interactions. Their main purpose is to reduce emissions while trying to achieve a target. In the case of Chile, it is zero net emissions by 2050. However, several dimensions need to be considered in order to achieve an integral and sustainable development path, such as the parameters that can be tackled and the tools available. Good examples are economic growth, the addressing of income distribution and institutional arrangements promoting macroeconomic and financial stability in the policy framework of climate change policies (NGFS, 2019). When modelling these dimensions, sophisticated computational processes are required together with the best assumptions on those parameters determined with both empirical evidence and/or normative criteria described in (Nordhaus, 1993).

In particular, the most remarkable Chilean experience combining energy models and the newest models in macroeconomics was the MAPS project (Ministry of the Environment, 2016), whose updated version is currently being used by the Ministry of Finance to establish the costs and benefits of climate policies for the NDC to be presented in 2020. The participative process of MAPS built the scenarios of mitigation policies with around 11 models of each sector and the assessment of 6 scenarios that delivered lessons that are presently used to set up the new attempts in this learning-by-doing process. In this chapter, we want to review the main 10 parameters identified in the modelling process of MAPS and its newest version – recognized by its significance in the literature – and briefly discuss the uncertainties related to their determination and some challenges for the future modelling processes. Also, we want to introduce some tools that, from a macroeconomic and financial perspective, may allow to help mitigate climate change.

Following reference (Butler, 2014), we identify some of the most relevant parameters in the literature for which the uncertainty is relevant at the time of the modelling process, and of the same significance value for the Chilean modelling case. These parameters are: 1) Population, 2) GDP growth, 3) Carbon intensity (prices and technology costs), 4) Carbon cycle, 5) non-CO_2 forcing, 6) equilibrium climate sensitivity, 7) damage function and exponent coefficient, 8) pure rate of time preference (discount rate) and 10) time horizon.

From the list of parameters identified as the most relevant for climate mitigation modelling, some are provided by model-databases or expert criteria (Álvarez *et al.*, 2017). Furthermore, some parameters come from purely scientific or descriptive evidence, like the equilibrium climate sensitivity, while others are normative or prescriptive, like the discount rate. In this regard, we discuss the main issues around the estimate of this list of parameters while assessing the climate policies for Chile.

Given the previous process upon which Chile determined its NDC, we can consider that the main drivers for a mitigation path from a reference scenario of emissions are population and GDP growth rates. As for population, despite the official forecast of population by 2050, we need to consider other relevant sources like those presented by the United Nations Population Division (United Nations, 2016), where global population towards 2100 ranges between 9.49 to 13.2 billons, somehow impacting the initial forecast of population by region and at national level, including Chile. We can observe a good example of the importance of this phenomenon, on the relevant immigration process experienced by Chile over the last five years, representing a 4% of the total population.

At the same time, GDP growth is the main driver for energy consumption hence an important input of CO_2 emissions estimates, also determinant for sectoral activity growth and for the entire macroeconomic frame. Models' performance in the short and long term has an acceptable assessment. However, the uncertainty is relevant in the long term. An identification strategy for this parameter would be the review and comparison of a theoretical and empirical observation of economic growth at the different phases of development of the countries in the past. For instance, for the new Chile's NDC estimate, we considered the forecast information available at that time, as well as the theory of growth, stablishing the convergence rate according to the phase of development. Nonetheless, uncertainty grows gradually, as a result of the lack of information about the future and the causal dynamics of the other non-observable variables that may affect the forecast, such as political stability and social behavior.

Moreover, parameters related to carbon intensity and non-CO_2 forcing, are modeled by decarbonization plans due changes in energy, following assumptions in prices and expected cost of technologies. The drop-off on solar photovoltaic technology construction costs is the main instance of unpredicted behavior of a technology, as noted in the previous chapter. Similarly, the intensity is related with the value added of the economy measured by the GDP. The modelling process does not consider the decouple between emissions and the GDP observed in the past and highly expected in the future as exposed in (Cohen *et al.*, 2017). We can see some preliminary symptoms in the Chilean case, where a good example can be found in the UK as shown in Fig 21.

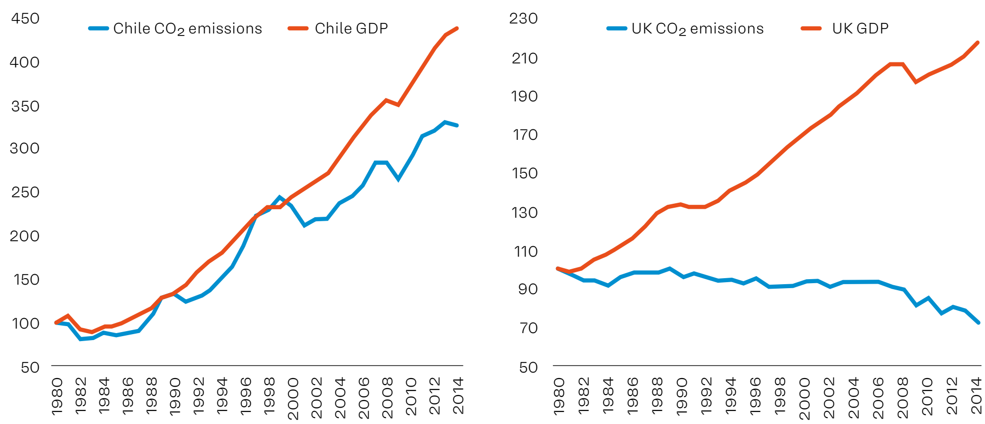

Figure 21: Decoupling the economic growth of CO_2 emissions (reference year 1980). Source: Own elaboration based on World Bank and IMF World Economic Outlook information.

Looking forward, the decarbonization process of economy shall consider that a technological change and adoption of clean technologies should facilitate economic growth with less emissions, even in the setup of the reference scenario. If the expected net gains between operational expenditure (OPEX) and capital expenditure (CAPEX) investments are so significant, a natural adoption of technologies should be introduced in the base-line scenario, although it is sometimes omitted by the modelers[4]. In the same way, the uncertainty around the modeled sector that captures CO_2 is relevant in many cases. For example, if we look at the Chilean case for 2016, around 65% of the emissions were captured by the forestry sector and we will need to improve this measurement in order to certify GHG-neutrality.

Another source of uncertainty in the modelling process of climate policy actions is the pure rate of time preference (discount rate) that tells us the rate at which future damages and cost of climate change are discounted to the present. This parameter is particularly sensitive, and its adoption usually responds to a

4 Nonetheless, market barriers, market imperfections and failure to coordinate among agents are also, as noted before in chapter 3, relevant issues that might justify the requirement of public policies to help overcome such difficulties and generate suitable environments to implement interventions effectively or to adopt new technologies.

normative criterion varying from different goals that are assumed. In addition, the time horizon parameter determines the degree of information available and, at the same time, the level of uncertainty exposed in policy design.

In contrast, such parameters not considered in the preliminary exercises of the climate policy assessment in Chile, such as the carbon cycle, the equilibrium climate sensitivity and the damage function coefficient, are links between economics and the physical systems that shall be developed in accordance with the international literature on climate science.

Additional to parameter uncertainty, there are several economic tools that may prove critical to climate change mitigation. Krogstrup and Oman (2019) reviews macroeconomic and financial policies for climate change mitigation. Financial policies, such as carbon tax or public-private partnerships, seem to be central but not enough, as they need to be supplemented with financial and monetary policies. On the one hand, financial tools aim to reduce short-term bias, improve the governance of financial institutions and help the development of green financial securities (like the first green sovereign bond in Americas issued by Chile)[5] and regulatory tools. On the other hand, monetary policy tools may be directed to integrate climate risk analytics into collateral frameworks to boost green asset prices (green quantitative easing).

However, more evidence needs to be drawn from the policies that have been applied by some countries or those to be applied in the near future, in order to assess what combination of economic tools works better that can be adapted to the Chilean economy.

In order to contribute to the main purpose of reducing emissions and increasing the welfare of society, a regular building phase of modelling capacities requires an ongoing review of assumptions and parameters, and an equally regular improvement of data sources at both local and international levels. Similarly, effective fiscal, financial and monetary policy tools that may help to mitigate climate change shall need to be assessed. Working this way, we may reduce uncertainty while using these instruments as a rigorous tool for data driven policies.

5 "Chile issues its first Green Bond and meets record demand with a historically low rate", Ministry of Finance of Chile, 20 June 2019, https://www.hacienda.cl/english/press-room/news/archive/chile-issues-its-first-green-bond-and.html.

Conclusions and future work

Since the beginning of the 21st century, the development of participatory processes in the field of energy and climate change has been consolidated in Chile. Although these practices have not been fully institutionalized, the updating of NDCs follows this logic, in particular by integrating the scientific community in a non-binding process of dialogue and exchange. The Ministries of Energy, Environment and Finance have created their own research skills, thereby producing the analyses and evidence that support the proposed contribution. This process has been supported with studies conducted by consulting teams. During 2019, the work of the ministries consisted of a long-term projection with the objective of determining the trajectory required to reach the goal of GHG- neutrality by 2050, in accordance with the decarbonization commitment acquired as a country. The update of the contribution emerges as an intermediate milestone of this process, within a 2030 planning horizon, consistent with the long-term view.

The Paris Agreement requires NDCs to be updated every five years, with the logic that each update becomes more ambitious than the previous one. In order to address these challenges, a cooperative effort was consolidated between the Mitigation Bureau and partner ministries in Chile, with the aim of preparing an analysis document that will serve as a basis for prioritizing such efforts aimed at giving robustness to the final decision that will lead to an NDC update.

Updating NDCs will require an ongoing work to prepare baseline information, sectoral analyses and mitigation measures. These analyses are developed in a context of uncertainty that requires an assessment of robustness, flexibility and resilience, with a further need to involve social, environmental and territorial factors, consistent with the reality and changes the country is facing.

The main conclusions and recommendations of this work are summarized as follows:

› Regarding the level of ambition of the NDC mitigation proposal:
  - GHG-neutrality target for Chile by year 2050 is aligned with the climate change agreement in Paris (COP 21) and the 1.5 °C target.
  - The level of ambition of the updated NDC proposal is clearly higher than current NDC. In fact, for the BAU scenario, current NDC increases yearly GHG emissions by year 2030.
  - Following the recommendations for the presentation of information on contributions (Katowice Measures) and international trends, the NDC update has integrated absolute targets, the carbon budget and maximum peak per year. Compared with the current NDC, this change is a clear progress in the type of metrics adopted, thus improving the transparency of the commitments and monitoring systems. In addition, specific studies have sought to provide the necessary evidence.
  - The mitigation actions studied for the NDC proposal are consistent with GHG-neutrality by year 2050. Nevertheless, these results are highly dependent on LULUCF capture levels (65 $MtCO_2eq$ yearly). Despite being out of the scope of this document, the authors identify this issue as a relevant uncertainty. Additionally, the voluntary phase-out plan for coal-fired power plants is also a major uncertainty that should be considered.

› Need for a permanent, formal work among the different ministries, international agencies, research teams, the private sector and civil society to allow for an ongoing monitoring and assessment. The necessity to contribute to the design and develop science-based policies is one of the key challenges of the Ministry of Science, Technology, Knowledge and Innovation in Chile. This challenge requires the building of a permanent institutional capacity to address public needs by means of the systematization and translation of the primary evidence produced by the national scientific community. In light of the COP25 Scientific Committee's recent experience, we suggest the Ministry to play an interface role between evidence and public policies, generating an active interaction among the national scientific community and the public sector institutions involved in Climate Change. Upon building this institutional capacity, we expect that the Scientific Committee for Climate Change – proposed in the Framework Law for Climate Change – will enhance scientific and social capital through a formal dialogue where the outcome of the scientific community will be the design, implementation and assessment of public policies, national contributions, long-term strategies and sectoral plans to address the progress and impacts of Climate Change in Chile and its regions. For this purpose, the development of human capital with specific competences as facilitators between science, public sector, industry, and community is required.

› Permanent and strategic assessment of multiple scenarios and sensitivities is required to define public policies that better orient the decisions of the different actors.
› Continue to make progress in the analysis and assessment of policies and instruments that enable the implementation of measures. It is key to develop monitoring systems of existing solutions against preliminary analyses. This is due to the fact that the basic information of the analysis integrates information of several sources, either of national or international sources, which should be reviewed and updated on a permanent basis; particularly, efforts should be made to improve the local representativeness of each one of the variables, e.g. prices, costs, projections, among others.
› The use of Marginal Abatement Cost (MAC) curves, in contrast to the use of sector models, requires an explicit analysis of consistency and interactions that is not usually assessed. MAC curves obtained in the analysis of the mitigation options for Chile show the existence of measures that have negative mitigation costs. This occurs due to a variety of reasons, but the main may be capital-intensiveness, i.e. despite operational savings, these measures are not implemented because decision-makers have budgetary constraints or their minimum acceptable discount rates are higher. Another common reason is that decision-makers do not have perfect information to make their decisions. A detailed analysis on why these measures are not deployed in the reference scenario – despite their high social profitability – is critical, as also is the assessment of necessary public policies that would allow their implementation. It is necessary to go beyond technical and economic analysis to assess the implementation of the mitigation measures and incorporate the impacts these measures may have considering the social context, cultural relevance and political feasibility. Also, it is essential to understand climate change as a complex and multidimensional risk, which cannot be understood in isolation from other challenges the country is facing.
› A macroeconomic assessment of scenarios with and without mitigation measures should be a key element of the future methodology that supports the NDC for Chile. To deal with this challenge, we propose a formal methodological loop that incorporates a macroeconomic assessment as part of the whole process.
› The benefits of integrating black carbon mitigation measures, in addition to their effect on mitigation, show the importance for their integration into comprehensive mitigation strategies.
› Specific nature-based and non-energy solutions have not been considered within the strategies, so they are outlined as a great potential and challenge of systematic studies for the near future. It is necessary to elaborate a system to assess these measures:
  • The relative importance of non-energy sectors (industrial processes, waste, agriculture and forestry) will undergo a steady growth by 2050, partly because mitigation in these sectors is proportionately more modest than in the energy sector. This implies that potential for abatement in non-energy sectors needs to be studied in greater depth, and particularly increasing the emphasis on the agriculture sector, as promoted by the special report on climate change and land published in 2019 by the IPCC.
  • Mitigation in Agriculture and Waste sectors has an important component on the demand side; modifications of food choices, reduction of food loss and waste, reduction of GHG emissions and improvement of food systems resilience. As for waste, changes in consumption patterns, waste valorization, and conscious individual control of waste generation are actions that cannot be bypassed that have been strengthened via education.
› Regarding the limitations of this analysis, the incorporation of a scenario for renewable energy exportation from Chile should be considered. This exportation can be performed by a combination of electricity networks in LATAM, production of synthetic fuels (i.e. hydrogen) or the attraction of foreign industry to Chile. The economic impact of this scenario should be assessed. Additionally, this type of strategies will contribute to the position of Chile in terms of Article 6 of the Paris agreement.

- In addition, there is a need to better understand the role of Article 6 in implementing its NDC and if Chile is going to use cooperative approaches in this context. Recent studies by the World Bank and the International Emissions Trading Association indicate that this Article 6 has the potential of substantially reducing the costs of NDC implementation by mid-century, together with reducing global emissions in a relevant portion.

Finally, we should not forget that not only climate change represents a risk factor in accelerating, strengthening, amplifying and multiplying situations of uncertainty, conflict, violence and political crisis in the future, but proposed control and mitigation measures may also generate conditions of instability. Climate risks will be increased by the local conditions of poverty and inequality, but they may be controlled by means of adequate investments in institutional response and adaptation capacities, which implies structural transformations that strengthens the social fabric, the preparation of the population and governance conditions. On the contrary, the adoption of inappropriate policies may accelerate or even amplify uncertainty and conflict. The current social crisis in Chile is a stark reminder of these two types of enabling conditions that we need to consider.

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