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ROADMAP FOR THE ENERGY TRANSITION IN CHILE

FINAL REPORT

OCTOBER 28, 2022

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Thanks to the Ministry of Energy of Chile for its permanent collaboration in the development of this study.

Published by energiE and MRC Consultants and Transaction Advisers.

www.energiE.cl / Badajoz 130, Office 1201, Santiago, Chile.

https://mrc-consultants.com/ / Paseo de la Castellana 123, Esc. Dcha. 5-B, 28046 Madrid, Spain.

November, 2022.

To cite this document: energiE - MRC, "Roadmap for Energy Transition in Chile", 2022.

ACKNOWLEDGMENTS

This report has been driven by the Enel Group in Chile and prepared by energiE in collaboration with MRC, as an analytical and participative consideration on the steps and the path Chile must follow to advance in its transition to decarbonization. This study has had the voluntary participation of various actors of recognized prestige and diverse profiles, with the objective of sharing and enriching with diverse contributions, and thus being able to convey their vision on the most relevant issues and identify potential ways to advance towards the goals and commitments entered into by Chile until 2050.

Special thanks to the following participants for their collaboration throughout the study:

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- Aura Rearte	ACESOL
- Carlos Cortés	AGN
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- María Trinidad Castro	World Energy Council Chile
- Marina Hermosilla	Chile Foundation (*Fundación Chile*)
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- Patricia Darez	350renewables
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Santiago, October 28, 2022

Subject: Foreword by the General Manager of Enel Chile

The fight against climate change is one of the great challenges of the 21st century. We find ourselves in a time of major challenges that become opportunities to accelerate the transition to a more just and planet-friendly society. To achieve this, we need to focus our efforts on seeking innovative, timely and effective solutions for the planet and humanity. Undoubtedly, the impact of climate change requires us to prioritize short- and long-term actions to adapt and avoid major effects. The climate crisis is evidence of the unsustainability of production and consumption processes. Its aftermath has led to the loss of biodiversity, reducing the resilience of ecosystems, and has become a social, political and economic emergency in many countries. Rising temperatures and extreme weather events affect life in the most vulnerable territories and, in particular, the most vulnerable communities.

We have undertaken great efforts on the subject of decarbonisation. In September 2022, we were the first company to stop using coal to generate electricity in Chile and we still have more to contribute by finding ways and solutions through innovation, the creation of new paradigms, investment and education, but we must do it collectively and decisively.

Motivated to contribute to this collective development, the Enel Group presents the study "Roadmap for the Energy Transition in Chile", carried out by the consulting firms energiE and MRC and with the inclusive participation of various public and private institutions, unions, academia and experts in the country, as a technical and inclusive proposal initiated by Enel that seeks to accelerate the necessary transition towards the sustainable decarbonization of the energy model in our country, sharing and enriching various visions on the most relevant issues and identifying potential ways forward towards a country without emissions. We encourage this initiative because we are aware that the energy transition may not be seen as a possible future, but as our present and only future in order to reduce the negative impact that people and industries have on our environment. This is the way forward to ensure that our children and our children's children receive a world that allows them to grow and develop to their full potential.

This transformation is framed within the compliance with the Chilean greenhouse gas emissions reduction target and the consideration of other key aspects of energy policy, such as security of supply, competitiveness of the energy-economic system, compatibility with growth criteria, environmental & social sustainability and just energy transition.

This study developed in the year 2022 is carried out considering the global scope of the fight against climate change and the commitment made by the countries at the last COP 26 in Glasgow. In this sense, we provide this Roadmap as a contribution of an additional perspective in the considerations and national debates on the subject and in preparation for the country's participation in the COP 27 to be held next November 2022 in Sharm El-Sheikh, Egypt.

In this search for solutions and call to action, all parties must play a role: companies must integrate sustainability at a strategic level, modifying their industrial and productive processes; people must rethink their consumption decisions; public policies must promote a new development model, with specific goals for the territories and with long-term projection.

This open and collaborative proposal, in which multiple stakeholders were involved, was carried out in three participatory workshops, four round tables and a series of discussion and validation meetings, achieving a total of more than 200 participants and its most outstanding merit lies in the comprehensive view of all the aspects necessary to achieve a sustainable and fair change; Among them, the situation of present and future energy demand, the inclusion of intelligent and non-conventional technologies, the development of electric mobility, distributed generation, green hydrogen, the cost-benefit analysis for the country's economy and an analysis of the impact on employment that will lead to labor reconversion and the creation of new job offers. All this, grounded with a proposal of scenarios and concrete goals for this process.

I am immensely grateful to all the people who participated in this study that marks the path to follow in order to advance in the construction of the country we dream of.

Fabrizio Barderi
General Manager Enel Chile

Maurizio Bezzeccheri
Enel Group Director for Latin America

Santiago, October 28, 2022

Subject: Foreword by energiE's Partner Director

Climate change is the greatest global threat and challenge of our era. Today, the world is facing drastic changes such as drought, heat waves, forest fires, rising sea levels, floods, storms, loss of biodiversity and the imbalance of life-supporting ecosystems in an increasingly noticeable and severe manner.

The increase in the concentration of greenhouse gases (GHG) in the atmosphere and their consequences on ecosystems and humanity began to be a matter of concern for the international community several decades ago. The adoption in 1992 of the United Nations Framework Convention on Climate Change ("UNFCCC" or "Convention"), whose objective is to achieve "...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" was a manifestation of such concern.

But the news that the scientific world has given us this year is not altogether encouraging, nevertheless, Chile is acknowledged to have faced climate change with a proactive position in its international agenda and negotiations on climate change, increasingly recognizing its importance in public policy and also in the ambition of the commitments that the country has acquired.

By virtue of the above, I would like to give special thanks to ENEL Chile for having promoted and materially supported this initiative, as well as contributing with expertise and the know-how of similar initiatives developed simultaneously in other countries of the region. I would also like to thank the professional teams of energiE and MRC, as well as the stakeholders who accepted our invitation to participate and contribute to the success of this project, which represents a contribution to the elaboration of results and public policy proposals that will allow us to continue advancing on Chile's path towards carbon neutrality.

Daniel Salazar Jaque
Partner Director energiE

EXECUTIVE SUMMARY

The energy transition is an irreversible process driven by public policies that go beyond climate change and include multiple initiatives and variables. Increasingly frequent extreme weather events caused by climate change urge all stakeholders and governments to focus on the need for action. Additional public policies further accelerate the energy transition in pursuit of other objectives such as air quality, security of supply, circular economy, decarbonization of the economy, green growth and employment associated with clean technologies.

The Paris Agreement provided very important signals to investors in terms of challenges, credibility and transparency of the commitments made by governments to fight climate change. The outcome was a landmark for three reasons: 1) Ambitious and broadly supported targets were set; 2) Strong awareness of the key role of climate finance; 3) Increased commitment to transparency on targets and actions taken.

Nationally Determined Contributions (NDCs) play a key role in providing companies and stakeholders with much-needed visibility into the future evolution of the investment landscape. NDCs and corresponding Climate and Energy Action Plans developed by governments are published in a transparent fashion by the UN for review by local and global stakeholders, including private sector investors. Governments are expected to develop and maintain ambitious, transparent, comprehensive and reliable plans that clearly state their objectives, as well as the policies and instruments developed to achieve them.

Targeted deployment on specific drivers could play a key role in accelerating the energy transition. It is in this context that the right technological, regulatory and market instruments allow the available technologies to play a key role and make them a suitable choice for a smooth and cost-efficient transition.

The preparation of this roadmap brought together different actors, both from the public and private sectors, as well as academia, trade associations and NGOs, in order to obtain a cross-cutting vision of the aspects that must be considered in the development of initiatives that will allow Chile to advance in an organized manner in the process of reducing emissions.

Only transition scenarios are capable of meeting the emission reduction commitments established for the year 2050. The sectors with the greatest contribution to the emissions inventory are the electricity sector, the transport sector and the industry sector. Without contributions from these three groups, the transition scenarios, and therefore compliance with the net-zero objectives by 2050, are impossible. The rest of the sectors, even with smaller contributions, also must maintain declining emissions trajectories, or with moderate growth compared to the growth of their demand.

To achieve the decarbonization targets, deep sectoral transformations are required in the power sector, transport sector, industrial sector, and tertiary sectors (residential, commercial and public sector consumption), which requires significant volumes of investment over the entire horizon of the study.

Specifically, the cumulative investment in the Base Scenario to 2050 amounts to US$184 billion, whereas, to achieve the decarbonization targets, this must be increased by 9% in the Fast Transition scenario to US$199 billion and by 28% in the Accelerated Transition scenario to US$235 billion.

Several public policies are identified, which should be prioritized during the current and following decades, in order to focus efforts on a strategy that expedites the closing of gaps and progress towards emission reduction targets in a consistent and structured manner.

The energy industry is making progress through multiple actions to reduce and mitigate GHG emissions. This translates, for example, into a wide adoption of reliable and emission-free energy generation, where the increase in VRE requires the design and promotion of enabling conditions that recognize their attributes and allow their requirements to be met through efficient market signals.

This will increasingly pave the way for lower emission energy carriers, where reliable and emission-free electricity is destined to play a key role in the decarbonization of transport and industry, and where electrification cannot reach, H_2 will be the carrier that will do the rest of the job.

1 DEFINITIONS AND ABBREVIATIONS

Abbreviation	Definition
ACERA	Chilean Renewable Energy and Storage Association - *Asociación Chile de Energías Renovables y Almacenamiento*
ACESOL	Chilean Solar Energy Association - *Asociación Chilena de Energía Solar*
AGN	Association of Natural Gas Companies - *Asociación de Empresas de Gas Natural*
IEA	International Energy Agency
ANESCO	Chilean Association of Energy Efficiency Companies - *Asociación Nacional de Empresas de Eficiencia Energética*
CCH	Central Chile
CLAPES UC	Latin American Center for Economic and Social Policies of the Pontifical Catholic University of Chile. - *Centro Latinoamericano de Políticas Económicas y Sociales de la Pontificia Universidad Católica de Chile*
UNFCCC	United Nations Framework Convention on Climate Change
Commission or CNE	Chilean Energy Commission - *Comisión Nacional de Energía*
Coordinator or CEN	Chilean Energy Coordinator – *Coordinador Eléctrico Nacional*
CORFO	Corporation for the Promotion of Production - *Corporación de Fomento de la Producción*
LTCS	Long-term Climate Strategy
VRE	Variable Renewable Energy
ETSAP	Energy Technology Systems Analysis Programme
GHG	Green House Gasses
GIZ	German Agency for International Cooperation
NG	Natural Gas
HDV	Heavy Duty Vehicles
LDV	Light Duty Vehicles
H2/H_2	Hydrogen

GH_2	Green Hydrogen
INDAP	Chilean Institute for Agricultural Development - *Instituto de Desarrollo Agropecuario*
IPCC	Intergovernmental Panel on Climate Change
ISCI	Institute of Complex Systems Engineering - *Instituto Sistemas Complejos de Ingeniería*
MAG	Magallanes Region
NDC	Nationally Determined Contribution
NOG	Great North Region - *Norte Grande de Chile*
NREL	National Renewable Energy Laboratory
LTEP	Long-Term Energy Planning
TEP	Annual Transmission Expansion Plan
GDP	Gross Domestic Product
SEC	Electricity and Fuel Superintendency - *Superintendencia de Electricidad y Combustibles*
SEN	Chilean Electrical System - *Sistema Eléctrico Nacional*
SERCOTEC	Technical Cooperation Service - *Servicio de Cooperación Técnica*
LULUCF	Land Use, Land Use Change and Forestry

2 INTRODUCTION

Climate change is the greatest global threat and challenge of our time. Today, the world is facing drastic changes such as drought, heat waves, forest fires, rising sea levels, floods, storms, loss of biodiversity and the imbalance of life-supporting ecosystems in an increasingly noticeable and severe manner.

The increase in the concentration of greenhouse gases (GHG) in the atmosphere and their consequences on ecosystems and humanity began to be a concern of the international community several decades ago, with the adoption in 1992 of the United Nations Framework Convention on Climate Change (UNFCCC or *Convention*), whose objective is to achieve "...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".

To that end, stabilization of concentrations must be within a time frame sufficient to allow ecosystems to adapt naturally to climate change; to ensure that food production is not threatened; and to allow economic development to proceed in a sustainable manner.

In the context of the Convention, the Kyoto Protocol, enacted in Chile by Supreme Decree No. 349 of 2004 of the Ministry of Foreign Affairs, established emission reduction commitments for developed countries (Annex I), in consideration of their historical responsibility for GHG levels in the atmosphere. In this context, and based on the principle of common but differentiated responsibilities, developing countries (Annex II) did not assume emission reduction obligations.

This protocol was not sufficient to achieve a reduction in global GHG emissions. Therefore, after multiple negotiations to define the instrument that would replace the Kyoto Protocol, the Paris Agreement was reached in 2015, in which the parties commit to "Keep the increase in global average temperature well below 2 °C above pre-industrial levels, and to pursue efforts to limit this temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change."

In this context, Chile submitted its first NDC in 2015, committing to achieve progress on mitigation, adaptation, capacity building, technology transfer and climate change financing. The analysis of the global ambition of the NDCs evidences that there is still much room for further commitment to meet the agreed global goal, also with mitigation actions conditional on financing support and technology transfer.

Chile submitted a new NDC in 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 (95 $MtCO_2eq$ in 2030), includes a carbon budget between 2020 and 2030 (1110 $MtCO_2eq$) and peak emissions for 2025. Chile also recognizes its 2030 target as a medium-term goal to achieve its long-term goal of GHG neutrality by 2050.

These definitions have begun to bring about changes with unprecedented force and speed, which challenges public and private agents, as well as the civil society, to identify the enabling conditions and the appropriate route for the development of a key sector for the country's economy, visualizing the joint effect of the different measures, goals, actions and public policies.

This is why Chile presented its Long Term Climate Strategy (LTCS) at COP26 in order to consolidate the State's vision to address climate change and comply with the provisions of Article 4(19) of the Paris Agreement, which states that the parties must formulate their LTCSs taking into account the temperature objective established in the agreement and "taking into account their common but differentiated responsibilities and respective capabilities, in the light of different national circumstances".

While the Paris Agreement does not define in detail the format or content of the LTCSs, the collective efforts of countries (33 of which have delivered strategies to date), international institutions and other experts have established some fundamental principles and best practices.

Notwithstanding the above, the news from the scientific world this year is not altogether encouraging. The latest report of the Intergovernmental Panel on Climate Change (IPCC) of April 2022 concludes that[1]:

a) The global average temperature has risen by 1.09°C in the last four decades, something unprecedented in hundreds of thousands of years;
b) Human influence is indubitable and the dominant cause of global warming; and
c) Unless there are immediate, rapid and large-scale emission reductions in the coming decades, temperature growth will exceed 1.5°C and 2°C during the 21st century.
d) Despite the last IPCC report, it is recognized that Chile has faced climate change with a proactive position in the international climate change agenda and negotiations, increasingly recognizing its importance in public policy and also in the ambition of the commitments that the country has acquired.

Based on this experience and considering the national reality, Chile has just adopted its Framework Law on Climate Change, which contains the main contents of the LCTS, being this the long-term instrument that will define how the goal of GHG neutrality and increased resilience will be achieved by 2050 at the latest.

2.1 Purpose

The purpose of this study is to establish and evaluate different energy scenarios through a multivariate analysis in order to identify the main aspects that shape public policy measures

[1] Source: IPCC Working Group I Report (2021)

that will allow Chile to achieve Carbon Neutrality by the year 2050. For this purpose, the study included the following activities:

1) Define a view on how the Chilean energy system can be developed in accordance with IPCC and UNFCCC trajectories and national commitments on Climate Change policies;
2) Enrich the debate on the Chilean energy system, incorporating objective and factual considerations (costs and benefits) on the main decisions to be addressed in the coming years (i.e. taxes, consumption, electrification of energy demand, development of renewable energies and infrastructure, transportation model and services, among others);
3) Develop arguments and analytical support for key issues, i.e. switching to cleaner energy carriers, wholesale markets, among others, that could drive the evolution of the regulatory framework;
4) Reinforce the adequacy and appropriateness of a long-term zero GHG emissions roadmap for Chile's Climate Change policies in the international context.

2.2 Scope

Within the scope of this study, the emissions' trajectories of the different sectors of the economy are evaluated, and the key actions that must be executed to achieve the proposed trajectories are identified, all of which is developed through a multivariable modeling that allows analyzing, structuring and establishing the optimal route based on projected costs of the different technologies, as well as restrictions established for each scenario, configured based on the goals established in the different public instruments used for the preparation of the study.

The study was based on public information, obtained mainly from the National Energy Balance (*Balance Nacional de Energía*) of 2019, baseline year with which the energy prospection model is parameterized; the Long Term Energy Planning developed by the Ministry of Energy from which values, projections, and detailed analysis were obtained for each subsector of the economy, as well as sectorial information obtained from different public sources, specifically from the national strategies of electromobility and green hydrogen (GH_2).

Lastly, we would point out that during the course of this study, as a result of Russia's invasion of Ukraine, the countries and economies of reference in the process of reducing emissions, and the world in general, have had to face a deep crisis - both in economy and energy - which has given rise to a global restructuring - still underway - in which a process of revision of priorities and objectives has already been identified, in which energy security and price/cost control are increasing in relative significance. Indeed, various European countries are adopting emergency measures to deal with the energy crisis amid growing pressure on Russian gas supplies, in addition to OPEC's decision to cut oil production, which is causing alarm and concern in both the European Union and the USA, which will soon face a winter of energy shortages and consequent price increases and a slowdown in growth.

The effects and projections of the above are, incidentally, beyond the scope of this paper, but they set a context that cannot be ignored at the end of the study.

3 CONTEXT

The purpose of this section is to describe the main instruments that were used as a basis for the study in order to structure the environment in which this energy prospection assessment was developed. Likewise, the instruments that have the status of law will be considered as part of the basic definitions for the construction and definition of scenarios for the exercise, from which sensitivity criteria will be defined to evaluate the impact of advancing certain measures with respect to those already defined in the current sectoral strategies in order to analyze their effect on emissions trajectories and on the levels of investment required to achieve these goals.

3.1 Long-term Climate Strategy

The Framework Law on Climate Change (*Ley Marco de Cambio Climático*) establishes the objective of achieving and maintaining carbon neutrality and advancing towards climate change resilience by 2050 at the latest. It also establishes principles, a governance system, management instruments, and adequate information and participation systems, which allow moving towards a neutral development in GHG emissions, reducing vulnerability, increasing resilience and guaranteeing compliance with the international commitments assumed by the State of Chile to face the challenges imposed by Climate Change.

One of the climate change management instruments established in the Framework Law on Climate Change corresponds to the Long-term Climate Strategy (*Estrategia Climática de Largo Plazo*), which defines the general long-term guidelines that the country must follow in a cross-cutting and integrated manner to achieve carbon neutrality, this was presented by Chile at the COP26 held in 2021. Additionally, an intermediate goal is established as a commitment associated to the Nationally Determined Contribution (NDC), which are periodically updated according to the economic and political conditions of the country.

In this regard, the new NDC incorporates several goals to 2030 in terms of GHG mitigation and short-lived climate pollutants, adaptation and resilience, highlighting water security, oceans, circular economy, forests, peatlands and ecosystems; all this to move towards an integrated and synergistic vision in the design and implementation of climate action in Chile, additionally within the pillars that were incorporated into the NDC goals were that these should be addressed under a scheme of just transition and sustainable development. [2]

Chile is a small emitter, historically contributing approximately 0.25% of global emissions, however, it is an active and ambitious actor in its emissions mitigation commitments as demonstrated by the carbon neutrality goal and the update of the NDC with an ambitious goal

[2] Source: Long-term Climate Strategy (*Estrategia Climática de Largo Plazo*), Government of Chile.

for the year 2030, with the objective of demonstrating strategies and innovations to achieve the carbon neutrality process in a safe manner and under the fair transition and sustainable development approach indicated above.

The following is a brief summary of the emissions context for 2018, which was defined in the LTCS as the benchmark for the new NDC targets:

Total GHG emissions of the country (excluding the Land Use, Land Use Change and Forestry (LULUCF) sector) were 112,313 kt CO_2eq, increasing by 128% since 1990 and by 2% since 2016. The main GHG emitted was CO_2 (78%), followed by CH_4 (13%), N_2O (6%), and Fluorinated Gases (3%).

The Energy sector (fossil fuel consumption for energy purposes) is the main GHG emitter representing 77% of total emissions in 2018, mostly due to emissions resulting from the burning of coal and NG for electricity generation; of liquid fuels for land transportation.

The LULUCF sector, the only GHG absorber in the country, is a net sink sector and corresponds to the forestry sector and remains as a sink throughout the entire time series. In 2018, net GHG removals accounted for -63,992 kt CO_2eq mainly due to the increase in forest biomass and wood products. A peak of emissions from the sector stands out in 2017 when 570,000 ha were affected by fires in Forest Land, Cropland and Grassland.

With this, the balance between GHG emissions and removals from Chile (i.e. including LULUCF) reached 48,321 kt CO_2eq. The main drivers of this trend are the burning of fossil fuels and Forest Land.

Sector	1990	2000	2010	2013	2016	2017	2018
1. Energía	33.631,4	51.746,4	66.607,7	79.901,3	86.191,0	86.896,1	86.954,3
2. Procesos industriales y uso de productos (IPPU)	2.224,2	4.803,6	4.279,6	5.084,5	5.977,1	6.079,8	6.611,3
3. Agricultura	11.834,8	13.708,9	12.921,1	12.597,4	11.881,3	11.724,0	11.789,4
4. UTCUTS	-60.152,6	-73.364,3	-76.966,4	-77.561,5	-74.697,9	-11.710,3	-63.991,9
5. Residuos	1.519,0	2.742,6	4.133,6	5.095,1	6.106,6	6.515,7	6.957,6
Balance [7]	**- 10.943,1**	**- 362,9**	**10.975,6**	**25.116,9**	**35.458,2**	**99.505,3**	**48.320,7**
Total [8]	**49.209,5**	**73.001,4**	**87.942,1**	**102.678,4**	**110.156,0**	**111.215,6**	**112.312,6**

Figure 1 balance and total GHG emissions (kt CO_2eq) by sector, 1990-2018 series. Source: 4th Biennial Update Report of Chile on Climate Change (*4to Informe Bienal de actualización de Chile sobre Cambio Climático*).

The Draft for the Framework Law on Climate Change contemplates an ambitious reduction of emissions by 2050 from 130 million tonCO2eq (in the reference scenario) to 65 million tonCO2eq in the carbon neutrality scenario, which considers that by 2050 these emissions will be neutralized from the forestry sector.

The plans associated with the Long-Term Climate Strategy focus on four main pillars: mitigation, adaptation, integration, and means of implementation, and in accordance with the above, the main elements necessary to correctly address the development of this study are described below. Specifically, one of the key elements to properly understand the modeling to be carried out is found in the intermediate emission targets. Particularly in the NDC update[3], Chile committed to implement the following short-term mitigation measures:

a) **M1)** Chile commits to a GHG emissions budget that will not exceed 1,100 $MtCO_2eq$ between 2020 and 2030, with peak GHG emissions by 2025, and to reach a GHG emissions level of 95 $MtCO_2eq$ by 2030.
b) **M2)** A reduction of at least 25% of total black carbon emissions by 2030, with respect to 2016. This commitment will be implemented mainly through national policies associated with air quality. In addition, this will be monitored through a permanent and periodic work on the improvement of the black carbon inventory information.

Furthermore, other integration measures that should be considered in the development of the study that are related to emission reduction objectives, which allow for a more detailed analysis of the modeling, including the following:

c) **I4)** Chile commits to sustainable management[4] and recovery[5] of 200,000 hectares of native forests, representing GHG captures of around 0.9 to 1.2 $MtCO_2eq$ per year by 2030.
d) **I5)** Chile commits to reforest 200,000 hectares, of which at least 100,000 hectares correspond to permanent forest cover, with at least 70,000 hectares with native species. The recovery and reforestation will be carried out on land that is preferably suitable for forestry and/or in priority conservation areas, which will represent captures of between 3.0 and 3.4 $MtCO_2eq$ per year by 2030.

[3] Nationally Determined Contribution 2020 Update (*Contribución Determinada a Nivel Nacional Actualización del 2020*), Government of Chile

[4] Sustainable management of native forest: set of knowledge and techniques aimed at favoring the regeneration, recovery, conservation and/or protection of the native forest, ensuring the production of diverse goods and services in a sustained and optimal way, always preserving the values of the forest ecosystem.

[5] Recovery of native forest: set of knowledge and techniques aimed at recovering, reestablishing and restoring the capacity and functionality of native forests degraded or affected by forest fires.

In addition, the NDC update defines sectoral commitment measures, which will be used as a benchmark parameter to analyze each of the different subsectors of the economy analyzed in this study.

Finally, it should be noted that the objective of the LTCS was to implement sectoral responsibilities for each of the different ministries in Chile, assigning specific measures to each ministry, in order to promote the efficient use of resources, and thus generate a reporting structure that allows constant monitoring of the sectoral goals. As a consequence, it is expected that the governance of the process will allow generating a structure for the allocation of the financing of the transition process for the country.

3.2 Decarbonization Process

As part of the key elements to move towards carbon neutrality, in June 2019, the country's generating companies that own coal-fired power plants signed an agreement with the Chilean Government to start the decommissioning process of these plants with a deadline of 2040. It is important to note that in the year the agreement was signed, the coal matrix for electricity generation represented approximately 40% of the country's installed capacity, consisting of 28 thermoelectric power plants totaling 5,500 MW.

In this regard, we highlight that, according to the 2019 National Energy Balance, 78% of CO_2 emissions are caused by the energy sector, with the electric power industry being the main culprit with 41.5%, where a portion of CO_2 emissions come from coal-fired power plants, followed by transportation with 31.3%, followed by NG and diesel/fuel oil power plants.

In light of the above, it is noteworthy that the contribution of the removal of coal-fired power plants from the energy mix is the most relevant element of the energy transition process and the optimized routes for emissions trajectories. On the other hand, although the Agreement established a deadline of 2040, various voices in the sector are pushing to bring this date forward, either to 2035 or even 2030. Therefore, it is relevant to evaluate the impact of these measures on the operation of the energy sector, particularly on how the replacements associated with these phaseouts will be addressed.

Furthermore, the authorities have conducted several studies on how to approach the decarbonization process, given that will be a significant technical challenge for the operation, particularly in terms of inertia levels, short circuits, provision of primary and secondary reserves and system stability, so moving towards a decarbonized system with a high presence of VRE must be approached strategically and with a high degree of planning.

Notwithstanding the above, both in the energy sector as well as nationwide, there is a broad consensus that the decarbonization process should be carried out in the shortest possible time.

Additionally, the process has been established to be addressed under a just transition approach. Since at the sites of these plants, particularly the municipalities of Iquique, Tocopilla, Mejillones, Huasco, Puchuncaví and Coronel, a large part of the economy is based on the operation of these plants both directly and indirectly, the just transition process establishes that it must be carried out in agreement with the local communities.

The phase-out schedule established the decommissioning of the first 1,047 MW of the eight oldest plants by 2024. These units are located in the municipalities of Iquique (1), Tocopilla (4), Puchuncaví (2) and Coronel (1), and together represent 19% of the total installed capacity of coal-fired power plants. The medium- and long-term stage consists of the commitment to define deadlines in new work groups constituted every five years, which will allow establishing specific phase-out schedules, with the common vision of the public and private sectors for the phase-out of the total fleet of coal-fired power plants before 2040.[6] In addition, this year Enel ended the operation of the Bocamina II power plant, making it the first company to completely eliminate coal from its energy mix. For the upcoming year, the Decarbonization Plan in force in the Final Report on the Short-Term Node Price for the year 2021 was considered. It specifies the decarbonization schedule as follows:

Plant	Date	Type
Tocopilla U14	Jan-22	Cease Operations
Tocopilla U15	Jan-22	Cease Operations
Ventanas 2	Apr-22	Cease Operations
Bocamina 2	May-22	Cease Operations
Mejillones 1	Dec-24	Cease Operations
Mejillones 2	Dec-24	Cease Operations
IEM	Dec-25	Conversion to NG
Andina	Dec-25	Conversion to Biomass
Hornitos	Dec-25	Conversion to Biomass
Angamos 1	Nov-28	Cease Operations
Angamos 2	Nov-28	Cease Operations
Nueva Ventanas	Nov-28	Cease Operations
Campiche	Nov-28	Cease Operations

Figure 2: Decarbonization Plan (Source: Final Short-Term Node Price - First Half 2021) (*ITD Precio Nudo Corto Plazo – Primer Semestre 2021*)

The total withdrawal of coal in Chile, as mentioned above, will generate high impact challenges for the operation of the SEN, particularly associated with the areas where these plants are located. In the Great North (*Norte Grande*) area of the country there is a large amount of VRE, based on both solar photovoltaic and wind energy, so that during daytime hours - although much more could be generated with this type of plants - the restrictions of operation to

[6] Source: Ministry of Energy of Chile https://energia.gob.cl/noticias/

minimum stable load, as well as the congestion of the transmission system that discharges from the *Norte Grande* area to the central area, limit the maximum feasible injection of VRE. In this sense, the Chilean authorities have already established the construction of a new HVDC Kimal - Lo Aguirre line, which will interconnect the northern zone with the central zone of the country, with a capacity of 3,000 MW, which is expected to alleviate the restrictions between both zones.

On the other hand, during the next few years, intensive work will be required to define the operation needs of the SEN, particularly on how it will be operated in the absence of coal-fired power plants. In a first stage, NG has been studied as a transitional fuel, in order to support the grid with inertia attributes and short-circuit levels that allow keeping the grid operating safely. However, progress is being made in evaluating how renewable power plants, together with power electronics technologies or devices that generate inertia (synchronous condensers) could generate enabling conditions to move towards a grid without thermal power plants.

Among the measures that have been evaluated to date is the migration of some coal-fired thermal power plants to a carbon neutral fuel such as biomass; however, as of the date of publication of this study, these decisions are still in the consideration stage, so they will not be considered in the current prospective exercise.

3.3 Long Term Energy Planning (LTEP)

The Long-Term Energy Planning (*Planificación Energética de Largo Plazo - PELP* in Spanish) allows for the projection of the energy sector's behavior into the future, visualizing the joint effect of the different measures, goals, actions and public policies, is a process established between articles 83 and 86 of the General Law of Electric Services (*Ley General de Servicios Eléctricos*) and regulated in Decree Nr. 134, of October 2016, which enacts the Long-Term Energy Planning Regulation.

It aims to project the country's energy demand and supply for different future scenarios, in a horizon of at least 30 years, so that they are considered in the planning process of the electric transmission systems carried out by the National Energy Commission. The process must be carried out considering a broad and effective involvement of the citizenship.

As mentioned above, its primary objective is to be the main input that guides the expansion of transmission carried out by the National Energy Commission, establishing -for example- the future of electricity generation and storage that should be considered for the purpose of evaluating the expansion of transmission systems.[7]

[7] Source: LTEP 2023 - 2027 Preliminary Report (*Informe Preliminar PELP 2023 – 2027*)

It is important to note that the long-term energy planning process in Chile, is not a binding exercise for agents, however it promotes and establishes guidelines for the industry, with the objective of giving location and market signals to agents to guide their investment decisions.

The LTEP has been carried out continuously since 2018, its first process regulated the period 2018-2022, and currently the Ministry of Energy is completing the development of the second process 2023-2027. Annually, the Ministry of Energy as part of the LTEP process must issue Annual Update Reports (AUR – *Informes anuales actualizados*, *IAA*, in Spanish) which update the results achieved in the base document, taking into account the different global conditions that affect the expected operation of the Chilean energy system, which by its nature as a fuel and technology importing country is largely subject to the international environment and therefore the route proposed in the LTEP must be evaluated annually on if it should undergo general modifications that allow aligning the country's expectations. This input is highly relevant to align the decisions made by the CEN in its annual transmission expansion plans.

The LTEP process ensures that all current and future energy needs of the Chilean society are met in the best possible way. Thus, it can establish limits, conditions and recommendations, so that the energy infrastructure, and in particular the electricity infrastructure, is developed in a sustainable manner, focusing on social, environmental, regional, economic and technological aspects.

As part of its development, the LTEP is carried out in a highly participatory process involving the general public, industry experts, academia, researchers, and consultants, who allow structuring in a systematic way the future needs of the Chilean energy system. These needs are systematized through scenarios, which allow evaluating different supply conditions, technology costs, demand levels, incorporation of new technologies, regional development, impacts on CO_2 emissions, among other variables that allow defining components that generate a particular energy scenario.

In the LTEP 2023 - 2027, the following three (3) long-term energy scenarios were defined:

1. Slow Post-Covid Recovery **(RECOVERY – *RECUPERACIÓN*** in Spanish**)**
2. Towards Carbon Neutrality by 2050 **("CN")**
3. Accelerating the Energy Transition **("TEA")**

According to LTEP 2023 -2027 specifications, energy scenarios have the specific objective of guiding the expansion of electricity transmission, however, they also allow to:

1) Design and evaluate new or developing public policies, both in the energy sector as well as in other related sectors.

2) Identify opportunities for the development of innovative technological solutions, in order to take the actions required for their adoption and implementation.
3) Highlight specific needs of communities and regions throughout Chile regarding the quality of energy services and the development of infrastructure projects.
4) Develop additional analyses and studies, both by the Ministry of Energy and by other institutions, both public and private.

Accordingly, the scenarios proposed in the LTEP are used as a basis for the development of this study, since they already provide a structured and systematized analysis, and also have a widely generalized consensus in the industry that can be used as a basis for a prospective assessment.

The structured scenarios can be summarized in their overall objective as follows:

1. Slow Post-Covid Recovery: Associated with the impact on the economy, the energy transition is slowing down, both locally and globally, and the focus is on carrying out only those activities necessary to increase air quality in cities, implement energy efficiency and meet the NDC goals by 2030.
2. Towards Carbon Neutrality by 2050: In addition to the previous measures, the inclusion of new enabling technologies for the transition is reinforced, measures beyond those established by law are implemented, thus achieving greater growth in electromobility and energy efficiency measures, as well as the introduction of the GH_2 industry in Chile, which allows reaching carbon neutrality by 2050. It should be noted that this scenario is the one considered as the basis for the elaboration of this study.
3. Accelerating the Energy Transition: It includes a deep electrification of various sectors of the economy, massively introducing electromobility, the development of GH_2 with a focus on the export of large quantities of electricity, seeking a 100% renewable operation by the year 2050 and that the commitment to carbon neutrality is achieved before that year. This scenario will be considered as a sensitivity alternative in this study.

Although the three scenarios have the same objective, their main differentiation lies in the degree of change and in the rate of introduction of new technologies into the Chilean matrix, which also shapes the levels of investment required to achieve the objectives proposed by each scenario, thus adjusting the impact on the Chilean economy that the energy transition process will entail. The scenarios can be summarized as follows:

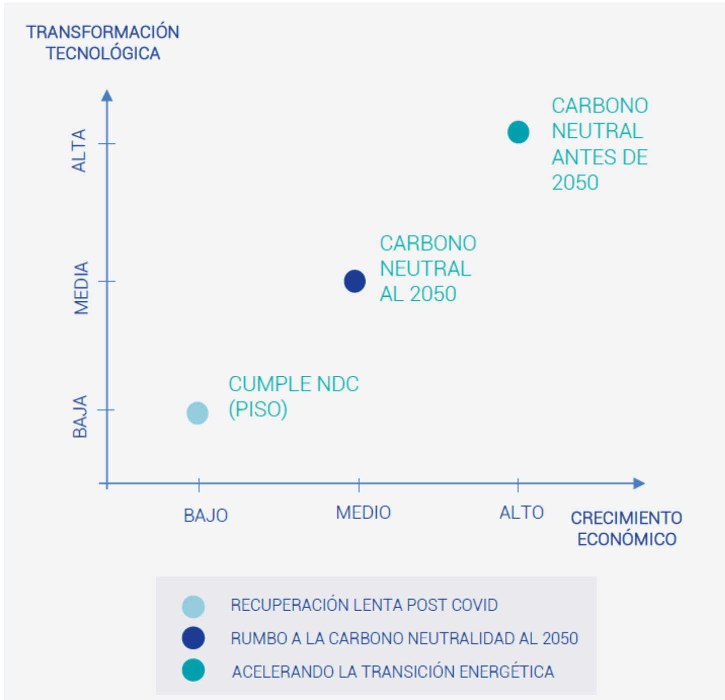


Figure 3 LTEP Energy Scenarios (Source: LTEP 2023 – 2027 Preliminary Report - *Informe Preliminar PELP 2023 – 2027*)

It should be noted that each scenario is built based on the structured statistics of the productive sectors on the basis of the National Energy Balance (Balance Nacional de Energía), the plans and public policies already defined by law, the Long-Term Climate Strategy and the macroeconomic projections defined by different public instruments, so that the LTEP planning exercise has a cross-cutting nature and a broad focus in its construction.

3.4 Electromobility Strategy

The National Electromobility Strategy aims to establish strategic axes, as well as specific measures and goals that allow the accelerated and sustainable development of electric transportation from a comprehensive, global and participative perspective. This strategy plays a relevant role in the process of achieving carbon neutrality since 36.6% of Chile's final energy consumption corresponds to the transportation sector, which is responsible for about 25.5% of the country's total GHG emissions. In 2018, GHG emissions from the transport sector were recorded at 28,615 kt CO_2eq, increasing by 214.5% since 1990 and by 8.4% since 2016.[8].

[8] GHG Inventory, Ministry of Environment (*Inventario de GEI, Ministerio de Medio Ambiente*) 2020.

In this regard, the focus of the strategy is framed within four axes, with actions to be developed in the short and medium term, which address the following aspects:

Axis 1 - Sustainable means of transportation and financing: Instruments to promote zero-emission transportation; Acceleration of zero-emission transportation by segments; Circular economy and transformation; and Enabling new technologies and uses.

Axis 2 - Charging infrastructure and regulation: Increased charging network coverage; Tariffs and integration with the electric grid, regulation and standards.

Axis 3 - Research and human capital: Development of human capital; Promotion of domestic industry; Research and innovation.

Axis 4 - Dissemination, information and coordination: Knowledge transfer; Coordination and coordination of actors; International cooperation.

Within the strategy, short- and medium-term goals have been established to accompany the process of incorporating electromobility into the country's economy. Consequently, these goals will be considered within the modeling to be developed in this study, in order to determine the impact and effect on the functioning of the energy ecosystem of a large-scale incorporation of electromobility.

It is worth noting that the axes of the strategy not only aim to implement the established goals, but also to generate the enabling conditions in terms of financing, charging infrastructure, technological standards, associated regulation, development of human capital, so it is a broad strategy aimed at providing comprehensive coverage to the country's needs when electromobility is developed.

According to the above, the goals established in the strategy are:

1) Urban public transportation, 100% of new additions must be zero-emission vehicles.
2) Light and mid-sized vehicles, 100% of sales must be zero-emission by 2035.
3) Freight Transportation over land and Intercity Buses, 100% of the sales of vehicles for intercity passenger transportation and overland freight transportation shall be zero emissions by 2045.
4) Mining, Forestry, Construction and Agricultural Machinery: 100% sales for heavy vehicles over 560 kW of power will be zero emissions from 2035, and medium vehicles over 19 kW from 2040.

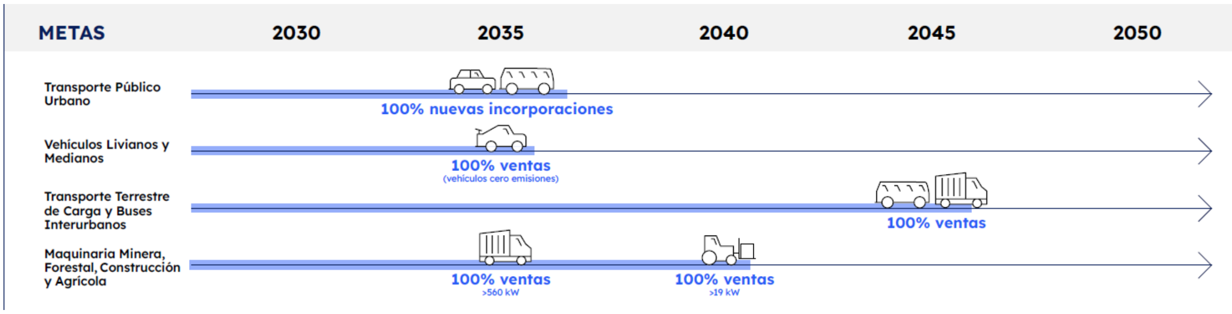


Figure 4: National Electromobility Strategy Objectives (Source: Ministry of Energy, 2022, Chile)

3.5 National Green Hydrogen Strategy

In 2020, the Ministry of Energy published the National Green Hydrogen Strategy in Chile, which, among other aspects, seeks to take advantage of the opportunity to produce and export GH_2 and its derivatives, which include ammonia, methanol and synthetic fuels.

The National Green Hydrogen Strategy in Chile arises from the contribution that this clean fuel could have in the context of the current climate crisis and the favorable growth projections of the global demand for energy supplied with H_2 in different sectors of the economy. Its development considers three objectives9:

i) Produce the cheapest green H_2 on the planet by 2030 (less than 1.5 USD/kg);
ii) To be among the top three exporters by 2040 and;
iii) To have 5 GW of electrolysis capacity under development by 2025.

The Action Plan for the strategy develops four main lines of action10:

1) promotion of the domestic market and exports;
2) regulations, safety and piloting;
3) social and regional development;
4) capacity building and innovation.

The strategy estimates that by 2050 the levelized cost of GH_2 will be between 0.8 - 1.1 USD/kg, depending on the area of the country where it is produced. By 2030, GH_2 produced in the

[9] National Green Hydrogen Strategy in Chile (*Estrategia Nacional de Hidrógeno Verde en Chile*), 2020, Chilean Government

[10] National Green Hydrogen Strategy Main outlines, Parliamentary Technical Advisory, Nicolás García Bernal, November 2020 - *Estrategia Nacional de Hidrógeno Verde Principales lineamientos, Asesoría Técnica Parlamentaria, Nicolás García Bernal, Noviembre 2020*

Atacama Desert and the Magallanes Region would have the lowest levelized cost of production (without considering compression, transportation and distribution costs) in the world.

The national GH_2 strategy considers 3 stages, consisting of waves of actions aimed at achieving the established goals:

Phase 1 (2020 – 2025):

-Anticipating the deployment of GH_2 in priority applications in Chile to build a local market: 1) refinery use; 2) domestic ammonia; 3) mining trucks; 4) heavy road trucks; 5) long-range buses; 6) injection into gas networks.

-Efforts and regulation that incentivize production and encourage demand for applications that are closer to market and/or have an established, concentrated and large-scale demand.

Phase 2 (2025 – 2030)

-Leveraging local expertise to enter international markets. It considers the green ammonia production and export industry through the extraction and promotion of consortia of scale.

-Establishment of agreements to accelerate the export of H_2.

Phase 3 (2030 – onwards)

Exploiting synergies and economies of scale to advance as a clean energy supplier, for applications that will include the use of green ammonia in shipping and synthetic fuels in aviation.

The national GH_2 strategy also contemplates the need to strongly promote the development of the industry both in the Norte Grande area, associated with the great photovoltaic and wind potential of this area, with one of the highest capacity factors in the world at photovoltaic level in the Norte Grande area, for exports to, for example, Asian markets and a massive development of GH_2 in the Magallanes area, taking advantage of capacity factors higher than 50%11, thus generating a privileged area for the production of GH_2 for exports, for example, to European markets.

Consequently, within the elaboration process of the study, the potential uses of GH_2 in the different industries of the country will be analyzed in detail, in order to determine its effects on the energy mix and the transitions between fuels, so as to analyze and understand the effects on the specific emissions trajectories of each sector and the levels of investment required to

[11] Identification of Renewable Potential: Wind, Green Hydrogen in the Region of Magallanes and Chilean Antarctica, February 2021, Ministry of Energy, Chile (*Identificación de Potenciales Renovables: Caso Eólico, Hidrógeno Verde en la Región de Magallanes y de la Antártica Chilena, Febrero 2021, Ministerio de Energía, Chile*)

achieve a cost-effective replacement towards technologies that can use H_2 in their production processes.

4 PARTICIPATORY PROCESS

One of the key aspects to be considered in the preparation of this roadmap was to bring together the various groups; the public and private sectors, academia, trade associations and NGOs, in order to obtain a cross-cutting vision of the aspects that should be considered in the development of initiatives that will allow Chile to move forward in an organized manner in the process of achieving carbon neutrality.

This milestone is a key element in the development of public policy proposals, given that the transition exercise will have a significant impact on the different economic sectors, which will require projects that will allow them to modify their current consumption patterns in specific periods of time. Likewise, the information gathered from the different roundtables will allow to adequately structure the scenarios to be evaluated in the prospective exercise, in order to assess the impact generated on the country's emissions trajectory when considering -or not- certain public policies in the modeling exercise.

It should be noted that the participatory process consisted of three phases in order to incorporate the opinion of the stakeholders in the process of developing the Roadmap.

a) Phase 1–Incubation: a preliminary stage was developed with different experts of the sector in individual meetings, in order to analyze the main lessons learned from similar experiences, as well as to evaluate their opinion, so as to generate a critical perspective from which to start the modeling exercise.
b) Phase 2–Extended panels: As a second stage of the participatory process, four thematic roundtables were held to invite different experts in the sector to express their opinions. The panels were held in public so as to allow the participation not only of experts but also of the general public. The following is a summary of the topics addressed in each of these roundtables and their main messages and conclusions.
c) Phase 3–Validation: Finally, round tables were held to validate the preliminary results of the roadmap, in order to gather the views of the authorities (Ministry of Energy, National Energy Commission, National Energy Coordinator and Superintendency of Electricity and Fuels), as well as those of the economic sectors with the greatest impact on the exercise (electricity sector, mining).

The participatory exercise significantly enriched the exercise, gathering diverse opinions that were key in the construction of the scenarios, as well as in the elaboration of the public policy proposals.

The following is a summary of the Expanded Roundtables held during Phase 2.

4.1 Panel 1: Electricity Matrix: Transition and Evolution towards Carbon Neutrality

During this session the following experts participated: Rodrigo Moreno (ISCI – Universidad de Chile), Alex Santander (Chilean Ministry of Energy); Claudio Seebach (Chilean Association of Power Generators); Patricia Darez (ACERA); Sara Larraín (Sustainable Chile - *Chile Sustentable*); Carlos Cortés (AGN); Ricardo Rodriguez (GH_2 Association - *Asociación de H_2V*). The main topics addressed were the following:

a) The decarbonization process requires a considerable amount of VRE, as well as the introduction of new technologies, such as storage and demand response. Additionally, how to replace conventional generation with conventional generation curves by variable generation with increasing levels of uncertainty must be evaluated.
b) One of the relevant challenges for the future system will be the high level of digitalization and electrification of other sectors (air conditioning, transportation, industry, mining), which will trigger greater complexity for the planning and operation of electricity systems. Additionally, the impact on the SEN for the promotion of the production of green fuels, particularly GH_2, must be evaluated.
c) The studies carried out highlight the need for a deep penetration level of storage and demand management, approximately 6 GW of demand management supply and 4 GW of storage by 2040, a situation that would be feasible. In this regard, the studies show that it is important for generation to grow with a portfolio approach and not only focused on one type of technology, which should be picked up through market signals (sufficiency signal).
d) It was noted that in the preliminary studies conducted, the externality cost of retiring coal in 2025 would be around 25 USD/Ton. The externality of removing one ton of CO_2 from the atmosphere is expected by the experts to be between 600 and 800 USD/Ton, which is not included in the planning and operation models. Given the above, it was suggested that, if we want GH_2 to compete, the green tax should -depending on the design- be in the range of 55 and 120 USD/Ton.
e) Problems with the market design and its management at the dispatch level are pointed out, which would prevent progress towards a highly decarbonized system. The extreme drought of the last years has evidenced greater problems with the operation of the system and its reliability. More planning is required to evaluate the problems that will occur in the face of the plans for the phase-out of coal-fired generators and prepare the enabling conditions. It is not only about dates but about preparing the system for the moment of transition. Not just this, but also the added fact that the Paris Agreement and the NDCs compel us to do so.
f) An important point made is access to financing for storage projects. Revenue flows for this type of projects are not clear, given that there is regulatory uncertainty. In this

regard, it is necessary to advance a regulatory scheme that allows for greater certainty regarding future flows in terms of energy, power and complementary services.

g) In order to replace the capacity of coal-fired power plants, approximately 25 GW of new projects will be required by 2030, so it is necessary to work on the need of improving the regional work, as well as the associated permits process, and thus accelerate the entry of new projects.

h) Finally, the role of NG is mentioned as an essential input for the transition, but that in the future it will also have to start its withdrawal.

As a key summary:

1) Order decarbonization plan, establish enabling measures (regulatory or market), avoid elasticity, so the system should be prepared at the time of making operational decisions.

2) Just Transition (governance, local action plans) for the phase-out of coal-fired power plants.

3) Innovation: National Innovation Plan (*Plan Nacional de Innovación*) triggering actions in the science and technology fields.

4.2 Panel 2: "Networks and Technologies for the Energy Transition"

The following experts attended this session: Rodrigo Palma (Universidad de Chile); Aura Rearte (ACESOL); Rosa Serrano (Universidad de Manchester, UK); Eduardo Calderón (Energy Transmitters - *Transmisoras*); Luigi Sciaccaluga (Energy Platform - *Plataforma Energía*); Eduardo Esperguel (CNE). The main topics covered were the following:

a) At the network and technology level for the energy transition, we observe a context of high uncertainty (very high), completely different from the system in which we lived a few years ago. Particularly, we observe a very decoupled transmission, high levels of curtailment, comparable to the deficit projected in the worst-case scenario projected by the CEN.

b) One of the topics that has not been sufficiently treated is the implementation of demand management (there is no active demand) and the development of micro-grids. It is necessary to work on a distribution reform that enables such conditions, which is also conditioned by the current context (pandemic, geopolitical crisis, economic crisis).

c) In relation to the distribution reform, the experts note that there are no incentives to promote the connection of projects at this level, given that the regulation is mainly focused on the supply of demand, so it should be focused on allowing the management and integration of distributed resources in a massive way. The introduction of storage in distribution should be accelerated, for which increasing levels of modernization of the network, control and communications are required.

d) An important focus on data management is required, given that a system with many disseminated resources requires an important management, currently there are problems with data management by the CEN, therefore, there are doubts about the quality of the information with which the sector works. These gaps must be addressed in order to move towards a distributed system.
e) On the other hand, it is said that a wide "palette" of solutions should be available, that is, to be prepared for when the conditions are right to activate each one, and not come up with a solution once faced with a problem. Innovation is key to evaluate these solutions.
f) Lastly, the experts pointed out the necessity to work on exports not only to neighboring countries but also to other continents, through new energy carriers, such as GH_2.

4.3 Panel 3: Energy Consumers: Process and Consumption Transformation

The following experts partook in this session: Mónica Gazmuri (ANESCO); Javier Bustos (ACENOR); Rainer Schroeer (GIZ); María Isabel González (ENERGETICA); Rubén Guzmán (Ministry of Energy). The main topics discussed were:

a) Energy efficiency has not been the main focus of discussion in the sector; there is a lack of awareness of effective energy efficiency measures among users and the real impacts of these measures in economic and environmental terms are not put forward.
b) According to studies, 35% of CO_2 reductions may come from energy efficiency measures. According to ANESCO, 80% of energy use in Chilean industry comes from thermal sources, and only 20% of consumption is electrified.
c) There is no indication of progress in energy efficiency on the market, nor are there incentives for distributors or the industry in general. There is a lack of tangible measures of traceability and transparency regarding the cost-effectiveness of the measures adopted by the industry, and there is no global and coordinated vision of the measures; each one operates independently, avoiding synergies between energy efficiency projects.
d) The experts argue that there is a lack of clear goals in the Energy Efficiency Law: they are very lax and lack ambition. The impact expected is a reduction of 5.5% in consumption by 2030 and 7% by 2035, representing 6.8 million tons of CO_2. The Ministry of Energy places the focus on creating short-term goals that are enforceable and traceable.
e) The main barriers associated with the development of the energy efficiency market are pointed out as: lack of significant knowledge among customers to carry out energy

efficiency projects; it is not classified as a priority and lack of risk financing for these projects. Are customers willing to adapt their processes to implement energy efficiency measures? There appears to be no clear incentive to manage energy.

f) Energy grids abroad have been observed to promote energy efficiency measures as a result of high energy prices.
g) The panel's experts point to the fact that there seems to be no clear strategy to face the costs that the industry will face both in investment and operation (cost of energy) associated with the process of demand electrification. A key question is asked: what price of energy do we need to move towards carbon neutrality?
h) Regarding the role of the consumer, there are many un-answered questions. Demand aggregators do not have clear regulation and objectives. The impacts on customers are not adequately quantified. Much focus is laid on the operation of the system at generation level with little concern for customers. Technological adaptation and energy education for customers is required.
i) The experts suggest that a better coupling between sectors is needed; improving production processes to optimize energy use, the link between efficient production and renewable generation creates a distinguishing feature for the products (exports) generated by the national industry.
j) The Framework Law on Climate Change will allow trading CO_2 emissions at the transaction market, which would drive the transformation of processes. The discussion of the change in the energy mix and particularly in the use of diesel in the industry has been focused on dates and not on the trajectories and measures required to reach the final state; clear measures are required to advance in decarbonization, particularly in terms of prices and efficient measures for both residential and industrial consumption.
k) Large consumers point out that the energy sector -in recent years- has placed great emphasis on infrastructure needs for the energy transition, forgetting that the center of the sector's development should be focused on the energy user. Therefore, the cost of the process for the country should be evaluated. They point out that higher electricity prices have an impact on all economic sectors and on the entire population.
l) Additionally, they state that the impact of the energy sector on GDP growth is not given by physical investments in infrastructure, but by the cost of electricity for the rest of the economy. Finally, they regret that the cost of electricity supply has ceased to be a structural focus of public policy. The policies of recent years have not focused on the energy user and they demand that this be corrected.

4.4 Panel 4 " Economy and Sustainable Development to achieve Carbon Neutrality "

The following experts were invited to this roundtable: Luis González (CLAPES UC); Pablo Badenier (Former Chilean Minister for the Environment); Marina Hermosilla (Chile Foundation - *Fundación Chile*); Michel Leporati (Universidad de Talca); Rubén Guzmán (Ministry of Energy). The following topics were assessed:

a) Carbon neutrality generates multiple challenges in different sectors of the economy; it is not only a problem of electricity generation. The sectors that generate most uncertainty to reach carbon neutrality correspond to the development of forests and biodiversity (forest fires, use of firewood) and transportation (electromobility even with high CAPEX).
b) Tools are required to develop economic instruments for carbon neutrality, such as the green tax (proposed to be implemented in all sectors), *cap and trade* and emissions compensation systems.
c) Naturally, the green tax alone will not enable the NDC goals to be met, so a set of measures must be promoted to enable the transition, and not a single tool. The experts note that today the world average for the green tax is 30 USD/ton, much higher than the current tax in force in Chile of 5 USD/ton.
d) The experts consider that it is important that public policies focus on the fact that the carbon tax corresponds to a mitigation measure and not to a permanent income (it has been observed that it can represent approximately 0.2% of the GDP).
e) The growth rate of the electromobility market should be evaluated. Another point to be evaluated with greater attention is the forest sector, biodiversity, and demand for firewood, which has not been exploited to its full potential in regards to achieve carbon neutrality. In this regard the experts recommend emphasizing strategies that increase capture capacity, and how to follow up on these measures.
f) Efforts should be made to decouple the economy from greenhouse gas emissions, as has been done in the United States and the United Kingdom.
g) There are sectors that may not participate much in the decarbonization strategy (e.g. agriculture). There is a lack of incentives associated with the operating costs of these sectors. It should be noted that in order to develop decarbonization strategies, scientific and technological capacity is required in the territories at the regional level, which is not currently deployed on a massive scale, and therefore resources are required from both the state and private industry.
h) This is an interdisciplinary challenge; it is not only an energy issue. It therefore requires a broad approach to the problem, given that it is a very broad problem with a high territorial and multisectoral emphasis.

i) In order to implement measures such as the carbon tax, it is necessary to take into account the most affected sectors. As an alternative measure, subsidies could be proposed to encourage investment in energy efficiency or electromobility systems that generate a similar effect.
j) There is too much of a focus on the green tax. A focus on instruments that offset emissions have not been widely explored to date.
k) The food sector is lagging far behind others in its contribution to the decarbonization process; progress must be made in regards to work in sectors that are territorial and cultural in nature in order to achieve long-term effects. In this regard, incentives are required for technological adoption and the promotion of production in the sectors that lag behind. The strategy must be deployed taking into account the territories, as part of the just transition.
l) The experts note that it may be a risk to incorporate the carbon tax into the fuel tax as an instrument for decarbonization; however, given the current inflationary context, it is a complex measure to implement.
m) The policies to be implemented must be cost-efficient for the population, in the study developed by CLAPES it was even observed that even with 100 USD/Ton the migration does not take place by itself in the transport sector, given the high CAPEX that are required for electric transport. So, a policy with defined trajectories is required through command and control mechanisms that enable the transition. The investment in transportation is expected to be high in order to achieve the goals.
n) Within the projects financing mechanisms, it should be considered as a risk variable. The capital seeking to finance resources that contribute to carbon neutrality should be recognized with a lower risk, even though the banking sector is still at odds with this vision.
o) Sustainability should be at the center of risk analysis and should be promoted with public mechanisms that are currently available to reach a higher percentage of lagging sectors. INDAP, CORFO, SERCOTEC have a relevant role, with a broad focus in the territories. As circular economy instruments, there is a national organic waste strategy and the development of a circular economy roadmap, which should be considered and adapted for the process of achieving carbon neutrality.

5 TIMES MODELING

The scenario analysis for the decarbonization trajectories for Chile was performed using the TIMES-Chile model, developed specifically for this purpose. TIMES is a model generator developed and maintained by ETSAP (Energy Technology Systems Analysis Programme), under the International Energy Agency (IEA) technology collaboration program.

TIMES allows bottom-up modeling using linear programming techniques to achieve a least-cost energy system optimized according to a set of user constraints over medium and long-term time horizons. Typical constraints included in a TIMES model are related to capacity increase limits, environmental objectives to simulate energy policies, technical constraints related to the availability and operation of generation technologies, limitation of available energy resources, etc.

TIMES is a partial equilibrium model, since it only covers the energy market, and not a general equilibrium model for the whole economic sector. The model assumes a perfect competition market driven by energy demand, which is projected exogenously according to key factors such as GDP or population growth, and which conditions the development of the energy system.

5.1 TIMES Development Context and Main Resolution Features

TIMES-Chile includes a detailed breakdown of the demand sectors, as shown below.

5.1.1 Transport Sector

This sector accounts for 37% of the country's emissions contributions in the 2019 national energy balance sheet. The analysis goes into the following detailed structure:

Road Passenger Transportation	Road Freight Transportation	Railway transportation	Water transportation	Air transportation
•Private vehicles •Public transportation (buses)	•Light vehicles •Heavy vehicles	•Passengers (urban - regional) •Freight shipping	•Passengers •Freight	•Private •Commercial

Figure 5 Transport Sector Detail (Source: Prepared by the authors)

The following factors are used for modeling:

a) Number of vehicles
b) Level of activity
c) Occupancy and tonnage of vehicles

d) Consumption by fuel type (electricity, gas, H_2)
e) Projections of vehicle efficiency increases
f) Total passenger-kilometer or ton-kilometer demand

The above variables allow evaluating the impact of the measures and the requirements of new energy vectors for the transport sector. For air and maritime transport, in line with Chile's climate commitments, only emissions from domestic transport are considered.

5.1.2 Industrial Sector

This sector represents 38% of the contributions to the country's emissions in the 2019 national energy balance and incorporates the contribution of copper mining. The industries considered in this sector include (more details on Table 12 section 7.4):

a) Cement
b) Iron and steel
c) Iron ore mining
d) Copper mining
e) Other various mines
f) Petrochemical industry
g) Pulp and paper
h) Sugar
i) Fish production
j) Miscellaneous industries

The general considerations proposed in the LTEP are used for modeling:

i. For each industry, the type of consumption is considered, this includes motor use, transportation, thermal energy or other uses.
ii. Each type of use is structured according to an energy vector and technology, e.g. electricity, diesel, gas, etc.
iii. The possibility of new energy sources in the production chain is enabled, e.g. GH_2, biofuels, among others.

5.1.3 Residential, Commercial and Public Services Sector

The contributions of these sectors to the country's emissions in the national energy balance for the year 2019 is 16% in the case of the residential sector, 5% in the case of commercial sector and 1.3% in the case of the public sector. They are the sectors with the lowest contribution in relation to the main economic activities of the country.

The following breakdown is applied, considering the different energy uses:

a) Heating in buildings
b) Cooling in buildings
c) Water heating
d) Cooking
e) Lighting
f) Other equipment (aggregates)

The general considerations proposed in the LTEP are used for modeling:

i. Each type of use is structured according to an energy vector and a technology, e.g., electricity, gas, biomass, etc.
ii. The possibility of new energy vectors in the production chain is enabled, for example, GH_2, biofuels, among others.

iii. Modeling Specifications for the Case of Chile

TIMES-Chile is a multi-regional model. The country has been divided into seven geographic regions, grouping the administrative regions according to the Figure 6. This geographic resolution offers the possibility of analyzing the flows of different energy products from high potential areas (solar in the north and wind in the south) to the main consumption areas in central Chile.

The time period of the analysis extends to the year 2050, with annual temporal resolution and breakdown of each year into characteristic time slices, in order to capture the seasonal and diurnal variation of demand and production of variable renewables. Four seasons have been considered in the analysis according to the following distribution.

Season	Time periods of the year		Number of days
S1	01-Jan	15-Mar	74
S2	16-Mar	31-May	77
S3	01-Jun	31-Aug	92
S4	01-Sep	31-Dec	122

Table 1 Time structure of the TIMES-Chile model; Seasons (Source: Own elaboration)

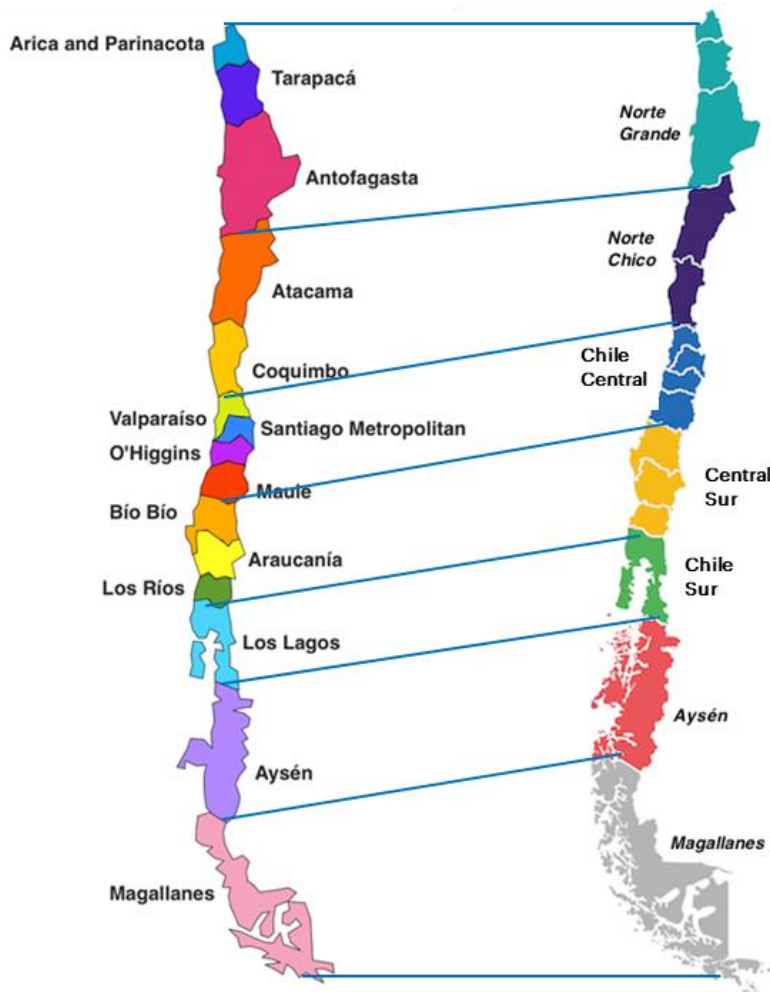


Figure 6 Regional structuring of the TIMES-Chile model (Source: Own elaboration)

A typical day was analyzed for each season, divided into six periods over its 24-hour duration, as shown below.

S	N (Night)		L (Dawn)		M (Morning)		D (Day)		P (Peak)		E (Evening)	
	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
S1	0	1	2	5	6	8	9	13	14	16	17	23
S2	0	2	3	6	7	9	10	17	18	19	20	23
S3	0	2	3	5	6	8	9	17	18	20	21	23
S4	0	2	3	5	6	8	9	13	14	16	17	23

Table 2 Time structure of the TIMES-Chile model; Typical days (Source: Own elaboration)

This approach results in a resolution of 24-time segments, which is considered adequate for a long-term energy planning exercise. To study the detailed operation of a power system that relies heavily on VRE, a more in-depth analysis with specialized power system models is required.

The variable generation of wind, PV and hydro generation sources is captured through the variation of capacity factors over the 24-time segments defined in each of the regions of the model, the averages of these factors can be seen in Table 3. For the modeling of the behavior of the VRE plants, the actual generation of the years 2017 to 2020 was considered in order to extrapolate a generation profile by zone and hourly block.

Region	Average CF (%)
Great North	35%
Small North	29%
Central Chile	29%
Southern Chile	31%
Los Lagos	34%
Aysén	34%
Magallanes	37%

Region	Average CF (%)
Great North	32%
Small North	29%
Central Chile	25%
Southern Chile	24%
Los Lagos	19%
Aysén	19%
Magallanes	19%

Table 3 Average Capacity Factors (CF) (Left Wind, Right Solar PV) (Source: Open Energy - *Energía Abierta* - CNE)

In the case of hydroelectric generation, an average of the historical production of the last five years of SEN operation was considered in order to project an average dry hydrology for the entire analysis horizon.

5.2 Technological Representation

TIMES-Chile includes a portfolio of hundreds of available technologies that can be introduced into the country's energy system during the optimization process. For each of these technologies, a pathway for capital cost reduction and efficiency improvement through 2050 is included.

For technologies of the power sector and, specifically, for renewable energy and battery technologies, the cost reduction pathways are presented in Figure 7[12]. Technology costs were defined based on LTEP estimation and NREL background.

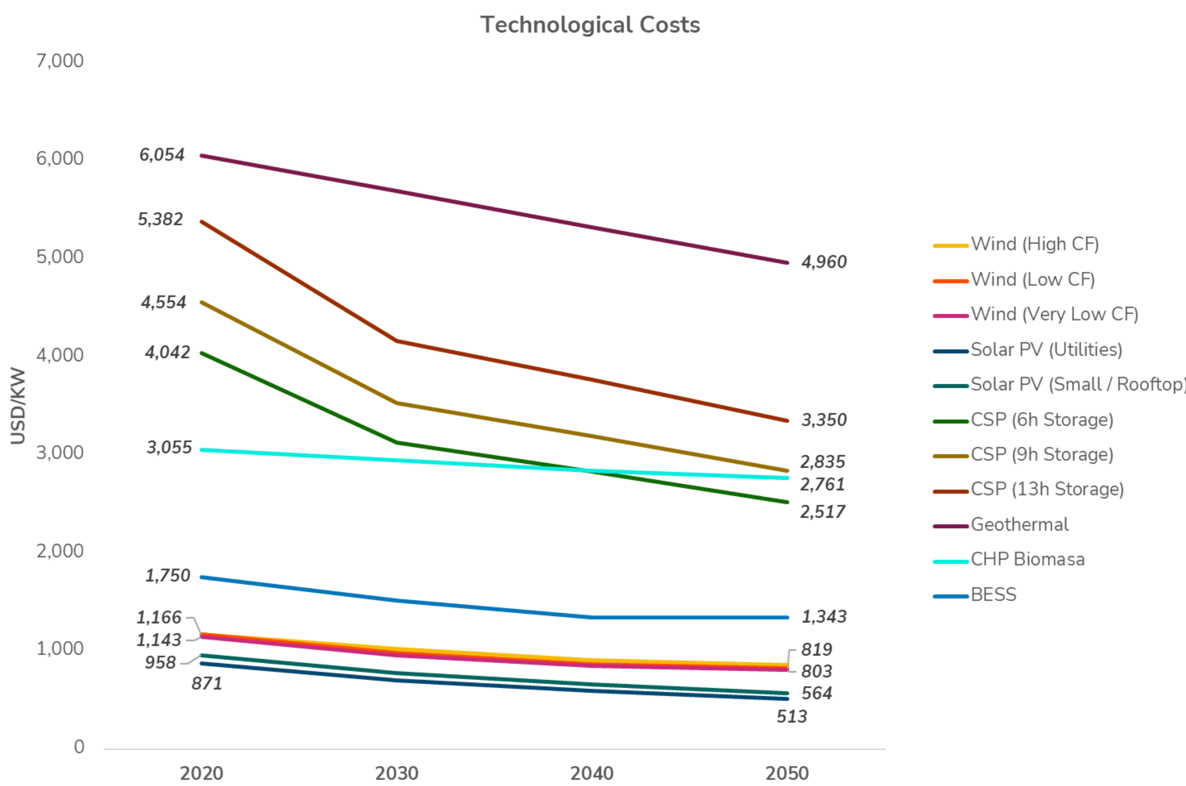


Figure 7 Technological Costs (Source: LTEP – NREL)

The maximum potential for renewable energy deployment in each region was based on the LTEP input assumptions and can be seen in the following figures. For the development of distributed generation, the option of residential and industrial solar rooftops is enabled.

[12] The hydro (reservoir and run-of-river) and CHP Biogas technologies have constant cost values in real terms of 3,250 USD/KW and 3,500 USD/KW respectively.

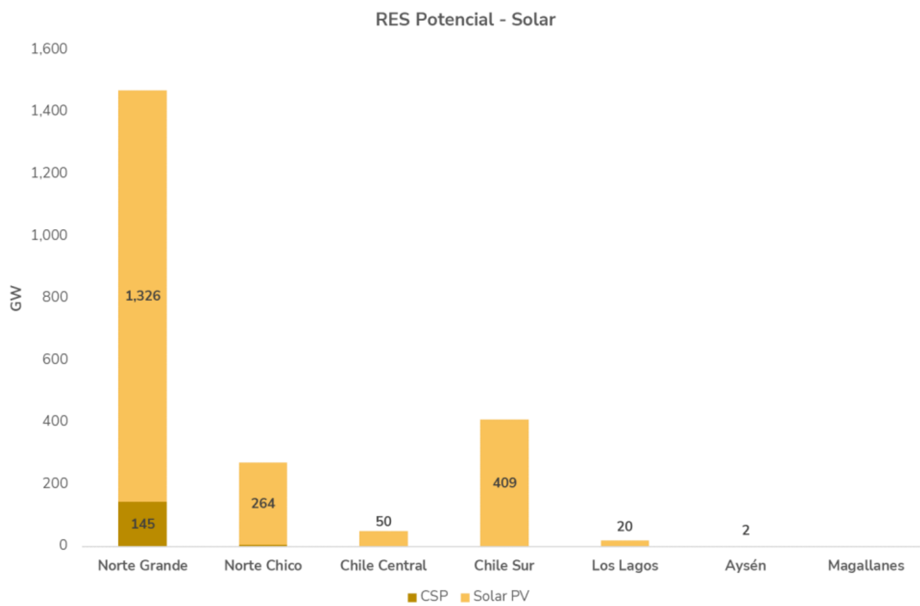


Figure 8 Renewable Potential; Solar (Source: LTEP 2023 – 2027 Preliminary Report - *Informe Preliminar PELP 2023 – 2027* - and Green H_2 National Strategy Chile - *Estrategia Nacional H_2 Verde Chile*)

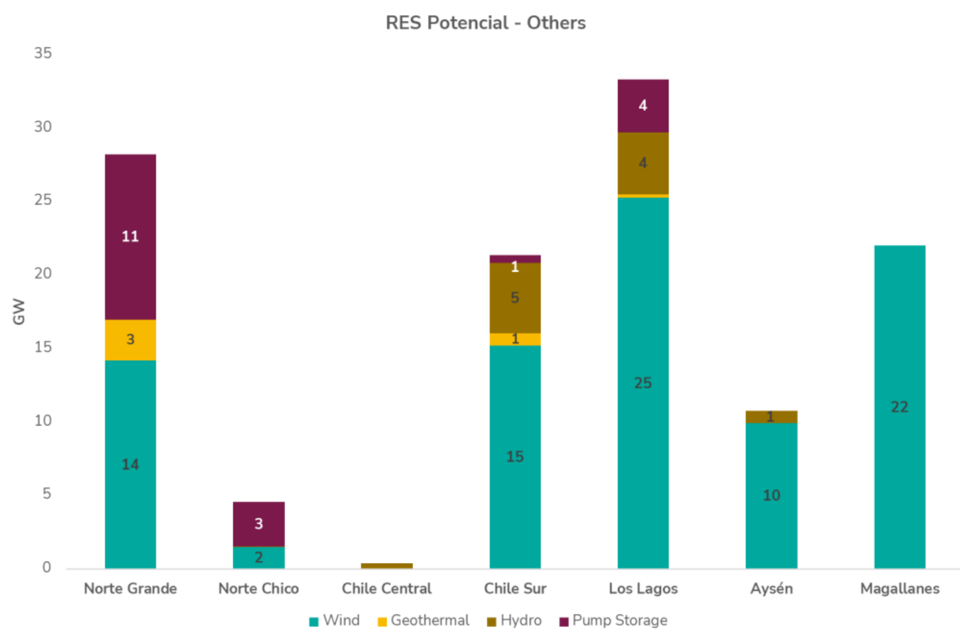


Figure 9 Renewable Potential (Others) (Source: LTEP 2023 – 2027 Preliminary Report - *Informe Preliminar PELP 2023 – 2027* - and Green H_2 National Strategy Chile - *Estrategia Nacional H_2 Verde Chile*)

As modeling requirements, it was established that for each MW of solar or wind capacity incorporated into the system, this should be compensated with 15% of synchronous (clean) generation, in order to cover the reserve requirements.

5.3 Other relevant input

Besides the data related to technology, the prices of fuel imports and their projection for the time horizon of the analysis are key data for the model. The values used for the analysis of this scenario are presented in Figure 10.

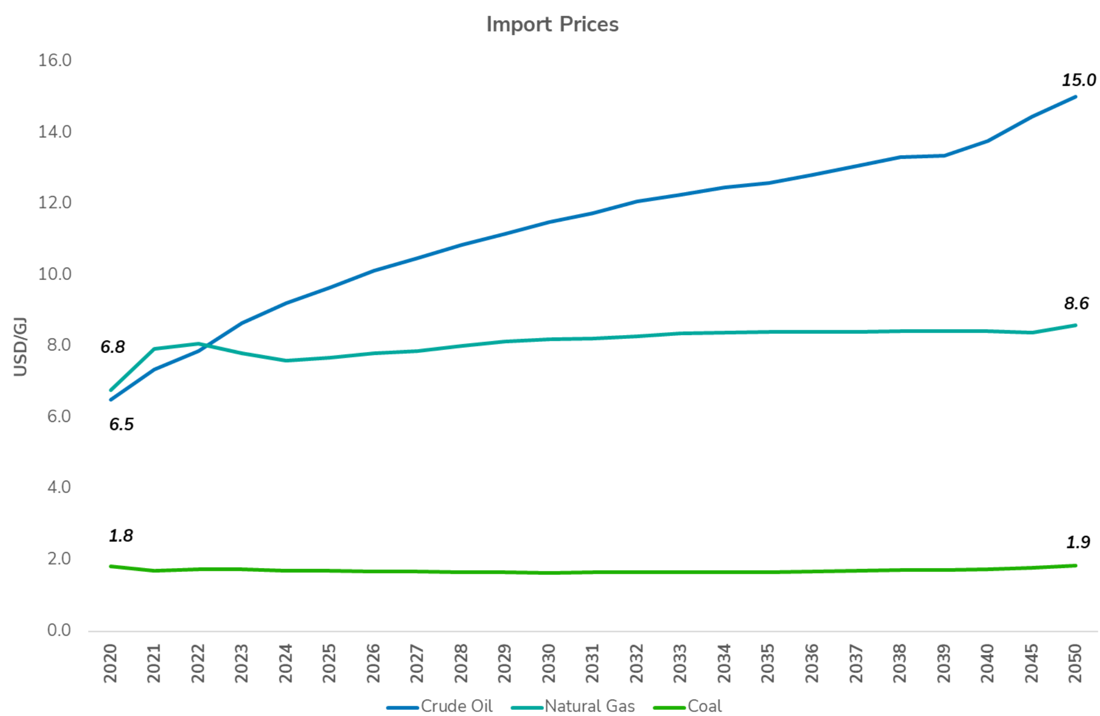


Figure 10 TIMES-Chile model; fuel import prices (Source: LTEP 2023 – 2027 Preliminary Report - *Informe Preliminar PELP 2023 – 2027*)

In the different scenarios, a tax on CO_2 emissions from the electricity sector is applied at various levels. Three CO_2 tax models were considered in the LTEP 2022 analysis (Figure 11), which are also used in the current scenarios. Finally, a discount rate of 6% is used in the calculations.

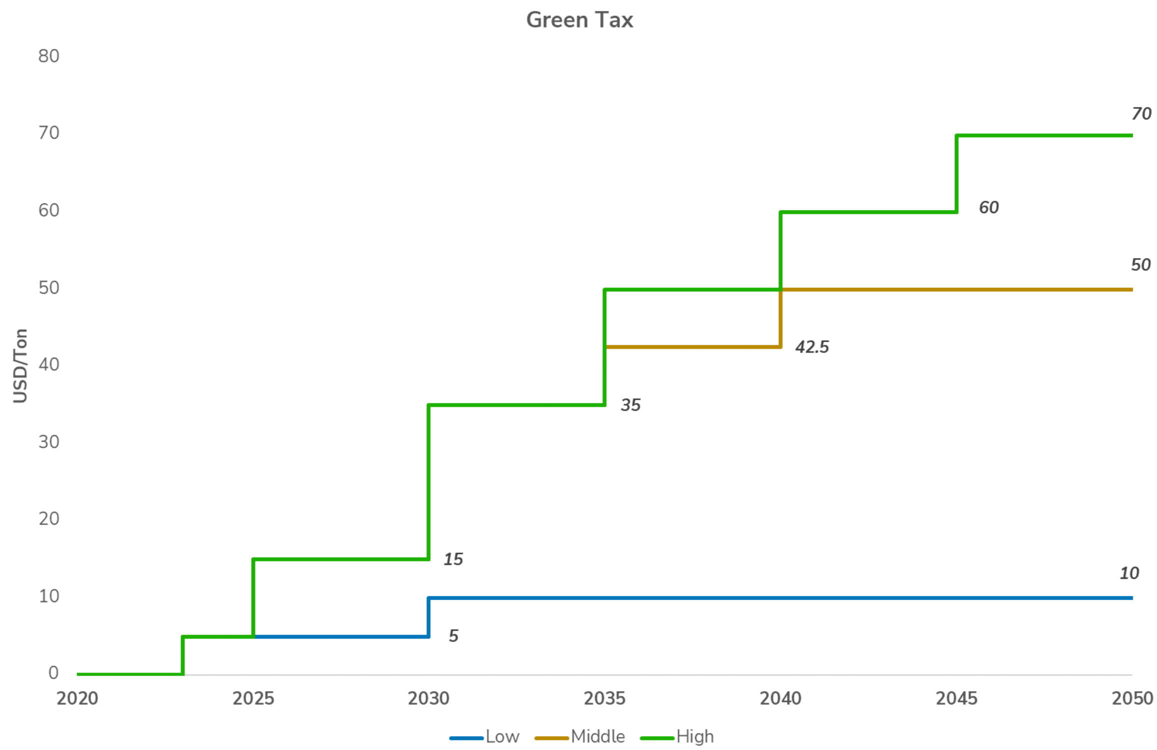


Figure 11 CO_2 tax rates (Source: LTEP 2023 – 2027 Preliminary Report - *Informe Preliminar PELP 2023 – 2027*)

5.4 Scenario Definition Process

Three different scenarios were analyzed using the TIMES-Chile model. The definition process and details of the scenarios are presented below.

The purpose of the present project was not to replicate the LTEP scenarios, but to create a comparative view of the possible decarbonization pathways of Chile's energy system. Therefore, besides the reference scenario in which all the corresponding measures of the LTEP reference scenario were applied, a "*Cap and Compare*" approach was used in the two alternative scenarios, following the steps below.

1) Step 1: The global GHG emissions trajectory was set as an upper threshold in the optimization model for the two energy policy scenarios "Fast Transition" and "Accelerated Transition".
2) Step 2: Underlying socio-economic factors were defined and included in the scenarios (GDP projection, population, etc.).

3) Step 3: A set of key scenario factors were identified and included in the model as specific measures, while other scenario factors were left as an open space for change in the energy system, or as elements of comparison with the LTEP scenarios.
4) Step 4: The optimization model was run with all influencing factors and constraints mentioned.
5) Step 5: The response of the optimization model was compared with the LTEP projections to obtain information on the quality of the model results.

Once the 5 previous steps had been completed, and after obtaining satisfactory results that mainly met the decarbonization obligations for the year 2050, all the scenarios were established with the characteristics described in the following chapter.

5.5 Specifications and Considerations by Scenario

As mentioned in the previous section, three scenarios were defined and analyzed:

a) In the "Base Scenario", a "current policies" approach is represented, where only the policies and measures foreseen today were applied leaving the model to optimize until 2050 only under economic parameters.
b) The "Fast Transition" scenario includes additional measures. In this scenario, the level of global emissions reaches almost zero in 2050.
c) In the "Accelerated Transition" scenario, an acceleration in the rate of emissions reduction is set to reach 2050, ensuring carbon neutrality.
d) The main socioeconomic factors used as inputs for the three scenarios are the following, these are obtained from the LTEP 2023 - 2027 assumptions.

Item	Period	Base Scenario	Fast Transition	Accelerated Transition
Economic Growth	2021-2030	2.8%	2.8%	3.2%
	2031-2040	1.8%	1.8%	2.3%
	2041-2050	1.3%	1.3%	1.9%
Population	2030	20.7 million people		
	2050	21.6 million people		
Housing	2030	7,886 thousand dwellings	7,886 thousand dwellings	7,978 thousand dwellings
	2050	8,980 thousand dwellings	8,980 thousand dwellings	9,395 thousand dwellings

Table 4 Socioeconomic Factors (Source: LTEP)

The specific measures considered in each of the scenarios are presented in detail below.

Variable	Base Scenario	Fast Transition	Accelerated Transition
Limits on emissions from the energy sector	Without limitations	30.2 Mt CO_2eq in 2050 (approx.)	24.7 Mt CO_2eq in 2050 (approx.)
Macro indicators and demand	LTEP: "*Carbon Neutrality (CN)*"	LTEP: Mix of "CN" + Accelerated ("TEA")	LTEP: "*TEA*"
Residential sector	Without explicit measures	Technological standards for new construction and limits to renovations based on LTEP "TEA".	Same as Fast Transition
Commercial and public sectors	Without explicit measures	Technological standards for new construction and limits to renovations based on LTEP "TEA".	Same as Fast Transition
Transportation sector	Minimum EV and H_2 penetration based on LTEP	Technological standards 5 years behind LTEP "TEA". Ban on light-duty combustion vehicles by 2040.	Technological standards based on LTEP "TEA". Ban on light-duty vehicles - combustion vehicles - by 2035.
Industrial sector	Without explicit measures	Technological standards for engines based on LTEP "TEA". Potential for the use of solar thermal according to LTEP.	Same as Fast Transition
Electricity Sector	Coal phase-out by 2040. CO_2 price of $10/Ton by 2050. No CCS standards.	Coal phase-out by 2035. CO_2 price of $43/Ton by 2035, $50/Ton by 2040 and $50/Ton by 2050. Mandatory CCS for all gas plants after 2035.	Coal phase-out by 2030. CO_2 price of $50/Ton by 2035, $60/Ton by 2040 and $70/Ton by 2050. Mandatory CCS for all gas plants after 2030.

Variable	Base Scenario	Fast Transition	Accelerated Transition
GH_2 Exports	No minimum export thresholds. Target: 50% of H_2 production comes from dedicated renewable plants (PV or wind).	Export thresholds (5 TWh in 2030, 100 TWh in 2050). Target: 50% of H_2 production comes from dedicated renewable plants (PV or wind).	Export thresholds (10 TWh in 2030, 170 TWh in 2050). Target: 50% of H_2 production comes from dedicated renewable plants (PV or wind).

Table 5 Measures per scenario (Source: Own elaboration)

6 OVERALL RESULTS

6.1 Global Emissions Trajectory

Only the transition scenarios are capable of meeting the emission reduction commitments established for the year 2050. The reduction effort of these scenarios is mainly concentrated in the period 2040 - 2050, although it should start immediately and maintain a constant decreasing evolution.

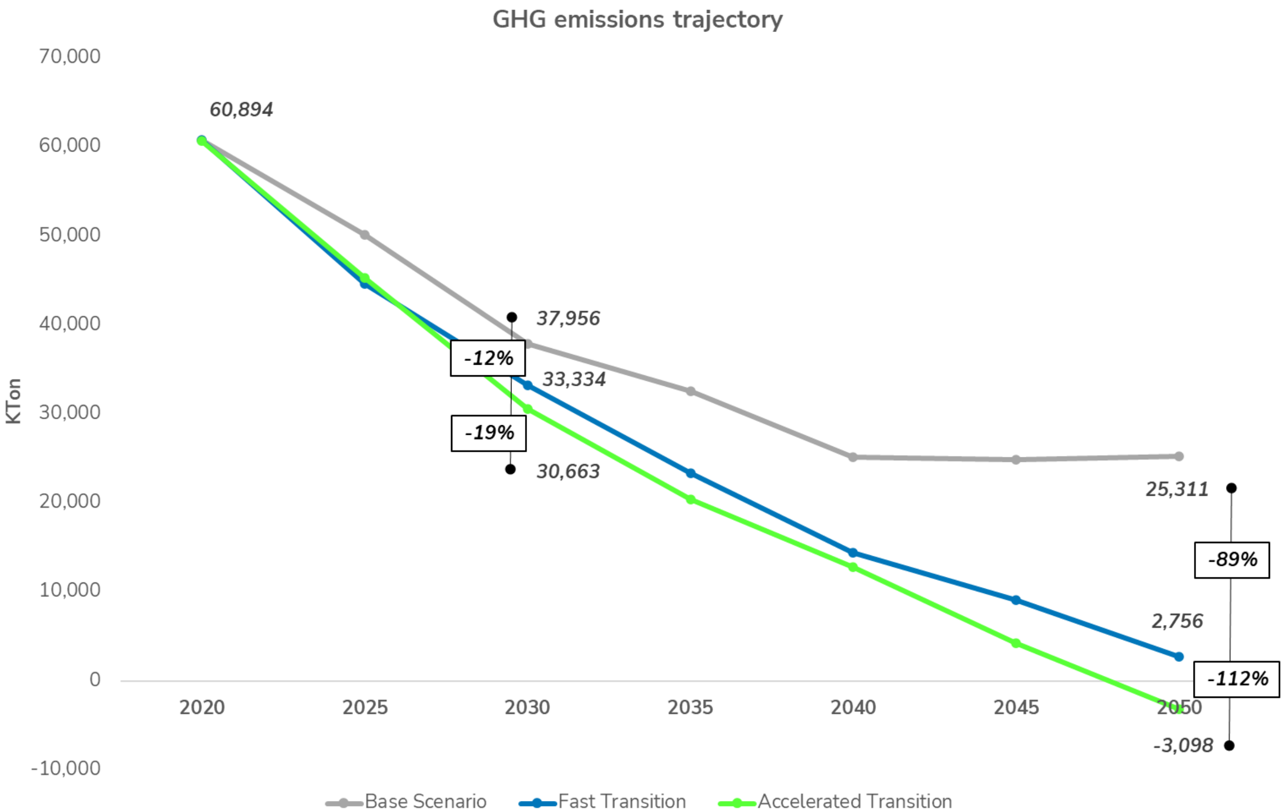


Figure 12 Overall Emissions Trajectory (Source: TIMES-Chile Model)

The sectors with the largest contribution to the emissions inventory are the electricity sector, the transport sector and the industry sector. Without contributions from these three groups, the transition scenarios and therefore compliance with the "net-zero" objectives by 2050 are not possible. The rest of the sectors, even with smaller contributions, must also maintain declining emissions trajectories, or with moderate growth compared to the growth of their demand.

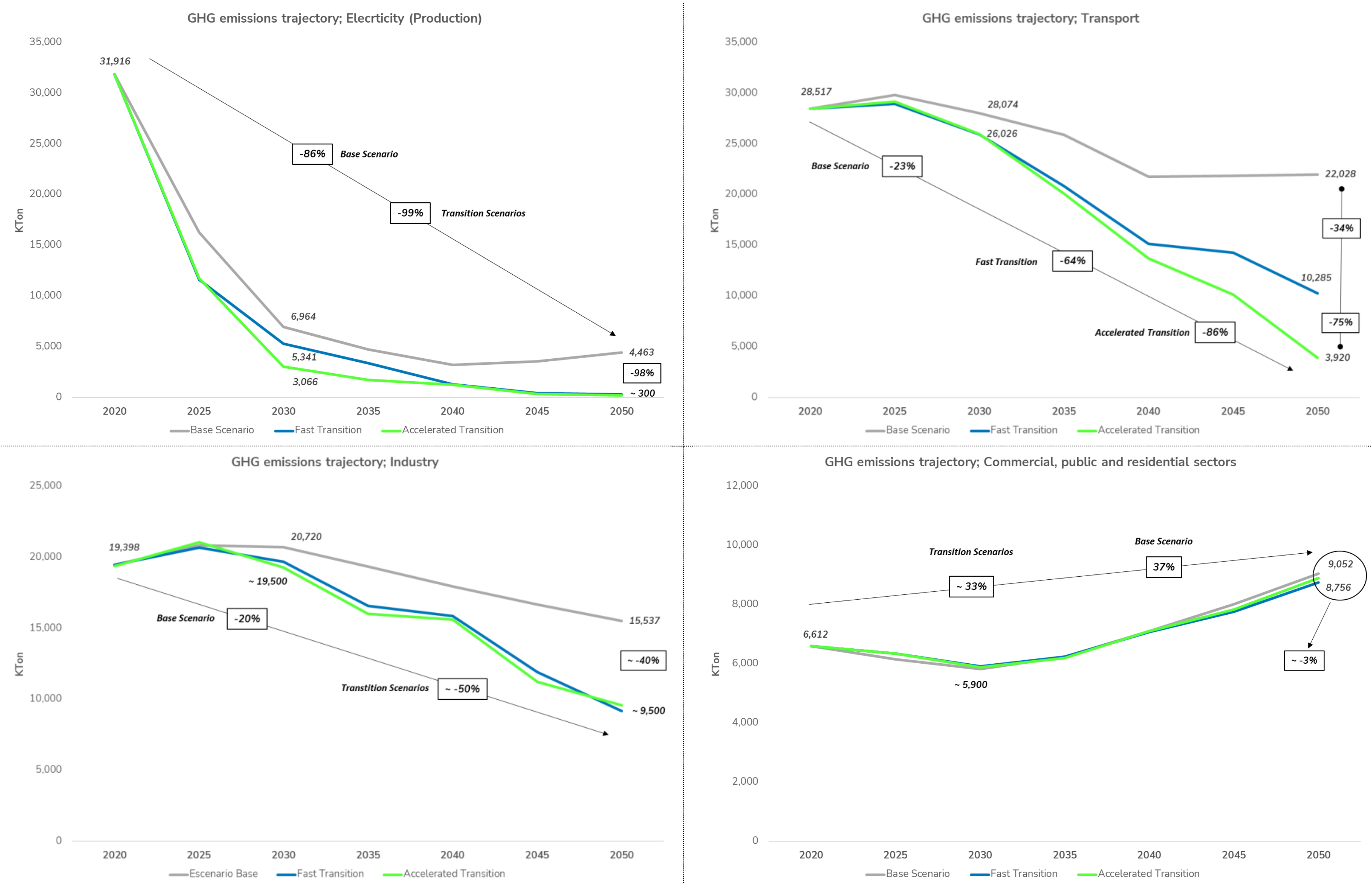


Figure 13 Emissions trajectory per sector (Source: TIMES-Chile Model)

As previously exposed, the GDP scenarios (and therefore energy demand) of each of the scenarios are different, so it is relevant to find a metric that can compare the three scenarios in a relative way, without possible distortions caused by absolute values. Energy intensity is ideal to carry out this comparison. This shows how the Accelerated Transition scenario requires minimizing energy intensity compared to the other scenarios.

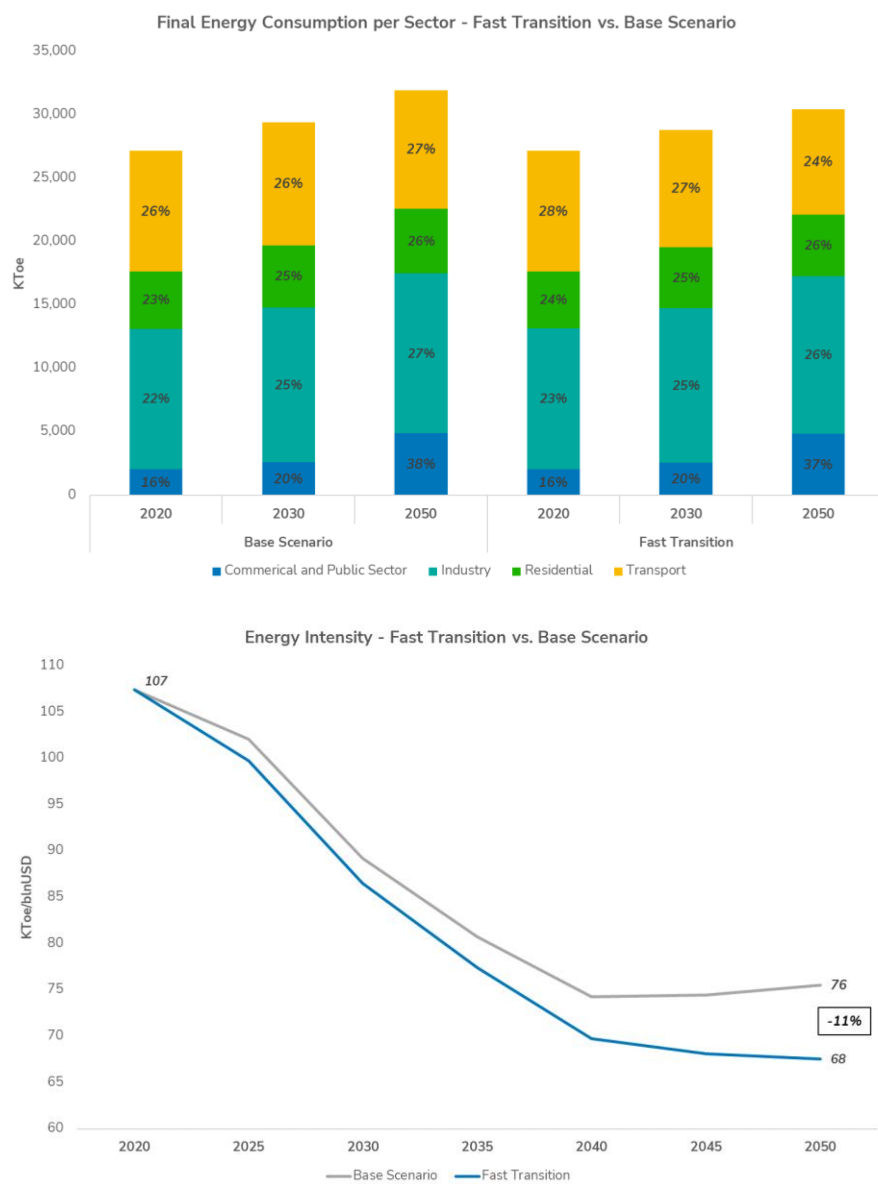
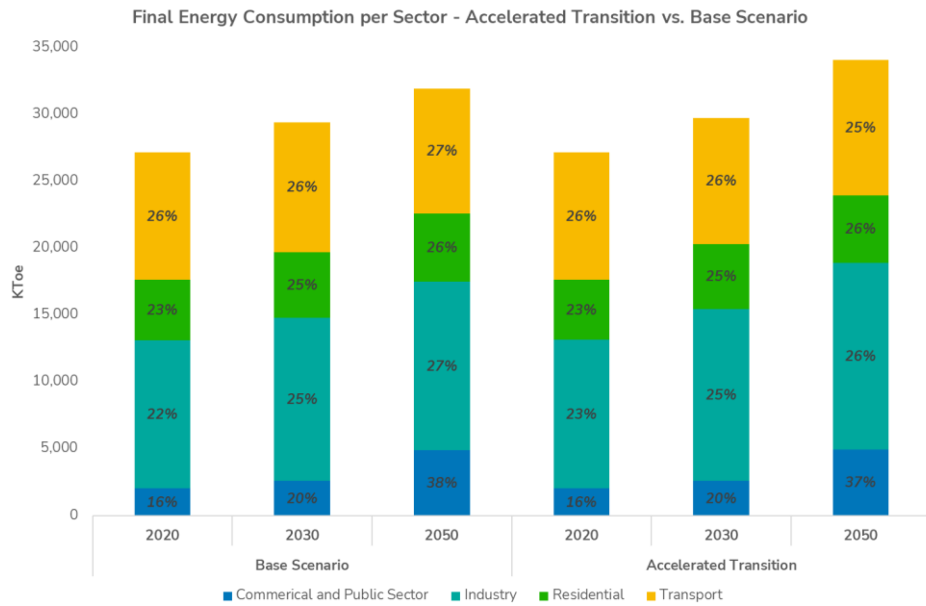


Figure 14 Final energy consumption and energy intensity; Rapid Transition (Source: TIMES-Chile Model)



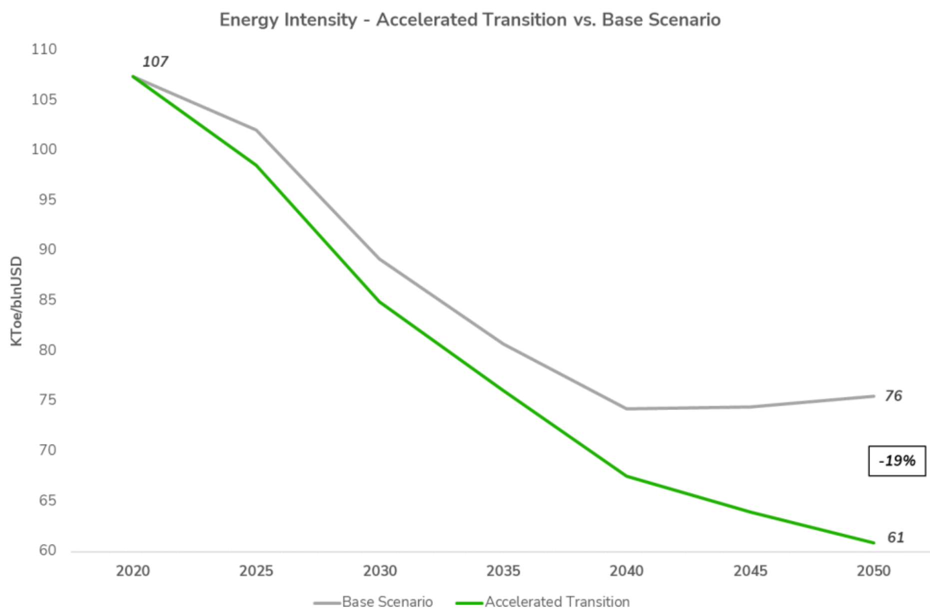


Figure 15 Final energy consumption and energy intensity; Accelerated Transition (Source: TIMES-Chile Model)

As a result of the need to gradually reduce energy intensity, it is necessary to decouple economic growth from the consumption of fossil fuels to feed this increase, thus requiring a transition to non-polluting fuels and a progressive change in the mix of primary energy sources from fossil fuels to clean sources.

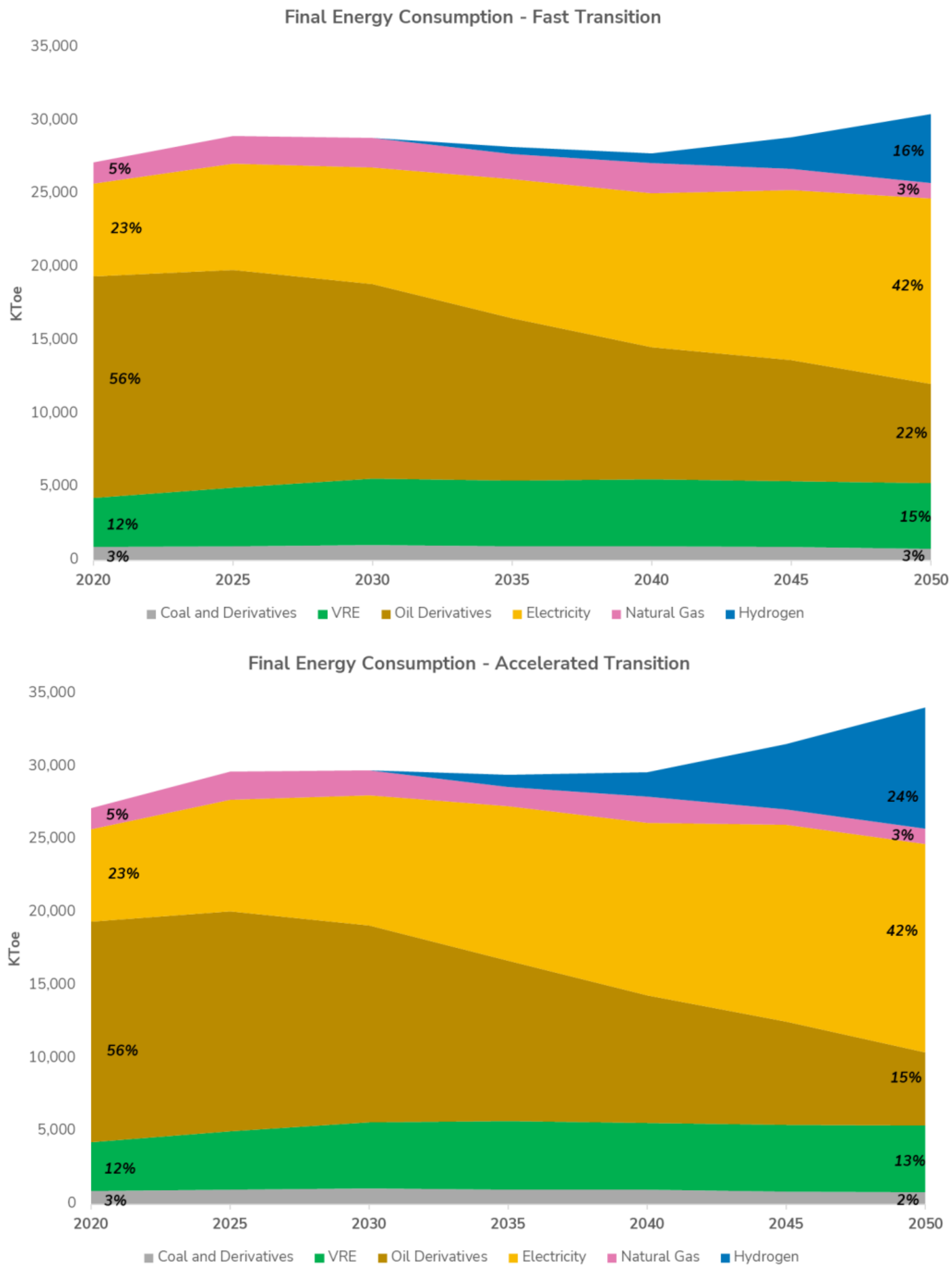


Figure 16 Final energy consumption per fuel in transition scenarios (Source: TIMES-Chile Model)

6.2 Main Trade Offs between Scenarios

To achieve the decarbonization targets, as detailed in subsequent chapters, at least the following sectoral transformations are necessary:

a) In the electricity generation sector, a change in the generation mix is required to move from the current situation, with a high thermal component, to a mix that is almost 100% renewable. This implies -first of all- the shutting down of coal-fired power plants, but also the displacement and replacement of the diesel fleet. This will only be possible if large volumes of investment are ensured in clean technologies such as wind and solar (photovoltaic and thermal), and in batteries, together with availability and capacity based on NG, which should begin to be withdrawn from 2040 onwards.

b) The transportation sector is key to achieving a clean economy. The current vehicle fleet is undergoing a major transformation to achieve the objectives. In road vehicles, the light vehicle fleet is being 100% electrified, while larger vehicles are switching to H_2. The aviation sector must contribute by hydrogenizing its consumption.

c) The industrial sector is the third sector in terms of emissions and must also make a significant contribution to the energy transition. Therefore, the electrification of sub-sectors such as copper, fisheries, petrochemicals, saltpeter and steel will be necessary. As with transport, H_2 also plays a fundamental role, helping to reduce emissions in sub-sectors such as saltpeter, sugar and others.

d) Finally, the tertiary sectors (residential, commercial and public sector consumption), which have a lesser impact on emissions inventories, must ensure that their very significant increases in demand (associated with GDP growth) are not covered by emission sources, and in this sense, the use of biomass and the electrification of inefficient consumption is necessary.

7 RESULTS BY SECTOR

7.1 Electricity

The electricity sector is key to driving the transition to an emission-free economy. It must jointly support 1) the expected increase in demand, produced by the electrification of the other sectors, and 2) a change in the generation mix to ensure that future technologies are based on renewable or low-emission sources.

7.1.1 Emission trajectories

The electricity sector is key to the decarbonization process, since in all scenarios it reduces its emissions by at least 86% with regards to 2020. This means that even in the Base Scenario, the sector's contribution to the transition is necessary.

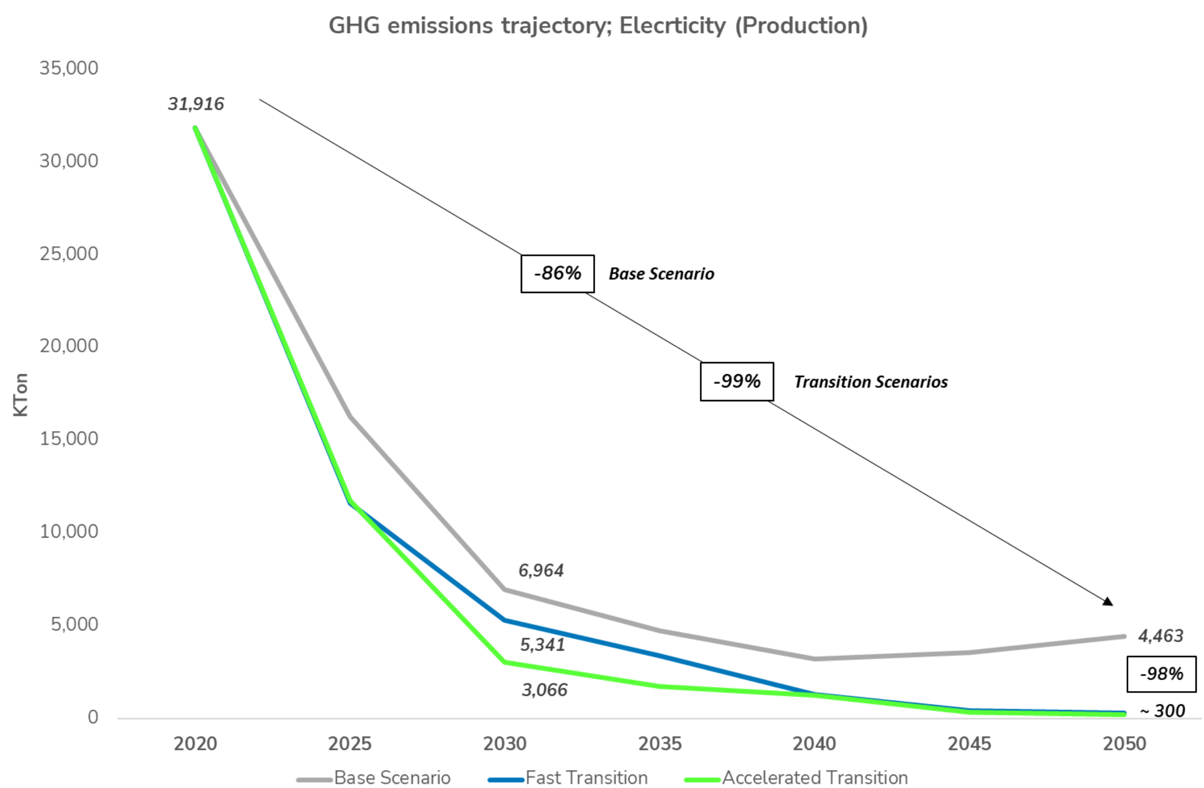


Figure 17 Emissions Trajectories of the electricity generation sector (Source: TIMES-Chile Model)

During the period 2020 - 2035, in all scenarios, emissions are drastically reduced due to the phase-out of coal-fired power plants. In the period 2030 - 2050, coal-fired generation is residual (or zero) and emission reductions are determined by the level of the green tax and CO_2 capture requirements in gas-fired plants.

Finally, by the year 2050, zero emissions are reached in the transition scenarios as a result of the combined application of an aggressive green tax and the capture requirements mentioned above.

7.1.2 Electrification KPIs at the national and regional scope

The benefits associated with the electrification of demand are key in the process of decarbonization of the economy, since in all scenarios, and with greater relevance in the transition scenarios, the rest of the sectors tend to electrify their demands.

Sector	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Commercial and Public Sec.	50%	49%	49%	52%	49%	48%	51%	50%	50%
Industry	33%	36%	38%	35%	36%	39%	39%	43%	45%
Residential	34%	37%	38%	34%	38%	40%	34%	38%	40%
Transport	4%	13%	19%	7%	28%	30%	8%	29%	30%

Table 6 Electrification rates of sectoral demand (Source: TIMES-Chile Model)

The table above shows that in order to reach the net-zero targets in the transition scenarios, all sectors have to electrify at higher rates than in the Base Scenario. Particularly relevant is the contribution of the transport sector, which increases its electrification rates by more than 10 points in 2050 in both transition scenarios. This means that energy demands, which are constantly growing, are increasingly supplied by electricity sources, and given the installed capacity matrix, this implies that less CO_2 emissions are released each month.

The Sub-section 7.1.5 details the growth of electricity demand in relation to the electrification of other sectors' demands.

7.1.3 Installed Capacity: On Grid, Off Grid, and Distributed Generation

In order to move towards carbon neutrality, and as has already been stated, the decarbonization of the electricity sector and the change to a practically 100% clean generation mix is key.

As shown below, in all scenarios there is a transition to a cleaner generation mix, dominated by wind (approx. 35% of the mix in all scenarios) and solar PV (both utility scale and distributed, another approx. 35% of the mix).

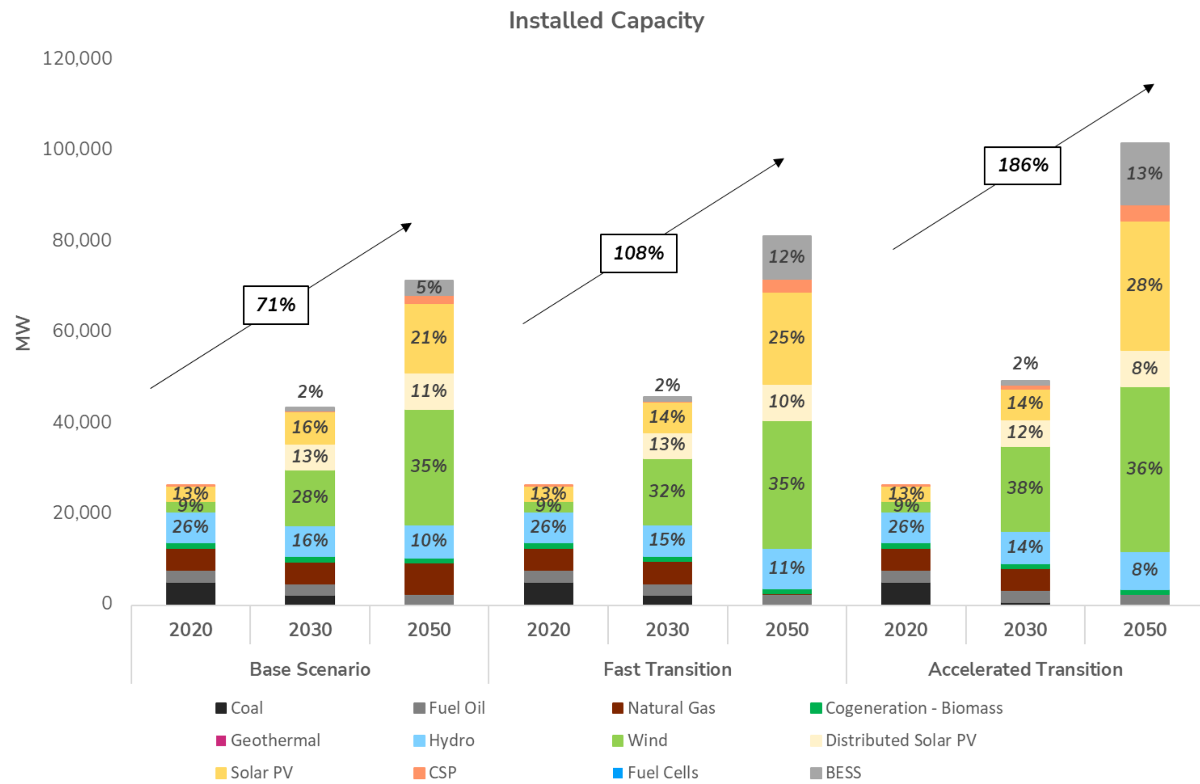


Figure 18 Installed Capacity by scenario (Source: TIMES-Chile Model)

On the other hand, thermal generation sources are gradually disappearing from the mix. In addition to the expected closure of coal-fired plants, gas and fuel oil-fired plants will be phased out in the transition scenarios.

Finally, it is worth noting the increasing presence of storage in the form of batteries in the long term. This is key to be able to balance the very significant amount of non-dispatchable energy present in the generation mix.

At the regional level, the following figure shows topographically the distribution of installed capacity in each of the modeled regions[13]. In the Base Scenario, the Norte Grande region becomes the region that will have the most installed capacity in the long term (38%) due to renewable sources, both solar and wind. The shutdown of coal-fired power plants causes the central areas of the country to lose weight (Central Chile and Central Sur, 50% to 35%), so it will be key to adequately prepare the transmission system for these challenges.

[13] The Base Scenario and the Accelerated Transition scenario are depicted. The capacity distribution of the Fast Transition scenario is very similar to the Accelerated Transition scenario.

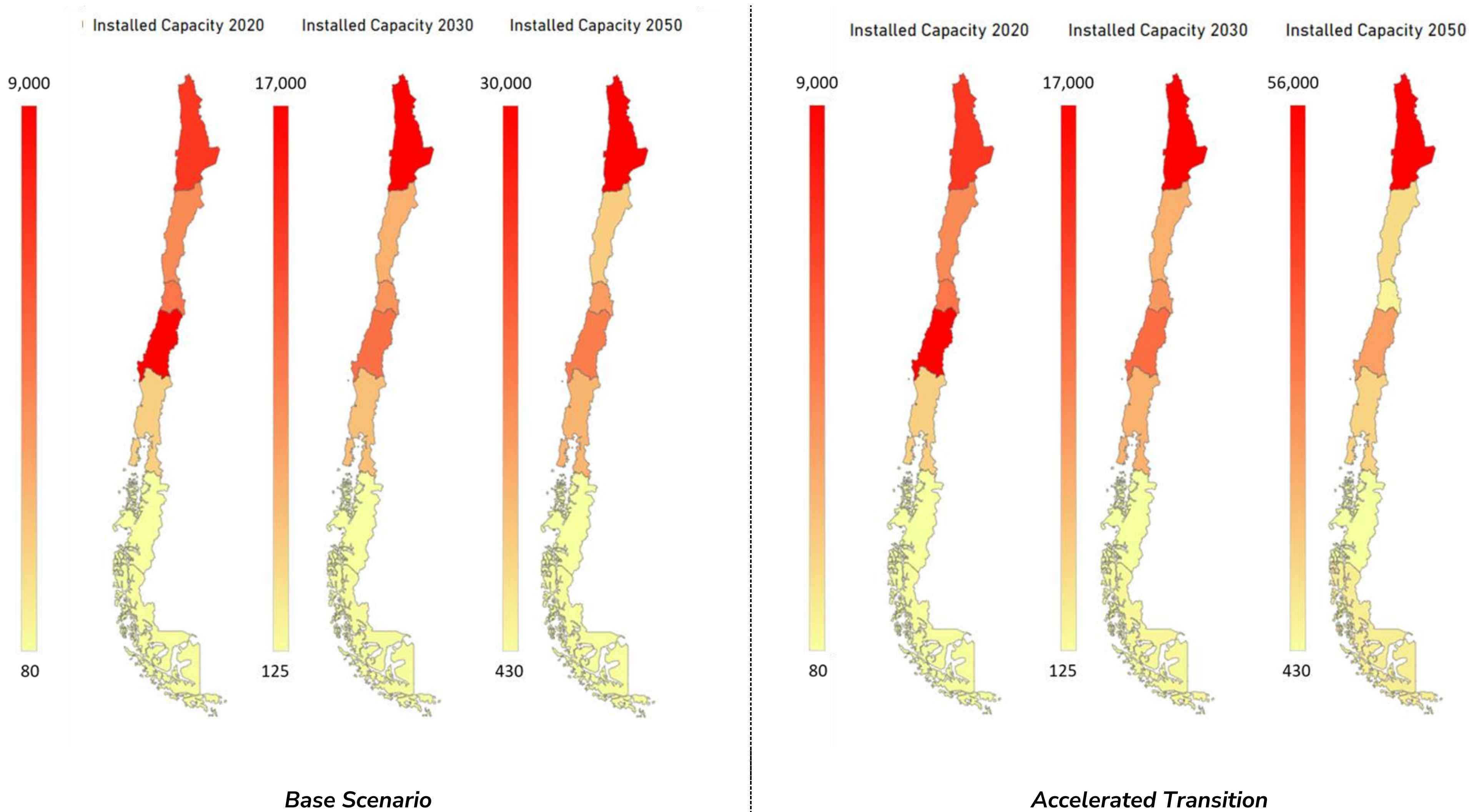


Figure 19 Regional Distribution of Installed Capacity (MW) (Source: TIMES-Chile Model)

In the transition scenarios, this effect is much more pronounced, reaching a rate of more than 50% of installed capacity in the Great North, with the central regions also showing the closure of additional thermal capacity, lowering its proportion to less than 30%.

It should be noted that, in all scenarios, the installed capacity in the Magallanes region increases relatively significantly (1% to approximately 8% in the long term), driven by the demands associated with GH_2 generation.

The above paragraphs refer to installed capacity connected to the grid and do not include off-grid assets, which are dedicated to GH_2 generation. If these were included, the results are even more striking, especially in transition scenarios.

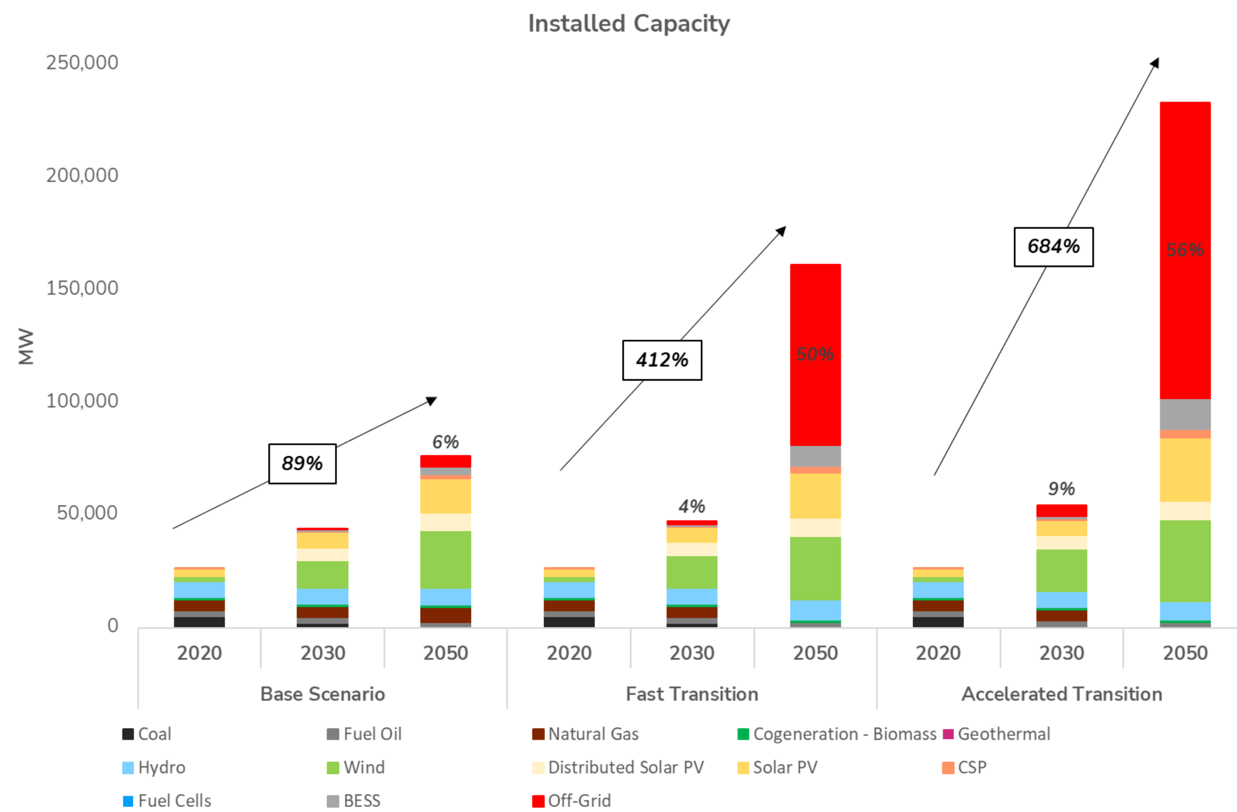


Figure 20 Installed capacity by scenario considering Off Grid assets (Source: TIMES-Chile Model)

More than 50% of the installed capacity the transition scenarios will be dedicated to GH_2 generation (without injecting any energy into the grid). Section 7.3 provides more details on the location and use of these assets.

Finally, the relevance of distributed resources is evident in all scenarios, according to the LTEP assumptions, there would be a potential of 8 GW for such technologies in Chile. This potential is exhausted in all scenarios, distributed by type of installation as shown in the following figure.

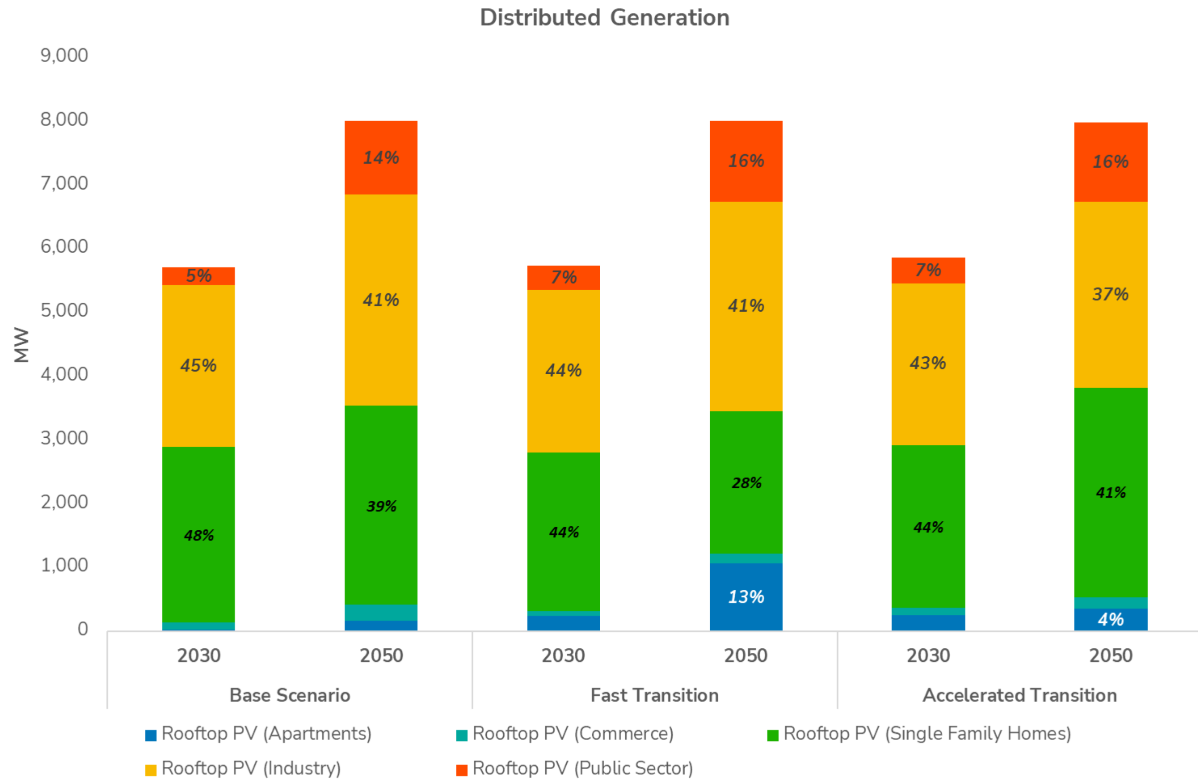


Figure 21 Distribution of resources apportioned by type (Source : TIMES-Chile Model)

7.1.4 Generated Electricity

The generation dispatch follows the path set by the installed capacity, and is almost completely decarbonized, being practically 100% clean in the transition scenarios.

In the long term, the main generation sources are wind energy, photovoltaic energy and generation through batteries. The latter can store up to 70 TWh of energy in the Accelerated Transition scenario, highlighting their influence in balancing the system under conditions of very high penetration of non-dispatchable renewable energy.

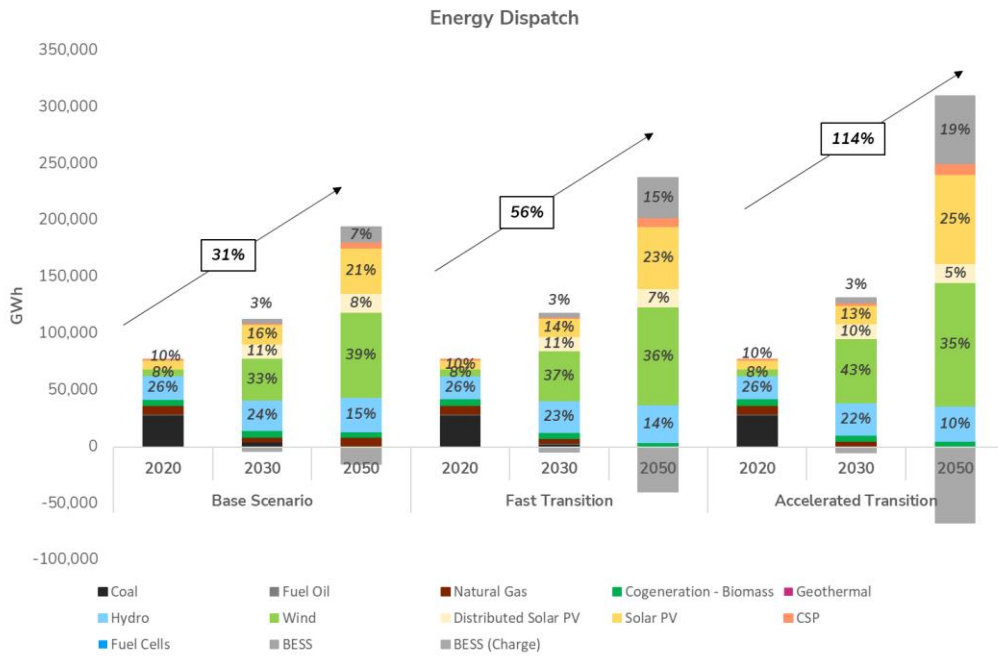


Figure 22 Generation dispatch by scenario (Source: TIMES-Chile Model)

The figure above shows how the influence of renewable energies is increasing in all scenarios, being close to 90% of the dispatch already in 2030, this requires accelerated progress in the security needs of the SEN to operate the system with a deeply renewable mix, particularly with respect to the requirements of inertia, short circuit and voltage control. In 2050, this figure drops to values close to 80-85%, depending on the scenario, but not because of the influence of thermal sources, but because of the very important contribution of batteries to help meet demand and ensure a feasible dispatch from a technical and economic point of view (minimizing curtailments). For the year 2050, in the Accelerated Transition scenario, about 66 TWh of energy stored in batteries is foreseen.

Figure 23 shows the regional distribution of dispatch. As in the previous case, in all scenarios there is a geographic redistribution over time, from coming mainly from the central zone of the country, almost 50% of the energy, to being dominated by generation in the Great North, 35% of the dispatch in the Base Scenario. In the transition scenarios, when generation from thermal sources ceases, it reaches 50% for the Great North.

Given this situation, it is important to evaluate the electrical links between the regions and their possible reinforcements to ensure the correct transit of electrical energy between regions. In the first place, the Table 7 shows the energy imported and exported by region, from the first moment, in all scenarios, Central Chile imports energy from the rest of the regions, initially from the Southern Center region, and already from the year 2030 and in the long term, from the Great North, in significant volumes.

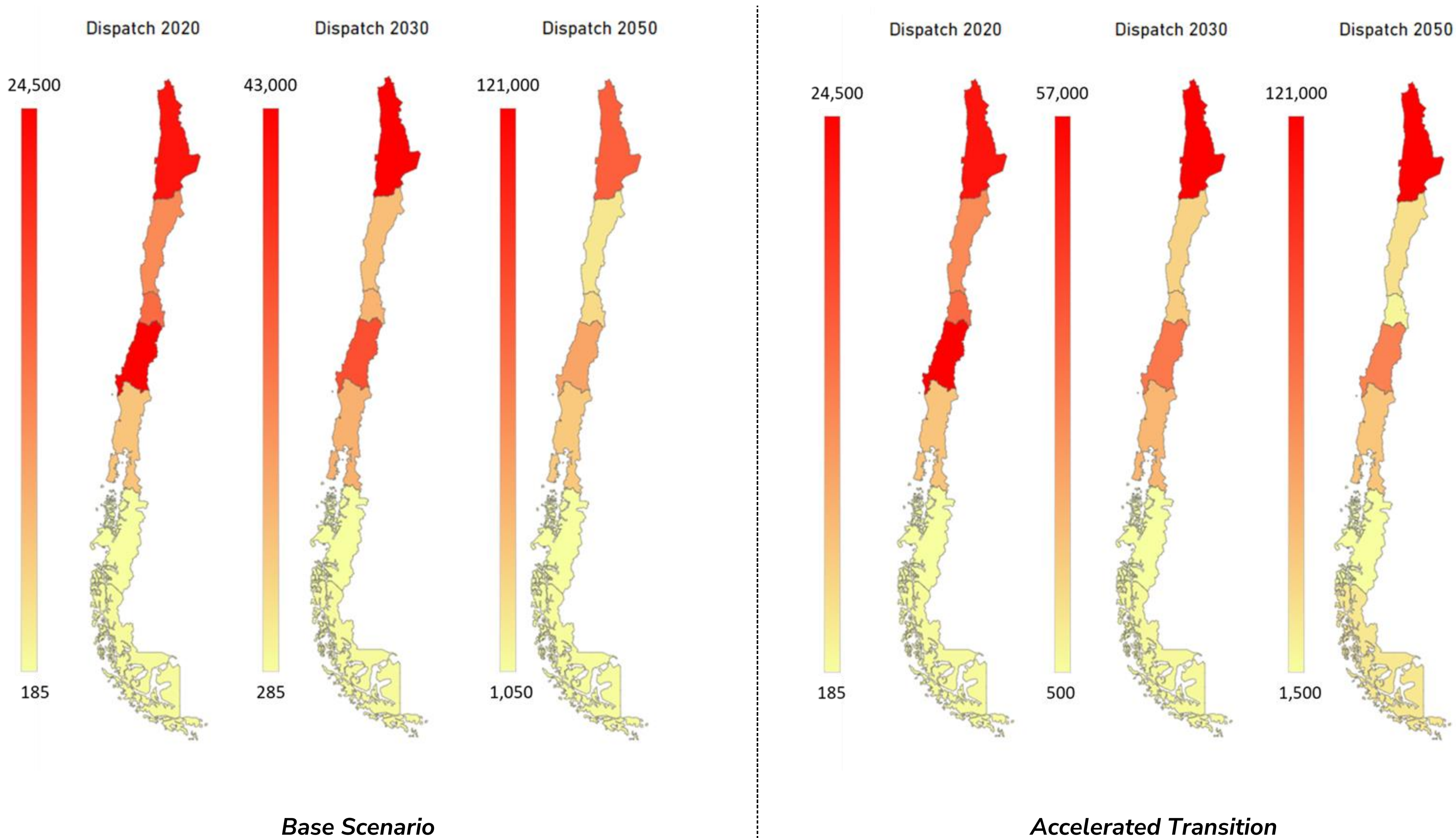


Figure 23 Regional distribution of the generation dispatch (GWh) (Source: TIMES-Chile Model)

Region	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Great North	-2.8	-18.3	-32.4	-2.8	-20.4	-53.7	-2.8	-26.7	-61.2
Small North	-3.8	-0.5	6.7	-3.8	0.6	2.2	-3.8	2.5	3.0
Central Chile	15.2	32.1	47.8	15.2	32.9	66.2	15.2	36.7	75.8
Southern Center	-8.6	-9.6	-15.3	-8.6	-7.8	-4.1	-8.6	-6.8	-16.9
Southern Chile	0.0	-3.7	-6.8	0.0	-5.2	-10.7	0.0	-5.7	-0.8
Aysén	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Magallanes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7 Imported (+) or exported (-) electric power in TWh by region (Source : TIMES-Chile Model)

To achieve these flows, the following energy transmission capacities between regions are required. These, up to 2030, are the same in all scenarios and correspond to those planned by the CNE in its Transmission Expansion Plan.

From 2050 onwards, capacity increases are optimized by the model to ensure that energy can flow optimally between regions.[14].

Interconnection	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Great North – Small North	1,500	2,300	2,300	1,500	2,300	2,300	1,500	2,300	2,300
Small North – Central Chile	1,900	2,300	2,400	1,900	2,300	2,400	1,900	2,300	2,300
Great North – Central Chile	0	3,000	3,000	0	3,000	6,000	0	3,000	7,000
Central Chile – Southern Center	2,700	2,700	3,800	2,700	2,700	3,300	2,700	2,700	3,800
Southern Center – Southern Chile	200	1,500	1,500	200	1,500	1,500	200	1,500	1,500

Table 8 Exchange capacity between regions in MW (Source : TIMES-Chile Model)

As can be seen, the most important increase in transmission capacity, and the key to decarbonization, is the link between the Norte Grande and Central Chile, which is key for both the 2030 and 2050 horizons. Without this, and its increases, it is very difficult to reach the levels of exchanges of Table 7. Increasing the capacity of the grid to meet demand during this period involves investments ranging from US$1.7 to US$2.5 billion.

[14] This work considers Chile as a system that is electrically isolated from its neighbors. Although it is possible to generate sensitivities in this respect, the LTEP guidelines have been followed on this particular item.

7.1.5 Demand by Region, structured by sector

Electricity demand, understood as final energy consumption, which does not consider losses or intermediate uses (upstream consumption, etc.), is shown in the following figure.

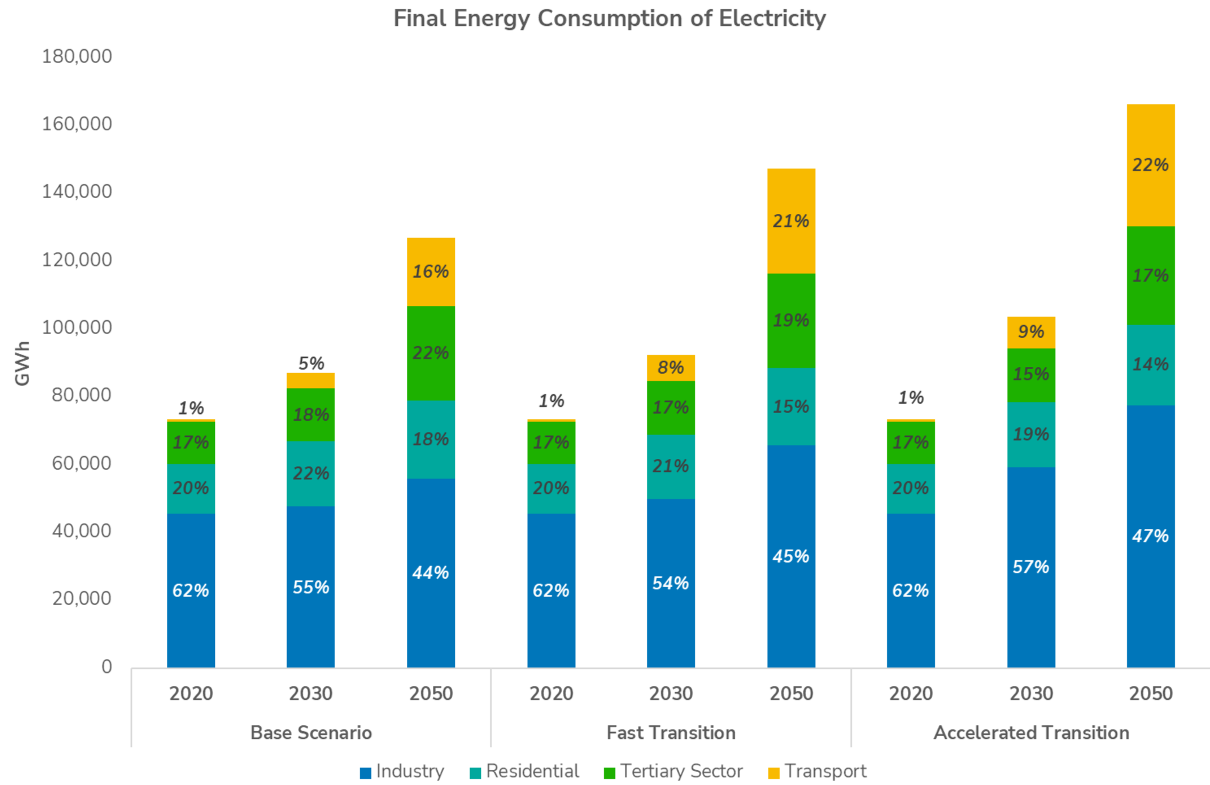


Figure 24 Final consumption of electric energy per sector (Source: TIMES-Chile Model)

The electrification process means that all sectors will increase their final consumption, the most relevant increase being that of the transportation sector, which will go from marginal consumption at present, to take on certain relevance in 2030, and become the second largest energy demander in 2050.

At the regional level, the highest consumption is found in Central Chile and the Great North. The growth dynamics are very similar in the three scenarios, and relative consumption by region tends to increase in Central Chile and to lose weight in the north (although in absolute values it grows in all regions). This effect, which occurs in all scenarios, is due to the increase in electricity demand in Central Chile caused by the electrification of transportation (mainly) and of the residential and tertiary sectors, which will require an increase in the internal distribution capacities in the regions where demand increases occur, so that the electrification process is developed under a concept of safety, resilience and economic efficiency.

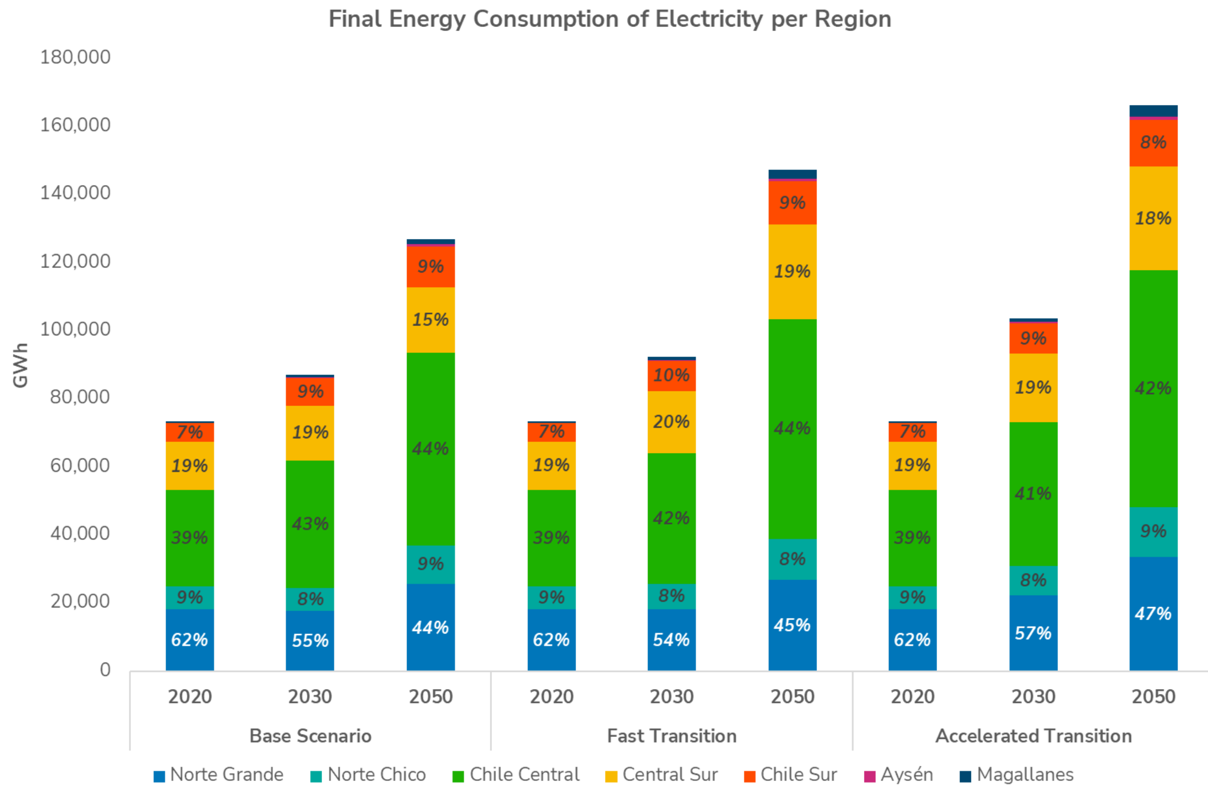


Figure 25 Final consumption of electric energy by region (Source: TIMES-Chile Model)

7.1.6 Electricity Subsector Summary

The electricity sector is key to Chile's energy transition and for achieving the objectives committed to for the year 2050. It is possible to verify that:

a) The sector practically decarbonizes its generation sources, and therefore its end uses, as part of demand, in all scenarios, not only in transition scenarios. This is strongly associated with the country's current Decarbonization Plan.

b) The speed of emissions reduction is by far the fastest among all sectors, and only in the decade 2040 - 2050 does it require additional incentives to achieve the virtual decarbonization of generation sources in the transition scenarios.

c) The constant electrification of demand leads to significant investment requirements. These investments are mainly based on renewable sources and storage,

d) The latter is key to achieve the transition, with installed capacities and a very relevant use in the long term.

e) The transmission grid and its successive expansions are also key to the success of the transition scenarios, since without them it is impossible to connect the regions rich in natural resources (sun, wind) with the central regions where most of the demand is concentrated.

f) The distribution network must also be adapted to allow the transition to a highly electrified system, so its growth criteria must include elements of safety, resilience and economic efficiency, in an environment where distributed generation will be a relevant player.

7.2 Transport

7.2.1 Emission Trajectories

Transportation is currently the second largest contributor to GHG emissions in Chile, after the electricity sector. The reference scenario leads to a gradual reduction of emissions until 2040 and then stabilizes (Figure 26). Emissions from road transport continue to decline, but emissions from aviation and shipping are increasing, leading to a stabilization of total emissions.

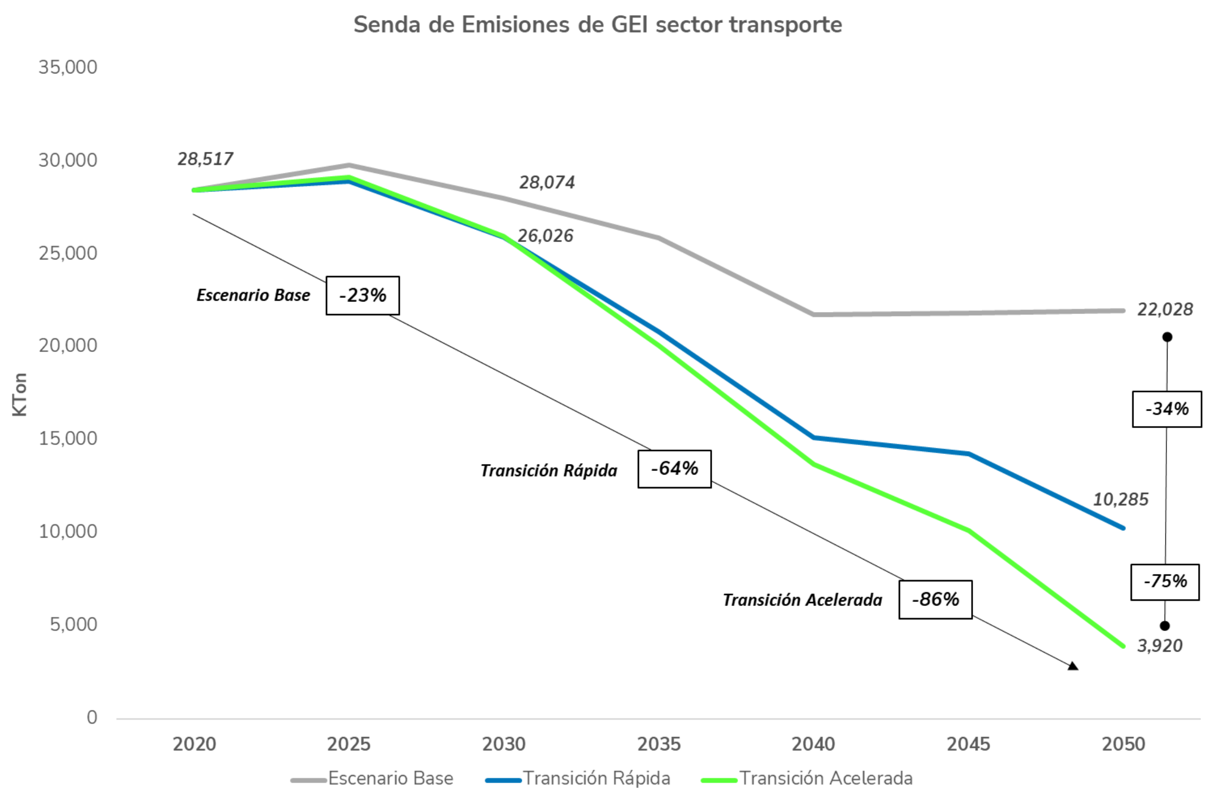


Figure 26 Emissions trajectory of the transportation sector (Source: TIMES-Chile Model)

In the Fast Transition scenario, the reduction between 2025 and 2040 is faster than in the Base Scenario, driven by the decarbonization of road transport. Aviation is projected to decarbonize further, mainly after 2045, when GH_2 penetrates as a fuel, leading to a further reduction between 2045 and 2050.

The Accelerated Transition scenario shows a continued reduction in overall transport emissions, driven by a rapid decarbonization of road transport from 2025 due to accelerated electrification of the sector, and complemented by reduced emissions from aviation and shipping as clean fuels (mainly H_2) are gradually introduced in greater proportion in the sector from 2040 onwards.

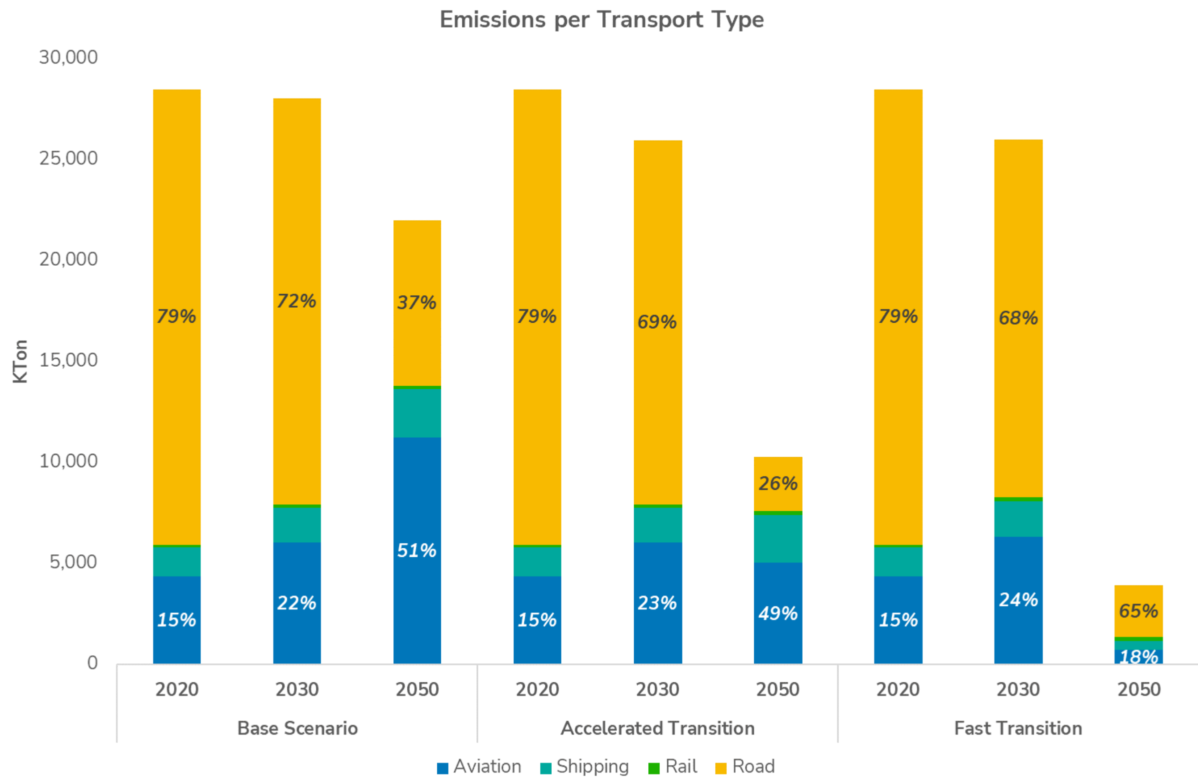


Figure 27 Emissions by transport type for each scenario (Source: TIMES-Chile Model)

Looking at the geographic distribution of emissions from the transport sector, Central Chile and Southern Central Chile are the regions with the highest level of emissions and, consequently, the regions where the greatest decarbonization effort is being made in the transition scenarios (Figure 28).

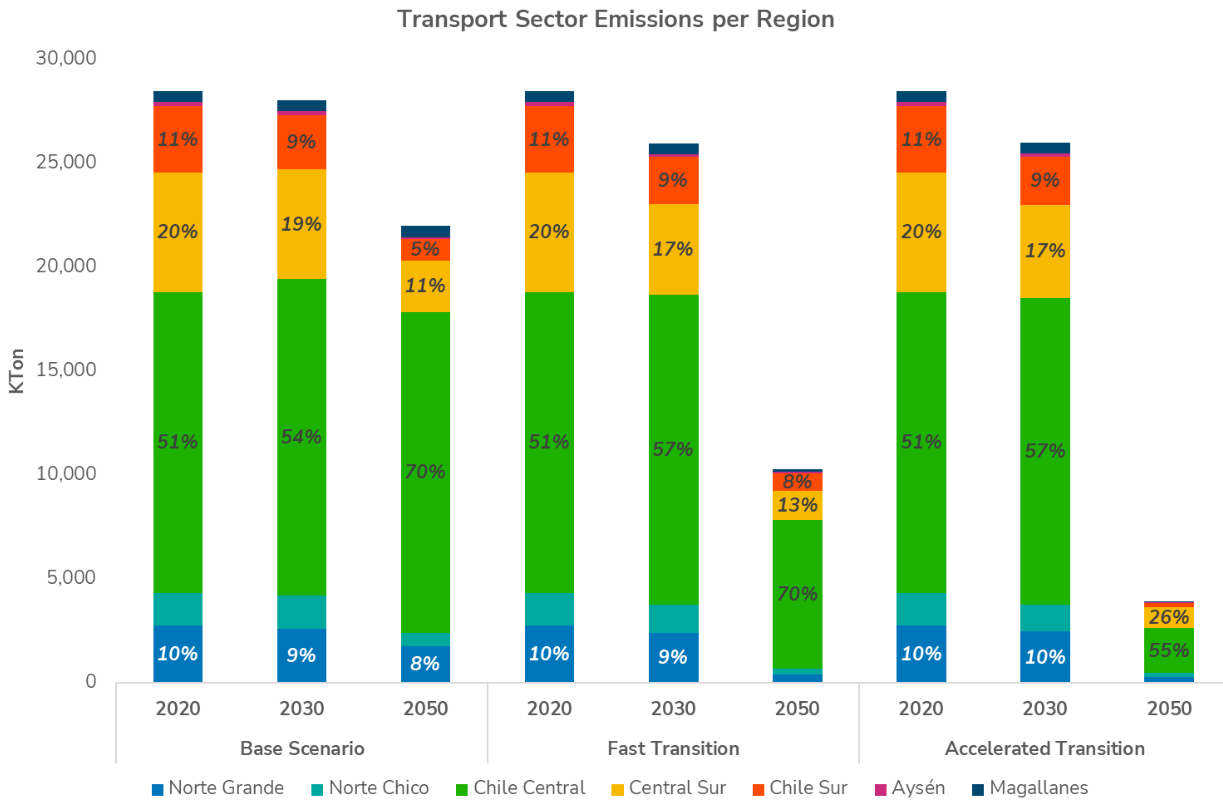


Figure 28 Transport sector emissions for each scenario and region (Source: TIMES-Chile model)

A more detailed analysis in Central Chile shows a drastic 76% reduction in road transport emissions between 2025 and 2040 in the Fast Transition scenario, and 79% in the Accelerated Transition scenario (Figure 29).

The following table shows CO_2 emissions by type of vehicle for Central Chile and for the road transport subsector, separating public and private means of transport.

Vehicle Type	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Intercity Bus	268	237	195	268	237	204	268	240	226
Urban Bus	807	352	0	807	352	0	807	323	0
Freight	2,144	963	0	2,144	963	0	2,144	963	0
Motorcycles	43	62	46	43	60	70	43	61	78
Private Vehicles	6,344	7,206	4,493	6,344	6,972	776	6,344	6,577	675
Public Vehicles[15]	634	449	0	634	383	0	634	386	0

[15] Taxis

Vehicle Type	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
TOTAL	10,240	9,269	4,733	10,240	8,967	1,050	10,240	8,549	978

Table 9 Emissions (in KTon) road transport sub-sector in Central Chile (Source: TIMES-Chile Model)

Aviation emissions continue to increase significantly in the Base Scenario. In the Fast Transition scenario there is an equally rapid decarbonization of almost 40% between 2045 and 2050, while in the Accelerated Transition scenario this reduction reaches 87% (Figure 29). As mentioned above, this is achieved with the introduction of green H_2 in aviation after 2045.

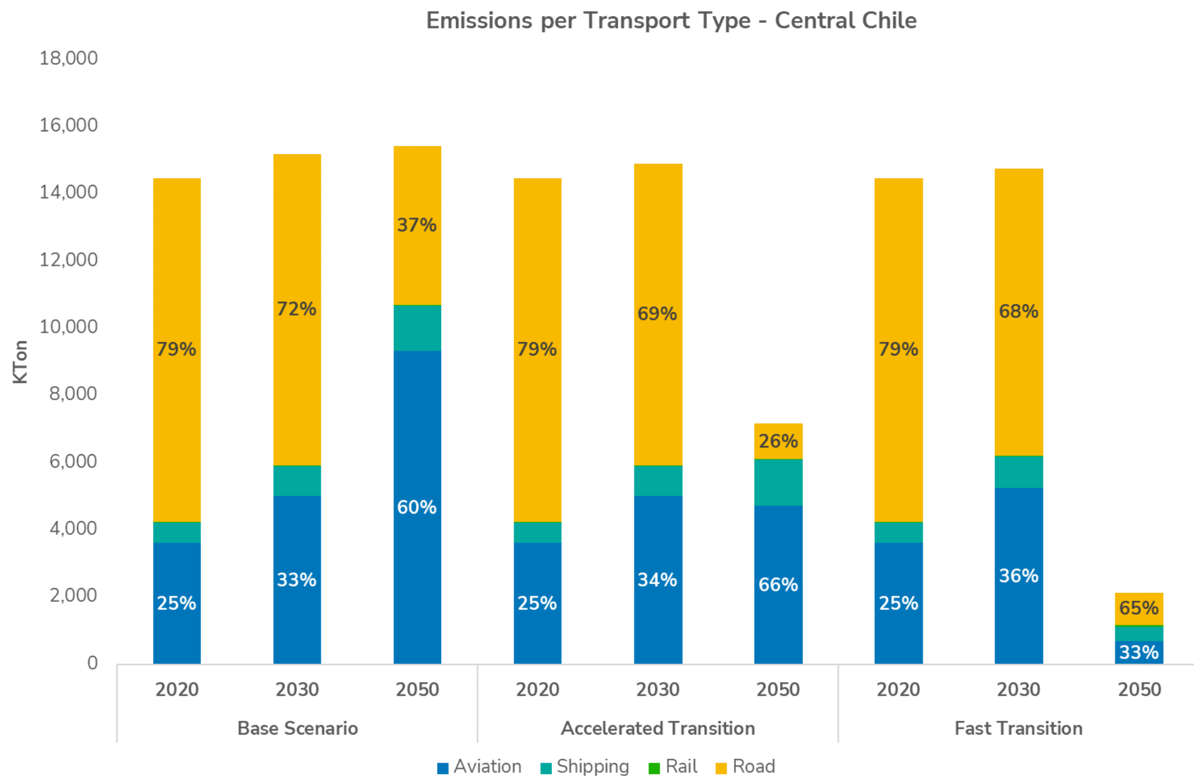


Figure 29 Emissions in the transportation sector in Central Chile (Source: TIMES-Chile Model)

In south-central Chile, the dominant emissions sector is road transport, which shows a reduction in emissions even in the Base Scenario (Figure 30). In the Fast Transition scenario and the Accelerated Transition scenario, there is a sharp reduction between 2035 and 2040 in emissions from road transport, followed by a stabilization in the period between 2040 and 2050. Private road vehicles are fully decarbonized and go electric in 2050, and the remaining emissions are due to hybrid buses, LDVs[16] and some efficient HDVs[17] that still require fossil fuels.

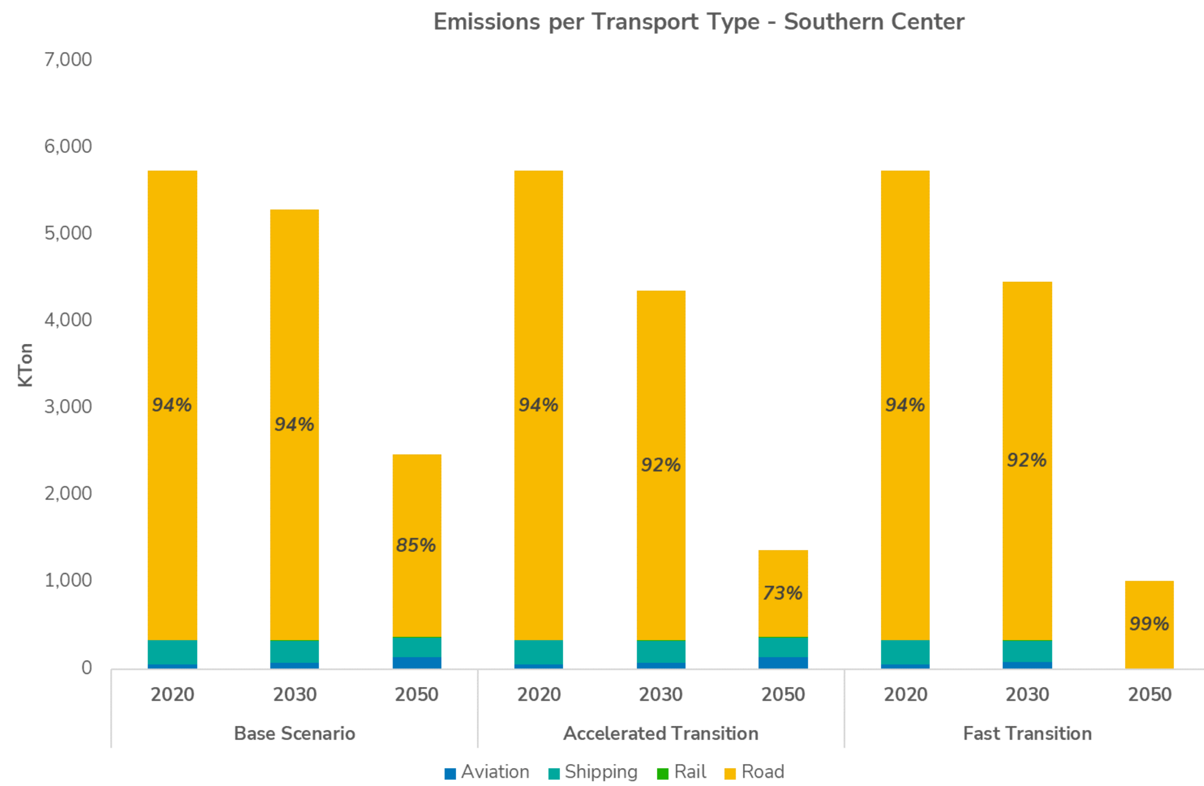


Figure 30 Emissions in the transportation sector in the Southern Center (Source: TIMES-Chile Model)

The overall final energy consumption in transportation can be seen in Figure 31 for the three scenarios considered.

[16] Light Duty Vehicles.
[17] Heavy Duty Vehicles.

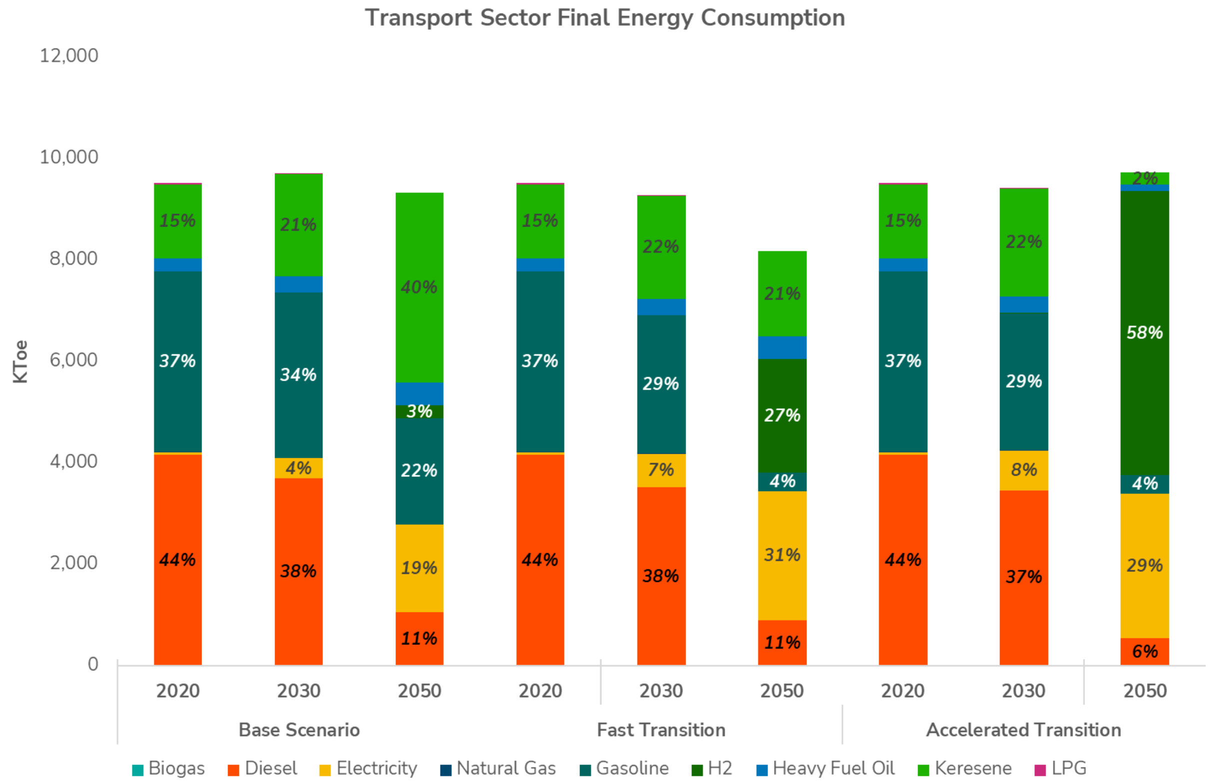


Figure 31 Final energy consumption in the transportation sector (Source: TIMES-Chile model)

The main differences between the Base Scenario and the Transition scenarios are the major electrification of road transport and the introduction of GH_2 in aviation after 2040. Note that transport demand in the Accelerated Transition scenario is higher than in the other scenarios due to the different GDP projection used for this scenario.

A closer examination of road transport (which is the most energy-intensive sector) in Figure 32 reveals the dramatic change in the fuel mix between 2030 and 2050. Road transport in 2050 is dominated by electricity and, although a small amount of fossil fuels remains, it is mainly used in heavy-duty vehicles, where H_2 is also introduced. Small amounts of gasoline are consumed in light hybrid vehicles.

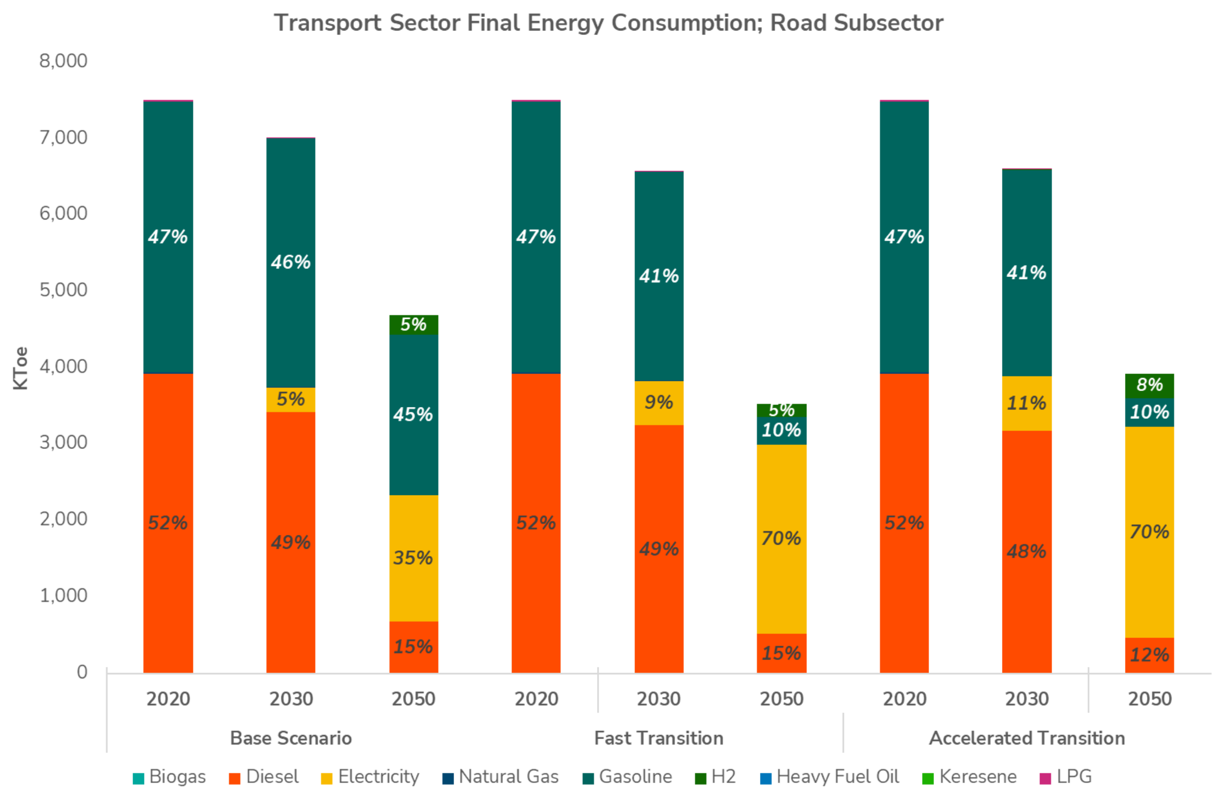


Figure 32 Final energy consumption of the road transportation sector (Source: TIMES-Chile Model)

7.2.2 Impact of Electromobility on Electricity Demand by Region

The decarbonization patterns of the transport sectors presented in the previous section are largely achieved through the electrification of the road transport sector. The overall increase in the use of electricity has already been presented in section 7.1.5 at the national level. The specific modes of road transport in which electricity is consumed are private vehicles and buses, while freight transport in light vehicles consumes a fairly low amount of electricity (Figure 33).

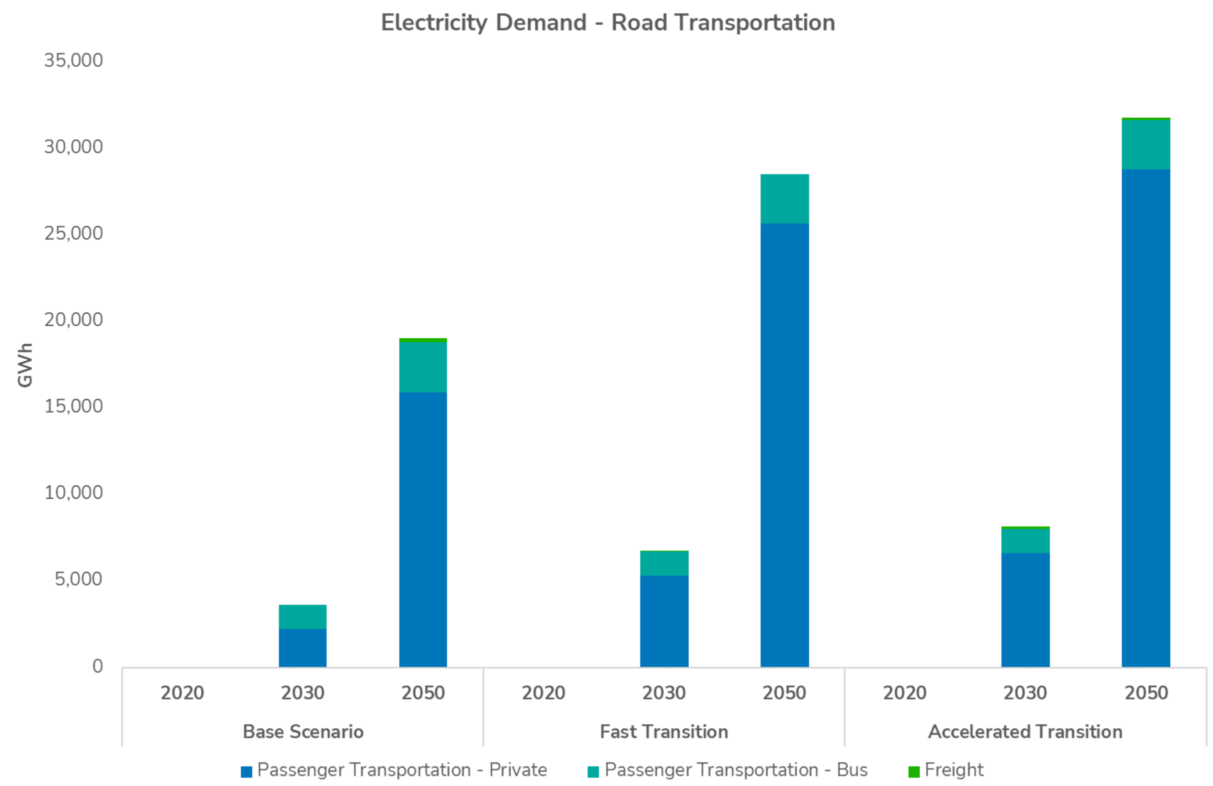


Figure 33 Electricity demand associated with highway transportation (Source: TIMES-Chile Model)

A closer look at the regional level shows that by 2050 the regions of Central Chile and South-Central Chile consume the largest amount of electricity in road transport, reaching a level of 17 TWh in the Fast Transition scenario and almost 18 TWh in the Accelerated Transition scenario (Figure 34).

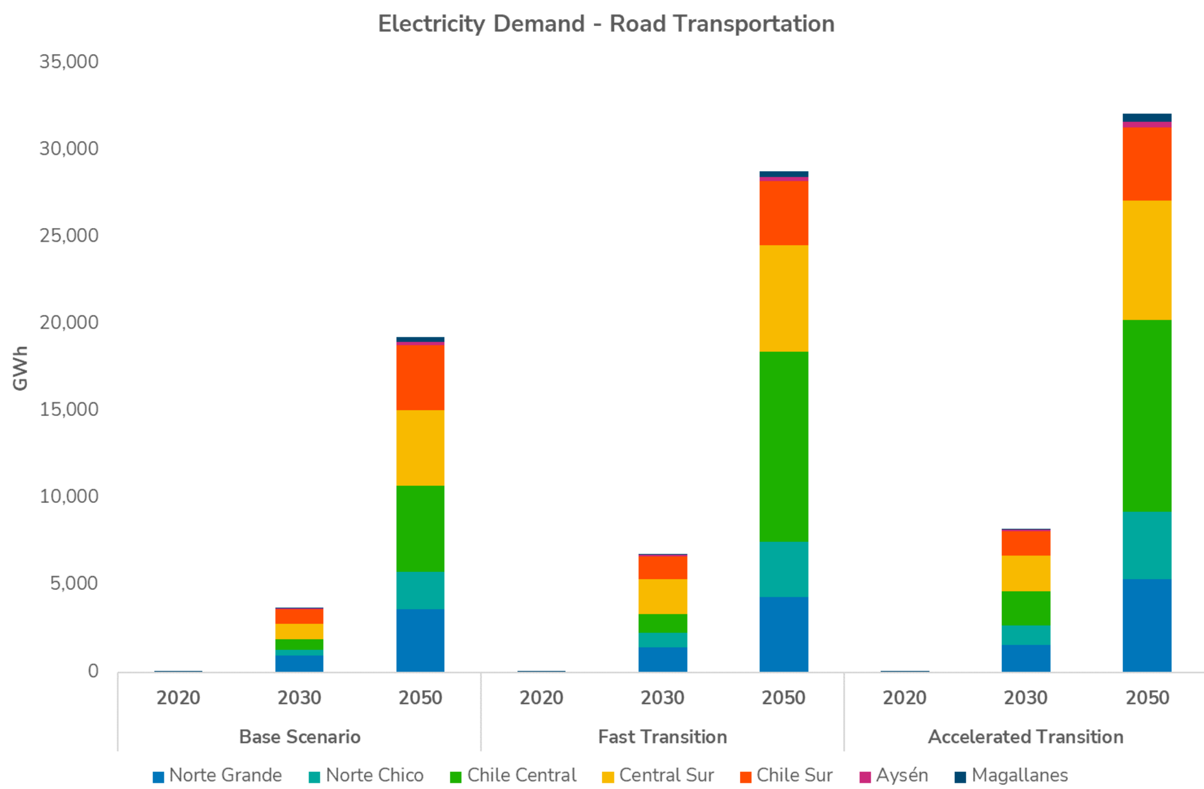


Figure 34 Regional electricity demand caused by road transportation (Source: TIMES-Chile Model)

The share of electric vehicles in the private vehicle, bus and LDV fleet at the national level can be seen in the figure below. It is interesting to note that, even in the Base Scenario, about 80% of the private vehicle fleet will be electric in 2040 (Figure 35). In the Fast Transition scenario, the share of electric vehicles in private vehicles reaches approximately the same level and more than 95% of buses are electric in 2050. In the Accelerated Transition scenario, the share of electric vehicles in private vehicles exceeds 90% in 2030, and electric buses account for more than 97% of the total fleet.

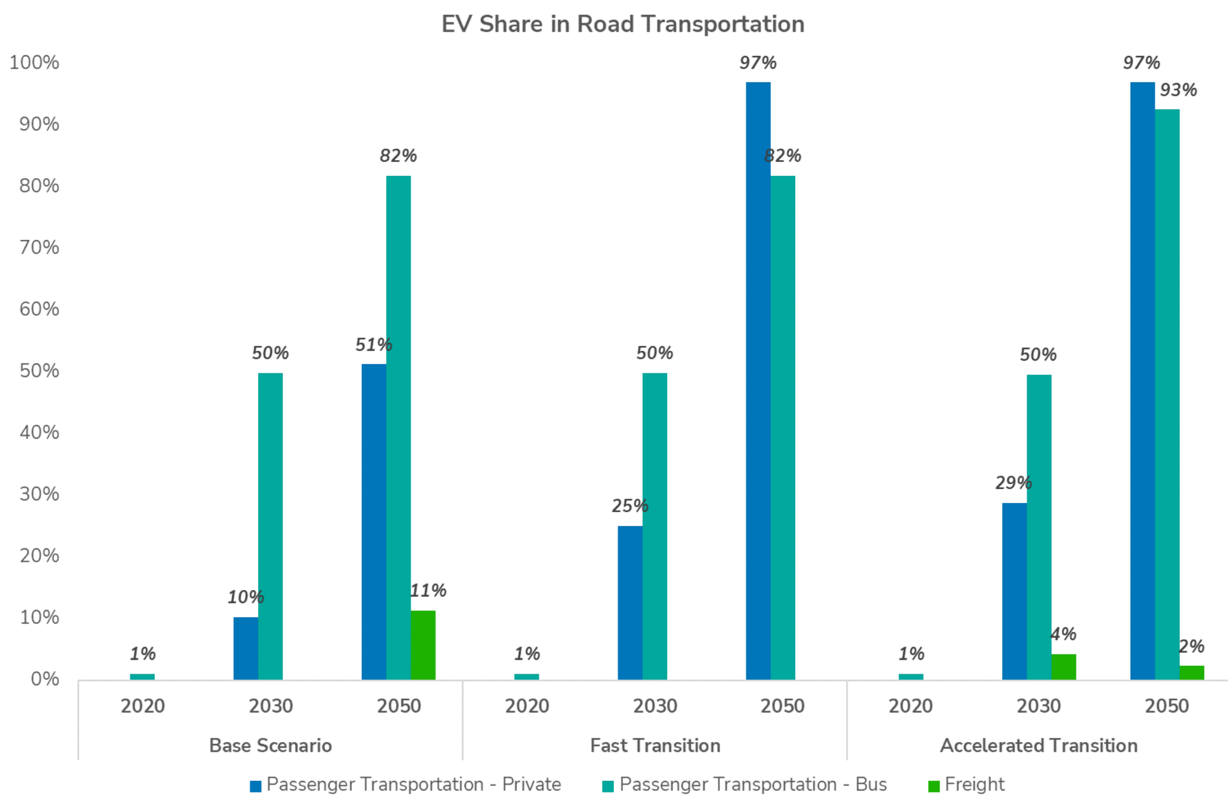


Figure 35 Proportion of electric vehicles in road fleets (Source: TIMES-Chile Model)

The total number of electric cars (private and cabs) by region in the three scenarios can be seen in Table 17. As expected, the fleet in central and south-central Chile covers most of it.

Region	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Great North	0	216	706	0	271	824	0	295	1,001
Small North	0	97	539	0	206	697	0	248	843
Central Chile	0	0	1,143	0	154	3,968	0	320	3,964
Southern Center	0	141	1,146	0	632	2,049	0	653	2,323
Southern Chile	0	209	943	0	340	943	0	355	1,050
Aysén	0	0	53	0	19	75	0	27	91
Magallanes	0	0	72	0	1	150	0	1	206
Sector TOTAL	**1**	**664**	**4,603**	**1**	**1,624**	**8,707**	**1**	**1,901**	**9,478**

Table 10 Fleet of electric vehicles by region (thousands of vehicles) (Source: TIMES-Chile Model)

7.2.3 Aviation Trajectory

Aviation was identified as one of the key sectors for transport decarbonization, mainly through the introduction of new energy carriers (GH_2). The largest amounts of H_2 are consumed in both transition scenarios in the Central Chile region (Figure 36), where the highest demand from air transport is allocated. In the analysis of regional H_2 generation in section 7.3.2 it was noted that a certain amount of GH_2 is produced in Central Chile (CCH) that would cover aviation demand. The region with the second largest aviation H_2 consumption is the Great North (NOG), which has the second largest demand in aviation services, but also produces a huge amount of GH_2. H_2 is consumed in Magallanes (MAG) (where it is produced locally in large quantities) and in Southern Chile (SCH), where adequate quantities are also produced locally to meet aviation demand.

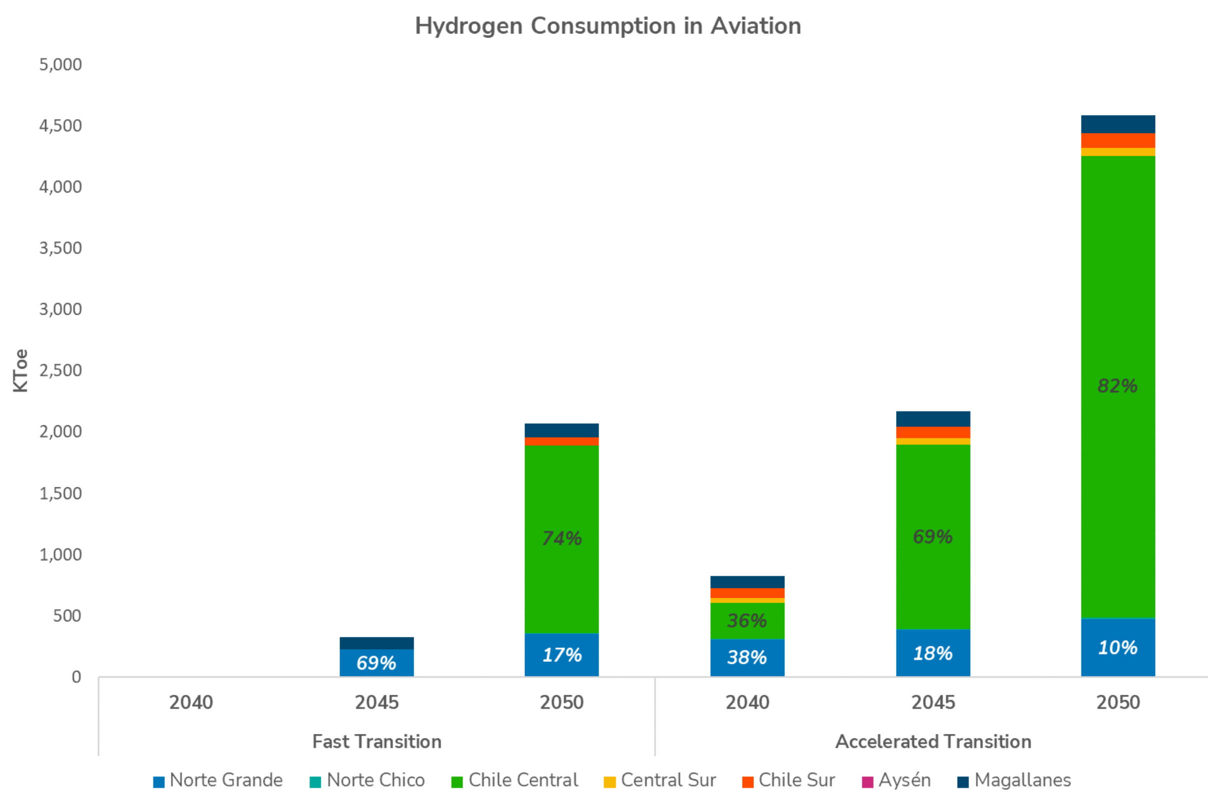


Figure 36 H_2 consumption in aviation by region (Source: TIMES-Chile Model)

7.2.4 Rail Transportation Assessment

Rail electricity consumption is rather limited to metro and intercity trains in central, south-central and southern Chile (according to the assumptions included in the LTEP) and only totals around 1 TWh in 2050.

It is important to note that in the present analysis the demand for rail services is taken from the LTEP scenarios, where a very limited penetration of rail for intercity passenger and freight travel is assumed. This has a direct effect on rail energy consumption and corresponding emissions. However, the role of rail transport, and especially electrified rail, in the process of decarbonization of the energy system should be reevaluated. The Chile on Rails (*Chile Sobre Rieles*) program could be an important starting point and its impact on the demand for services should be taken into account and incorporated in future scenario analyses.

7.2.5 Other Means of Transportation

Bicycling and the extensive use of micro mobility and "last mile" mobility options could also contribute significantly to reducing energy demand in road transport, and should be part of an integrated energy and transportation planning approach.

7.2.6 Transportation Subsector Summary

The transportation sector in Chile has considerable potential for decarbonization, as it is currently based mainly on fossil fuels. The key pathways identified by the analysis of the scenario results are:

a) Decarbonization of road passenger transport through full electrification of automobiles (private cars and cabs) and extensive electrification of buses.
b) Decarbonization of road freight transport through the introduction of low displacement electric vehicles and medium and heavy H_2 vehicles.
c) Decarbonization of aviation through the introduction of H_2 after 2040, and decarbonization of shipping through the introduction of GH_2-based fuels after 2035.
d) The results obtained in terms of land vehicles are consistent with the goals established in the National Electromobility Strategy; therefore, it is suggested that its implementation be strengthened in the short and medium term.

7.3 Hydrogen

7.3.1 Hydrogen Production: On and Off Grid

As indicated in the inputs to the model and in the scenario definition (section 5), and in the analysis of the results of the electricity sector (section 7.1), the assumptions associated with GH_2 production, especially for export in the transition scenarios, mean that the development of this energy vector differs considerably from one scenario to another. There is no doubt that, without the use of this input, the transition to a low-emission economy would not be possible.

At the production stage, the development of the H_2 business is still scarce in 2030, but important in 2050, with great relevance in the transition scenarios. The large production centers will be located in the Great North, Central Chile and Magallanes, taking advantage of these regions' own resources (especially the sun in the Norte Grande and wind energy in Magallanes) and their proximity to national demand (Central Chile and Norte Grande), as well as possible export points, particularly to North American and Asian markets from the Norte Grande area and European markets in the case of the Magallanes area.

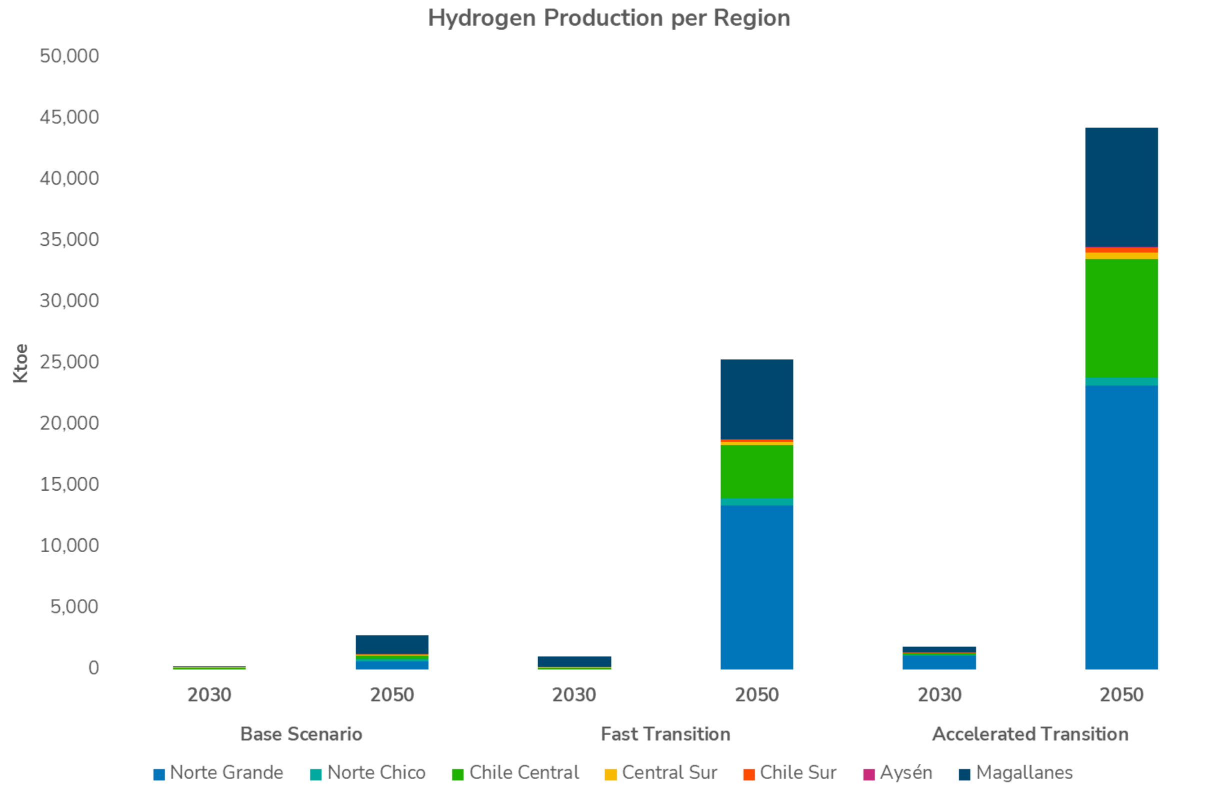


Figure 37 Hydrogen production by region (Source: TIMES-Chile Model)

The production of H_2 can be carried out in two ways, either with assets connected to the power grid, with the electrolyzers remaining as SEN demands, or in isolation, i.e., without connecting to the power grid. Figure 38 shows how as soon as H_2 quantities are relevant, production tends to be fully dedicated, not connected to the grid, using the renewable potential of the Norte Grande and Magallanes regions.

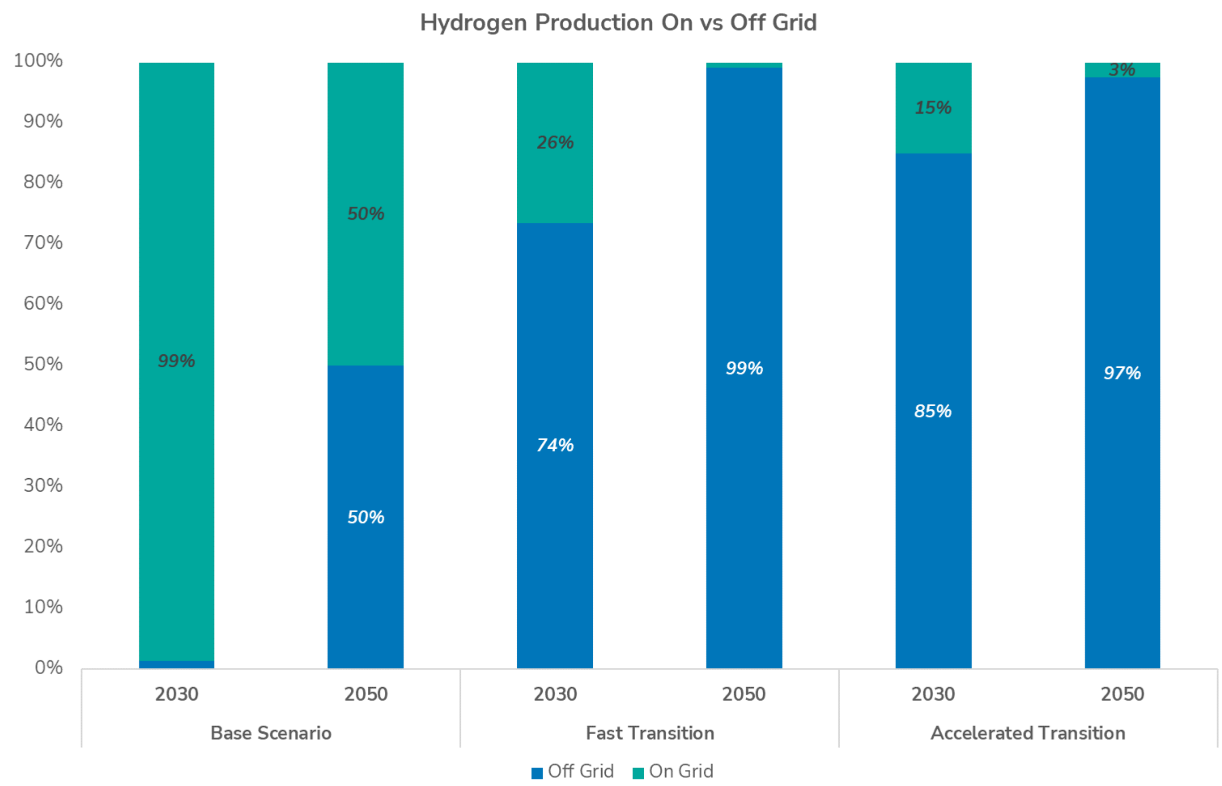


Figure 38 On Grid vs. Off Grid Hydrogen Production (Source: TIMES-Chile Model)

The strong off-grid development of production implies that a very important part of the installed electricity capacity (see section 7.1.3) is not really associated with final electricity demands, and is therefore supported by H_2 consumers (international importers and domestic demand).

7.3.2 Consumption by Region and Main Uses

H_2 production shows the locations and types of grid connection, but does not show the end uses of H_2. Figure 39 details such uses excluding exports, i.e. domestic H_2 uses. It is expected that in all scenarios the industry will need relevant H_2 consumption to achieve carbon neutrality. This will not be possible without the participation of transport in the long term. For refineries, H_2 is presented as a transitional element from 2030 onwards.

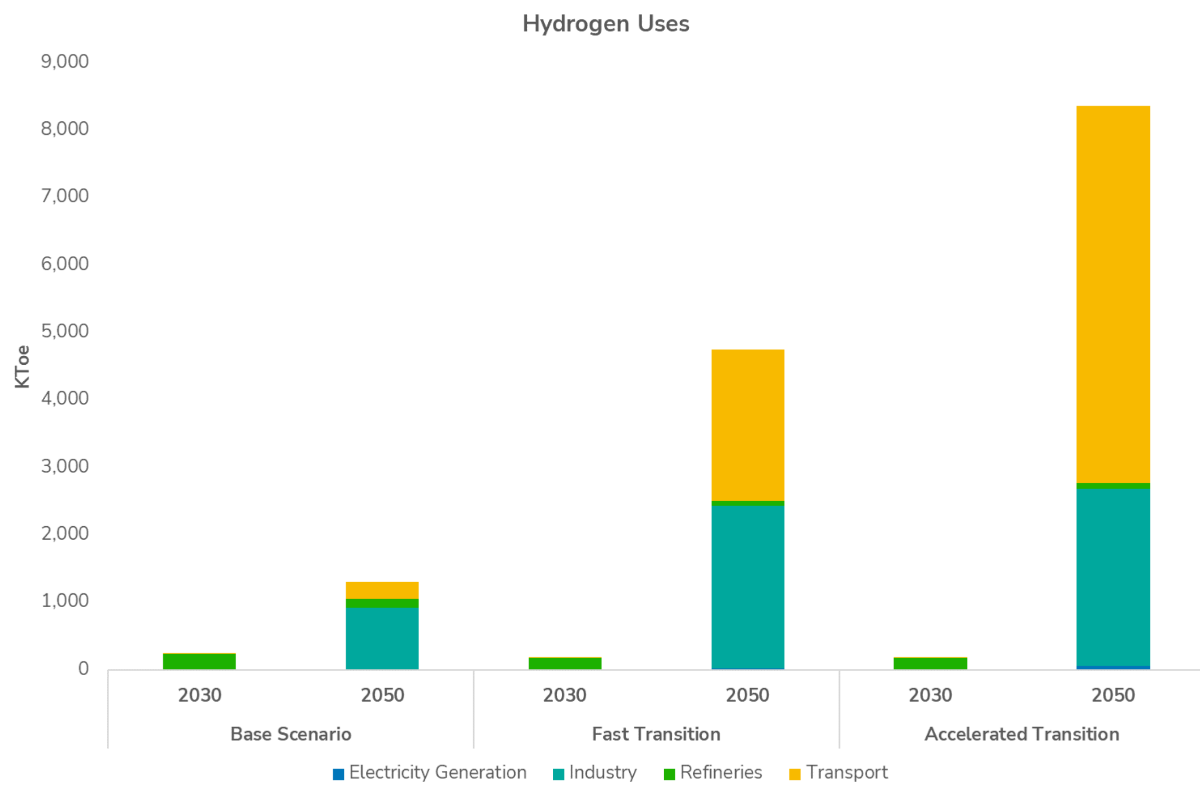


Figure 39 Hydrogen Uses by Scenario (Source : TIMES-Chile Model)

Specifically, for the industrial sector, these uses correspond to a large extent to heat production or copper production processes.

Process	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Heat Production	0%	100%	7%	0%	100%	64%	0%	100%	62%
Copper Production	0%	0%	93%	0%	0%	36%	0%	0%	38%
Engines	0%	0%	0%	0%	0%	0.2%	0%	0%	0.2%
Sector TOTAL	***N/A***	***100%***	***100%***	***N/A***	***100%***	***100%***	***N/A***	***100%***	***100%***

Table 11 Hydrogen Uses in the industrial sector (Source: TIMES-Chile Model)

At the regional level, the energy transition involves a significant hydrogenization of consumption in the Central Chile region, mainly associated with air transportation. The Norte Grande region is the other major consumer of H_2, associated with industrial processes, with a focus on large-scale copper mining.

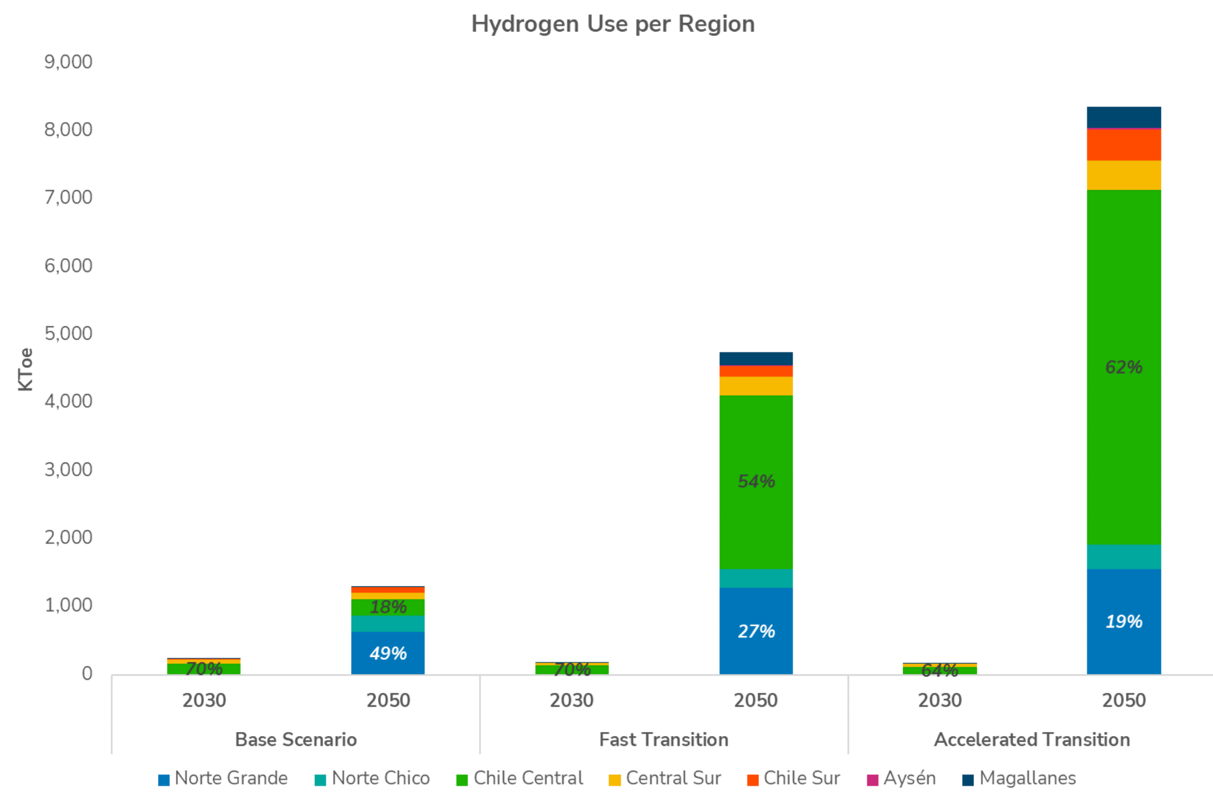


Figure 40 Hydrogen Uses by scenario and region (Source: TIMES-Chile Model)

7.3.3 Export

H_2 exports occur in two forms, the first as H_2 itself, i.e., directly the exported molecule in liquid form, and the other in the form of ammonia.

The H_2 exports are shown in Figure 41 and Figure 42. The first shows how in the base scenario, without forced export demands in the model, H_2 is not exported; in the transition scenarios, however, it is exported at the levels formulated by the National Green Hydrogen Strategy, distributed in about 30% from Magallanes and the remaining 70% from the Great North.

In the case of ammonia, this is exported in all scenarios, in the transition scenarios from different locations in the country, and in the Base Scenario, the wind potential in Magallanes is used for exports (not forced as an input variable to the model).

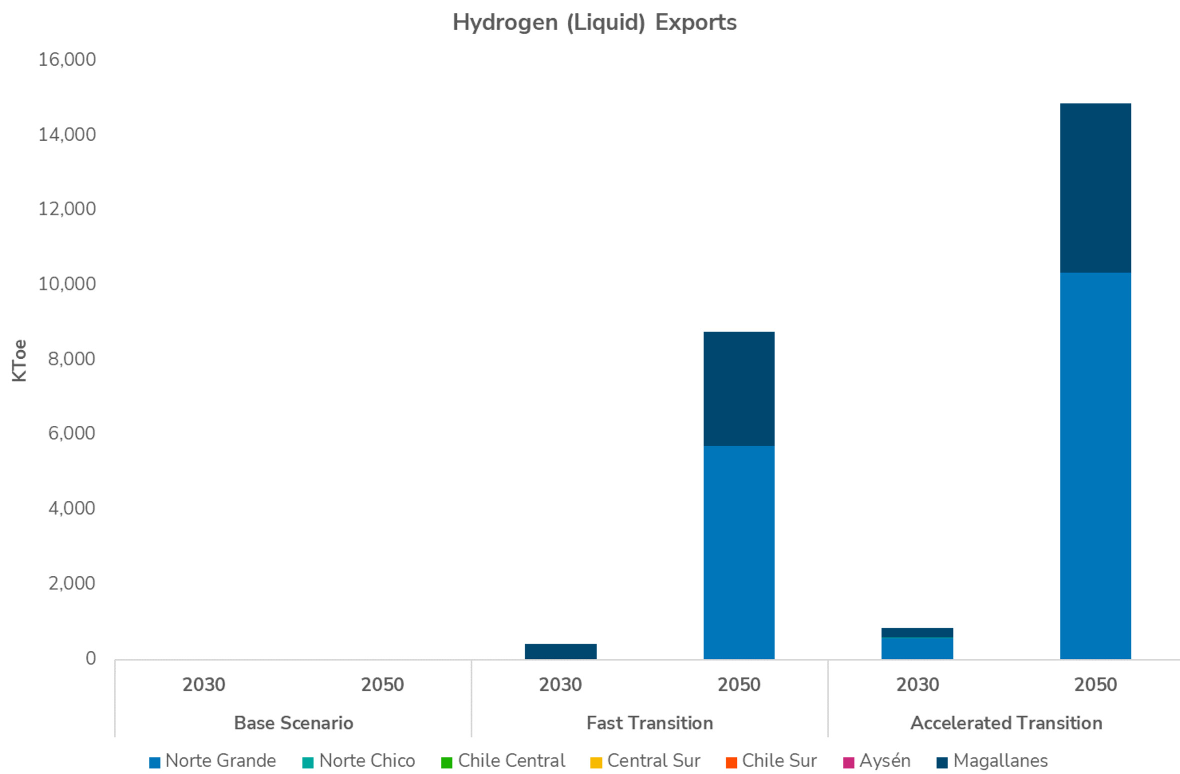


Figure 41 Green Hydrogen Exports (Source: TIMES-Chile Model)

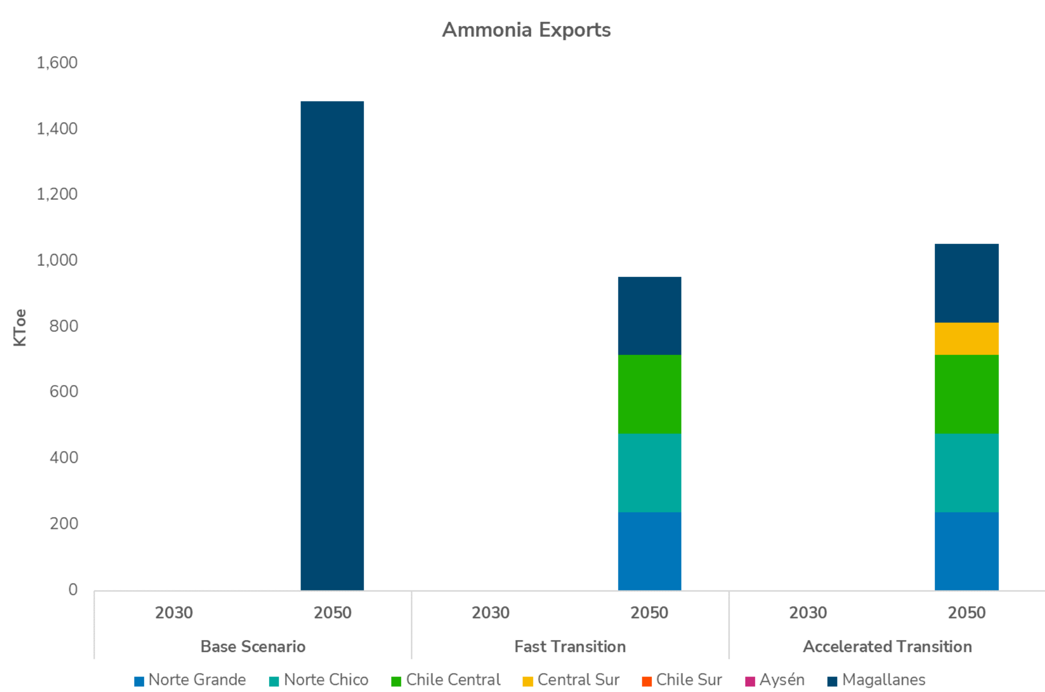


Figure 42 Exports of green ammonia (Source: TIMES-Chile Model)

7.3.4 Electricity Generation for Hydrogen Production

In electricity terms, about 285 TWh of H_2 need to be produced to meet exports and national needs in the Accelerated Transition scenario, and about 170 TWh in the Fast Transition scenario, both in 2050. These are about 6 times and 4 times more, respectively, than in the Base Scenario.

Such production is mainly concentrated in the Great North, Central Chile and Magallanes, and as shown in Figure 38, it is mostly achieved through the use of dedicated plants.

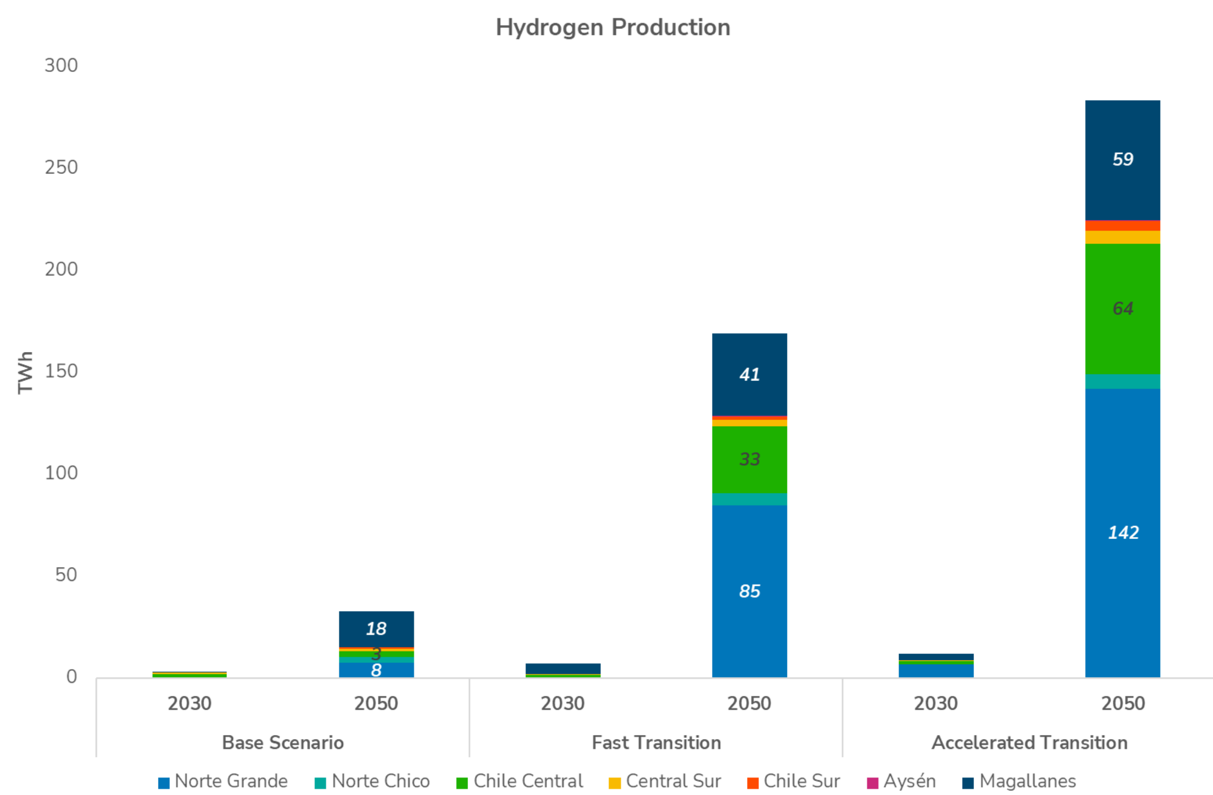


Figure 43 Hydrogen production by region (Source: TIMES-Chile Model)

These production volumes require the consumption of about 50 TWh of electrical energy in the Base Scenario, 230 TWh in the Fast Transition scenario and almost 390 TWh in the Accelerated Transition scenario, distributed almost identically to those in the previous figure. There are only small differences due to the different efficiency of the ammonia conversion and gas liquefaction processes.

7.3.5 Marginal cost of production

The following figure shows the marginal costs of GH_2 production (at the output of the electrolyzer). These are used as a reference for the selling price of GH_2 on international markets.

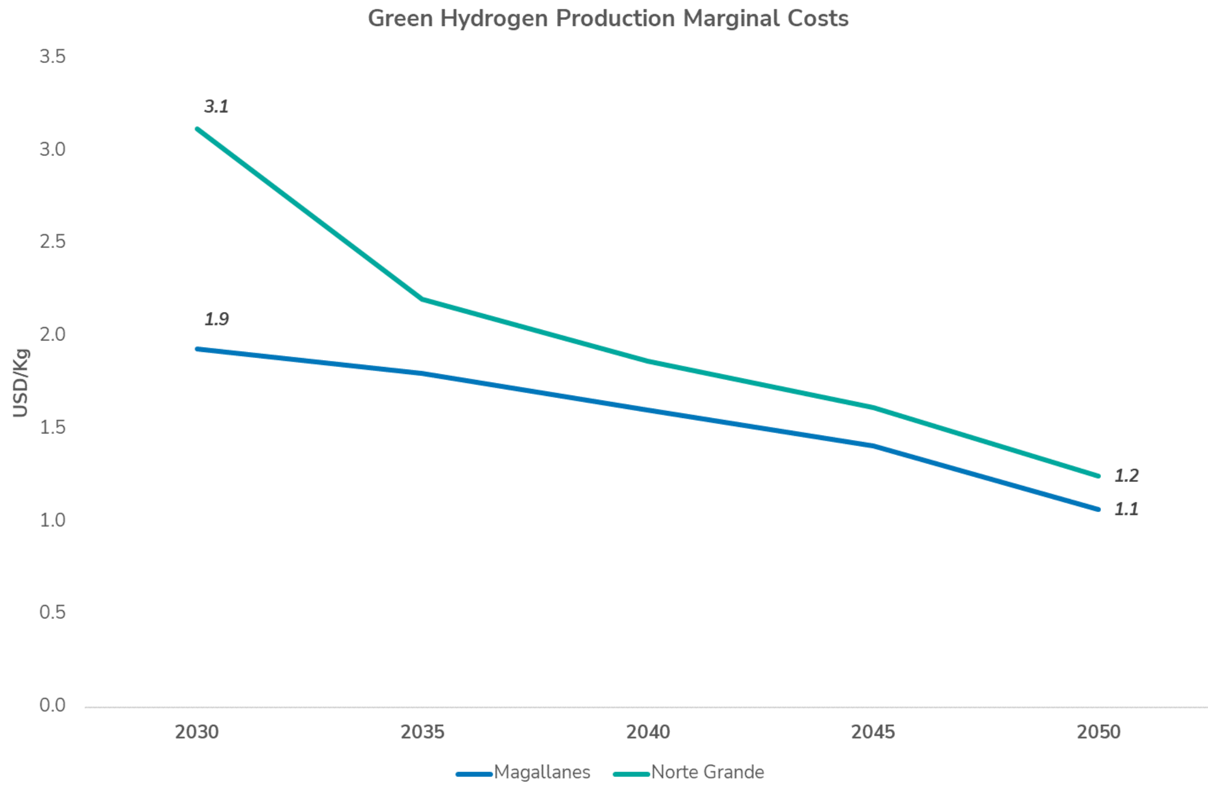


Figure 44 Marginal cost of GH_2 production in the main export regions (Source: TIMES-Chile Model)

7.3.6 Subsector Summary

The energy transition and the road to carbon neutrality cannot be traveled without the use of the H_2 vector. All scenarios, including the base scenario, make use of H_2 to limit the use of polluting fuels.

In the transition scenarios, H_2 production and consumption soar compared to the Base Scenario for two reasons. On the one hand, there are forced export demands for the product, which are in line with the national strategy; on the other hand, the transition scenarios show that in order to reach 2050 with zero net emissions, it will be necessary to hydrogenize certain demands that are difficult to electrify, such as industrial uses and air transport.

Furthermore, in relation to production costs, one of the guidelines of the National Green Hydrogen Strategy is being fulfilled, which specifies that the objective is to obtain a production cost of less than 1.5 USD/kg, which is confirmed in both production points, both in the Great

North region and in the Magallanes region, where the massive production of GH_2 is being carried out.

7.4 Industryy

The industrial sector in Chile includes all activities related to the extraction of raw materials (copper, iron ore, etc.) and other transformations into intermediate/finished products, cement manufacturing, the paper industry, as well as some other marginal productions. Overall, the sector accounts for 37.8% of total final energy consumption, 60% of electricity consumption and almost 45% of NG distributed to end users in 2019 (15% if the part used for electricity generation is taken into account); also, the industrial sector is responsible for about 21% of the total CO_2 emissions of the Chilean energy system.

The sector's energy mix is dominated by petroleum products and electricity (34% and 35% respectively), followed by biomass (18%) used almost entirely in the pulp and paper industry, and NG (8%), while coal consumption for industrial end uses is limited. Therefore, the key contribution of the industrial sector towards a decarbonized system is mainly related to the substitution of petroleum products (technologies powered by petroleum derivatives) to CO_2-free energy sources.

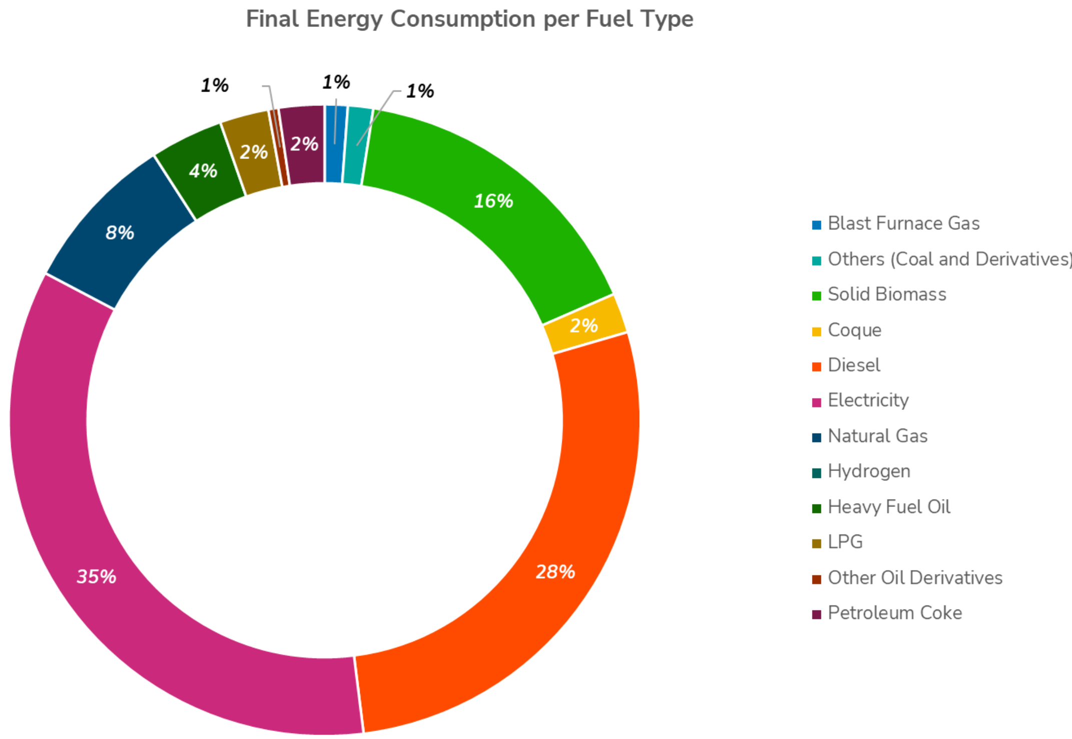


Figure 45 Final energy consumption in industry; By fuel type (Source: LTEP)

This study analyzes the following subsectors, units of measurement and sectoral chains to represent energy flows and technologies in Chile and explore their evolution over time.

Activity	Sector chain approach
Copper	copper production / copper recycling[18], copper end products
Potassium nitrate/saltpeter	motors, heat for industrial processes, other electrical uses, etc.
Iron	sintering/pellet production and raw material preparation, blast furnaces[19].
High/Low quality pulp and paper	heat production for industrial processes / furnaces, pulp production (mechanical, chemical, recycling), preparation of high/low quality paper.

[18] The "copper recycling" item includes the demands derived from all the processes required to recycle and reuse the material. In TIMES-Chile current version, this item could not be disaggregated from the "copper production" item.
[19] The "Blast Furnaces" item is assumed to be part of the iron industry.

Activity	Sector chain approach
Metallurgy/Steel	motors, industrial process heat, other electrical uses (information obtained from LTEP)
Petrochemistry	motors, industrial process heat, other electrical uses (information obtained from LTEP)
Cement	cement kilns, clinker production (dry/wet), cement production
Sugar	motors, industrial process heat, other electrical uses (information obtained from LTEP)
Fishing	motors, industrial process heat, other electrical uses (information obtained from LTEP)
Other Industries (including agribusiness and construction)	motors, industrial process heat, other electrical uses (information obtained from LTEP)
Mining (other)	motors, industrial process heat, other electrical uses (information obtained from LTEP)

Table 12 Breakdown of subsectors and sectoral chains in the industry (Source: LTEP)

A portfolio of new technology options is used to investigate the impact of substitutions on final consumption and GHG emissions, subject to predetermined demand levels over the analysis horizon. The new technologies cover identified areas of potential change, such as fuel switching and efficiency improvements, and which also reflect "key" sectoral measures, such as the phase-in of H_2-based technologies for machinery and thermal uses and the banning of less efficient electric motors.

7.4.1 Emission Trajectories

At the national level and in the Baseline Scenario, the sector's CO_2 emissions are reduced by 20% in 2050 compared to 2020. In this baseline development, the sector's contribution to the overall emission reduction targets is not sufficient to achieve the desired mitigation goals. The two alternative (target-oriented) scenarios show that the contribution of industrial activities should be significantly higher and achieve a reduction of at least 50% compared to the base year.

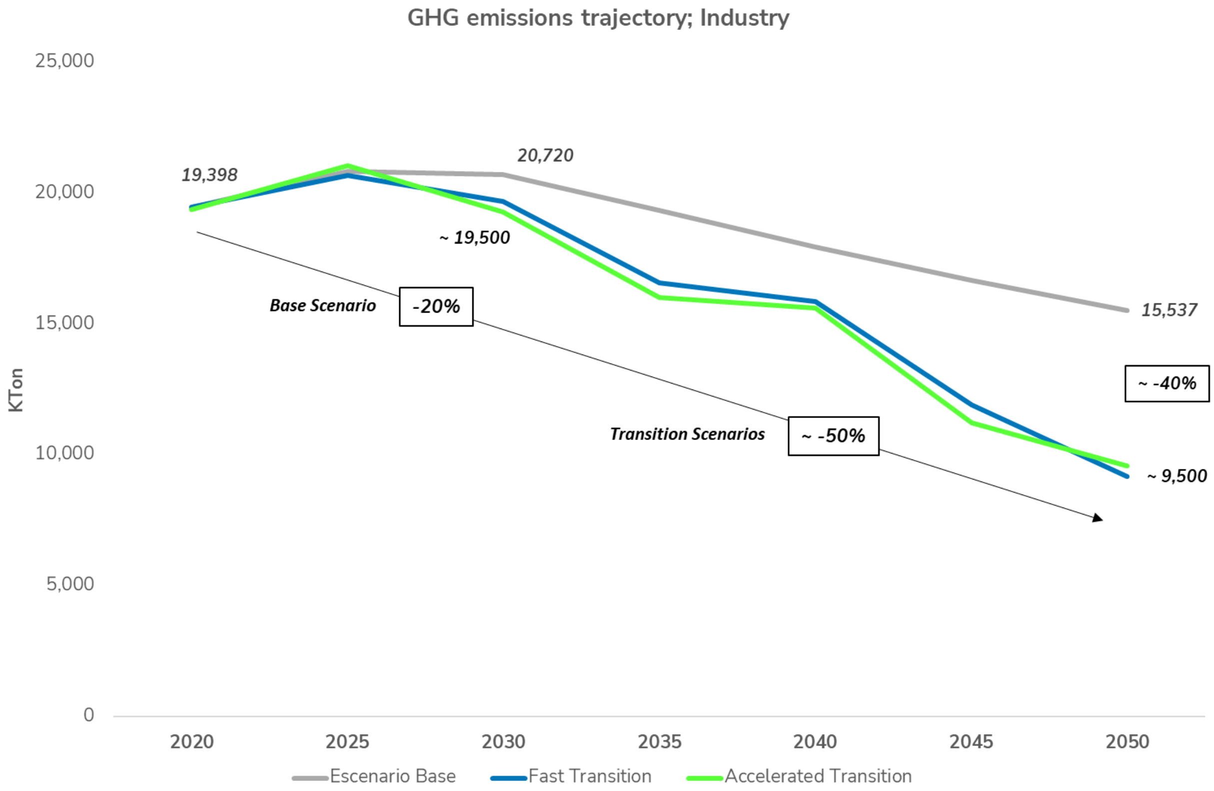


Figure 46 GHG emissions for the industrial sector (Source: TIMES-Chile Model)

The breakdown of emissions at the subsector level shows that the activities that are difficult to reduce in the long term are the heavy copper and iron industries. The marginal activities, grouped in the "other industries" group, are expected to respond best to the emissions minimization targets, with a projected reduction of more than 90% from the base year in the alternative cases.

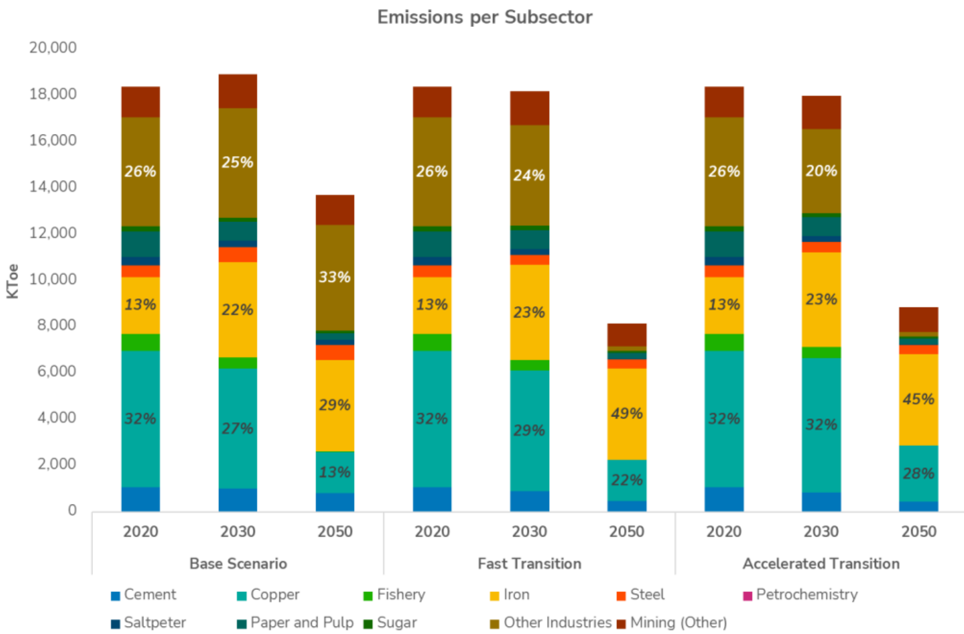


Figure 47 GHG emissions for the industrial sector (Source: TIMES-Chile Model)

The industrial activities with the highest consumption are expected to be the mining sector (copper), followed by "other industries" and paper production, as shown in the following figure.

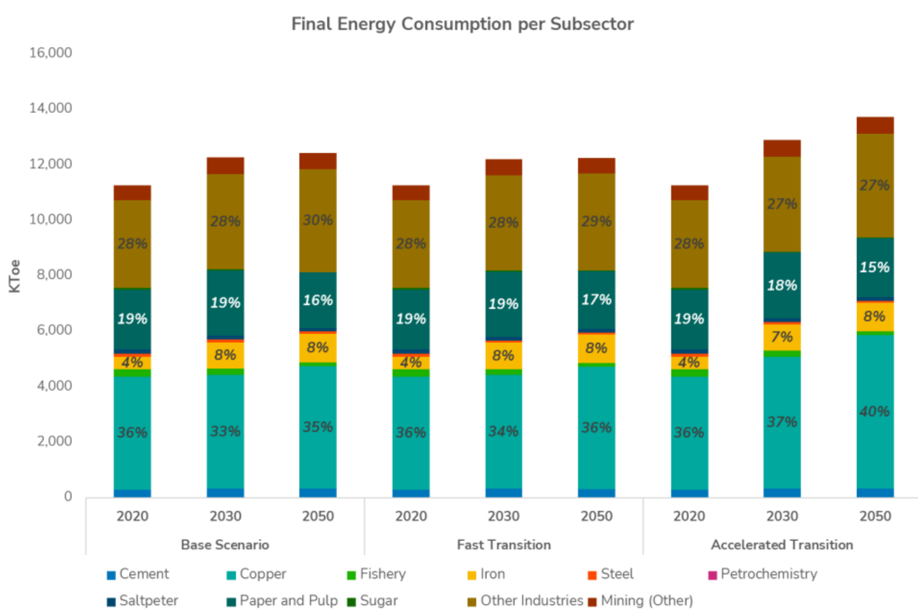


Figure 48 Final energy consumption by scenario and industry sub-sector (Source: TIMES-Chile Model)

In terms of fuels, it is estimated that the use of gas oil will gradually decrease, being replaced by electricity, which dominates final energy consumption (particularly in the alternative scenarios). H_2 is estimated to be relevant from 2035 onwards, driven by policies aiming to reduce emissions and the corresponding projects and measures related to the H_2 chain in the country. On the other hand, biomass will remain flat in its use throughout the horizon in all scenarios, following the level of activity of the paper industry.

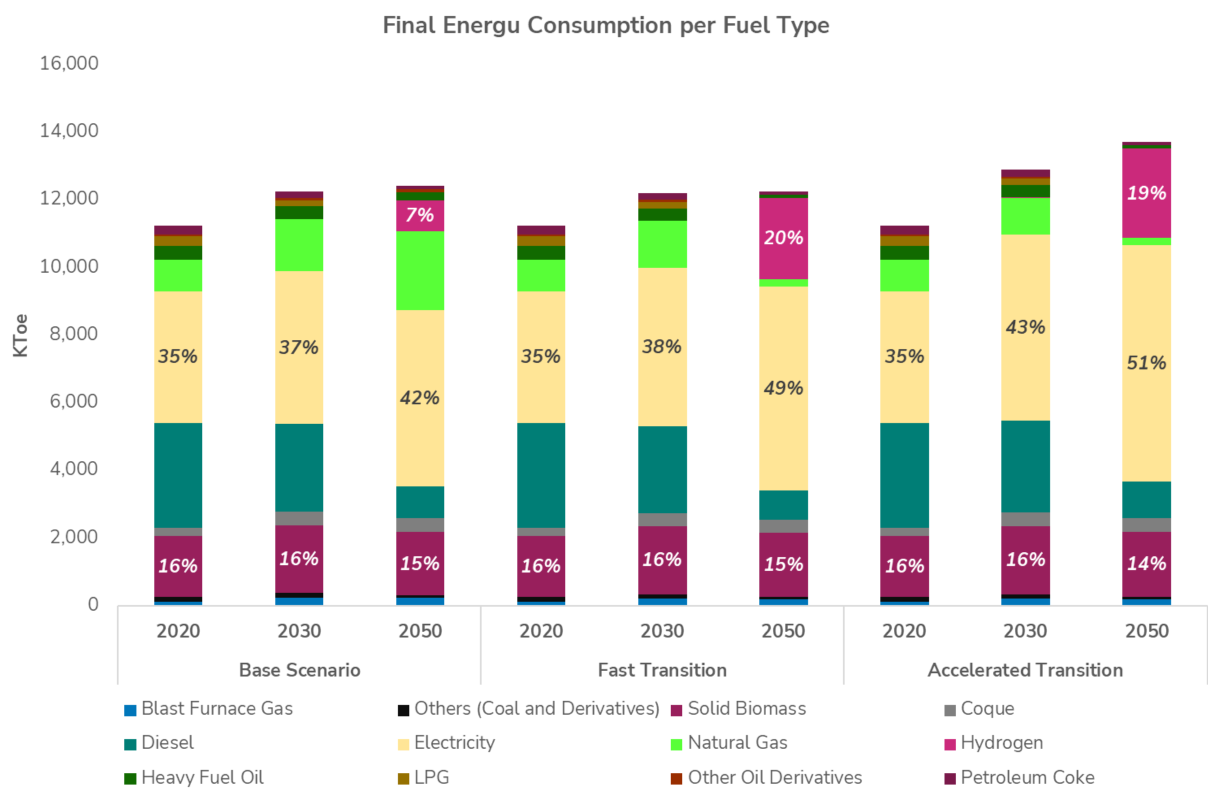


Figure 49 Final energy consumption by scenario and fuel type (Source: TIMES-Chile Model)

The location of the most energy-intensive activities also leads to different emission reduction rates at the regional level (especially in the alternative scenarios). The reduction in Aysén, Magallanes and southern Chile (with respect to the base year) is of the order of 95%; the reduction in central Chile is projected to be around 75% in the alternative scenarios in 2050, while slower reduction rates are projected for the northern and central-southern regions (where the heavy processes of the iron industry are located).

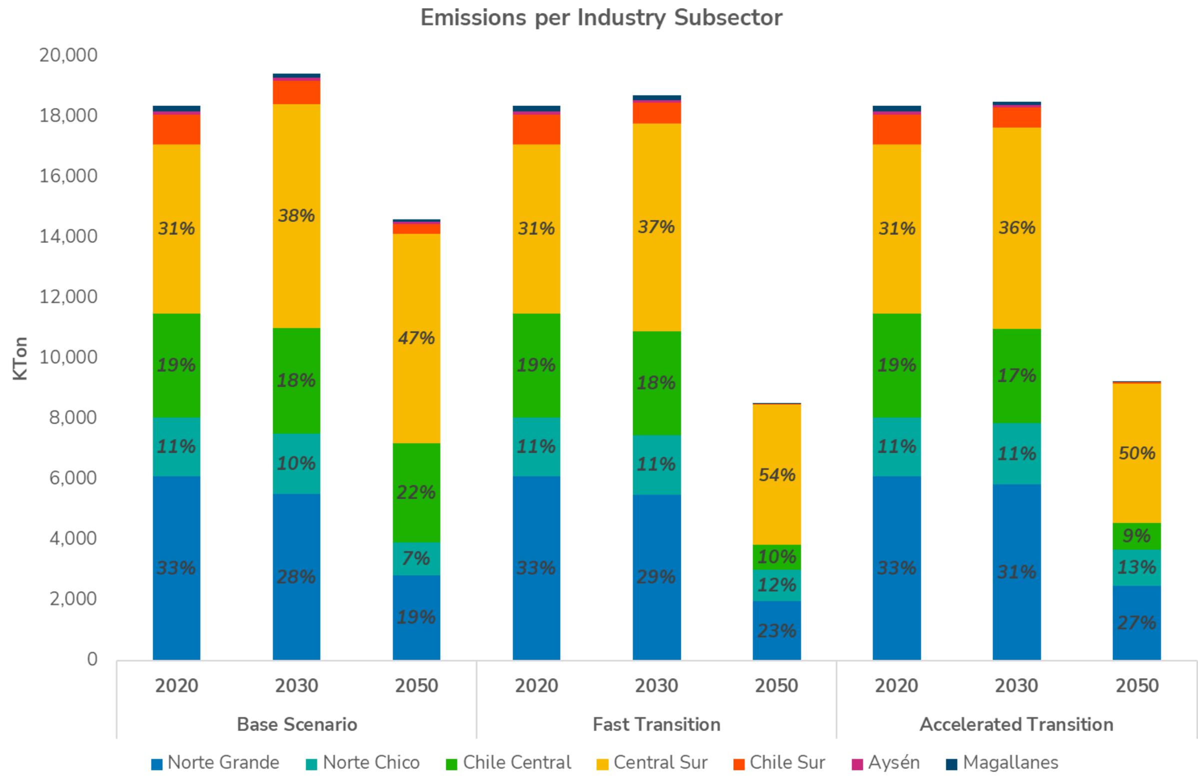


Figure 50 GHG emissions by region; Industry Sector (Source: TIMES-Chile Model)

7.4.2 Behavior of the Main Sub-sectors

Four key industrial sub-sectors have been chosen to highlight some conclusions of the scenario analysis in relation to certain indicators (electricity use, use of petroleum products -mainly oil and derivatives- and H_2 penetration), as well as the different behavior of the sub-sectors.

Sub-Sector	Use of electricity	Reduction in the use of petroleum products	Use of H_2
Copper industry	Gradual increase to almost 70% of total consumption in all cases by 2050. Medium/low space for electrification.	Significant reduction in the use of petroleum products for machinery (heavy vehicles, earthmoving equipment) in all cases (up to -70%).	High penetration of H_2 (H_2-powered machines) in the sector to replace petroleum products, reaching about 20% of total consumption in the long term.

Sub-Sector	Use of electricity	Reduction in the use of petroleum products	Use of H_2
Other industries	>50% of total consumption after 2035 in the alternative cases (constant with respect to the year 0 level of 30% in the base case).	Very high reduction in the use of petroleum products for machinery (gas oil) and heat production (LPG), up to -92% in the alternative case compared to the base year.	Very high penetration of H2 (up to 32% of total consumption in 2050), mainly for heat production.
Paper and pulp	Relatively constant with respect to the base year level (20% of total consumption) in all cases. Limited space for electrification has been identified.	Very high reduction in the use of petroleum products (fuel oil) in heat production.	Average penetration of H_2 to replace the contribution of petroleum products in heat production (up to 11% of total consumption). The role of biomass (CO_2-free) remains key and reduces the penetration space for H_2.
Cement	Electrification in the alternative case up to 65% of total consumption; limited electrification in the base case (up to 15% in 2050). Large potential for electrification (electric furnaces - rotodynamic heaters) has been identified.	Very high reduction of petroleum products (petroleum coke) used in the furnaces.	There is no H_2 penetration in the subsector. Based on available data, process electrification appears to be more promising for mitigating emissions from the activity in the alternative scenarios.

Table 13 Behavior of the main industry sub-sectors (Source: Prepared by the authors)

7.4.3 Electrification KPIs at national and regional level

Table 14 shows the electrification ratios for each industry sub-sector. It can be seen that copper mining transitions to electrification in a very relevant way in all scenarios, as well as the fishing, petrochemical and steel sectors.

Sub-Sector	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Sugar	3%	4%	32%	3%	4%	23%	3%	4%	42%
Cement	7%	16%	15%	7%	26%	57%	7%	34%	66%
Copper	53%	58%	67%	53%	58%	67%	53%	60%	67%
Iron	10%	24%	31%	10%	24%	31%	10%	24%	31%
Mining (Other)	17%	18%	23%	17%	18%	23%	17%	21%	23%
Other Industries	33%	32%	30%	33%	36%	50%	33%	45%	50%
Paper and pulp	21%	19%	18%	21%	20%	21%	21%	20%	22%
Fishing	6%	30%	95%	6%	31%	94%	6%	31%	94%
Petrochemistry	65%	72%	81%	65%	76%	74%	65%	74%	74%
Saltpeter	14%	35%	56%	14%	35%	48%	14%	36%	47%
Steel Industry	61%	52%	63%	61%	75%	78%	61%	75%	78%
Sector TOTAL	***35%***	***37%***	***42%***	***35%***	***38%***	***49%***	***35%***	***43%***	***51%***

Table 14 Electrification of the industrial sector by subsector (Source: TIMES-Chile Model)

At the regional level, the Great North is the region that most electrifies its industrial consumption, driven by the copper mining industry; at the other extreme, the central-south zone has a low electrification since the main fuel source is biomass from the paper industry.

Region	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Aysén	6%	18%	43%	6%	26%	71%	6%	39%	71%
Southern Center	22%	20%	20%	22%	23%	36%	22%	26%	38%
Central Chile	44%	42%	39%	44%	43%	46%	44%	51%	47%
Southern Chile	25%	34%	46%	25%	37%	57%	25%	37%	58%
Magallanes	10%	23%	44%	10%	35%	70%	10%	35%	74%
Small North	44%	54%	65%	44%	55%	62%	44%	57%	63%
Great North	42%	47%	57%	42%	48%	58%	42%	51%	59%
TOTAL Sector	***35%***	***37%***	***42%***	***35%***	***38%***	***49%***	***35%***	***43%***	***51%***

Table 15 Electrification of the industrial sector by region (Source: TIMES-Chile Model)

7.4.4 Hydrogenation KPIs at the national and regional levels

In the Base Scenario, only the copper industry has to hydrogenize its consumption; the rest of the sectors must do so in the transition scenarios if the decarbonization targets are to be met.

Sub-Sector	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Sugar	0%	0%	0%	0%	0%	77%	0%	0%	58%

Sub-Sector	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Cement	0%	0%	0%	0%	0%	0%	0%	0%	0%
Copper	0%	0%	20%	0%	0%	20%	0%	0%	18%
Iron	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mining (Other)	0%	0%	0%	0%	0%	19%	0%	0%	19%
Other Industries	0%	0%	1%	0%	0%	32%	0%	0%	32%
Paper and pulp	0%	0%	1%	0%	0%	11%	0%	0%	11%
Fishing	0%	0%	0%	0%	0%	6%	0%	0%	6%
Petrochemistry	0%	0%	0%	0%	0%	26%	0%	0%	26%
Saltpeter	0%	0%	0%	0%	0%	44%	0%	0%	45%
Steel Industry	0%	0%	0%	0%	0%	22%	0%	0%	22%
Sector TOTAL	***0%***	***0%***	***7%***	***0%***	***0%***	***20%***	***0%***	***0%***	***19%***

Table 16 Electrification of the industrial sector by sub-sector (Source: TIMES-Chile Model)

The regional analysis reveals that, in order to achieve the decarbonization objectives, very important contributions are needed in Central Chile, and of relative importance in the rest of the regions.

Region	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Aysén	0%	0%	2%	0%	0%	24%	0%	0%	24%
Southern Center	0%	0%	1%	0%	0%	6%	0%	0%	6%
Central Chile	0%	0%	5%	0%	0%	41%	0%	0%	40%
Southern Chile	0%	0%	3%	0%	0%	4%	0%	0%	4%
Magallanes	0%	0%	0%	0%	0%	28%	0%	10%	24%
Small North	0%	0%	12%	0%	0%	17%	0%	0%	16%
Great North	0%	0%	16%	0%	0%	24%	0%	0%	23%
Sector TOTAL	***0%***	***0%***	***7%***	***0%***	***0%***	***20%***	***0%***	***0%***	***19%***

Table 17 Electrification of the industrial sector by region (Source: TIMES-Chile Model)

The combination of electrification and hydrogenization processes, added to biomass consumption, means that in the transition scenarios, 85% of industrial consumption will come from clean sources. Without them, 20% more than in the base scenario.

7.4.5 Industry Subsector Summary

The industry sector is key to achieving the decarbonization objectives by 2050, for which the following points are noted:

a) In order to achieve carbon neutrality, significant contributions are required from the industrial sector, with 85% of its consumption coming from non-emitting sources.

b) 50% of consumption is electrified, and 20% is hydrogenized. Efficiency improvements in the processes cause final consumption to grow moderately compared to economic growth.
c) By subsector, the copper mining sector transitions in all scenarios to clean technologies, with the rest of the sectors needing to increase their contributions in the transition scenarios if they are to reach the reduction target by 2050.
d) In terms of energy forms, the different regional dynamics are driven by the electrification rate (which in turn reflects the location of renewable energies and their exploitation) and by the location of H_2 production (driven by projects and export targets) and heavy/light industries.
e) The "Other Industries" item represents a large part of industrial consumption (25%) as a result of the sum of many different activities, which makes it difficult to isolate specific policies for them.
f) Agriculture is not explicitly differentiated in energy statistics; its energy consumption is grouped with "Other Industries". Therefore, specific efficiency improvements and potential changes are hidden in the generic representation of that sub-sector.
g) A better "inventory" of existing processes and technologies in the industrial sub-sectors (and country specific characteristics, barriers, maturity of best available options) would greatly increase the accuracy of the quantitative analysis.
h) Recycling (and other elements of the circular economy) can be considered to increase the possibility of reducing energy uses. As a hypothetical example, copper recycling is depicted.

7.5 Residential, Public and Commercial Use

The residential, public and commercial sectors are grouped into a single section due to their lower impact on the total results (emissions trajectory, final energy consumption, etc.). In particular, the service sector, according to the national energy balance, includes public health and commercial activities. In the framework of this study (following the LTEP approach), it is divided into two categories only: "public" and "commercial".

Overall, the sector accounts for about 6% of total final energy consumption, 16% of electricity consumption and almost 8% of natural gas distributed for end uses in 2019, and is responsible for a marginal share of the total CO_2 emissions of the Chilean energy system (about 3%).

The sector's energy mix is dominated by electricity (54% of the sector's final consumption), followed by petroleum products (36%) and natural gas (9%), while coal and biomass consumption are almost zero. Therefore, the key contribution of the utilities sector towards a decarbonized system is mainly related to the possibility or opportunity to replace petroleum products (oil-fired technologies) with non-CO_2 forms of energy, and (indirectly) to improving the efficiency of electrical appliances (a large part of the sector's consumption).

In this analysis, the following end uses are represented: building heating and cooling, water heating, cooking, lighting, other appliances (aggregates) for both public and private activities, and street lighting. A comprehensive repository of new technology options has been organized to explore fuel replacement options and energy efficiency improvements, as well as the impacts of dedicated policies, in the face of high growth in demand from the sectors[20].

7.5.1 Emission Trajectories

The combined emissions trajectory of the sectors is shown in the following figure. It shows how in the three scenarios the paths are very similar, with an increase with regards to the base year of approximately 37%, due to the strong increase in energy demands and a reduction between the Base Scenario and the transition scenarios for the year 2050 of 3%.

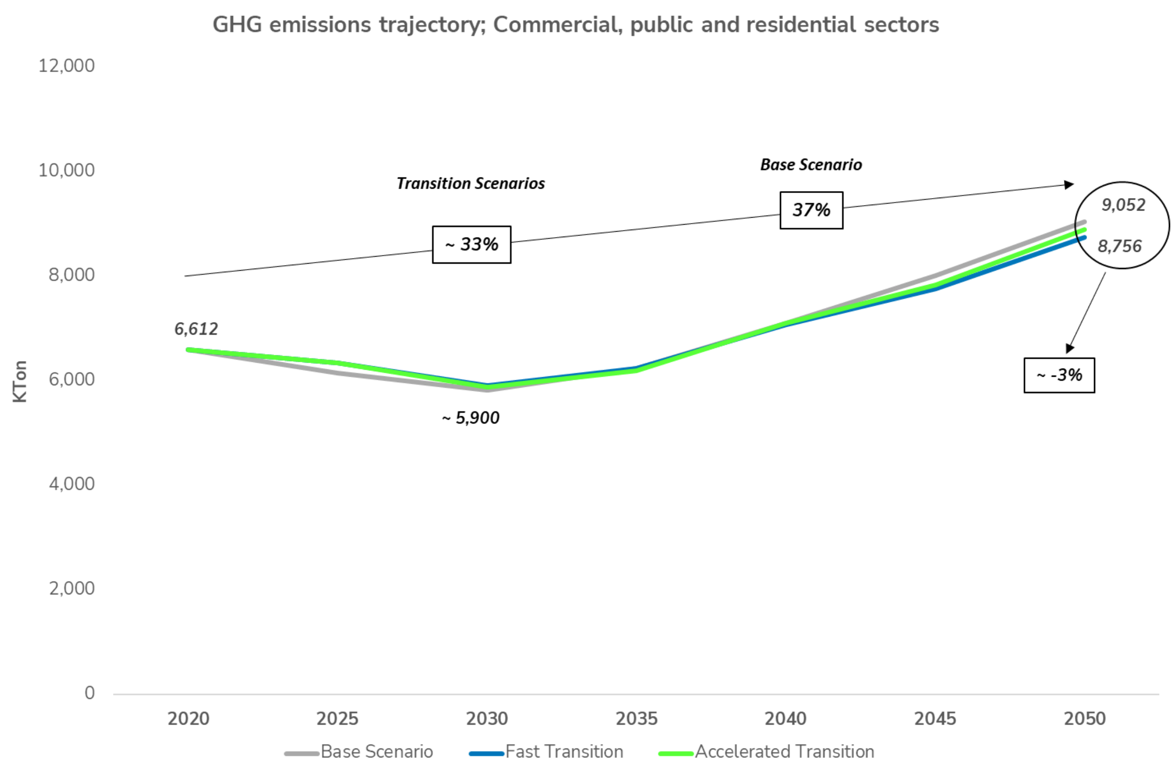


Figure 51 GHG emissions for residential, public and commercial sectors (Source: TIMES-Chile Model)

[20] Base year demand values (12.44 million square meters for private activities, 17.89 million square meters for public activities, 0.4 million street lighting points) and projected values (scenario specific) are obtained from the LTEP.

Specifically, for the residential sector, greenhouse gas emissions from energy use are currently quite low (compared to emissions from the electricity sector, transport and industry). With the measures considered in this set of scenarios, the main reduction in emissions is observed during the period from 2020 to 2030, and then stabilizes around the same levels.

For the services sector, at the national level, emissions are expected to maintain an increasing trend, similar to all scenarios (the transition scenarios show only a limited emission reduction of 3% compared to the baseline scenario for 2050), due to a partial electrification of thermal end-uses. This is because neither sector-specific actions (only minor measures related to building retrofitting have been proposed and implemented in the simulation), nor the CO_2 cap at the national level (acting mainly on other sectors more sensitive to changes, such as the electricity sector, to meet the overall targets) are sufficient to "decouple" emissions from demand growth.

7.5.2 Demand Growth

The previous emissions trajectory is related to the fact that LPG and natural gas consumption levels remain approximately the same after 2030 (Figure 52) in the residential sector, while any increase in total energy demand is covered by electricity. The total level of final energy consumption also stabilizes after 2030 in the transition scenarios, although the demand for services continues to increase, as the population and its income level increase. This is attributed to the introduction of more efficient technologies in final energy consumption in the residential segment.

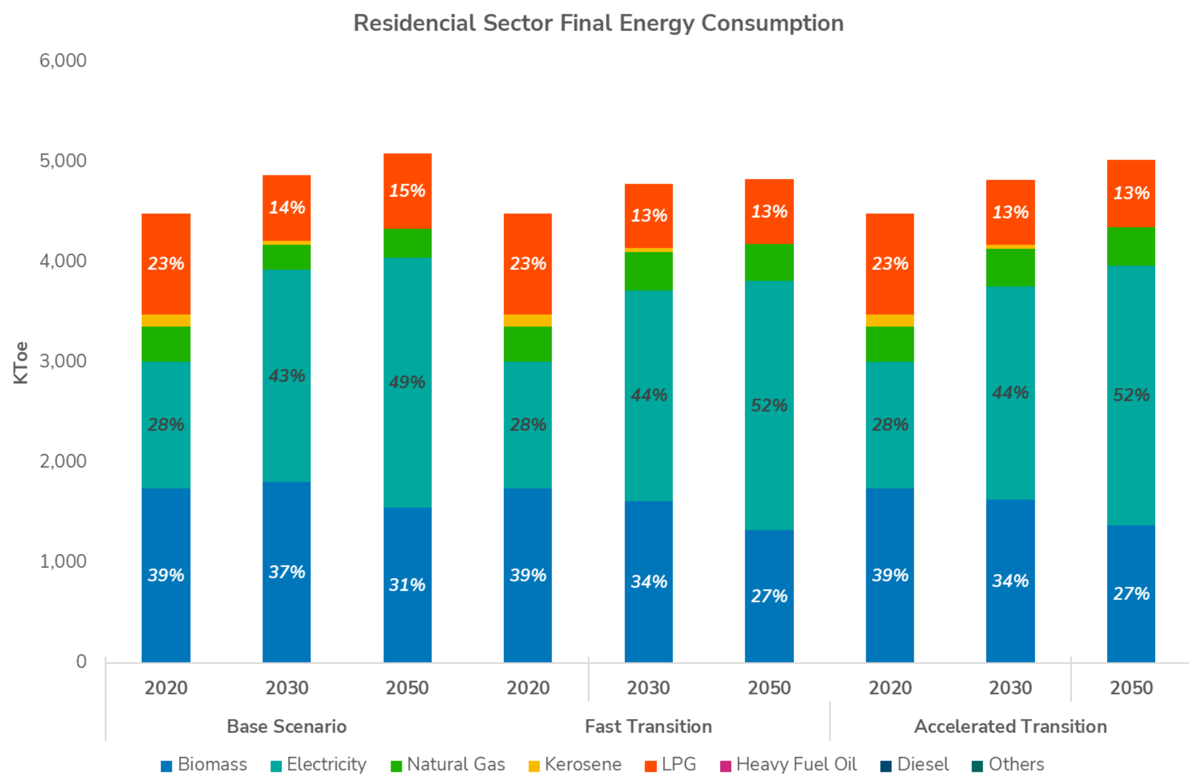


Figure 52 Final energy consumption in the residential sector (Source: TIMES-Chile Model)

In the service sector, no specific factor is activated for the substitution of oil products by other cleaner forms of energy (natural gas, electricity, H_2, renewable energies) for heating, cooking and other uses. The impact of sector-specific measures (e.g., regulatory measures and technology standards) is still largely unexplored. Total final consumption is expected to double by 2050 with small differences between scenarios.

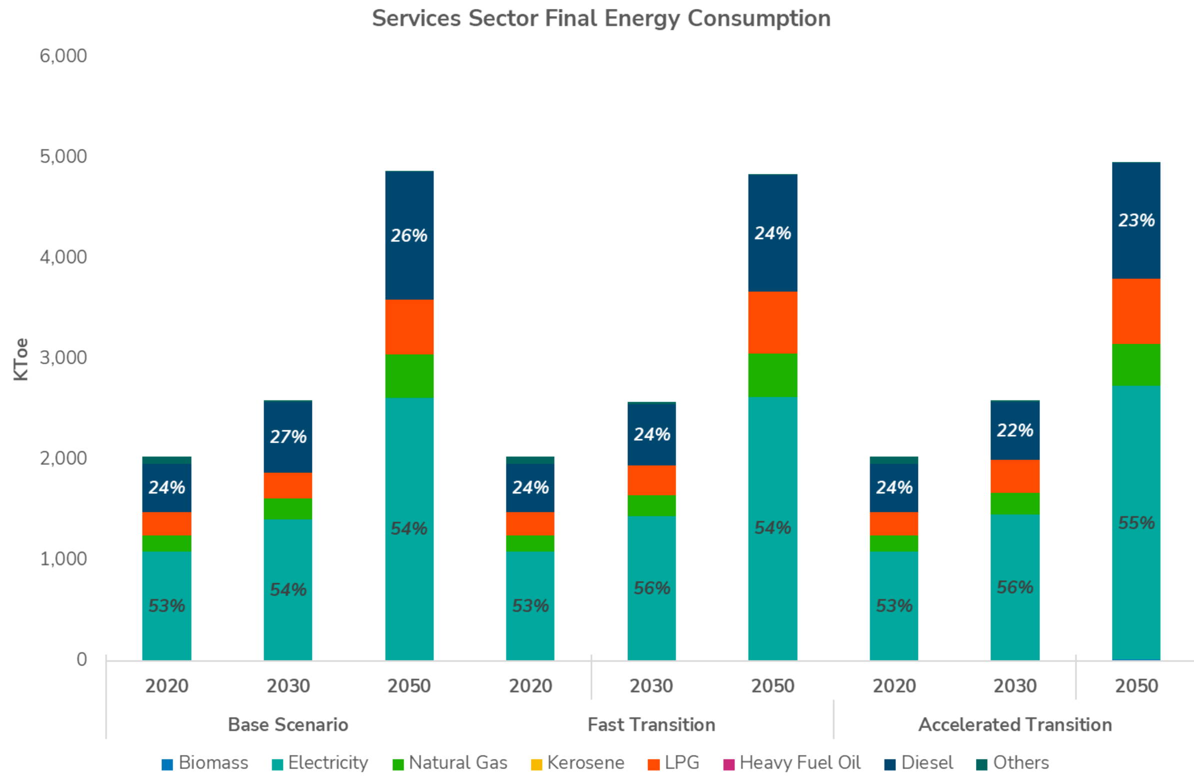


Figure 53 Final energy consumption in the services sector (Source: TIMES-Chile Model)

The only exception to this trend is in the projection of street lighting consumption (a component of the above), where new technological standards (at least 30% more efficient) and the replacement of existing luminaires with more efficient options lead to a reduction in electricity use for all scenarios analyzed (-30% in 2050 compared to the base year).

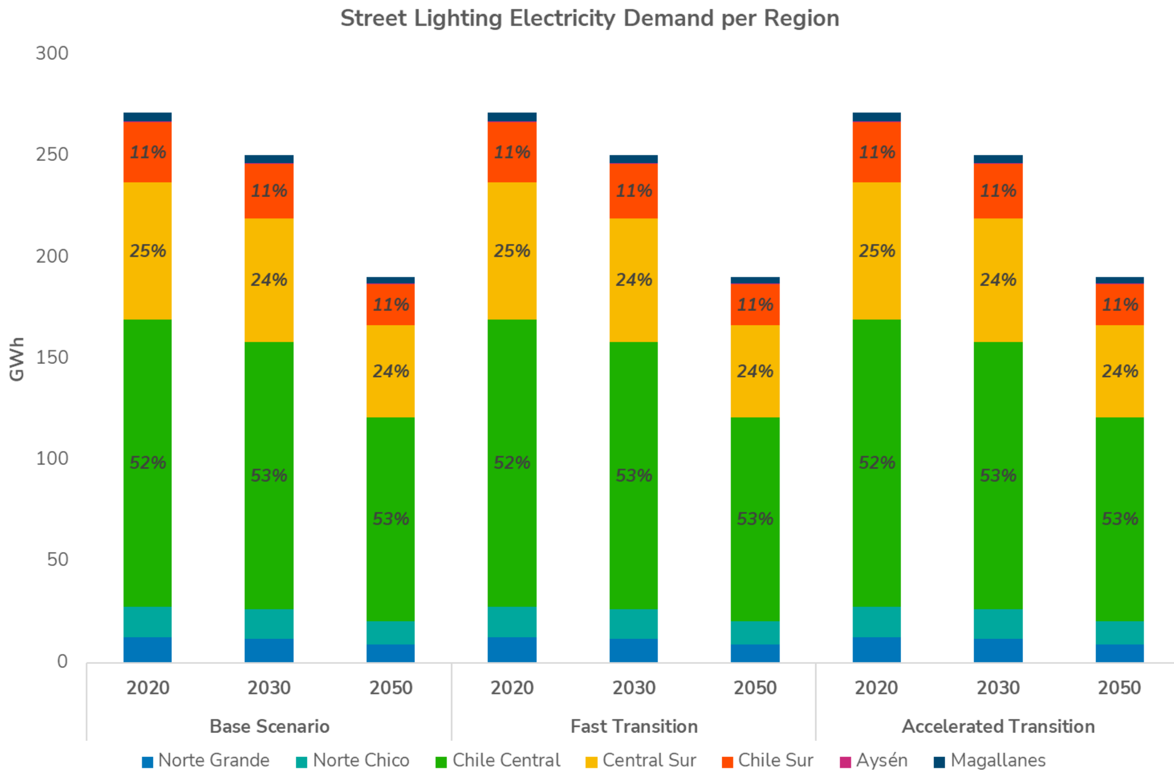


Figure 54 Regional electricity consumption (public lighting) (Source: TIMES-Chile Model)

In the residential sector, electricity consumption by region is projected to increase in all regions at an increasing rate through 2035 (CAGR of 4% at the national level). Electricity consumption in the residential sector in Central Chile covers 57% of the total and is projected to increase to 70% of total residential electricity consumption by 2050.

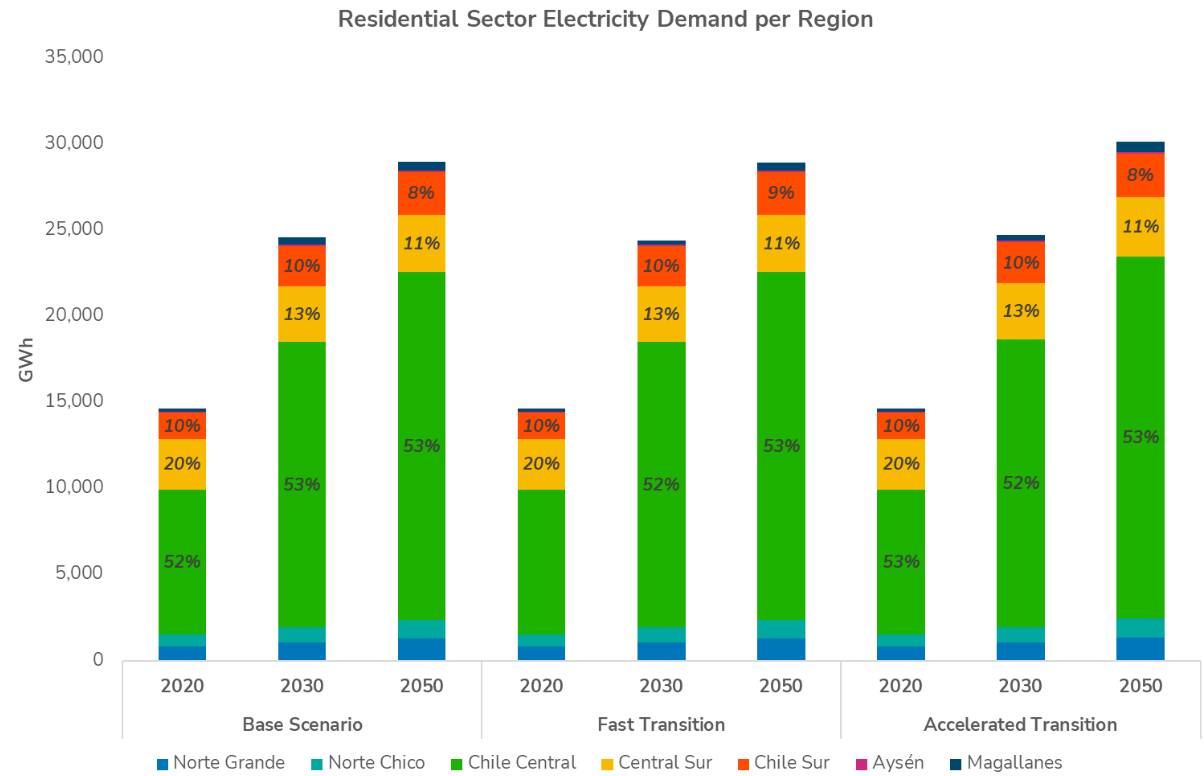


Figure 55 Electricity consumption by region in the residential sector (Source: TIMES-Chile Model)

Consumption for commercial (business-oriented) activities is projected to grow by almost a factor of 3 by 2050 (compared to the base year), particularly in regions such as Central Chile (where the vast majority of activities are located, accounting for almost 75% of the electricity used in the sector in 2050), Aysén and Magallanes (which are the areas with the greatest potential for growth compared to the rest of the country).

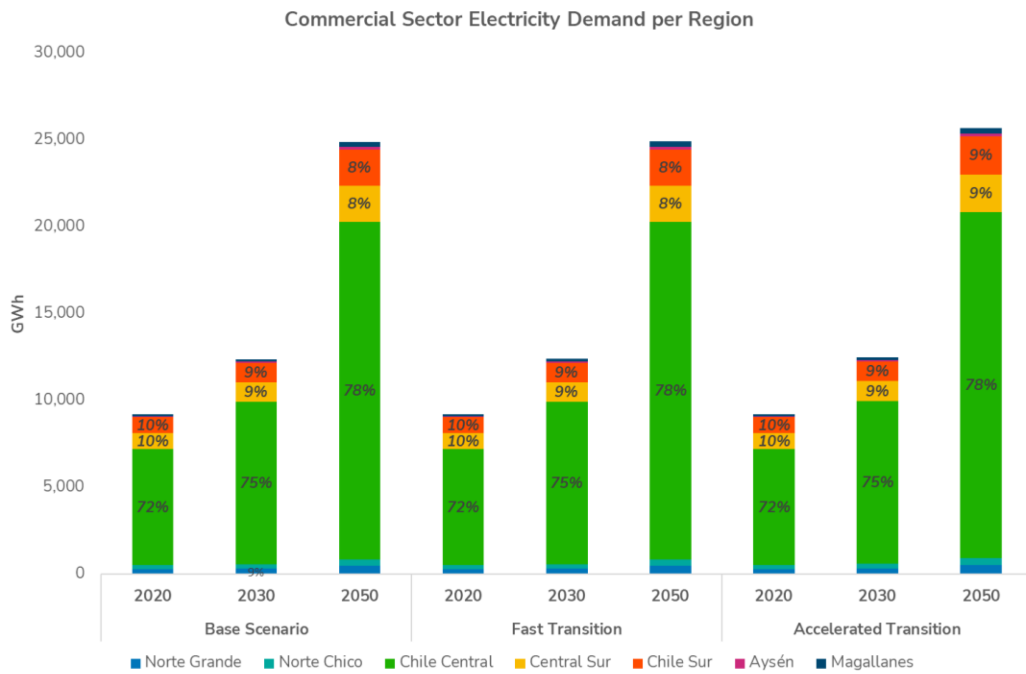


Figure 56 Electricity Consumption by Region in the Commercial Sector (Source: TIMES-Chile Model)

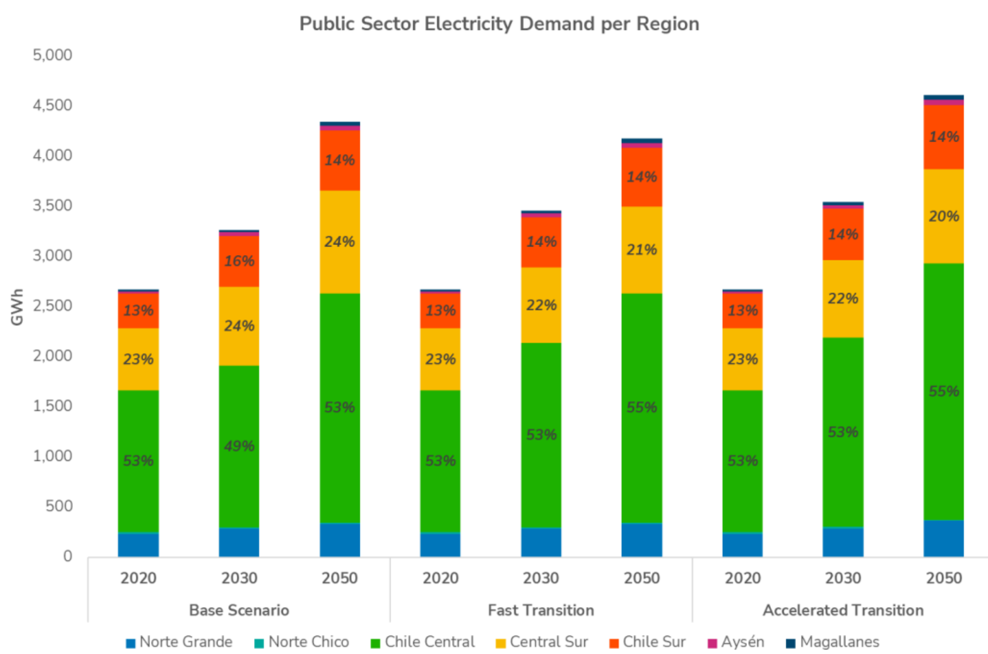


Figure 57 Electricity consumption by region in the public sector (Source: TIMES-Chile Model)

7.5.3 Electrification KPIs at the national and regional levels

The electrification of the residential and service sectors is shown in the following table.

Sector	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Residential	34%	37%	38%	34%	38%	40%	34%	38%	40%
Commercial and Public Sectors	50%	49%	49%	52%	49%	48%	51%	50%	50%

Table 18 Electrification rates in the residential and service sectors (Source: TIMES-Chile Model)

It can be seen that it is very similar in all scenarios and years, and is close to 40% of consumption for the residential sector and 50% for the service sector.

The following tables show the regional level in detail. In both sectors, the Central Chile region leads the electrification process since the applications to be replaced are based on inefficient fossil sources. In the rest of the sectors, biomass, which does not emit, is not electrified, although its efficiency is improved by switching to dry biomass.

Region	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Aysén	52%	64%	69%	52%	64%	69%	52%	64%	69%
Southern Center	48%	59%	64%	48%	59%	64%	48%	59%	64%
Central Chile	58%	79%	87%	58%	80%	85%	58%	80%	85%
Southern Chile	31%	32%	35%	31%	35%	41%	31%	35%	40%
Magallanes	11%	16%	18%	11%	17%	21%	11%	17%	21%
Small North	8%	9%	9%	8%	9%	11%	8%	9%	11%
Great North	6%	16%	24%	6%	10%	22%	6%	14%	25%
Sector TOTAL	34%	37%	38%	34%	38%	40%	34%	38%	40%

Table 19 Electrification of the residential sector by region (Source: TIMES-Chile Model)

Region	Base Scenario			Fast Transition			Accelerated Transition		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Aysén	43%	41%	31%	38%	33%	43%	31%	43%	36%
Southern Center	35%	27%	21%	25%	22%	31%	21%	35%	25%
Central Chile	63%	63%	65%	63%	65%	65%	65%	63%	65%
Southern Chile	41%	39%	33%	37%	35%	40%	33%	41%	36%
Magallanes	47%	63%	63%	64%	64%	57%	63%	48%	65%
Small North	33%	43%	43%	43%	43%	39%	43%	33%	44%
Great North	12%	13%	14%	13%	14%	13%	14%	12%	15%

Region	Base Scenario			Fast Transition			Accelerated Transition		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
Sector TOTAL	50%	49%	49%	52%	49%	48%	51%	50%	50%

Table 20 Electrification of the service sector by region (Source: TIMES-Chile Model)

7.5.4 Diesel and Biomass Use

For the residential sector, in the model, dwellings are separated into single-family houses and apartments, in order to model the different energy consumption behavior of these two categories. The total energy consumption by use and type of housing can be seen in Figure 58 and Figure 59. Energy consumption in single-family dwellings is dominated by heating, while in the case of apartments the dominant consumption is due to appliances (which is electricity only).

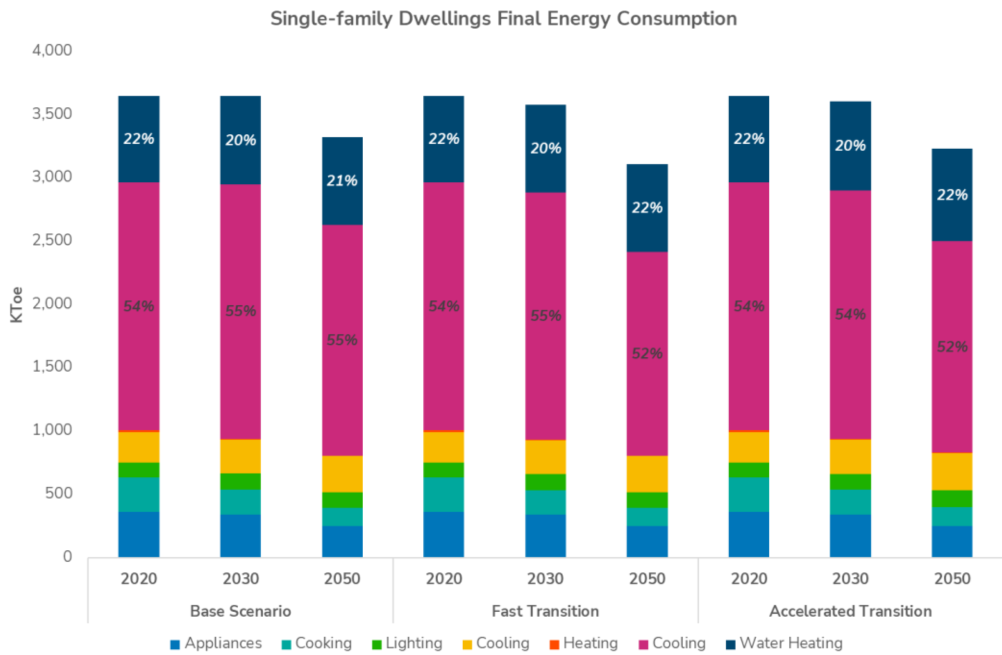


Figure 58 Final energy consumption by use in single-family dwellings (Source: TIMES-Chile Model)

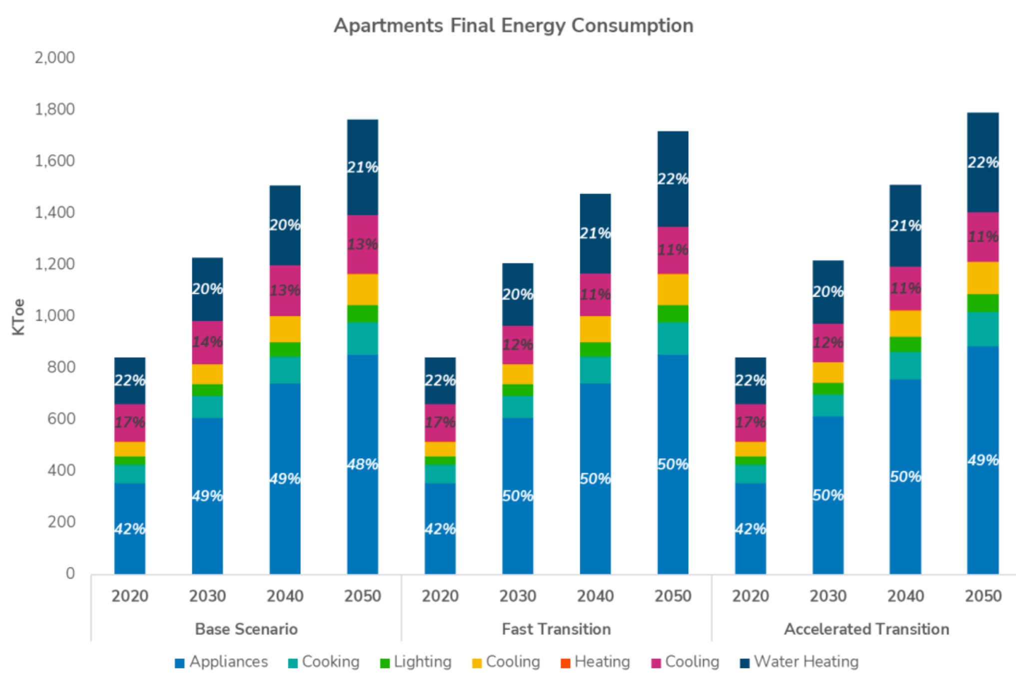


Figure 59 Final energy consumption by use in apartments (Source: TIMES-Chile Model)

The breakdown of energy consumption in the residential sector into regions (Figure 60) reflects the geographic distribution of the population and also the specific climatic conditions of each area. Notably, the use of biomass varies considerably between regions, as does the use of natural gas. The largest amount of energy is consumed in the regions with the largest population, namely Central Chile, and its southern neighboring regions. In all scenarios and all regions, biomass use is fully replaced by dry biomass gradually until 2040.

The energy consumption of the service sector (Figure 61), on the other hand, also reflects the distribution of population and public services in the regions, as well as the expected growth of economic activities at the regional level. The energy mix by region is expected to remain relatively constant over the time horizon with limited substitution between energy forms, thus maintaining the predominance of fossil fuel-based thermal services in regions such as Magallanes and Small North, and on the other hand the dominance of purely electrical services (advanced tertiary) in regions such as Central Chile.

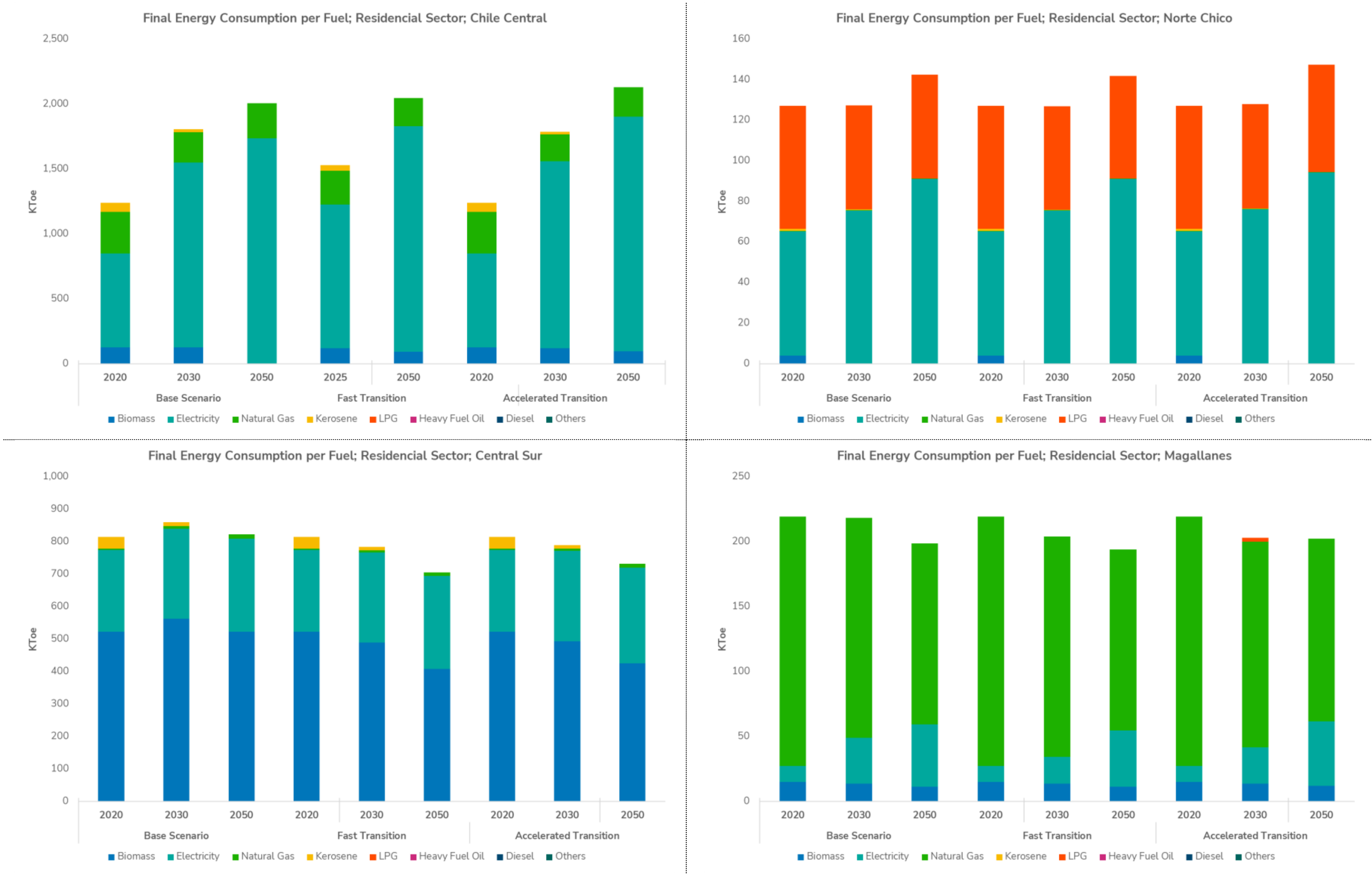


Figure 60 Final energy consumption of the residential sector for selected regions (Source: TIMES-Chile Model)

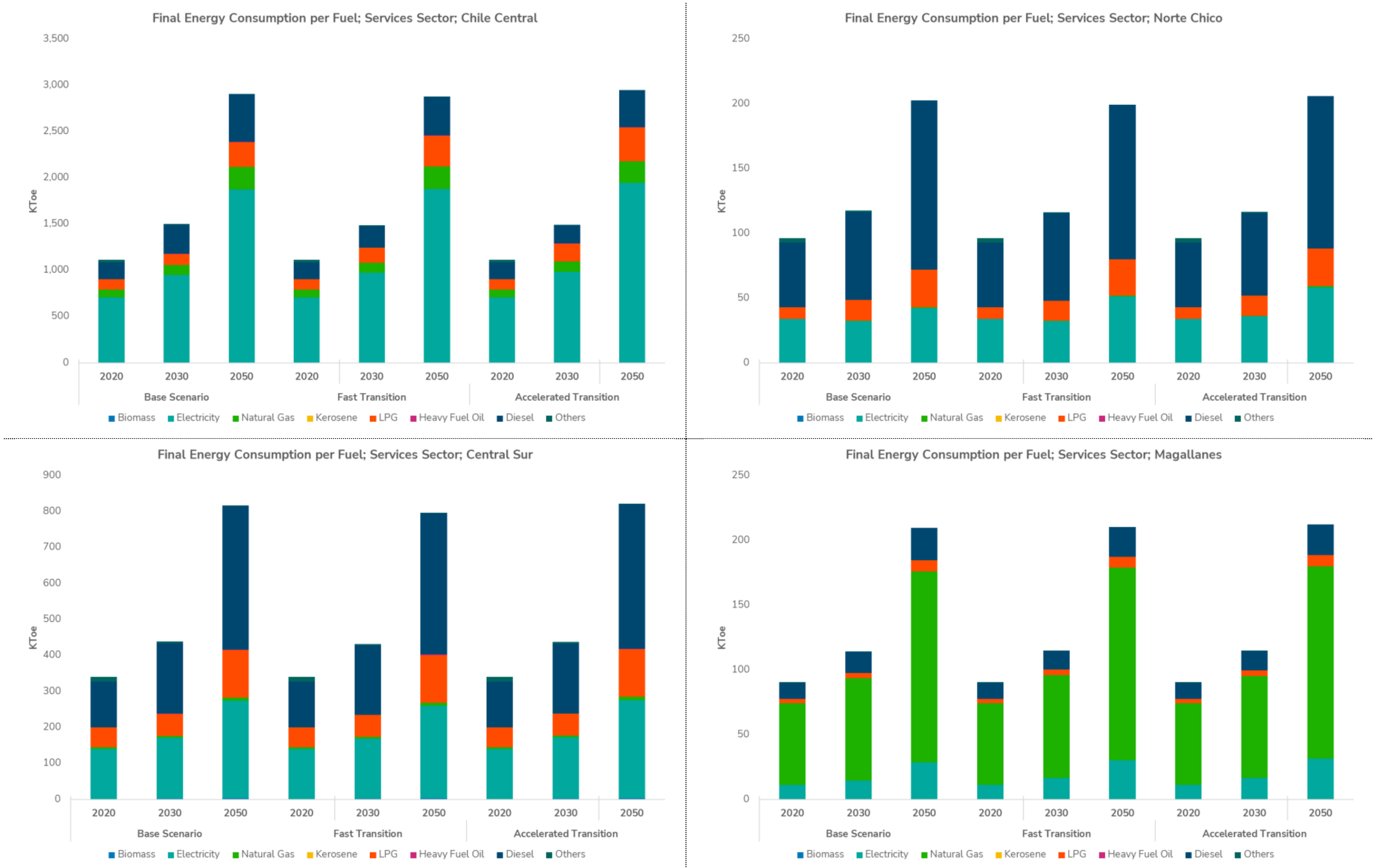


Figure 61 Service sector final energy consumption for selected regions (Source: TIMES-Chile Model)

7.5.5 Subsector Summary

According to the specific measures included in the LTEP and reproduced in the baseline scenario analysis, the residential sector shows considerable emission reduction potential (more than 30%) between 2020 and 2030, which stabilizes around 2050. This is a combination of the use of biomass, which already covers a large share (almost 40%) of household energy consumption nationally (and is considered to produce zero GHG emissions) and the projection that most of the increase in demand will be covered by electricity, leading to further electrification of the sector. Specific additional policies could be developed for the substitution of the remaining fossil fuels consumed until 2050, which are LPG and natural gas used for heating, water heating and cooking.

On the other hand, a more robust view of service sector projections would require considerable improvement in data collection and analysis at the end-use level. Based on the limited information available, high percentages of fuel and electricity consumption were assigned to the "Other" subsector, limiting the possibility of exploring substitution alternatives in more detail (e.g., potential in identifying actual energy use, technologies involved, consumption patterns, electrification and renewables). In addition, the regional breakdown of sectoral consumption (provided by the LTEP) led to the same indicators and intensities in all regions, thus limiting the possibility to adequately simulate energy patterns in different areas of the country[21].

Below are some key points to provide future planning efforts with a list of information gaps found in this study that should be addressed:

a) The source files (statistics) do not include hotel data (numbers, or square meters). Assuming that the energy balance sheet accounts for the associated consumption, it is important to assign a demand value for this activity.

b) The total electricity consumption of commerce/services (sum of shopping centers, supermarkets, hotels, banks, clinics) extracted from the LTEP -18.1 PJ for the service sector- does not fully coincide with the corresponding item in the national energy balance -33.2 PJ for the same sector-. It is necessary to check the consistency of the input data.

c) The KPI[22] of the LTEP refer only to the specific intensity of electricity. This works quite well for pure electric services (e.g. lighting) but not very well for hybrid services such as, for example, water heating. It would be important to improve data collection and analysis for other critical services (heating, cooking, etc.).

[21] In the absence of accurate information from official/local sources, the limited data available from previous (local) planning exercises and from the national energy balance were "processed" to introduce some regional specific elements (especially for heating) on the basis of residential data.

[22] Key Performance Indicators.

d) Electricity-specific KPIs are not region-specific. This means that all regions are assumed to have the same energy demand per unit of activity, without taking into account some geographical conditions (e.g. average outdoor temperature, etc.).

e) Information on "stocks" (e.g., number of appliances) and other similar (technology-specific) statistical data are not collected in the LTEP. For a proper bottom-up analysis, this data would allow for a more refined representation of energy dynamics.

7.6 Evaluation of Investment Rates

In order to carry out the emission reduction plans described in the previous sections, significant volumes of investment are required over the entire horizon of the study.

Specifically, the cumulative investment in the Base Scenario to the year 2050 amounts to US$184 billion, while in order to achieve the decarbonization targets, this must be increased by 9% in the Fast Transition scenario to US$199 billion and by 28% in the Accelerated Transition scenario to US$235 billion. On average, these amounts amount annually to US$6.1 billion in the Base Scenario, US$6.6 billion in the Accelerated Transition scenario and US$7.8 billion in the Fast Transition scenario.

This implies that in order to reduce the 25,000 kilotons diverted from the decarbonization target by the year 2050 (see Figure 62) in the Base Scenario, an increase in investments of about US$1.5 trillion per year is required over the next 3 decades.

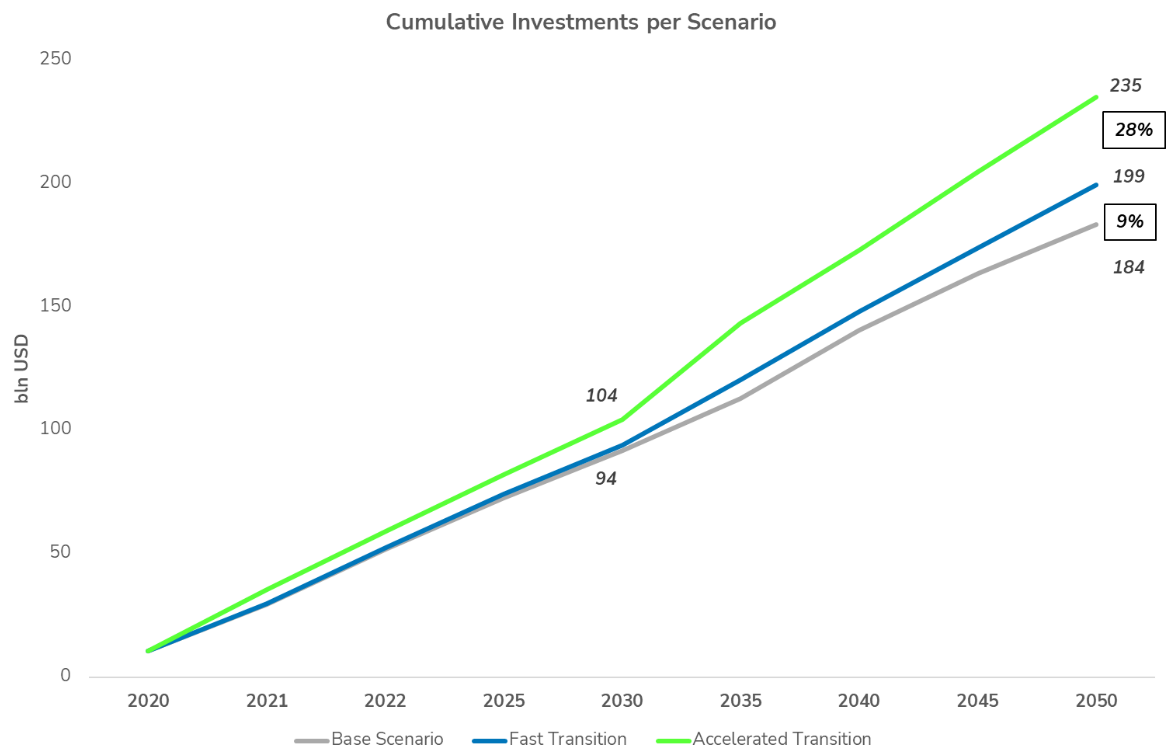


Figure 62 Cumulative Investment by Scenario (Source: TIMES-Chile Model)

If we analyze the data by sector, we can see (Figure 63) that the transportation sector is clearly the one with the highest investment requirements, followed by the tertiary sector in the Base Scenario. In the transition scenarios, the transition to higher rates of electrification and hydrogenation of the economy means that investments in the electricity sector will increase significantly. The table below shows how, in order to achieve the decarbonization targets compared to the Base Scenario, investment levels are up to 220% higher in the electricity sector and up to 30% higher in the transport sector.

Sector	Fast Transition			Accelerated Transition		
	2020-2030	2031-2040	2041-2050	2020-2030	2031-2040	2041-2050
Electricity	21%	109%	123%	65%	220%	211%
Transport	3%	2%	1%	6%	31%	18%
Industry	0%	1%	1%	31%	12%	15%
Residential + Services	0%	-1%	0%	0%	1%	5%
TOTAL	4%	10%	19%	14%	41%	44%

Table 21 Increases in investment in the transition scenarios with regard to the Base Scenario (Source: TIMES-Chile Model)

The industry sector is only affected, compared to the Base Scenario, in the Accelerated Transition scenario, while investment volumes in the residential and services sectors are maintained throughout the years and scenarios.

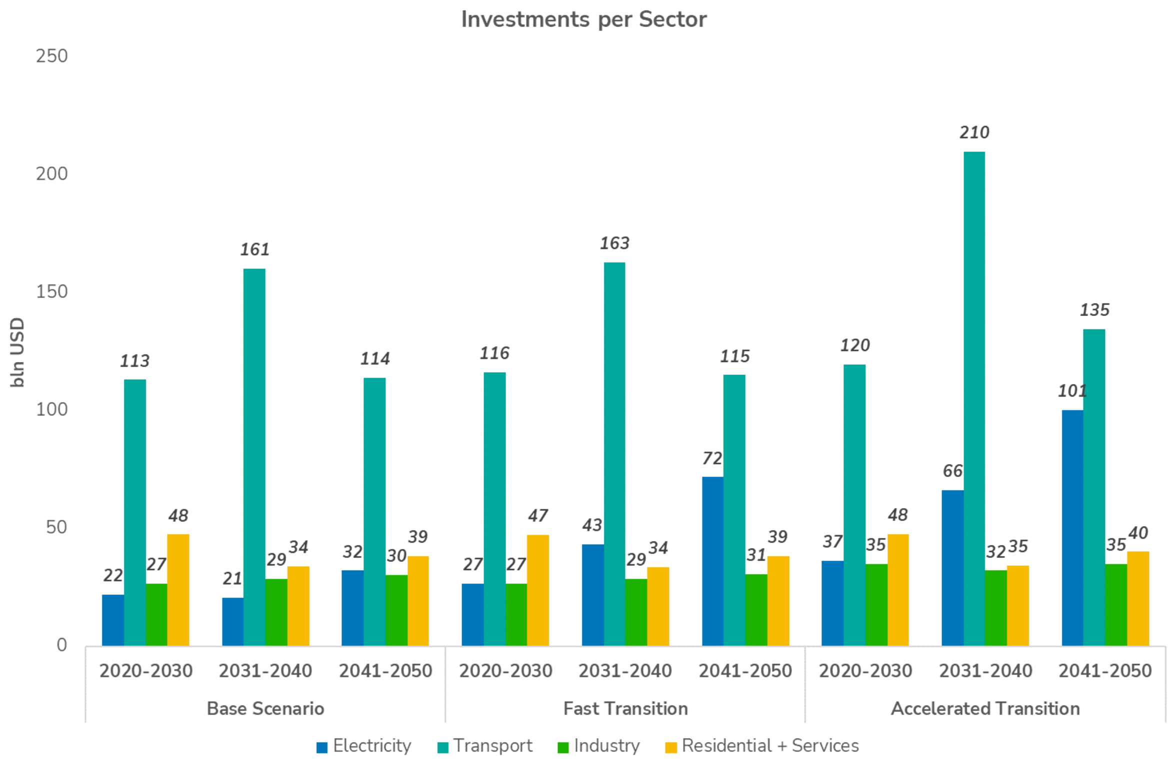


Figure 63 Investment by sector and decade (Source: TIMES-Chile Model)

The transportation sector dominates investments in all scenarios due to the need to change the vehicle fleet to a more sustainable and efficient one; this point is especially relevant in the transition scenarios as the entire fleet of light vehicles is electrified. The hydrogenization of aviation also drives up investment figures in the transition scenarios.

On the other hand, the electricity sector, with the lowest investments in the Base Scenario among all sectors, needs a very relevant increase in the volumes to be converted if the process of electrification and hydrogenization of consumption (through GH_2) is to be successfully completed and also to meet the export targets formulated in the National Green Hydrogen Strategy.

7.6.1 Cost-benefit analysis

This chapter compares the Base Scenario, which falls short of the committed decarbonization targets, with the transition scenarios from an economic point of view.

It is expected that the application of policies and regulatory tools that incentivize the path to a carbon-free economy, and which involve additional investments, will result in scenarios that are costlier than the Base Scenario. On the other hand, such scenarios have the associated benefit of reducing pollutant emissions to the atmosphere.

The following table shows the net present values of the costs associated with each sector[23], in each scenario, and the comparison between cases. Positive values in the comparison mean increased costs in the transition scenarios.

Sector	Base Scenario	Fast Transition	Accelerated Transition	Fast vs Base	Accelerated vs Base
Electricity	36	59	83	22	47
Transport	182	186	214	4	32
Industry	109	109	141	1	32
Residential and Services	138	138	140	0	2
TOTAL	**465**	**492**	**579**	**27**	**113**

Table 22 Net present value of costs for each sector (billions of dollars) (Source: Prepared by the authors)

In addition, in each scenario, all types of energy sources are consumed, most of which are imported from abroad, while energy sources, such as GH_2, are exported. This balance is shown in Table 23, which is negative, i.e., the transition scenarios generate an income flow to the economy, thanks to the exports of H_2[24].

Sector	Base Scenario	Fast Transition	Accelerated Transition	Fast vs Base	Accelerated vs Base
Fuels	116	85	67	-31	-49

Table 23 Net present value of fuel balance (billions of dollars) (Source: Prepared by the authors)

Finally, by balancing the two tables, the net present value of savings (or costs) for each scenario is obtained. Figure 64 shows the results for the Fast Transition scenario. The cost increases between scenarios, especially those related to the electricity sector, are offset by savings in the

[23] Investments costs, fixed and variable O&M costs are considered.

[24] These exports are valued conservatively.

fuel balance, i.e., H_2 exports, combined with savings in international fuel imports due to fuel substitution and efficiency investments, result in a positive net value.

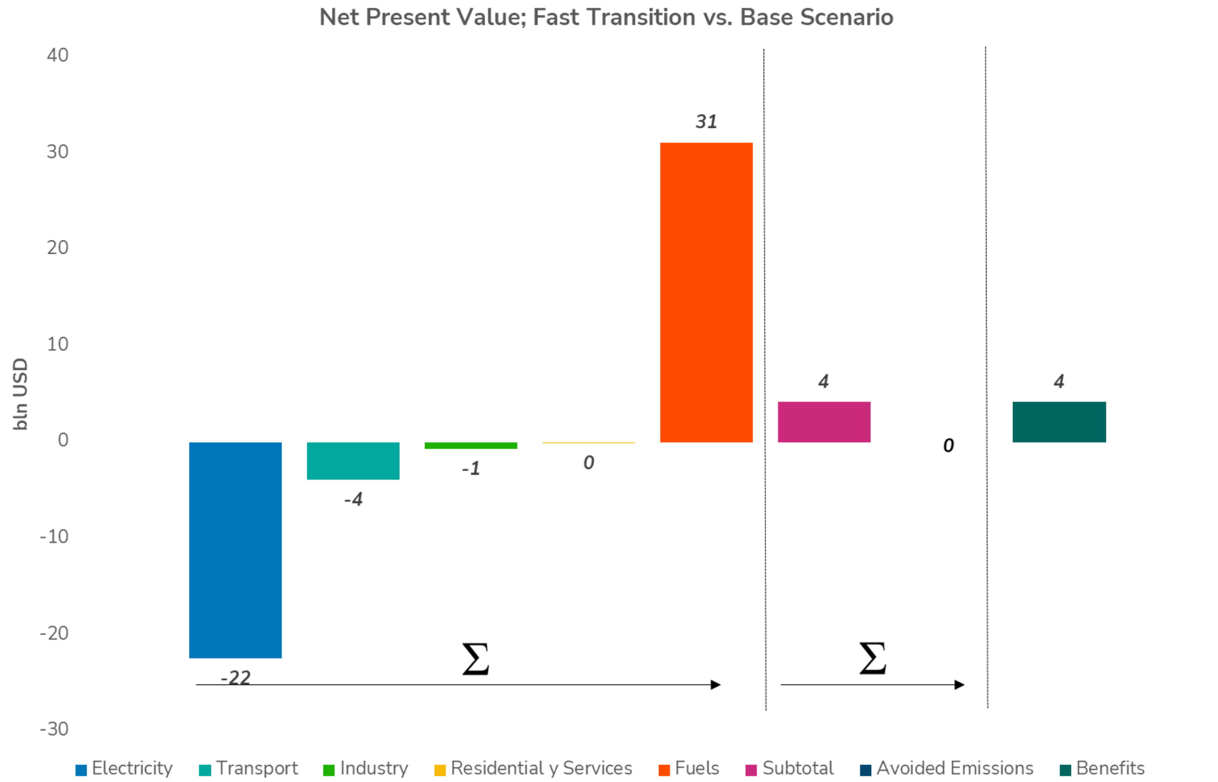


Figure 64 Cost-benefit analysis for the Fast Transition scenario (Source: Prepared by the authors)

The results of the Accelerated Transition scenario are shown in Figure 65. As shown, in this scenario, the net present value of the investment and operating costs of each sector compared to the fuel trade balance gives a negative result of 64 billion dollars, i.e., the savings in the use of imported sources and H_2 sales abroad are not enough to offset the additional investments required. Particularly relevant in the electricity sector, as in the previous case, to which are added increases in the transport and industrial sectors.

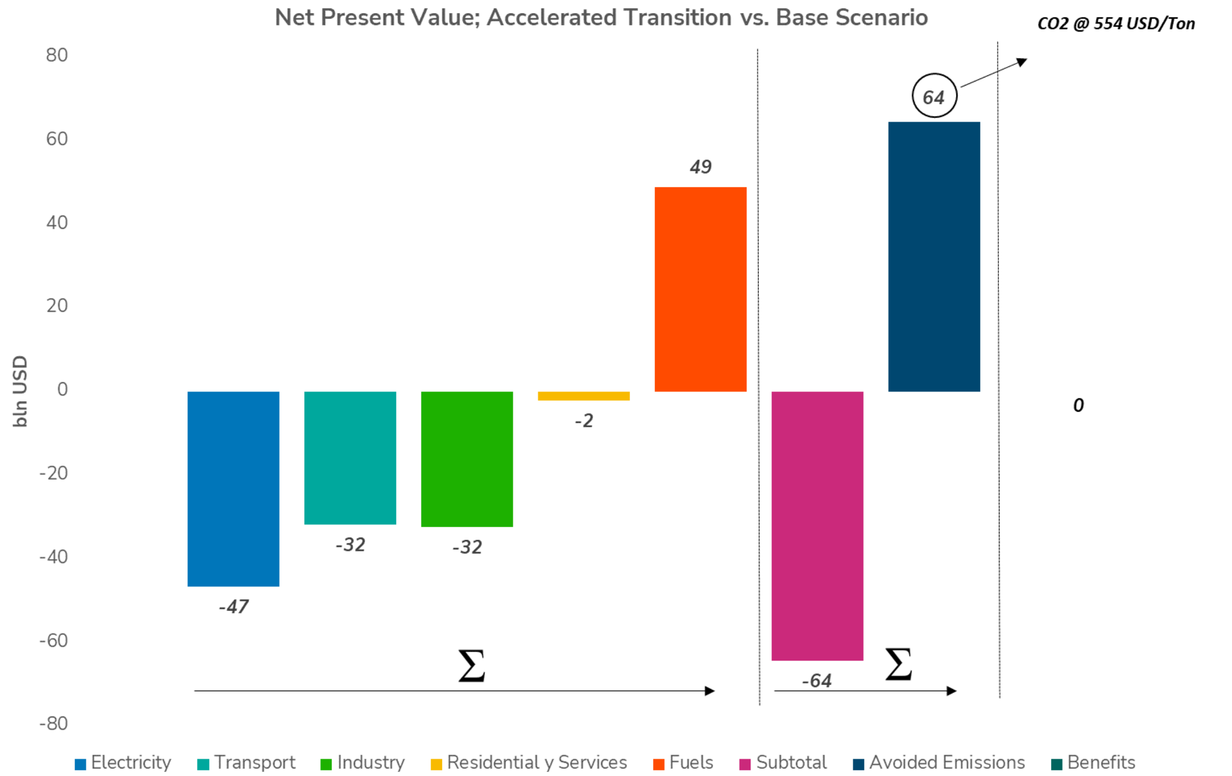


Figure 65 Cost-benefit analysis for the Accelerated Transition scenario (Source: Prepared by the authors)

To arrive at a net present value of zero, the value of avoided emissions (about 405 million tons of CO_2 over the study horizon) must offset the incremental costs of the scenario. This occurs at a social cost of CO_2 of USD 554/ton. The value may be high, but it is consistent with a scenario in which additional investments in the electricity sector will not reduce CO_2 emissions, since the sector has been fully decarbonized, and the effort has to be shifted "to the last mile", i.e. the Accelerated Transition scenario, to reach carbon neutrality more quickly and efficiently than the Fast Transition scenario, has to decarbonize at a higher rate (demands are higher as explained above) and in more complicated sectors (aviation, various industries, etc.).

8 PUBLIC POLICY PROPOSAL

8.1 Phase-out and Substitution of Coal-Fired Generation

The process of phasing out coal-fired generators requires simultaneously taking care of the conditions for such phase-out to occur without jeopardizing safety and economic efficiency, and at the same time to generate conditions that allow for the incorporation of new infrastructure and supply of replacement capacity. This requires permanent monitoring and supervision, which needs to be formalized through governance to monitor progress and validate the steps that are being taken.

This process must be supported by the various technological alternatives available, where the role of Storage stands out, for which its insertion must be accelerated through better regulations, so that business models capture higher revenues via main products (energy/power) or services; the role of NG, as a bridge or transitional fuel, which requires restrictions to be released and compete in market conditions equivalent to the rest of the technologies; the role of the Transmission Grids, which during the present decade urgently need to introduce more technology and adopt new operational practices, while for projects under development or construction, greater State sponsorship is required, through agile regulated processes/studies and more effective action by its agencies.

But the contribution of the electricity sector to the transition and reduction of emissions is not only in the retirement of the coal generation fleet but also in the installation of a massive volumes of VRE - at a much higher rate than the first 10 GW - but also in the challenge of installing more than 20 GW during the present decade and 20 additional GW in the following decade. And in this area, the design and mandate of the sectoral institutional bodies and agents must be reviewed, since it is necessary to speed up and give a sense of urgency to the processes leading to the obtaining of permits, citizen participation, intervention and use of the territory, among others. Therefore, it is necessary to make institutional arrangements in the sense indicated above.

Finally, the need for this process to be conducted with a just transition approach is highlighted, both from a gender perspective and from the need to incorporate new competencies to optimize the performance of workers or provide training for them to adapt to new roles and positions, better known as upskilling and reskilling, respectively, concepts that define the change faced by the labor world in an environment of profound and disruptive technological transformations.

8.2 Green Tax

Considering the local reality, and the application of a carbon tax, known as green tax, there is a reasonable consensus to increase it. Since it is the main economic instrument to reduce and eliminate emissions in electricity generation, its increase should be progressive and be accompanied by modifications to its design in order to correct the distortion it currently generates. Specifically, we are talking about including it in the variable cost of the emission producing generating fleet, and not taxing the withdrawals that have an emission-free supply.

Different experts participating in the process in which this study was developed postulate as reasonable an increase towards the range of 25-30 USD/Ton, even more so when the world average is around 30 USD/Ton.

Notwithstanding the above "consensus" of the experts, the amount of the CO_2 tax requires specific studies to determine the shadow price associated with CO_2, consistent with the marginal cost of the measure that allows meeting emission reduction targets.

The green tax alone does not allow meeting the goals established in the NDCs, therefore it should be understood as one more tool that is part of a design or strategy that should include a set of measures that allow progress in reducing emissions, such as updating emissions standards leading to require CCS (carbon capture and storage) systems, which could act in combination or as a substitute for an aggressive green tax (cost-effectiveness assessment).

As part of this design and strategy, the public policy to be promoted should recognize the green tax as a mitigation measure and not as a permanent income (0.2% of GDP), since the greatest decrease in emissions will occur during the present decade, thanks to the phase-out of the main share of the coal-fired generation fleet, and then NG will be the fossil fuel with the highest placement, but with much lower emissions.

Finally, it has been identified that during the decade 2041-2050, the complete withdrawal of thermal generation sources would only be possible with a high green tax, in the order of 70 USD/Ton, otherwise it is not possible to ensure zero emissions in electricity generation by 2050.

8.3 Distributed Resources: Acceleration of New Solutions and Reform.

The growing electrification of consumption, plus the disruptive changes that are yet to come, require the strengthening of the networks so that they can provide a higher quality and more resilient service. A clear example of this challenge is the ban on the sale of light cars with combustion engines during the next decade, to make way for electromobility, which requires regulatory and infrastructure arrangements and adaptations to enable this transformation.

In another area, the sustained requirement for grid connection solutions for small-scale means of generation has accumulated a demand for more symmetrical conditions for this interaction. Therefore, access and use of distribution grid infrastructure requires a different incentive model, since the current regulatory model -revenues based on demand level- does not provide incentives for the inclusion of distributed production, storage or energy efficiency resources.

Supplementing the above, the introduction of more technology for monitoring this grid, as well as for its technical and commercial management, should be considered and promoted, since the future architecture of the grid will have advanced levels of management and prediction at the wholesale (or upstream) level, This will have to interact with a comparable or equivalent level of management and forecasting at the retail level (downstream), for which technological capabilities that are not present today at the distribution level are key, not only for balancing or control functions, but also to capture the efficiencies that will be at stake.

Finally, in this new paradigm, the investments to be made in a segment such as distribution - which will continue to be a regulated monopoly- require new rules and certainties that, on the one hand, ensure efficient investments but, at the same time, guarantee financing through regulated revenues.

8.4 Wholesale Generation Market

While it is true that the electricity market design was pioneering 5 decades ago and provided price signals for decision making by both private agents and the authority, this design operated correctly for a predominantly hydrothermal technology mix -without disruptive changes- of a scale and dynamics of investments where it was feasible to regulate and centralize decisions.

But today, electricity markets and infrastructure that are moving rapidly towards low emissions, with a different portfolio of technological options, present other types of challenges, therefore, the Chilean electricity market design based on costs accumulates a high level of (over) regulation and centralization of decisions.

An emblematic case is represented by "storage-type" solutions, which - for example - challenge the design rules of a cost-based market and force to promote mechanisms that promote different business models according to their functionality or performance. Even more so when end customers -mainly industry- increasingly have access to very competitive supply contracts, as a result of low VRE development costs, but must face grid (or systemic) charges for various concepts, which generates incentives to evaluate self-production or self-generation type solutions, for example, with storage, in order to alleviate their grid charges, and which could act as an enabler of greater demand management.

The introduction of new solutions and technologies need to be developed in an environment of greater competition with more decentralized operating decisions, for which the cost-based market is identified as a stumbling block rather than an enabler, particularly for storage and also for the role that demand-side management will have to play.

Therefore, there is a high consensus in the industry to move towards a price-based market, plus services, and for this to be a two-price market, one day-ahead and one real-time, so that there are sufficient efficiency incentives in the availability of resources, in order to avoid having to purchase energy in the real-time market, which usually has greater variability.

In conjunction with a reform such as the one indicated above, changes should be made to the institutional framework of the electricity sector, particularly with regard to the purpose or mandate of each of the relevant agencies, for example, in terms of free competition and market monitoring, among others.

The design and implementation of reforms such as those indicated is complex and sophisticated, therefore, it is necessary to advance in analysis and migration studies towards a supply market, both for energy and capacity, which at the same time mobilizes new infrastructure and agents that have been passive to date, i.e., demand.

8.5 Demand and Consumption: Energy Education and Culture versus Environmental Contingency Reaction.

The general perception reached during the preparation of the report indicates that the industrial sector is not promoting relevant actions to help reduce emissions from its production processes and has rather taken a reactive position, particularly when faced with environmental contingencies.

This represents a lost opportunity, in circumstances where 80% of energy use in Chilean industry comes from thermal sources, and only 20% of consumption is electrified, even more if we consider ANESCO's estimates that about 35% of CO_2 reductions come from energy efficiency (EE) measures.

In the field of energy efficiency, the factors that explain this situation are concentrated in the lack of knowledge and disaffection of users for effective EE actions, the lack of risk financing for these projects, and the absence of incentives in the distribution segment, all of which make up a not very encouraging picture. This contrasts, for example, with the self-assessment of the mining sector, which claims to have a performance in energy efficiency comparable to other countries with mining tradition.

The substitution and replacement of intensive use in sectors such as transportation and industrial processes in general are not seen as a priority in the industry's plans and programs, which makes us identify the need to take action as soon as possible, so that during the next decade and the following decade we will begin to see results.

The Framework Law on Climate Change enacted this year represents a significant milestone through which the State of Chile is obliged to face climate change with a State policy and define the mechanisms that the country will use to change the way in which, for example, we transport, feed, clothe and produce energy. Thus, the State is involved and obliged to take concrete actions to address climate change in its 17 ministries, regional governments and all municipalities in Chile.

The above, as a result of its demonstrative and multiplicative effect, is expected to bring the industrial sector to, for example, CO_2 emissions transaction mechanisms, which could promote the transformation of processes or demand management, through aggregation, greater control, and even interruptibility of this, among others.

Notwithstanding the above, we note that large consumers of electricity subscribe to and support the process of reducing emissions from the electricity mix, for example, through the search for renewable energy supply, but demand that public policies be oriented towards "how" this process is enabled or developed. At the same time, they express a critical opinion on the ongoing transition process, considering the strong emphasis placed on the large volumes of investment required, to the detriment of -or without due care in- the tariff effects on end customers, therefore, they demand to evaluate the cost of this for the country.

8.6 Lagging Sectors: Forestry, Biodiversity, Agriculture, Transportation, urgency in the introduction and incentive of technology.

Sectors have been identified that are lagging behind in their actions to combat climate change, which represents a significant risk and uncertainty regarding the goals committed to for the present and following decades, particularly to achieve carbon neutrality, since -for example- a large part of the capture and compensation required to achieve net zero rests on the preservation of forests and biodiversity.

The recurrence of forest fires and unregulated use of firewood, without aggressive protection plans or programs, encourage the perception of risk and uncertainty in the opinion of many experts. Emphasis on strategies to increase capture capacity, and follow up on these measures, are urgently needed.

The discussion and debate on mitigation measures focused on the electricity sector at a national level does not correspond to the scarce progress in terms of local pollution, in circumstances where the high levels of particulate matter is one of the main problems in the central-southern area of the country, which in some way makes the urgent need for greater regulation of biofuels such as firewood and pellets invisible, as well as the striking absence of policies to promote green fuels such as biofuel or bio diesel. Fortunately, during the development of this study, a bill has been passed to regulate solid biofuels, which seeks to regulate the use of firewood, pellets, briquettes, charcoal and agricultural waste -declaring them fuels- and to establish requirements for their commercialization, considering that, at present, they are largely responsible for atmospheric pollution due to the humidity they concentrate.

Another expression of the existence of lagging sectors is manifested through the "absence" or null participation in the decarbonization strategy of sectors such as agriculture, which, for cultural, risk aversion and historical reasons, among others, do not find incentives for the introduction of technology and reduction of operating costs.

In short, incentives are needed to reverse this situation, both to incorporate more technology and to promote production in the sectors that lag behind, such as those mentioned above, which requires the deployment of a territorial strategy that also considers the dimensions of just transition. Here the presence, intervention and support of the State is essential.

Finally, special mention should be made of transportation in its various forms or uses, particularly urban transportation, which is projected to undergo a profound transformation because of the decrease in costs that we should observe during the present decade and with greater force during the next decade, in addition to the banning of light vehicles with combustion engines.

However, in the short term, the still high costs of investment in light vehicles and the development that has not yet matured in the case of cargo transportation, for example, in mining, make us foresee a rather slow progress in its insertion during the next few years, but this should not make us lose focus on the decisions and policies that should be promoted.

8.7 Capillarity of public instruments: INDAP, CORFO, SERCOTEC.

The development of decarbonization strategies requires scientific and technological capacity to be deployed in the territories, particularly at the regional level, which is currently not deployed.

This is an interdisciplinary challenge; it is not only an energy issue, but also requires diverse perspectives to address the problem, given that it is a multifactorial challenge with a high territorial and multisectoral emphasis.

For example, the food sector is mentioned as one of those that lags far behind others in the challenge of reducing emissions, therefore, it is urgent to advance and work in sectors that have a regional and cultural character to achieve long-term effects.

Sustainability in sectors such as food or agriculture should be at the center of risk analysis and should be promoted with public mechanisms that are currently available to reach a higher percentage of lagging sectors such as these. In addition, work must be done to obtain more information from the sector, to adequately orient public policies and investments, so as to achieve cost-efficient objectives in terms of emissions reduction. Therefore, organizations and institutions such as INDAP, CORFO, SERCOTEC have a relevant role, due to their specificity, capillarity, and capacity to reach those territories or isolated areas.

This is a concrete expression of how the State - together with the communities - can promote and take charge of the new development models that contribute to the reduction of emissions, raising their entrepreneurial, organizational, and commercial capacities, so that they become a source of opportunities and growth.

Notwithstanding the above, within the project financing mechanisms, private financing can support and complement the efforts of the State, considering as a risk variable that capital seeking to finance resources that contribute to carbon neutrality should be recognized with a lower risk, in this matter the banks still must comply with this vision.

8.8 Roadmap

In order to meet the challenges presented by the energy transition of each economy or country, it is necessary to have various resources and tools to project future scenarios and derive from them actions that can be ordered and synthesized to answer questions such as: Where are we, where do we want to go, what gaps exist, how do we move forward, what are the key actions and levers, among others.

Along with the above, it is also necessary to overcome the growing tension between safety, efficiency, and emissions reduction.

For this reason, it is necessary to have an instrument that allows focusing efforts on a strategy and model that speeds up the closing of gaps and progress towards emission reduction goals in a consistent and prioritized manner.

The following are the main fronts on which public policies should be deployed and which will be prioritized during the present and following decades.

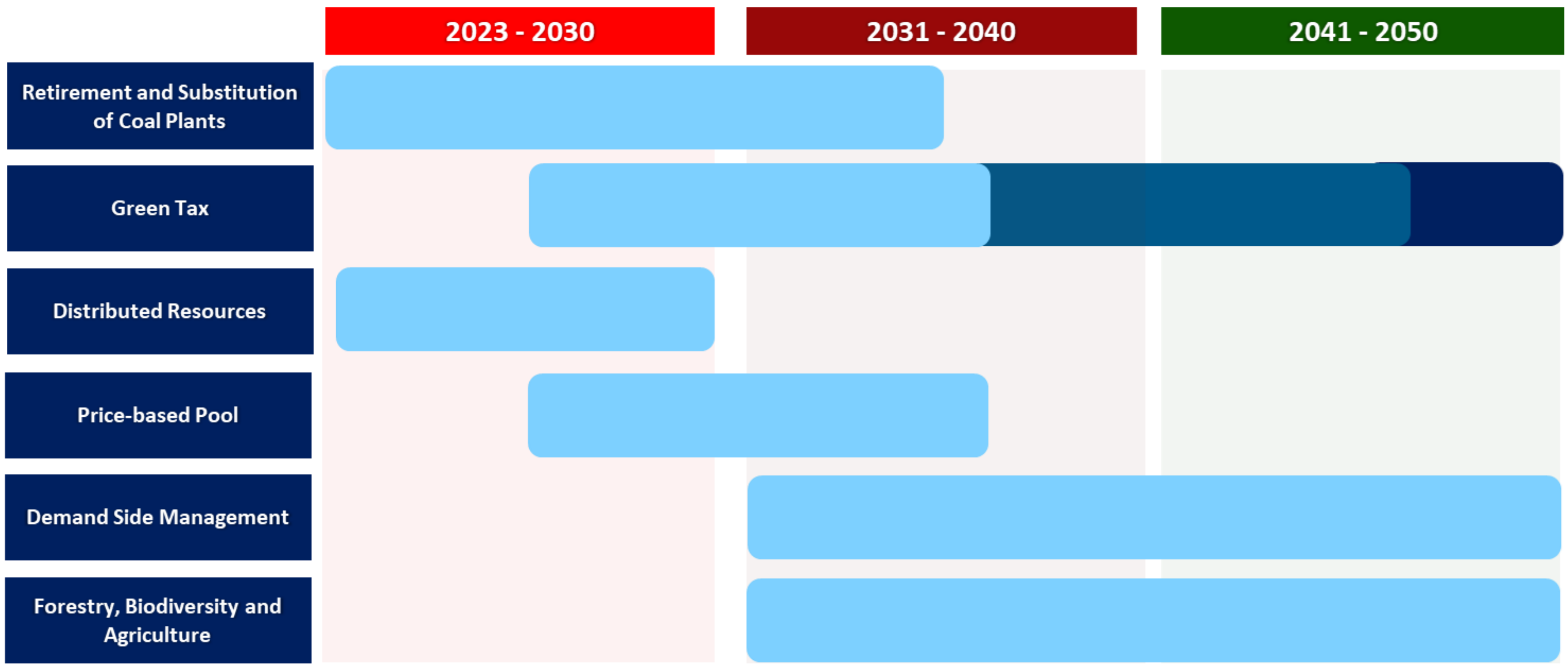


Figure 66 Public Policy Roadmap (Source: Prepared by the authors)

9 CONCLUSIONS AND SUGGESTIONS

In the fight against climate change, the energy industry is making progress through multiple actions to reduce and mitigate greenhouse gas emissions. This translates, for example, into a wide adoption of reliable and emission-free energy generation sources, where the increase in variable renewable energies requires the design and promotion of enabling conditions that recognize their attributes and allow their requirements to be met through efficient market signals.

This requires, for example, the use and reconversion of existing infrastructure, the development of new infrastructure, the insertion of new sources and technologies, the reconversion of processes, the digitalization of the grid, which are fundamental both to manage generation from VRE and to support a participation of demand and energy efficiency in end uses.

This will pave the way - increasingly - to lower emission energy carriers, where reliable and emission-free electricity is destined to play a key role in the decarbonization of transport and industry, and where electrification cannot reach, H_2 will be the vehicle that will do the rest of the job.

The energy transition roadmap presented is designed with a medium- and long-term vision, also including immediate actions, so that in a joint work of institutions and stakeholders, the foundations of a path towards a future without greenhouse gas emissions will continue to be consolidated and strengthened. The foregoing is summarized in the following conclusions and recommendations:

1) In the short term, the electricity sector will make the main and earliest contribution to the emissions reduction process, concentrated mainly in the current decade through the phase-out of coal-fired plants.
2) To ensure the retirement of the coal-fired fleet, not only regulatory and process management actions must be adopted, but also the substitution of such capacity must be made feasible. The new VRE capacity to be incorporated (2.5x by 2030 and 4x by 2040) represents a large-scale challenge in terms of land use, financing, grid development, system security and market design, among other factors.
3) NG plays a key role in the transition, that is, during this and the next decade. Although it is the lowest emission generation alternative, it can reduce emissions even further (-70%) through capture systems, and to achieve its retirement it requires an aggressive green tax, such as 70 USD/Ton by 2050.
4) The location of large generation projects, installed mainly in the northern area in the case of photovoltaic generation and wind power in the central southern area, will require

increases in the transmission grid, so planning with slack in these points should be promoted to allow the insertion of renewable energies.

5) To reach the carbon neutrality goal by 2050, the contribution of the electricity sector is not enough. The transport and industrial sectors are contributors of emissions and must be mobilized in the short term, therefore they must either accelerate their electrification or advance in the introduction of H_2.
6) Electrification of road transport leads to significant savings in terms of energy and greenhouse gas emissions, which requires state intervention by banning the sale of combustion engines. But focus should also be placed on the aviation sector, which will increase its level of emissions as a result of economic growth in the coming decades. This is a good opportunity for the introduction of H_2.
7) The results obtained in terms of transportation are consistent with the National Electromobility Strategy, so the implementation of the goals defined in this public instrument should be deepened.
8) The electrification of consumption and industrial processes plays a fundamental role in the transition process. The energy consumption of petroleum derivatives decreases moderately if specific measures are not adopted with respect to the price of carbon. If these are adopted, it is possible to replace oil derivatives, a scenario in which H_2 in the mining and metallurgical industries, and biomass in the paper and sugar industries increase considerably by 2050.
9) In the long term, the production of H_2 for export drives the installation of a large volume of VRE, mainly off grid, which leads to the formation of dedicated but large-scale electrical systems, which poses challenges -for example- regarding land use and regulations for the development of such infrastructure, among others.
10) It is necessary to promote an aggressive strategy in terms of positioning Chile as a major GH_2 producer worldwide, allowing the installation of the associated infrastructure, as well as the development of innovation that allows the country to position itself as a world leader in the production of this fuel.
11) Residential uses are mostly electrified, although biomass continues to be a significant vector for single-family homes in the long term. However, more efficient technologies are used, and only dry biomass and pellets are considered after 2030.
12) The main public policies of the present decade are around:
    a) Governance and - permanent - implementation of an action plan to ensure the phase-out and replacement of the coal-fired fleet.
    b) Reforming the electricity market, both at the wholesale and distribution levels, both to allow the massive incorporation of storage systems and to promote demand management, which is necessary to move towards a decarbonized system.

c) Correction of distortions and gradual increase of the Green Tax.

13) For the next two decades, actions should be deployed to mobilize the sectors that are lagging behind in the process of reducing emissions (Industry in general, Forests, Biodiversity, Agriculture, Transportation, among others), although during the present decade the instruments and strategy should be designed so that such mobilization takes off and occurs from 2030 onwards.

14) The cost of electricity supply must be a structural focus of public policy and thus advance in one of the dimensions of the just energy transition so that the benefits of the transformation process reach everyone, mainly through the competitive and efficient operation of energy markets.

Finally, it should be reiterated that as a result of Russia's invasion of Ukraine, the countries and economies of reference in the emissions reduction process, and the world in general, have had to face a deep crisis -both economical and energetic- which has initiated a global reordering -still in development- in which a process of revision of priorities and objectives is already identified, in which energy security and price/cost control are increasing in relative significance. This process is far from being cleared in the short term, and both its duration and its subsequent consequences will be of a structural nature. This has not been addressed in this study.

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