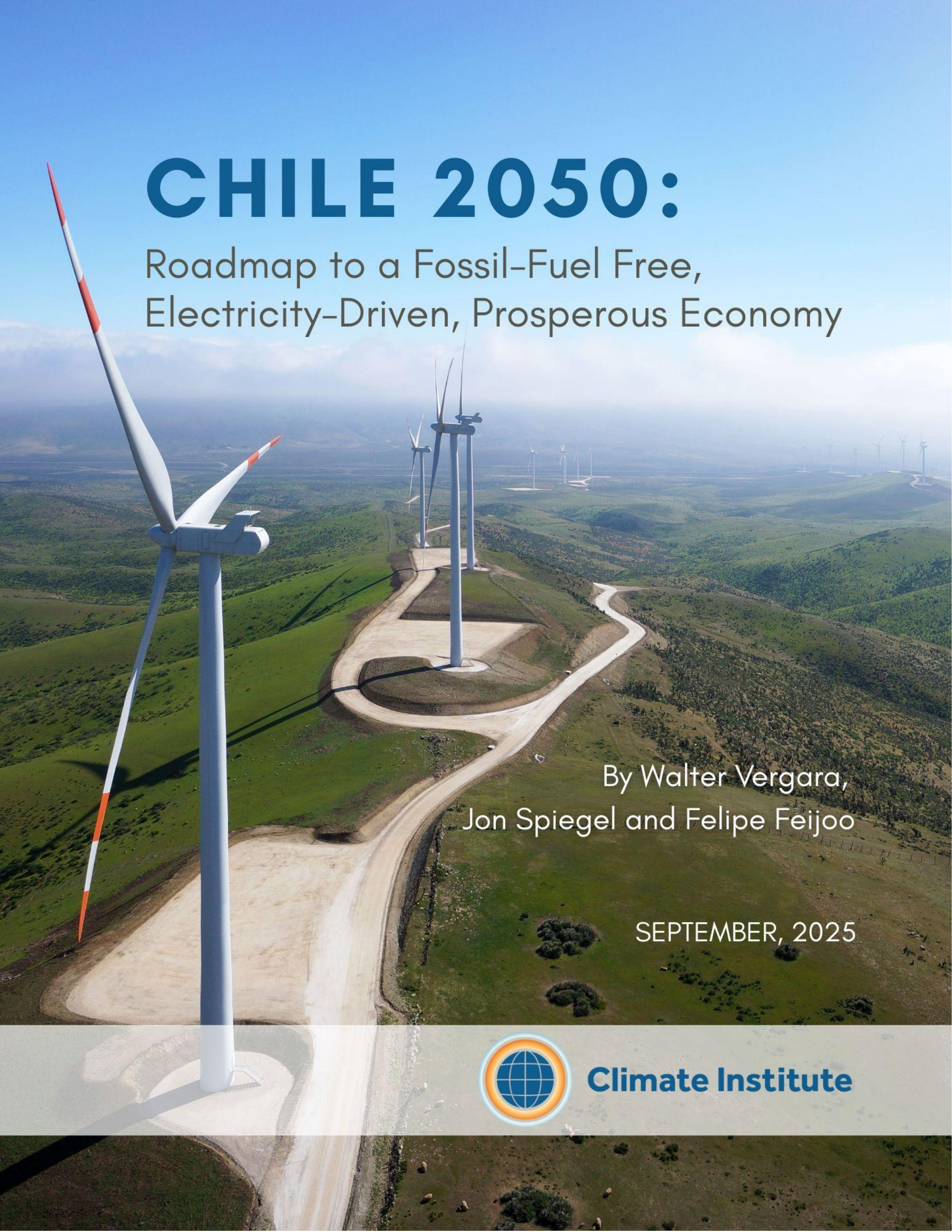

# CHILE 2050:

## Roadmap to a Fossil-Fuel Free, Electricity-Driven, Prosperous Economy

By Walter Vergara,
Jon Spiegel and Felipe Feijoo

SEPTEMBER, 2025

Climate Institute

**CLIMATE INSTITUTE STUDY**

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This publication was prepared by The Climate Institute as part of its efforts to advance research and dialogue on pathways to a sustainable energy future. It is intended to inform policymakers, practitioners, and the public. The report has undergone internal review, but it is not a formally edited or typeset publication.



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# Dedication

*To the children of the next generation,*
*including Gabriel, Sami and Lucia*.

*“We are all aware of the effects of climate change and the need to take care of the whole of creation.”*

*Pope Leo XIV, June 2025*

# Acknowledgements

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# Acronyms and Abbreviations

| | |
|---|---|
| BAU | Business as Usual |
| BCN | Biblioteca del Congreso Nacional |
| CCGT | Combined Cycle Gas Turbine |
| CEN/NEC | Coordinador Eléctrico Nacional (National Electricity Coordinator, Chile) |
| CLEE | Chilean Law on Energy Efficiency |
| CNS | Carbon Neutrality Scenario |
| COP | Conference of Parties (UNFCC) |
| CSP | Concentrated Solar Power |
| DOE | U.S. Department of Energy |
| DRI | Direct Reduced Iron |
| EAF | Electric Arc Furnace |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| EFE | Empresa de los Ferrocarriles del Estado (Chile Railways) |
| ENSO | El Niño Southern Oscillation |
| EPA | U.S. Environmental Protection Agency |
| ERA5 | ECMWF Reanalysis v5 |
| EV | Electric Vehicle |
| GACMO | Greenhouse Gas Abatement Cost Model |
| GCAM | Global Change Assessment Model |
| GOC | Government of Chile |
| HVAC | High Voltage Alternating Current |
| HVDC | High Voltage Direct Current |
| ICE | Internal Combustion Engine |
| IEA | International Energy Agency |
| IKI | International Climate Initiative |
| IRENA | International Renewable Energy Agency |
| IREC | International Renewable Energy Credit |
| LCOE | Levelized Cost of Electricity |
| LCOH | Levelized Cost of Heat |
| LCOS | Levelized Cost of Storage |
| LCOTr | Levelized Cost of Transport |
| LFAC | Low Frequency Alternating Current |
| LNG | Liquified Natural Gas |
| NCEI | NOAA National Centers for Environmental Information |
| NES | National Electromobility Strategy |
| NGCC | Natural Gas Combined Cycle |

| | |
|---|---|
| NOAA | U.S. National Oceanic and Atmospheric Administration |
| NPV | Net Present Value |
| PELP | Planificación Energética de Largo Plazo |
| PV | Photovoltaic |
| PUCV | Pontificia Universidad Católica de Valparaíso |
| RE | Renewable Energy |
| UNEP | United Nations Environment Programme |
| UNFCC | United Nations Framework Convention on Climate Change |
| VRE | Variable Renewable Energy |
| ZES | Zero Emissions Scenario |

**List of Units**

| | |
|---|---|
| BTU | British Thermal Unit |
| EUR | Euro |
| GW | Gigawatt |
| GWh | Gigawatt-hour |
| kWh | Kilowatt-hour |
| MMBTU | Million British Thermal Units |
| MWh | Megawatt-hour |
| MW | Megawatt |
| PJ | Petajoule |
| TWh | Terawatt-hour |
| USD | U.S. Dollar |

# Preface

Strategic and impactful climate action depends on a keen sense of climate urgency, coupled with professional competence and leadership. This book stands to help Chile achieve a prosperous, electricity-driven economy by 2050.

In a best-in-class, bold analysis, the authors build on their life-long experiences, focusing on the very specific, sui generis energy development potential of Chile, which would allow for a fossil-fuel-free Chile by 2050.

This book goes to print in 2025, during the hottest summer ever recorded in the northern hemisphere. We almost get used to horrendous pictures of parched fields, groundwater scarcity, burning forests, and deadly winds and floods —yet we see ever more of them. Charts and scales go up, and not back down again.

We are not meeting set UNFCC targets. Climate change is outpacing forever drawn-out negotiations, while average temperatures rise and some local climate change patterns have become hard to bear. Regardless of theoretical options, humans cannot reverse climate into stable mode, once it has been destabilized.

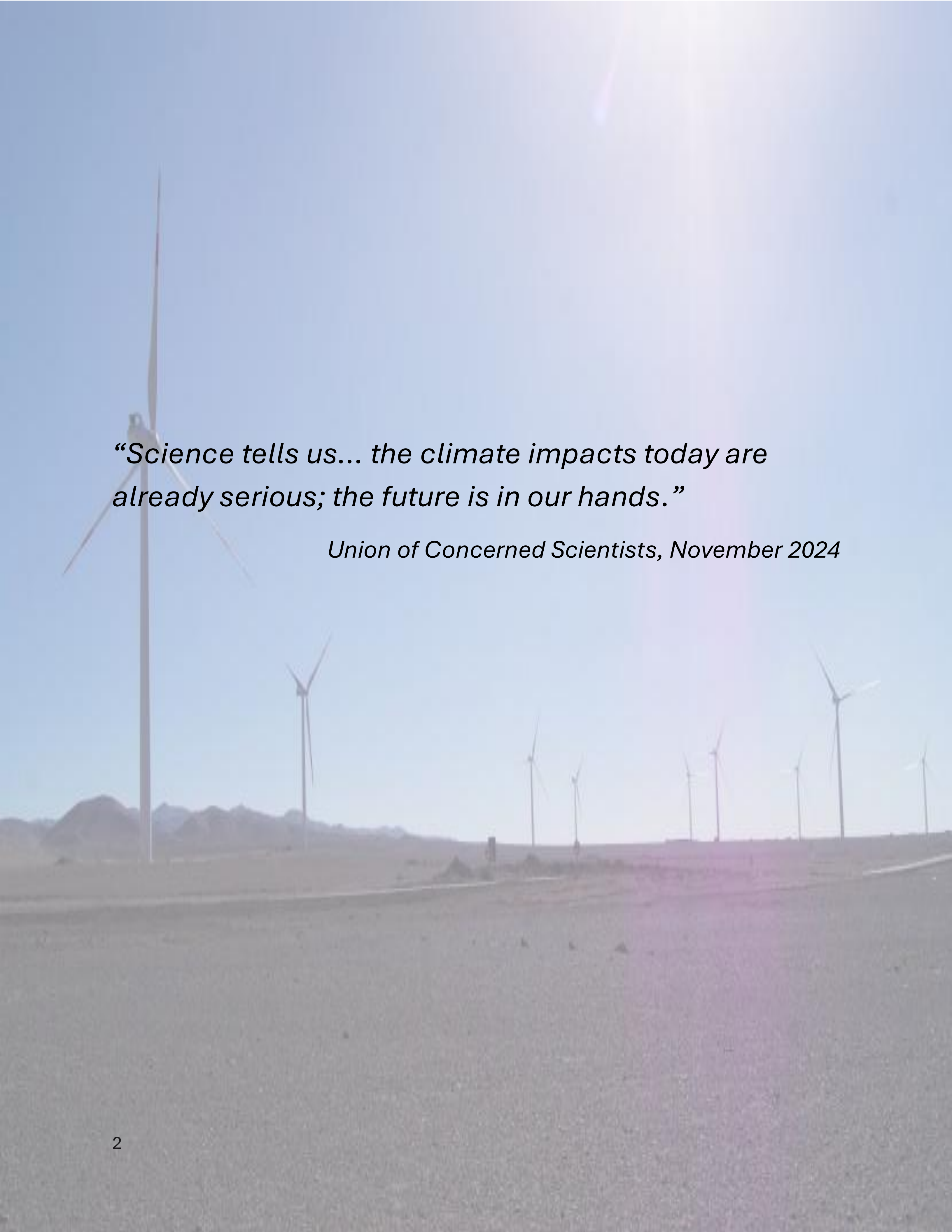
It is better to invest ahead of the curve. Yet, socially, technically, and economically the international community remains extremely challenged as we try to salvage what our Blue Planet Earth has uniquely in our universe – the miracle and treasure of life in all its forms, on a livable planet.

Although the transition to sustainable electric energy is profitable in the medium and long run, it requires significant investments in infrastructure and energy storage now. So far, patterns of underfunding and "too little, too late" stand in the way of technically possible turnarounds.

This is an exemplary report. Many places on Earth need roadmaps charting intermediate goals along the path to 2050. Policymakers and investors need concrete, unemotional, transactional plans like this *Chile 2050: Roadmap to a Fossil Fuel-Free, Electricity-Driven, Prosperous Economy*. Chile is endowed with exceptional geographic and electrification opportunities. This review of opportunities, costs, and benefits has what it takes to energize the development of a tangible action and investment plan.

*Maritta R. v. Bieberstein Koch-Weser*

*President, Earth3000*



*“Science tells us... the climate impacts today are already serious; the future is in our hands.”*

*Union of Concerned Scientists, November 2024*

# Abstract

Chile has pledged to achieve greenhouse gas (GHG) neutrality by 2050 by decreasing emissions across all economic sectors and promoting energy efficiency. These measures are projected to eliminate half of emissions by 2050 compared to current projections, with the remaining emissions offset by carbon sinks in forestry and agriculture. While the pledge achieves carbon neutrality, the economy would still utilize fossil energy resources by mid-century.

The current analysis documents the economic costs and benefits of fully electrifying the economy using renewable resources, displacing all fossil fuels. This requires expansion of the electric power system, of storage and transmission capacity, and of rapid adoption of alternative electrical technologies.

The study quantifies the current and projected levelized costs of electricity, transport, heat, steam generation, key electrical industrial processes, and electricity storage, and documents the economic consequences for each electrified service. It also estimates the cost of storage and transmission required to meet all new power demands.

The analysis assesses the economy-wide costs associated with providing services such as electricity; electric cargo and passenger transport; electric fisheries and mining; electric heat and steam generation in industry, commerce, and households; along with electricity storage. It also estimates capital savings, energy-efficiency benefits, job-creation opportunities, reduced morbidity and mortality rates, and the overall impact on economic activity. Furthermore, it outlines a schedule for mobilizing new capital, while accounting for the retirement of stranded assets. The analysis identifies regulatory, institutional, policy, and cultural obstacles, and evaluates the policy requirements and implications of transitioning to a fully electrified economy.

The study concludes that large-scale production of very low-cost electricity in Chile — leveraging its abundant solar radiation, wind, and other resources, aided by a strong institutional and policy framework—will foster rapid technological change across various sectors including in industry, mining, transportation, commerce, and households. This will make it financially attractive for the nation to become a fossil fuel-free society by 2050.

The transition to an electrified economy will create numerous opportunities for innovation, generate hundreds of thousands of jobs, contribute to substantial economic growth, promote billions of dollars in business development, and reduce the costs of goods and services. Engaging in this transformation, poises Chile to become a global exemplar of a post-fossil fuel economy. Other nations may benefit from following its lead.

# 1. Introduction

Under the current global greenhouse gas emissions trajectory, climate impacts are already becoming more intense, with increasingly damaging effects on humans and ecosystems. Therefore, the need to take bold, immediate action has become extremely urgent. However, at the current pace of actions taken to reduce emissions, the goals outlined in the Paris Agreement are unlikely to be met.

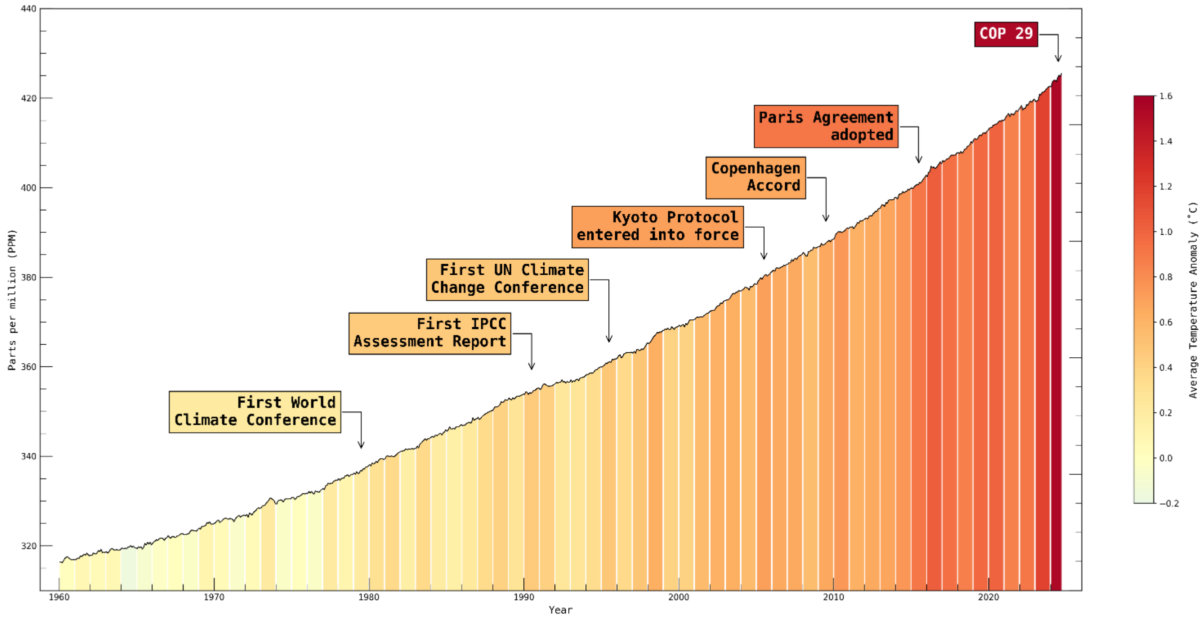
For example, the limit of 1.5°C temperature anomaly above pre-industrial levels by mid-century—endorsed in the Paris Agreement and widely seen as the best hope to avoid major climate-driven disruptions to the biosphere— is now acknowledged to be very difficult to reach. According to ERA5, which provides hourly temperature data from 1940 onwards, the global average temperatures in September 2024 (*Setchell, H, 2020*) and March 2025 (*NCEI, 2025, April 10*) were already 1.5°C above the pre-industrial level. The 1.5°C threshold has been surpassed almost continuously since July 2023 (*Copernicus Climate Change Service*, October 9, 2024).

Additionally, many sea-surface temperature records were broken in 2024 by large margins (Cheng et al., 2025). The North Atlantic, Gulf of Mexico and Mediterranean Sea surface temperatures were far above their normal historical averages for much of 2023 (*Physical Sciences Laboratory*. *Map Room (SST)*, 2025). Global daily mean temperatures were also at record levels for most of 2024. These deviations are truly unprecedented in the meteorological records. Given the status and direction of greenhouse gas emissions, records will continue to fall.

At some point, there is a need to admit that efforts launched by the UN and shepherded by the Conference of Parties (COP) to the UNFCCC to rein in global greenhouse gas emissions have so far failed (Figure 1). Consensus actions commensurate with the magnitude of the challenge have been elusive and political leadership from key actors counterproductive. Until the situation changes, it will be up to individual actors (nations, institutions, and local governments) to launch and implement aggressive efforts.

After all, climate-induced damage to human settlements and livelihoods is not theoretical or expected to take place in the far future. For example, the costs of climate disasters in the United States alone were already estimated at $95.1 billion in 2023 (NOAA-NCEI, 2025). Globally, it has been calculated that between 2000 and 2019, the world had a total of $2.8 trillion in losses and damage caused by climate change (UNEP loss and damage report, 2024). This is almost half of today’s GDP of Latin America.

**Figure 1: Atmospheric CO2 and Global Temperature against timetable of UNFCC events**




Beyond the effects on human activities, welfare, and economies, climate impacts are also threatening ecosystems. About 25% of species worldwide are already in danger of extinction (critically endangered under the IUCN Red List criteria) caused by habitat loss (WWF, Living Planet Report, 2024). Climate change is exacerbating the situation by placing an overlay of significant stress on environmental conditions, ultimately changing the distribution of plants and animals and affecting the viability of large ecosystems. [2]

Thus, the mounting financial and environmental costs argue for immediate and forceful action. A failure to embark on a radically different and immediate trajectory of emissions would place the world on a path to a much higher temperature increase over the course of this century. This increase would result in even larger damages and losses to human settlements, livelihoods and the ecosystems on which we all depend.

It is in this context that the report evaluates the potential benefits and costs for Chile in transitioning to a zero-emission economy by 2050, rather than merely achieving carbon neutrality. The selection of Chile is deliberate, as the country possesses the necessary natural and human resources, political determination, and institutional commitments to serve as an early global model for transitioning to a fossil fuel-free, prosperous economy. As

[2] For example, the stability of the Amazon ecosystem has been placed under doubt because of climate-induced changes in its hydrology and moisture balance (see Vergara W. and Scholz, 2011: https://documents1.worldbank.org/curated/en/228631468015874565/pdf/580370PUB0Asse10Box353792B01PUBLIC1.pdf). Likewise, the global coral ecosystem is already experiencing a collapse resulting from changes in sea surface temperatures and acidity.

the report contends, Chile's path towards eliminating fossil fuels would not only exemplify environmental responsibility but also be underpinned by a sound economic rationale.

*Chile's capital Santiago operates one of the world's largest electric bus fleets, a visible symbol of its clean energy transition. Photo: Dirección de Transporte Público Metropolitano (DTPM)*

In terms of natural resources, Chile has an enviable situation[3], with record solar radiance over vast extensions in the north; strong stable wind regimes along the coast and in the south; significant geothermal resources along its mountain chains; and record marine energy potential over its coasts and fjords, complemented by a sizable hydrological base.

Equally important, Chile has a commitment of State to manage and eventually reduce all carbon emissions in order to become a GHG neutral economy by 2050 ((Chile's Climate Change Framework Law (2022), (Congreso Nacional de Chile, 2022)). As envisioned, the current GHG policies (summarized for example in Ortiz and Zurita, 2023 and described later in the report), would reduce emissions by half, against the reference scenario, with the balance being compensated by carbon sinks in forestry and agriculture. It is a robust commitment, based on the substantial renewable energy endowments of the country, and backed by a firm national goal. However, under the current vision, the economy would continue using fossil resources, even by mid-century.

The objective of this analysis is to document the financial and economic costs and benefits of eliminating all fossil fuel use by 2050, primarily through electrifying all economic activities with renewable energy. This strategy represents an alternative decarbonization path based on rapid expansion of the renewable power sector. It involves transforming transportation into electric and hydrogen systems, including road, rail, and shipping, while phasing out fossil fuels in industry, agriculture, commerce, and households. Energy-intensive sectors such as industry, mining, and fisheries would also shift to electricity and renewable

[3] It is ironic that not long ago, Chile was widely characterized as energy-poor purely based on its limited access to fossil fuel resources.

hydrogen. Achieving this pathway requires large-scale deployment of renewable generation, storage and transmission capacity along with accelerated technological developments in the manufacture and use of electrical and hydrogen devices for power, steam and heat.

The report focuses on the analysis of coupled but gradual decarbonization of all these sectors of the economy. Sector coupling can contribute to cost efficiency in capital allocation by realizing synergies and linkages between different sectors of the economy.[4] It also enables the capture of potential savings in energy and infrastructure costs.

The analysis also reviews the benefits of decarbonization including energy savings, efficiency gains, better use of generation and of transmission infrastructure, reduced costs of goods and services, health benefits, and the value of avoided carbon emissions. The report examines the net employment generation and business opportunities, under the proposed scenario, and the potential for technological and entrepreneurial development.

However, this report is not a feasibility study and does not provide detailed descriptions of individual decarbonization actions. Instead, it offers general guidelines, with gross estimates of costs and benefits, of a pathway to a zero-emissions, electrified economy by mid-century.

**Methodology and data sources**. The analysis is based on publicly available government plans and information, data, and industry sources. Energy information was obtained from the Ministry of Energy, ENERDATA, and BP statistics. Information on energy infrastructure was downloaded from the global energy monitoring website (globalenergymonitor.org). Sector data was drawn from government reports and independent technical analysis. The business-as-usual scenario is the Government's Carbon Neutrality Scenario as described in Ortiz and Zurita, 2023. The specific costs of energy, transportation, industrial products, and delivery of heat to various sectors of the economy were estimated using the Chile module of the Greenhouse Abatement Cost Model (GACMO) as developed by the authors. Outputs of the transport sector under the Zero Carbon Emissions Scenario were estimated with the Chile module of the Global Change Assessment Model (GCAM). As this is an assessment of economic impacts, no fees, levies, or taxes are considered.

[4] Coupling of the decarbonization of the power and transport sectors at a Latin America regional level was already explored by Vergara et. al., 2021 (https://www.researchgate.net/publication/349443731_The-Opportunity_cost_and_benefits-of_the_coupled_decarbonization_of_the_power_and_transport_sectors_in_Latin_America).

# 2. Business as Usual Scenario: Carbon Neutral Economy Scenario by 2050 (CNS)

Chile has made the political commitment, through its Climate Change Framework Law (2022), to reach carbon neutrality by mid-century. This will be achieved through key mitigation strategies, including government and private sector joint goals and voluntary steps. The Framework Law outlines an ambitious and comprehensive roadmap for decoupling economic activity from carbon emissions, comparable to, and in some respects exceeding, the scope and reach of those espoused by advanced and committed economies in Europe.

Key strategies include improving sustainability in industry; producing green hydrogen; transitioning to electric transport; phasing out coal; improving energy efficiency; and promoting sustainable building practices. However, these measures are not sufficient to eliminate the economy's carbon footprint. To ensure carbon neutrality, the Government of Chile (GOC) plans to accumulate carbon stocks in natural vegetation.

For purposes of the analysis the BAU is based on the current policy goals to achieve carbon neutrality as outlined in the PELP (Long Term Energy Planning, 2021) and further described in 2023 (Toro C., and B. Munoz, 2023). As the proposed scenario covers all sectors of the economy, the BAU is also based on the goals outlined in the National Electromobility Strategy launched in 2021 (NES, 2021; estrategia_nacional_de_electromovilidad_2021_0.pdf (energia.gob.cl)), pertaining to the transport sector. It also considers the goals described in its (National Lithium Strategy: Discover the Strategy for the Economic Development of Chile - Gob.cl (www.gob.cl)), the provisions under the energy efficiency law (and its hydrogen generation strategy (green_h2_strategy_chile.pdf (energia.gob.cl). It finally considers the goals of the energy transition law (https://www.gob.cl/noticias/ley-transicion-energetica-promulgacion-caracteristicas/) an effort to increase and refine the energy transmission infrastructure, focusing on the development of transmission lines and encouraging competition and storage.

The BAU for the power sector is the accelerated carbon neutrality scenario, described in the PELP, with anticipated generation of 288 TWh by 2050 with zero GHG emissions and 72% Variable Renewable Energy. This scenario requires battery storage for flow control as well as an expansion of the transmission system including 1500 km, 2 GW HVDC to be commissioned by 2029.

ENAP oil refinery in Chile.

In transportation, the BAU envisions all light and medium weight vehicles sold in Chile by 2030 to be electric, and all heavy vehicles sold by 2040 to be 100% electric. The strategy calls for the set-up of incentives for the rapid adoption of electrical transport; the strengthening of the network of charging stations; training, research and development in electrical drives and ancillary systems; and promotion of international cooperation.

Under the Hydrogen Generation Strategy, Chile would become a major producer and exporter of hydrogen ($H_2$). For the domestic market, $H_2$ would be used as a feedstock for industry and as fuel for transportation. The current plan envisions an associated potential dedicated to hydrogen production of about 90 GW by mid-century.

The Chilean Law on Energy Efficiency (CLEE, 2021) establishes a National Plan, a consumer registry with energy management capacity, an implementation system, and efficiency label, and rating report to be issued for buildings. The Plan would be updated every five years and would include residential energy efficiency; minimum standards and labelling of appliances; energy efficiency in buildings and transport; energy efficiency in the productive sectors; as well as education and training programs to promote the efficient use of energy.

These actions are complemented by Chile's National Plan for Restoration of Landscapes and other land management measures anticipated to compensate for about half of the emissions of GHG by 2050, or roughly 65 million tons of $CO_2$ equivalent. The Plan aims to restore one million hectares of natural ecosystems through preventive fire management, sustainable forest management, and reforestation with native species.

Table 1 below summarizes some of the most relevant goals and policy instruments under the BAU.

## Table 1: Goals and Policy Instruments for the Carbon Neutrality Objective

| Topic | Goals | Policy instrument |
|---|---|---|
| Energy generation | (1) Reaching carbon neutrality by 2050,<br>(2) phasing out coal power by 2040, and<br>(3) increasing the share of renewable energy (RE) in electricity to 70% by 2030<br>Under an accelerated carbon neutrality scenario: 72% of variable renewable energy (VRE) by 2050 with zero emissions from the power sector. | Action Plan for Rapid Power Sector Decarbonization (PELP). |
| Electric Transmission | To encourage infrastructure development and promote storage facilities in the electricity market. | Energy Transition Law. |
| Transportation | Gradual electrification in road transport. | Electromobility Strategy. |
| Green Hydrogen | Associated 90 GW of renewable energy dedicated to the production of hydrogen for the domestic sector by mid-century. | Green Hydrogen Plan of Action. |
| Energy Efficiency | Adoption of energy efficiency goals renovated every five years. | Energy efficiency plan. |
| Green Steel 2030 | Low emissions steel production. | Memorandum of cooperation CORFO-AZA-SMS. |
| Land Management | One million hectares under restoration by 2030 and other unspecified measures. | National Restoration Plan. |

# 3. Proposed Scenario: Zero CO2 Emissions Economy Scenario by 2050 (ZES)

For this analysis, the proposed alternative considers all current mitigation strategies under the Carbon Neutrality Scenario. It also assumes that these strategies will be expanded and supplemented as needed to eliminate all fossil CO2 emissions by 2050, allowing Chile to achieve a zero-fossil-carbon emissions economy by mid-century. The elimination of fossil fuels would also reduce $NO_x$ and $SO_x$ emissions.

To ensure zero carbon emissions, the proposed scenario makes the following assumptions:

- **Electrification of the economy:** By mid-century all economic sectors and activities that rely on fossil fuel resources are electrified or substituted.
- **Power generation mix:** The system expands to meet the needs of a fully electric economy, relying solely on the use of renewable energy resources (wind, solar, hydro, geothermal, and biomass), supported by storage technologies and a sizeable expansion of the transmission system relying on new technologies. Storage capacity is scaled to optimize online generation capacity, while all natural gas power plants and gas infrastructure are phased out before 2050.
- **Transport sector:** All modes of transport are electrified, including passengers and cargo by road, rial, and ship. Specialized fleets (e.g., fishing and mining) are electrified using batteries or fuel cells. Aviation fuel use is also partially displaced.
- **Hydrogen:** Capacity for hydrolyzation of water is expanded to meet the demand for hydrogen in heavy duty/long-haul transportation applications as well as for specific uses in industry and some power generation through the retrofitting of Gas turbines.
- **Industry:** The industrial sector uses hydrogen and electricity to generate steam and heat, displacing fossil fuel use. In heavy industries, electrical alternatives replace fossil fuel-based high-heat applications in steel, cement and pulp and paper manufacture.
- **Building:** Residential and commercial space heating and cooling are fully electrified.
- **Energy efficiency:** Efficiency gains stem primarily from the adoption of inherently more efficient electric technologies, supplemented by building-sector efficiency programs.
- **Carbon sink:** No reliance on carbon sinks. The carbon captured through land-based sinks would be a contribution to a net reduction of atmospheric GHG emissions but does not affect the zero-carbon emission status of the economy.

The transition to 2050 is gradual and assumes that about one third of the GHGs are displaced by 2030, 60% by 2040 and the remaining by 2050. Benefits from the scenario are represented by:

- Savings in investment and operations from deploying cheaper sources of energy compared to the BAU.
- Lower recurring operation and maintenance cost by substituting fossil fuels across the economy with the use of electricity.
- Reduced transportation services and equipment costs using electric drives and cheaper electricity.
- Reduced industrial production costs from the use of green hydrogen and electricity to generate heat and steam.
- Benefits from avoided mortality and morbidity resulting from reductions in VOCs, $NO_x$, $SO_x$, and particulates emissions linked to the use of fossil fuel in transport and industry.
- Gains in grid efficiency through the achievement of a flatter daily demand curve and optimized deployment of battery storage and hydrogen.
- Net employment generation under the proposed scenario compared to BAU.
- New enterprise development opportunities.

The scenario also considers alignment with a transition that aims to make the electrical economy fair and inclusive for all, ensuring work opportunities and minimizing exclusion.

*Cerro Dominador concentrated solar power (CSP) plant, Atacama Desert, Chile. Photo: Cerro Dominador*

# 4. Chile's Energy Demand

This section characterizes the demand for energy today and in the future as estimated in the PELP in order to project the value and characteristics of future electricity demand in an electric economy.

*Santiago cityscape and highways at night. Photo: Hernán Claro.*

## a) Current demand for energy

In 2023, Chile's economy required approximately 1364 PJ (379 TWh) of final energy, a 12% post-COVID recovery since 2020. Transport was the largest energy consumer, followed by Industry and by Mining. Jointly, these sectors accounted for 70% of the energy used, making them the primary targets for electrification. In 2023, an estimated 302 PJ (84 TWh) were supplied by electricity, of which about 70% came from renewables. See Table 2 for a summary of sector demand.

## Table 2: Sector Energy Demand

| Sector | 2020 | | 2023 | |
|---|---|---|---|---|
| | **PJ** | **TWh** | **PJ** | **TWh** |
| Transport | 392 | 109 | 454 | 126 |
| Industry | 259 | 72 | 281 | 78 |
| Mining | 212 | 59 | 227 | 63 |
| Residential | 209 | 58 | 227 | 63 |
| Commerce and Public Sector | 94 | 26 | 101 | 28 |
| Agriculture | 43 | 12 | 65 | 18 |
| Others | 7 | 2 | 7 | 2 |
| Total | 1220 | 339 | 1364 | 379 |

Source: Balance Nacional de Energia 2020, Ministry of Energy, May 2022; Energiaabierta.cl accessed January 2025. Statista Market Research accessed December 2024, and author's estimates

### b) Projected energy demand under the Zero Carbon Emissions Scenario (ZES)

The CNS roughly assumes that half of the economy will be electrified by 2050. Under the ZES, however, 100% electrification is reached by mid-century (33% by 2030 and 60% by 2040).

The key differences between the scenarios are:

- Additional load on the electric system under the ZES, changing the magnitude and characteristics of the daily load curves.
- Higher energy efficiency is derived from the faster deployment of electric engines and devices.

The analysis estimates the actual work that needs to be delivered to power all economic activities under current energy demand projections.[5] The electricity required to meet these work requirements is calculated using the efficiencies of electrical devices, at the assumed gradual pace of electrification until 2050.

Electrification of all economic activities implies higher electricity demand than is expected under the CNS, 846 PJ (237 TWh) by 2050 vs. 1343 PJ (376 TWh) under the ZES. This means that during the transition period, from now until 2050, significant loads are gradually added to the demand for electricity and to the infrastructure requirements for generation, storage, transmission and distribution. This would be required despite an increased overall energy efficiency of the economy as it electrifies.

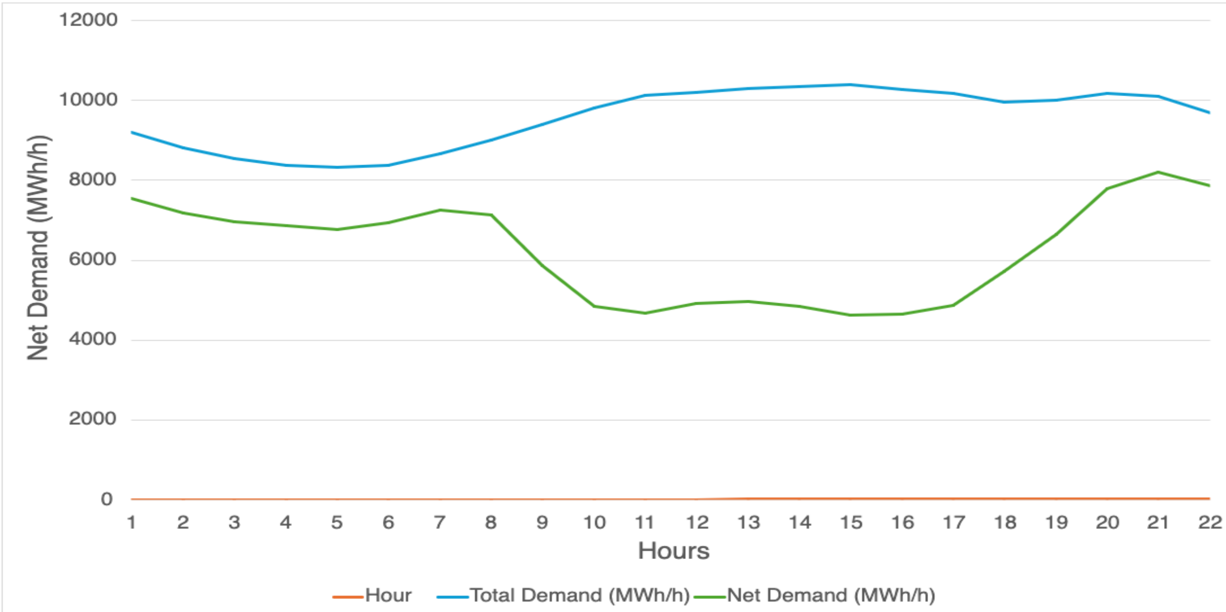
As the power system will gradually be dominated by renewables aided by the use of storage (batteries and hydrogen), it is critical to characterize the daily load curve. This will allow an estimate of the size and peak capacity of the generation matrix and its composition.

**Daily demand curve.** Typically, daily loads are calculated only for power generation (EPA, 2007; Castillo et al., 2022). However, in this case, the daily load curve must reflect the demand conditions of all sectors (transportation, industry, mining, fisheries, residential, commercial, and others).

The analysis uses a modeling of Chile's historical hourly electricity demand with data from the National Electricity Coordinator (NEC: *Servimos a Chile con Energía*, 2025). The annual electricity demand in 2024 was estimated at about 307 PJ or 85.3 TWh (*Chile Energy Information*, 2025). Total demand and "net demand" or total demand less electricity generated from wind and solar, are presented in figure 2. The difference between the two curves identifies the periods during which electricity generation by renewables and use of stored energy would need to be built up to meet demand patterns under today's conditions.

[5] Most of the energy contained in fossil fuels is not delivered as useful work to the economy but rather is released as heat. This is a consequence of thermodynamic limitations in the use of fossil fuels and the efficiencies of Otto and Diesel engines, and other fossil-fuel based devices. On the other hand, electricity has a very low entropy and can deliver most of its energy for end use. In other words, electric motors and engines are typically substantially more efficient that the counterpart fossil fuel engines and therefore can meet the work requirements with a comparatively smaller delivery of energy.

**Figure 2: Chile's current daily load curve for electricity demand (2023)**




Source: Author's estimates based on data from the National Electricity Coordinator (NEC)

Note that today the difference between the two curves is as much as 100% of the net demand. However, the daily load curve that matters for the analysis is the aggregate of all anticipated sector-based electricity demands as those electrify. Meeting energy demand using electricity, changes the total amount required as electrical devices improve energy efficiency significantly.

The analysis covers electricity generation, transport, industry, mining, fisheries, agriculture, commerce, and residential sectors. Table 3 outlines those sector demands and identifies electrical alternatives.

## Table 3: Current efficiencies of Energy and Electricity use by Sector

| Sector | Annual growth rate to 2050 (%) | Fossil fuels under current use | Efficiency of fossil fuel use (%) | Substitutes | Projected efficiency of electricity use by 2050 (%) |
|---|---|---|---|---|---|
| **Power generation** | 1% 2020-2029[6] | Natural gas, turbines. | 42 | Wind, solar generation. | 89 |
| **Transportation** Road passenger and cargo Rail passenger and cargo Coastal shipping. | 1.3 | Diesel, marine diesel and gasoline engines. | 32 | Electric engines Hydrogen-Fuel cells[7] for heavy duty applications. | 82 |
| **Mining** Copper, iron, and others. | 3.6 | Diesel and Natural Gas engines Fuel Oil boilers. | 39 | Electric motors and boilers. | 83 |
| **Industry,** iron/steel, paper/cellulose, Petrochemicals, cement, agroindustry, food industry, | 2.7 | Wood stoves Diesel and Natural Gas engines, furnaces. LPG, Natural Gas and Fuel Oil boilers. | 46 | Electric radiators Electric engines Electric boiler and furnaces. New fossil-fuel free processes in | 93 |

[6] C. Ortiz and Zurita B, 2023: Chile's Action Plan for Power Sector Decarbonization (nrel.gov) and author's estimates

[7] Heavy duty transportation vehicles are projected to preferentially make use of hydrogen fuel cells in which case the overall efficiency of H2 production and electricity delivery by the fuel cell is used.

| | | | | | |
|---|---|---|---|---|---|
| construction, others. | | | | cement, steel and pulp and paper. | |
| **Fisheries** | 4.9 | Diesel and Marine diesel engines<br>LPG boilers<br>Natural Gas engines. | 42 | Electric motors and boilers. | 83 |
| **Commerce** | 0.2[8] | Diesel engines<br>LPG, fuel oil and natural gas boilers<br>Wood stoves. | 59 | Electric motors and boilers<br>Electric radiators. | 89 |
| **Residential**[9] | Nil | Wood stoves, LPG and natural gas boilers. | 56 | Electric radiators<br>Electric boilers. | 99 |
| **Agriculture** | 2.5[10] | Diesel and gasoline pumps, trucks, processing equipment. | 50 | Electric pumps, vehicles and engines. | 89 |
| **Overall economy** | | | | | 86 |

[8] The use of energy in the commercial sector grew slightly between 2018 and 2019 (Pre COVID).
[9] The average use of energy in the residential sector was 8.1 MWh per dwelling in 2019 (https://energia.gob.cl/sites/default/files/20210601_-_sesion_1_mesa_ee_en_edificaciones.pdf) and it fell by 4% between 2009 and 2018
[10] Productividad del Sector Agricola: Una Mirada Global. Ministerio de Agricultura. ODEPA. January 2019.

## c) Projected electricity demand under the ZES

To estimate future electricity demand, projected energy demand under the CNS from the PELP was used. The work delivered to the economy was calculated based on the specific energy sources and the efficiencies of transformation devices (engines, boilers, furnaces, radiators; see Table 3). Required electricity was estimated using current efficiencies of alternative electric devices. The projected energy demand (as reported by the "Anuario Nacional de Energia", 2023), the electricity demand under the business-as-usual scenario (CNS), and the projected electricity demand under ZES are presented in Table 4.

**Table 4: Projected Energy and Electricity Demand**

| YEAR | Projected Energy Demand (PELP CNS) | | Estimated Work Delivered | | Projected Electricity Demand under the Carbon Neutrality Scenario | | Projected Electricity Demand under the Zero Emissions Scenario (ZES) | | Overall estimated energy efficiency under the ZES (%) |
|---|---|---|---|---|---|---|---|---|---|
| | TWh | PJ | PJ | | TWh | PJ | TWh | PJ | |
| 2030 | 379 | 1364[11] | 767 | | 106 | 381 | 152 | 544 | |
| 2040 | 448 | 1603 | 890 | | 178 | 634 | 350 | 1253 | |
| 2050 | 561 | 2006 | 1135 | | 237 | 846 | 373 | 1343 | 86 |

Source: The projected energy demand reflects the demand anticipated under the Carbon Neutrality Scenario (CNS or BAU) in the PELP. Work delivered is based on the degree of electrification under the Carbon Neutrality Scenario and the relative use of fossil fuel vs electric devices. The BAU's projected electricity demand is from the projections in the PELP. The CNS electricity use reflects the degree of electrification proposed in the PELP

[11] There is a discontinuity between the current energy final energy use as reported in energiaabierta.cl and the projections in the PELP. The current energy use in 2023 is already at the levels of the 2030 projection in the PELP. The authors opted to continue with the PELP projections for purposes of the estimates in the report.

by 2050. The projected ZES electricity demand is based on the assumed pace of electrification and the gains in energy efficiency derived from the relative use of electric devices.

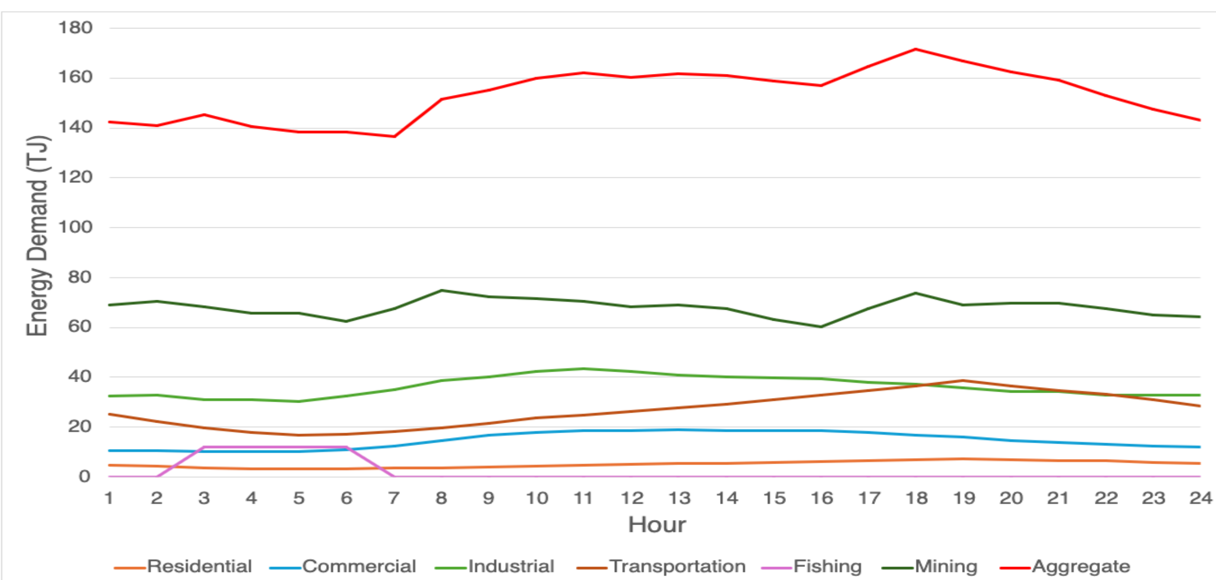
As shown in Table 4, projected electricity demand in 2050 (1343 PJ) is lower than the PELP's 2030 projection (1364 PJ). This underscores the significant impact of electrification on the economy. Projected hourly electricity demand was derived from estimates of sector-based power estimates in a fully electrified economy (see Annex A).

Some sectors will have a higher demand for electricity during periods that are traditionally low electricity-demand periods. An example is the energy demand for transportation, which is expected to be dominated by overnight charging. The replacement of natural gas and biomass for electricity in residential heating during evening and early morning hours is another example. The fishing fleet is also modeled to charge in the early morning hours.

The pace of the transition determines how fast sectors electrify. As indicated, it has been assumed that one third of the work required by the economy is electrified by 2030, from the current level of 24%, and 60% by 2040; all work requirements are met by electricity by 2050.

By mid-century, the combined hourly demand curve is flatter (Figure 3); the peak demand of 168 TJ (hour 18) is 28% higher than the lowest demand of 133 TJ (hour 7). This reduces variability and the strain on the grid. It also has the potential to lower the relative share of storage needed. However, it demands a reliable and substantial supply at all hours.

**Figure 3. Sector-based and aggregated Hourly Electricity Demand Curve by 2050**




Source: Authors' estimates (see Annex A for additional details)

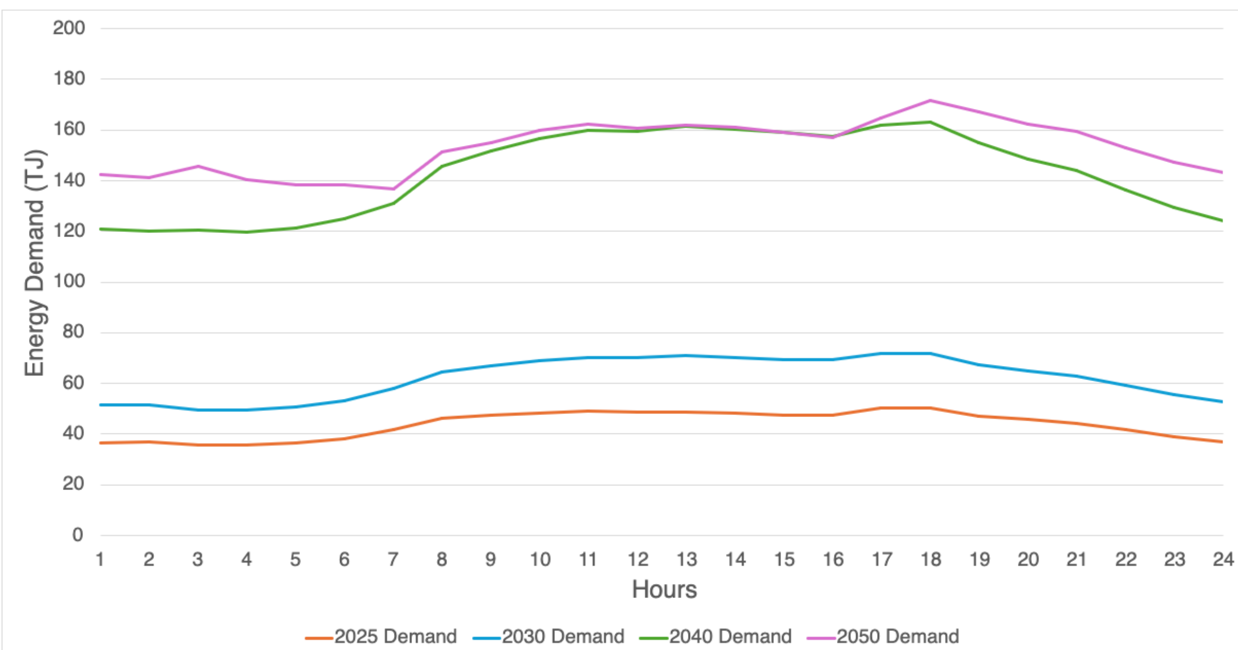
The energy demand and the electricity demand in 2050 are linked (all the economy has been electrified) and the overall efficiency is determined solely by the use of electrical devices. That is not the case during the transition period.

## d) Demand during the transition period

The projected 2040 peak energy demand is just slightly above the 2030 peak demand even though the projected overall demand for energy under the carbon neutrality scenario is projected to nearly double.[12] The calculated peak demand requirements for 2040 and 2050 are nearly the same (figure 4).

Also, the estimated increase in electricity demand under the ZES is 50% above the CNS by 2030, almost 100% by 2040 but falls to 60% of BAU energy demand by 2050 as the energy efficiency gains from electrification of the whole economy kick in. Electrification is the single most important step to improve energy efficiency, and it can be achieved without reductions in the level of energy use.

**Figure 4: Projected aggregated daily load energy curves for the Chilean economy (2025 to 2050)**

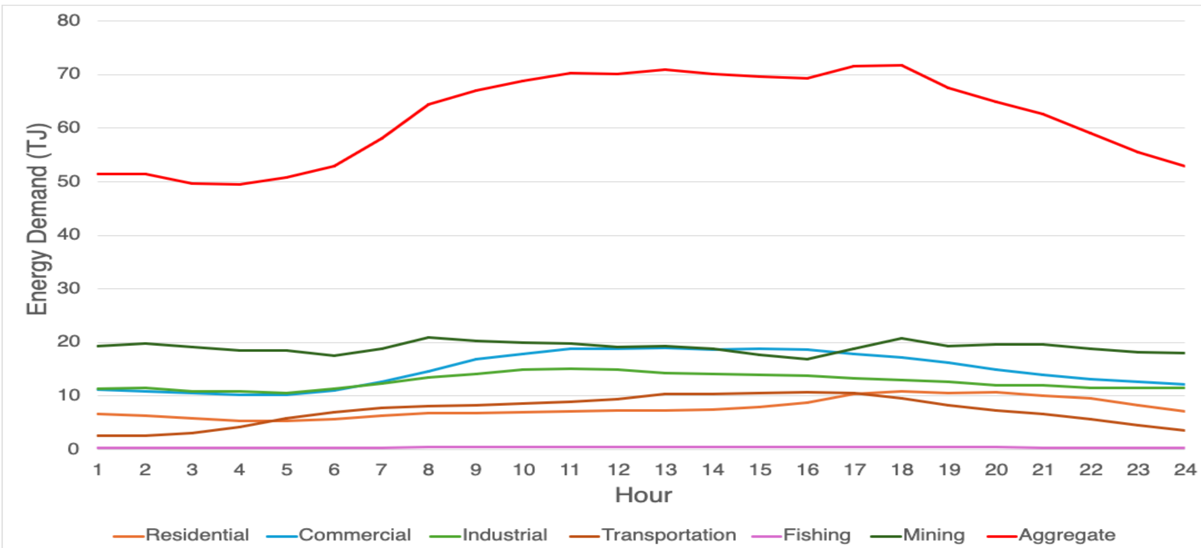



Source: Authors' estimates

[12] Chile's Action Plan for Power Sector Decarbonization (nrel.gov)

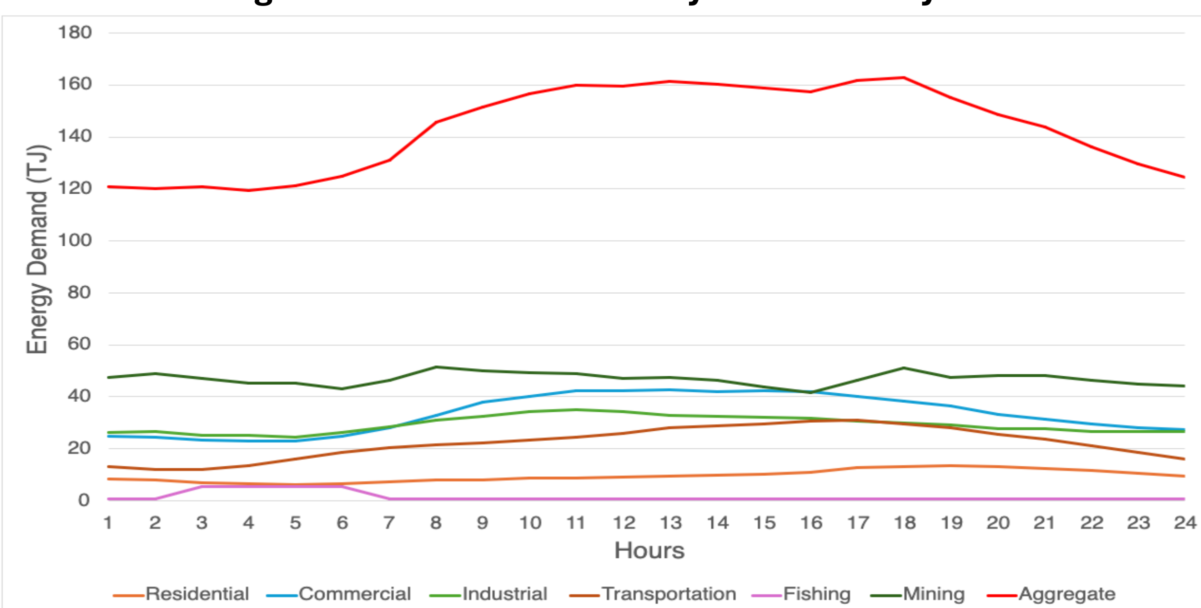
**Electricity demand during the transition period.** Sector-based hourly electricity demand for 2030 and 2040 was modeled, with the results shown in Figures 5 and 6. Electricity demand during non-working hours rises as new economic activities electrify, this increase is offset by the improved efficiency of electric devices

**Figure 5: Modeled Electricity load curve by 2030**




Source: Author's estimates

**Figure 6: Modeled Electricity load curve by 2040**




Source: Author's estimates

The electricity load curves show substantial load growth over time. By 2050, mining is projected to dominate electricity demand, followed by transport and industry.

**Estimate of generation capacity.** The estimated evolution of peak demand for electricity and the required peak capacity is shown in Table 5. The actual generation capacity in this analysis is sized at 10% over the nominal generation capacity to attend peak demand.[13] Two additional factors need to be considered regarding the size of generation capacity under the ZES: a) distributed generation capacity; and b) storage capacity.

> **Distributed generation capacity**. As of mid-2024, there were 3.6 GW of installed distributed power capacity, reflecting a 10-fold increase since 2008.[14] The use of distributed generation will ease the burdens on the expansion of the central generation system. However, more recently, there has been a period of deacceleration in growth of distributed power caused by transmission congestion. To promote growth, bottlenecks in infrastructure at the point of use would need to be addressed. For the purposes of this analysis, the distributed capacity has been maintained at a level that would contribute to the same fraction of total renewable capacity as served today, estimated to be at around 10%.[15]
>
> **Storage capacity.** The contribution of storage to future capacity has also been estimated. Under the PELP, in 2050, about 10 GW are expected to be storage capacity. The storage capacity under the ZES has been estimated on the basis of an analysis made for the power system under 100% renewables[16] (see section 5 and Annex B).

**Estimate of Peak capacity to meet demand.** The required capacity to meet demand by mid-century can be estimated based on the anticipated capacity factors for solar and wind as the system is fully based on renewables under the ZES scenario (See Table 5).

---

[13] The amount of generation capacity required to attend peak demand in a well-run grid is normally sized to have around10% more generation capacity than peak demand to ensure sufficient reserve power during high usage periods and have a margin to meet unforeseen circumstances. A substantial margin in generation and storage capacity is also desirable to prevent outages

[14] https://www.ibanet.org/opportunities-challenges-distributed-energy-chile

[15] Distributed generation has been also estimated as part of the PELP under the Carbon Neutrality Scenario. According to those projections, by 2050 about 32 GW of distributed energy are projected to contribute to the energy supply and demand through the grid. However, given the slow recent uptake in distributed capacity this projection seems high. Using a conservative estimate results in a higher requirement for the grid. https://energypartnership.cl/fileadmin/chile/highlights/Energy_Group_B2G_Distributed_Generation/20211012_Distributed_Genetarion_Projection_for_Chile.pdf

[16] An alternative scenario of projected storage, using the X-link methodology would resuls in significantly lower requirements in storage capacity.

## Table 5: Peak Electricity Demand and Peak Electricity Generation Capacity under ZES

| Item | TWh | Observations |
|---|---|---|
| Demand for electricity. | 373 | Estimated based on the projected energy demand under the PELP and the electrification of all the economy. |
| Losses during transmission & distribution. | 20 | Estimated as 5% of all electricity delivered to the grid. |
| Total supply. | 393 | |
| Peak demand (hour 18). | 48 | |

Source: Authors' estimates and projections in the PELP. In 2050 the capacity factor is 32% for wind, 36% for solar and 60% for CSP.

Some implications from the analysis are:

The adoption of the ZES will result in energy savings of the order of 660 PJ, by 2050, representing about one third of the projected energy demand under the CNS. The analysis concludes that by 2050 under the ZES the overall economy would have an energy efficiency of 86% and a total energy demand about the same as that projected for 2030 under the PELP.

Under the pace of transition, a significant increase in electricity demand will take place. This will imply major increases in generation and transmission capacity (see section 7). However, when compared with the PELP energy demand scenarios, the ZES represents significant cost savings in investment and operation (see section 7).

The flatness of the load curves anticipated under the ZES, reduces the need for major percentual allocations of storage capacity. This does not mean, however, that a substantial storage capacity allowance is not required (see section 5).

The reduction in the peak/valley demand ratio is also the result of increases in overnight electricity demand. To address overnight electricity demand, investments will need to be made in storage capacity and wind energy, even if relative costs are higher.

Despite energy efficiency gains, the additional capacity requirements are significant. Over 180 GW of generation and storage capacity will need to be in place by mid-century.

# 5. Future Supply of Electricity

This section estimates the supply of electricity and the associated composition of the renewable energy power matrix, required to meet future electricity demand. The analysis assumes that the 2050 composition of the power generation matrix is heavily reliant on wind and solar complemented with storage (batteries and hydrogen) and hydropower generation. Other resources[17] like geothermal and biomass are considered at the margin. It also eliminates the use of LNG and sizes supply for a much larger demand.

*Planta Solar Chañares, Atacama Desert, Chile — one of the country's largest photovoltaic power plants. Photo: ENEL*

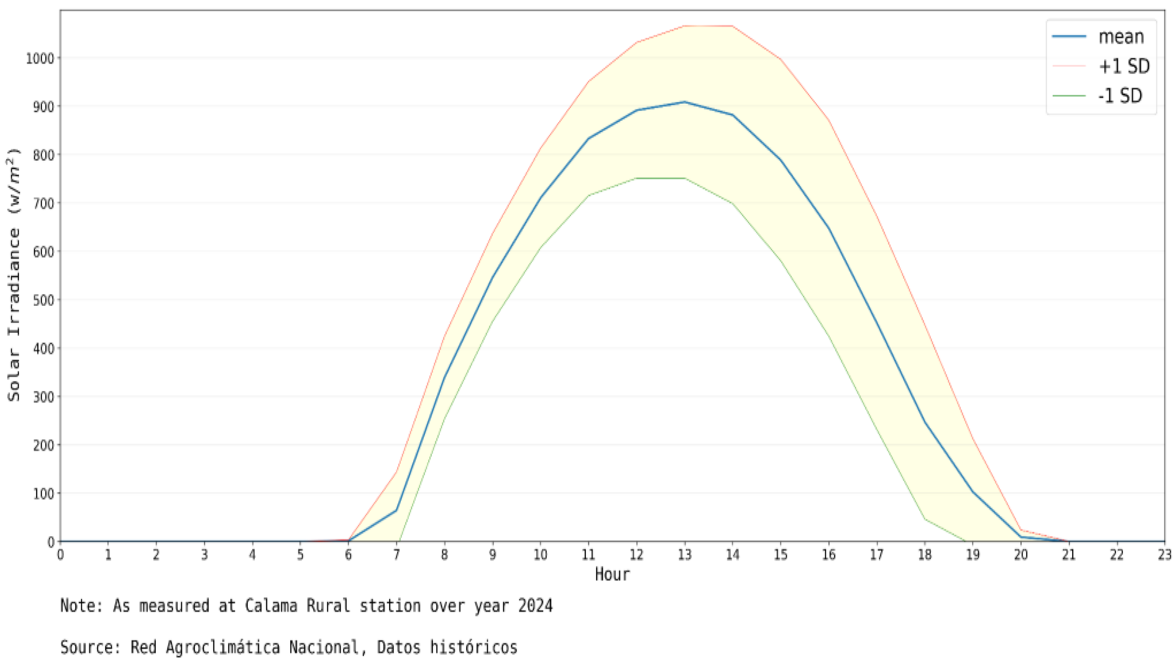
## a) Supply of renewable energy

**Diversity of supply.** The random nature of renewable energy resources calls for a more varied composition of the grid as a hedge against periods of renewable energy scarcity, for example, low wind or sustained periods of cloudiness. However, in the case of Chile, both the wind regimes in the south and along the coasts and the solar radiation in Atacama are remarkably robust. Additionally, Chile has the option of setting up H2 production facilities and has access to other renewable resources, including substantial endowments of geothermal and marine energy. Although marine energy applications are not yet viable to compete with solar or wind in Chile, it makes sense to maintain an active development program for the future. The inclusion of marine energy would further diversify future supply.

[17] Marine energy is not considered in this analysis, despite its large potential in Chile, given its currently high cost.

**Reliability.** Chile counts with a reliable solar energy resource. A solar data base for Chile is available (Molina et al., 2017) and several solar stations have operated for decades. The data available indicates radiation fluctuates between 15 and 30 MJ/m$^2$ throughout the year in Atacama. Based on data from stations in Antofagasta, daily solar radiance has been estimated (Marzo et al., 2017). Figure 7 presents the daily average radiation at the Catama station, which is well documented and thus is used in the analysis as typical of the conditions in the Atacama.

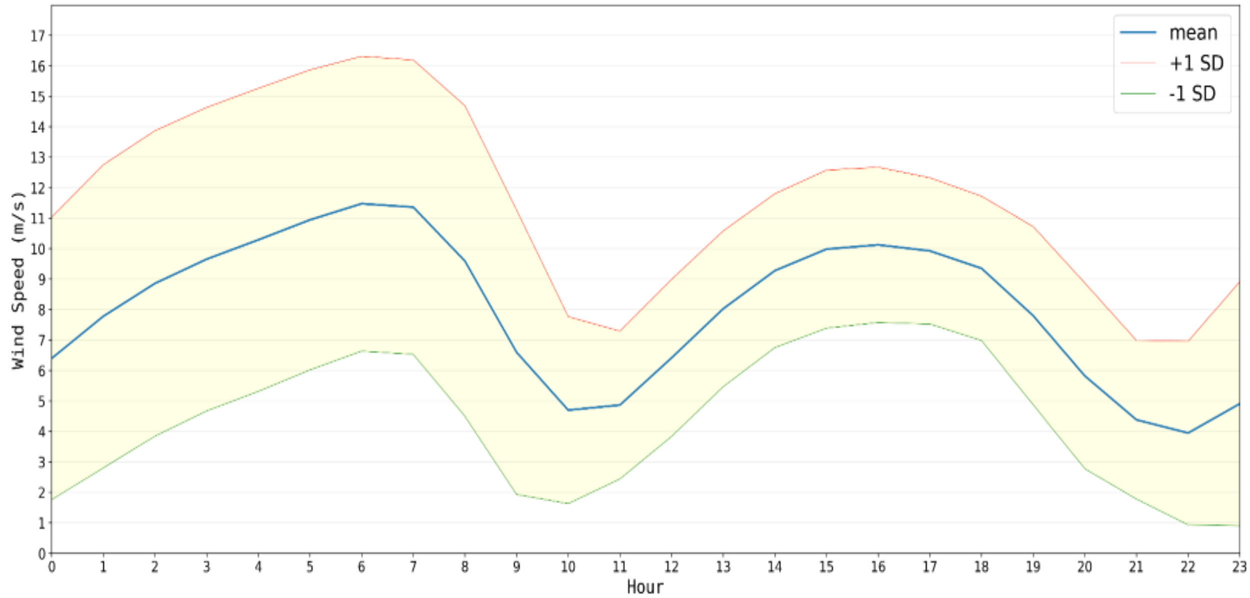
**Figure 7: Daily variation in solar radiation as measured in the Catama station in Antofagasta.**




Source: Red Agroclimatica Nacional, Datos Historicos, measurements reflect solar radiation at the surface.

In the case of wind, regimes in Chile are also consistent, matching or surpassing those elsewhere (Gomez-Fontealba et al, 2022). Wind variations during the day, at Catama, are less pronounced than solar (figure 8) and offer the ability to produce energy when solar radiation is not available.

**Figure 8: Daily variation in wind intensity as measured in the Catama station in Antofagasta at 80 m above surface.**




Note: As measured near Calama in 2011 and 2012

Source: Wind and Solar resource measurement campaign, Wind and Solar resource measurement campaign

Source: Red Agroclimatica Nacional, Datos Historicos

**Storage.** Despite well documented average profiles, both wind and solar production are random. A wind and solar dominated system will require storage as protection to ensure a smooth daily supply as well as safety against interannual variations. A review of a long series of production of wind and solar energy plants is ideally required to optimize the share of storage in the system. Such data is still being developed, and a clearer picture will emerge as more renewable projects come online.

By way of example, in Germany a review using 35 years of hourly time series data for renewable generation and load, recommends 56 TWh of storage in a 540 TWh (10% ; (Ruhnau & Qvist, 2021) demand to be supplied entirely by renewables, mostly solar and wind. Also, in Spain, a recent report considers up to 6% of reversible storage capacity in a system with large available hydro power (Alonso et al., 2011).

Likewise, a recent U.S. review of supply-side options to achieve 100% clean electricity by 2035 (Denholm et al., 2022) highlights the role of diurnal storage to balance demand and renewable output year-round; it estimates up to 12 TWh of diurnal storage for a 9000 TWh demand.

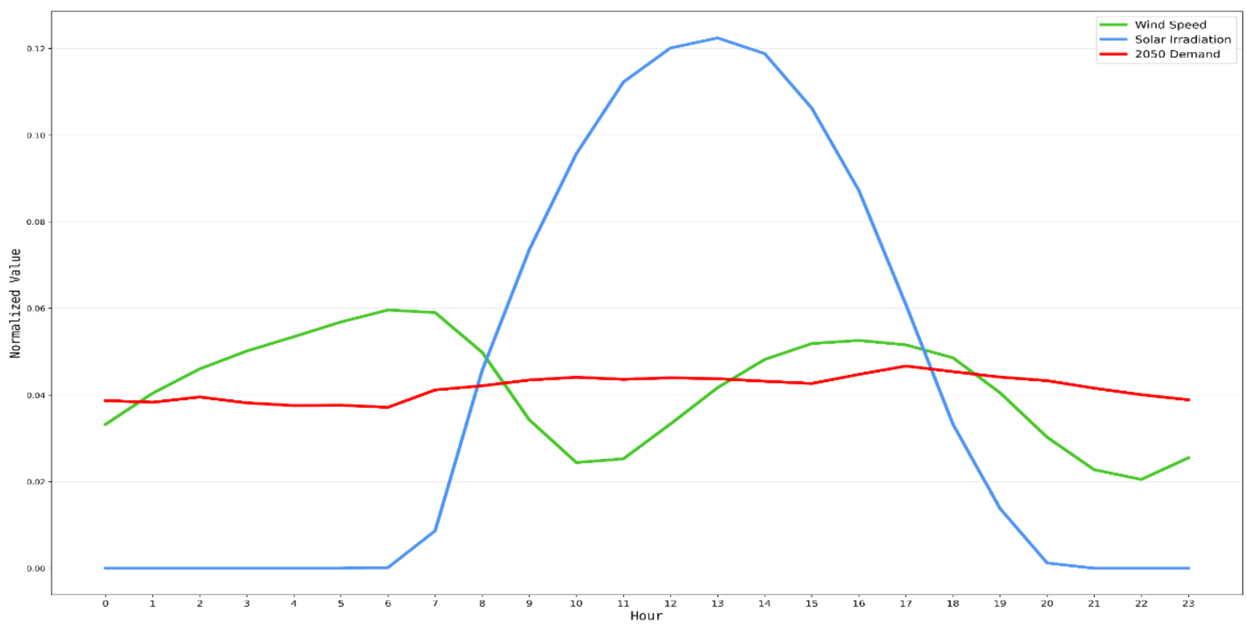
b) Use of battery storage in the future power matrix

Sizing storage capacity not only addresses the daily imbalance in demand and supply but also optimizes investment and reduces curtailment of generation capacity (Jacobo J., 2025).[18] It should also cover extreme events and inter-annual variability.

Modeling the optimal storage capacity is beyond the scope of the current analysis. Instead, a simplified supply/demand analysis using normalized curves is applied. Energy deficits and surpluses are addressed within daily supply and demand with a peak capacity sized to meet peak demand. Further details are provided in Annex B.

**Demand supply balance.** A comparison of demand characteristics with solar and wind supply[19] in Chile is shown in Figure 9. Anticipated demand is relatively stable, while wind is more consistent than solar. This stability underscores the importance of incorporating wind energy into the power matrix, even if its costs are higher.

**Figure 9: Normalized supply and demand**




Source: Author's calculations.

The analysis concludes that central capacity would need to be complemented with energy storage to meet demand during periods when generation is inadequate. The

[18] Curtailment has become significant in recent years; for example, 3.4 TWh of renewables were curtailed between January and September of 2024. https://www.pv-tech.org/chile-curtailed-3-4twh-of-renewable-capacity-up-to-september-2024/. It reached 0.65 TWh in January 2025, a record in the country (https://renewablesnow.com/news/chile-curtails-record-653-gwh-of-renewable-power-in-jan-1271423/)

[19] Data drawn from the Catama station, weather records.

battery storage capacity required, assuming an 8-hour discharge, is 31 GW[20] and is complemented with 2 GW of CCGT capacity using energy stored in Hydrogen and 3 GW of energy stored as thermal energy in CSP plants (this equals close to half of projected CSP-generation installed capacity).

**Use of H2 as an energy carrier.** Under the ZES, hydrogen is expected to fill key niches in the energy supply/demand balance, including heavy duty transportation, retrofitted combined cycle power generation plants and specialized industrial applications. All hydrogen is projected to be generated using solar/wind.

**Inter-annual variability.** Managing the inter-annual variability of renewable energy is challenging, especially for wind and hydropower. Solar energy varies less yearly, and offshore wind power is more stable than onshore wind. However, there will be periods of less wind. A key issue to assess is the influence of the El Nino Southern Oscillation (ENSO) on wind energy production, as well as its impact on the wind potential at different sites across Chile (Watts et al., 2017).Despite the impact of inter-annual variations in determining storage needs, insufficient data limited the analysis and therefore its impact on supply was not considered. It is clear however that more storage capacity will be needed to handle fluctuations in wind supply, possibly through increased hydrogen production during periods of high wind.

**Role of distributed energy.** Chile's distributed energy resources consist of power plants with capacities up to 9 MW, connected to the grid via distribution or transmission lines, and net billing units with up to 300 kW of capacity, primarily connected through distribution lines within the service area of the distribution company. The latter is infrequently utilized.

As of July 2024, Chile’s Independent System Operator (ISO) reports that the installed capacity of distributed generators is 3.6 GW 79% solar, 12% thermoelectric, 7% hydroelectric, and 2% wind. The number of operating small distributed generation systems (PMGDs) fell from 493 in 2022 to 322 in 2023. The projections for distributed capacity under the PELP (Toro, 2021) place its contribution at 20 GW by mid-century. This analysis maintains a slightly lower contribution (17 GW), accounting for the recent slowdown in growth.

[20] During the transition period, in lieu of a similar analysis, a share of 25 of the installed renewable energy capacity is used.

**Composition of the power matrix.** The composition of the power matrix under the CNS is presented in Table 6. The ZES composition was estimated to minimize overall costs, with several scenarios considered.[21]

The lowest cost scenario uses a higher share of PV than wind but requires more storage (see Section 7, Table 16). Total capacity also includes the projected distributed capacity by 2050, 33 GW of storage (batteries and CCGT), and 3 GW of CSP thermal storage. Under others, the scenario uses 7 GW of geothermal and biomass. The balance also considers 5 % transmission losses.

## Table 6: Composition of the Power Matrix under the CNS and ZES by 2050 (GW)

| | Carbon Neutrality (CNS) | Zero Carbon Emissions (ZES). Installed Capacity | Zero Carbon Emissions (ZES). Net Generating Capacity | Estimated energy delivered in 2050 (TWh)[22] |
|---|---|---|---|---|
| Wind | 35 | 56[23] | 49 | 137 |
| Solar PV | 39 | 56 | 49 | 154 |
| Solar CSP | 4 | 6 | 6 | 18 |
| Distributed | 20 | 17 | 17 | 30 |

[21] The scenarios considered variations in the relative shares of PV; Wind and CSP (see Section 6, Table 15).

[22] To estimate actual amount of energy generated by source, the installed capacity was multiplied by its online factor. The difference between demand and generation at certain times of the day was used as the required storage. There were 8 hours with generation deficit. The discharge capacity of storage was set at 8 hours resulting in a capacity of 36 GW(see Annex B for details).

[23] The capacity for wind and PV in this table reflects the option of equal shares of wind and solar, which is justified in the discussion in section 7. It was increased by a 10% margin on total generating capacity to reflect maintenance stoppages as well as unexpected shutdowns.

| | | | | |
|---|---|---|---|---|
| Battery Storage (using periodic surpluses from wind and solar) | 10 | 31 | | |
| Storage embedded in CSP | | 3[24] | | |
| CCGT using hydrogen generated by wind and solar during periodic surpluses from wind and solar | | 2[25] | | |
| (total nominal storage capacity) | 10 | (36) | | |
| Hydro | 8 | 8 | 8 | 27 |
| Others | 7 | 1 | 1 | 7 |
| Total | | 180 | 130 | 373 |
| Losses | | | | 20[26] |
| Margin | | (14) | | |
| Delivered to the grid | 125 | | | 393 |

Source: Author's estimates

To meet daily demand, the total estimated 2050 capacity of the system is 180 GW, including a 10% margin of net generation capacity to address maintenance time and unexpected stoppages and 5% transmission losses. Ideally, the matrix should also have enough capacity to meet extreme events (low wind periods or dry hydrology). But this is not considered.

[24] Uses 50% of CSP nominal capacity as embedded storage (Gasa et al., 2022).
[25] Added to the nominal storage capacity of the system.
[26] Losses under the ZES have been kept at 5% down from recent 6.5%, reflecting the use of advanced transmission systems like multipoint HVDC, and reconductoring associated to lower losses and other technology improvements (section 7).

# 6. The cost of electricity generation in Chile

This section presents an estimate of the anticipated levelized cost of electricity generation. It does so by estimating future composition and costs of the power matrix needed to meet demand. The pace of adoption of renewables depends largely on their competitiveness against fossil fuels, global technology advancements, and policy decisions.

*Horizonte wind farm, Atacama Desert, Chile. Photo: Colbun*

## a) Trends in investment costs

In 2024, the world economy reached about 4.6 TW of installed renewable energy power generation capacity (Renewable Energy Statistics 2024 (irena.org)), about 1.6 TW more than in 2020. This rapid increase presages continued fast growth, driven increasingly by economics. As of mid-2025, Chile's share was 25.5 GW or 0.6%[27] of the global total (International Trade Administration, 2025). The growth in generation capacity has occurred alongside a steady, at times dramatic, decrease in both investment and generation costs, a trend expected to continue despite short-term geopolitical disruptions.

For example, onshore wind turbine prices fell from $1,800/kW in 2008 to $900/kW-$1,100/kW in 2023 (Land-Based Wind Market Report_2024 Edition_Executive_Summary.pdf (lbl.gov). Similarly, solar[28] panels have dropped from about $4000/kW in 2008 to less than

[27] This is already well above global averages as the population of Chile is .24% of the world's population.

[28] Solar panel prices have fallen by around 20% every time global capacity doubled

$500/kW in 2022. These trends extend to associated technologies like offshore wind and Concentrated Solar Power (CSP).

Table 7 summarizes trends in investment costs for renewable energy technologies from 2012 to 2022 as reported by IRENA (Renewable power generation costs in 2022 (irena.org)). The table also presents improvements in capacity factors, which have a major influence on generation costs.

## Table 7: Trend in Global Investment Costs and Improvements in Capacity Factors for Renewables (2012-2022)

| Technology | Investment cost in 2012 ($/MW) | Investment cost in 2022 ($/MW) | Capacity factor in 2012 (%) | Capacity factor in 2022 (%) |
|---|---|---|---|---|
| Solar PV | 5125 | 833 | 14 | 17 |
| CSP | 10082 | 4274 | 30 | 36 |
| Wind onshore | 2179 | 1274 | 27 | 37 |
| Wind offshore | 5217 | 3461 | 38 | 42 |

Source: IRENA 2023

Likewise, Table 8 summarizes the current estimated investment costs per MW installed in Chile, based on reported costs for installations in the country. The average real electricity generation costs have declined substantially during the period 2008-21, mostly as a result of lower cost facilities coming on-line (IMF Country Report No. 24/42, 2024) and is now estimated at 0.068 $/kWh. The lower costs associated with renewables have contributed the most to the decline as have improvements in operation and maintenance.

https://ourworldindata.org/data-insights/solar-panel-prices-have-fallen-by-around-20-every-time-global-capacity-doubled

## Table 8: Estimated Investment Costs in Chile ($ per MW Installed, 2020)

| Technology | Estimated Investment Costs | |
|---|---|---|
| Solar PV | 870 | Average current investment costs in Chile. |
| Wind onshore | 1190 | Average current investment costs in Chile. |
| Wind onshore with 8 hr storage | 1360 | Based on projected costs of La Cabana wind farm under construction with 106 MW nominal capacity and BESS of 34 MW. |
| Wind offshore | 3900 | Based on recent costs of offshore facilities in Europe. |
| CSP | 3610 | Based on the reported investment cost of Cerro Dominador. |
| Natural Gas (combined cycle) | 920-1200 | Prices reported in the US |
| Coal | >1800 | Coal-fired power plant construction costs. |

Solar PV and wind on shore are already less costly than natural gas and coal. Barring any unexpected development, a continuation in the reduction of investment costs for solar (PV and CSP) and wind technologies is anticipated as well as a continuation in gains in efficiency and cost effectiveness for other renewables such as tidal and wave energy technologies.

On the other hand, both natural gas and coal-based power plants reflect mature technologies with relatively limited space for major improvements in efficiency. From an economic perspective, there is no justification to opt for more expensive technologies.

Policy decisions can influence future investment costs. Long-Term Energy Planning (PELP) and the goal of achieving carbon neutrality encourage market investments in renewables. The predicted installed capacity to meet demand by 2050, which is 103 GW under the CNS, and 180 GW under the ZES, both significantly exceed today's capacity. The required rate of increase for renewables under the ZES is considerable (Table 9).

## Table 9: Evolution of the Renewable Generation Capacity by 2050 (GW) under the ZES

| Source/Year | 2024 | 2050 | Capacity increase as % of 2024 capacity |
|---|---|---|---|
| Wind | 4.7 | 56 | 12,000 |
| Solar PV | 10.3 | 56 | 540 |
| CSP | 0.1 | 6 | 60,000 |
| Distributed | 3.6 | 17 | 470 |
| Battery storage | Negligible | 31 | |
| Thermal Storage | | 3 | |
| CCGT using H2 | 0 | 2 | |
| Hydro | 7.5 | 8 | |
| Others | | 1 | |

Source Based on estimates of installed capacity by mid-2024 and data presented in National Climate Resilience Assessment in Chile, IEA, July 2024; Independent System Operator (ISO) July 2024 and Statista, accessed December 2024.

**Projected investment costs.** The projected investment costs out to 2050 are estimated using learning rates,[29] which reflect investment cost reductions each time capacity doubles. IRENA's reported learning rates (Table 10) were examined while NREL projections were also considered for comparison.

## Table 10: Learning Rates for Solar, PV, Wind, and CSP[30]

| Solar Utility PV | CSP | Wind Onshore | Wind Offshore |
|---|---|---|---|
| 34% | 22% | 17% | 9% |

Future capacity additions in the short term were estimated based on projects currently under construction and announcements. Table 11 presents the projects underway as of mid-2024.

[29] Learning rates or experience rates are defined as the rate at which the per unit cost of a technology is expected to decline with every doubling of cumulative production. A thorough discussion of applicability of leaning rates in electricity generation technologies can be consulted in : Azevedo I et. al. Modelling Technology Learning for Electricity Supply Technologies. Carnegie Mellon University, May 2013

[30] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf

## Table 11: Installed Capacity and Projects under Construction (as of mid-2024)

| Technology | Capacity Installed (MW)[31] | Projects Under Construction (MW) |
|---|---|---|
| Solar | 9,773 | 7,729[32] |
| Wind | 4,644 | 2,200[33] |
| CSP | 110 | 0[34] |
| Battery Storage | 404 | 588[35] |
| Green Hydrogen | 2 | 396 [36] |
| Hydro | 7,347 | 1,407[37] |
| Biomass | 523 | Not available |
| Geothermal | 84 | 50 MW[38] |
| Natural Gas | 3895 | 0 |
| Coal | 3754 | 0 |

[31] http://energiaabierta.cl/visualizaciones/capacidad-instalada/

[32] https://www.pv-magazine.com/2024/03/12/chiles-2023-solar-installations-hit-1-65-gw/

[33] https://www.bnamericas.com/en/analysis/data-insights-chiles-29gw-pipeline-of-wind-projects#:~:text=Chile%20has%20a%2029.4GW,to%20projects%20currently%20being%20built.

[34] Chile - SolarPACES reports 3 projects fully permitted but not yet under construction with a total nominal capacity of 1,440 MW.

[35] https://constructionreviewonline.com/news/metlen-and-glenfarne-agree-on-landmark-588-mw-solar-and-1610-mwh-bess-projects-portfolio-in-chile/

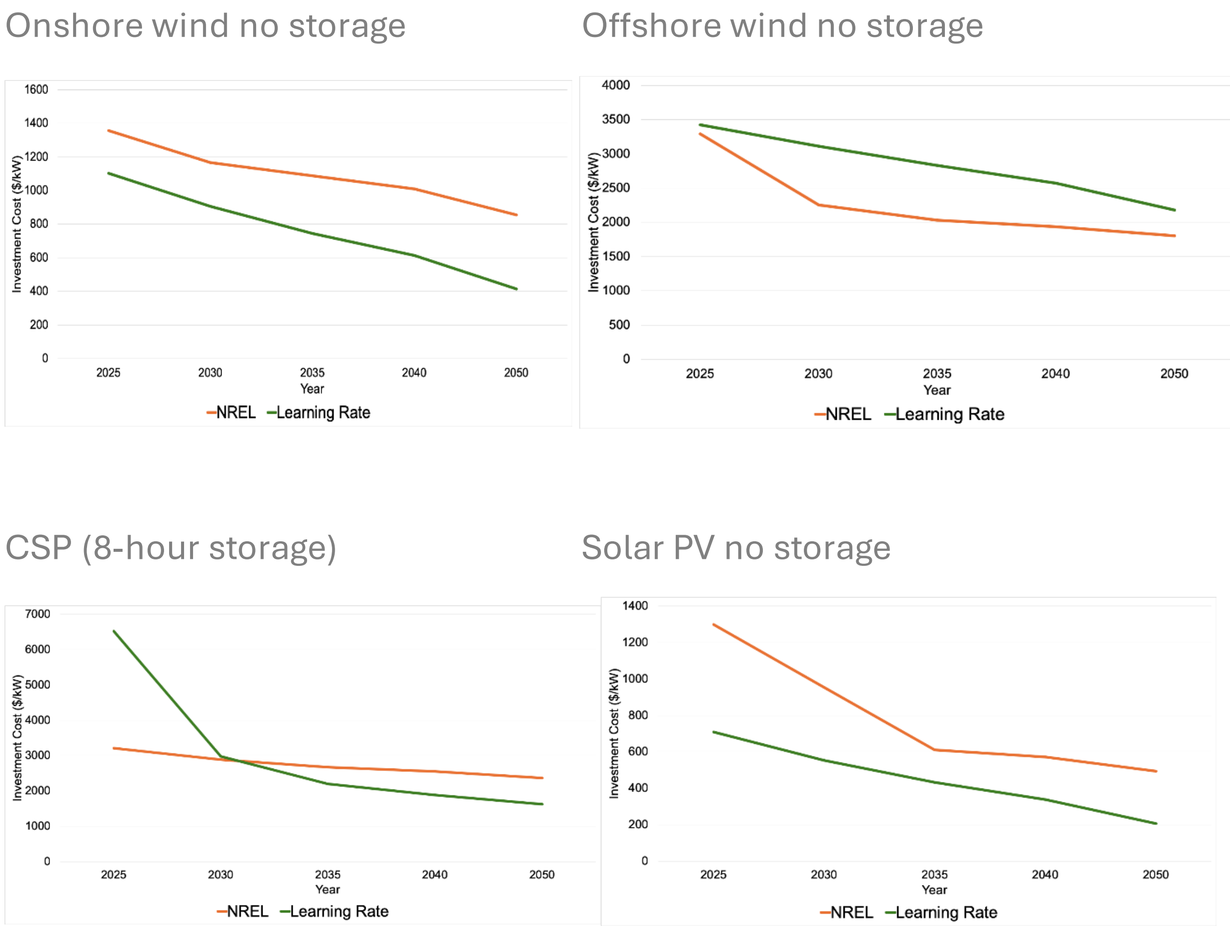
[36] https://gh2.org/countries/chile#:~:text=Six%20projects%20by%202025&text=The%20companies%20are%20Enel%20Green,up%20and%20running%20by%202025.

[37] Top five hydro power plants in development in Chile (power-technology.com)

[38] https://www.power-technology.com/data-insights/power-plant-profile-mariposa-geothermal-power-project-chile/#:~:text=Mariposa%20Geothermal%20Power%20Project%20(Mariposa%20Phase%20I),is%20expected%20to%20get%20commissioned%20in%202024.

Future investment costs were estimated using the learning rates and the projected doubling of global capacity. These were compared with the NREL projections. The resulting projections were then used to estimate future LCOEs in Chile (Figure 10).

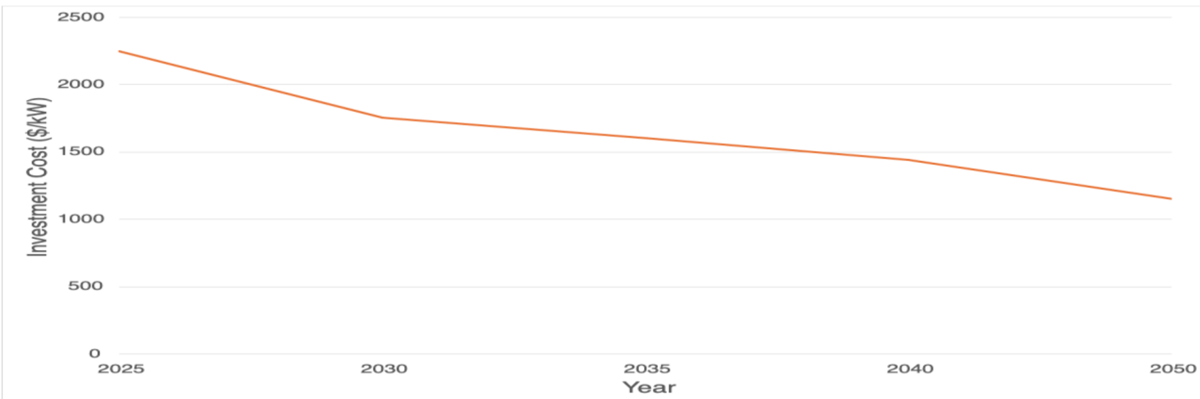
**Figure 10: Projected Investment Costs in Chile for renewable sources of energy**




In most cases, except for offshore wind, the NREL investment cost projections are higher than the estimate using learning rates. While the use of learning rates in Chile, may be more accurate, the NREL projections provide more conservative cost estimates for electricity generation. To remain conservative the NREL cost projections were used

Investment costs were also estimated for utility-scale lithium-ion battery facilities, using data provided by NREL (Cole and Karmakar 2023).[39] As these are energy storage systems, the investment cost data in the literature reflects costs per unit of energy stored ($/kWh), in contrast to the investment costs for generating units which are expressed in $/kW. Therefore, these estimates were converted to costs per unit of power using the power output for the systems (8 hours). The estimated LCOS (levelized cost of storage) is presented in Figure 11.

**Figure 11: Investment costs for utility scale Lithium battery stand-alone units**




Source: Author's estimates

## b) Estimate of the levelized cost of electricity generation

The projected total investment required in generation and storage capacity during the period of analysis was calculated using the data presented in Figures 10 and 11. The accumulated investment cost, including the cost of the necessary new transmission infrastructure in current value by 2050 is estimated at $212 billion, out of which about half is the cost of generation capacity, with the balance in storage and transmission investments (Section 7). Reducing the share of wind decreases the total investment in generation but increases the investment in storage.

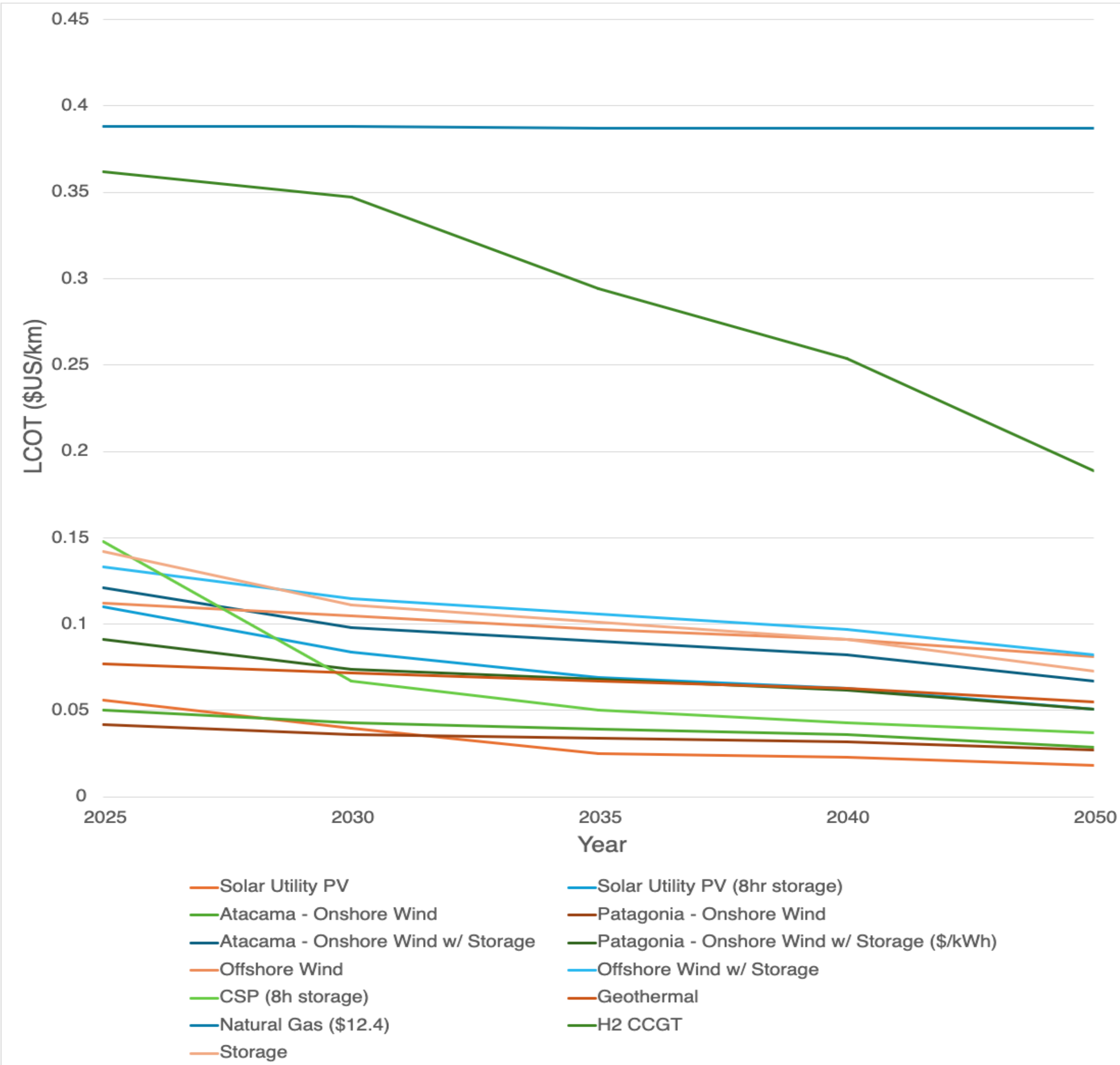
To estimate future LCOEs in Chile, the projected investment, operation, and maintenance costs were utilized. GACMO was used to make the calculations.[40] The results are

[39] https://www.nrel.gov/docs/fy23osti/85332.pdf#

[40] The online factors used are for wind in Atacama 0.36; in Patagonia 0.52; PV in Atacama: 0.32 (after Armijo and Philibert, 2019); and for CSP in Atacama 0.60 (with storage; after Hernandez et al, 2020). Other factors used in the analysis include estimates of Operation and Maintenance costs, annual capacity, and others. The assumptions used are listed in Annex C.

summarized in Figure 12. While investment costs weigh heavily in the calculation, other factors, such as solar irradiance and wind fields, have also a significant impact.[41]

**Figure 12. Projected LCOEs of renewables vs. natural gas over time ($/kWh)**




Source: Author's estimates using GACMO outputs[42]

[41] The analysis relies on the estimates by Anacona H. et. al., 2023, and Munoz R. et al, 2018 to size wind speeds in Patagonia and Atacama and the measured irradiance in Atacama for the PV and CSP estimates is based on the data base from NIH (https://pmc.ncbi.nlm.nih.gov/articles/PMC5665918/).

[42] The outputs of GACMO for the calculation of LCOEs, are summarized in Appendix B (https://docs.google.com/spreadsheets/d/1xFCGaUSUMSeKWK7C2dHPa3uwgQoLrntC1wksUTUpaV4/edit?usp=sharing

Among the options analyzed, utility-scale solar PV yields the lowest LCOEs. The study shows that by 2050, utility-scale PV in Atacama could produce electricity for about $0.02/kWh. Onshore wind in Patagonia and Atacama follows at $0.03/kWh. Storage costs are estimated at $0.07/kWh.

These findings suggest that these regions are among the most cost-effective globally for power generation, positioning Chile as a world leader for low-cost electricity. The LCOEs for wind in Patagonia are even lower than those projected in Atacama. However, the relative location to users and the higher costs of transmission (Section 7) will influence market decisions.[43]

The use of Artificial intelligence may further contribute to cost reductions in the renewable energy sector by improving forecasting for energy production, grid management, and sustainability. For example, AI tools have increased solar energy efficiency by 20% via enhanced panel orientation and improved sunlight tracking. The renewable energy market is projected to grow, with AI expected to play a role in this process. Similar impacts are anticipated in all sectors of an electrified economy. For example, in the Electric Vehicle sector, AI may be used to improve energy management and charging efficiency.

In summary, the analysis concludes:

The absolute difference between the LCOEs of PV and wind is relatively minor—approximately 1 cent per kilowatt-hour by 2050—reducing the impact of their share of total capacity on overall costs.

Despite wind being somewhat more costly than solar and facing offshore and Patagonia transmission cost challenges, its extended availability throughout the day (see Figure 11) justifies its priority inclusion in the energy mix. The addition of storage increases the LCOEs for PV and wind, yet both remain highly attractive over time.

The rapid reduction in $H_2$ costs makes CCGT (combined cycle gas turbines) retrofit with hydrogen (as well as other applications of hydrogen in transport and industry), more competitive over time, although not as cost efficient as PV or wind. Yet, this is an attractive option to strengthen firm capacity and resilience in a fully renewable matrix.

NGCC (natural gas combined cycle) plants cannot compete with solar and wind. NGCC plants are outcompeted even by CSP, and by PV and wind facilities with storage, justifying their closure, potentially ahead of schedule.

Finally, although Battery energy storage systems (BESS) integrated systems are initially more expensive, the gap with stand-alone units shrinks over time as storage costs fall. The potential to store energy at low costs provides a strong argument to accelerate the electrification of all sectors of the economy.

[43] The main grid still has to connect to the local grid in Patagonia.

# 7. Transmission requirements and costs

In this section, the type, magnitude and costs of the transmission infrastructure needed for a fully electrified economy are estimated.

In early 2025, Chile had a total transmission line length of 39,570 km at the 110 kV to 500 kV voltage levels (CEN, 2018), with only about 4,500 km at 500 kV. The system is being expanded to accommodate additional renewable capacity envisioned under CNS.

While the Ministry of Energy has prioritized the expansion and modernization of transmission infrastructure, the pace of commissioning of new transmission must accelerate to match future requirements under the ZES. It would also benefit from further efforts to modernize and develop new transmission technologies and approaches that enable faster, higher-capacity, and more efficient delivery.

For now, the GOC commissions an annual transmission plan from the National Electricity Commission (CNE). Recently, CNE approved the Preliminary Technical Report of the Transmission Expansion Plan 2024 (prepared by CEN), comprising 34 works with an estimated global investment of USD 2,259 million (CEN, 2024). A list of key high-voltage projects in implementation or planning is included in Table 12.

**Table 12: Key Planned National Grid Transmission projects (500 kV and above) under Construction or Planning**

| Expansion project | Type | Length (km) | Estimated cost (US $ billion) | Capacity (MW) | Projected year of completion |
|---|---|---|---|---|---|
| Diguenes-Nueva Pichirropulli | Overhead AC line 1000 kV; (2x500 kV) | 300 | 0.36 | 1,700 | 2031 |
| Entre Rios-Diguenes | Overhead AC line 1000 kV; (2x500 kV) | 80 | 0.33 | 2,300 | 2029 |
| Second circuit of | Overhead AC line | 196 | 0.06 | 1,400 | 2029 |

| | | | | | |
|---|---|---|---|---|---|
| Ancoa-Charrua | 1x500 kV | | | | |
| Kimal- Lo Aguirre | HDVC line 600 kV | 1390 | 2.00 | 3,000 | 2029 |
| Nueva Lagunas-Kimal | Overhead AC line 1000 kV; (2x500 kV) | 190 | 0.20 | 1,700 | 2026 |
| Alto Jahuel-Lo Aguirre | Overhead AC line 1000 kV; (2x500 kV) | 258 | 0.16 | 1,880 | Under construction 2024 |
| Los Changos-Crucero Encuentro | Overhead AC line 500 kV | 139 | 0.17 | | Under construction 2024 |

Source: Annual Transmission Plans 2021-2023; Global Data Power database consulted November 2024 (Power Industry Business Development - GlobalData) Complemento a la propuesta de Expansion de la Transmision. 2024. Informe Tecnico Definitivo del Plan de Expansion Annual de Transmision 2023 and 2024.

## a) Alternative technologies for expansion of the transmission system

The standard option to bring wind and solar power over long distances from the generation points to demand centers is through HVDC lines. HVDC provides lower losses and transmission costs over longer distances. However, given the significant investment required to accommodate the large demand expansion under the ZES (from 288 PJ [80 TWh] today to 1343 PJ [373 TWh] by 2050),[44] it is critical to also explore emerging transmission technologies. The report considers the following options, evaluating potential advantages for their deployment:

**Reconductoring.** In the short term, upgrading existing circuits via reconductoring with advanced conductors may provide extra time and space for longer term investment decisions. Advanced composite-core conductors can carry up to twice the current of conventional conductors. Typically, reconductoring replaces the conventional steel core

[44] See section on Estimate of Future Electricity demand in Planificación Energética de Largo Plazo | Ministerio de Energía

with a lighter and smaller composite core (ceramic or glass fibers) without requiring new rights of way, new tower structures or compromising integrity.

This means more aluminum can fit within an equivalent diameter, increasing the line's rated capacity. By avoiding many of the costs of laying out new lines, reconductoring projects typically cost less than half of new lines, for similar capacity increases (Chojkiewicz et. al., 2024). Until recently, reconductoring has been limited to short line applications, However, recent developments seek its application on longer lines, by adding substations with new connection points for power sources or storage facilities (Chojkiewicz et. al., 2024).

There are several 500 kV transmission lines already in operation and others under construction in Chile. These lines represent an early opportunity to double their capacity in the short term, with major investment savings and shorter implementation timelines.

**Low frequency transmission.** Low frequency transmission systems have been proposed to transmit from remote wind farms.[45] Low frequency AC (LFAC) technology can potentially reduce the total cost of existing transmission systems by increasing the power transfer capacity of high-voltage AC cables operating at low frequency and removing the offshore converter relative to high-voltage DC systems.

Recent analysis indicates a cost advantage of LFAC over HV systems at intermediate distances (Xiang et al., 2021). This option is relevant for Chile as their wind potential in the south and offshore is substantial and transmission infrastructure represents a major fraction of the total cost of remote wind.

**Multi terminal HVDC (MHVDC).** Most HVDC lines are "point to point," meaning they only connect to the grid at the very beginning and end of the lines. An alternative is HVDC lines with the ability to connect into longer lines at different points without ending the line (NREL, 2024). In essence, a multi terminal HVDC[46] would allow entry by different plants, potentially with different operators, along the line, enabling gains in the efficient use of infrastructure.

There is growing experience with MHVDC. The Atlantic Wind Connection (AWC) Project is the first offshore backbone electrical transmission system proposed in the United States. The AWC Project would enable up to 7000 megawatts (MW) of offshore wind capacity to be

[45] Low frequency means a frequency lower than 50/60 Hz, typically 16.7 Hz. Low Frequency AC transmission for offshore wind power: A review - ScienceDirect

[46] In Germany, the four grid operators TenneT, Amprion, 50Hertz and TransnetBW are jointly developing three multi-terminal HVDC hubs to connect HVDC offshore wind export links directly with onshore HVDC links to bring the wind power down south, avoiding the investment in additional converters and the operational energy losses in such converters.

integrated into the regional high-voltage grid along the U.S. North Atlantic coast[47] and would enable different wind projects, managed by different operators, to access a common infrastructure.

A key issue is the trade-off among the cost of building combinations of point-to-point HVDC, multiterminal HVDC, and HVAC lines. This is being reviewed in the U.S. as part of the National Transmission Planning Study (DOE, 2024). A similar approach could be an option for multi generation solar and wind projects in Atacama or for a backbone offshore infrastructure along Chile's long coastline. Table 13 provides a comparison of these different technologies and their applications for Chile.

## Table 13: Alternative Transmission Technologies for Future Expansion of the Grid in Chile

| Transmission Technology | Application | Advantages | Limitations | Cost |
|---|---|---|---|---|
| HDVC | Longer distance transmission at high voltage. | Slightly more power can be transmitted than for AC.<br>Lower losses per unit of distance. | Noncompetitive over shorter distances. | Cheaper for lengths of 800-1000 km or more. |
| Reconductoring | Alternative to new circuits or new lines. | It avoids new infrastructure.<br>It uses existing rights of way, speeding up permitting and implementation processes. | Number of eligible lines in Chile is small. | Typically, less than half the cost of new lines for similar capacity increases across all voltage levels. |
| Low Frequency AC | For links to offshore, or remote wind farms | Compared to HVAC, the low frequency of LFAC results in lower charging | Absence of commercial-size LFAC projects to obtain cost data, | Estimated to be cost-effective over HVAC and HVDC systems in the |

[47] In mid-2025, political decisions devoid of technical and financial considerations have placed into doubt the implementation of required wind energy infrastructure in the US. While this will setback the development of wind energy in the US, global reductions in investment and O&M costs will continue to favor worldwide expansion of the industry.

| | | | | |
|---|---|---|---|---|
| | | current, lower transmission losses and larger transmission capacity.[48] LFAC eliminates the large expense of an offshore converter station. | and operational parameters. | intermediate distance (100 to 500 km) for both offshore connections and remote onshore wind energy[49]. |
| Multi terminal HDVC | Same as HDVC | Increased grid and supply security[50]. Improved balance of renewable power at higher penetration levels. Flexible power routing across different points in the grid[51]. | Large initial infrastructure requirements. | A potentially significant cost saving for connecting areas with many generator plants as could the case in Atacama, Serena or offshore. |

Distance and voltage determine the relative competitiveness between the different transmission options. Figure 13 illustrates how distance affects the choice of system for remote or offshore wind.

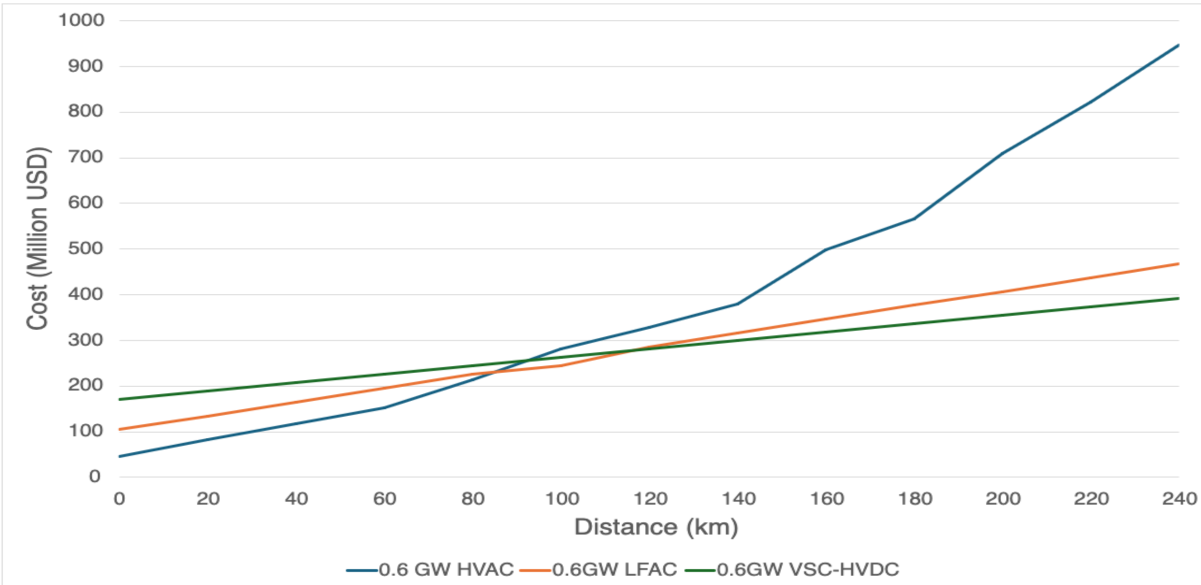
[48] Comparative economic analysis of low frequency AC transmission system for the integration of large offshore wind farms - ScienceDirect

[49] Comparison of cost-effective distances for LFAC with HVAC and HVDC in their connections for offshore and remote onshore wind energy | CSEE Journals & Magazine | IEEE Xplore

[50] Benefits of Multi-Terminal HVdc Under Extreme Conditions via Production Cost Modeling Analyses | IEEE Journals & Magazine | IEEE Xplore

[51] Review of modular multilevel converter based multi-terminal HVDC systems for offshore wind power transmission - ScienceDirect

**Figure 13. Comparison of Investment Costs for HVDC, HDAC and LFAC for transmission lines from remote Wind Generation Capacity**




Source: Based on data presented in: https://www.researchgate.net/publication/369635460_Comparison_of_Cost-effective_Distances_for_LFAC_with_HVAC_and_HVDC_in_Their_Connections_for_Offshore_and_Remote_Onshore_Wind_Energy...

## b) Estimate of high voltage transmission requirements

Projected nominal generation capacity by 2050 and during the transition period is estimated in Section 4. For the purposes of this analysis, it is assumed that by 2030, all existing 500 kV lines will be reconductored, thereby doubling their capacity at half the cost. Similarly, it is supposed that all new transmission lines longer than 800 km will utilize HVDC technology, and new HVDC lines commissioned post-2030 will connect to a multi-HVDC backbone to be established between Atacama and the central region. Additionally, it is assumed that all new remote wind energy installations will connect to the grid via LFAC technology.

All new solar capacity is assumed to be in the North (Atacama)[52] with a capacity equivalent to 47.5% of the total wind and solar. Most wind capacity (47.5% of total wind and solar) will be likewise located in the North, with a fraction in the south and/or offshore. All CSP will also be in Atacama. Storage capacity is assumed to be at or near HVDC lines. The resulting required infrastructure is presented in Table 14.

[52] Corresponds roughly to Scenario C in: cne.cl/wp-content/uploads/2023/03/Obras-ITP-2022-Webinar.pdf

Distributed capacity will reduce not only central generation but also the distribution requirements. Under the ZES scenario, 17 GW of distributed generation by 2050 is assumed by 2050. The projected distributed generation has been deducted from the national transmission requirements. The results are shown in Table 14.

The analysis also assumes that offshore and remote wind capacity use LFAC starting in 2040. All electricity generation in Atacama will be connected via a multi HVDC line, with the backbone built in the 2030s. The associated investment is included in Table 14. Details of the calculations are included in Annex C.

The location of new renewables will generally not coincide with the location of decommissioned gas plants. Therefore, the assumption is that all new renewable energy generation capacity will require new transmission lines. However, until the gas plants are retired, they are expected to contribute to meet peak demand while renewable generation capacity is built up. If some gas plants are retrofitted to use hydrogen, the assumption is that no additional investment in transmission would be required for those plants.

## Table 14: Projected Transmission Infrastructure Requirements for Renewable Energy Generation

| Year | Nominal Renewable Capacity Installed, (GW) | Net additional capacity (GW) | New Reconductored lines and length | New HVDC lines, including multiterminal HVDC and length | New LFAC lines and length | Associated investment ($ billion) |
|---|---|---|---|---|---|---|
| 2025 | 25 | | 0 | 0 | | |
| 2030 | 69 | 44 | 5/2114 km | 5/7000 km | 1/150 | 18 |
| 2040 | 115 | 46 | 1/300 km | 7/9800 km | 1/150 km | 24 |
| 2050 | 163 | 48 | 0 | 7/9800/ km | 2/3000 km | 24 |

Source: Authors' estimates. The nominal renewable energy capacity includes all solar, wind, hydro, storage and geothermal but excludes distributed as these will not require significant additional high voltage transmission infrastructure. Details of the assumptions are included in Annex B.

In conclusion, the expansion of the grid system will demand substantial investment of about $66 billion in the next 25 years with a major share in the last 10 years. Reconductoring existing lines offers a short-term option that can accommodate immediate transmission needs at a fraction of the cost of new lines. In the medium term, MHVDC starting in Atacama can provide flexibility and cost savings. LFAC lines are a rational option to bring in remote or offshore wind capacity to load centers.

Like all other annualized costs in this report, the analysis estimates LCOTr (levelized cost of transmission) calculated as the annualized capital cost of the transmission infrastructure to be deployed plus the expected operation and maintenance costs, divided by the annual electricity expected to flow across the system. The transmission infrastructure required depends on the composition of the matrix. However, the variation in total costs is small across the scenarios considered.

The relative share of different energy resources also affects the investment needed for storage. The estimated storage and transmission costs for the different scenarios are summarized in Table 15. Increasing the share of wind reduces storage requirements. It also reduces transmission requirements, as some wind fields are closer to the center of the country.

## Table 15: Impact of composition of Matrix on Storage and Transmission requirements

| Wind share (%) | PV share (%) | CSP share (%) | Estimated required storage (GW) | Estimated Investment in Transmission Infrastructure ($ billion total by 2050) |
|---|---|---|---|---|
| 20 | 75 | 5 | 39.2 | 70 |
| 20 | 78 | 2 | 44.2 | 70 |
| 30 | 68 | 2 | 37.3 | 68 |
| 47.5 | 47.5 | 5 | 36.3 | 66 |
| 50 | 45 | 5 | 36.1 | 66 |
| 58 | 40 | 2 | 35.0 | 65 |
| 70 | 28 | 2 | 33.1 | 63 |
| 80 | 18 | 2 | 32.5 | 62 |

Source: Author’s estimates

## c) Combined levelized cost of generation and transmission

The combined levelized cost of generation, including storage and transmission, is influenced by the proportion of individual energy sources within the power matrix. Table 16 presents a comparison of different scenarios in which the ratio of solar to wind capacity changes. The estimated LCOE includes the capital cost of generation, transmission and storage. An increased dependence on PV necessitates greater storage capacity, which has a higher investment cost than PV or wind,[53] and therefore increases the estimated cost of generation. The use of AI may further reduce the cost of deployment of transmission grids by enhancing efficiency. AI could be used to optimize the integration of the transmission grid with large scale renewable energy generation centers, support predictive maintenance and support monitoring and fault detection by early diagnosis of anomalies.[54]

However, the increase in share of PV decreases the LCOE of the system. However, the difference in total costs remains modest. For purposes of the analysis, a scenario that maximizes diversity of supply is used (wind 47.5%/ PV 47.5%/ CSP 5%), even though it does not result in the lowest combined costs of generation, storage and transmission. But given the relatively low differences in costs, this scenario brings added value of resilience and does not over rely on one single source of energy. The resulting total cost of generation and transmission for this scenario is used to estimate the costs of services in subsequent sections.[55]

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[53] The costs of storage, however, are expected to fall faster relative to the reductions in costs of generation capacity.

[54] The use of AI may further reduce the cost of deployment of transmission grids by enhancing efficiency. AI could be used to optimize the integration of the transmission grid with large scale renewable energy generation centers, support predictive maintenance and support monitoring and fault detection by early diagnosis of anomalies.

[55] The use of other scenarios considered do not change the overall conclusions of the analysis on the relative performance of electric vs fossil fuel options.

## Table 16: Impact of composition of Matrix on the Levelized Cost of Electricity Generation and Transmission.

| Wind share (%) | PV share (%) | CSP share (%) | LCOTr $ cents/kWh) | LCOE[56]( ($ cents/kWh) | Total [57]($ cents/kWh) |
|---|---|---|---|---|---|
| 20 | 75 | 5 | 0.48 | 2.97 | 3.94 |
| 20 | 78 | 2 | 0.49 | 2.95 | 3.84 |
| 30 | 68 | 2 | 0.47 | 3.00 | 3.99 |
| 47.5 | 47.5 | 5 | 0.44 | 3.20 | 4.06 |
| 50 | 45 | 5 | 0.43 | 3.20 | 4.07 |
| 58 | 40 | 2 | 0.42 | 3.20 | 4.08 |
| 70 | 28 | 2 | 0.40 | 3.30 | 4.11 |
| 80 | 18 | 2 | 0.39 | 3.30 | 4.12 |

Source: Author's estimates

Final distribution to end users adds to the total cost of electricity. The electrification of the economy will require a substantial upgrade of the distribution grid. The distribution costs include physical infrastructure (transformers, substations, poles and wires) as well as their operation and maintenance.

In Chile, electricity distribution costs are determined through a Distribution Added Value assessment. The assessment determines distribution costs, including investment, O&M, and administration. A detailed cost analysis of distribution is beyond the scope of this study. Based on Chile's tariff breakdown, we adopt a distribution cost roughly equivalent to the transmission cost.[58]

[56] Includes levelized cost of storage.

[57] Includes fixed charge for distribution.

[58] The National Energy Commission (CNE) sets these charges based on a four-year process of technical studies to assess the efficient costs of distribution. This is called the Value Added of Distribution and typically represents around 10 % of the total electricity costs while transmission costs are estimated at about 10%.

# 8. The Competitiveness of Electric Transportation in Chile

Today, the transportation sector is the largest and most complex user of energy in Chile. This section examines the relative competitiveness of electric transportation systems across modes and within the timetable of the ZES. It uses the context of global technological developments in electrical drives and the characteristics of transportation systems in the country.

As noted, the GOC has outlined a comprehensive strategy for electrification of transportation (NES, 2021) as part of Chile's Carbon Neutral Economy vision. This strategy calls for rapid electrification of road transport for passenger and cargo, the incorporation of new electric rail lines, and the gradual electrification of industrial and agricultural rolling stock.

Under the proposed ZES, the electrification of the transport sector would cover all modes of transport and vehicles, including transport of passengers and cargo by road, ship and railroad— excluding only aviation.


*Electric bus in Santiago, Chile. Photo: La Confederación Nacional del Transporte de Carga de Chile (CNTC-CHILE)*

The aviation sector presents unique challenges. Key is the energy density of batteries or alternative fuels. In this analysis, aviation is not included for electrification by mid-century.

However, aircraft and engine manufacturers, airlines, fuel producers, governments, and international organizations—have worked over the past decade to promote sustainable aviation fuels, most notably derivatives from vegetable oils.

ICAO (International Civil Aviation Organization), a UN Specialized Agency adopted two sector-wide aspirational goals in 2010: (i) a 2% annual improvement in fuel efficiency, and (ii) carbon-neutral growth from 2020 onward. These efforts hold promise to make aviation less fossil-fuel dependent, but given current progress, aviation is not targeted for full decarbonization by 2050.

**Transport Fleet.** The transportation components considered include: (a) all domestic passenger transport (road, rail, waterways); (b) all cargo transport (road, rail, ship); (c) fishing fleet; (d) mining trucks; (e) rail. Characteristics of the current fleet are listed in Table 17.

## Table 17: Characterization of Transport Fleet in Chile (2023)

| Fleet Segment | Number of vehicles | Energy use (TJ) in 2022 | Million Ton km | Million Passenger km |
|---|---|---|---|---|
| Rail<br>Passengers<br>Cargo | 470<br>4337 | 3,963 | 3,665 | 1,053 |
| Road | 6.44 million | 398,408 | | |
| Light duty vehicles<br>Buses<br>Trucks | 6.04 million<br>61,035<br>339,854 | 204,789<br>92,068<br>101,550 | 73,887 | 73,564<br>94,051 |
| Waterways<br>Cargo | 2,886<br>242 | 12,716 | 37,448 | 23.64 |
| Fishing fleet | 2,572 | 10314 | | |
| Mining truck fleet | 1.592 (as of 2014) | 87,289 | 22,233 | |

Sources: GCAM Chile outputs; Directemar, 2024 report, INE circulation permits; INE annual railway survey,

### a) Pace of electrification of the transportation sector

**Projected growth of the transport sector.** Different elements of the fleet are expanding at different rates. For example, the passenger car fleet is growing annually at 3.2% (2010-

2025)[59] but between 2024 and 2028 growth is projected to slow to 1.4% (*Chile Motor Vehicles Sales Growth*, 2025). The public transport market in Chile (metro and buses) is expected to grow annually by 3.2%, while the bus market is projected to grow annually at 1.9% in the short-term. The truck fleet has remained mostly static and is expected to stay near current levels.[60] The fishing fleet is also expected to remain static. For this analysis, the composite fleet is projected to grow at 1.3%, essentially the same rate as the overall projected growth of the economy. At this rate, the mid-century fleet will be about 138% of today's size.

The ZES adopts the pace of conversion of light and heavy vehicles for cargo and passengers already outlined in the electro-mobility strategy. To this it adds specific goals to electrify the fishing fleet, all mining trucks, rail, and domestic shipping of cargo and passengers. The intention is to replace essentially all internal combustion engines with electric drives, or in some heavy-duty applications, fuel cells powered by hydrogen generated through water hydrolysis. Table 18 compares BAU and ZES paces and extent of electrification.

## Table 18: Comparison of the Pace of Electrification of Transportation under BAU (Carbon Neutral Scenario) and the ZES (Zero Carbon Emissions) Scenario

| Fleet component | Carbon Neutral Economy | Zero Carbon Emissions Economy |
|---|---|---|
| 100% new passenger vehicles | 2035 | 2035 |
| 100% of additions to public transport vehicles | 2035 | 2035 |
| 100% of additions to road cargo fleet | 2045 | 2045 |
| 100% of additions to mining fleet and agricultural machinery over 560 kW | 2035 | 2035 |

[59] https://www.ceicdata.com/en/indicator/chile/motor-vehicles-sales-growth
[60] Statista Motor vehicle fleet size in 2012-2022.

| | | |
|---|---|---|
| 100% of additions to mining fleet and agricultural machinery over 15kW | 2045 | 2045 |
| Fishing fleet converted to Fuel Cell | | 2030 |
| Coastal ships electrified | | 2040 |
| Mining trucks converted to Fuel Cell | | 2030 |
| Other vehicles in industry (forklifts, specialized trucks) | | 2030 |
| All rail uses electric engines | | 2050 |

## b) Relevant innovations in electric drive systems

Besides demand-driven economies of scale, improvements in electric-drive efficiency and reduced costs of EV battery packs will help determine future costs. The cost of lithium-ion EV battery packs has decreased by over an order of magnitude since 2010 and is projected to continue falling in the short term (Goldman Sachs, 2024), and over the next decades (NenPower, 2025). Further reductions will make a major impact on the levelized cost of transportation.

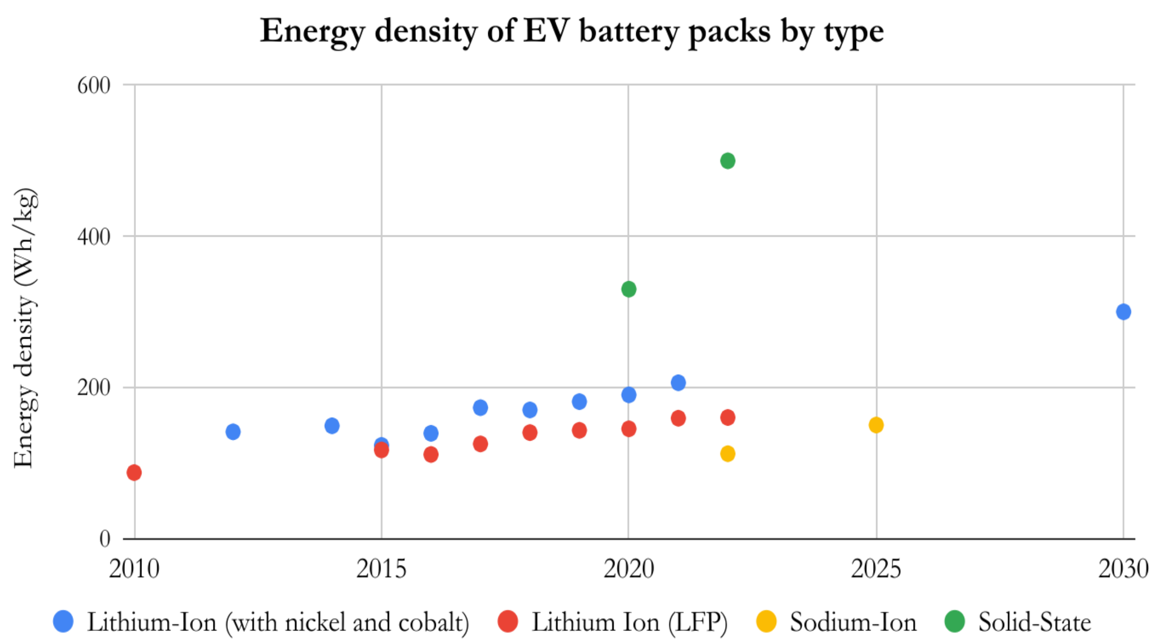
In addition to lithium-ion batteries, recent developments in both solid-state lithium batteries and sodium batteries need to be considered for their potential impact on transportation costs.

The benefits of solid-state EV batteries (SSB) include:

- **Higher energy density:** SSBs can store more energy than lithium-ion batteries of the same size and weight. They have a potential energy density of more than 500Wh/kg (Bloomberg, 2023). This could lower pack prices later this decade and enable longer-range vehicles (Kothari, 2024).
- **Faster charging.** The solid electrolyte has lower resistance than liquid electrolyte.
- **Quick cost reductions**. While SSBs are currently pricier than lithium-ion, costs are projected to fall toward parity by 2030 (Staats, 2023).

Figure 14 shows the expected evolution in energy density for batteries. Figure 15, likewise shows projected cost reduction.[61] If solid state batteries can compete on costs, they could enable larger autonomies even for heavier vehicles.

**Figure 14: Projected energy density of EV battery packs (Wh/kg)**




Source: MIT (https://www.technologyreview.com/2023/05/11/1072865/how-sodium-could-change-the-game-for-batteries/)

The advantages for sodium ion batteries include:

- **Raw Material Abundance:** Sodium is one of the most common elements on Earth.
- *Cost*: sodium-ion batteries are generally cheaper to manufacture.
- **Environmental Impact:** Sodium extraction can carry comparatively smaller footprints.
- **Performance in Cold:** Sodium-ion batteries tend to perform better in cold temperatures compared to lithium-ion batteries.

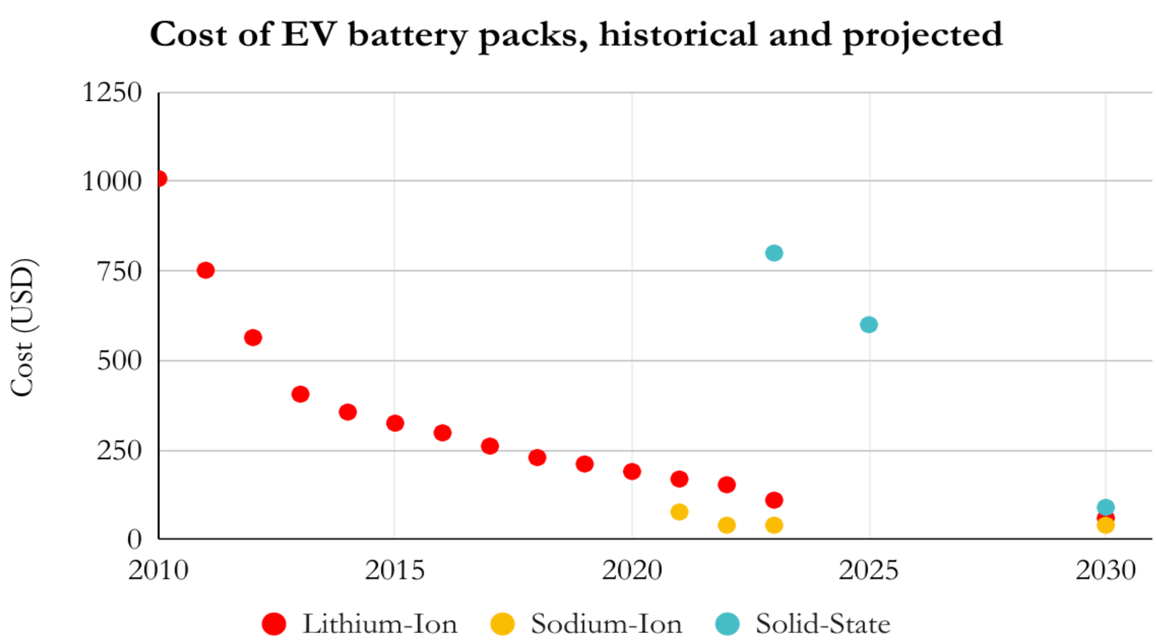
Sodium-ion batteries, although still not market-ready, are seeing significant development. The first-generation sodium-ion cells cost around $77/kWh, and the next generation could drop to $40/kWh, as shown in Figure 15 (Hanley, 2021), making them an attractive option for

[61] In June 2025, Toyota announced the introduction of a passenger vehicle with 1000 miles of autonomy using sold state batteries (https://vecharged.com/news/toyota-solid-state-battery-breakthrough/).

stationary applications. Their energy densities, however, will limit application and autonomies in vehicles.

When forecasting the market for electric vehicles, these developments support the contention that major improvements in range, cost, safety, and performance are likely. While the analysis is based on the projected costs for lithium-ion batteries, market penetration in Chile of solid state and sodium batteries should benefit the pace of electrification. Based on these considerations, the analysis uses an aggressive projection on cost reduction of batteries and utility-scale storage.

**Figure 15: Projected cost of alternative battery pack systems for EV ($/kWh of storage)**




Source: U.S. Department of Energy (https://www.energy.gov/eere/vehicles/articles/fotw-1272-january-9-2023-electric-vehicle-battery-pack-costs-2022-are-nearly)

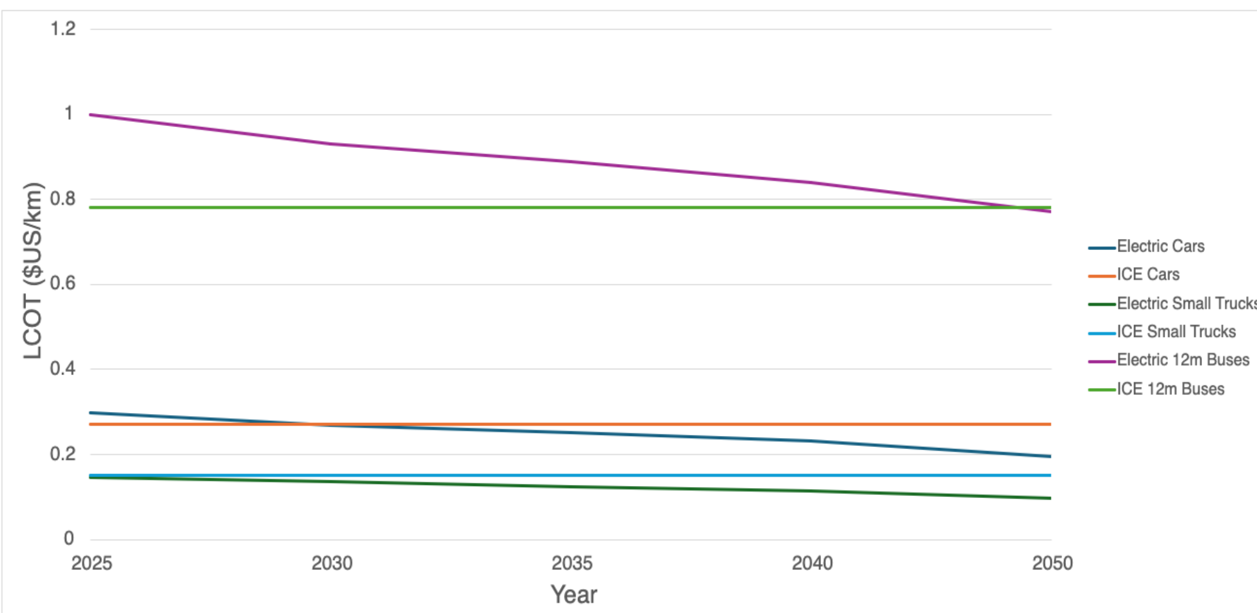
## c) Estimate of the Levelized Cost of Transportation (LCOT)

The LCOT for several modes was estimated using GACMO, projected capital costs of electric vehicles drives, and forecasted LCOEs. The capital cost for each mode of transportation was estimated using the current cost of the vehicle plus the cost of the electric drive.

**Projected competitiveness of electric transportation.** The cost of the electric drive constitutes a significant portion of the total cost of electric vehicles. With the anticipated reduction in the costs of lithium-ion batteries, electric vehicles will become more competitive over time. Improvements in battery density and performance will also enhance the benefits of electric vehicles over time. The analysis projects (Section 6) that electricity costs decline materially as the grid transitions to renewable sources, further increasing the competitiveness of electric vehicles. In the analysis, the cost of the battery pack declines over time to reflect the current consensus projection of prices (refer to Figure 11). These costs were compared with those for alternative internal combustion engines. An additional calculation estimated the LCOT for fuel cell powered vehicles ($LCOH_2$). Assumptions used are included in Annex C.

The results of a comparative analysis of levelized cost of transportation of light-weight electric vehicles versus internal combustion vehicles are shown in Figure 16. These confirm that electric automobiles are already competitive in the Chilean market and that small trucks will be in the next few years. Electric standard-length buses remain more expensive initially but gradually gain competitiveness and converge toward the end of the period.

**Figure 16: LCOTs of light electric vehicles vs ICE vehicles over time**

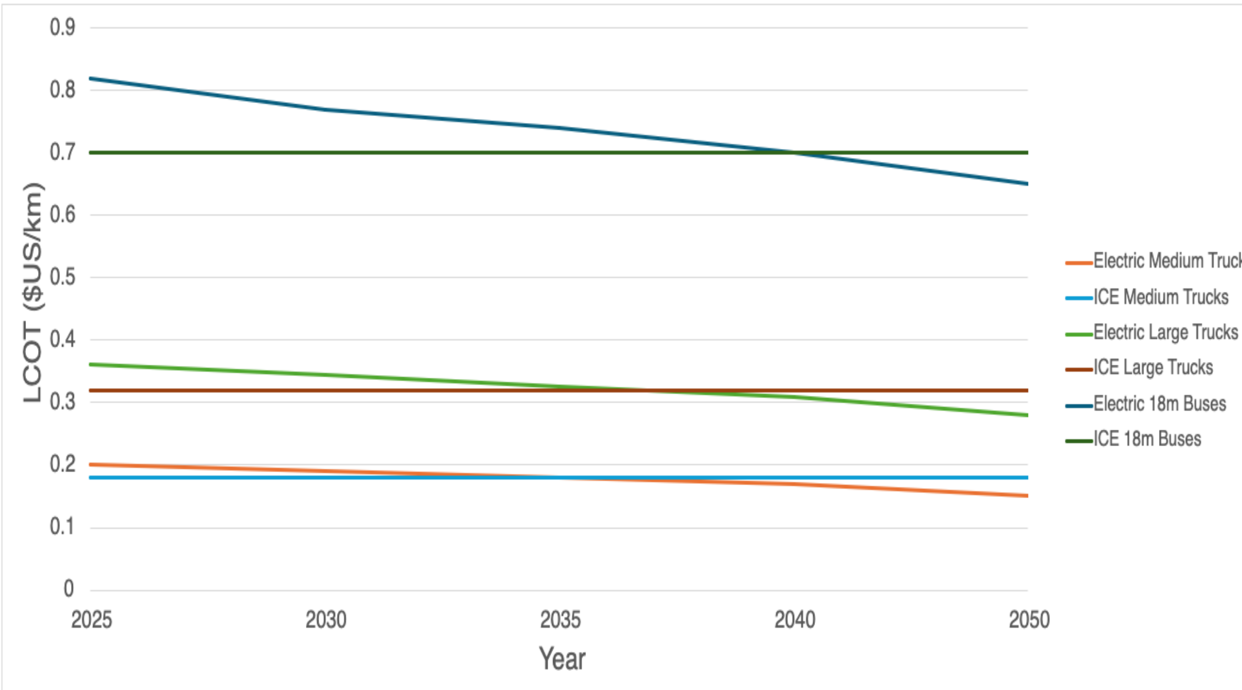



Gasoline Cost = $0.53/L; Diesel Cost = $0.45/L

Source: author's estimates based on GACMO outputs.

The results of a similar analysis for heavier vehicles (18 m long buses and medium and heavy trucks) are shown in Figure 17. The results indicate that while more expensive at present, battery powered heavier electric vehicles improve competitiveness during the period of analysis and match or outperform ICE heavy vehicles before mid-century.

**Figure 17: LCOTs of heavier electric vehicles vs ICE vehicles over time**



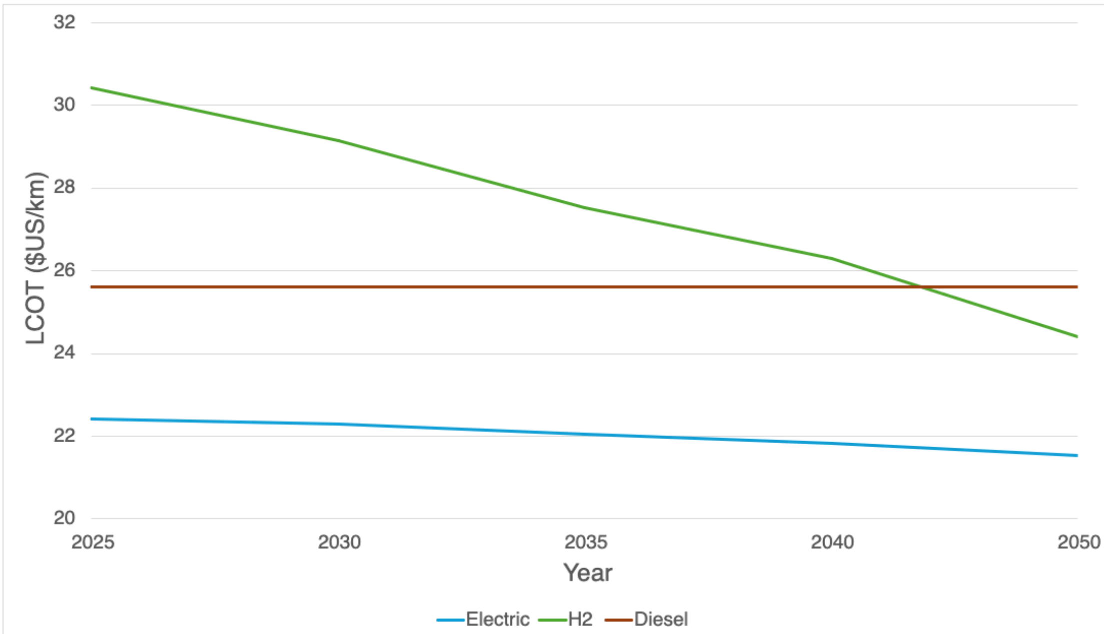

Diesel Cost = $0.45/L

Source: Author's estimates based on GACMO outputs.

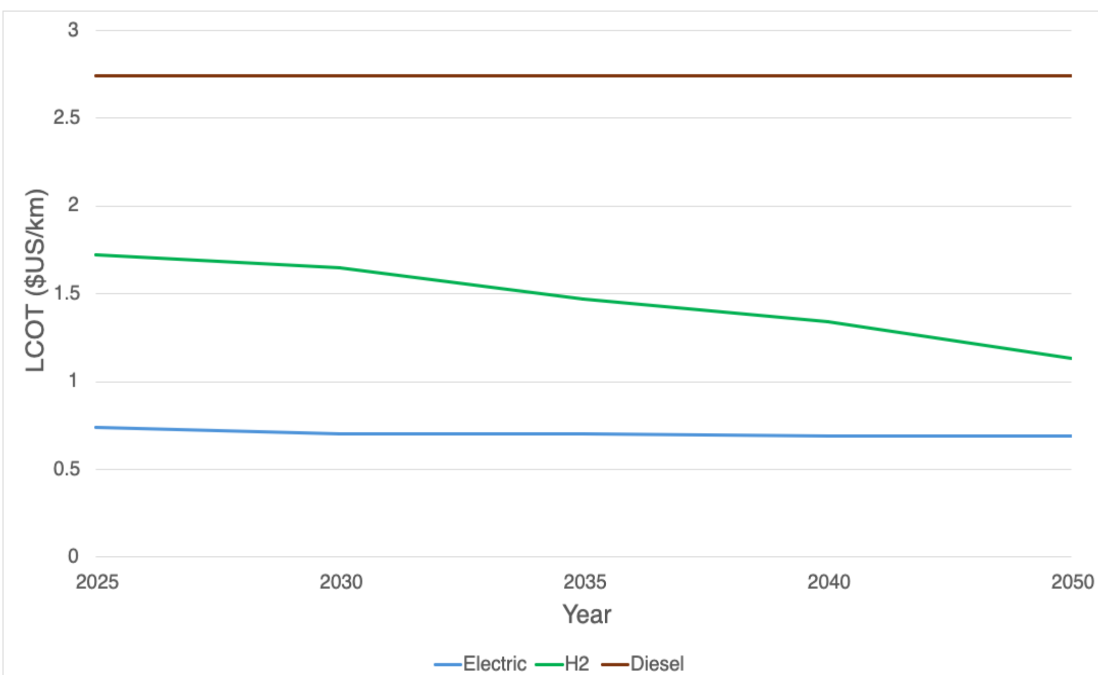
For heavier vehicles, such as heavy trucks, mining trucks, and fishing vessels, the option of fuel cells powered by hydrogen was also examined and estimated costs of hydrogen production and fuel cell use were calculated and compared with the diesel-based options. The results of the costs of diesel versus fuel cells or battery vehicles are shown in Figure 18.

**Figure 18: LCOTs for electric, H2 fuel cells and diesel-powered mining trucks and fishing vessels**

a) Mining Trucks




c) Fishing Vessels




Source: Author's estimates based on GACMO outputs.

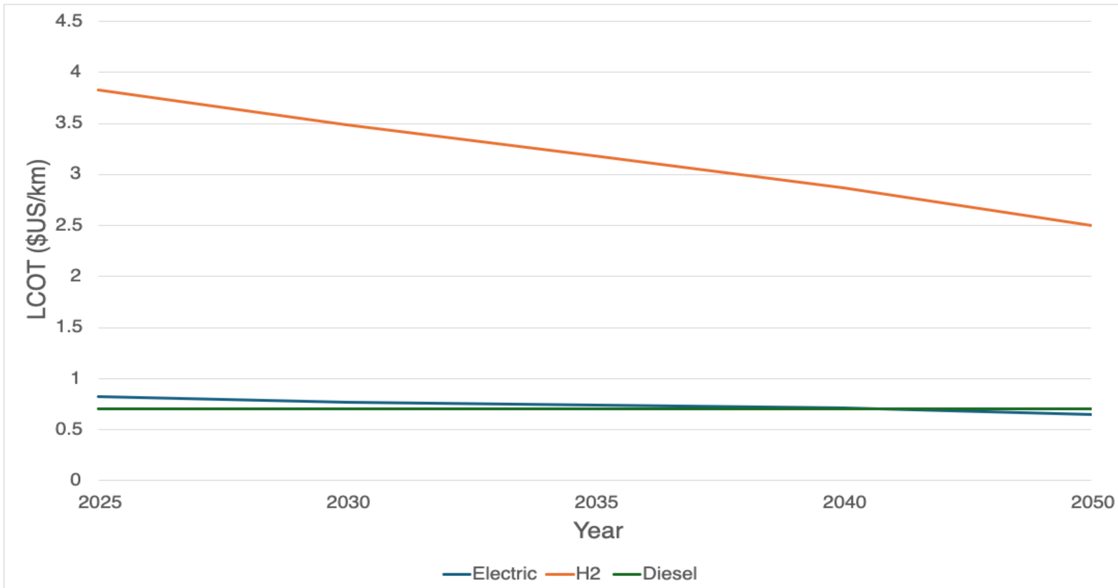
In both cases, the electric or fuel cell options clearly outperform diesel. The costs of fuel-cell mining trucks are projected to outperform the battery-operated option as the costs of $H_2$ in Chile decline rapidly. Battery operated fishing vessels are projected to remain the cheaper option during the period of analysis, but fuel cells are projected to match by mid-century.


*Electric and hydrogen-ready mining trucks in Chile. Photo: Javiera Pizzoleo*

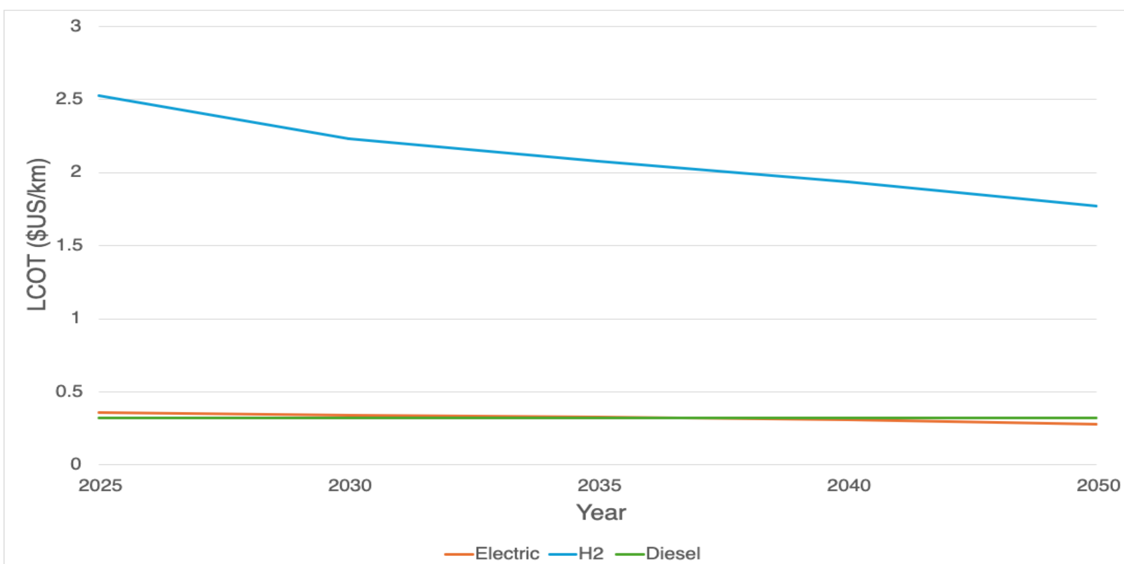
Figure 19 shows the LCOTs for heavy trucks and 18 m buses comparing batteries, fuel cells ($H_2$) and diesel. The analysis indicates that the $H_2$option remains uncompetitive throughout the period examined. The electric option, however, becomes competitive and outperforms diesel by 2035-2040.

**Figure 19: LCOT for 18 m buses and heavy trucks: electric, $H_2$, and diesel**

a) Buses



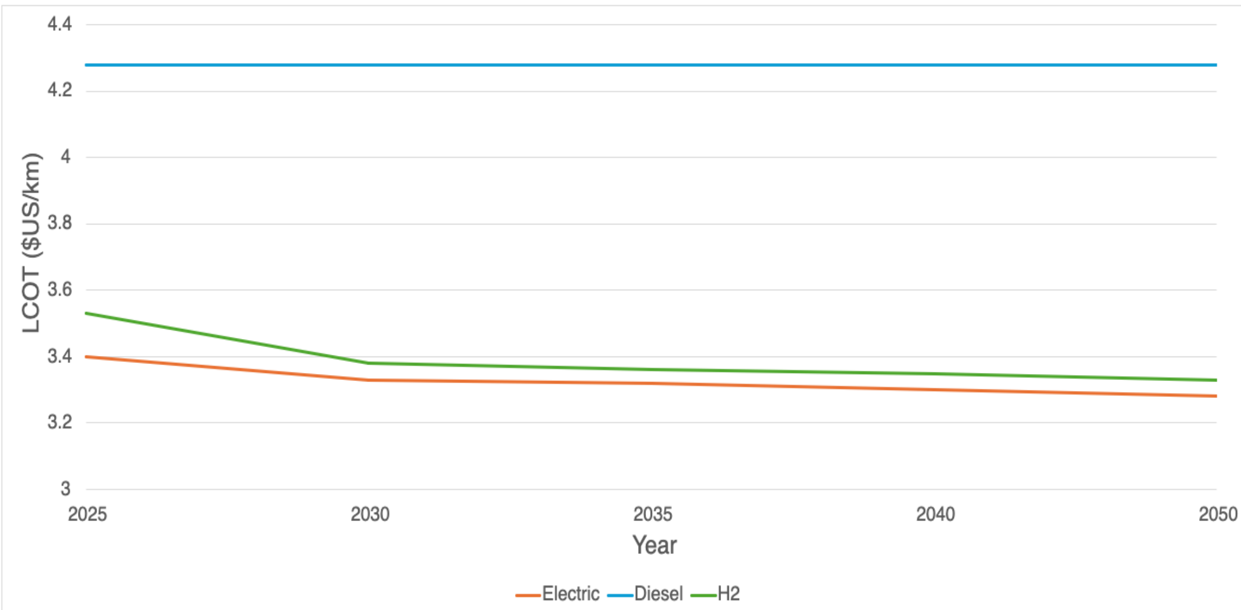

b) Trucks




Source: Author's estimates based on GACMO outputs.

The case for electric rail is straightforward. The capital and maintenance cost of electric locomotives are already 20% cheaper than diesel (Ligterink et al., 2017) and the maintenance costs are 20-25%lower than for diesel engines. Elimination of diesel in rail will also have a health benefit, as rail lines cross near urban areas in Chile. However, the electric infrastructure is missing and can be very costly (Nunno, 2018). The resulting comparative LCOTs are presented in Figure 20.

**Figure 20: LCOT for Rail**



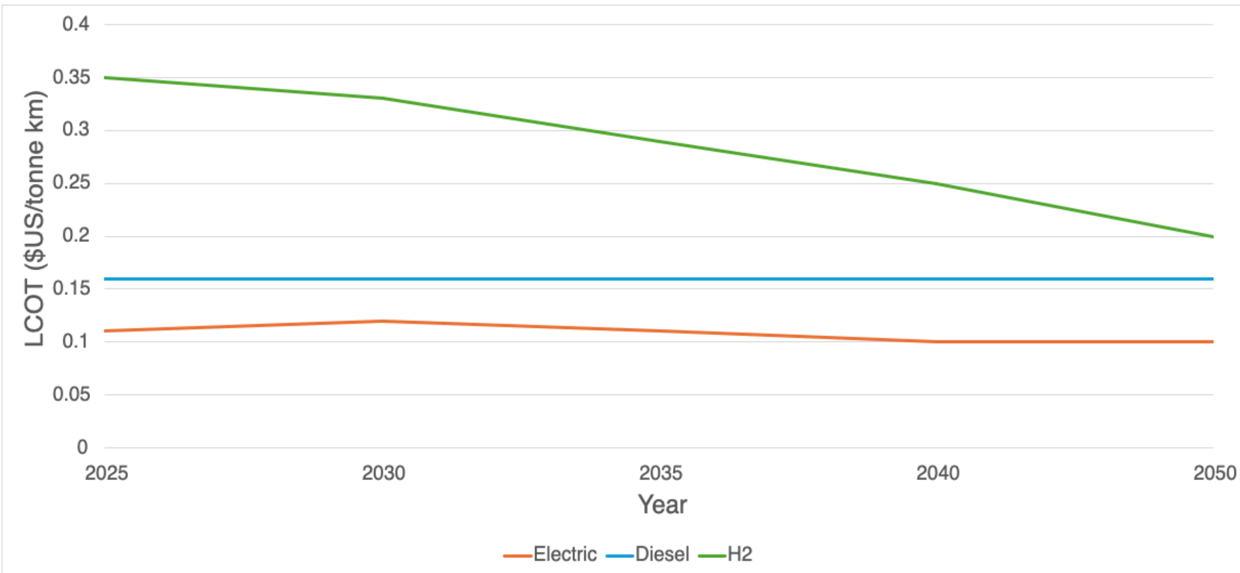

Source: Author's estimates based on GACMO outputs.

Electric coastal shipping (cargo and passengers) is still under development. Electrical infrastructure in ports and docks is not yet widely available. As in the case of electric rail in Chile, the port charging infrastructure will be expensive. Still, there are already electric ferries in operation with overnight recharging in Denmark, Norway, and New Zealand. In Denmark, dock charging uses an advanced charging system that can charge 4.1 MWh batteries in less than 10 minutes (WALL-Y, 2024). Electric ferries have also been considered for deployment on the U.S. West Coast.

Electric ferries are reported to have a capital cost that is 15-20% greater than a standard diesel ferry (Hildreth, n.d.). But maintenance and operation costs are significantly lower. An analysis of the ferry operation costs in Denmark (Abrahamsen, 2020) concludes that the electric option is cheaper when all costs are considered.

The results of an analysis of LCOT for coastal ships in Chile versus the diesel option, using cost estimates from existing operations in Scandinavia, are presented in Figure 21. The numbers indicate that the electric option is already competitive.

**Figure 21. LCOT for Electric and Diesel and H2-powered Coastal Ships**




Source: Author's estimates based on GACMO outputs.

In summary, the analysis reveals:

The electric options for light transport are already highly competitive in Chile, as they are elsewhere. The edge of electric options gradually increases as the industry internalizes reductions in cost of electricity, savings in battery storage, and anticipated innovation in electric drives.

Heavier electric vehicles are expected to become competitive later during the analysis period. However, innovation in heavy-duty segments is progressing rapidly and the edge may be realized earlier.

The fuel cell option for heavier vehicles appears suitable for mining trucks.

For rail, the electric option can replace all diesel locomotives today.

There is economic justification to start a wholesale transformation of the transportation fleet.

# 9. Use of hydrogen in transportation and power generation

This section reviews the economic competitiveness of hydrogen for use in fuel cells for heavy-duty transportation,[62] and in electricity generation to power retrofit, or new, CCGT. The use of hydrogen as a reducing agent in steel manufacturing and as a fuel in other industrial operations is covered later in the industry section. Other applications, such as oil refining or ammonia production, are not explored under the ZES.

The GOC has established a National Green Hydrogen Strategy. This strategy aims to develop the hydrogen sector for both domestic use and export markets. It is ambitious and prioritizes hydrogen for heavy vehicles and as a refinery feedstock.

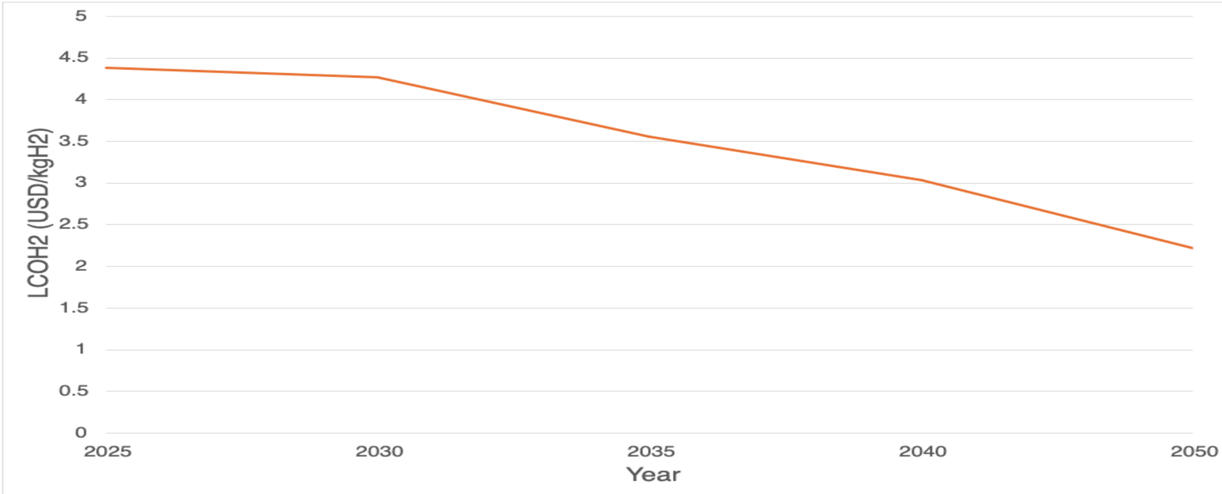
## a) Estimate of the levelized cost of H2 (LCOH2) production in Chile

Hydrogen production costs are highly dependent on the cost of electricity and of the electrolyzer. Section 6's electricity cost projections and IRENA electrolyzer[63] cost forecasts are used to estimate $LCOH_2$ (Figure 22). Anticipated cost reductions reflect technology gains and reductions in the cost of electricity.

Hydrogen used as fuel in the transportation sector requires a fuel cell. Their competitiveness versus electric batteries depends on energy density (weight in heavy-duty use), efficiency of hydrogen use, and costs.

[62] For purpose of this analysis, heavy duty vehicles are defined as those weighting over 13 metric tons as defined by the Federal Highway Administration (FHWA) of the United States.
[63] Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal

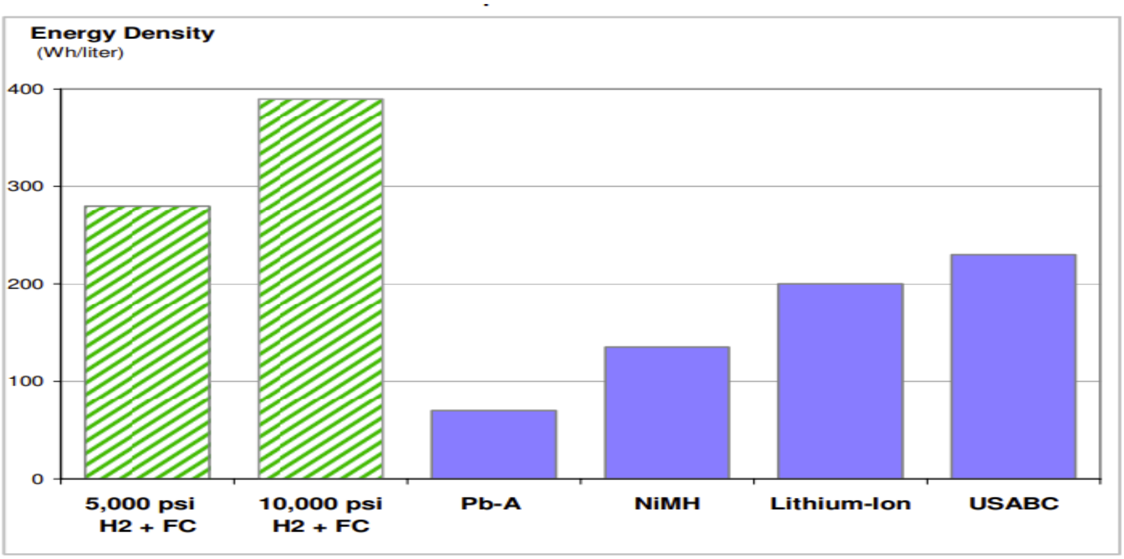
**Figure 22. Levelized cost of Hydrogen**




Source: Author's estimates based on GACMO outputs. H2 production parameters based on Navarrete A. and Y. Zhou (2024). Assumes capital cost in 2025 is $1500/kW

As discussed in the transportation section, lithium-ion batteries exhibit energy densities of 200-250 Wh/kg, while solid-state lithium batteries already reach 300 Wh/kg but are projected to exceed 500 Wh/kg. Fuel cell systems generally provide higher effective energy density (Figure 23), with only minimal additional weight needed to extend vehicle range.

**Figure 23. Energy density of fuel cell systems and electric batteries**[64]



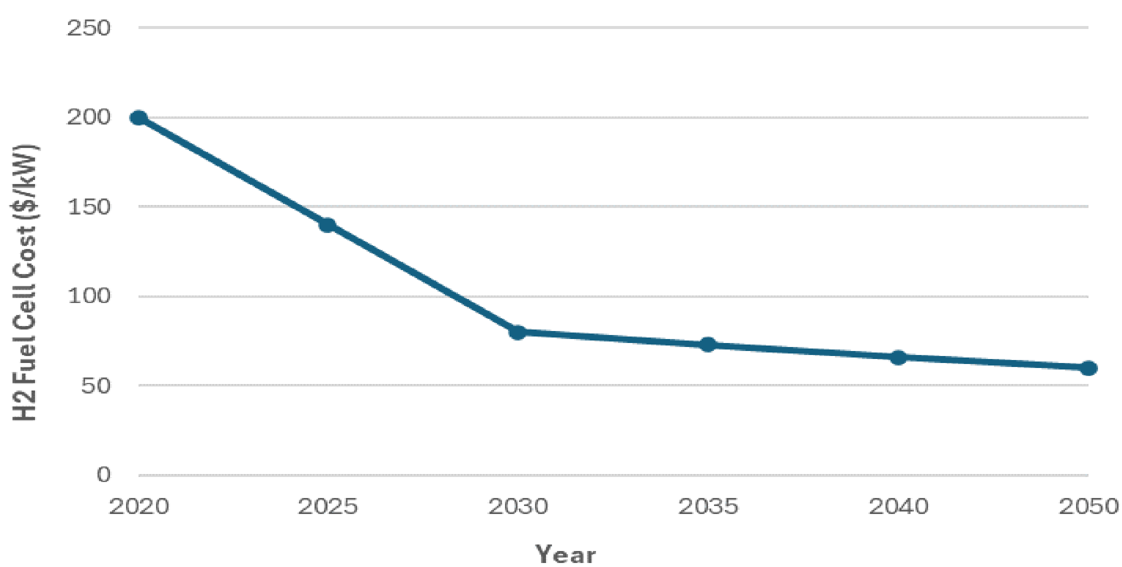

Source (Thomas, 2009)

[64] USABC refers to the United States Battery Consortium concept battery.

In contrast, electric vehicle battery weight rises significantly for longer ranges, particularly in heavy-duty applications. Consequently, fuel cells are anticipated to be more competitive in heavier transportation applications. Fuel cells operate at up to 60% efficiency, below electric engines (85-95%) but well above ICEs. This analysis assumes 60% efficiency for fuel cells.

At the point of delivery of energy there are two key components influencing costs: Hydrogen itself and the fuel cell system. Fuel-cell cost estimates use DOE Hydrogen Program data (2023),[65] just under $200/kW in 2020, projected to fall to $60/kW by mid-century (Figure 24).[66]

**Figure 24. Projected Fuel Cell Costs over time**




Source (DOE, 2023)

[65] https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/23002-hd-fuel-cell-system-cost-2022.pdf?Status=Master

[66] On the other hand, fuel cells require significant investment in hydrogen production, storage, and distribution infrastructure, which is currently just nascent, and not included in the estimates, compared with the anticipated growth in electrical charging networks.

*Paracelsus hydrogen production and storage facility in Chile's Atacama region. Source: Atacama Hydrogen Hub.*

## b) Levelized cost of transport using H2 through fuel cells

Based on these projections, the levelized cost of transportation using hydrogen (LCOH2) was estimated with GACMO for heavy-duty transportation in Chile including, mining trucks, fishing boats, heavy duty trucks, coastal ferries/ships, and 18 m interurban buses. The assumptions are summarized in Table 19.

### Table 19: Assumptions Made in the Estimate of LCOT for H2 Powered Fuel Cell Vehicles

| Vehicle | Base cost (Investment cost of vehicle ex fuel cell system) | Current cost of fuel cell system | Autonomy (km/kg H2) | Assumptions |
|---|---|---|---|---|
| Fishing boats | $120,000 | $12,000 | 4.3 | 12 m length; 80 HP cell (60 kW). Average cruising speed 15 km/h; |

| | | | | |
|---|---|---|---|---|
| Mining trucks | $2,652,500 | $400,000 | 0.5 | CAT 793F mining truck; 1980 kW cell. Average speed 60 km/h |
| Heavy duty trucks | $205,000 | $98,400 | 3.9 | SCANIA V8; 492 kW cell. Average speed 112 km/h |
| Coastal ships | $4,800,000 | 500,000[67] | 0.3 | Based on the cost and cargo capacity of the 82 m MF Hydra with 2 by 200 kW fuel cells[68]. |
| Inter urban 18 m buses | $300,000 | $51,600 | 1.6 | VOLVO B8RLE Euro VI. 258 kW cell. Average speed 24 km/h |

As reported in Section 8, $H_2$ fuel cells are competitive for fishing fleets and mining trucks but less for medium-duty applications like heavy-duty trucks and interurban buses.

## c) Hydrogen-Fueled Gas Power Plants

Hydrogen could also be used to generate electricity in combined cycle gas turbines (CCGT). This is an option already being deployed in other regions. For example, a commercial-sized unit is scheduled to start operation in 2029 in Singapore[69] and the Government of Germany is also examining their deployment at scale.

Hydrogen CCGT can increase the share of firm capacity in the power grid, aiding the integration of intermittent sources and compensating for solar and wind supply fluctuations. CCTs systems are efficient and relatively easy to convert to hydrogen. They

[67] https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/fc353_james_2023_o-pdf.pdf

[68] https://aws-a.medias-ccifi.org/fileadmin/cru-1713531284/norvege/user_upload/Norled_port_presentation_27.05.21.pdf

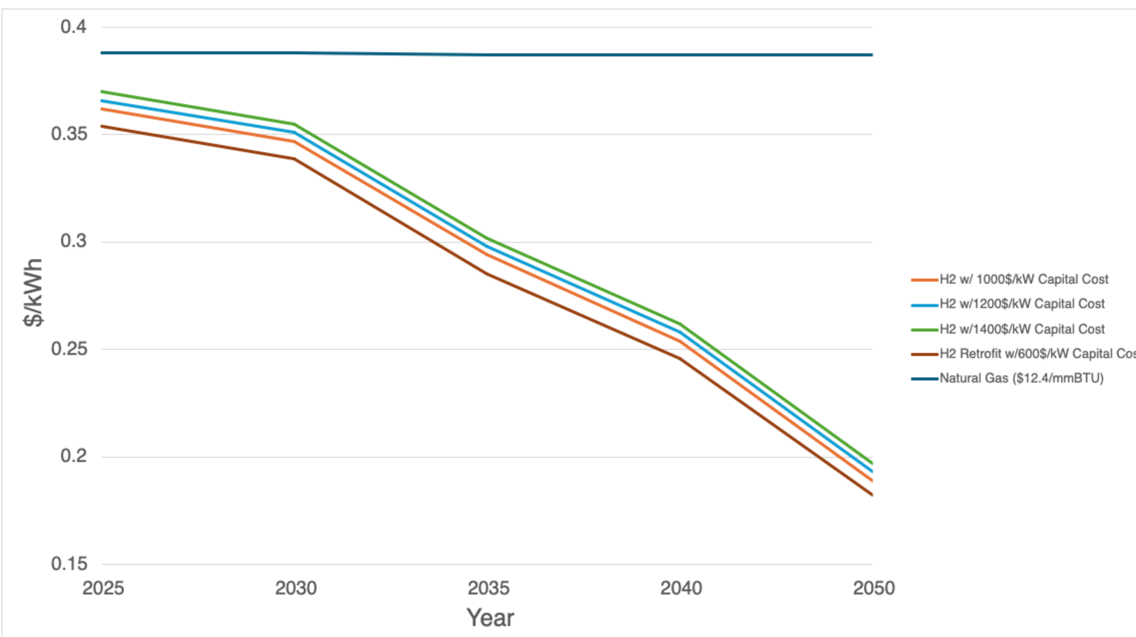
[69] PacificLight Power has secured the rights to construct a 600MW hydrogen-ready CCGT facility in Singapore. The local Energy Market Authority has awarded the company the opportunity to build, own and operate the new plant, with operations set to begin in January 2029 (https://www.power-technology.com/news/pacificlight-ccgt-plant-in-singapore/?cf-view).

also exhibit a rapid ramp up time, like those in combined cycle gas turbines, which allows quick response to supply gaps.

Existing gas-powered CCGT plants could be retrofitted to use hydrogen,[70] requiring investment but avoiding stranded-asset losses. There are several CCGT plants in Chile that could be the subject of retrofits. These include the plants at Mejillones (0.5 GW), Tocopilla (0.4 GW), San Isidro (0.7 GW), Nehuenco (0.7 GW). A $H_2$ retrofit program for CCGT plants could also accelerate the displacement of gas from the power system.

A recent analysis (Öberg et al., 2022) finds that hydrogen-fueled gas turbines can be competitive under strict limits on gas use, as is the case under the ZES. The study's estimates confirm that $H_2$-fueled CCGT outcompetes natural gas, especially with retrofits (Figure 25).

**Figure 25. Projected competitiveness of H2 fueled CCGT vs standard units.**




Source: Estimates based on a gas CCGT with an investment cost of $1000/MW, a 400 MW power output, and a retrofit with a $600/MW investment cost.

[70] While there is not a great deal of experience with this type of retrofit, the technology is available and there is clarity on what needs to be done: modifications to the combustion system, including new burners optimized to use hydrogen's combustion characteristics, upgrades to the fuel supply system and adjustments to manage the potential NOx emission concerns resulting from the higher flame temperatures.

# 10. Electrification of the Chilean Industry

This section focuses on the potential to electrify energy demand in industry in Chile and ascertain the current and anticipated competitiveness of the generation of heat/steam[71] using electricity.

Industry accounts for 22% of Chile's total energy use (Ministerio de Energía Gobierno de Chile, 2022). Most energy is used as process heat and for provision of steam at varying temperatures and pressures. Other energy requirements in the sector are met through the use of fuels to power engines, motors, compressors and heat pumps (gas and electricity) as well as transport fuels. An important energy demand is represented by heavy industries' (steel, cement, pulp and paper) energy intensive processes, like for kilns and high temperature furnaces.

Many of the technologies needed to electrify industry are already available commercially, while others are being developed or are expected to become commercial during the analysis period. Some Chilean firms are already considering the use of advanced electrical technologies, even in cases where the adoption of electrical options has been considered challenging. Furthermore, there are opportunities for parties in Chile to take an active role in advancing these technologies.

## a) Electrification potential of key industrial sectors

To better understand the prospects for decarbonization, a summary of the most relevant aspects of energy use by industry in Chile is presented below:

**Steel Industry**. Huachipato , Chile's only steel mill (800,000 tons per year) closed in late 2024.[72] Current domestic demand of 2.4 million tons (75% imported) is met largely through cheap Chinese imports and ferrous scrap recycling. This is the highest ratio of imports to domestic manufacturing in a decade.. Huachipato's energy use was about 16 TJ/year.[73]

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[71] Globally, heating and cooling applications are among the largest consumers of energy. For example, industrial heating applications (generation of heat and steam) account for nearly 20% of global energy consumption, space heating and cooling, and water heating account for 15% of global energy consumption (Bellevrat & West, 2018). In Chile, according to the PELP, 36% of the use of primary energy is used for heating across all economic sectors.

[72] The closure was the result at least in part of the expiration of the anti-dumping tariffs on Chinese steel.

[73] This is based on an estimated use of 19.8 GJ per ton and the production at Huachipato of 800,000 tons/year (https://www.resources.nsw.gov.au/sites/default/files/2022-11/report-reduction-of-ghg-emissions-in-steel-industries.pdf)

While no active steel mill units remain in operation in Chile,[74] industry with the support of the government has introduced the Green Steel Plan 2030 (Ortega, 2024). As part of this plan, the Production Development Corporation (CORFO) has a public tender for the use of the "Boquerón Chañar" project, which is one of the country's largest underground iron ore deposits. The bidding process will require that a portion of the extracted iron ore be used as raw material in the integrated production of green steel at Huachipato.

Key cost components in green steel manufacturing are iron ore, hydrogen, electricity, and capita, in all of which the country has a competitive advantagel.

- The country can supply electricity from renewable energy at very low costs (Section 6).
- Chile has iron ore deposits, including in Atacama'sChilean Iron Belt, known for its premium quality,[75] making it a significant exporter of iron ore.
- Green hydrogen potential is strong due to low-cost electricity and declining green hydrogen production costs.

The integrated benefits of affordable hydrogen and electricity can lead to the production of low-cost green steel for domestic use and possibly for export. This presents a valuable opportunity that Chile could capitalize on. The analysis considers that before 2050 a green steel plant with a capacity equivalent to the domestic consumption of steel would be in operation in the country.

**Use of Hydrogen as a reducing agent in the manufacturing of Green Steel.** In a green steel plant, iron is reduced in a process called direct reduce iron (DRI), which feeds its product into an electric arc furnace. The $H_2$-DRI process advances steel production decarbonization byusing hydrogen as a reducing agent instead of coke or naturalgas, greatly lowering CO2 emissions. When hydrogen is made via electrolysis with renewable energy, it becomes "green $H_2$" with minimal $CO_2$ emissions.

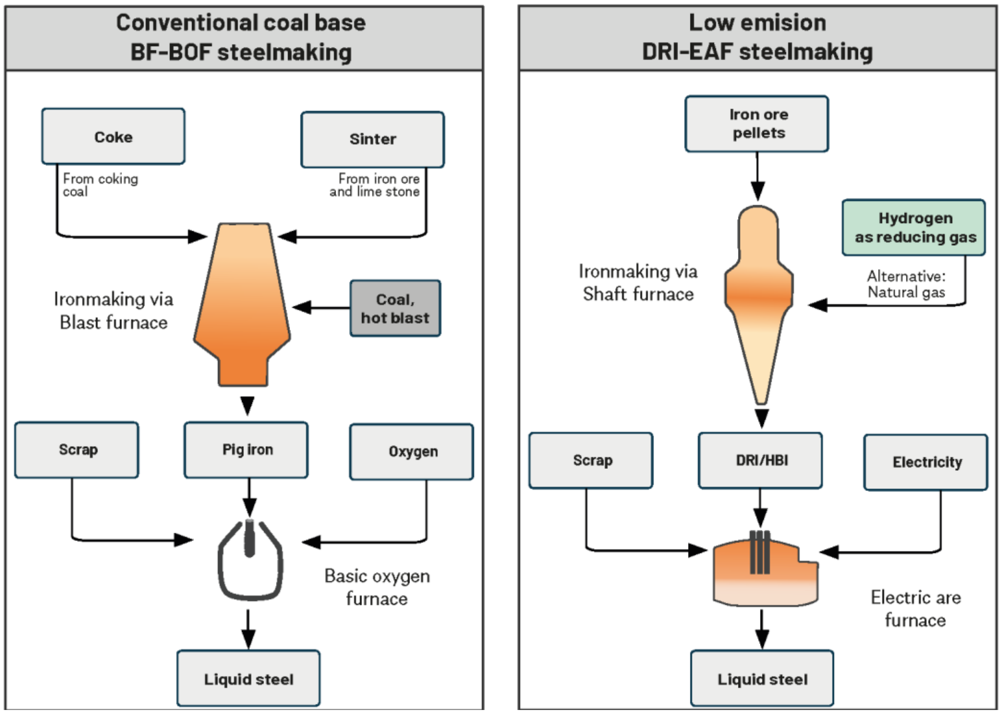
The furnace is used to convert directly reduced iron into liquid steel without affecting quality.[76] The furnace also yields valuable slag as a byproduct, similarly to traditional blast furnaces. Manufacturing would be achieved without fossil fuels (Figure 26).

[74] There are still other minor steel companies/players in Chile such as Aceros AZA SA that will continue with production. There is some question on whether or not they can make up Huachipato market share.

[75] Some Chilean iron ore has an iron content of 67% and low contaminants which makes it ideal in the manufacture of steel.

[76] This process is also known as the Hydrogen Direct Reduced Iron (H2-DRI)

## Figure 26: Schematic for Conventional Steel and Green Steel (using direct iron reduction with hydrogen)




Source adapted from Hüttel and Lehner, 2024

Technological advancements are enhancing the feasibility of green $H_2$-DRI by improving efficiency of direct reduction and of the electrolyzer, decreasing production costs and lowering renewable electricity expenses. These developments make green $H_2$-DRI an attractive alternative to traditional steelmaking.

There is at least one industrial-size $H_2$-DRI plant being built, and others in planning stages that will use the $H_2$-DRI process. In Boden, Sweden, the Stegra plant[77] is set to be the world's first renewable hydrogen-powered steel mill.

An estimate of the levelized cost of green steel in Chile (LCOS) has been made, with the assumptions listed in Table 20, and the results presented in Figure 27.

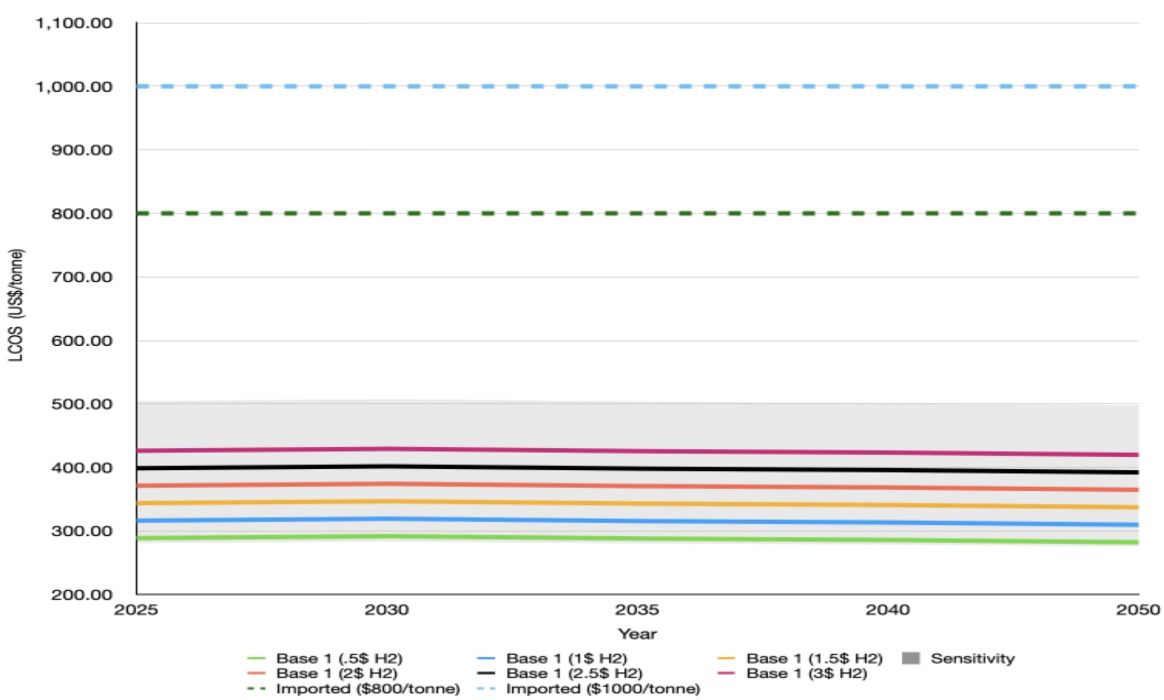
[77] Using a 690 MW electrolyzer, it will produce green hydrogen to replace coal in iron ore reduction and steel production, aiming to cut CO2 emissions by up to 95% compared to traditional methods. Backed by major funding, Stegra plans to produce five million tons of green steel annually by 2028, with operations starting in 2026 (https://stegra.com/). Also, German steel company Salzgitter has already started construction on a direct-reduced iron (DRI) plant and electric arc furnace in an effort to start producing steel with near-zero emissions as early as 2026, with a full switch-over by 2033.

## Table 20: Assumptions made in the Estimate of the LCOS (Green Steel using the H2-DRI-EAF process)

| Item | Assumptions |
|---|---|
| Capiral cost | $800 to $1200 per ton of steel |
| Size of the plant | 1.8 million tons/year |
| Iron use | 2.6 million tons/year, 65% iron content |
| Electricity use | 500 kWh/ton of steel |
| Hydrogen use | 55 kg |
| Other operational costs | Annually 4% of capital costs |

In summary, the results indicate that the $H_2$-DRI-EAF process for manufacture of steel could be very competitive under present conditions, even competing with cheap steel imports. The results further validate current efforts to promote the use of this technology in Chile. Few nations could deploy a combination of cheap electricity, low-cost hydrogen and high-quality iron deposits.

**Figure 27: Estimated LCOS of Green Steel manufacture in Chile**




Capital cost ranges from $800/tonne steel produced annually to $1200/tonne steel produced annually
H2 cost ranges from $0.5 to $3
H2 price of $2.5 is current LCO of H2 in 2025
H2 price of $0.5 is projected LCO of H2 by 2050

*Modern steel production facility in Chile. Photo: Aceros AZA.*

**Cement Industry**. The annual consumption of cement in Chile is about 4.0 million tons (Perilli, 2024). Chile imports around one million tons of cement annually, despite having over 10 million tons of installed capacity. Cement production necessitates substantial energy due to the elevated temperatures required to heat limestone. Currently, coal serves as the primary energy source. On average, the production of one ton of cement demands 3.4 GJ of thermal energy and 110 kWh of electrical energy.

Approximately 90% of the industry's total energy consumption comes the calcination of limestone in the kiln. Various options are being suggested to facilitate the electrification process in cement manufacturing. One good summary is included in Rowland J. 2024. Two electrification options are of particular interest:

**Combined use of electric arc furnace.**

> Electric Cement integrates cement and steel production using an electric arc furnace (EAF). In this process, traditional lime is replaced with spent cement powder from concrete waste, which is similar in composition to EAF slag. The high temperatures of steelmaking reactivate the cement. After tapping off the steel, the slag cools rapidly in air and is ground into a powder with a chemical composition akin to modern clinker. This will create significant requirements

for power over a short period of time which will require a grid capable of meeting large surges in demand.[78]

The option however would necessitate of the reactivation of steel manufacture and Chile and also proximity between the steel and the cement processes. Both requirements are possible but not immediate. However, the option is worth considering in the process of decarbonizing industry in Chile.

**Electrochemical decarbonation.**

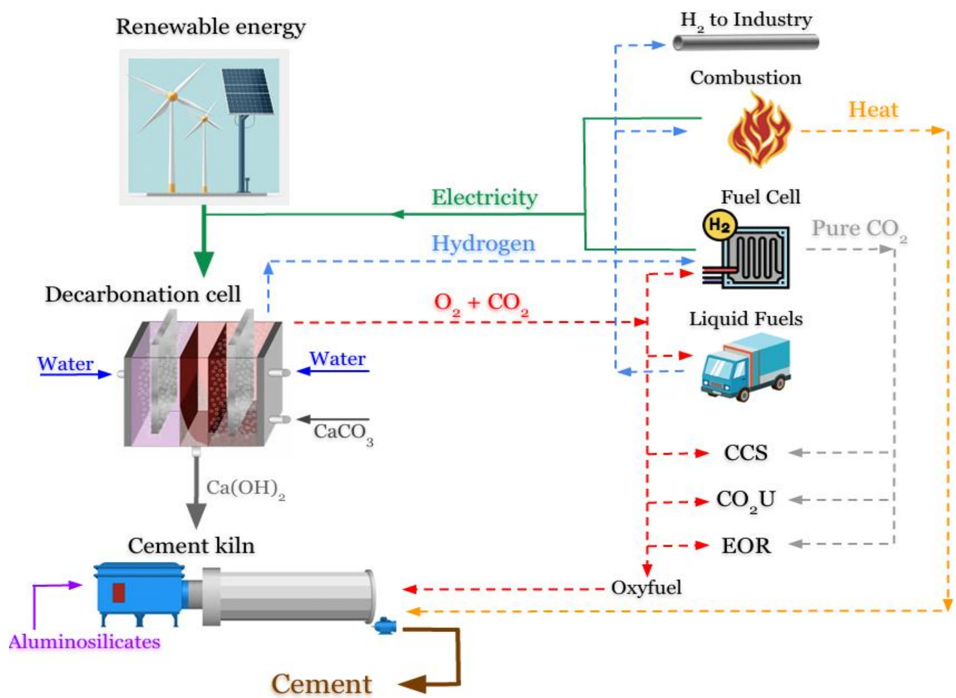
Electrochemical reactors replace coal or gas by converting $CaCO_3$ into $Ca(OH)_2$ and releasing pure $CO_2$, which can then combine with $SiO_2$ to form alite (the key mineral in Portland cement), with $H_2$ as a byproduct.

Calcium carbonate serves as the main kiln feedstock, while the resulting solid silica can supplement cement or mortar to improve strength and durability. The hydrogen generated during this process can be utilized as fuel within manufacturing operations or employed to generate electricity via a fuel cell (Figure 28).

This process addresses carbon emissions from both fossil fuels and limestone calcination, which are traditionally the sector's main carbon sources.

[78] The high heat, high power requirements of calcination have also led to proposals to integrate CSP (Concentrated Solar Power) generation plants with cement manufacture.

**Figure 28: Schematic of electrochemical decarbonation in cement manufacture.**




Source adapted from Johnson, 2019

Though still in development, enough information exists to gauge its competitiveness. For example, a recent study indicates that the process would be cost competitive with traditional cement manufacture if electricity is available at $0.02/kWh (Volaity S., et. al, 2025). The synergies with green hydrogen and low-cost electricity make this alternative worth considering for Chile. Additionally, the electrochemical decarbonation process could be integrated into existing cement plants, reducing capital costs and easing its adoption long term.

In the absence of detailed costs of equipment, this analysis provides a preliminary comparison of electrochemical decarbonation against conventional processes, based primarily on energy requirements, operating costs, and broad capital estimates. The assumptions are listed in Table 21, and the results are presented in Figure 29. The resulting estimate indicates that decarbonation can be cost competitive with current cement manufacturing. If the social cost of carbon is also included, the economics could swing in favor of electrochemical decarbonation.

## Table 21: Assumptions made to estimate Competitiveness of Electrochemical Decarbonation Cement Process

| Item | Assumptions |
|---|---|
| Size of the plant | 1800 tons/day |
| Capital cost | $150 million to $100 million[79] vs $110 million for a conventional plant[80] |
| Energy use | 6 MJ per ton of cement[81] vs 4.6 MJ per ton of cement for a conventional plant |
| Water use | negligible[82] vs 1.0 lt per ton of cement[83] |
| Maintenance costs | 25% of production costs vs 15% in a conventional plant[84] |

[79] There are not commercially available electrochemical decarbonation plants yet in operation. The estimated investment costs is based on the reported cost of the plant under construction by Sublime Systems in Holyoke, New Hampshire, adjusted by size.

[80] Capital costs for a conventional cement plant are based on estimates at cembureau.com.

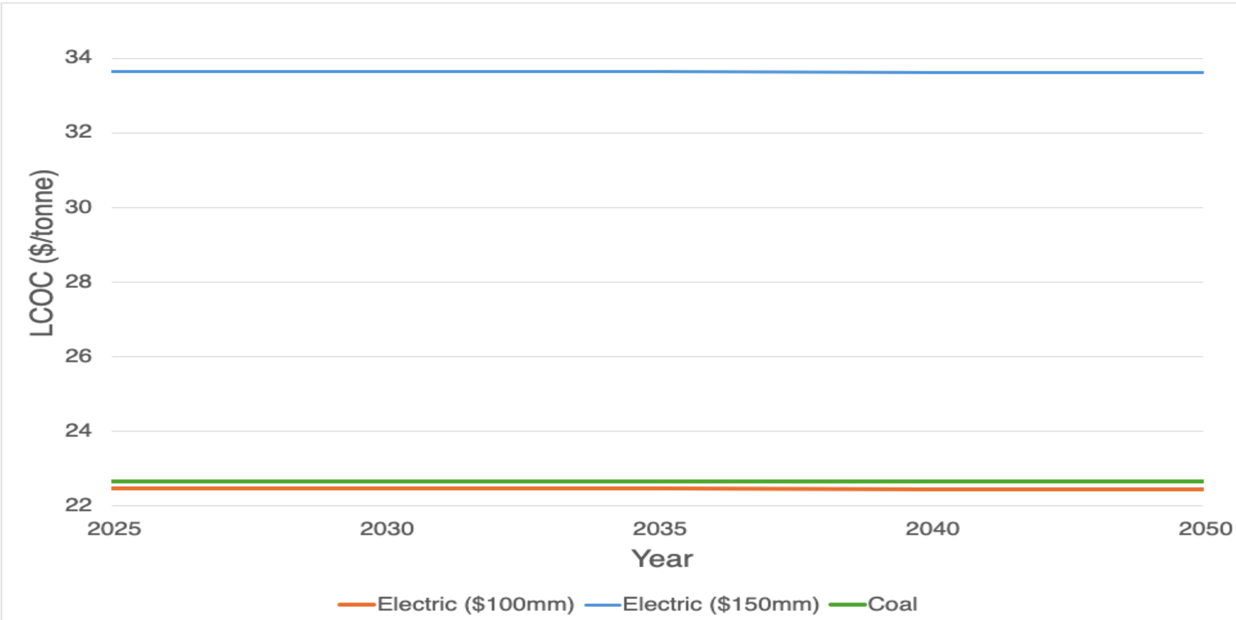
[81] https://pmc.ncbi.nlm.nih.gov/articles/PMC7293631/

[82] Assumes that all water consumption would be recovered from the dehydration of Ca(OH)2 and that H2 is used to fuel the kiln and water would be condensed from the flue gas.

[83] The cost of water for industrial use varies greatly due to to the tradability of water rights. To be conservative the costs of industrial water was estimated at $0.01 per lt.

[84] https://thecementinstitute.com/maintenance-in-the-cement-industry/

**Figure 29: Estimated levelized cost of cement via electrochemical decarbonation process vs the conventional process.**




Source: author's estimates. The price of coal is set at $140/ton with a caloric content of 30 MJ/kg

**Mining**.

**Copper.** Chile is the world's largest producer of copper, representing about 24% of the global production. In 2023, Chile produced 5.3 million tons of copper, largely for export. Mining operations are energy intensive, with most demand met by electricity and a major share dedicated to seawater desalinization and pumping. Within mining itself, concentration and leaching solvent extraction dominate electricity use. Currently, copper mining in Chile requires 12 GJ per ton.

It can be said that copper production in Chile is already heavily electrified. However, current industry projections of electricity use (COCHILCO, 2023) foresee a nearly 40% increase in demand by 2033. Increased production capacity and greater desalination needs will strain future supply infrastructure. Energy use by mining trucks is discussed in the transportation section.

**Lithium.** Chile is the second largest lithium producer and holds the world's largest reserves. The Atacama region has the lowest global lithium production costs, thanks to a favorable climate for evaporation and existing infrastructure from nearby copper mining operations.

In 2023, Chile produced 56,000 tons, nearly all for export. Chile is by far the largest producer of lithium carbonate with 61 percent of global production of in 2021. In the process, subsurface lithium brine is pumped to solar drying ponds for concentration. Therefore, energy use in lithium mining in Chile is relatively modest.

The balance energy demand is supplied by electricity used in the purification stages. Lithium production in Chile[85] requires 0.8 MWh of electricity, and 4.3 GJ of diesel and natural gas per ton of Lithium Carbonate. In both the copper and lithium industries, the key concern is the prospect for a significant additional demand for electricity in the future.

**Paper and Cellulose**.

This sector has the second largest heat demand in the country (20.6 TWh per year). The paper and cellulose processing requires heat at less than 200 °C, steam from boilers at 500 °C, and lime kilns operating at 1000 °C or higher. Worldwide, as an industry, paper and cellulose rank as the most carbon intensive in tCO2/unit of GDP (Furszyfer Del Rio et. al., 2022) . The industry has been switching to more energy-efficient sources, with 40% of total power use now drawn from bioenergy and alternative fuels.

The most energy intensive step is lime production within the chemical recovery cycle for chemical pulp mills,[86] conventionally powered by fossil fuels, such as natural gas or coal, in lime kilns.

**Plasma Calcination in the Pulp and Paper Industry**.

Plasma calcination is an electrical method for lime production. This process replaces the traditional combustion-driven lime kiln with an electric gas-plasma calcination reactor, ionizing $CO_2$ via an electrically generated arc. The ionized $CO_2$ can reach temperatures of up to 5000°C which facilitates the calcination reaction.

Plasma calcination offers various advantages over traditional lime kilns. Reburning lime mud using plasma can decrease the calcination process time from 1.5-4 hours in a lime kiln to only a few seconds in a plasma reactor, leading to better process control and much smaller equipment.

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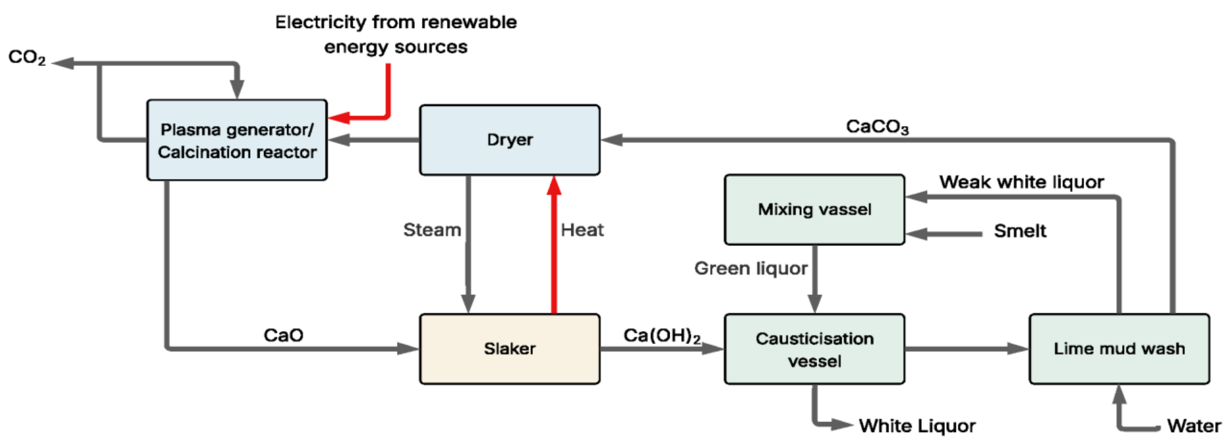
[85] This includes the evaporation of brine which requires 307 MJ and 265 MJ of diesel per ton of 6% Li brine at the Salars in Atacama, and the concentration of product into LiCO3 which takes place in Antofagasta, Chile, for refinement and processing (https://www.sciencedirect.com/science/article/pii/S0921344921003712) where 4 tons of brine are used per ton of final product requiring 1500 MJ of electricity, 400 MJ of diesel and 2,800 MJ of Natural Gas.

[86] The reaction for production of calcium hydroxide also generates CO2 emissions, similar to what happens in cement production.

However, plasma calcination is not yet fully commercially available, and only limited technical economic evaluations exist. The key issue is the comparative economics of plasma versus lime kilns under Chile's current and projected future conditions of power cost and production capacities.

Plasma technology has the potential to fully replace conventionally used lime kilns and is the basis for the economic comparison with traditional kilns.[87] Based on KTH data (Dylong, 2024) and the costs of Chilean electricity and natural gas, a comparative estimate of the Levelized Cost of Calcination has been made for a 15 MW unit producing 200 kg/day of CaO in the pulp and paper industry. The process diagram for the plasma calcination process is illustrated in Figure 30.

**Figure 30: Diagram of a Plasma calcination plant for Pulp and Paper Manufacture**




Source: adapted from Dylong, 2024

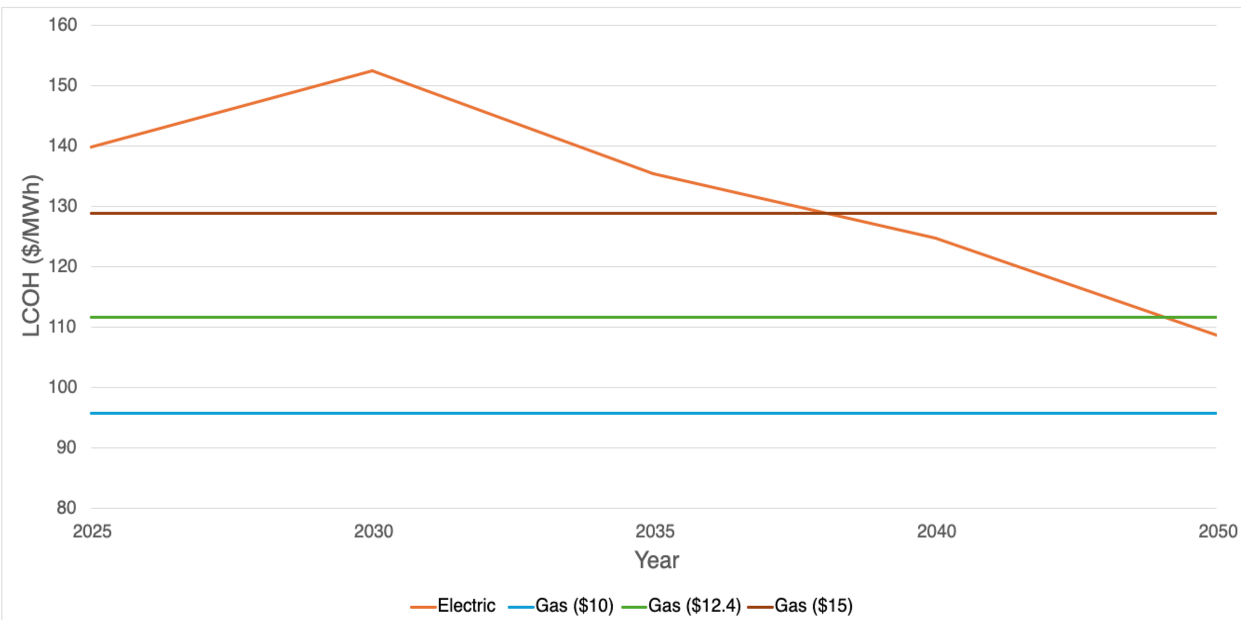
The economic competitiveness of plasma calcination depends on both capital costs (sensitive to reactor design such as plasma temperature) and operating costs (sensitive to electricity prices). Chile's relatively low-cost electricity should favor consideration of electric kilns. The full list of assumptions is listed below (Table 22) and the results are presented in Figure 31. The estimate concludes that the plasma calcination process is likely to be cost competitive by 2050.

[87] Other technologies referenced before may have a similar potential.

## Table 22: Assumptions Made in the Estimate of the Plasma Calcination Process for Pulp and Paper Manufacture

| Item | Assumptions[88] |
|---|---|
| Size of plant | 202 tons of CaO per day |
| Investment cost | \$11.6 million for the plasma calcinatory vs \$18.4 million for the traditional Lime kiln |
| Energy requirements | 8.0 MJ (electrically powered) per kg of CAO for the plasma calcinator vs 7.0 MJ for the traditional lime kiln (natural gas powered) |

**Figure 31: Levelized costs of calcination through a conventional rotary lime kiln and an electric (plasma calcination) kiln in pulp and paper production**




Source: Author's estimates

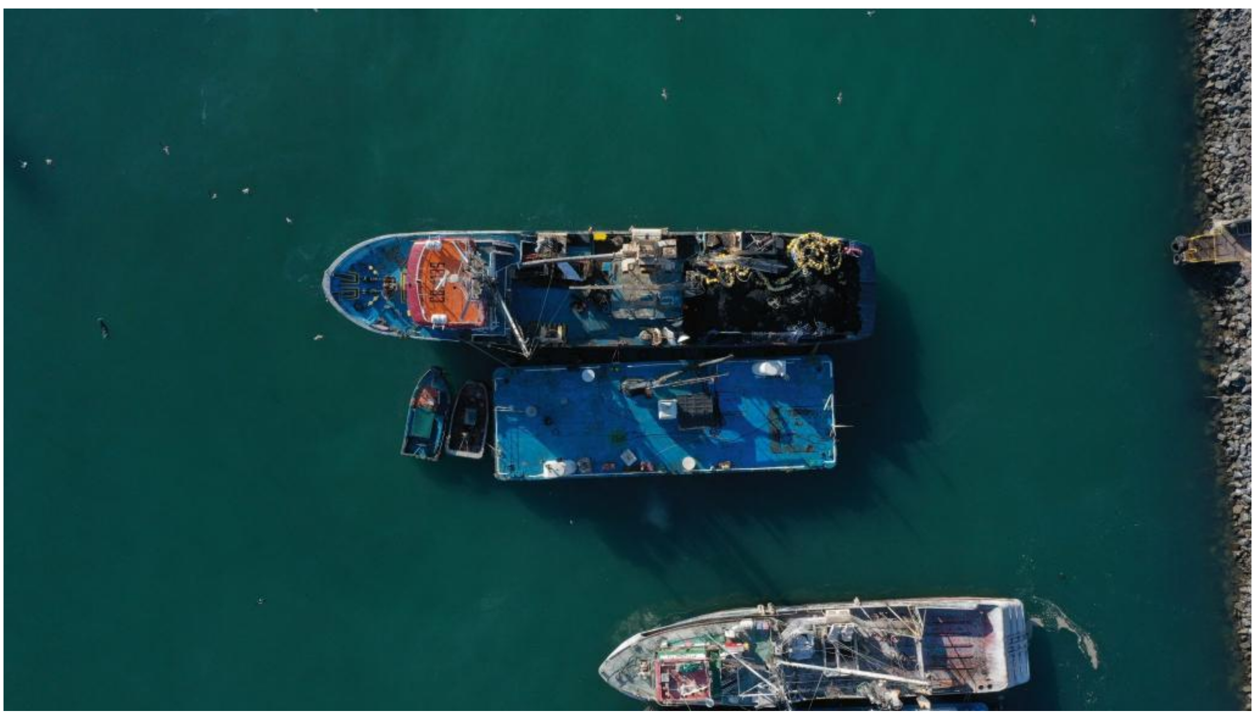
[88] https://kth.diva-portal.org/smash/get/diva2:1904026/FULLTEXT01.pdf

**Fisheries**.

Chile is the world's 8th largest fishing nation, producing 3.4 million tons in 2022 (Boletin SUBPESCA, 2024). In 2022, it was responsible for $8.5 billion exports (Plummer, 2024). The country has a large fishing fleet with significant production of anchovies, sardines, hake, and other valuable commercial species.

The sector consumes 2.6% of Chile's annual energy demand. Main uses include aquaculture, cold storage, and refrigeration (mostly electric) as well as the energy used for the fishing fleet in which diesel fuel is used (energy requirements of the marine fleet are discussed in the transportation section).

Most of the energy required in aquaculture is used in the production of fish feed, accounting typically for over 90% of total energy use in salmon farms. Given the remote location of most farming operations in Chile, off-grid wind and solar facilities are being increasingly considered.



*Camanchaca fishing operations in Chile. Photo: Mundo Acuícola.*

**Agroindustry**

Agroindustry, including agriculture and food production, accounts for about 9.2% of energy demand in Chile. The sector is heterogeneous, with many small-scale units. It relies on natural gas and diesel in boilers and electricity for irrigation, refrigeration, and pumping in different cleaning processes. This sector is the most reliant on low-temperature heating and cooling, and therefore, more likely to see fast returns on shifting operations to electricity.

A summary of the degree of electrification in industry is presented in Table 23.

## Table 23: Degree of Current Electrification of Industry in Chile

| Industrial Sector | Degree of electrification |
|---|---|
| Cement | Low. Most energy is required in high temperature applications, using coal. |
| Mining | |
| Copper | High (61% of demand was met by electricity in 2022)[89] |
| Lithium | The concentration of the brine largely uses solar energy. Electricity and fossil fuels are used in pumping, transport and further processing. |
| Prospect Green Steel | Green steel would be completely electrified. |
| Paper and Cellulose | Low with 40% of demand being met by biomass and alternative fuels |
| Fisheries | Most energy is used in freezing (60%) and primarily uses electricity. Fishing fleet uses 17% of total, mainly marine diesel. Aquaculture is responsible for 9% and moving toward renewables[90]. |
| Agro-industry | Electricity use varies depending on the sector. It also is a user of diesel and natural gas in heating and food processing. |

[89] Proyeccion del consumo de energia de la mineria de cobre 2022-2033. Colchico. 2023
[90] Eeindustria.centroenergia.cl accessed November 2024.

## b) Electrification of the provision of heat and steam in the industrial sector in Chile

The total use of natural gas in 2023 was 0.27 exajoules (EJ) (The Global Economy, 2023). About 40% (0.11 EJ) was used for heat and steam generation for all sectors. Process heat is required in chemical, mining, cement, agroindustry, iron, and steel industries.

**Cost of gas.** Today, most gas used in Chile is imported as LNG. The country has two LNG terminals that receive these imports. The current import price into the Quintero terminal is $12.50/MMBTU (Naturalgasintel.com, consulted June 2025). Imports from Argentina, via pipeline are quoted in the range of $10 to $11 per MMBTU based on a formula linked to crude prices. However, CNE (CNE, 2024) uses a projection of $9.5/MMBTU for 2025 and about the same for 2030 and 2040. The cost range is used as a reference when making comparative estimates with electric devices for the provision of heat.

**Potential substitution of gas by electricity.** The potential contribution of electricity-generated heat and steam to the performance of Chile's grid is significant. As these loads enter the system, there may be a flattening of the load curve therefore enabling a higher degree of efficiency of power supply. Process heat and steam[91] can act as stored energy, reducing the need for battery storage by shifting loads to coincide with renewable availability, which benefits both industry and the grid.

A range of mature technologies are available to cover many of the heating requirements. Heat pumps can address low temperature needs. Electric boilers can already substitute for gas boilers up to temperatures of 500 °C. Induction heaters and specialized boilers can reach up to 1000 °C. Other electric applications are emerging to substitute fossil fuels for specialized heating. The prospect of cheaper electricity as the country's power sector decarbonizes makes a strong argument to electrify these applications.

**Solar energy for industrial process heat (SIPH).** Besides electric heat and steam, direct solar energy is also an option for industry. A well-developed application is Concentrated Solar Power (SCP), discussed in Section 5, holds substantial potential for mining and other industries in Atacama.

Smaller scale, in situ, solar-powered industrial steam generation is attracting notable interest. This form of generation installs sole solar heating or hybrid (electric solar) to meet specific process requirements for steam or heat in sectors like mining, chemicals, and

[91] Thermal storage can provide energy for extended periods of time. Potentially, surplus heat produced in the summer could be made available for heating requirements during cooler months (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Power-to-heat_2019.pdf?la=en&hash=524C1BFD59EC03FD44508F8D7CFB84CEC317A299)

desalination. A U.S. review (Shoenberger et al., 2020) explores these applications. Since SIPH is very location- and industry-specific, comparative economics are not examined in this analysis.

Table 24 shows the state of readiness of various technologies as applied to the industrial sector in Chile.

## Table 24: State of Readiness of Electrical Technologies for the provision of Heat and Steam to Industry

| Industrial Sector | Technology | Developmental Stage | Advantages | Barriers |
|---|---|---|---|---|
| Broad application in low temperature processes | Electric heat pumps | Commercial and in use in Chile | Higher efficiency; lower costs of O & M. | Heat pumps often involve high up-front capital expenditure and companies need to integrate unfamiliar technologies into their facilities. |
| Broad application in medium to high temperature applications | Electric boilers | Commercial | Higher efficiency; faster ramp up times; lower costs of O & M. Cheaper option in most applications | Initial investment costs. Need of a wider demonstration effect in Chile. design limitations when heating element boilers exceed 4 MW in capacity. |
| High-pressure steam | High voltage immersed electrode boilers | Already used in leading industries in Europe | Superior control and quick ramp up and reduction of energy output. | Limited availability and use in Chile; high initial installation costs. |
| | Jet type electrode boilers | Currently small but growing market | Efficiency and superior control of energy output. | Limited current use and high initial set up costs. |
| | Induction heaters | Early commercial use. | Much higher energy efficiency. | Limited availability and use in Chile; high initial installation costs. |

| | | | | |
|---|---|---|---|---|
| Broad application. Specialized use in the food industry. | Electric vapor compressor | Commercial use | Significantly improves energy efficiency in industrial evaporation processes. | Expensive equipment compared with conventional options. |
| Cement industry | Electrochemical decarbonation of $CaCO_3$ | Proof of concept | Eliminates use of fossil fuels. $H_2$ byproduct is enough to power kiln. | Still under development. Plant being built in the US but requires further investment to scale up. |
| | Kiln electrification | Prototypes in operation | Eliminates use of fossil fuels. | Still under development. |
| | Roto Dynamic heater (RHD) | First commercial unit in operation in 2024 | Eliminates use of fossil fuels. | Not yet in wide application. |
| Steel industry | Molten oxide electrolysis | Pilot reactor in operation. | Eliminates use of fossil fuels, | Not yet in wide application. |
| | Direct reduction Furnace with hydrogen | Commercial units already in operation | Uses hydrogen for the reduction of Iron displacing coke. Eliminates use of fossil fuels, | There may be short term limits in the availability of hydrogen depending on pace of adoption. |
| Paper and cellulose | Plasma calcination | Proof of concept | Eliminates use of fossil fuels | Technology still at concept stage |
| Broad application | Electric motors and pumps | Commercial and in wide use. | Reduced cost of operation and maintenance. Ease of adoption. | Requires rapid ramp up of equipment suppliers. |

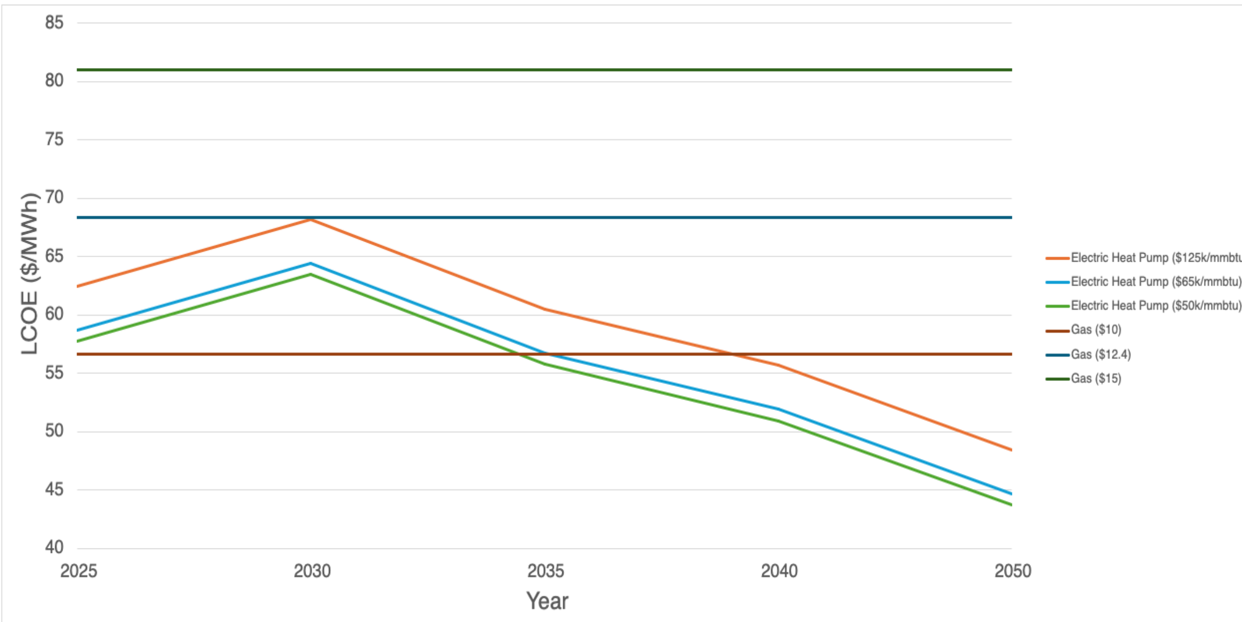
## c) Levelized cost of electric heat generation in Chile

**Industrial heat pumps** utilize electricity and low-temperature heat from a primary source to efficiently supply thermal energy for buildings and industrial processes. They have the highest thermal efficiency among heating options, reducing overall energy consumption, operational costs, and emissions.

Large heat pumps can provide heat up to 160 °C. Electric heat pumps are already commercial but need to gain additional market share to meet all low temperature applications in Chile. There is a growing demand for heat pump installation – notably in light industry, where there are typically lower temperature heating requirements. (breweries, dairy industry, food processing, paper).

Heavy duty heat pumps are also widely used in drying kilns, evaporators, and steam jets. There is a great variation in costs, but simple paybacks for industrial-size heat-pump applications are typically 2 to 5 years. Figure 32 compares the levelized cost of generating heat (LCOH) using heat pumps versus natural gas heat pumps under current Chilean gas prices. The results show a strong case for industrial electric heat pumps.

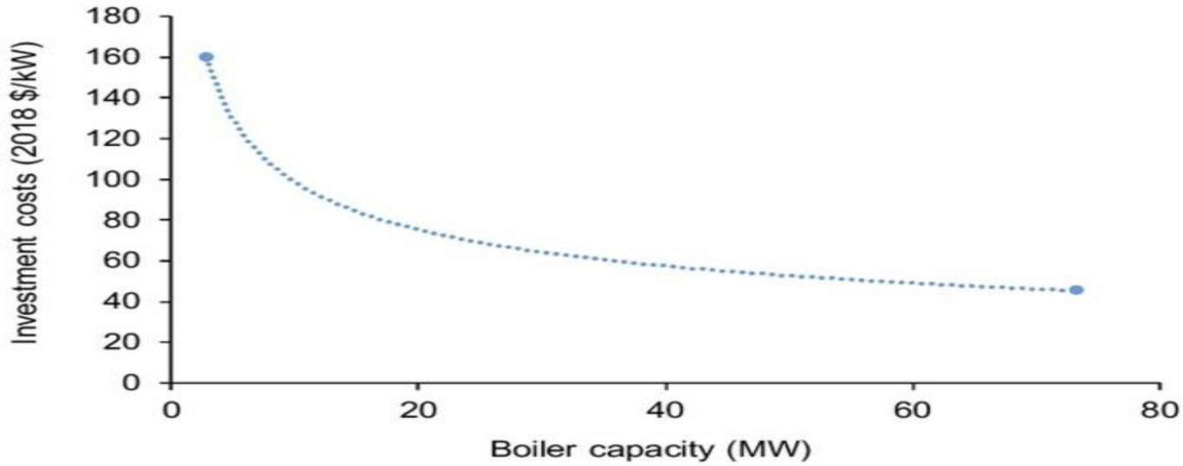
**Figure 32. LCOH of 100,000 MMBTU equivalent electric heat pumps vs natural gas heat pumps in Chile**




Source: Authors estimates based on GACMO outputs.

**Electric boilers** are a well-developed application. The current cost of electric boilers in the US as estimated by the Berkeley Lab is shown in Figure 33.

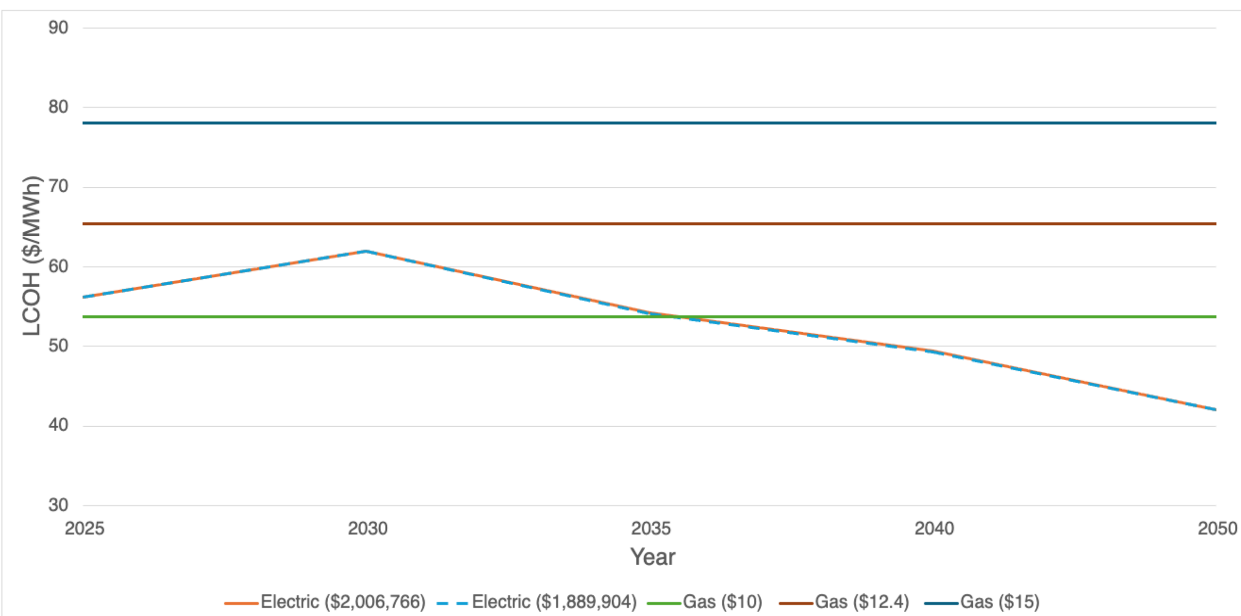
**Figure 33: Estimated cost of electric boilers**




Source: Zuberi M. et al, 2022

An estimate of the levelized costs of boilers is shown in Figure 34. The current costs of electricity and the price range for gas in Chile were used. The projected LCOE of electricity as estimated in section 6 was used to project operation costs as described above. The full list of assumptions is listed in Annex C.

**Figure 34: LCOH of Electric vs Natural Gas 100 MMBTU/hr boilers**



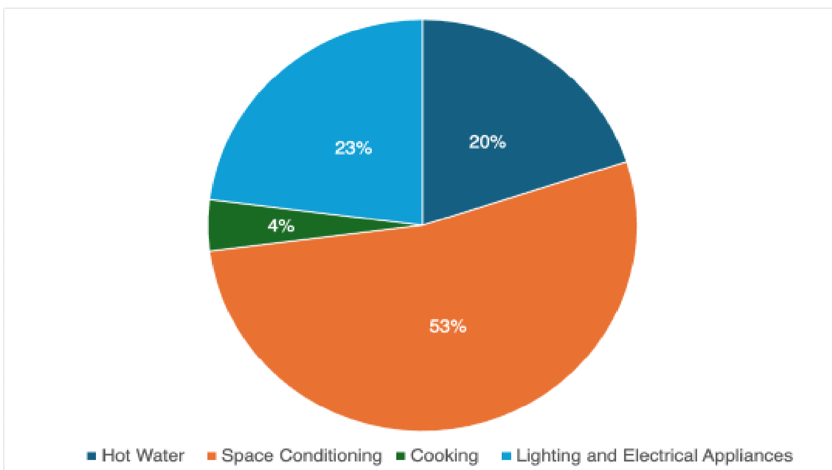

Source: Author's estimates.

# 11. Electrification of residential and commercial buildings

## a) Households

Energy demand in the residential and commercial sectors represents 22% of the total energy use[92] and about 35% of the current electricity demand (Observatorio BES, n.d). Households account for 69% of total energy use. A Ministry of Energy study (Government of Chile, 2021) concluded that the average annual household consumption is about 8 MWh. About 25% comes from electricity, 37% from fossil fuels, and the remainder from fuelwood.[93] In terms of end use, the same assessment estimates that over 50% of the total energy use is in space heating.[94] Figure 35 summarizes the findings of the analysis.

**Figure 35. Energy use in the residential sector**




(Government of Chile, 2021)

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[92] This estimate is based on the total energy used as reported in the Balance Nacional de Energia (https://energia.gob.cl/sites/default/files/documentos/2022_informe_anual_bne_2020.pdf).

[93] From the perspective of energy sources, most of the energy was provided by biomass, basically fuelwood for calefaction (38%), followed by electricity (25%), LPG (22%) and natural gas (12%).

[94] A 2018 survey of 3500 households, representative of the sector in Chile found that over 50% of all energy was used in heating and acclimation (2028 Uso de energia en los hogares de Chile: https://energia.gob.cl/sites/default/files/documentos/resumen_ejecutivo_caracterizacion_residencial_2018.pdf.

Under the proposed ZES scenario, all demand for energy in the residential sector would be met by electricity. This implies:

- Electricity would displace natural gas (mostly in urban areas) and fuelwood (in rural regions) in space heating applications. While switching from fuelwood would not reduce fossil carbon emissions, it would improve health and promote the development of local industry.
- Electric stoves and ranges would displace gas, kerosene and LPG stoves, improve indoor air quality and promote the development of equipment suppliers as well.
- Hot water is provided by solar and electricity, already widely available, displacing natural gas.

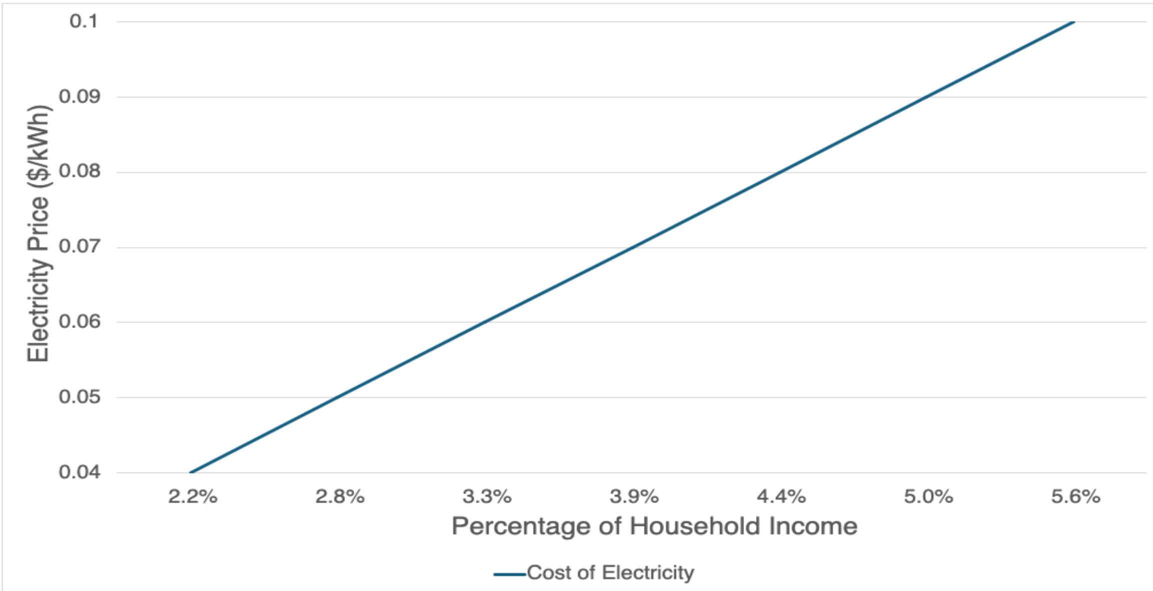
Technology options.

**Electrical heat pumps**. Electrical heat pumps can replace condensing gas boilers for space and water heating with far greater energy efficiency. Variable speed compressors that can adjust to heating loads, and smart thermostats could further cut energy use. While these developments are easier in high income apartment buildings in urban settings in Chile, the challenge is the high initial cost of heat pumps versus continuing to use firewood in rural households.

**Electric heaters.** Electric heaters combined with household insulation are a proven alternative to the use of firewood, they are relatively inexpensive and easy to install. The firewood used in Chile is typically of low quality, characterized by high humidity and low heating efficiency. It is often utilized in poorly insulated households. Its consumption is mainly concentrated in dispersed rural regions located at the country's southern latitudes, making precise characterization of its use challenging. It has been estimated that the peak load met by firewood in Chile is approximately 10 GW, with the annual energy requirement ranging between 17,000 and 22,000 kWh (Verástegui et al., 2020).

The key obstacle to the use of electric heaters is the cost of electricity. Even at the cheapest tariff ($0.11/kWh), resistive heating would consume a large share of rural income (Figure 36). From an economics perspective, the cost of electricity must be weighed against deforestation and lost ecosystem services.

**Figure 36: Cost of electricity for space heating as a percentage of household income in rural areas in Chile[95]**




Source: Author's estimates

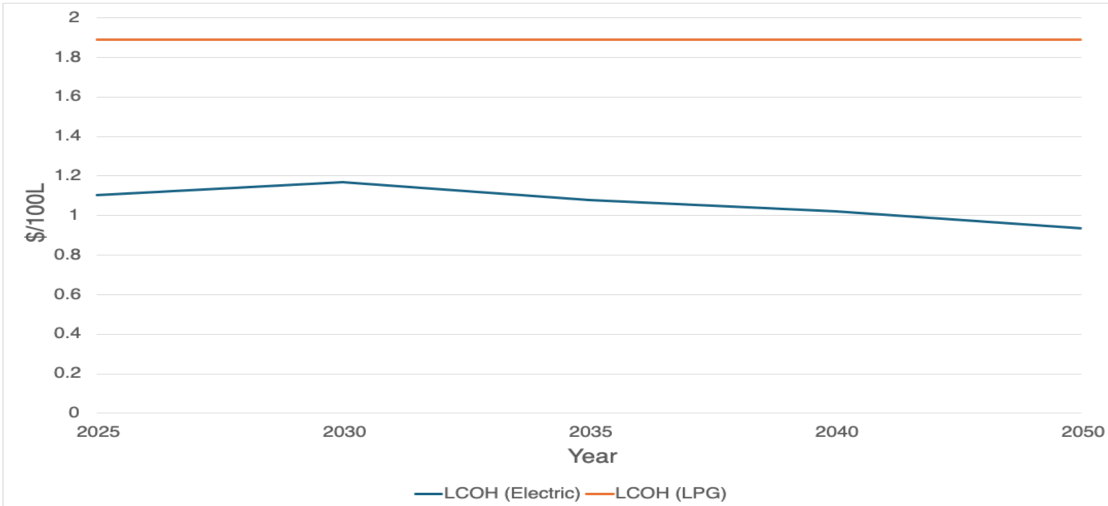
**Electric stoves**. Electric stoves, especially induction, are slowly being adopted in Chile as an efficient alternative to LPG, natural gas, and firewood. Their high efficiency makes them especially attractive. Nevertheless, LPG remains the main cooking fuel due to financial and cultural factors.

LPG stoves have lower investment and operational costs. However, electric induction cooktops reduce energy consumption and may offer long-term savings depending on the relative costs of LPG and electricity. For example, a recent comparative analysis in Ecuador (Martínez-Gómez et al., 2016) found induction electric stoves favorable in terms of economics and social acceptability. Likewise, a comparison in Indonesia found induction cooktops to be competitive.

For this analysis, the LCOH of boiling 100 liters of water with an LPG versus induction was calculated using current Chilean energy and equipment prices. The results are summarized in Figure 37.

[95] The estimate is based on a rural household consumption of 4 MWh per year (.33MWh per month), electricity costs of $0.05/kWh to $0.10/kWh) and a rural monthly median income of $600.

**Figure 37: Estimated LCOH of LPG vs Induction cooktops in Chile**




Source: Author's estimates

**Solar water heaters**. The survey of energy use in households (Ministerio de Desarrollo Social y Familia Gobierno de Chile, 2022) reports that domestic hot water accounts for about 20% of all energy use and 34% of fossil fuel use in the residential sector. At the same time, it was estimated that as late as 2017 (Ministerio de Desarrollo Social y Familia Gobierno de Chile, 2022), 11% of households lack access to clean hot water.

Chile has a high potential for using solar energy to meet household hot water demand. A recent study (Naranjo et al., 2025) indicates that over 9% of hot water requirements are already met by solar, including industrial solar water heaters, particularly in the northern regions and the Santiago metropolitan region. Further penetration of solar energy would directly displace fossil carbon without requiring electrification.

## b) Commercial buildings

The commercial and public sector buildings account for 6% of the energy use in the country (Ministerio de Energía Gobierno de Chile, 2022). The sector predominantly uses electricity and natural gas. Most of the energy is used in lightning and space heating. Table 25 presents a summary of energy use in public buildings.

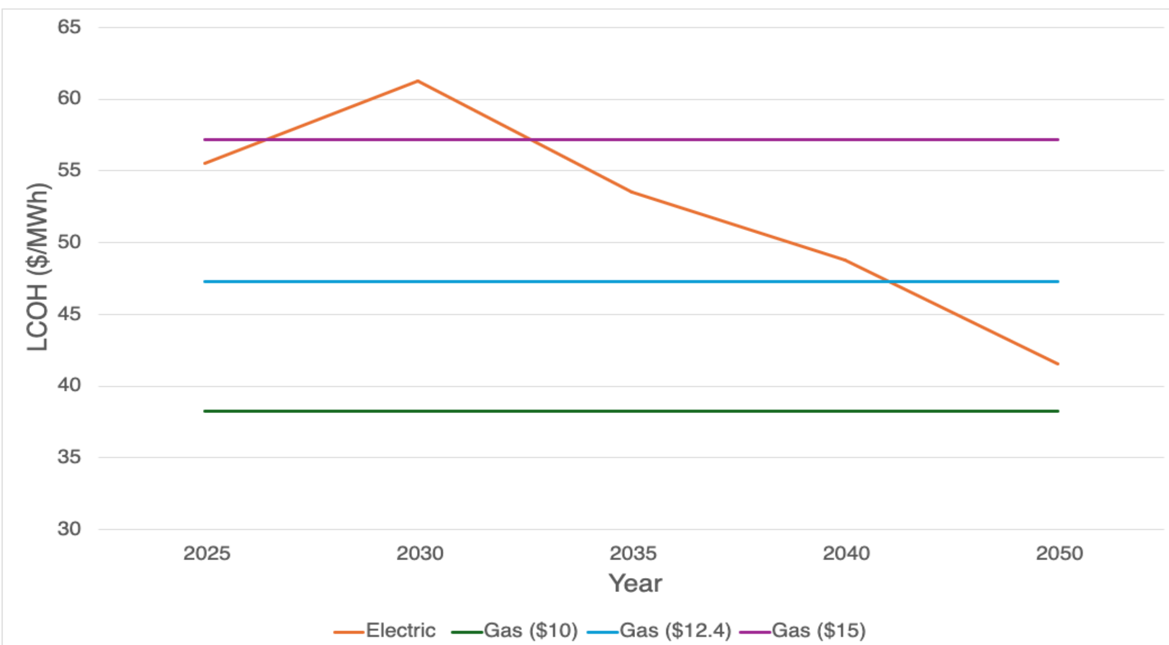
## Table 25: Use of Energy by Source in Public Buildings (2020)

| Energy source | Total use (GWh equivalent) |
|---|---|
| Electricity | 100 |
| Natural Gas | 20 |
| Total | 120 |

Source Government of Chile, 2021

Electrification options for commercial and public buildings are similar to those available for households. The main alternative to natural gas is the adoption of electric heat pumps. The estimated LCOH using electric heat pumps versus natural gas in boilers is presented in Figure 38 at various prices of gas. It shows that electric heat pumps will outcompete gas in the short term.

**Figure 38: LCOH using electric heat pumps vs the use of natural gas in boilers (60,000 BTU rating)**



# 12. Cost and Benefits of the Electrification of the Economy

The electrification of the economy will carry some economic costs but also result in large economic benefits. In this section the results of the quantitative analysis of these costs and benefits are summarized. Categories assessed include stranded assets, health benefits, gains from the efficient operation of a renewable energy-based power grid, energy efficiency gains, jobs and enterprise creation, the external benefit from decarbonizing the economy, and impacts on the costs of products and services.

## a) The value of stranded assets

As the Chilean economy electrifies over a few decades, significant capital assets linked to fuel oil production, distribution and use would become idle representing a cost to the overall economy of the nation. This section examines the value of the assets that would become stranded as the result of electrification using renewable energy resources.

*ENAP Bío Bío refinery, one of Chile's largest fossil fuel facilities. Photo: Empresa Nacional del Petróleo (ENAP)*

Although Chile is not a major fossil fuel producer or exporter, it does operate infrastructure that will require decommissioning. Table 26 lists by type of facility the inventory of the largest fossil fuel assets.

## Table 26: Inventory of Fossil Fuel Assets Subject to Decommissioning or Closure under the Zero Emissions Scenario

| Infrastructure | Number of units | Standard lifespan (years) |
|---|---|---|
| Oil storage | 3 | 20 |
| Oil refineries | 3 | 75 |
| Oil power plants | 5 | 50 |
| Natural Gas refineries | 1 | 30 |
| Natural Gas power plants | 2 | 45 |
| LNG import terminals | 2 | 40 |
| Coal power plants | 6 | 60 |
| Natural Gas pipelines | 6 | 100 |
| Resource endowment | Anticipated annual production by year of closure (2030) | Cumulative production from 2030 to 2073 |
| Natural Gas Fields | 13.76 billion cubic feet | 47.63 Bcf |

Source: Authors' data compilation from ANERT Energy Industry in Chile, 2022 report and global energy monitor (gem.com).

To estimate the value lost at decommissioning, the assets depreciation was estimated based on the start-up date, the standard lifespan by asset class and the date of anticipated closure. The remaining value was used as the value of the stranded asset. Some facilities in Chile are passed their scheduled lifetime and therefore their closure does not carry any book value to the economy. The overnight capital cost assumptions were taken from Binsted M., et al, 2020. The results are summarized in Table 27. The calculated value of stranded infrastructure is $19.4 billion.

## Table 27: Estimated Value Lost at Decommissioning by Asset Class ($ million)

| Asset class | Overnight capital cost (million US$) | Estimated value lost at closure (2030) |
|---|---|---|
| Oil storage | 18.9 | 2.4 |
| Oil refineries | 5,680.4 | 3,213.0 |
| Oil power plants | 588.3 | 564.2 |
| Natural Gas refineries | 45.0 | 21.3 |
| Natural Gas power plants | 2755.9 | 2407.5 |
| LNG import terminals | 3047,4 | 2807.3 |
| Coal power plants | 4603.8 | 4,143.4 |
| Natural Gas pipelines | 6684.3 | 6,247.6 |
| Total | | 19,406.7 |

Regarding the gas deposits, production estimates for all active gas fields were used to project the volume of unextracted gas if production ceases in 2030. The present net value of the unproduced gas was calculated based on projected annual production from 2030 to 2073, assuming continued operation until depletion. The gas left underground is valued at $166.1 million. The net present value estimated based on the anticipated curves of production until exhaustion of the fields (see Table 28) is $48.1 million.

## Table 28: Estimated NPV of Gas Left on the Ground until Exhaustion of Current Fields Under Production

| Year | Annual Gas Production (Bcf) | Cash Flow (millions) | Discount factor (10%) | Present value (millions) |
|---|---|---|---|---|
| 2030 | 13.76 | $48.16 | 0.5132 | $24.72 |
| 2035 | 9.53 | $33.36 | 0.3505 | $11.69 |
| 2040 | 6.88 | $24.08 | 0.2394 | $5.76 |
| 2045 | 4.76 | $16.66 | 0.1635 | $2.72 |
| 2050 | 3.70 | $12.95 | 0.1117 | $1.45 |
| 2055 | 3.39 | $11.87 | 0.0763 | $0.91 |
| 2060 | 3.07 | $10.75 | 0.0521 | $0.56 |
| 2065 | 1.59 | $5.57 | 0.0356 | $0.20 |
| 2070 | 0.53 | $1.86 | 0.0243 | $0.05 |
| 2073 | 0.42 | $1.47 | 0.0186 | $0.03 |

In summary, the total value of stranded fossil infrastructure and gas fields is conservatively estimated at $20 billion. This does not include industrial and transportation infrastructure associated oil derivatives such as gasoline and diesel stations, industrial sized boilers, furnaces, and other related assets.

### b) Health benefits

Electrification yields major health benefits. Moving the power grid to renewables displacing fossil fuels will eliminate its emission of criteria airborne pollutants (CO, NOx, SOx) and/or avoid expensive tail-treatment to prevent their emissions. Electrification of transport will also eliminate emissions of airborne pollutants including particulates greatly benefiting exposed populations in urban areas. Eliminating on-site fossil fuel combustion in factories and buildings can reduce indoor air pollutants and prevent impacts on factory and office workers. Electrification in the residential sector for all heating and cooling requirements displacing fossil fuels and/or wood will bring cleaner air, healthier homes for rural and urban populations.

**Impact from eliminating particulate matter.** The main sources of particulate matter include pipe-tail emissions from transportation vehicles, coal combustion and indoor air pollution caused by burning of fuelwood. In Chile, at least 60% of the country's urban population live in cities where ambient $PM_{2.5}$ exceeds the annual ambient air quality standard (AAQS) of 20 μg/m3 (Jorquera, 2021).[96] For example, the average $PM_{2.5}$ in Santiago in 2023 was 21. 3 μg//$m^3$. The WHO standard is 5 μg/m3

Epidemiological studies have found a strong association with exposure to ambient $PM_{2.5}$ and myopia, atherosclerosis, and diabetes incidence as well as respiratory illnesses and premature deaths in vulnerable and elderly populations (Busch et al., 2024).[97] It has also been found that with each increment of 10 μg//$m^3$ in the 2 day mean concentration of $PM_{2.5}$ there has been a 1.5% increase in daily mortality in Santiago (Nawaz et al., 2023).[98] In 2023, this translated to 1113 premature deaths caused by exposure to particulates in the city.

**Impact from eliminating $SO_x$ and $NO_x$.** Nitrogen oxides come from many sources, including tailpipe emissions from vehicles (cars, trucks and buses), power plants, off-road equipment used in agriculture, and other agricultural sources. Sulfur oxides come from fossil fuel combustion by power plants, large industries, and mobile sources, and from some industrial processes. NOx and SOx contribute to adverse health effects and to the formation of ground-level ozone and fine particle pollution. $NO_2$ and $SO_2$ are both linked with adverse effects on the respiratory system (EPA, 2024).[99] Additionally, $NO_x$ and $SO_x$ contribute to adverse respiratory and cardiovascular effects associated with exposure to ozone at ground level and fine particulates.

A recent meta-analysis (Chen et al., 2022)[100] found robust and reliable effects for $SO_2$ (per 10 μg/$m^3$) with chronic obstructive pulmonary diseases (COPD) and cardiovascular diseases (CVD). $NO_2$ (per 10 μg/$m^3$) was found to have effects for childhood asthma, preterm birth, lung cancer, diabetes, and COPD. CO (per 1 mg/$m^3$) was significantly associated with Parkinson's disease and CVD.

A U.S. based, national-level benefit per ton estimate for directly emitted $PM_{2.5}$, $SO_2$/$pSO_4$, and $NO_X$ for point-source sectors, including on-road vehicles, non-road engines and equipment, trains, marine vessels, and aircraft, was completed in 2020 estimating impacts

[96] https://www.sciencedirect.com/science/article/abs/pii/S2212095520306787
[97] https://www.nature.com/articles/s43247-024-01634-x
[98] https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023JD038808
[99] https://www.epa.gov/sites/default/files/2016-06/documents/20120320factsheet_secondary_standards.pdf
[100] https://pubmed.ncbi.nlm.nih.gov/36437665/

by 2025 (Wolfe et al, 2019).[101] The EPA also assesses the benefit per ton of airborne pollutant avoidance based on the impacts on morbidity and mortality in the U.S. (EPA, 2024).[102] These estimates provide a simple tool for estimating monetized benefits from eliminating the mobile source of emissions.

The benefit per ton estimates were adjusted to account for the cost differences in health systems in the United States versus Chile[103] and used to size the benefits from conversion of the road transportation fleet in Chile. The total exhaust emissions by vehicle type in Chile were taken from Osses et al[104] and updated to 2023, based on the growth of fuel consumption.[105] The assumption is that all these fuels will be replaced and consequently all associated emissions will be eliminated through the electrification of the fleet. The results are presented in Table 29.

## Table 29: Monetized Benefits from Eliminating the Source of Airborne Pollutants from Road Transport in 2023

| Airborne pollutant | Total emissions by the fleet in 2023 (tons/year) [106] | Adjusted Benefit ($/ton) | Total benefit from elimination of road transport point sources ($million/year) in 2050 |
|---|---|---|---|
| PM | 2.0 | 20,875 | 0.06 |
| NOx | 104.7 | 1,350 | 0.19 |
| VOCs | 7.9 | 1,169 | 0.12 |
| CO | 93.1 | | |
| Total | | | 0.37 |

[101] https://pmc.ncbi.nlm.nih.gov/articles/PMC7259328/
[102] https://www.epa.gov/benmap/sector-based-pm25-and-ozone-benefit-ton-estimates
[103] The health systems costs in the US are considerably higher than in Chile. For example, the health cost per capita in the US is $8,608, the corresponding figure in Chile is $1074 (https://www.nationmaster.com/country-info/compare/Chile/United-States/Health)
[104] https://www.researchgate.net/publication/359548975_High-resolution_spatial-distribution_maps_of_road_transport_exhaust_emissions_in_Chile_1990-2020
[105] The volume of fuels derived from oil in Chile increased by 16% between 2020 and 2023 (https://es.statista.com/estadisticas/1227245/volumen-ventas-combustibles-derivados-petroleo-chile/
[106] https://www.researchgate.net/publication/359548975_High-resolution_spatial-distribution_maps_of_road_transport_exhaust_emissions_in_Chile_1990-2020

**Avoidance of premature deaths through elimination of airborne sources of pollution.** For purposes of the analysis, an estimated value of a statistical life in Chile was taken as $4.6 million (Parada-Contzen M., et. al., 2013). Continued exposure to airborne pollutants would lead to 1,245 premature deaths by 2050, valued at $15 billion annually.

## c) Improvements in the operation of the grid

Energy supply should closely match demand to avoid reducing the output of power generators (curtailment) or experiencing a shortage. It is challenging to achieve this balance with a grid relying entirely on renewable sources, given seasonal and daily output fluctuations. Operating at optimal efficiency requires careful investment planning and minimizing operating costs.

**Avoidance of curtailment.** Curtailment occurs when renewables are forced to reduce or stop power generation, decreasing the amount of electricity, and thus, the return on investment from the affected facilities. It typically results from grid congestion and/or sudden fluctuations in demand. Grid operators may also need to curtail renewables to maintain system frequency performance.

For instance, high levels of curtailment occurred in Chile in 2023 (Molina, 2023), leading to at least a loss of 0.74 TWh during the first 5 months of that year and over 3.5 TWh during 2024 (Touriño & Murray, 2024). This level of curtailment equals more than a month of production.

To minimize curtailment, a grid operator may need to increase the ability to store energy. Long-duration energy storage (LDES) is an option to strengthen the power supply system. LDES is defined as storage capable of delivering electricity for 10 or more hours in duration. In parallel, investments in transmission infrastructure that prevent congestion as well as instituting demand response programs would also reduce the need for curtailment.

Beyond these measures, smoothing demand—flattening daily demand curves—keeps load constant and lets generators run at rated capacity.

**Ideal long term storage capacity.** The projected daily demand curves were utilized to estimate the optimal capacity for long-duration energy storage. Table 30 presents the estimated peak-to-low demand ratio from 2020 to 2050. The ratio of these values can be interpreted as an indicator of the flatness of the demand curve, while the area beneath the median provides an estimate of the capacity required to store energy during daily operations.

## Table 30: Projected Evolution of the Electricity Demand Characteristics

| Year | Peak/to low demand ratio | Daily demand (GWh) |
|---|---|---|
| 2030 | 1.45 | 417 |
| 2040 | 1.36 | 959 |
| 2050 | 1.26 | 1030 |

Gradual flattening of the curve is expected during the period analyzed. The flattening will result in avoidance of curtailment. The grid is expected to operate at a higher average online factor, defined as the total power generated/the total nominal power if the plants were used all the time (no curtailment), under the conditions of the ZES. The online factor is increasing because loads from different sectors at varied times are added to the demand. As surplus electricity is stored in batteries and hydrogen, the online factor further increases. The deployment of capital invested in the power matrix is thus more effectively used. Eliminating curtailment translates into $ 1.7 billion[107] in avoided investments in storage and a reduction in operations costs.

### d) Energy efficiency gains

Switching from the conditions assumed under the CNS to full electrification of the economy (Table 4) is estimated to save 663 PJ annually by 2050 (185 TWh). This energy will not be used by the economy. The value of these savings based on the current value of oil[108] is equivalent to $7.1 billion.

### e) Savings caused by the reduction in the cost of energy

In addition to the energy savings, the ZES will also deliver energy at a lower cost. A power matrix, solely based on solar/wind and other renewables, would reduce the cost of energy

[107] A simple estimate of the benefits of avoiding curtailment is based on avoiding the current situation where one month of equivalent production is lost. By 2050 one month of power production is equivalent to monetizing 48 TWh at the LCOE at the time or $1.7 billion.

[108] As of mid-2025 the price of a barrel of WTI is $66. The oil in a barrel represents 0.0000062 PJ if fully combusted.

delivered to the economy. The estimated LCOE, including generation, storage, transmission and distribution, would be $0.041/kWh.

Many the savings will be from heat delivered by electricity instead of LNG and rolling stock using electricity or hydrogen instead of diesel. These are estimated in the specific reductions in cost of goods and services (Section G below).

## f) The external benefit from decarbonizing the Chilean economy

Chile has a low carbon footprint; it contributes just 0.2% to global greenhouse gas emissions. The analysis in this report has not used the value of carbon to justify investments in renewable energy generation and transmission capacity nor for the use of alternative electric technologies.

However relatively small, the elimination of all $CO_2$ emissions still contributes to avoiding further global damage to the biosphere. This section explores the economic value of this contribution.

**Market price.** There is not yet a global market for carbon emissions. Instead, there are regional (European Union), country-based (China, South Korea, New Zealand, for example) and sub-national (California Cap and Trade) markets.[109] These markets also differentiate between emitter classes, with varying values for land, energy, aviation, and industry. Additionally, prices fluctuate widely (see Figure 39), making it difficult to assign a single present value to emissions. Instead, one might look at the social value of carbon.

[109] By one account there are over 72 carbon markets operating today: (https://www.kwm.com/au/en/insights/latest-thinking/around-the-world-in-carbon-trading-a-glance-at-regulated-regimes.html)

**Figure 39. Variation of Prices in the European Union Allowance Carbon Market ($/ton CO2 e) (2005-2024)**


Source: (Homaio, 2024)

**Social cost of carbon (SCC).** The SCC has been defined as the "monetary value of the net harm to society from emitting one ton of GHG (as CO2 e) into the atmosphere in a given year."[110] It is used to guide actions and regulations that prevent future climate damage.

There are several estimates of the social cost of carbon (for example in EPA, 2016; Rennert et. al, 2021), with widely diverging results, illustrating the difficulty of assessing current and future climate damage amid the many variables that need to be considered, such as GDP growth, population, emission reduction pace, and discount rates. For illustration purposes, some social carbon estimates are included in Table 31.

[110] US Environmental Protection Agency (EPA) Report on the Social Cost of Greenhouse Gases Estimates Incorporating Recent Scientific Advances: Final 2023 report.

## Table 31: Estimates of the Value of Social Carbon

| Source | Value in $ 2020. 2020-2050 | Method | Discount rate[111] and other assumptions |
|---|---|---|---|
| EPA | $190-$310 | Modular approach involving four modules: socioeconomics; climate; damage; and discount rates. | Discount rate at 2% |
| RFF (Resources for the Future) | $61 at 2% discount rate<br>$168 at 3% discount rate | Probability projection of GDP, population, emissions and discount rates. | Discount rates between 2% to 3%.<br>Simplified estimate of climate damage.<br>Ignores risk of tipping points. |
| IWG (Interagency Working Group) | $42-$69 | Considers the probability of discontinuities (tipping points). | Discount rate at 3% |
| Government of Chile[112] | $63.4 | Updated to a level designed to encourage emission reductions in public investment projects. | N.A. |

**Future market valuation**. A future market value can also be projected based on expected global demand, supply, and climate commitments. For example, the Net Zero 2050 scenarios prepared by the Network for Greening of Financial Systems (NFGS, 2024) estimate carbon prices of between $100 and $200/ton of $CO_2$e in 2030, rising faster until 2050. The International Energy Agency estimates that carbon prices will not exceed $250 by 2050 (IEA, 2021), as regulatory policies are assumed to play an important role before mid-century.[113] Other carbon market outlooks have prices under $250 by mid-century (BNEF, 2024).

Chile emitted ~110 Mt$CO_2$e in 2022 (SNIChile, 2024), with projections of ~70 Mt$CO_2$e annually by 2050 under the Carbon Neutrality Scenario.[114] Using the Social Cost of Carbon,

[111] The use of a lower discount rate places a higher value on future damages and suggests society should pay more now to prevent those damages.
[112] The Government of Chile updated the social cost of carbon in June 2024 (https://www.gob.cl/en/news/social-cost-of-carbon-updated-to-encourage-reduction-of-co2-emissions/).
[113] This assumption should remain valid despite the short-term disruptions caused by single large volume actors in the market
[114] Countries can now trade carbon credits internationally and include them in their climate goals through cooperative agreements or with each other on internationally tradable mitigation outcomes.

these emissions are valued at $10 billion annually, possibly higher under future market valuations. At today's ETS, the value is about $5 billion per year.

## g) Impact on the cost of goods and services

**Savings in the cost of heat.** The reduction in the costs of provision of heat resulting just from using electric boilers versus natural gas-based boilers is estimated at $1.6 billion/year.[115]

**Reduction in the cost of transport.** Electrification of transportation or use of $H_2$ in heavy-duty applications is projected to lower annualized transport costs (Section 8), reducing the cost of most transportation services. The cost reduction is estimated at $0.6 billion annually.

**Reduction in the cost of industrial output.** The production of steel using green steel is projected at$400/ton by 2050. This represents a saving of about $500/ton compared with current import costs. By 2050, steel consumption is projected to be 5 million tons,[116] resulting in savings of $2.0 billion. The production of cement using electrochemical decarbonation is expected to save about $43/ton by 2050. Producing 4 million tons of cement using the electrochemical process would save $0.2 billion.

[115] The reduction in costs of heat was made on the basis of the estimated levelized cost of heat (Figure 34) in a gas boiler ($66/MWh when gas is quoted at $12.4/MMBTU) vs the costs of heat generated in an electric boiler ($41/MWh). The overall demand for heat is equivalent to 0.11 EJ (30.5 TWh) in 2023 (40% of the heating value of natural gas used) projected to be 64 TWh by 2050 under the CNS.

[116] This assumes a growth rate in consumption of 3% per year.

## h) Impact on capital outlays

The electrification of the economy will require capital outlays for grid expansion, additional renewable generation capacity, and transmission. It will also avoid capital investments, such as additional gas-based generation capacity required to maintain power and other services and the costs of additional LNG facilities to maintain those services. Other capital costs, like the differential in costs between an electrical and a diesel/otto transportation fleet were not included (Table 32).

### Table 32: Impact of Electrification on Capital Outlays by 2050 ($ billion)

| Item | Additional capital outlays |
|---|---|
| Investments in renewable generation capacity[117] | 103 |
| Investments in storage capacity | 43 |
| | |
| Expansion of the transmission grid | 66 |
| | **Avoided capital outlays** |
| Investments in gas-based generation capacity[118] | 3 |
| Investments to maintain the LNG storage capacity and gas pipeline infrastructure[119] | 1 |
| Expansion of refinery capacity[120] | 1 |

[117] This is the average cost of investments required to provide the additional 166 TWh (excludes the capacity already installed, estimated at 14GW; see table 4) through the deployment of 160 GW of generation capacity and 34 GW of battery storage capacity ($2.2 million per MW installed, and CSP $2 million per MW).

[118] Under the PELP, Gas-fueled turbines continue to operate until 2050 but no additional generation or storage capacity is added. However, the existing CC turbines and LNG would require maintenance investments of the order of 10% of current capital costs.

[119] The value in 2050 of CC turbines and gas pipelines is estimated at about $9 billion.2310

[120] This assumes that demand for diesel and marine diesel for heavy vehicles and gasoline and diesel for interurban bus service under the CNS scenario continues until 2050 but that reduction in the use of diesel and gasoline caused by the electrification of light and medium heavy-duty vehicles as considered in the CNS more than compensates for the increase. It also assumes that the refinery capacity can be adjusted to serve the extant demand for middle distillates at marginal cost.

## i) Summary of Benefits and Costs

### Table 33: Summary of Benefits and Costs

| **Category** | **Value by 2050 (2023 $ billion)** |
| --- | --- |
| **NPV of Accumulated losses caused by the value of stranded assets up to 2050** | |
| Value of stranded capital | (19.4) |
| Value of stranded gas deposits | (<0.1) |
| **Total** | **19.4 (average annual cost: 0.8 )** |
| **Value of Annual Efficiency Gains** | |
| Gains from more efficient operation of power grid | 2.1 |
| Gains from improvements in energy efficiency | 7.1 |
| **Total** | **9.2** |
| **Annual Savings in the Costs of Services** | |
| Savings from lower costs of heat generation | 1.6 |
| Reductions in the cost of transport | 0.6 |
| Reductions in the cost of industrial outputs (steel) | 2.0 |
| Reductions in the cost of industrial outputs (cement) | <0.1 |
| **Total** | **4.2** |
| **Value of Annual Health Benefits** | |
| Value of avoided health costs | 0.4 |
| Avoidance of premature deaths | 15.0 |
| **Total** | **15.4** |
| **Annual External Benefits in 2050** | |
| Social value of avoided carbon emissions | 10.0 |
| **Accumulated capital outlays** | |
| Capital investment (in power generation and transmission) | 212.0 |

# 13. Job creation

An economy-wide decarbonization effort in Chile would lead to job creation in various sectors, while also resulting in job losses in others. New jobs would be gained in renewable energy installations, operation and maintenance, grid modernization, electric transport, electrification of industry, mining, fisheries, commerce, residential buildings, and other areas. Conversely, jobs would be lost in refineries, fuel transportation and processing, coal and gas plants, and among providers of fossil fuel-driven equipment as these sectors decline in demand.

**Electricity generation.** There are several global estimates of job creation from constructing and operating renewable energy facilities as well as estimates for the U.S. and for the European Union. A recent assessment by IRENA and ITO (IRENA and ITO, 2023) estimates that the renewable energy industry created over 13 million jobs in 2022. IRENA also projects millions more will be needed for the transition. In the United States, the DOE estimated (DOE, 2022) that the wind power industry employed 120,000 in 2021, while the solar energy employed nearly 300,000 in 2023 (IREC, 2024. Globally, renewable energy is seen as a net job creator.

An analysis of the job creation associated to the value chain for renewable energy in Chile (Osorio-Aravena et. al., 2025) under a scenario of full decarbonization[121] has been recently completed. It concludes that the transition scenario to reach a fully renewable energy system in Chile by 2050, would result in more socioeconomic benefits including net job generation.

For purposes of this report, the net job generation factors by source of electricity have been estimated based on data reported in the literature for the US economy. These factors are considered conservative for the case of Chile, given the relatively higher cost of labor in the US (Chile vs US, 2025).

In the power sector, temporary jobs are created during construction, while full-time permanent jobs are caused by the long-term operation and maintenance requirements of these facilities. On the other hand, the full conversion of the power matrix to renewables will cause the closure of all fossil fuel power plants as well as the closure of the LNG terminals, as gas will no longer be required. The parameters used are presented in Table 34. The net new jobs by 2050 is estimated at 181,500.

[121] The scenario is a cost-optimized pathway that would imply achieving a fully de-fossilized energy system across power, heat, transport and desalination sectors by 2050, in which there are no transmission restrictions through interregional grid transmission.

## Table 34: Parameters used in the Estimate of Jobs Created by the Electricity Generation Requirements by Mid-century

| Item | Indicator [122] |
|---|---|
| Solar PV | 1.5 job years per GWh |
| Solar CSP | 0.44 job years per GWh |
| On shore wind | 0.32 job years per GWh |
| Geothermal | 0.48 job years per GWh |
| CCGT H2[123] | 0.21 job years per GWh |
| Closure of refineries (Operation and maintenance of refineries) | 200 jobs per 100,000 BPD refinery |
| Closure of LNG terminals (Operation and maintenance of LNG terminals) | 200 |
| Net total | |

Source: Author's estimates

**Electric transportation.** The electrification of the transportation fleet will create jobs and new enterprises, particularly during the establishment and maintenance of charging infrastructure and possibly in the assembly of electrical vehicles in Chile. Most light vehicles in Chile are imported but opportunities exist in the assembly of trucks, coastal ships, and ferries.

[122] The job estimates under both scenarios were made on the basis of the job elasticities (direct + indirect jobs) as reported by the IMF (https://www.imf.org/-/media/Files/Publications/WP/2022/English/wpiea2022101-print-pdf.ashx)
[123] Assumes that natural gas power plants are retrofitted for the use of $H_2$.

Also, under the National Lithium Strategy, Chile intends to promote the development of the supply chain for end products. While the strategy is not specific on the targets in the development of the supply chain, key elements include mining, processing, and manufacturing of Lithium battery components.

*Workers at a Codelco mine. Photo: Codelco*

It is estimated that of all jobs created in Lithium electrical batteries in California, 43% are in EV manufacturing, 26% are in battery component, cell, and pack manufacturing, and only 6% of jobs are in mining or critical minerals extraction.[124] Participation of Chile in manufacture of battery components would greatly increase the number of jobs associated with the lithium industry.

One early target is the manufacturing of cathodes in Chile. Plans to set up a lithium cathode factory in northern Chile are being discussed.[125] If Chile moves into actual assembly of battery packs, the job impact will be considerably higher. For purposes of the job analysis, a cathode manufacturing unit sized for production of 50,000 tons

[124] New research reveals steps California must take to capture more jobs from lithium battery boom - News

[125] An estimated investment of $290 million is planned for a project in the Antofagasta region, which could produce 50,000 tons of LFP cathode material per year. Commissioning is planned for the end of 2025. https://blog.investchile.gob.cl/byd-project-for-chilean-lithium-processing-plant

of cathodes material per year has been considered. Further integration into battery packs could be justified by EV and storage demand.

On the other hand, the complete electrification of transportation would cause the closure of refineries in the country as demand for middle distillates would disappear. A summary of the estimate of jobs gained and lost is presented in Table 35.

## Table 35: Estimate of additional Jobs created by Electric Transportation requirements by Mid-century

| Sector | Jobs under CNS | Jobs under ZES |
|---|---|---|
| Charging infrastructure | 4,700 | 5,200[126] |
| Vehicle assembly | | |
| Value chain in lithium battery production | N.A. | 27,300[127] |
| Operation and maintenance of gas stations[128] | No losses | (6,000) |
| Operation and maintenance of light-duty otto and diesel vehicles[129] | No losses | (3,600) |
| Total | 4,700 | 22,900 |

**Expansion of the Grid Infrastructure.** The expansion of the transmission infrastructure will also be associated with job creation. The analysis assumes that Chile would embark in the deployment of novel transmission infrastructure. This will also have an impact on the expansion of research facilities and enterprise development.

New transmission infrastructure creates jobs in construction, maintenance and long-term operation. For example, NREL estimates (Goldberg and Keyser, 2013) one full time job per medium voltage transmission line. In the case of offshore

[126] Based on the estimates made for the US fleet (https://theicct.org/pr-new-study-estimates-over-160000-jobs-to-be-created-by-uss-ev-charging-infrastructure-buildout-jan24/) normalized for the fleet size in Chile and assuming that 10% of the jobs will be created in heavy duty applications and other modes not considered under the CNS. The car fleet in Chile is about 1/15th of the size of the fleet considered to be electrified in the above reference analysis.

[127] Based on estimates made for the manufacture of 10000 GWh of battery storage capacity in the US (https://www.upjohn.org/research-highlights/ev-battery-production-will-need-large-and-specialized-workforce, compared with an estimated production of 88 GWh (13 GW x 8 hours) in Chile by 2050.

[128] There are about 1500 gasoline stations in Chile ( https://www.fne.gob.cl/wp-content/uploads/2017/10/Road-Fuel-Chile.pdf) with an estimated 6,000 full time employees.

[129] As of early 2025, there were 1254 car repair and maintenance services in Chile. Most of them are single owner operations(https://rentechdigital.com/smartscraper/business-report-details/list-of-car-repair-and-maintenance-services-in-chile) with an estimated 2-4 employees.

transmission lines, significantly more labor is required for installation, operation, and maintenance, including in the management of port facilities and service vessels.

## Table 36 Estimate of Jobs Created in the Expansion of Transmission Infrastructure

| Type of expansion | Jobs per km of new transmission infrastructure | New lines (km) | Total jobs created by 2050 under the ZES |
|---|---|---|---|
| HVDC[130] | 5-14 | 26,600 | 133,000 |
| AC[131] | 16-56 | 450 | 7,200 |
| Total | | | 140,200 |

**Manufacture of Hydrogen.** Jobs will be created across the supply chain, including in the electrolysis units, hydrogen storage and distribution. A recent analysis of the job generation potential in the EU (Ganter et. al., 2024) estimates green $H_2$ electrolysis generates about 0.8 jobs per MW. In the case of Chile, the analysis estimates the need for about 484 million tons of $H_2$ per year by mid-century (see Table 37 below). To generate this amount of hydrogen an electrolyzer capacity of 8 GW is required, generating about 6,400 jobs.

[130] Based on jobs created in the North Path Transmission Project in New Mexico and the Southern Spirit project between Texas and Lousiana as reported by the New Mexico Renewable Energy Transmission Authority (nmreta.com) and businessdownload.com.
[131] https://cleanenergygrid.org/transmission-and-jobs/

## Table 37 Hydrogen Manufacturing Requirements and Associated Jobs

| | H2 requirement (Million tons/year) | Job generation potential |
|---|---|---|
| Steel manufacture | 0.24[132] | |
| Heavy vehicles | 0.54[133] | |
| Power generation | 449[134] | |
| Total | 450 | 6,400 |

**Electrification of heavy industry and mining.**

**Re-opening of steel manufacturing.** A new green steel manufacturing capacity sized to meet domestic demand by 2050 (about 3 million tons) adds 3,900 permanent jobs[135], with broader durable manufacturing multipliers of 10–20.[136] Green steel manufacturing in Chile has export potential, indicating opportunities for further capacity expansion within the country.

**Expansion of cement manufacturing.** Electrifying the cement process through electrochemical decarbonation has the potential to grow the domestic industry and compete with exports. The number of jobs in cement manufacture is estimated at about 178 per million tons of production.[137] If Chile were to increase manufacturing to 4 million tons with electrochemical units, meeting all local consumption, the permanent jobs generated would be only about 200. But the net effect would be the reactivation of the industry.

[132] It considers that 80 kg H2 are required per tons of green steel produced (https://www.world-energy.org/article/26045.html) and steel manufacture is enough to meet domestic use (3 Million tons/year)

[133] Uses a growth in the fleet of heavy vehicles of 38% by 2050, based on an annual growth rate of 1.3%/year and the conversion of half of the fleet of heavy trucks and cargo ships to use of hydrogen in fuel cells.

[134] It considers the use of 15.6 tons of Hydrogen per sec for 2 GW generation capacity, representing an overall 27% roundtrip efficiency (https://www.gevernova.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/future-of-energy/hydrogen-for-power-gen-gea34805.pdf)

[135] Based on the employment at the Butler green steel plant in the US (https://news.bloomberglaw.com/environment-and-energy/green-steel-jobs-multiply-with-biden-energy-plan-granholm-says)

[136] https://www.epi.org/publication/updated-employment-multipliers-for-the-u-s-economy/

[137] Based on data from the US where 15,000 persons are employed in the production of about 84 million tons/year. https://www.ibisworld.com/united-states/employment/cement-manufacturing/551/

**Estimate of total new jobs by 2050.** All added, nearly 350,000 jobs would be added to the economy though the implementation of the ZES scenario by mid-century. The current labor force in Chile is about 10 million.

Many of these jobs will require technical training and specialized skills, inducing the vocational and higher education system in Chile to open and/or strengthen curricula. It will also provide the scientific community with many opportunities to broaden research opportunities, contributing to the development of the nation.

At the same time, jobs in construction, assembly lines, and vehicle operation would attract less-skilled labor. Likewise, the remote location of some of the wind and solar power plants creates training opportunities for ethnic minorities, like the Aymara in northern Chile and the Mauche in the central region of the country. Overall, the analysis finds diverse job opportunities aligned with a just transition.

On the other hand, some jobs will be lost in the natural gas industry, refineries, and operation and maintenance shops for internal combustion engines. Other occupations in the local industry of fossil fuel-based boilers and furnaces will also be affected but it is reasonable to assume that at least a good fraction of those will migrate to the corresponding electrical options.

## Table 38: Summary of Job Opportunities under the ZES Cumulative to Mid-Century

| Sector | Jobs generated |
|---|---|
| Power generation | 181,500 |
| Electric Transport | 18,200 |
| Grid Infrastructure | 140,200 |
| Hydrogen manufacture | 6,400 |
| Green steel | 3,100 |
| Decarbonized cement manufacture | 200 |
| Total | 349,600 |

# 14. Enterprise creation

The changes brought about by the electrification of the economy create not only jobs but also new business and enterprises. The ZES scenario requires expanded business activity to meet the demand for electrical services and products that rely on electricity-based manufacture. Table 39 below summarizes some of the opportunities.

## Table 39: Some Opportunities for Business and Enterprise Development in the Domestic Market

| Business | Business size by 2050 | Estimated cumulative investment (US billion) |
|---|---|---|
| Wind turbine manufacturing and assembly | 11,000 5 MW turbines in operation | 42[138] |
| Wind turbine installation | 11 ,000 5 MW turbines installed | (included above) |
| Solar cell assembly and installation | 56 GW | 17[139] |
| Manufacture of Li cathode | 200,000 tons of cathode material | 1[140] |
| Development and Installation of high voltage grid | 27,000 km of new line installed | 81 |
| Electric battery assembly[141] | 31 GW[142] | 37 |
| CSP assembly and installation | 6 GW | 3.6[143] |
| Electric transport charging stations[144] | 100,000 stations | 0.03 |
| DC high voltage charging stations | 100 stations | 2.8[145] |
| Electric transport medium duty vehicle (distribution trucks, buses) chassis assembly | 10000 vehicles | 0.01[146] |

[138] Assumes an average cost over the period of $0.75 million per MW installed.

[139] Assumes an average cost over the period of $0.30 million per MW installed.

[140] Based on the announced investment in the Atacama plant.

[141] The analysis considers only the utility size storage capacity.

[142] Based on a cost of $1.2 million per MW, anticipated by 2050.

[143] It assumes that the average cost of installation is about 30% of the total investment cost, which is estimated in the report as $2000/MW by 2050.

[144] Based on the analysis made by ICCT (https://theicct.org/pr-new-study-estimates-over-160000-jobs-to-be-created-by-uss-ev-charging-infrastructure-buildout-jan24/) and assuming that the charging networks in Chile attend a fleet of 10 million vehicles by 2050, most of these being light duty vehicles, with one charger for each 100 vehicles, or 100,000 charging stations and a cost of $300/station.

[145] Based on an estimated cost of $28,000 for a 50kW DC networked station (https://propertymanagerinsider.com/how-much-do-commercial-dc-fast-chargers-cost/)

[146] Uses a cost of $12,000 for chassis assembly of a heavy truck (https://www.purplewave.com/market-value/commercial-trucks-medium-heavy-duty/trucks/truck-chassis)

| | | |
|---|---|---|
| Manufacture of electric ferries and coastal ships | 4,000 coastal cargo vehicles and ferries | 0.3 |
| H2 production (electrolyzers)[147] manufacturing and assembly for domestic market | 7 GW | 14 |
| Green steel manufacture | Domestic capacity at 2.4 million tons/year | 2.9[148] |
| Green cement manufacture | Domestic capacity at 4.0 million tons/year | 1.0[149] |
| Total | | 203 |

The potential for business development opportunities is significant and varied. Transforming the Chilean economy to an electrified economy would not only impact the energy sector but also create ripple effects across all sectors. The business opportunities highlighted in Table 37 is a partial list.

Other opportunities such as provision of heating services in commerce and households as well as the assembly of fuel cells likely will represent business options but were not estimated. As a middle-high-income country, Chile could benefit from these changes in manufacturing and services for both the domestic market and exports. Allocated over a 25-year period the annual investment[150] equals about 3% of annual GDP.

## a) Capital flows

The investment required for expanding generation and transmission is estimated to be $212 billion over 24 years. Business development opportunities beyond generation and transmission are conservatively projected at an additional $80 billion over 24 years. This amounts to approximately $12 billion per year, representing 3.5% of the GDP in 2024.

Chile offers a favorable business environment, with robust institutions and a supportive private-sector framework, free trade agreements, and strong infrastructure. The country already attracts foreign direct investment (FDI) averaging over 18 billion per year.[151] In the first two months of 2025, Chile received $ 2.3 billion in FDI showcasing strong recent

[147] Based on a current average cost of $2000/kW https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24005-clean-hydrogen-production-cost-pem-electrolyzer.pdf

[148] This assumes an investment cost of $1,200/ton of steel.

[149] This is based in an investment of $150 million per 1,800 tons/day of capacity and total domestic production of green cement of 4.0 million tons/year.

[150] The actual flow of investments accelerates over time.

[151] https://www.investchile.gob.cl/wp-content/uploads/2024/12/FDI-Report-eng-2023.pdf

investment activity. Its FDI to GDP ratio is nearly 85%,[152] which is considered high in the region. Its gross fixed capital formation is estimated at about 22% of GDP.[153]

Investment opportunities related to the electrification of the economy are expected to extend capital flows beyond current figures. Investment trends in renewable energy are particularly strong in the region, with Brazil and Chile leading in both investment and implementation. The potential for substantial returns in this sector enhances the attractiveness of Chile for foreign direct investment.

New investment will also support domestic capital creation, additional human resource formation, and further job generation in the manufacture of electrical devices, transmission lines and ancillary equipment. This additional potential job demand was not calculated.

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[152] https://www.state.gov/reports/2024-investment-climate-statements/chile/

[153] https://data.worldbank.org/indicator/NE.GDI.FTOT.ZS?locations=CL. Gross fixed capital formation is a component of expenditure that indicates how much of the new value added in an economy in invested rather than consumed.

# 15. Policy and Regulatory Requirements.

Chile has already enacted, and is further complementing, a comprehensive policy framework for its energy transition. This study posits that the foundational elements for the complete transition to an electrically driven economy using renewable energy are already established. Moreover, many of the actions necessary are already embedded into existing policy decisions. However, complete transformation of the energy system and of the broader economy will still require additional measures.

To provide context, the study concludes that most actions and investments necessary for transitioning to a fully electrified economy are both economically viable and financially appealing. Additionally, it highlights that economic benefits are projected to increase over time due to continued declines in the costs of electricity, electrical technologies and hydrogen manufacture, driven by trends in investment, operational efficiencies, and economies of scale.

Still, to accelerate the transition some additional actions might be required:

**Facilitate expansion of transmission infrastructure.** The expansion of the power system required to meet the demand of a fully electrified society will require a likewise expansion of the transmission capacity. But, while the expansion of the power generation capacity is unlikely to encounter major land use challenges due to the planned locations in Atacama, Patagonia, and some offshore sites; expansion of transmission infrastructure from generation to demand nodes, would.

One expects that some major industrial users will be located near generation points, but most other users will be at a significant distance. The study recommends that the opportunities for reconducting existing high voltage lines be exhausted at the outset as these will not require new rights of way and that HVDC lines allow for multi-entry points to reduce the set-up of new transmission corridors. Both requirements will reduce land tenure issues, and the overall cost of the system, if not of individual operators. As the transmission infrastructure is in the hands of the private sector, both requirements could be included in the Energy Transition Law and regulations.[154]

[154] The legal framework that regulates how the power transmission industry operates in Chile is based on the Energy Transition Law, 21721 of 2024. The Law and its complementary regulations determine standards applicable to any power generation, transmission or distribution facility regarding technical, safety, coordination, quality, information and economic aspects of appropriate power sector operation.

Additionally, given the potential benefits from the use of LFAC lines, it might be convenient to support, through CORFO, R&D activities in LFAC applications in Chile, even financing the set-up of a demonstration line for offshore wind facilities.

**Promote the development of storage capacity.** The appropriate amount of storage is essential for the effective operation of a fully renewable grid. Adequate storage capacity will minimize curtailment and ensure adequate supply. Investment in storage tends to be more costly than in generation, which may lead to underinvestment in storage solutions, in turn potentially resulting in curtailment. It would be beneficial if new generation capacity investments were linked to investment in storage facilities. This could be incorporated into the regulations outlined in the Energy Transition Law.

**Promote adoption of smart grid tools.** Distribution power grids will encounter increased variability from renewable resources and the need to integrate distributed energy resources. The digitalization of the grid will assist in load forecasting, fault detection, and enhance reliability. Advanced digital technologies (Advanced Metering Infrastructure, Smart Meters; Sensors and Monitoring Systems) would enable two-way communication between utilities and consumers, real time monitoring and optimization of energy flow all of these are tools that would promote efficient transmission of electricity.

To support a smart distribution grid there is a need to: a) integrate digital grid technologies into long-term planning, considering distributed resources; b) develop standards to ensure seamless communications and integration between different grid components; and c) provide support to utilities and consumers to invest in smart grid tools.

**Pass the savings in electricity generation costs to end users.** On April 30, 2024, the Government of Chile enacted legislation to unfreeze electricity rates. The law enables consumers to settle their outstanding debts to power producers through installments added to their electricity bills. Additionally, the law introduced a subsidy aimed at reducing electricity costs for approximately one million vulnerable households and provided benefits to communes with coal-fired generation facilities.

Chile's transition to renewable energy is expected to significantly reduce electricity costs, with utility-scale PV potentially as low as $0.02/kWh before transmission fees (see figure 12). This affordability will support broader economic electrification, provided that savings reach end users. Currently, fossil fuel plants are paid high tariffs to offset their expenses. Contracts should not allow fossil plants to buy cheap renewable power and resell it at inflated tariffs.[155]

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[155] At the projected electricity prices, there may no longer be a need for the same level of annual subsidy for vulnerable families.

Generators have accumulated a large debt resulting from past tariff stabilization mechanisms, high investment costs and low market electricity prices. Passing the debt to consumers has yielded increases in the cost of electricity to end users. As cost-effective renewable generation enters the grid, the overall cost of electricity will decrease. In the meantime, innovative financing solutions like IDB INVEST's financial facility[156] can play an important role in stabilizing costs to consumers.

**Promote access to the electricity market from individual small producers.** Despite their initial success, PMGDs are currently experiencing a degree of deceleration. Recent regulatory changes[157] have been introduced to provide incentives and to foster storage solutions to complement traditional PMGDs plants. A major innovation involves creating time blocks for PMGDs to charge batteries when solar generation peaks and discharge energy at night or after peak hours. This rule could also lead to a new price regime based on the time-of-day energy is added to the grid.

Promotion of PMGDs with storage can reduce transmission congestion, providing extra time for expansion of infrastructure for utility-scale projects. Additionally, PMGDs with storage could enhance the flexibility and resilience of distribution energy grids, which may prove crucial in addressing potential disruptions to domestic energy services caused by extreme weather conditions, such as droughts or severe storms, as already experienced in Santiago.[158]

**Support infrastructure for electric transportation.** The analysis finds that for most light and medium transportation modes, electric drives are or will shortly become competitive in Chile. A growing fleet will accelerate investment in maintenance and repair facilities. However, there is a role to play for the State in the development of charging infrastructure.[159]

Already, the National Electromobility Strategy includes measures such as preferential parking spaces with charging stations and exempting EVs from road space rationing. But, as the electrification of transport accelerates and covers other segments of the fleet, including heavy vehicles, the need for DC fast charging stations will increase at bus stations, ports and other facilities. Additional incentives (preferential access to government installations

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[156] https://www.idbinvest.org/en/news-media/idb-invest-reaffirms-its-commitment-chiles-energy-sector-record-mobilization-private

[157] https://www.ibanet.org/opportunities-challenges-distributed-energy-chile

[158] https://apnews.com/article/chile-blackout-power-outage-south-america-failure-electricity-8224a4cbcfc98c4f17e7d1e3b00936b5

[159] In the US, under the deficit reduction act, federal tax credits are available to support the development of charging infrastructure. The "Trans-European Energy Networks" (TEN-E) regulation provides funding for development of the energy infrastructure, including EV charging infrastructure, throughout Europe. The TEN-E Regulation supports the deployment of fast-charging stations along major highways and in urban areas. Source: https://ec.europa.eu/energy/infrastructure/ten-e/ten-e-regulation_en.

for charging stations; financing for set-up of rapid charging networks) may need to be considered to facilitate market penetration.

**Ease adoption of green hydrogen.** The analysis projects a very rapid decrease in the cost of hydrogen. The government, through CORFO, is actively promoting electrolyzer technology with subsidies, financial support and strategic partnerships. Also, the government is considering additional investments, with multilateral funding, yet to be fully defined.[160]

To ensure a sustainable green hydrogen production capability for transport, industry, and power generation, there may be a need to for support in: a) the development of fuel cells for heavy vehicles (ferries, heavy trucks); b) use of hydrogen as a reducing agent in steel production; c) assistance in the retrofitting of existing Combined Cycle Power plants to run on hydrogen.

**Maximize value of Lithium resources.** Lithium production is regulated by the state. There are ongoing discussions within the government about balancing exports with value-added domestic production. The National Lithium Company aims to facilitate further industrial processes, including battery assembly and recycling. CORFO tenders are managing value-added manufacturing

This analysis indicates a potentially significant impact on employment and enterprise development from the production of lithium cathodes. Given the country's advantages in terms of both the quality and quantity of the resource, investment in planning and research and development, aimed at achieving vertical integration of the industry within Chile, with the final product being batteries for electric vehicles and power storage, is warranted.

**Promote large scale production of green steel and electrification of other heavy industries.** As with lithium, the quality and quantity of iron ore summed to the availability of low-cost green hydrogen and electricity, supports a national strategy for green steel manufacture, building on the agreement already reached for a plant in Huachipato. The analysis indicates a significant cost advantage for Chile in steel production. The strategy could target the supply to the domestic and regional markets.

Likewise, the report indicates that there is a strong incentive for Chile to promote the electrification and use of Hydrogen in other heavy industries, where technology is in active development and where Chile may offer competitive advantages in terms of the cost and

[160] The European Commission, the European Investment Bank (EIB), KfW Development Bank, CORFO and the Chilean Ministry of Energy have recently signed agreements to support Chile's growing renewable hydrogen industry with financing commitments through CORFO of Euros 200 million.

source of electricity and hydrogen (electrochemical decarbonation in cement manufacture and plasma calcination in pulp and paper production).

Finally, there are options for electrification of energy services in commerce (space heating) and households (space heating, provision of hot water, and cooking) that warrant promotion campaigns, including regulatory incentives.

To support the transition process, the training and educational system will be under strain. An effort is required to support the vocational and higher education infrastructure for it to be able to provide the many technical and scientific skills necessary. A summary of the recommendations is presented in Table 40.

## Table 40: Summary of Policy and Regulatory Recommendations

| Issue | Goal | Steps | Policy Instrument |
|---|---|---|---|
| Expansion of transmission infrastructure | Achieve a transmission grid capable of meeting the needs of a fully electrified economy by 2050. | 1. Prioritize reconducting of existing medium voltage lines<br>2. Fund R&D for LFAC demonstration line<br>3. Regulate expansion of HVDC lines to include multiple entry points. | Modifications to the **Energy Transition Law** and regulations. |
| Expansion of storage capacity. | Facilitate a 100% renewable electric matrix with minimum curtailment. | Tie investments in new generation capacity to investment in storage facilities. | Modifications to regulations for the **Energy Transition Law and regulations.** |
| Facilitate access to market for small individual producers, | Optimize the contribution of distributed energy to overall power supply. | Establish price regime for PMGDs based on the time-of-day when energy is added to the grid. | Modifications to regulations for the **Energy Transition Law and regulations.** |
| Reduce impact of accumulated debt of | Allow savings in generations costs during the | Expand reach of current Tariff Stabilization Fund to benefit a bigger share of consumers. | Updates to **Tariff Stabilization Fund.** |

| | | | |
|---|---|---|---|
| electricity generators on electricity prices | transition to pass directly to end users | | |
| Support the deployment of a smart distribution grid: | Improve reliability of the grid | 1. Integrate digital grid technologies into long-term planning.<br>2. Develop standards for seamless communication between different grid components.<br>3 Provide support to utilities and consumers to invest in smart grid tools. | Modifications to regulations for the **Energy Transition Law and regulations.** |
| Support electric fleet transportation infrastructure. | Enable a fully functioning electric transportation system. | Support DC fast charging stations at bus depots, ports and other facilities. | Modifications to the **National Electromobility Strategy.** |
| Support the use of Hydrogen applications in Transport, Industry and Power Generation. | Optimize the use of hydrogen as a complement to electricity in the economy. | Support<br>1. The development of fuel cells for heavy vehicles (ferries, heavy trucks)**.**<br>2. The use of Hydrogen as a reducing agent in Steel production.<br>3. The retrofitting of existing Combined Cycle Power plants for their use of Hydrogen. | Add provisions to the **Green Hydrogen Action Plan.** |
| Electrify heavy industry | Exploit cost advantages energy and H2. | Support<br>1. Development of green steel.<br>2. Electric decarbonation in cement.<br>3. Plasma calcination in pulp and paper. | New **electric industry plan.** |

| | | | |
|---|---|---|---|
| Electrify commerce and households | Enable electrification of heat services and provision of hot water. | Support a program (incentives and regulations) for: Retrofit of heat, hot water, cooking applications. | Strengthen inter-ministerial dialogue on commerce and residential buildings. |
| Promote technical and vocational training. | Contribute to development of a skilled labor force commensurate with the level of effort demanded. | Encourage the development of appropriate curricula in learning centers.<br><br>Finance a grant program for skills expected to be in high demand. | Add provisions for workforce development programs to the Just Transition Strategy. |

## a) Cultural Barriers

As with all changes in society, the transition to a fully electrical society will need to address barriers that are more cultural than technical or financial. However, the experience gained with the introduction of electric buses in urban areas and the gains in the generation of electricity using solar and wind, prepare to an extend the path ahead. Cultural barriers remain and need to be understood and addressed. These include:

**Social acceptance and public perception.** Social acceptance will depend on how the general public engages with the changes and perceives the net benefits in daily life.

In Chile acceptance of wind and solar is already high with very strong support across the political landscape and a strong concern for the impacts of climate change. The government has already taken measures to continue garnering public support. For example, the GOC with the collaboration of the International Climate Initiative (IKI, 2018) through the Department of Dialogue and Civil Society at the Ministry of Energy is operating an evaluation index for gauging social acceptance and identification of measures to maintain/increase public support. This is a line of action that will help to keep the high acceptance of renewable energy in the country.

Likewise, Chile has made substantial progress achieving social acceptance of electric transport. A number of polls (bnamericas, 2023) have shown a very high acceptance of private electric vehicles. However, they also highlight the importance of awareness of the electromobility strategy.

For public transport, Chile already has the largest bus fleet worldwide outside of China. The acceptance of public transport is remarkably high and growing rapidly. Factors that contribute include: the political leadership in the nation, the perception that the buses have contributed to improving air quality and reduced noise, and the operational cost savings.

Other segments of the transport sector (mining trucks, coastal ships, and rails) have a relatively smaller set of stakeholders and the financial advantages of the electrical or fuel cell options make adoption compelling. This will also be the case for industry and commerce, where large financial considerations will in the end dictate the outcome.

A different landscape faces electrification in the rural residential sector. Even with the deployment of aggressive incentives, the use of fuelwood in the rural sector has ingrained cultural attitudes that may delay electrification. There are two mitigating factors: the use of fuelwood for heating in rural areas is relatively small and there is a limited reliance on fossil fuels for heating or cooking.

**Community engagement.** Strong bonds with the local communities and society at large are crucial to facilitating ownership of the changes being undertaken. The political process in Chile has already delivered a mandate to move toward a low-carbon society. Additional steps, like participation in local decision-making, transparent communication, and dissemination of impacts (job creation, improvements in environmental quality) further facilitates the process. It must be said, however, that in the development of the PELP and strategies for electromobility and hydrogen there has already been strong participation.

**Disruption of the fossil fuel economy.** While Chile is already moving toward a low-carbon future, the pace of change implied under the ZES will require additional disruptive changes in the fossil fuel industry. Operators of natural gas facilities, refineries, and gas depots are expected to resist the transition due to economic concerns, job losses, and closure of productive infrastructure. The best antidote is to document that the changes will bring economic benefits, new jobs, and productive assets. A significant training component to redirect affected workers toward emerging opportunities will help.

# 16. Conclusions

Transforming Chile into a fossil fuel-free economy constitutes a major policy, institutional, and financial effort, but one that is within reach of its society. This conclusion is based on the country's resource endowment, state commitment, and the technical and financial viability of the technologies involved. This transformation would bring about substantial investment, job generation, reduced costs for end users of energy, transportation, and industrial services and products, new and expanded large business opportunities, intellectual and technology development, and substantial efficiency gains.

By mid-century, if Chile fully transits to renewable energy, it will require about 1343 PJ of energy, to meet all the projected demand, close to the 1364 PJ projected for 2030 under the Carbon Neutrality Scenario. Thus, the transition would induce a major improvement in energy efficiency, inherent in the use of electricity, saving an estimated 663 PJ by 2050 when compared to the CNS. At the current cost of oil,[161] these savings would represent almost $7.1 billion per year.

In addition to the energy savings, the ZES will also deliver energy at a lower cost. A power matrix, solely based on solar/wind and other renewables would reduce the cost of energy delivered to the economy. The estimated LCOE, including generation and storage, is $0.03/kWh.

The generation of electricity needed to power the economy by 2050 requires a capacity of approximately 180 GW, including battery storage, provided there is 17 GW of distributed energy. This capacity can be mainly made up of wind and solar energy facilities, with additional contributions from hydro, biomass, and geothermal sources. The investment required for the new capacity is estimated to be $103 billion dollars[162] from now until 2050. To operate efficiently, it is estimated that the power system will require about 36 GW[163] of storage capacity, with an estimated cost of $43 billion.

Significant transmission infrastructure will be needed to deliver electricity to end users. By using advanced technologies like reconductoring, LFAC, and multi-terminal HVDC, costs could be reduced to an estimated $66 billion by 2050. Still, the transmission costs will increase the cost of the delivered power by about $0.005/kWh, mostly due to the need for

[161] As of mid-2025 the price of a barrel of WTI is $66. The oil in a barrel represents 0.0000062 PJ if fully combusted.

[162] The investment required considers the already installed capacity (as of 2024) and the pace of increase in electricity demand during the gradual electrification of the economy.

[163] Some of the storage is provided by retrofitted CCGT and CSP facilities.

additional long-haul lines to bring power from Atacama, southern, and coastal areas to the centers of consumption. A similar cost increase has been assumed for distribution.

## Table 41: Estimated Investment Costs in Generation, Storage and Transmission Capacity ($ billion)

| | Generation | Storage | Transmission | Total |
|---|---|---|---|---|
| Total (2025-2050) | 103 | 43 | 66 | 212 |

To electrify the whole economy, transportation services, industrial, commercial, and residential activities would need to transition to the use of electrical sources and devices. There are already viable options to meet many of these needs. In some cases, fossil-fuel free alternatives are not yet fully commercial (e.g., cement, pulp, and paper). The analysis finds it justified for Chile to embark in the emerging technologies.

- **Transport.** The electrification of transportation services would require not only the electrification of road transport or light vehicles but also heavy-duty vehicles, rail and coastal and fishing fleets. The projected reduction in electricity costs and projected reductions in cost for electric drives means that the cost of moving goods and services using electricity is increasingly financially attractive.
    - *Hydrogen in transport*. The analysis finds that hydrogen use as fuel in heavy-duty vehicles is already viable for mining trucks and will become more attractive for fishing boats as costs decline. It also concludes that hydrogen can fill niches, complementing battery-driven vehicles. By 2050, hydrogen use in fuel cells is projected to be competitive for many heavy-duty vehicles. Further, hydrogen use in retrofitted gas turbines is identified as a valuable way to provide firm capacity while reducing stranded gas assets.
    - *Economic savings*. The analysis concludes that the whole-sale electrification of transportation would save the economy $0.6 billion per year by 2050 in capital and operating costs, compared with the CNS scenario. Most savings come from electrifying long-haul and heavy vehicles, including mining and fishing fleets.
- **Industry.** The provision of industrial heat using electricity has many applications throughout the sector where it outperforms the use of natural gas. Electrification of process activities is estimated to save $1.6 billion by 2050. Additionally, there are attractive opportunities for Chile to leverage advances in the production of green

steel and electrical manufacture of cement and paper, using of inexpensive electricity and affordable hydrogen. Specifically, the analysis finds that:

- *Green steel*. The production of green steel in Chile using direct reduction of iron with hydrogen is supported by low-cost electricity, the availability of high-grade iron, and low-cost hydrogen production. These conditions make Chile's Atacama region an ideal location for green steel production. Chile is well positioned to become an exporter of low-carbon green steel.
- *Cement manufacture*. Like steel, the availability of low-cost electricity supports the development of electrochemical decarbonation processes in cement manufacturing. While the process is still conceptual and lacks detailed cost data, this is an industrial sector where Chile can benefit from an early adoption stance.
- *Pulp and paper*. Also, the use of an electric (plasma calcination) process in the production of pulp and paper is expected to be competitive in a few years, as the technology is further developed and the benefits from cheap electricity and easy access to raw material materialize. As in the case of electrochemical decarbonation of cement, plasma calcination offers opportunities for Chile to become a leader in technological development in pulp and paper manufacture.
- *Heat provision*. More generally, the analysis concludes that electric heat for industrial applications (as well as in commercial and residential use), such as electric boilers and heat pumps, is already competitive and can deliver significant savings.

- **Residential activities.** The provision of heat in the residential sector presents challenges for electrification, especially in rural households that use firewood as the main source of energy. To displace fuelwood, an incentive scheme is likely needed to protect rural incomes. In urban areas, the displacement of LPG and natural gas by electricity is much more attractive. Many technological options are already competitive in urban areas, but adoption will still require financial and regulatory support to address barriers to entry and stimulate adoption.

- **Commercial activities.** Like industry, the commercial sector will benefit from financially attractive options to shift energy consumption to electricity. Heat pumps and boilers already have a foothold on the market and are expected to become more financially attractive as electricity costs fall.

- **Job generation.** The analysis concludes that the electrification of the economy is a net job generator. It estimates that about 350,000 permanent jobs will be created by 2050. Many of these jobs will require technical training and specialized kills inducing the vocational and higher education system in Chile to open and/or strengthen curricula. It will also provide the scientific community with many opportunities to expand fields of inquiry further contributing to the development of the nation. Some jobs will be lost in the natural gas industry, in refineries and operation and maintenance shops for internal combustion engines.

- Other occupations involved in the local industry of fossil fuel-based boilers and furnaces will also be affected but it is reasonable to assume that at least a good fraction of those will migrate to the corresponding electrical options. The losses in the natural gas industry linked to power generation were estimated at 200 and the losses from the closure of refineries at 450. The losses in maintenance and repair auto shops are estimated at under 4000 permanent jobs.

- **Investment and Enterprise Creation.** In addition to the immediate effect on employment creation, the necessary economic transformation could significantly enhance opportunities for investment and local business growth. The investment required in the expansion of the power matrix and the transmission system is $218 billion over 24 years; business development opportunities created by the electrification of the economy beyond those related to generation and transmission have likewise been conservatively estimated at an additional $80 billion over 24 years. This is equivalent to over $12 billion per year or 3.5 % of the GDP in 2024. This would be a substantial contribution to a long-term prosperous economy, one based on clean, sustainable, modes of production.

  Chile does have the institutions and private sector framework to facilitate a high level of capital creation. It does attract foreign direct investment (FDI). Its FDI to GDP ratio is nearly 85%,[164] which is considered high in the region. For reference, the gross fixed capital formation in Chile is estimated at about 22% of GDP.[165] Alongside capital investments, one should expect a spillover effect on the broader economy, with impacts in the provision of manufacturing and contracting services, architectural and engineering services, environmental and social assessments, transportation

[164] https://www.state.gov/reports/2024-investment-climate-statements/chile/
[165] https://data.worldbank.org/indicator/NE.GDI.FTOT.ZS?locations=CL

and shipping services and others. The spillover will further contribute to increases in the standards of living.

- **Other co-benefits.** The electrification of the economy brings additional benefits. These include:
  - Health. A health benefit which is caused by the elimination of emissions of airborne pollutants, including PM, $SO_x$ and $NO_x$. The analysis estimates that these benefits translate into $ 15 billion per year, when monetized against the reductions in morbidity and mortality.
  - Carbon. A carbon emission reductions benefit estimated to be at about 70 million tons of CO2 by 2050. Using the social cost of carbon, these emissions are valued at $10 billion per year.

- **Costs.** Conversely, several assets would be stranded, including refineries, LNG terminals, and natural gas power plants, whose closure was not considered under the CNS. Eliminating the demand for gas in Chile will also shut down existing gas fields. The calculated value of the stranded infrastructure and fields is conservatively estimated at $20 billion over 25 years.

- **Policy and regulatory framework.** The analysis finds that Chile has already enacted the key policy and regulatory pieces to support the transition to an electrical economy. To realize the potential of complete electrification, the study identifies a series of policy and regulatory recommendations complementing what is already enacted. Some aspects the analysis finds critical for the full electrification of the economy include:
  - Regulatory support for advanced transmission technologies, which are essential to keep transmission costs low.
  - Regulations to link storage and generation investments.
  - Regulatory support for hydrogen heavy-duty transport, power generation, and heavy industry.
  - Financial incentives and support for household electrification, especially in rural and low-income areas.
  - A proactive industrial policy to direct private sector investment into electricity-driven, hydrogen-based, heavy industry.
  - Facilitate the delivery of savings in electricity generation directly to end users.
  - Promote the strengthening and/or adoption of curricula at the vocational and higher education level to meet the skill requirements of an electrical society.

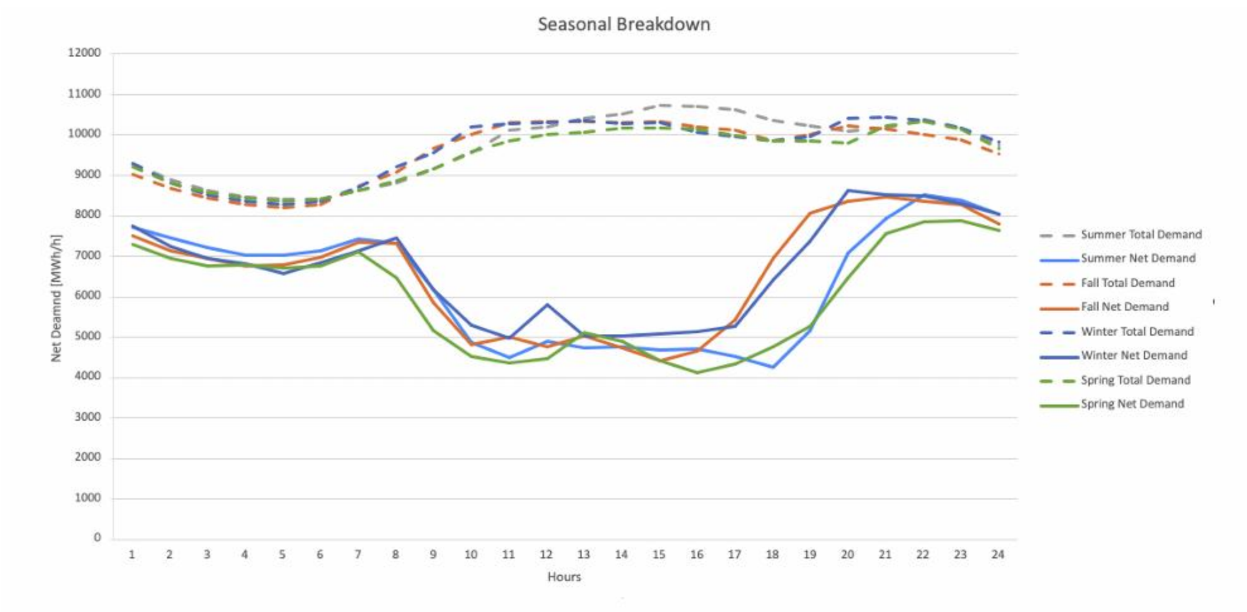
**Cultural barriers.** The analysis finds that Chile has made considerable strides to understand and address cultural barriers. An example is the lengthy consultation process already undertaken in the development of the PELP and the Electromobility strategy, and the work of the Department of Dialogue and Civil Society at the Ministry of Energy which has in place standards to evaluate ownership and participation of community groups. However, a transition of the scope discussed in this analysis will require continuing and expanding activities to ensure social acceptance; expand community engagement; and communicate benefits and opportunities for those sectors negatively affected, in particular the fossil-fuel industry.

# ANNEXES

## Annex A. Modeled sector-based hourly demands

The modeling of Chile's historical hourly electricity demand used data from the National Electricity Coordinator, including total demand and “net demand” or total demand minus electricity generated from wind and solar. The hourly net demand curve reveals which hours of the day should be prioritized for building out renewable energy supply. See Figure A.1

**Figure A.1 Seasonal daily curves of electricity demand.**




Chile 2023 Hourly Electricity Demand Data

Hourly energy demand was estimated with the assumption that the Chilean economy becomes fully electrified in 2050. Energy demand during non-working hours increases significantly by 2050 when all economic activity is electrified. This trend is mostly driven by overnight charging in the transportation industry (including the fishing fleet) and increased evening and night electricity demand in the residential sector as heating demand (mostly wood and oil in the status quo) becomes electrified.

In the absence of detailed records of sector-based load curves, data from other countries was used to model the behavior in Chile. For the residential, commercial, and industrial sectors load curves published by Hayes B., et al, (2013) in the UK in 2013 and curves published by National Technical University of Athens (2006) for Greece were used as the basis for the modeling. For transport a load curve for the current transportation sector in California was used (Mc. Carthy R. et. al. (2006)).

For the fishing fleet it was assumed that the fishing boats would all charge early morning for their daily work, or even for a trip of two days. Therefore, the load would be slanted toward those periods. For the mining sector, data from Haas, et. al (2020) based on the copper industry was used. Chile mines more than just copper (lithium, iron) and those energy demand profiles may look different than copper. However, copper does account for roughly 80% of all Chilean mining activity and Haas and coworkers did include data from La Escondida mine in their analysis.

The energy use projections were based on the CNS scenario and the estimated growth rates in energy use as reported in Table 3. The projected hourly variations in energy use are summarized in Tables below (all data in TJ).

**Table A.1 Modeled daily load curve for the residential sector**

| Hour | Current % Demand | Current Demand | 2040 % Demand | 2040 Demand | 2030 Demand |
|---|---|---|---|---|---|
| 1 | 0.58 | 19.12 | 0.29 | 15.67 | 18.69 |
| 2 | 0.57 | 18.79 | 0.28 | 14.84 | 18.14 |
| 3 | 0.53 | 17.47 | 0.26 | 13.94 | 16.93 |
| 4 | 0.51 | 16.81 | 0.27 | 14.32 | 16.65 |
| 5 | 0.51 | 16.81 | 0.29 | 15.46 | 17.11 |
| 6 | 0.56 | 18.46 | 0.39 | 21.03 | 20.40 |
| 7 | 0.62 | 20.44 | 0.56 | 30.25 | 25.37 |
| 8 | 0.67 | 22.09 | 0.71 | 38.31 | 29.66 |
| 9 | 0.65 | 21.43 | 0.83 | 44.55 | 31.73 |
| 10 | 0.65 | 21.43 | 0.81 | 43.49 | 31.31 |
| 11 | 0.64 | 21.10 | 0.79 | 42.19 | 30.57 |
| 12 | 0.65 | 21.43 | 0.76 | 40.71 | 30.19 |
| 13 | 0.64 | 21.10 | 0.72 | 38.78 | 29.21 |
| 14 | 0.64 | 21.10 | 0.70 | 37.71 | 28.78 |
| 15 | 0.67 | 22.09 | 0.70 | 37.76 | 29.44 |
| 16 | 0.76 | 25.05 | 0.77 | 41.48 | 32.86 |
| 17 | 0.97 | 31.98 | 0.87 | 46.62 | 39.41 |
| 18 | 0.99 | 32.64 | 0.94 | 50.31 | 41.32 |
| 19 | 0.95 | 31.43 | 1.00 | 53.60 | 41.77 |
| 20 | 0.98 | 32.31 | 0.99 | 52.98 | 42.17 |
| 21 | 0.93 | 30.66 | 0.92 | 49.20 | 39.58 |
| 22 | 0.86 | 28.35 | 0.72 | 38.73 | 33.90 |

| | | | | | |
|---|---|---|---|---|---|
| 23 | 0.73 | 24.07 | 0.52 | 28.00 | 26.83 |
| 24 | 0.61 | 20.11 | 0.38 | 20.55 | 21.28 |

**Table A.2 Modeled daily load curve for the commercial sector**

| Hour | Current % Demand | Current Demand | 2040 % Demand | 2040 Demand | 2030 Demand |
|---|---|---|---|---|---|
| 1 | 0.59 | 5.99 | 0.59 | 1.95 | 3.97 |
| 2 | 0.57 | 5.79 | 0.57 | 1.88 | 3.84 |
| 3 | 0.55 | 5.59 | 0.55 | 1.82 | 3.70 |
| 4 | 0.54 | 5.48 | 0.54 | 1.78 | 3.63 |
| 5 | 0.54 | 5.48 | 0.54 | 1.78 | 3.63 |
| 6 | 0.58 | 5.89 | 0.58 | 1.92 | 3.90 |
| 7 | 0.66 | 6.70 | 0.66 | 2.18 | 4.44 |
| 8 | 0.77 | 7.82 | 0.77 | 2.54 | 5.18 |
| 9 | 0.89 | 9.04 | 0.89 | 2.94 | 5.99 |
| 10 | 0.94 | 9.55 | 0.94 | 3.11 | 6.33 |
| 11 | 0.99 | 10.06 | 0.99 | 3.27 | 6.66 |
| 12 | 0.99 | 10.06 | 0.99 | 3.27 | 6.66 |
| 13 | 1.00 | 10.16 | 1.00 | 3.30 | 6.73 |
| 14 | 0.98 | 9.95 | 0.98 | 3.24 | 6.60 |
| 15 | 0.99 | 10.06 | 0.99 | 3.27 | 6.66 |
| 16 | 0.98 | 9.95 | 0.98 | 3.24 | 6.60 |
| 17 | 0.94 | 9.55 | 0.94 | 3.11 | 6.33 |
| 18 | 0.90 | 9.14 | 0.90 | 2.97 | 6.06 |
| 19 | 0.85 | 8.63 | 0.85 | 2.81 | 5.72 |
| 20 | 0.78 | 7.92 | 0.78 | 2.58 | 5.25 |
| 21 | 0.73 | 7.41 | 0.73 | 2.41 | 4.91 |
| 22 | 0.69 | 7.01 | 0.69 | 2.28 | 4.64 |
| 23 | 0.66 | 6.70 | 0.66 | 2.18 | 4.44 |
| 24 | 0.64 | 6.50 | 0.64 | 2.11 | 4.31 |

**Table A.3 Modeled daily load curve for the industrial sector**

| Hour | Current % Demand | Current Demand | 2040 % Demand | 2040 Demand | 2030 Demand |
|---|---|---|---|---|---|
| 1 | 0.75 | 25.08 | 0.75 | 22.71 | 23.89 |
| 2 | 0.76 | 25.41 | 0.76 | 23.01 | 24.21 |
| 3 | 0.72 | 24.08 | 0.72 | 21.80 | 22.94 |
| 4 | 0.72 | 24.08 | 0.72 | 21.80 | 22.94 |
| 5 | 0.70 | 23.41 | 0.70 | 21.19 | 22.30 |
| 6 | 0.75 | 25.08 | 0.75 | 22.71 | 23.89 |
| 7 | 0.81 | 27.09 | 0.81 | 24.52 | 25.80 |
| 8 | 0.89 | 29.76 | 0.89 | 26.94 | 28.35 |
| 9 | 0.93 | 31.10 | 0.93 | 28.16 | 29.63 |
| 10 | 0.98 | 32.77 | 0.98 | 29.67 | 31.22 |
| 11 | 1.00 | 33.44 | 1.00 | 30.27 | 31.86 |
| 12 | 0.98 | 32.77 | 0.98 | 29.67 | 31.22 |

| | | | | | |
|---|---|---|---|---|---|
| 13 | 0.94 | 31.43 | 0.94 | 28.46 | 29.95 |
| 14 | 0.93 | 31.10 | 0.93 | 28.16 | 29.63 |
| 15 | 0.92 | 30.76 | 0.92 | 27.85 | 29.31 |
| 16 | 0.91 | 30.43 | 0.91 | 27.55 | 28.99 |
| 17 | 0.88 | 29.43 | 0.88 | 26.64 | 28.03 |
| 18 | 0.86 | 28.76 | 0.86 | 26.04 | 27.40 |
| 19 | 0.83 | 27.75 | 0.83 | 25.13 | 26.44 |
| 20 | 0.79 | 26.42 | 0.79 | 23.92 | 25.17 |
| 21 | 0.79 | 26.42 | 0.79 | 23.92 | 25.17 |
| 22 | 0.76 | 25.41 | 0.76 | 23.01 | 24.21 |
| 23 | 0.76 | 25.41 | 0.76 | 23.01 | 24.21 |
| 24 | 0.76 | 25.41 | 0.76 | 23.01 | 24.21 |

**Table A.4 Modeled daily load curve for the transportation sector**

| Hour | Current % Demand | Current Demand | 2040 % Demand | 2040 Demand | 2030 Demand |
|---|---|---|---|---|---|
| 1 | 0.05 | 3.62 | 0.65 | 23.36 | 18.65 |
| 2 | 0.07 | 5.07 | 0.58 | 20.68 | 17.19 |
| 3 | 0.16 | 11.58 | 0.51 | 18.35 | 17.85 |
| 4 | 0.33 | 23.88 | 0.46 | 16.53 | 20.99 |
| 5 | 0.55 | 39.80 | 0.43 | 15.45 | 26.01 |
| 6 | 0.69 | 49.93 | 0.45 | 15.91 | 30.06 |
| 7 | 0.78 | 56.45 | 0.47 | 16.90 | 33.17 |
| 8 | 0.81 | 58.62 | 0.51 | 18.35 | 35.05 |
| 9 | 0.82 | 59.34 | 0.56 | 19.90 | 36.46 |
| 10 | 0.82 | 59.34 | 0.61 | 21.89 | 37.93 |
| 11 | 0.85 | 61.51 | 0.64 | 22.97 | 39.53 |
| 12 | 0.91 | 65.85 | 0.68 | 24.14 | 41.98 |
| 13 | 1.00 | 72.37 | 0.72 | 25.71 | 45.53 |
| 14 | 1.00 | 72.37 | 0.76 | 26.99 | 46.48 |
| 15 | 1.00 | 72.37 | 0.80 | 28.68 | 47.73 |
| 16 | 1.00 | 72.37 | 0.85 | 30.21 | 48.86 |
| 17 | 0.95 | 68.75 | 0.90 | 32.12 | 48.96 |
| 18 | 0.80 | 57.89 | 0.95 | 33.84 | 46.27 |
| 19 | 0.62 | 44.87 | 1.00 | 35.68 | 42.87 |
| 20 | 0.52 | 37.63 | 0.95 | 33.83 | 38.85 |
| 21 | 0.46 | 33.29 | 0.90 | 32.19 | 36.04 |
| 22 | 0.34 | 24.60 | 0.86 | 30.72 | 31.78 |
| 23 | 0.23 | 16.64 | 0.81 | 28.76 | 27.41 |
| 24 | 0.14 | 10.13 | 0.74 | 26.72 | 23.23 |

**Table A.5 Modeled daily load curve for the fisheries sector**

| Hour | Current % Demand | Current Demand | 2040 % Demand | 2040 Demand |
|---|---|---|---|---|
| 1 | 1.0 | 1.29 | 0.00 | 0.00 |
| 2 | 1.0 | 1.29 | 0.00 | 0.00 |

| | | | | |
|---|---|---|---|---|
| 3 | 1.0 | 1.29 | 1.00 | 19.53 |
| 4 | 1.0 | 1.29 | 1.00 | 19.53 |
| 5 | 1.0 | 1.29 | 1.00 | 19.53 |
| 6 | 1.0 | 1.29 | 1.00 | 19.53 |
| 7 | 1.0 | 1.29 | 0.00 | 0.00 |
| 8 | 1.0 | 1.29 | 0.00 | 0.00 |
| 9 | 1.0 | 1.29 | 0.00 | 0.00 |
| 10 | 1.0 | 1.29 | 0.00 | 0.00 |
| 11 | 1.0 | 1.29 | 0.00 | 0.00 |
| 12 | 1.0 | 1.29 | 0.00 | 0.00 |
| 13 | 1.0 | 1.29 | 0.00 | 0.00 |
| 14 | 1.0 | 1.29 | 0.00 | 0.00 |
| 15 | 1.0 | 1.29 | 0.00 | 0.00 |
| 16 | 1.0 | 1.29 | 0.00 | 0.00 |
| 17 | 1.0 | 1.29 | 0.00 | 0.00 |
| 18 | 1.0 | 1.29 | 0.00 | 0.00 |
| 19 | 1.0 | 1.29 | 0.00 | 0.00 |
| 20 | 1.0 | 1.29 | 0.00 | 0.00 |
| 21 | 1.0 | 1.29 | 0.00 | 0.00 |
| 22 | 1.0 | 1.29 | 0.00 | 0.00 |
| 23 | 1.0 | 1.29 | 0.00 | 0.00 |
| 24 | 1.0 | 1.29 | 0.00 | 0.00 |

**Table A.6 Modeled daily load curve for the mining sector**

| 2030 Demand | Hour | Current % Demand | Current Demand | 2040 % Demand | 2040 Demand | 2030 Demand |
|---|---|---|---|---|---|---|
| 1.95 | 1 | 0.85 | 24.71 | 0.85 | 53.87 | 39.29 |
| 1.95 | 2 | 0.87 | 25.30 | 0.87 | 55.14 | 40.22 |
| 3.90 | 3 | 0.84 | 24.42 | 0.84 | 53.24 | 38.83 |
| 3.90 | 4 | 0.81 | 23.58 | 0.81 | 51.34 | 37.44 |
| 3.90 | 5 | 0.81 | 23.55 | 0.81 | 51.34 | 37.44 |
| 3.90 | 6 | 0.77 | 22.39 | 0.77 | 48.80 | 35.59 |
| 1.95 | 7 | 0.83 | 24.13 | 0.83 | 52.60 | 38.37 |
| 1.95 | 8 | 0.92 | 26.75 | 0.92 | 58.31 | 42.53 |
| 1.95 | 9 | 0.89 | 25.88 | 0.89 | 56.41 | 41.14 |
| 1.95 | 10 | 0.88 | 25.59 | 0.88 | 55.77 | 40.68 |
| 1.95 | 11 | 0.87 | 25.30 | 0.87 | 55.14 | 40.22 |
| 1.95 | 12 | 0.84 | 24.42 | 0.84 | 53.24 | 38.83 |
| 1.95 | 13 | 0.85 | 24.71 | 0.85 | 53.87 | 39.29 |
| 1.95 | 14 | 0.83 | 24.13 | 0.83 | 52.60 | 38.37 |
| 1.95 | 15 | 0.78 | 22.68 | 0.78 | 49.44 | 36.06 |
| 1.95 | 16 | 0.74 | 21.55 | 0.74 | 46.90 | 34.21 |
| 1.95 | 17 | 0.83 | 24.13 | 0.83 | 52.60 | 38.37 |
| 1.95 | 18 | 0.91 | 26.46 | 0.91 | 57.67 | 42.07 |
| 1.95 | 19 | 0.85 | 24.71 | 0.85 | 53.87 | 39.29 |
| 1.95 | 20 | 0.86 | 25.00 | 0.86 | 54.51 | 39.76 |
| 1.95 | 21 | 0.86 | 25.00 | 0.86 | 54.51 | 39.76 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1.95 | 22 | 0.83 | 24.13 | 0.83 | 52.60 | 38.37 |
| 1.95 | 23 | 0.80 | 23.26 | 0.80 | 50.70 | 36.98 |
| 1.95 | 24 | 0.79 | 22.97 | 0.79 | 50.07 | 36.52 |

Selected average daily load curve from Haas et al., 2020, just for electricty demand (40-50% of mining energy demand) and averaged for top copper mine in top 5 copper producing countires (Chile Escondida mine is the largest) (Copper seems to be the majority of Chilean mining activity); 2040 daily loads curves not adjusted for shift to full-electric, just a level increase.

https://www.researchgate.net/publication/339610763_Copper_mining_100_solar_electricity_by_2030

## Annex B. Estimate of storage requirements based on supply/demand daily curves.

**Electricity balance by 2050.** According to the PELP the energy use in 2050 is 561 TWh in a year. But when substituted with electricity, the economy requires only 373 TWh (see table 4) in a year. This is what needs to be delivered by the power system in 2050.

Firm Capacity. To properly estimate the firm capacity projected to be in the system by 2050, there is a need to estimate the projected hydropower, geothermal and biomass generated electricity.

**Hydropower**. The assumption is made in the analysis that hydro capacity is the one projected under the PELP. No major additional hydro capacity will come online and capacity will grow from 7.5 GW today to 8 GW by 2050.

Hydro is tapped by the rain regime in the area. According to the CEN, hydro delivered 15 TWh in 2022, a year of low hydrology. It is estimated that hydropower delivered 31% of all electricity in 2024, a year of good hydrology (Climate Action Tracker. Chile, accessed July 2025). The electricity use in 2024 in Chile was 88 TWh (Lowcarborpower.org accessed July 2025).

Thus, 88TWh x .31 as an estimate of hydropower delivery to the system in a year of good hydrology; that is: 26.6 TWh, say 27 TWh as an upper bound if no more hydropower units come on stream.

**Biomass**. In 2022, biomass accounted for 438 MW of installed capacity. In 2023 it delivered 6.3% of total electricity generation, or about 5.5 TWh (Americas market intelligence Chile. Accessed July 2025). It is assumed that biomass contribution is marginally increased to 6 TWh

**Geothermal.** Chile has only one geothermal plant in operation, Cerro Pabellón with a capacity of 48 MW. It will almost double capacity to 81 MW by 2026. In 2023 it generated 0.5 TWh. With the expansion, it could generate nearly 1.0 TWh.

**Total firm generation.** The firm generation always available in the supply is hydro+geothermal + biomass which is 27+1+6 =34 TWh in a year.

**Distributed energy**. In addition to firm energy there is a need to account for distributed energy which is not part of the central generation system. As of July 2024, the installed capacity of distributed generation in Chile was 3.6 GW. About 79% of it is solar and is delivered during day hours. Therefore, it is assumed that the online factor at best is that of utility size solar, but much lower than in Atacama. The analysis uses an online factor of 0.2 (Aurora energy research, 2025).

The study assumes 17 GW of capacity by 2050, thus the electricity delivered (optimistically) would be 17 GW x 8760 h X 0.2 = 29.7 TWh, say 30 TWh.

**Electricity demand in 2050.** The demand has been calculated at 373 TWh. Firm and distributed capacity are able to deliver 64 TWh (27 from hydropower, 6 from biomass, 1 from geothermal and 30 from distributed energy).

**Central generation capacity.** The central generation capacity required is therefore 309 TWh (373-64). But there is a need to account for losses. The analysis assumes that 5% of generation delivered to the grid is lost (down from the historical 6.5% for Chile, but not better to be conservative) on account of the improvements to the transmission grid. Therefore the central generation capacity would need to generate 393 TWh (373/.95).

Out of these, 329 TWh (total minus firm capacity and distributed, 393 TWh – 64 TWh) needs to be supplied by wind and solar and CSP directly and via storage, and customers would receive 309 TWh (20 are lost during transmission) in a year with a composition of 47.5/47.5/5. Wind/PV/CSP to meet the demand, delivering 846 GWh per day (309/365 days).

In addition, there is a need to ensure that peak capacity requirements are met. The peak capacity requirement for 2050 has been estimated at 48 GW (table 5), the peak capacity requirement is met.

**Estimate of nominal capacity.** The daily generation is 901 GWh before losses (329 TWh/365 days). The online factors used in the analysis are: 0.36 for wind onshore, 0.32 for PV and 0.6 for CSP in Atacama (footnote number 40):

901 GWh/24 h= 37.5 GW= wind capacity x 0.32 + PV capacity x 0.36 + CSP capacity x0.06. (wind capacity = PV capacity and CSP capacity is (5/47)x.06 wind capacity)

Solving for Wind, Wind Capacity=49 GW, PV capacity=49 GW and CSP=5 GW. Total, is 103 GW. These are the amounts required to estimate storage.

**Estimate of storage requirements.** The requirements for storage are estimated based on the hourly electricity balance using the normalized values from figure 9. The shortage is estimated at 288 GWh. This means the deficit can be met with storage of 36 GW with a discharge of 8 hours.

# Annex C. Assumptions made in the calculations of LCOs

**Transportation**

| Vehicle Type | Investment Cost ($US) | O&M Cost | Capacity | Life (yrs) | Notes |
|---|---|---|---|---|---|
| 12m Fishing Boat (H2) | 2025: 128,400<br>2030: 124,820<br>☐2035: 124,380<br>☐2040: 123,960<br>2050: 123,600 | 2% | 26,825 (km/yr) | 30 | Fuel eff.: 4.3 (km/kgH2)<br>Fuel cost equal to LCOH2 |
| Mining Truck (H2) | 2025: 2,932,500<br>2030: 2,812,500<br>2035: 2,798,500<br>2040: 2,784,500<br>2050: 2,772,500 | 2% | 19,345 (km/yr) | 20 | Fuel eff.: 0.5 (km/kgH2)<br>Fuel cost equal to LCOH2 |
| Heavy Truck (H2) | 2025: 273,880☐<br>2030: 244,360<br>2035: 240,916<br>2040: 237,472<br>2050: 234,520 | 2% | 127,750 (km/yr) | 20 | Fuel eff.: 3.86 (km/kgH2)<br>Fuel cost equal to LCOH2 |
| Medium Truck (H2) | 2025: 161,644<br>☐2030: 139,075<br>☐2035: 131,407<br>2040: 123,739<br>☐2050: 110,653 | 2% | 127,750 (km/yr) | 20 | Fuel eff.: 5.79 (km/kgH2)<br>Fuel cost equal to LCOH2 |
| Light Truck (H2) | 2025: 84,475<br>☐2030: 69,049<br>☐2035: 64,054<br>2040: 59,058<br>☐2050: 50,641 | 2% | 91,250 (km/yr) | 20 | Fuel eff.: 6.95 (km/kgH2)<br>Fuel cost equal to LCOH2 |
| 18m Bus (H2) | 2025: 336,120<br>2030: 320,640<br>☐2035: 318,834<br>2040: 317,028<br>☐2050: 315,480 | 2% | 19,345 (km/yr) | 20 | Fuel eff.: 1.57 (km/kgH2)<br>Fuel cost equal to LCOH2 |

| Vehicle Type | Investment Cost ($US) | O&M Cost | Capacity | Life (yrs) | Notes |
|---|---|---|---|---|---|
| 12m Bus (H2) | 2025: 237,328<br>2030: 220,632<br>☐2035: 212,350<br>2040: 204,069<br>☐2050: 188,776 | 2% | 40,000 (km/yr) | 20 | Fuel eff.: 1.34 (km/kgH2)<br>Fuel cost equal to LCOH2 |
| Car (H2) | 2025: 28,100<br>2030: 25,700<br>☐2035: 25,420<br>☐2040: 25,140<br>2050: 24,900 | 0.5% | 12,045 (km/yr) | 20 | Fuel eff.: 118.65 (km/kgH2)<br>Fuel cost equal to LCOH2 |
| Freight Train (H2) | 2025: 2,500,000<br>☐2030: 2,356,000<br>☐2035: 2,339,200<br>2040: 2,322,400<br>2050: 2,308,000 | 100,000 ($/yr) | 100,000 (tonne-km/yr) | 50 | Fuel eff.: 0.0012 (kgH2/tonne-km)<br>Fuel cost equal to LCOH2 |
| Ship (H2) | 2025: 4,800,000<br>☐2030: 4,656,000<br>☐2035: 4,639,200<br>☐2040: 4,622,400<br>☐2050: 4,608,000 | 0.8% | 8,880,000 (tonne-km/yr) | 50 | Fuel eff.: 0.06 (kgH2/tonne-km)<br>Fuel cost equal to LCOH2 |
| 12m Fishing Boat (Elec.) | | | | | |
| Mining Truck (Elec.) | 2025: 3,295,000<br>☐2030: 3,250,000<br>☐2035: 3,245,500<br>☐2040: 3,230,500<br>☐2050: 3,220,000 | 0.5% | 19,345 (km/yr) | 20 | Fuel eff.: 0.04 (km/kWh)<br>Fuel cost equal to LCOE |
| Heavy Truck (Elec.) | 2025: 257,400<br>☐2030: 239,370<br>☐2035: 230,790<br>☐2040: 219,760<br>☐2050: 202,250 | 0.5% | 127,750 (km/yr) | 12 | Fuel eff.: 1.0 (km/kWh)<br>Fuel cost equal to LCOE |
| Medium Truck (Elec.) | 2025: 140,284<br>☐2030: 128,584<br>☐2035: 122,284<br>☐2040: 114,584<br>☐2050: 101,784 | 0.5% | 127,750 (km/yr) | 12 | Fuel eff.: 1.5 (km/kWh)<br>Fuel cost equal to LCOE |

| Vehicle Type | Investment Cost ($US) | O&M Cost | Capacity | Life (yrs) | Notes |
|---|---|---|---|---|---|
| Light Truck (Elec.) | 2025: 69,523<br>☐2030: 61,705<br>☐2035: 57,667<br>☐2040: 52,649<br>☐2050: 44,433 | 0.5% | 91,250 (km/yr) | 12 | Fuel eff.: 1.8 (km/kWh)<br>Fuel cost equal to LCOE |
| 18m Bus (Elec.) | 2025: 516,600<br>☐2030: 481,830<br>☐2035: 464,610<br>☐2040: 442,840<br>☐2050: 407,750 | 0.5% | 100,000 (km/yr) | 12 | Fuel eff.: 1.47 (km/kWh)<br>Fuel cost equal to LCOE |
| 12m Bus (Elec.) | 2025: 251,100<br>☐2030: 231,930<br>☐2035: 223,560<br>☐2040: 212,390<br>☐2050: 195,250 | 0.5% | 40,000 (km/yr) | 12 | Fuel eff.: 1.25 (km/kWh)<br>Fuel cost equal to LCOE |
| Car (Elec.) | 2025: 25,616<br>☐2030: 23,033<br>☐2035: 21,529<br>☐2040: 19,745<br>☐2050: 16,698 | 0.5% | 12,000 (km/yr) | 15 | Fuel eff.: 7.7 (km/kWh)<br>Fuel cost equal to LCOE |
| Freight Train (Elec.) | 2025: 2,380,000<br>☐2030: 2,308,000<br>☐2035: 2,300,800<br>☐2040: 2,276,800<br>☐2050: 2,260,000 | 100,000 ($US) | 100,000 (tonne-km/yr) | 50 | Fuel eff.: 0.02 (kWh/tonne-km)<br>Fuel cost equal to LCOE |
| Ship (Elec.) | 2025: 4,680,000<br>☐2030: 4,608,000<br>☐2035: 4,600,800<br>☐2040: 4,576,800<br>☐2050: 4,560,000 | 0.8% | 8,880,000 (tonne-km/yr) | 50 | Fuel eff.: 1.02 (kWh/tonne-km)<br>Fuel cost equal to LCOE |
| 12m Fishing Boat (Diesel) | 140,000 | 2% | 26,825 (km/yr) | 30 | Fuel eff.: 0.2 (km/L)<br>Diesel cost: 0.45 ($US/L) |
| Mining Truck (Diesel) | 3,400,000 | 1% | 19,345 (km/yr) | 20 | Fuel eff.: 0.14 (km/L)<br>Diesel cost: 0.45 ($US/L) |

| Vehicle Type | Investment Cost ($US) | O&M Cost | Capacity | Life (yrs) | Notes |
|---|---|---|---|---|---|
| Heavy Truck (Diesel) | 150,000 | 1% | 127,750 (km/yr) | 12 | Fuel eff.: 3.4 (km/L)<br><br>Diesel cost: 0.45 ($US/L) |
| Medium Truck (Diesel) | 80,000 | 1% | 127,750 (km/yr) | 12 | Fuel eff.: 5.6 (km/L)<br><br>Diesel cost: 0.45 ($US/L) |
| Light Truck (Diesel) | 60,000 | 1% | 91,250 (km/yr) | 12 | Fuel eff.: 9.1 (km/L)<br><br>Diesel cost: 0.45 ($US/L) |
| 18m Bus (Diesel) | 350,000 | 1% | 100,000 (km/yr) | 12 | Fuel eff.: 3.0 (km/L)<br><br>Diesel cost: 0.45 ($US/L) |
| 12m Bus (Diesel) | 170,000 | 1% | 40,000 (km/yr) | 12 | Fuel eff.: 4.0 (km/L)<br><br>Diesel cost: 0.45 ($US/L) |
| Car (Gasoline) | 20,500 | 1% | 12,000 (km/yr) | 15 | Fuel eff.: 16.8 (km/L)<br><br>Gasoline cost: 0.53 ($US/L) |
| Freight Train (Diesel) | 3,000,000 | 125,000 ($US) | 100,000 (tonne-km/yr) | 50 | Fuel eff.: 0.008 (L/tonne-km)<br><br>Diesel cost: 0.45 ($US/L) |
| Ship (Diesel) | 4,000,000 | 1% | 8,880,000 (tonne-km/yr) | 50 | Fuel eff.: 0.25 (L/tonne-km)<br><br>Diesel cost: 0.45 ($US/L) |

**Industry**

| Tech. | Investment Cost | O&M Cost | Capacity | Life (yrs) | Notes |
|---|---|---|---|---|---|
| Steel H2-DRI-EAF | 800 - 1200 ($/tonne-steel) | 2% | 1,800,000 (tonne-steel/yr) | 20 | Energy eff.: 500 (kWh elec./tonne-steel), ☐55 (kgH2/tonne-steel)<br><br>Electricity cost equal to LCOE<br><br>H2 cost equal to LCOH2 |
| Elec. Induction Stove | 385 ($US) | 0% | 100 (L) | 20 | Energy eff.: 0.012 (kWh/L)<br><br>Electricity cost equal to LCOE |
| LPG Stove | 139 ($US) | 0% | 100 (L) | 20 | Energy eff.: 0.018 (kWh/L)<br><br>Fuel cost equal to 0.09 ($US/kWh) |
| Steam Electric Boiler (100MMBTU) | S1[166]: 2,006,766 ($US)<br><br>S2: 1,889,904 ($US) | 1% | 800,000 (MMBTU/yr) | 20 | Energy eff.: 99%<br><br>Electricity cost equal to LCOE |
| Steam Electric Boiler (30MMBTU) | S1: 939,903 ($US)<br><br>S2: 904,561 ($US) | 1% | 240,000 (MMBTU/yr) | 20 | Energy eff.: 99%<br><br>Electricity cost equal to LCOE |
| NG Boiler (100MMBTU) | 3,500,000 ($US) | 0.95 ($US/ MMBTU) | 800,000 (MMBTU/yr) | 20 | Energy eff.: 70%<br><br>Fuel cost equal to 12.4 ($US/mmBTU) |

[166] S*n* denotes Scenario *n*

| Tech. | Investment Cost | O&M Cost | Capacity | Life (yrs) | Notes |
|---|---|---|---|---|---|
| NG Boiler (30MMBTU) | 1,050,000 ($US) | 0.95 ($US/ MMBTU) | 240,000 (MMBTU/yr) | 20 | Energy eff.: 70%<br>Fuel cost equal to 12.4 ($US/mmBTU) |
| NG Boiler (0.6MMBTU) | 2,000 ($US) | 0% | 2,628 (MMBTU/yr) | 20 | Energy eff.: 90%<br>Fuel cost equal to 12.4 ($US/mmBTU) |
| Electric Heat Pump (100MMBTU) | 5,000,000 ($US)<br>6,500,000 ($US)<br>12,500,000 ($US) | 3% | 800,000 (MMBTU/yr) | 20 | Energy eff.: 100%<br>Electricity cost equal to LCOE |
| Electric Heat Pump (30MMBTU) | 1,500,000 ($US)<br>1,950,000 ($US)<br>3,750,000 ($US) | 3% | 240,000 (MMBTU/yr) | 20 | Energy eff.: 100%<br>Electricity cost equal to LCOE |
| Electric Heat Pump (0.6MMBTU) | 6,300 ($US) | 0% | 2,628 (MMBTU/yr) | 20 | Energy eff.: 100%<br>Electricity cost equal to LCOE |
| NG Heat Pump (100MMBTU) | 12,500,000 ($US) | 3% | 800,000 (MMBTU/yr) | 20 | Energy eff.: 70%<br>Fuel cost equal to 12.4 ($US/mmBTU) |
| NG Heat Pump (30MMBTU) | 3,750,000 ($US) | 3% | 240,000 (MMBTU/yr) | 20 | Energy eff.: 70%<br>Fuel cost equal to 12.4 ($US/mmBTU) |

| Tech. | Investment Cost | O&M Cost | Capacity | Life (yrs) | Notes |
|---|---|---|---|---|---|
| CaCO3 Calcination (Plasma) | 11,600,000 ($US) | 0% | 73,730 (tonne/yr) | 20 | Energy eff.: 2.22 (MWh/ tonne-CaCO3) Electricity cost equal to LCOE |
| CaCO3 Calcination (Lime Kiln) | 18,400,000 ($US) | 0% | 73,730 (tonne/yr) | 20 | Energy eff.: 1.94 (MWh/ tonne-CaCO3) Fuel cost equal to 0.09 ($US/kWh) |
| CaCO3 Calcination (Electrolyzer) | S1: 15,000,000 ($US)☐ S2: 30,000,000 ($US) | 0% | 73,730 (tonne/yr) | 20 | Energy eff.: 57.0 (MWh/ tonne-CaCO3) Electricity cost equal to LCOE |

**LCOH2**

| Year | Investment Cost | O&M Cost | Capacity | Life (yrs) | Electricity Consumption |
|---|---|---|---|---|---|
| 2025 | 2,000 ($/kW) | 2% | 17,702,500 (kgH2/yr) | 30 | 57.5 (kWh/kgH2) |
| 2030 | 1,600 ($/kW) | 2% | 17,702,500 (kgH2/yr) | 30 | 55 (kWh/kgH2) |
| 2035 | 1,400 ($/kW) | 2% | 17,702,500 (kgH2/yr) | 30 | 52.5 (kWh/kgH2) |
| 2040 | 1,200 ($/kW) | 2% | 17,702,500 (kgH2/yr) | 30 | 50 (kWh/kgH2) |
| 2050 | 800 ($/kW) | 2% | 17,702,500 (kgH2/yr) | 30 | 45 (kWh/kgH2) |

**LCOTr**

| Type | Cost per km | New Capacity | Cost per km-GW | Length |
|---|---|---|---|---|
| HVDC[167] | 2.5 ($mm/km) | 6 (GW) | 0.41 ($mm/km-GW) | 1,400 (km) |
| Reconductoring | 0.24 ($mm/km) | 1.7 (GW) | 0.14 ($mm/km-GW) | 300 (km) |
| LFAC[168] | 2.4 ($mm/km) | 3 (GW) | 0.78 ($mm/km-GW) | 150 (km) |

**Fuel Costs**

| Type | Cost |
|---|---|
| Electricity | 2025: 0.0546 ($US/kWh)<br>2030: 0.0603 ($US/kWh)<br>2035: 0.0526 ($US/kWh)<br>2040: 0.0478 ($US/kWh)<br>2050: 0.0406 ($US/kWh) |
| H2 | 2025: 4.79 ($US/kgH2)<br>2030: 4.58 ($US/kgH2)<br>2035: 3.82 ($US/kgH2)<br>2040: 3.26 ($US/kgH2)<br>2050: 2.35 ($US/kgH2) |
| Natural Gas | 12.4 ($US/mmBTU) |
| Diesel | 0.45 ($US/L) |
| Gasoline | 0.53 ($US/L) |
| LPG | 0.09 ($US/kWh) |
| | |

[167] It is assumed that the power generated by solar PV, CSP, and 80% of wind is transported via HVDC
[168] It is assumed that the power generated by hydro, "other," and the remaining 20% of wind is transported via LFAC

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Established in 1986, the Climate Institute was among the first organizations worldwide to focus on climate change. We work at the intersection of science, policy, and innovation to develop solutions that protect communities, promote climate justice, and speed the transition to a sustainable future.

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