NET ZERO WORLD INITIATIVE

Accelerating Global Energy System Decarbonization

Leadership and Community Engagement in Chile: Deploying Net-Zero Technologies and Solutions

Riccardo Bracho, Julie Doherty Kowalski, Nina Khanna, Virginie Letschert, Nicholas Deforest, Rongxin Lin, Keith Kline, Sara Lechtenberg-Kasten, Juan Pablo Carvallo, Loreta Lancellotti, Natalie Kempkey, Mijal Brady Berkowitz

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Suggested Citation: Bracho, Riccardo et al. *Leadership and Community Engagement in Chile: Deploying Net-Zero Technologies and Solutions*. 2024. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-90813. http://www.nrel.gov/docs/fy24osti/90813.pdf.

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UNITED STATES DEPARTMENT OF ENERGY

under Contract DE-AC36-08GO28308

Acknowledgments

The Net Zero World Chile team would like to acknowledge the contributions to this chapter from the U.S. Department of Energy (DOE) Office of International Affairs, DOE's multi-laboratory team, Chile's Ministry of Energy and partners, and other stakeholders.

The team extends its thanks to team members Robert Horner and Ashley Books of DOE's Office of International Affairs; Ronnen Levinson of Lawrence Berkeley National Laboratory and Angela Ortega Pastor of the National Renewable Energy Laboratory for serving as the report's peer reviewers; Guenter Conzelmann and Clarisse Kim of Argonne National Laboratory; Anthony Armaly and Erik Shuster of the National Energy Technology Laboratory; Ron Benioff, Andrew Billich, Britton Marchese, Madeleine Crouse, Holly Darrow, Barbara O'Neill, and Bethany Speer of the National Renewable Energy Laboratory; Naim Dargouth, Nan Zhou, Wei Feng, and Carolyn Szum of Lawrence Berkeley National Laboratory; Dan Gasper, Zarrar Khan, and the Global Change Analysis Model team of Pacific Northwest National Laboratory; and Clare Zimmerman of the United States Embassy in Santiago, Chile.

The team would also like to specifically recognize the team at Chile's Ministry of Energy, including Minister Diego Pardow, Dafne Pino (Regional Secretary of Energy to the Antofagasta Region–Secretaria Regional Ministerial de Energía [SEREMI] Antofagasta), Juan Pedro Searle, Andrea Varas, Alex Santander, María Helena Lee, Carolína Gómez, Carlos Toro, María José García, Felipe Mellao, Carolina Riobó, Ayleen Ramirez (SEREMI), and Dina Rojas (SEREMI).

Finally, the team's acknowledgments extend to the Mayor of Tocopilla, Ljubica Kurtovic, and the Tocopilla Net Zero World–Sister City Stakeholder Committee. The latter includes Yassets Egaña (former committee member) and Veronica Campos (Office of the Mayor of Tocopilla), Norma Tejada (community representative from Tocopilla), Miguel Alvarez (AES Corporation's workers representative in the Antofagasta region), Claudia Rosales (Engie representative in the Antofagasta region and committee member), Jorge Rabanal and Milován Troncoso (University of Antofagasta), and Dr. Damir Galaz (Catholic University of Chile, North Campus).

Acronyms and Abbreviations

ACRONYMS

AES	The AES Corporation
Argonne	Argonne National Laboratory
BAU	business-as-usual
BC	black carbon
CHP	combined heat and power
DER	distributed energy resources
DER-CAM	Distributed Energy Resources Customer Adoption Model
DES	district energy system
DOE	U.S. Department of Energy
GHG	greenhouse gas
GCAM	Global Change Assessment Model
HVAC	heating, ventilation, and air conditioning
IPCC	Intergovernmental Panel on Climate Change
LBNL	DOE's Lawrence Berkeley National Laboratory
LEAP	Low Emissions Analysis Platform
MoE	Chile's Ministry of Energy
NDC	Nationally Determined Contribution
NETL	National Energy Technology Laboratory
NZW	Net Zero World
ORNL	DOE's Oak Ridge National Laboratory
PNNL	DOE's Pacific Northwest National Laboratory
PV	photovoltaic
SEREMI	Secretaria Regional Ministerial de Energía (Regional Ministerial Secretary of Energy)
SHSG	solar heat gain coefficient
U.S.	United States
USD	U.S. dollars

ABBREVIATIONS

CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
Gt	gigatonne
kWh_{th}/m^2	kilowatt-hours thermal per square meter of floor area
M^2	square meter
Mt	million tonnes
$MtCO_2e$	million tonnes carbon dioxide equivalent
MW	megawatt
PM	particulate matter
$PM_{2.5}$	particulate matter with a diameter of 2.5 micrometers and smaller

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1 Overview

Chile, with a population of 19 million and over 50 percent of its electricity generation from renewable sources, has made a bold commitment to achieve greenhouse gas (GHG) neutrality by 2050, as outlined in its Climate Change Law (Law 21455, passed in 2022). The country's long-term strategy, established in 2021, estimates the capital expenditure required to reach carbon neutrality by 2050 at a net present value of $50 billion U.S. dollars (USD). This investment is anticipated to result in net present value future cost savings of $80 billion USD, due to lower energy consumption in a carbon-neutral scenario, yielding a positive net present value of $30 billion USD. The 2020 update to Chile's Nationally Determined Contribution (NDC) sets several key targets, including peaking emissions in 2025, limiting carbon dioxide equivalent (CO_{2e}) emissions to 95 million tonnes (Mt) per year by 2030, capping GHGs at 1,100 $MtCO_2e$ between 2020 and 2030, and reducing black carbon emissions by 25 percent by 2030, relative to 2006 levels. Presently, the majority of Chile's GHG emissions stem from the energy sector—notably, coal-based electricity production and diesel-based land transportation. While Chile has abundant solar and wind energy resources, a significant challenge is the geographical distribution of these resources; they are predominantly located in the north and south, whereas most of the population resides in the central region, which includes the capitol, Santiago.

The Ministry of Energy (MoE) in Chile is a founding partner of the Net Zero World (NZW) initiative, alongside the U.S. Department of Energy (DOE). The implementation of NZW in Chile is being spearheaded by Chile's MoE, DOE's Office of International Affairs, a team of technical experts from DOE's national laboratories, and various private and public sector partners, with a focus on highly tailored and actionable solutions.

The NZW team and its Chilean partners jointly identified and are advancing action in the following priority focus areas to help achieve the country's ambitious climate targets.

- **Energy-system-wide modeling**. NZW provides energy-system-wide modeling data and results that are crucial for strategic planning in electrification and decarbonization, helping Chile complete its Climate Change Mitigation Plan for the Energy Sector by 2024. This modeling, which includes work on the Low Emissions Analysis Platform (LEAP) and the Global Change Assessment Model (GCAM), is also vital for meeting the country's 2020 NDC goal of reducing black carbon emissions by 25% by 2030. Enhancements to the LEAP model, led by Chile's MoE and DOE's Lawrence Berkeley National Laboratory (LBNL) with support from Argonne National Laboratory (Argonne), include expanded cost-benefit analysis and updated pollution reduction analysis.
- **District energy**. The MoE focuses on district energy to decarbonize space heating and address air pollution health hazards with support from NZW. NZW Chile's support in district energy modeling and analysis is crucial for transitioning from wood/biomass burning and achieving the 2020 NDC black carbon reduction goal. It also contributes to the National Energy Plan's aim of connecting 500,000 users to district energy by 2050. This effort is led by LBNL with support from NREL and focuses on energy and cost savings, emission reductions, financing models, and regulatory framework development.
- **Just transition**. NZW works with the MoE, local communities, and other private and public sector stakeholders on the prioritization of a just energy transition, with a specific focus on

Tocopilla, a coal-dependent community near the Atacama desert with a population of 25,000 and one of Chile's highest poverty rates. This work is crucial for a just and sustainable transition for Tocopilla in the context of Chile's accelerated coal phase-out by 2040 and the over 439 megawatts (MW) of coal plant capacity already closed in this community, with plans for an additional 282 MW to close in 2024. The MoE and the NREL lead this effort, with support from Argonne, Oak Ridge National Laboratory (ORNL), and the National Energy Technology Laboratory (NETL).

- **Power decarbonization**. Central to Chile's 2050 carbon neutrality goal is a zero-emissions power system, focusing on coal phase-out by 2040, renewables integration, and clean hydrogen development. The NZW team, led by NREL, LBNL, and the MoE, is working on a regulatory framework plan and identifying advanced power electronics technologies to ensure grid security and reliability amid these transitions.

2 Energy System-Wide Modeling Results and Outcomes

During Phase I, (2021–2023), the NZW modeling team collaborated closely with the MoE to develop a comprehensive national-level LEAP model. This model complements the MoE's region-based approach by providing a holistic view of the energy system.

In Phase II, the focus expanded to enhance LEAP's capabilities, particularly in cost–benefit analysis and local pollutant projection under various decarbonization scenarios. The team integrated technology-specific costs and pollutant emission factors, such as those for particulate matter (PM) and black carbon, into the model. This integration enabled a detailed examination of the impact of decarbonization strategies on both economic and environmental fronts.

The analysis employed two main scenarios:

1. **Business-as-Usual (BAU) scenario**. Aligning with existing policies, this baseline scenario does not anticipate significant policy-induced technological changes.
2. **Accelerated Net Zero scenario**. This scenario incorporates aggressive energy efficiency improvements, fuel switching, and electrification across demand sectors.

The cost–benefit analysis performed using LEAP highlighted the financial implications of decarbonization. The analysis included demand costs and resources, focusing on the net present value of various measures and mitigation abatement costs. The results revealed that, between 2020 and 2050, investments in demand-side technologies under the Accelerated Net Zero scenario would be highly cost-effective, with a cost-benefit ratio of 1:3 and a net present value of $150 billion USD. Moreover, the scenario demonstrated a potential for 1.15 gigatonne (Gt) of cumulative CO_2 savings, highlighting its effectiveness in reducing CO_2 emissions.

The local pollutant analysis within the LEAP model provided crucial insights into the reduction of pollution co-benefits from decarbonization. The results showed dramatic potential for PM and black carbon emission reductions, particularly in the residential and transport sectors. For instance, the residential sector, primarily impacted by biomass combustion, could eliminate most $PM_{2.5}$ emissions by 2050 through efficiency improvements, fuel switching, and full electrification under the Accelerated Net Zero scenario. In contrast, the BAU scenario predicted a continued increase in annual building-sector $PM_{2.5}$ emissions, reaching 1.5 times the current levels.

In the transport sector, the analysis indicated that $PM_{2.5}$ emissions could be reduced by 84 percent from 2021 levels under BAU and by 95 percent under the Accelerated Net Zero scenario by 2050. These reductions would result primarily from the accelerated electrification of motorcycles, light-duty trucks, and the full deployment of battery electric and hydrogen vehicles for medium-duty and heavy-duty road freight. Similarly, black carbon emissions in transport could be cut by 60 percent by 2050 under the Accelerated Net Zero scenario, with significant reductions achievable through incremental efficiency improvements in rail freight and fuel switching in maritime shipping.

The power sector also showed promising results. Accelerating the phase-out of fossil fuels (coal and diesel) and increasing renewable generation could halve annual $PM_{2.5}$ emissions by 2030 under the Accelerated Net Zero scenario. These reductions would continue with the phasing-out of diesel fuel oil and liquified natural gas generation by 2040.

These findings have been instrumental in guiding the collaborative efforts between the NZW Chile modeling team and the MoE. The insights gained from the analysis are vital for decision makers, informing them about the prioritization of decarbonization actions, policy implementation, and clean energy investments. These analyses also underscore the significant economic and pollutant reduction benefits of various decarbonization strategies.

3 Implementation Action Progress and Outcomes

3.1 District Energy

In 2023, NZW focused on modeling thermal district energy systems (DES) as a potential strategy for Chile to improve the efficiency and economic performance of space heating. Modeling efforts for DESs in Chile consisted of two primary activities:

1. Detailed energy modeling of DES at a pilot project site at Recoleta-Independencia, and

2. Comparative analysis of DES potential versus competing technologies within key Chile climate regions.

The insights from these two DES analyses are instrumental to understanding the potential of DES in Chile. The Pilot Project analysis conducted at Recoleta-Independencia provides a comprehensive exploration of DES performance within a specific, real-world application. Meanwhile, the National Potential analysis examines the opportunity for DES, in comparison with other technology solutions, to deliver energy, cost, and environmental benefits versus the capital costs needed to deploy them—across a variety of building stock and climate sectors within Chile, and for the nation as a whole.

Details for both activities, including input data, assumptions, and model results, are provided in Appendix A.2.

3.1.1 District Energy Pilot Project Analysis

The DES pilot project in the Recoleta-Independencia neighborhood of Santiago, Chile, is a priority focus area due to its potential to provide critical information to advance DES thermal modeling for other projects in the country. The MoE provided data from the project for the modeling team for use as inputs to the EnergyPlus® models of each of the 13 buildings at the pilot site. EnergyPlus simulation of these models yielded heating and cooling load profiles, which were then integrated into a Modelica-based thermal DES model. EnergyPlus is widely used software that simulates and analyzes the whole-building energy consumption and performance of various building energy efficiency measures, while Modelica is an object-oriented simulation environment that permits modeling of more complex physical systems, such as multi-building DES.

The Pilot Project modeling effort consists of the following three distinct sub-activities:

1. Developing a thermal network model using the geolocations of the identified buildings in the pilot;
2. Analyzing the performance of the district heating system by integrating the building thermal load profiles with the thermal network model; and
3. Performing additional parametric simulations of building energy efficiency measures to assess their impact on building thermal loads and network performance.

The work on the Recoleta-Independencia Pilot Project aims to evaluate the energy use, cost, and environmental impacts of the DES. Encompassing 13 buildings with a combined floor area of 284,000 square meters (m^2), the pilot includes educational buildings, health care facilities, and laboratories. In 2023, the team evaluated the effects of building energy efficiency measures such as high-performance windows on annual heating and cooling loads. In 2024, the team will obtain quantitative results from other envelope measures such as roof insulation, wall insulation, and air sealing.

Analysis of the Recoleta-Independencia Pilot Project

- **Project scope**. Evaluation of a DES across 13 diverse buildings, including educational and health care facilities, covering a total floor area of 284,000 m^2.
- **Energy modeling**. Custom EnergyPlus models developed for each building, generating detailed heating and cooling load profiles for thermal DES analysis.
- **Energy efficiency scenarios**. Exploration of building-envelope efficiency measures (e.g., window, roof, and wall improvements) to assess their abilities to reduce annual heating and cooling loads.
- **Environmental and economic benefits**. Assessment of the DES's potential to save energy, lower energy costs, and reduce CO_2 and other emissions (e.g., $PM_{2.5}$), demonstrating the feasibility and advantages of DES in urban settings.

3.1.2 DES National Potential Analysis

The region-based DES National Potential Analysis evaluated the cost and performance of deploying DES across various Chilean climate zones. Using U.S. prototype building models modified to represent Chilean heating systems in the base scenario (wood stoves and biomass boilers for residential and commercial buildings), the analysis assessed energy consumption across four different technology scenarios: (1) business-as-usual (BAU); (2) a conventional district energy system (Conventional DES); (3) a district energy system with combined heat and power (DES with CHP); and (4) distributed energy resources (DERs), utilizing electrification with heat pumps and solar photovoltaic (PV) panels. The team applied the Distributed Energy Resources Customer Adoption Model (DER-CAM) to optimize technology selection and performance for a typical operational year to minimize each scenario's total annual energy cost, a metric that includes: (1) costs for fuel and electricity purchases, (2) operation and maintenance costs, and (3) costs for new equipment purchases annualized for the lifetime of each system component.

Key findings from the analysis include the following:

- **Total annual energy cost**. The Conventional DES and DES with CHP scenarios exhibited higher total annual energy costs than the BAU scenario, due to higher capital costs and fuel prices (see Appendix A.2: District Energy Modeling). The DER scenario, while also presenting higher capital costs, produced a net total annual energy cost savings thanks to higher heating equipment efficiency and local electricity generation from PV.

- **Environmental impact**. The Conventional DES, DES with CHP, and DER scenarios each substantially reduced emissions of CO_2, $PM_{2.5}$, and other pollutants by improving overall efficiency of heating services, and by utilizing technologies and fuels with lower emissions factors.
- **Electrification benefits**. The DER scenario eliminated local consumption of fossil fuels for space heating. While it incurred higher capital costs, it offered total annual energy cost savings due to lower operation costs, showing a positive opportunity for both environmental and economic benefits.

3.2 Just Transition

After the approval of the NZW Chile collaborative work plan in November 2022, the MoE and the DOE multi-laboratory team established the Chile Just Transition Working Group to focus on providing technical assistance and building capacity for just energy transitions in the coal-dependent community of Tocopilla. This city, which has a population of 25,000 in the north of Chile (in the area of the Atacama Desert) and one of the country's highest poverty rates, has already seen two coal plants close—directly affecting 589 employees (employees working in the plants) and indirectly affecting 1,275 employees (jobs associated with the plant but not at the plant). Engie's "Tocopilla" plant closed in 2022 and The AES Corporation (AES) Andes' "Nueva Tocopilla" plant closed in mid-2024.

The Just Transition Working Group seeks to advance a Sister City relationship between Tocopilla and the city of Lawrence, Kansas, and to advance information exchanges between Tocopilla and other cities in the United States that are undergoing energy transitions, with a goal to advance net-zero solutions and technologies by enabling local communities to work across borders on common environmental, economic, and social challenges and build long-term direct and sustainable relationships. To that end, in 2023, the Just Transition Working Group launched a nine-person Tocopilla Sister City Stakeholder Committee including federal representation from the MoE, the MoE representative to the region of Secretaria Regional Ministerial de Energía (SEREMI) Antofagasta, the Office of the Mayor of Tocopilla, community leaders, and representatives from Engie and AES Andes. Also in 2023, the team designed and implemented virtual information exchanges with key stakeholders in Tocopilla and U.S. cities, including Coshocton, Ohio; townships outside of Pittsburgh, Pennsylvania; Gallup, New Mexico; the Sister Cities International organization in Palo Alto, California; and the "Friends of Tocopilla" committee in Lawrence, Kansas, to focus on sharing lessons learned and best practices related to fossil fuel transitions and/or establishing Sister City programs.

Developing Community Relationships Across Borders

The creation of a sustainable Sister City relationship requires committed champions for the relationship, buy-in for both communities, and a vision to move the relationship from a concept to reality. The MoE designated Tocopilla, Chile, as the first city to participate in a Sister City relationship as part of the NZW Chile work program and established a Tocopilla Sister City Stakeholder Committee in May 2023. Based on criteria developed with the Tocopilla Sister City Stakeholder Committee and best practices shared from other successful clean energy deployment programs (such as the DOE Clean Cities program), the NZW Chile multi-laboratory team identified candidate cities in the United States for potential Sister City relationships, targeting city leaders and stakeholders facing similar challenges.

The Governing Board of Sister Cities Lawrence in Lawrence, Kansas, was one of the first to respond, and a "Friends of Tocopilla" committee, including educators, environmentalists, city planners, and cultural leaders was then established in Lawrence. The members of this committee are volunteering time and expertise to create a meaningful and sustainable Sister City relationship. Introductory webinars occur between citizens in each city, and the Governing Board of Sister Cities Lawrence is examining options for incorporation of the Friends of Tocopilla subcommittee into the organization and reviewing the proposed areas of collaboration under education, environmental, and cultural themes. The Net Zero World Chile team looks forward to supporting productive collaborations for Tocopilla-Lawrence and other Sister City relationships in support of inclusive and just energy transitions, including the first visit by the Tocopilla Sister City Stakeholder Committee to Lawrence in July 2024.

In April 2023 and March 2024, the MoE, SEREMI, and NZW multi-laboratory team technical experts participated in a capacity-building and technical assistance mission to Tocopilla to collect data for the Tocopilla Sister City relationship and participate in community sessions to better understand the community's needs for information related to fossil fuel transitions. In response to requests from the community during those public participation sessions, NZW developed and provided capacity-building support for Tocopilla and surrounding communities in the form of eight virtual Energy 101 webinars attended by more than 80 participants on the following topics of interest: clean hydrogen, solar photovoltaics, energy storage, seawater desalination, microgrids, re-utilization and recycling of photovoltaic panels, and energy efficiency for desert climates. Each webinar addressed topic-specific high-level technology information, deployment and business opportunities, environmental benefits, workforce development, and capacity-building requirements.

In August 2023, Chile's Minister of Energy Diego Pardow, Minister of Environment Maisa Rojas, Head of Planning and Development Division of the Regional Government of Antofagasta Pablo Rojas, and Tocopilla Mayor Ljubica Kurtovic officially presented the Tocopilla Socio-Ecological Just Transition plan, and the NZW team collaborated with the MoE and its regional office in Antofagasta to include NZW just transition work plan deliverables as 3 of its 120 concrete actions.

3.3 Power Decarbonization

The NZW power decarbonization work stream focuses on adoption of grid-enhancing technologies and support for Chile's Power Decarbonization Plan. The Power Decarbonization Plan is under development by the MoE to advance measures needed to comply with the Climate Change Framing Law requiring carbon neutrality by 2050. The first public discussion session was held in late September 2023. The NZW multi-laboratory team continues to support the MoE with content and strategy to develop the plan, targeting a publication date in late 2024.

The power decarbonization team identified grid-enhancing technologies as key resources for addressing Chile's renewable energy curtailment, especially in the northern area of the country, due to the technology's ability to increase renewable energy throughput on the transmission lines in that part of the country. The technology will also lower generation and storage project costs and reduce in-country emissions. In support of increasing the level of knowledge in-country related to the global deployment of grid-enhancing technologies, the NZW multi-laboratory team prepared capacity-building materials provided in webinars completed on June 29, July 6, July 13, and July 19, 2023, for the Chilean Electric System Operator (Coordinador Electrico Nacional), as well as staff from the MoE. The webinars focused on grid-enhancing technologies and dynamic line rating, which allow transmission lines to exceed their rated capacity under appropriate ambient conditions, potentially allowing for increases in throughput of renewable energy generation from the north of Chile without building new transmission. The webinars were complemented by in-person meetings with three key dynamic line rating providers and MoE staff during a visit to LBNL in August 2023. The NZW team advises MoE staff on the identification of suitable locations and designs for a potential pilot project. In addition to the technology development pilot project, NSW supports regulatory analysis to create a viable path for dynamic line rating adoption by Chilean transmission companies.

4 Next Steps

The NZW team continues to work with partners in Chile to advance rigorous, country-driven net zero pathways, and technical and investment plans, both at the energy-system-wide level. This work enables transformative decarbonization actions, including deep technical and analytic support on technology cooperation, policy solutions, procurement, investment mobilization, and workforce development. Specific priorities for calendar year 2024 include the following:

- **Energy-system-wide modeling**. The energy-system-wide modeling work stream will focus on the identification, evaluation, and modeling of new mitigation measures and enhanced modeling of green hydrogen and sustainable aviation fuels. This work will continue to enable local modelers, country energy system experts, and other stakeholders to collaborate on country-driven analyses at the national level to inform energy system planning in support of decarbonization actions for Chile's Climate Change Mitigation Plan for the Energy Sector required under its Climate Change Law and the upcoming revision of Chile's NDC.

- **District energy**. The district energy workstream will focus on the refinement of a national DES modeling framework and analysis related to alternative and complementary technologies. These activities will continue to support the reduction of wood/biomass burning in homes for heating and accelerate Chile's voluntary National Energy Plan goal of connecting 500,000 users to a district energy network by 2050. This work also advances plans to meet Chile's 2020 NDC goal in its Climate Change Law (21455) of reducing black carbon emissions by 25 percent by 2030.

- **Just transition**. The just transition workstream will identify funding opportunities for net-zero technology pilot projects for Tocopilla and move from virtual sister-city introductions to a series of in-person meetings in July 2024 between stakeholders in Tocopilla, Lawrence, and Coshocton, Ohio, to advance the development of a Sister City-just transitions work plan with a focus on education, workforce development, and youth engagement. This work will accelerate a just transition for repurposing of over 400 MW of coal capacity in Tocopilla to net-zero technologies in support of Chile's voluntary National Energy Plan goal for accelerated coal phase-out by 2040, and Chile's Climate Change Law (21455) commitment to achieve GHG neutrality by 2050.

- **Power decarbonization**. The power decarbonization workstream will provide technical assistance for the design of a regulatory framework for the deployment of new technologies in the Chilean transmission system. This workstream will also focus on the design of market-based mechanisms for procurement of ancillary services from variable renewable energy and storage technologies. This work will advance renewable energy investment via curtailment reduction and inform policy and regulations related to increasing renewable energy throughput on transmission lines in northern Chile. This will work will continue to support implementation of Chile's Power Decarbonization Plan and Chile's Climate Change Law (21455) commitment to achieve GHG neutrality by 2050.

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Appendices

A.1 Energy-System-Wide Modeling

Overview

In close collaboration with the MoE, the NZW modeling team incorporated costs and local air pollutants into the national LEAP model to demonstrate integrated and enhanced modeling capabilities, address existing data gaps, and expand cost–benefit and pollutant analysis for decarbonization scenarios. This analysis integrated technology-specific costs and pollutant emission factors, such as those for PM and black carbon (BC), into the national LEAP model. The team updated selected activity inputs to better align with the MoE's latest activity projections for the buildings and transport sectors. The analysis also utilized the two main scenarios defined and validated by MoE experts in Phase 1 work, including:

1. **BAU scenario**. This baseline scenario, consistent with the base cases used in Chile's recent long-term energy planning process studies, considers the impact of all existing policies, such as the Nationally Determined Contribution targets, the Electromobility Strategy, and the Energy Efficiency Law, but assumes no significant future policy-induced technological changes.
2. **Accelerated Net Zero scenario**. This scenario builds on the long-term energy planning process 2023–2027's Accelerated Energy Transition scenario by evaluating additional actions within each demand sector to further reduce energy demand and related CO_2 emissions. This includes implementing new or more-aggressive energy efficiency improvements, fuel switching, and additional electrification. The scenario is intended to evaluate the technical feasibility of additional decarbonization actions.

Cost–Benefit Analysis

The team used LEAP to perform cost-benefit calculations from a societal perspective, by summing up all the costs in the energy system and then comparing the costs of the two main scenarios. The analysis encompassed the following cost elements:

- **Demand costs**, which are expressed as total costs, costs per activity, or costs of saving energy relative to a specific scenario.
- **Resources**, including the costs of indigenous resources, imported fuels, and the benefits of exported fuels.[1]

The LBNL team collaborated closely with the MoE to incorporate existing demand-side cost–benefit analyses into LEAP. LBNL also gathered publicly available cost data to bridge the information gap for key technologies. The primary sources for cost information in this analysis included data from MoE for transport sector and resources costs and publicly available international data on the building sector, light industries, pulp and paper, steel, cement, and copper.

[1] At this stage, the analysis does not include costs associated with the transformation sector (such as generation, hydrogen, or biomass).

Leveraging the integrated capabilities of the LEAP model, the analysis focused on calculating the additional costs and energy savings to determine the net present value of various measures, as well as mitigation abatement costs.

Figure A-1, Figure A-2, and Figure A-3 depict the investments required in each of the demand sectors, highlighting the demand cost difference between the Accelerated Net Zero and BAU scenarios. This difference amounts to a total incremental cost of $80 billion USD between 2020 and 2050, discounted at 5 percent per year.

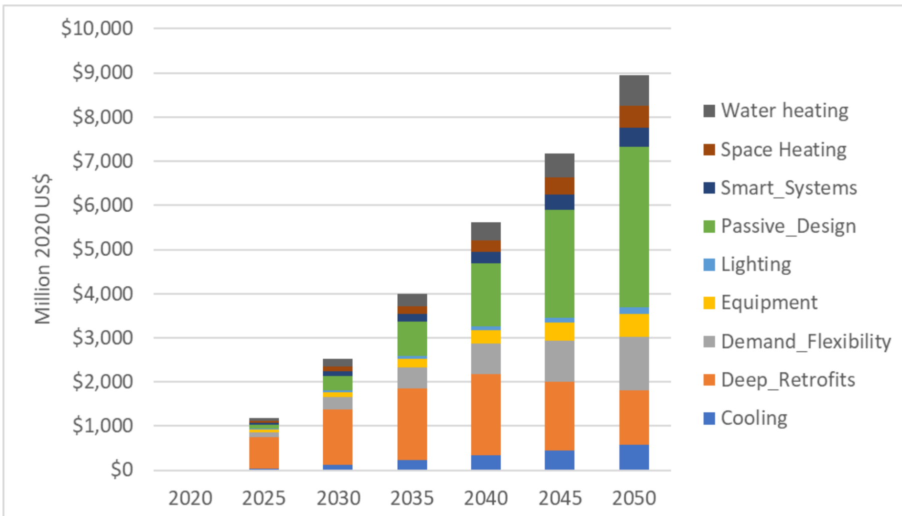


Figure A-1. Building sector investment cost (Accelerated Net Zero minus BAU scenario).

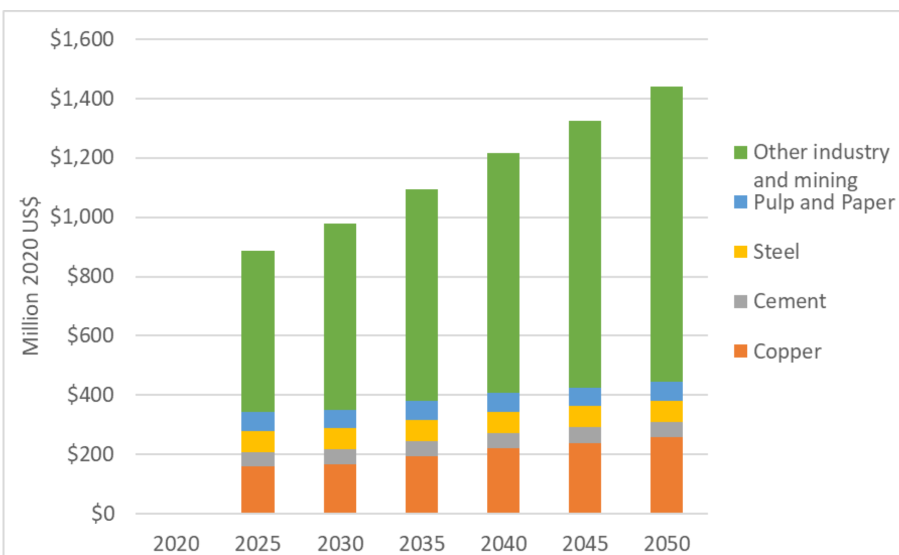


Figure A-2. Industry sector investment cost (Accelerated Net Zero minus BAU scenario).

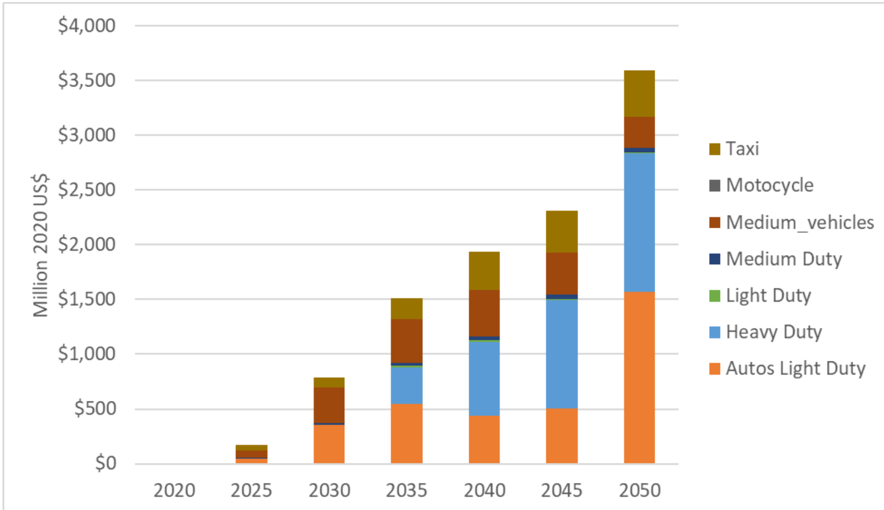


Figure A-3. Transport sector investment cost (Accelerated Net Zero minus BAU scenario).

Figure A-4 demonstrates the costs, in terms of investments in demand-side technologies, and the benefits, in terms of resources avoided. From 2020 to 2050, the investments in demand-side technologies are expected to be highly cost-effective, with a cost-benefit ratio of 1:3 and a net present value of $150 billion USD, discounted at 5 percent per year. Additionally, the modified LEAP model identified 1.15 Gt of cumulative CO_2 savings in the Accelerated Net Zero scenario compared to BAU, resulting in an average benefit of $130 USD per ton of CO_2e avoided during 2020–2050.

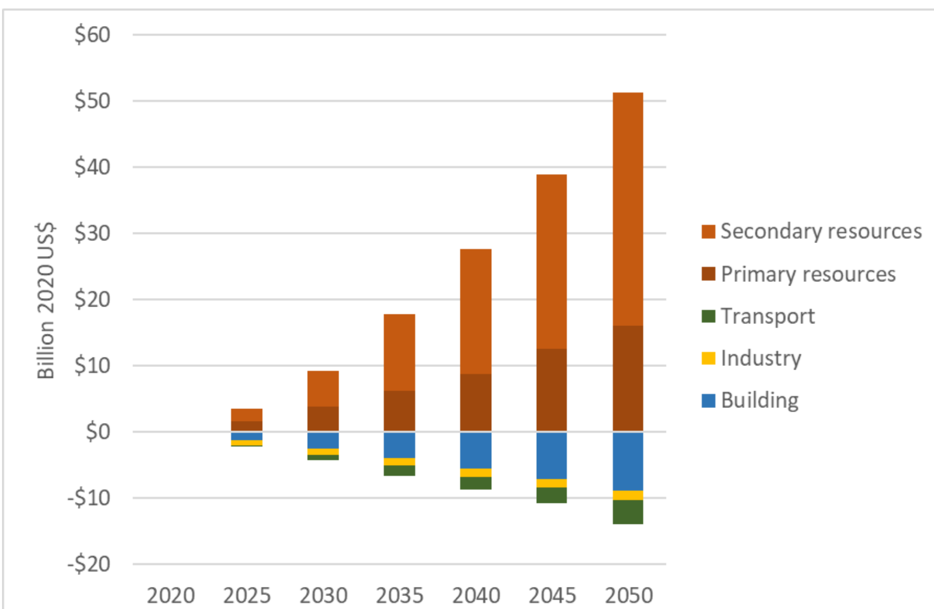


Figure A-4. Costs (-$) and benefits (+$) of demand-side measures (BAU minus Accelerated Net Zero scenario).

Local Pollutant Analysis

As part of the long-term energy planning process, the MoE evaluated the reductions of local air pollutants ($PM_{2.5}$) in the residential, transport, and power sectors for its Carbon Neutrality scenario. However, because this analysis employed several Intergovernmental Panel on Climate Change (IPCC) default emissions factors, it did not align with the MoE's region-based LEAP model. The NZW modeling team focused on integrating analyses of local pollutants (PM, BC) within the national LEAP model to enhance the quantification of pollution reduction co-benefits from decarbonization measures, incorporating improved data and expanded analysis. This included:

1. Aligning activity projections for key pollutant sources in the transport and residential sectors with the MoE's latest projections.
2. Collaborating with experts at the MoE and Ministry of Environment to develop updated PM and BC emission factors and integrating these directly into the LEAP model.
3. Expanding local pollutant analyses to quantify BC emissions from different transport modes, including road, rail, and maritime.

Using the enhanced modules for local air pollutant analysis, the results produced by the modified model revealed significant co-benefits from reducing PM and BC emissions below those resulting from the decarbonization measures modeled in the Accelerated Net Zero scenario. The residential sector, being the largest existing source of PM emissions from biomass combustion, also has the greatest potential for phasing out PM emissions. As shown in Figure A-5, measures like accelerated efficiency improvements, fuel switching, and full electrification of space heating under the Accelerated Net Zero scenario are projected to nearly eliminate all building biomass-related $PM_{2.5}$ emissions by 2050. In contrast, under the BAU scenario, annual $PM_{2.5}$ emissions in the building sector continued to rise through the late 2030s and remained 1.5 times higher than current levels. The majority of $PM_{2.5}$ reductions under the Accelerated Net Zero scenario came from energy efficiency improvements, including improved insulation and air-tightness to reduce heating losses; and full electrification of space heating through electric heaters and air source and ground source heat pumps in central and southern Chile by 2050. This translates into avoiding 2.75 million tonnes of $PM_{2.5}$ emissions cumulatively from 2024 to 2050.

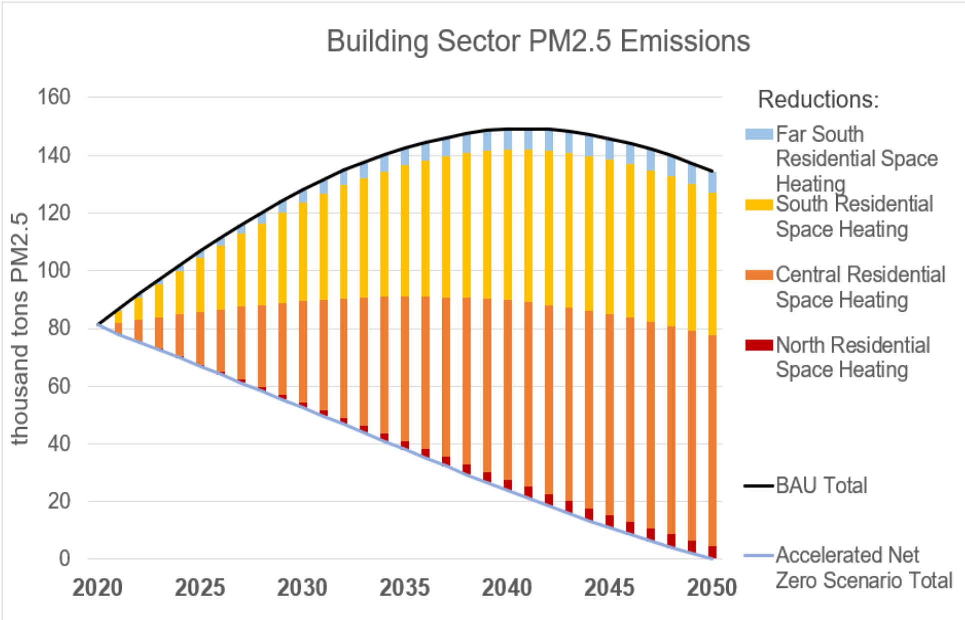


Figure A-5. **Building sector $PM_{2.5}$ emissions (BAU vs. Accelerated Net Zero scenario totals and reductions).**

As shown in Figure A-6, by 2050, annual transport $PM_{2.5}$ emissions can be reduced by 84 percent from 2021 levels under BAU and by 95 percent under the Accelerated Net Zero scenario. The additional $PM_{2.5}$ reductions stem from the accelerated electrification of motorcycles and light-duty trucks by 2050, and the full deployment of battery electric and hydrogen vehicles for medium-duty and heavy-duty road freight.

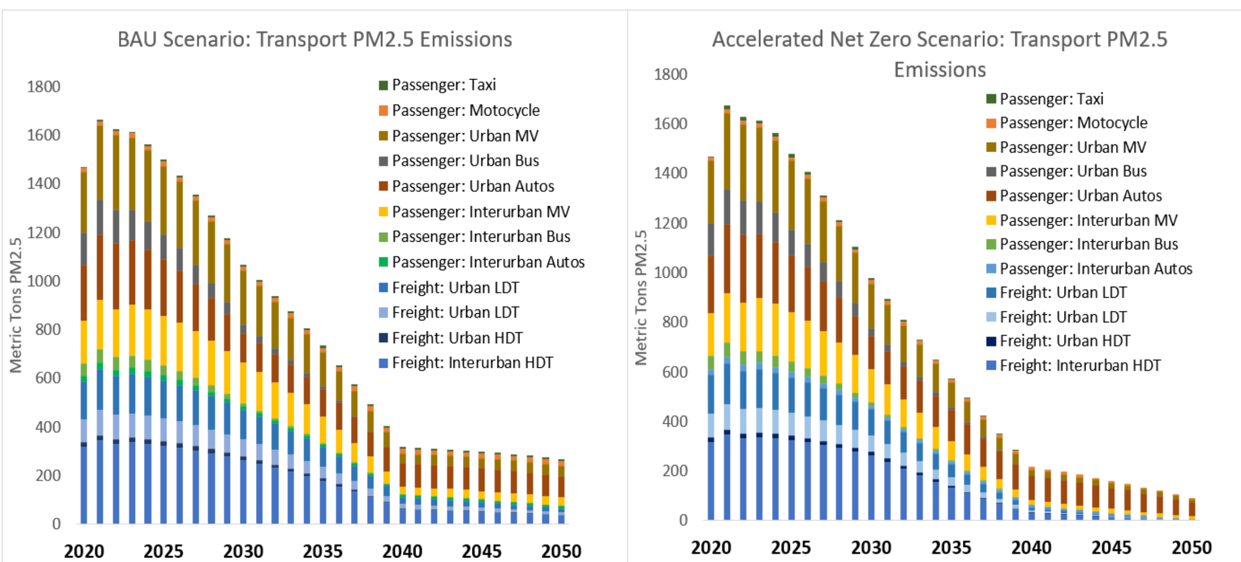


Figure A-6. Transport sector $PM_{2.5}$ emissions (BAU vs. Accelerated Net Zero scenario).

Similarly, as shown in Figure A-7, transport BC emissions can be reduced by 60 percent from 2021 levels by 2050 under the Accelerated Net Zero scenario. Significant BC emission reductions, approximately 120 tonnes annually by 2050, can be achieved through small incremental efficiency improvements in rail freight, followed by reductions of 50 tonnes BC from fuel switching to liquefied natural gas in maritime shipping. Cumulatively, from 2024 through 2050, 3,800 tonnes of BC can be reduced through these additional efficiency improvements, fuel switching, and accelerated electrification under the Accelerated Net Zero scenario. By 2050, most remaining BC emissions are expected to be from rail and maritime, indicating that further efforts to decarbonize these modes are needed to further reduce transport BC emissions.

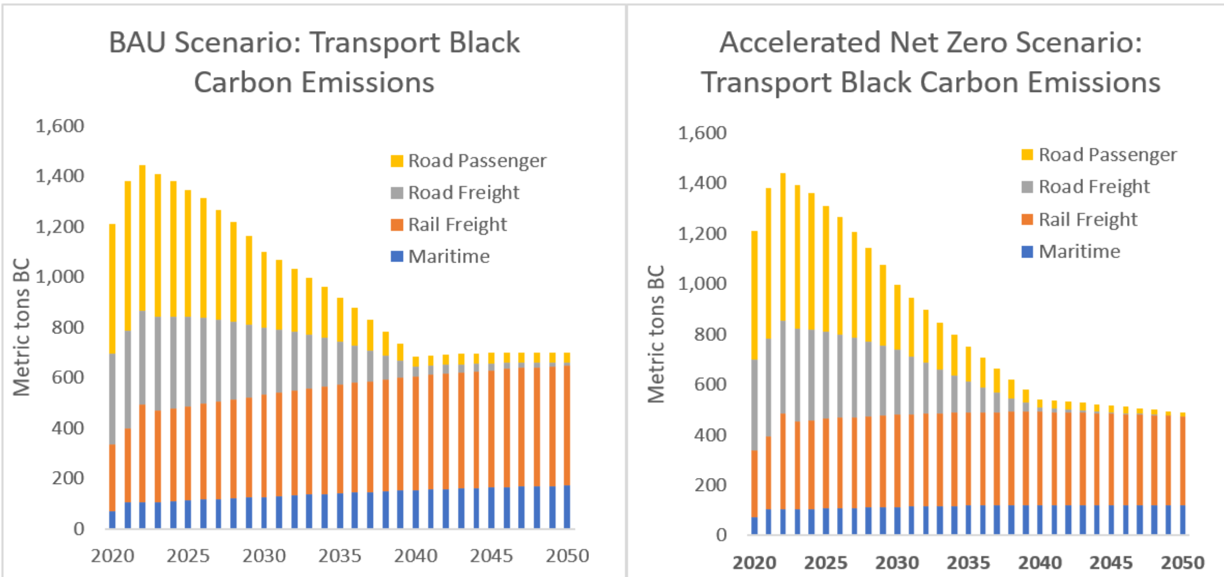


Figure A-7. Transport sector BC emissions (BAU vs. Accelerated Net Zero scenario).

In the power sector, accelerating the phase-out of fossil fuels (i.e., coal and diesel) and increasing renewable generation under the Accelerated Net Zero scenario can reduce $PM_{2.5}$ emissions from current levels, as shown in Figure A-8. By 2030, power sector $PM_{2.5}$ emissions can be halved from 2020 levels with the earlier phase-out of coal-fired generation under the Accelerated Net Zero scenario. This reduction will be followed by further decreases from phasing out diesel, fuel oil, and liquified natural gas generation by 2040, leaving only small remaining $PM_{2.5}$ emissions from biomass generation.

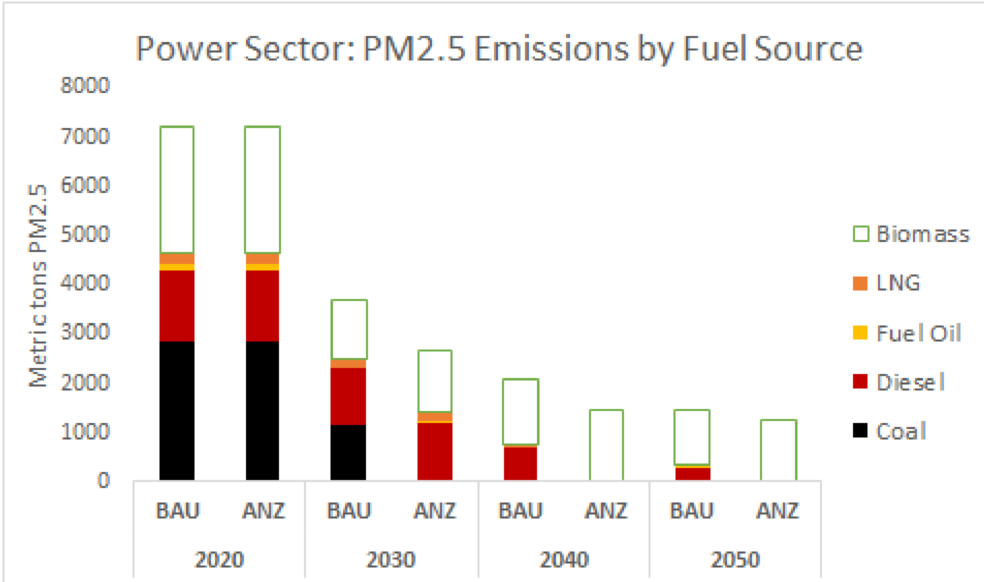


Figure A-8. Power sector $PM_{2.5}$ emissions (BAU vs. Accelerated Net Zero scenario).

Note: Biomass $PM_{2.5}$ emissions are shown separately, as they are not always reported in total power sector $PM_{2.5}$ emissions.

A.2 District Energy Modeling

Overview

The NZW modeling team collaborated with the MoE to estimate the potential benefits of deploying district energy systems as a net-zero technology solution. These systems aim to enhance the efficiency of space heating and cooling and to reduce their emissions. This work comprises two related modeling efforts: (1) detailed thermal modeling of a DES proposed for the Recoleta-Independencia pilot project, and (2) generalized modeling of DES deployment across multiple Chilean climate zones to estimate the national potential of DES in replacing existing fossil fuel space heating and domestic hot water systems.

Recoleta-Independencia Pilot Project

The MoE identified the DES pilot project in the community of Recoleta-Independencia (a community 4.3 miles/7 km north of the Santiago city center) as the initial site for detailed DES thermal modeling because of the applicability of the data from the project for other communities in Chile. Using data provided by the MoE, the modeling team developed energy models for the 13 buildings in the pilot site. The team simulated these models in EnergyPlus (a whole-building simulation tool that evaluates annual hourly heating, cooling, lighting, equipment, and other end-use energy consumption), which generated heating and cooling load profiles for the detailed modeling of a thermal DES in Modelica (a modeling language for component-oriented modeling of complex systems, such as a DES that is composed of heating plants, thermal piping network, heating load profiles, and associated controllers). The team also explored several building energy efficiency measures and their potential impact on the performance of the DES. In the current phase of work, the team is engaged in three sub-activities for pilot project modeling: (1) developing a thermal network model using the geolocations of identified buildings in the pilot; (2) analyzing the performance of the DES after integrating the building thermal load profiles with the thermal network model; and (3) conducting parametric simulations of building energy-efficiency measures.

The primary objective is to evaluate the energy use, energy cost, and environmental impacts of the energy system of the Recoleta-Independencia district, encompassing both heating and cooling. The team also assessed the potential impacts of applying specific building energy-efficiency measures across several types of buildings and district DES within the pilot project. Figure A-9 illustrates the proposed DES modeling framework, which employs modeling tools such as EnergyPlus, OpenStudio (an open-source software development kit for energy modeling with EnergyPlus, capable of parametric analysis of various predefined energy efficiency measures in OpenStudio's building component library), and Modelica. This framework provides a comprehensive approach to evaluating DES performance and assessing the potential impacts of building energy efficiency measures on the design and operation of a DES. This framework emphasizes standardized data exchange, facilitating seamless integration between each model component, thereby ensuring the consistency, accuracy, and ease of data interpretation. This framework will be used to analyze district DES in other pilot projects.

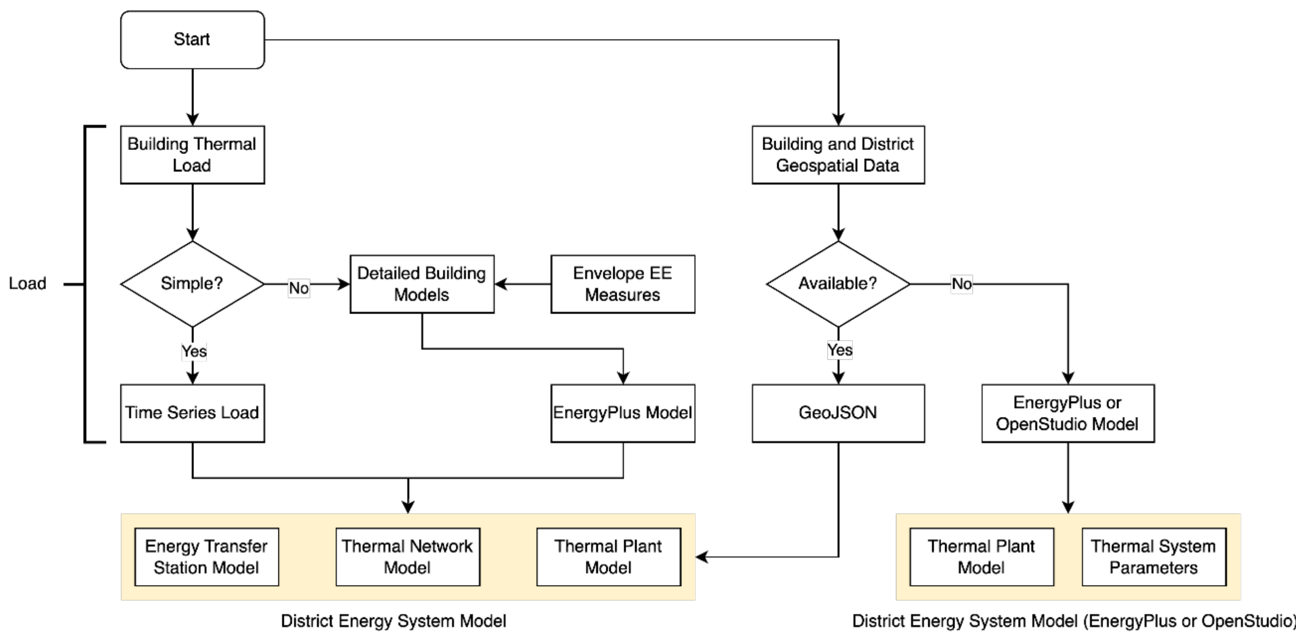
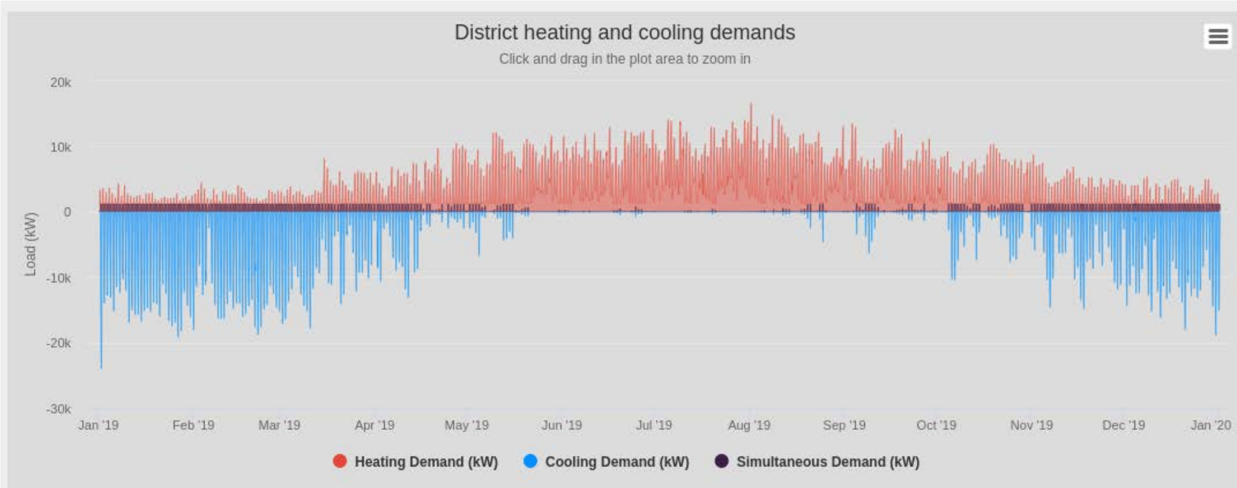
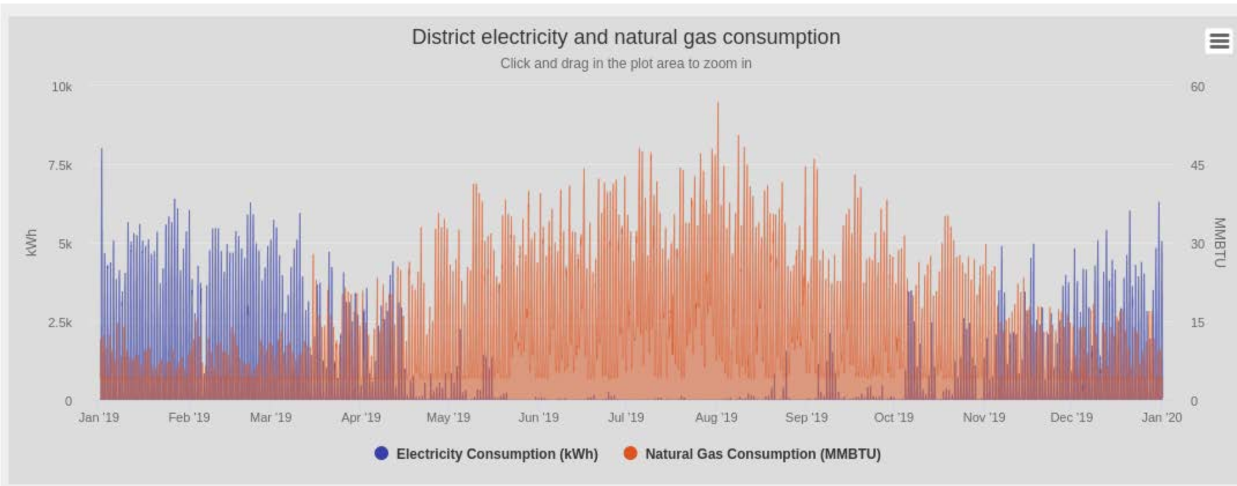


Figure A-9. Schematic diagram of the proposed DES modeling framework.

The entire pilot project encompassed 13 buildings with a combined floor area of approximately 284,000 m^2; these included educational institutions, health care facilities, and laboratories. The team began the analysis by generating a time series of district cooling, heating, and energy demands of each building, and then aggregating the simulated annual demand profiles from each building to the district level. Figure A-10 shows the aggregated annual hourly district heating and cooling load profiles, as well as the aggregated annual hourly site electricity and site natural gas consumption. The peak heating load reached 17 MW in August (winter), while the peak cooling load was 24 MW in January (summer).



(a)



(b)

Figure A-10. Aggregated annual hourly values of (a) district heating and cooling load profiles and (b) district site electricity and site natural gas consumption.

Based on the EnergyPlus models, the team implemented a suite of building-envelope efficiency measures, including upgrades to roofs, walls, and windows, to assess their impacts on the annual heating and cooling loads. To model the roof and wall measures, team members inserted expanded polystyrene board insulation into roof and exterior wall assemblies.

The baseline building models had single-pane transparent glass windows. As shown in Table A-1, the team evaluated two types of high-performance window retrofits: primary glazing systems and secondary glazing systems.

Table A- 1. Proposed Primary and Secondary Glazing System Measures

Window Solution	Version	Description	Thermal Transmittance (U-factor) [W/m²·K]	Solar Heating Gain Coefficient (SHGC)	Visible Transmittance	Annual Cooling Load Savings Fraction	Annual Heating Load Savings Fraction	Annual Total (Cooling + Heating) Load Savings Fraction
Baseline[a]	#1	Single-Clear	5.06	0.71	0.72	n/a	n/a	n/a
Primary Glazing System[b]	#1	Double-Clear	2.56	0.58	0.63	11%	23%	13%
	#2	Double-Silver	1.70	0.30	0.40	36%	20%	33%
	#3	Triple-Silver	1.53	0.22	0.40	43%	17%	38%
Secondary Glazing System (Mounted)[c]	#1	Single-Pane	2.84	0.50	0.56	20%	14%	19%
	#2	Double-Pane	1.99	0.30	0.40	37%	15%	33%

[a] The baseline glazing is single-pane transparent glass in a wood frame.
[b] "Primary glazing system" is a window retrofit option that replaces the existing window (single-pane transparent glass) with a double- or triple-pane vinyl frame window, either transparent glass (Option #1) or low-emissivity (low-E) glass (Options #2 and #3).
[c] "Secondary glazing system" is a window retrofit option that mounts a single-pane transparent glass or double-pane low-E glass vinyl frame window outside the existing window (single-pane transparent glass).

For this window efficiency analysis, the team deployed two DOE prototype building models: medium office and mid-rise apartment building. These models represent most commercial buildings across various climate zones. Figure A-11 shows the annual heating and cooling load savings following the retrofit with proposed primary and secondary glazing systems. Relative to the baseline use of single-pane clear glass in a medium office, the simulation results demonstrate that employing a double low-emissivity (low-E) glazed facade (primary glazing system #2) reduces annual cooling load by 36 percent (19.8 kilowatt-hours thermal per square meter of floor area [kWh_{th}/m^2]) cooling load lowers annual load heating load by 20 percent (2.8 kWh_{th}/m^2). A triple-silver glazing system as the primary glazing system retrofit (primary glazing system #3) can yield 43 percent and 18 percent savings in the annual cooling and heating loads, respectively, and 38 percent (26.2 kWh_{th}/m^2) reduction of the total annual heating and cooling load. Mounting secondary glazing system #2 (double-pane low-e glass) to existing windows reduces the total annual heating and cooling load by 33 percent (22.5 kWh_{th}/m^2). Compared to secondary glazing system #1 (mounting a single pane of transparent glass outside the existing window), secondary glazing system #2 yields similar heating load savings due to a trade-off between the reduced solar heat gains and window conduction heat loss. Secondary glazing system #2 reduces the cooling load by 37 percent via low thermal transmittance (U-factor) and solar heat gain coefficient (SHGC).

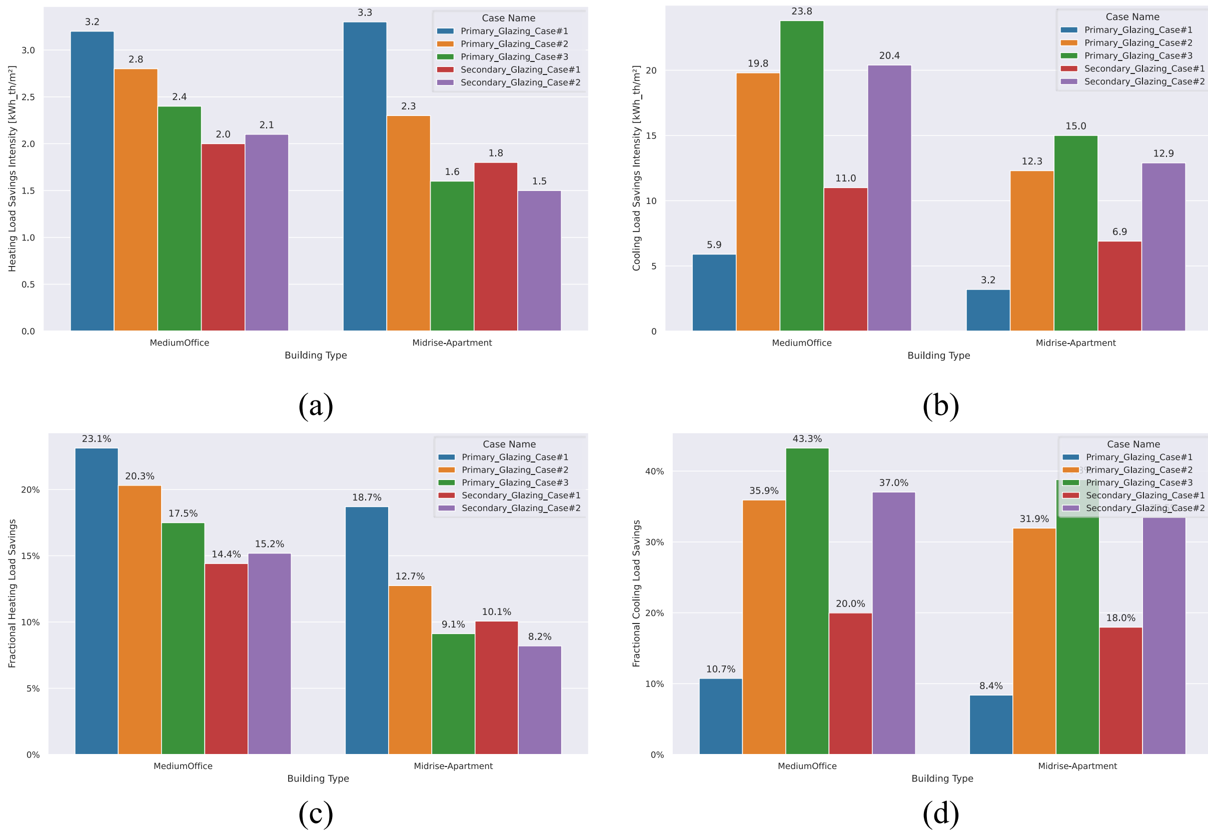


Figure A-11. Benefits of proposed window measures, including (a) annual heating load intensity savings, (b) annual cooling load intensity savings, (c) fractional heating load savings, and (d) fractional cooling load savings.

After completing the energy modeling of individual buildings in the pilot district, the team simulated various DES types as featured in CityBES (City Building Energy Saver), a tool developed by LBNL for energy modeling and analysis of a city's building stock to support district- or city-scale efficiency programs. The DES configurations simulated include (1) water-cooled chillers combined with boilers, (2) water-cooled chillers with ice-storage tanks and boilers, (3) heat-recovery chillers paired with heat pumps, and (4) geothermal heat pumps. In the baseline scenario, each building has conventional water-cooled chillers and natural gas boilers for space cooling and heating.

The team used an ideal heating, ventilation, and air conditioning (HVAC) system (one that meets all heating and cooling loads) in EnergyPlus for ease of calculating the heating, cooling, and other energy demands. Cost calculations were performed using a flat electricity price of 0.18 USD/kWh and a natural gas price of 0.12 USD/kWh (2022 Chilean electricity and natural gas price from the International Energy Agency[2]), reflecting the annual average prices of the commercial sector. Figure A-12 displays the annual electricity and natural gas consumption, alongside a utility cost comparison based on the collected data. There is no natural gas consumption for system types (3) heat-recovery chillers with heat pumps and (4) geothermal heat

[2] IEA, Energy Prices, IEA, Paris. Available at https://www.iea.org/data-and-statistics/data-product/energy-prices. License: Terms of Use for Non-CC Material.

pumps, as these systems operate entirely on electricity. Compared to the conventional chiller and natural gas boilers in existing buildings, central DESs with larger chillers have a higher coefficient of performance. Assuming a 10 percent energy loss in the distribution network, this type of DES can reduce the annual electricity consumption by 20 percent with an ice storage system and 18 percent without it. Although the geothermal heat pump system increases annual electricity consumption by approximately 111 percent compared to the baseline, it yields 26 percent savings in the annual utility cost, due to higher heating efficiency compared to traditional boilers and air-source heat pumps. However, with unbalanced annual heating and cooling load profiles, the geothermal heat pump system is expected to lose efficiency over time due to continuous unbalanced heating extraction from the ground. The team plans to refine the DES model in the 2024 work.

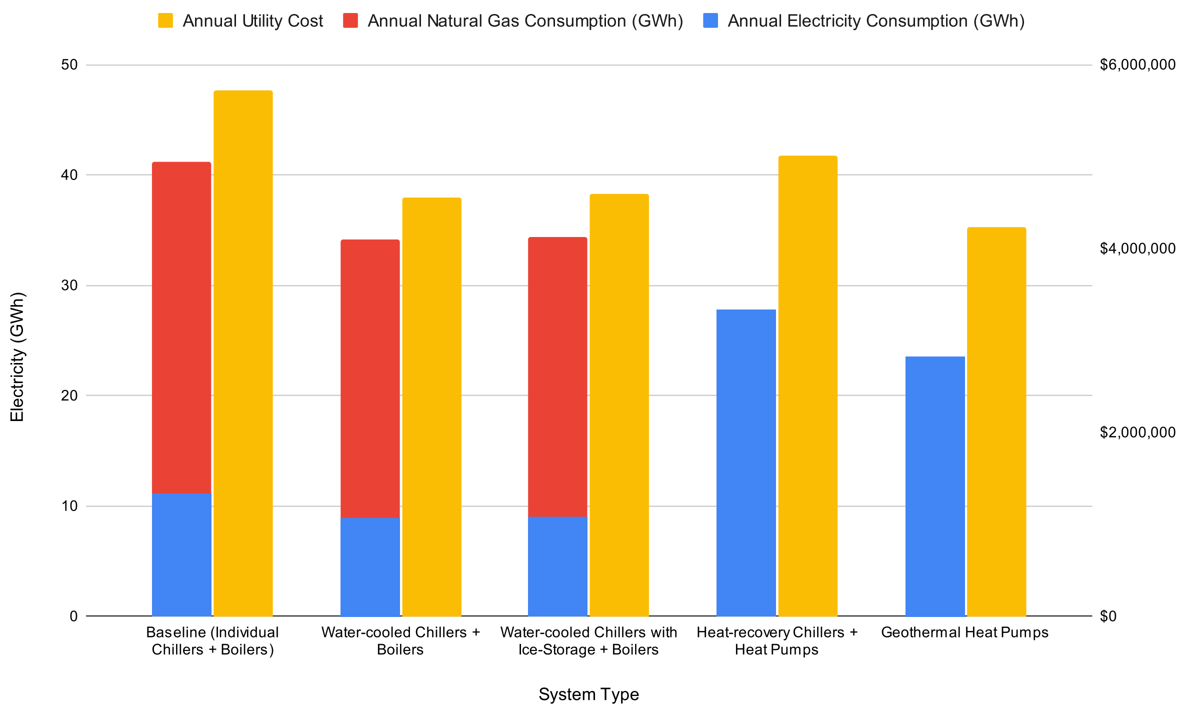


Figure A-12. Annual energy consumption and cost comparison between baseline and proposed DES system configurations.

District Energy Regional Analysis

The objective of the regional DES analysis is to evaluate the costs and performance associated with deploying DES and other thermal technologies in a variety of prototype buildings set within multiple climatic zones and locations deemed suitable for analysis. The specific Chilean thermal zone designations for the selected locations include the following:

- Santiago (Zone 3)
- Talca (Zone 4)
- Temuco (Zone 5)

- Puerto Montt (Zone 6)
- Coyhaique (Zone 7).

For each chosen location, the team selected individual prototype building models as components of the district system. It was a challenge to estimate typical Chilean building stock and energy load profiles because prototypical building models for Chile have not been developed. To address this, buildings from this U.S. region, specifically those built before 1980, were chosen to represent the Chilean building stock, because many Chilean buildings have not benefited from a modern building energy efficiency code. The team matched the typical meteorological year data from each Chilean location to U.S. climate Zone B typical hourly temperatures to find the most comparable conditions (International Energy Conservation Code Zone 3C in all instances). The team selected a mix of commercial and residential buildings for each district system, comprising:

- 225 mid-rise residential buildings (floor area 3,100 m^2 each);
- 18 single-family residential buildings (220 m^2 each);
- 10 medium office buildings (5,000 m^2 each); and
- 22 stand-alone retail buildings (2,300 m^2 each).

Heating systems within each building were modified to mirror those commonly used in Chilean structures—i.e., wood stoves and biomass boilers for residential and commercial buildings, respectively. These adapted building models were then simulated using local weather data in EnergyPlus to generate annual hourly thermal and electrical load profiles.

The modeling yielded a total system size of approximately 200,000 m^2 of building floorspace, with each type of building contributing an approximately equal share of the total system area. This system size is comparable to the Recoleta-Independencia pilot project but can be scaled by adjusting the number of buildings, which would adjust estimates for district energy efficiency, network thermal losses, and capital costs accordingly.

The team modeled DES and other technologies using the DER-CAM optimization tool, which assesses all input data—including estimated loads, technology costs, efficiencies, and other characteristics—to recommend optimized technology solutions for the site's needs. This analysis compared the following four technology scenarios:

- **Business-as-usual (BAU)**. Buildings continue to use their existing individual heating technologies and fuels.
- **Conventional DES**. Buildings are connected into a single thermal loop served by a central heating system.
- **DES with CHP**. Like DES, but with a central combined heat and power (CHP) generator unit providing cogeneration of electricity and heat.
- **Distributed energy resources (DER)**. This scenario employs heat-pump technologies, potentially augmented by solar photovoltaic generation and battery storage, as determined by DER-CAM.

The team applied additional parameters to estimate capital costs, efficiencies, emission rates, and other essential inputs for each technology and scenario, using DER-CAM to determine the optimal technology selection and to predict the energy and cost performance of each system throughout a typical year of operation.

Based on the optimization results obtained from DER-CAM for each location and technology scenario, the team assessed the following key metrics:

- **Total annual energy cost**. This metric encompasses the cost of fuel and electricity, including the annualized capital cost for new energy assets (Figure A-13).
- **Annualized capital costs**. These costs are associated with the introduction of new assets (Figure A-14).
- **Annual CO_2 emissions**. These emissions result from electricity and fuel usage across all buildings (Figure A-15).
- **Local particulate emissions ($PM_{2.5}$)**. These emissions stem from on-site fuel consumption (Figure A-16).

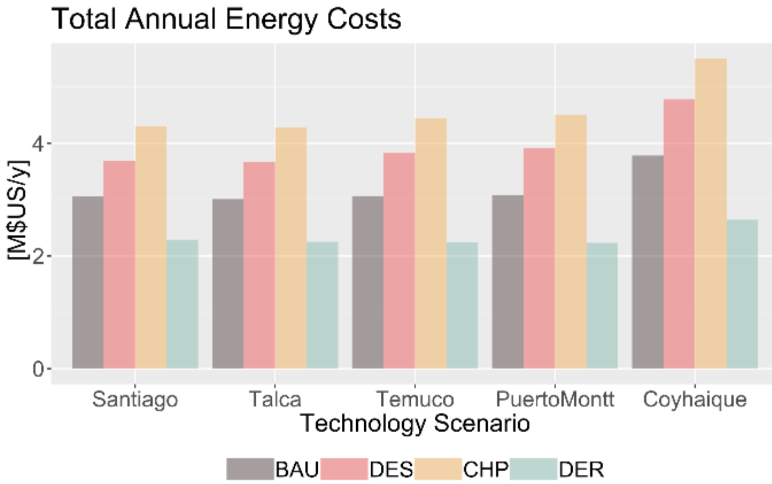


Figure A-13. Comparison of total energy costs for each technology scenario in USD.

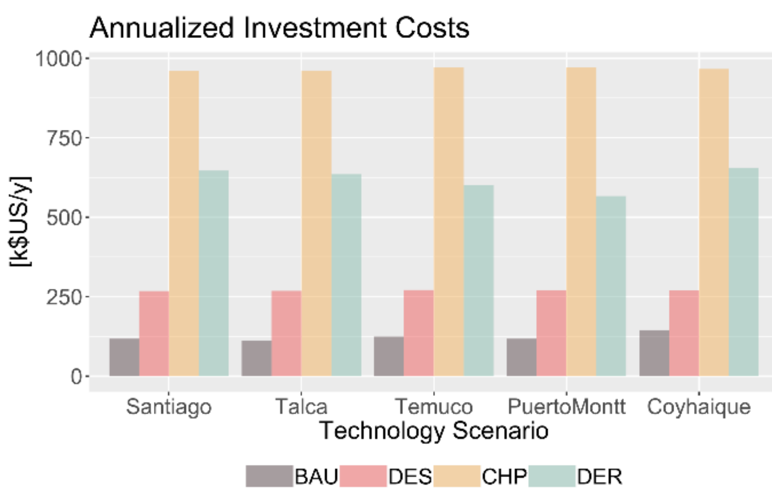


Figure A-14. Comparison of annualized capital costs for new thermal/distributed energy resource technologies in USD.

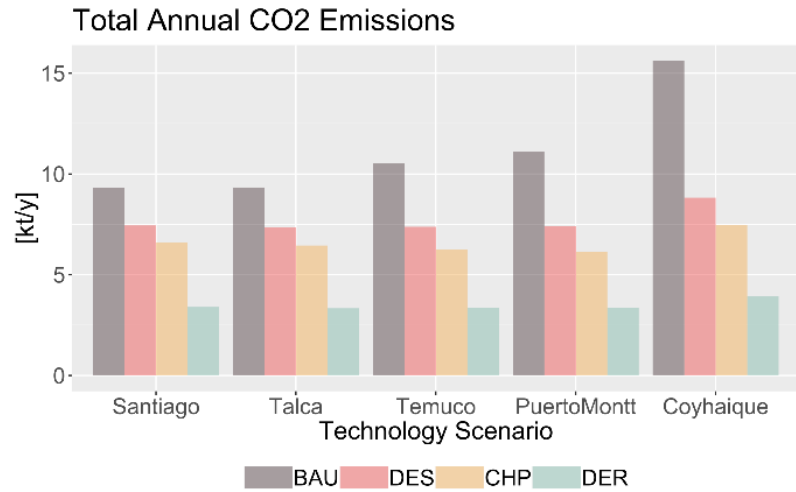


Figure A-15. Comparison of annual CO_2 for electricity and fuel used in systems.

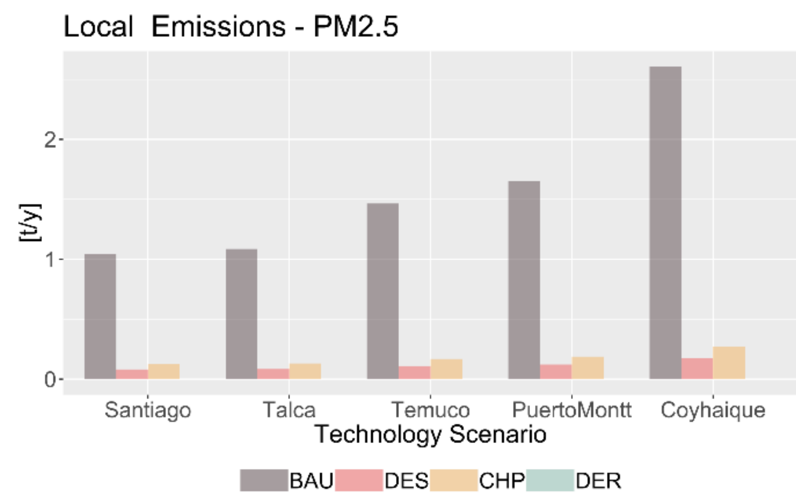


Figure A-16. Comparison of annual $PM_{2.5}$ emissions from local fuel consumption.

The analysis indicates that all technology scenarios offer potential benefits when compared to the BAU case. The centralized DES solution stands out for its improved efficiency and reduced fuel emission factors, leading to reductions in annual emissions of CO_2 (Figure A-15), $PM_{2.5}$ (Figure A-16), and other pollutants. However, due to the assumption that BAU heating technologies and fuels are inexpensive, the DES solution raises total annual energy costs (Figure A-13). This increase is attributed to the capital cost required for deployment (Figure A-14) and higher fuel prices when transitioning away from inexpensive biomass.

The DER with CHP solution exhibits a similar trend, with improved efficiency and local electricity generation contributing to reduced emissions and lower operating costs vs. BAU. Nevertheless, the substantial capital cost associated with CHP (Figure A-14) results in poorer overall cost performance compared to the simple DES, as indicated by CHP's higher total annual energy cost (Figure A-13).

The DER and electrification scenario forgoes local fuel consumption for heating, opting instead for air-source heat pumps and solar photovoltaics to augment the increased electrical load. This distributed energy resources scenario delivers both (a) emissions benefits, by eliminating local fossil fuel consumption, and (b) cost reductions, by providing annual electricity cost savings through local generation. This is the case despite capital costs exceeding those of the straightforward DES solution.

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NREL/TP-7A40-90813 • September 2024