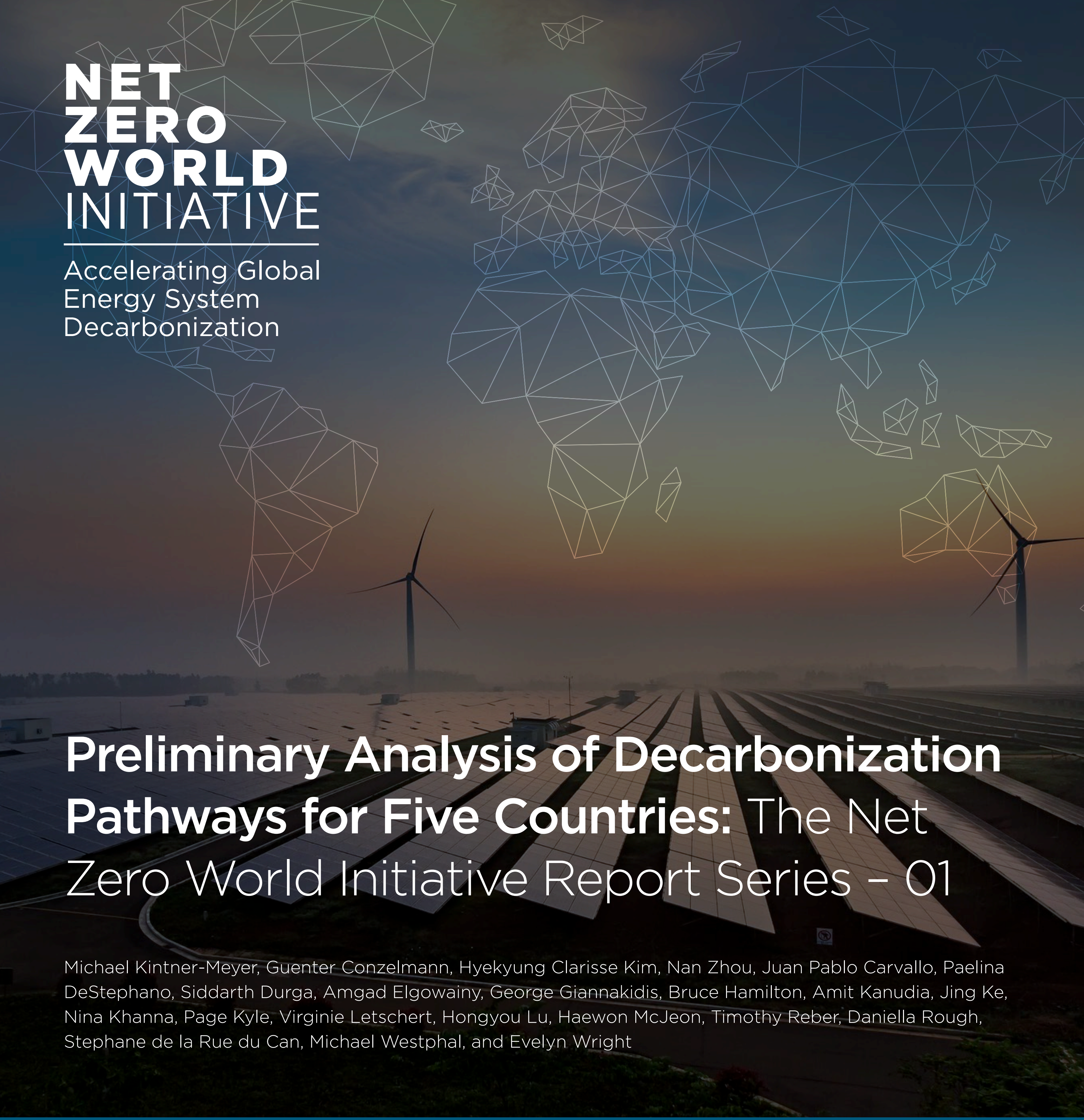

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Accelerating Global
Energy System
Decarbonization

Preliminary Analysis of Decarbonization Pathways for Five Countries: The Net Zero World Initiative Report Series – 01

Michael Kintner-Meyer, Guenter Conzelmann, Hyekyung Clarisse Kim, Nan Zhou, Juan Pablo Carvallo, Paelina DeStephano, Siddarth Durga, Amgad Elgowainy, George Giannakidis, Bruce Hamilton, Amit Kanudia, Jing Ke, Nina Khanna, Page Kyle, Virginie Letschert, Hongyou Lu, Haewon McJeon, Timothy Reber, Daniella Rough, Stephane de la Rue du Can, Michael Westphal, and Evelyn Wright

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- Government of Chile
- Government of Nigeria.

Note that at the time of this publication, the contents of the analysis for Argentina, Egypt, and Indonesia have not been reviewed by those governments.

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List of Acronyms and Abbreviations

APS	Announced Pledges Scenario
BAU	business-as-usual
BECCS	bioenergy with carbon capture and storage
BOF	basic oxygen furnace
CCS	carbon capture and storage
CH_4	methane
CO_2	carbon dioxide
COP26	2021 U.N. Climate Change Conference
COP27	2022 U.N. Climate Change Conference
DAC	direct air capture
ESDM	Ministry of Energy and Mineral Resources (Indonesia)
EJ	exajoule
ETP	Energy Transition Plan (Nigeria)
EV	electric vehicle
FABLE	Forest, Agriculture, and Biofuels in a Land use Model with Environmental services
GCAM	Global Change Analysis Model
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoules
GW	gigawatts
HVAC	heating, ventilation, and air conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LEAP	Low-Emissions Analysis Platform
LTS	long-term strategy
LULUCF	land use, land-use change and forestry
MAC	marginal abatement costs
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MMT	million metric tons
MM	metric tons
$MtCO_2$	metric tons of carbon dioxide
$MtCO_2e$	metric tons of carbon dioxide equivalent
NDC	nationally determined contribution
NEMO	Next Energy Model system for Optimization
PELP	long-term energy planning
PJ	petajoules
RE	renewable energy
SEforALL	Sustainable Energy for All
TIMES	The Integrated MARKAL-EFOM System
TWh	terawatt-hours
U.N.	United Nations

UNFCCC	U.N. Framework Convention on Climate Change
USD	U.S. dollars
yr	year

Executive Summary

Under the Net Zero World Initiative, the United States is mobilizing the capabilities of nine U.S. government agencies, led by the U.S. Department of Energy (DOE), to partner with philanthropies and multiple countries to cocreate and implement tailored technical and investment pathways to accelerate the decarbonization of global energy systems. In addition, 10 of the DOE national laboratories have built a consortium housed in the Net Zero World Action Center to implement this vision by providing the deep analysis and modeling required to carry out the vision.

As a whole-of-government program, the Net Zero World Initiative partners with countries committed to raising their climate ambitions by creating and implementing highly tailored, actionable technical and investment strategies that put a net-zero world within reach. The initiative enables country partners to harness the convening power and technical expertise of U.S. agencies and laboratories, international industry, and technical institutions while providing the United States an opportunity to learn from and deepen U.S. technical cooperation with key countries.

U.S. national laboratories, together with in-country partners, have been engaged in national modeling activities to provide the analytical underpinning for governmental decision makers at the national and regional levels to make informed climate and energy policy and investment decisions for the transition toward a net-zero future. These activities started with a rapid Phase I modeling effort to generate preliminary results in advance of the 2022 U.N. Climate Change Conference, or COP27. Phase I activities focused on high-level system-wide modeling efforts designed to glean preliminary insights on decarbonization pathway opportunities in preparations for more targeted modeling in Phase II.

In preparation for the Phase I modeling and to inform design of cooperation on implementation actions, the Net Zero World Initiative team conducted a landscape assessment of extant work, including significant studies by in-country technical institutions and government agencies, U.S. organizations and laboratories, intergovernmental organizations, nonprofit institutions, development banks and agencies, and consulting firms. This includes studies and programs by universities and technical institutions from the participating countries, the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), Sustainable Energy for All (SEforAll), the U.N. Environment Programme (UNEP), the U.N. Development Programme (UNDP), the World Resources Institute, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), the U.S. Agency for International Development (USAID), the World Bank and regional development banks, McKinsey, and many others. The Net Zero World Initiative team will further engage with program managers and technical experts involved in these activities in designing Phase II pathway modeling and technical support that will build on and complement their studies.

This report is the first of a series, with future Phase II work being informed by ongoing consultations with the partner countries to address country pathway analysis priorities. This future work will likely include evaluating detailed technological, policy, and investment options for key sectors and for energy systems holistically. This analysis may examine in greater detail

the economic and social benefits of net-zero energy transitions, including quality jobs and health outcomes, the impacts of price and supply volatility on energy investments and decisions, the risk of stranded assets, and related issues.

In the Phase II work, in cooperation and consultation with the participating countries, the Net Zero World Initiative team plans to more deeply evaluate economically advantageous opportunities for accelerating transitions to net zero energy systems by 2050. This may include identification of the technology and policy options and scale of economic, environmental, and social benefits of rapid transformations to net zero energy systems.

In Phase I, the DOE national laboratories participating in the Net Zero World Initiative completed a preliminary analysis of pathways in collaboration with partner countries as an initial step in offering supplementary information for reviewing the policy options and technology portfolios needed to achieve their ambitious climate, energy, and development goals. Different modeling approaches were applied to different countries to build on existing in-country work and based on country-specific contexts and interests.

The results of the Phase 1 pathway assessments highlight several common insights across the countries. National decarbonization strategies are determined by each country's existing energy infrastructure, the national and subnational resource availabilities, and their national preferences and valuations of advancing strategic energy system outcomes. Four essential mechanisms drive carbon reduction to varying degrees in each country:

1. Efficiency improvements of all end-use sectors
2. Fuel switching to clean energy carriers (electricity or hydrogen)
3. Greening the electric power supply through large deployments of renewable energy technologies
4. Carbon capture and storage (CCS) of remaining fossil-based systems.

These four mechanisms or technologies are all commercially available; however, meeting decarbonization goals will require a very rapid scale-up in technology deployment. Under Phase II and in close collaboration with in-country experts, the cost feasibility and challenges associated with this technology ramp-up will be investigated in detail.

All country-specific studies in this report looked at a range of policy or technology scenarios for each country and in most cases compared and contrasted them with a reference case, business-as-usual case, or no-policy case. The analysis reported here does not imply that any of the pathway scenarios is more likely than the others, nor is any particular pathway recommended for any of the countries. Findings are preliminary and indicative—they are not final results.

At the time of publication, the analysis and report contents had not been reviewed by the Governments of Argentina, Egypt, and Indonesia. The Net Zero World Action Center and partner countries will further evaluate these preliminary findings during Phase II.

Argentina: Executive Summary

In-Country Partners

The Argentina Ministry of Energy identified priorities for cooperation with the Net Zero World Initiative in mid-2022. The Net Zero World Action Center applied these priorities and other related studies to inform and guide the preliminary pathway analysis presented here.

Modeling Approach and Scenario Definitions

Argentina’s energy system was represented using the Global Change Analysis Model (GCAM) model with data refinements to generate results for three scenarios:

- Reference scenario
- Net Zero RE-Focus scenario, where RE is renewable energy: This scenario represented strong investments in RE generation technologies and some new natural gas electricity generation with CCS that is less than conventional natural gas generation in the historical period
- Net Zero CCS-Focus scenario, where CCS is carbon capture and storage, allows scale-up of new electricity generation from natural gas with CCS to exceed historical natural gas generation.

Both net-zero scenarios were defined with emission constraints starting from 2030 at nationally determined contribution, or NDC, levels and were then linearly reduced to net zero in 2050. Considering that Argentina is committed to continuing the use of natural gas, it was important to include the CCS-Focus scenario to explore the role of natural gas use with greenhouse gas (GHG) emission abatement. These two scenarios will help provide alternatives and information that can serve as a decision-making tool for the government.

Although CCS can be used in both scenarios, we assume more CO_2 storage is available due to lower costs of storage in the CCS-focus scenario, such that the total amount sequestered in 2050 is 57 $MtCO_2$, compared to 30 $MtCO_2$ for the RE-focus scenario.

Pathway Results

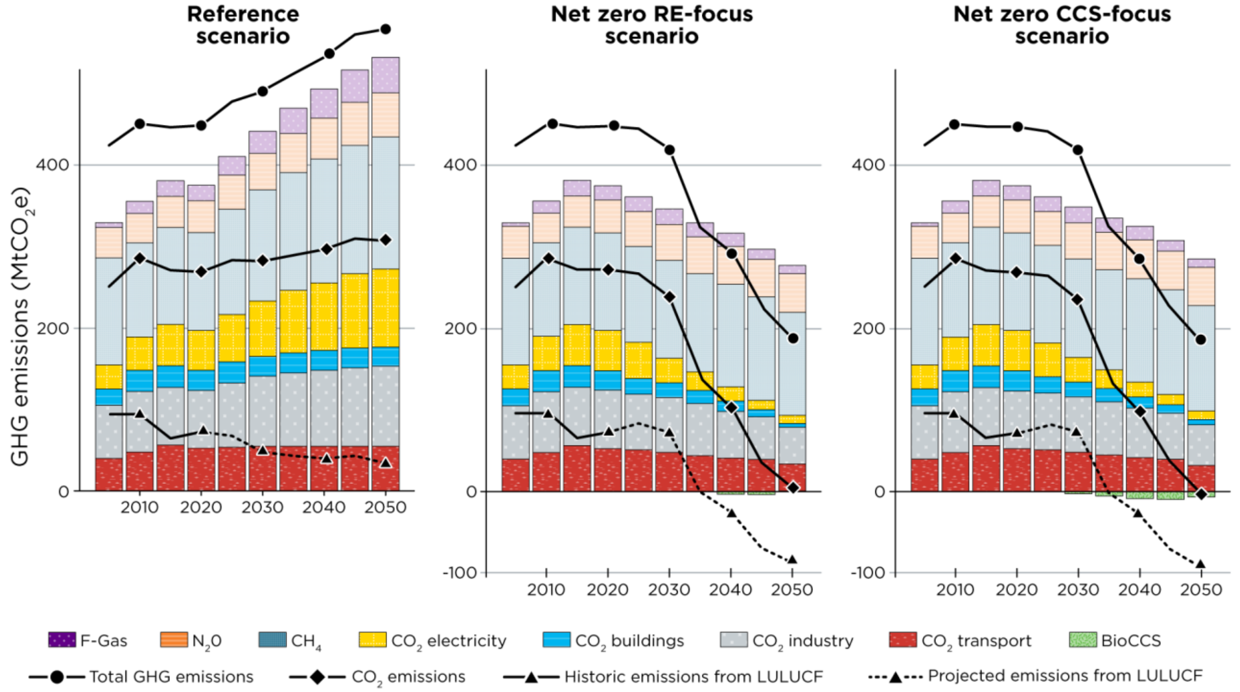

Figure ES-1. Argentina's emissions projections

1. Modeling results indicate that greening the electricity supply is a key driver for the carbon reduction portfolio in Argentina. The key technology pathways identified in the model are wind and solar electric capacity expansions and offsetting with CCS where natural gas is still used.
2. Emissions from continued use of fossil-based resources in the power and industrial sectors can be reduced with CCS technologies.
3. Investments requirements for decarbonization transitions across all sectors are significant.
4. Results indicate the importance of negative emissions to balance projected positive emissions over the entire projection horizon.
5. Significant reductions in energy consumptions are needed to drive emissions toward net zero. They can be achieved by fuel switching (primarily electrification of transportation and buildings) and energy efficiency improvements.

Argentina's large land surface provides opportunities for negative carbon emissions as a potential offset option. The sectoral analysis identifies opportunities in energy efficiency improvements and simultaneous fuel switching from fossil fuel-based building heating to electric heat pump heating as well as electrification of transportation. The Net Zero World Initiative will further investigate how Argentina can realize this transition with sufficient investments through more-detailed sectoral and higher regionally resolved analyses in Phase II.

Chile: Executive Summary

In-Country Partners

Initial pathway modeling for Chile was informed and guided by discussions with the Chilean Ministry of Energy. The Net Zero World Initiative team also worked collaboratively with researchers from the Pontificia Universidad Católica de Valparaíso.

Modeling Approach and Scenario Definitions

The Net Zero World Initiative team worked closely with the Ministry of Energy to build on and supplement the existing work in Chile's long-term strategy (LTS) and long-term energy planning (PELP) process. The Low-Emissions Analysis Platform (LEAP) forms the core of the PELP energy modeling. The initiative team extended the existing LEAP model for Chile to explore technical potential of national policy and technology scenarios and highlight supply-demand linkages. Detailed end-use technology information was represented in LEAP to evaluate additional technical opportunities in the industry, transport, and buildings demand sectors.
To complement the work with the Ministry of Energy, the Net Zero World Initiative team also applied GCAM in collaboration with researchers at Pontificia Universidad Católica de Valparaíso. GCAM was used to model potential pathways to reach the GHG emissions target set forth in the LTS while adopting some assumptions from the PELP. This work provides additional insights into decarbonization pathways and areas of interest such as clean hydrogen expansion and uncertainties around carbon land sinks.

The team explored two main scenarios aligned with the PELP process:

- The Business-as-Usual (BAU) scenario was consistent with the base cases used in recent PELP studies and assumed no significant future policy-induced technological changes.
- The Accelerated Net Zero scenario built on the PELP Accelerated Energy Transition scenario and introduced new or more aggressive energy efficiency improvement in the demand sectors as well as additional electrification.

Pathway Results

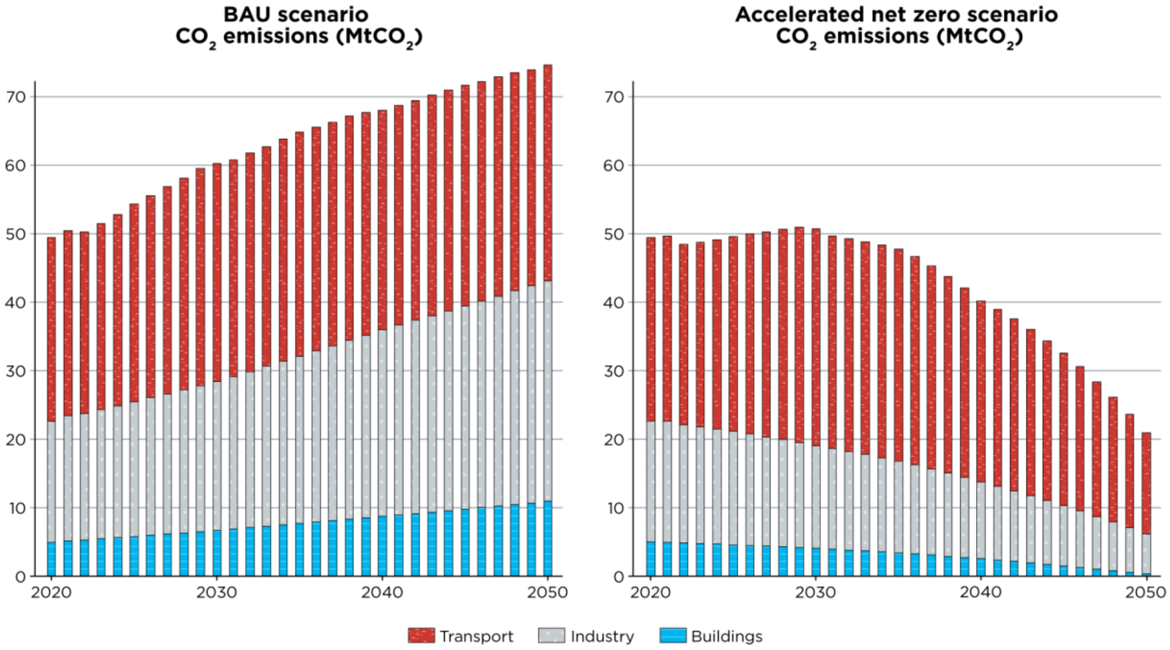

Figure ES-2. Chile's CO_2 emissions by sector, LEAP BAU and Accelerated Net Zero scenarios

1. Significant technical potential exists to reduce CO_2 emissions through accelerated energy efficiency improvements, electrification, and new zero-carbon fuel adoption. These cumulative measures could lead to rapid decline of emissions from end-use demand sectors and reinforce and exceed Chile's 2050 LTS targets.
2. In the absence of aggressive energy demand reduction measures, the ramp-up of CCS and clean hydrogen can offset a high-demand emissions trajectory, requiring additional infrastructure investments for the transport of hydrogen and CO_2.
3. Additional overall results include the following:
    A. Natural gas and petroleum products remain in 2050 under the Net Zero scenario, with less than 30% of primary share, which is down from 70% in 2020. Diesel demand may be reduced as much as 80% relative to 2020.

    B. Electricity demand growth in the highly electrified Accelerated Net Zero scenario can be offset by energy efficiency gains.

    C. Clean hydrogen production, which is a priority for Chile, will contribute to the electricity demand growth. Primary use of hydrogen will be for hard-to-electrify applications in the industry and transportation sectors.
4. High-resolution demand-side results include the following:
    A. **Transportation Sector:** Efficiency improvements and additional efficiency gains through electrification reduce transportation energy demand despite rising mobility activity. Total transportation emissions are likely to be reduced, with CO_2 emissions being 40% lower in 2050 than 2020. Alternative fuels (e.g., clean

hydrogen) have the potential to impact aviation CO_2 emissions during the analysis horizon.

   B. **Industrial Sector:** Decarbonization is possible through increased adoption of electrotechnologies such as industrial heat pumps and electric boilers for specific process heating applications and use of zero-carbon fuels for high-temperature applications.

   C. **Buildings Sector:** Energy demand can be significantly reduced through stringent energy efficiency measures, appliance standards, and scale-up of net-zero buildings. Transformation of this sector is technically possible through electrification of space and water heating with conventional technologies.

5. Supply-side insights include the following:

   A. Full implementation of Chile’s 2040 coal phaseout and the national electro-mobility strategy indicate steep emission reductions in the net-zero scenarios, which nearly reach the LTS goal by 2035.

   B. Decarbonizing the electric sector will require primarily scale-up of wind and solar capacity in the scenarios.

The preliminary modeling results indicate significant technical potential for (1) efficiency improvements in all demand sectors in buildings, industry, and transportation and (2) opportunities for scaling up renewable energy generation. In the modeled scenarios, fuel substitution in the transportation and industrial sectors drive up electricity demand that is met mostly by cleaner and non-fossil sources. Chile’s interest in hydrogen as a clean fuel could be extended to its use as storage capacity for the power sector, particularly as firm coal generation is phased out after 2040 and variable generation wind and solar capacities in remote areas (north and south) of the country are expected to grow.

Egypt: Executive Summary

In-Country Partners

Because of the early stages of Egypt’s participation in the Net Zero World Initiative and other commitments, the government of Egypt was not engaged in guiding this initial pathway analysis.

Modeling Approach and Scenario Definitions

The Phase 1 pathway analysis for Egypt focused on Egypt’s potential for renewable power expansion and its utilization for clean ammonia/hydrogen production and exports. This analysis builds on several recent memoranda of understanding with major companies to build pilot projects and explore the potential of electrifying ammonia production via clean hydrogen, as well as a recent report by the Oxford Institute for Energy Studies on Egypt’s low-carbon hydrogen development prospects that primarily examined the domestic market for hydrogen (Habib and Ouki 2021). The goal of this pathway analysis was to build on these recent developments and provide new strategic insights by analyzing opportunities for clean ammonia and hydrogen production and exports. Using an optimization model that represents global energy markets allowed the Net Zero World Initiative team to explore market opportunities for Egypt to export ammonia and hydrogen into international clean fuels markets. Global and regional market size and price dynamics for ammonia/hydrogen commodities were modeled to reveal insights into Egypt's competitiveness in emerging regional and global clean fuels markets.

Pathway Results

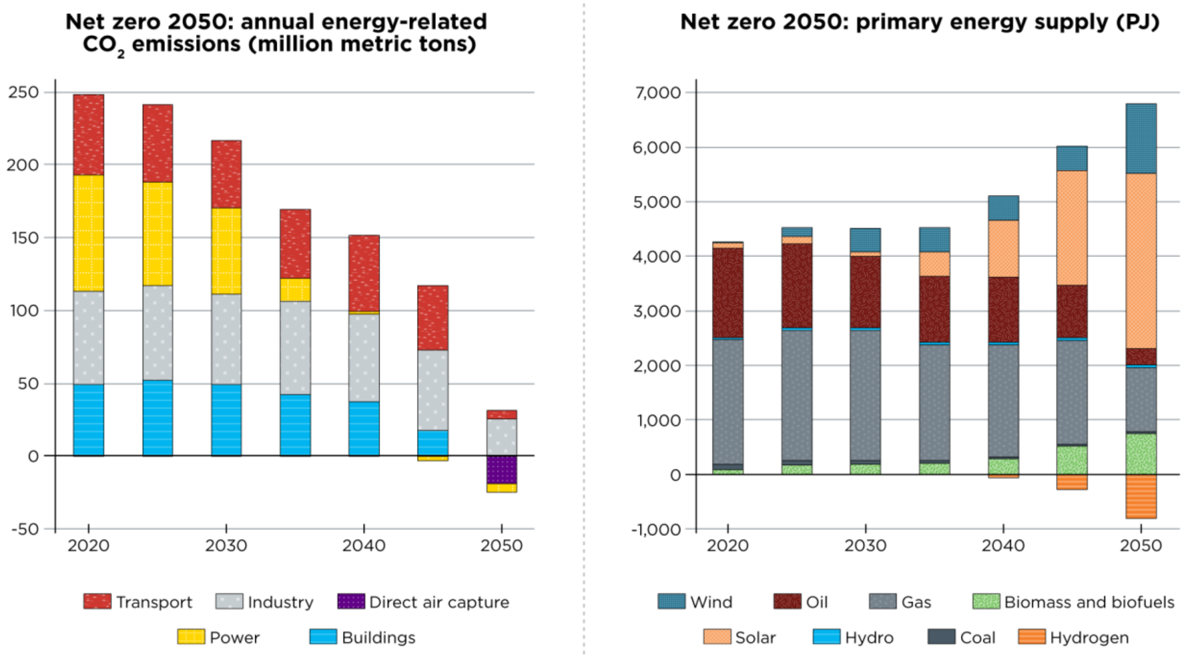

Figure ES-3. Egypt's emissions projections (left) and primary energy supply (right)

1. Egypt has tremendous renewable resources in the form of solar and wind energy, which can be deployed and scaled up to decarbonize the power sector while also providing the potential to produce clean ammonia/hydrogen for the export markets. The analysis for Egypt assumed exports in the form of ammonia until 2040 with the potential for clean hydrogen exports thereafter as the scale of production increases and the delivery infrastructure develops. Early interest and investments in ammonia and hydrogen pilot projects and a hydrogen investment target policy can provide a solid foundation for continuing hydrogen industry development and scale-up of production.

2. In the Net Zero scenario, emissions decrease gradually into the 2040s as the power sector decarbonizes before meeting the net-zero target in 2050 with the buildings and light-duty vehicle sectors being fully electrified. CCS, as well as advanced direct air capture technology, may become necessary to offset remaining emissions from industry and transportation.

3. In the Net Zero scenario, Egypt's primary energy mix shifts significantly to renewables (solar and wind) both for meeting domestic clean energy needs and for exporting clean hydrogen. Gas consumption drops by about half with the remaining gas being used in the industry and power sectors, much of it with CCS, as well as noncombustion chemical feedstocks. Almost 60% of final energy consumption comes from clean electricity and hydrogen.

Egypt has the potential to become an international player in the clean fuels markets by exporting clean ammonia and hydrogen due to its rich renewable resources and proximity to European markets. Under such a scenario, Egypt not only moves toward its own decarbonization goals but also contributes to the decarbonization of importing countries. The analysis for Egypt shows (1) how cost of project financing, variations in global/regional ammonia/hydrogen demand, and targeted clean hydrogen and renewable energy investments can drive Egypt's competitiveness in the emerging regional and global clean fuels markets and (2) how these investments and potential credits from the international trade of clean energy could shape the future of Egypt's energy infrastructure. Future analysis could explore how local decarbonization and energy security policies in potential importing regions could affect Egypt's export potential and competitiveness.

Indonesia: Executive Summary

In-Country Partners

The Indonesian Ministry of Energy and Mineral Resources (ESDM) identified priorities for cooperation with the Net Zero World Initiative. The Net Zero World Action Center applied these priorities and other related studies to inform and guide the preliminary pathway analysis presented here.

Modeling Approach and Scenario Definitions

The ESDM identified technical collaboration areas for application of Net Zero World Initiative analysis and capacity building assistance for energy system-wide decarbonization assessment. Based on discussions with the ESDM, the Net Zero World Initiative team applied LEAP and TIMES[1] models to create a two-model framework that supports ESDM's use of LEAP and benefits from robust price/cost-based pathway modeling capabilities provided by the TIMES optimization modeling engine. Three core scenarios were modeled: the No New Carbon Policies scenario, the Carbon Price Only scenario, and the Net Zero 2060 scenario. All three scenarios use population, gross domestic product (GDP), and energy service demand projections consistent with the International Energy Agency's Announced Pledges (IEA's APS) scenario.

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[1] TIMES is The Integrated MARKAL-EFOM System. For more information, see https://iea-etsap.org/index.php/etsap-tools/model-generators/times.

Pathway Results

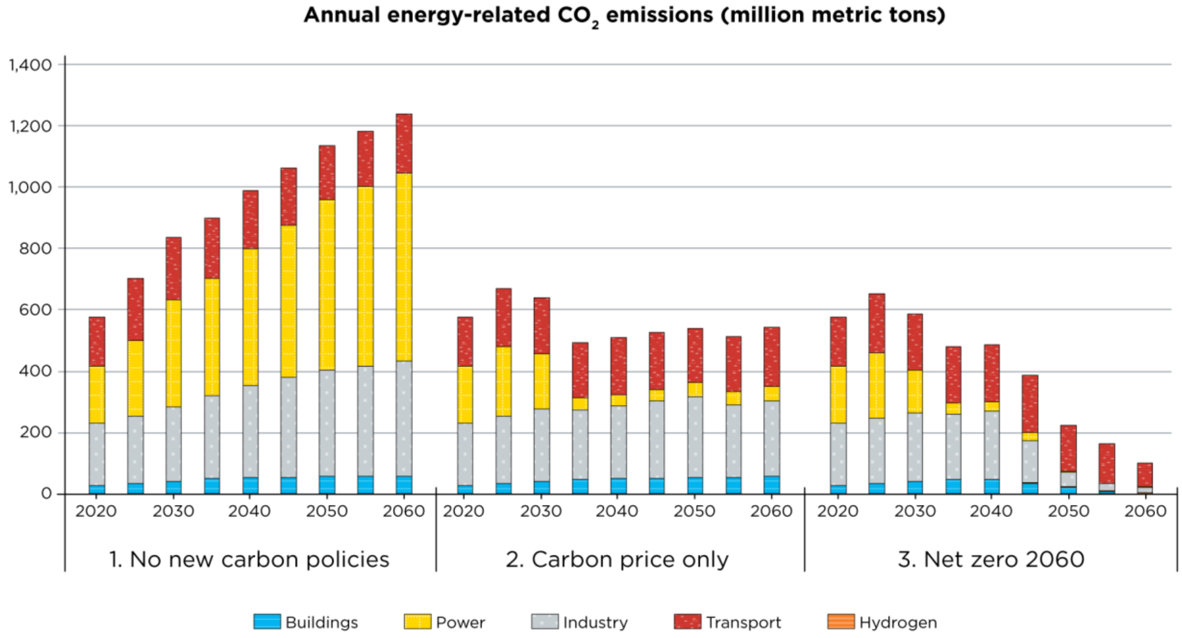

Figure ES-4. Indonesia's emissions projections

1. In the modeled scenarios, carbon pricing alone lowers carbon emissions in most sectors but does not lead to net zero.
2. Net-zero scenarios are achieved through full electrification of the buildings sector, an accelerated phaseout of fossil fuels in industry along with a scale-up of renewables, electrification of most of the transportation sector, and CCS to mitigate the remaining emissions.
3. Under a net-zero scenario, renewables scale up rapidly to almost 60% of primary energy supply and solar accounts for nearly half of all renewables in 2060. Coal ramps down quickly after 2030 and is phased out by 2050. Most remaining natural gas will be used for hydrogen production and electricity generation with CCS, as well as noncombustion feedstocks.
4. Moving toward net zero will accelerate the electrification of various end-use sectors and supercharge the already strong growth in national electricity demand particularly in later years, despite the deployment of a range of energy efficiency measures.
5. Total final energy consumption changes little with decarbonization, but the energy composition shifts toward low-carbon sources, including clean electricity and hydrogen.
6. Energy efficiency measures can cut transportation's final energy demand in half and can reduce industrial energy consumption by almost two-thirds.

7. Building efficiency measures can significantly reduce buildings sector consumption, lower system peak load, decrease grid storage requirements, and lead to significant savings.
8. Incentivizing daytime, grid-responsive, smart charging facilitates incorporation of renewable energy, reduces grid storage needs, and lowers the cost of electricity supply.

To meet its net-zero goals, Indonesia faces the challenge of building a low-carbon electric grid while simultaneously addressing rapid load growth in the buildings, industry, and transportation sectors. The analysis for Indonesia indicates ways for early demand-side and electrification actions to help make this challenge more achievable and affordable. Mobilizing investments in cost-effective energy efficiency, developing building codes and practices that reduce fast-growing cooling loads, and facilitating load shifting, particularly for electric vehicle charging, are early investments that can make a net-zero electricity supply more achievable and affordable by mid-century.

Nigeria: Executive Summary

In-Country Partners

Discussions with the Government of Nigeria, including the Energy Transition Office in the Office of the Vice President and the Ministry of Environment, informed and guided this preliminary net-zero pathway analysis.

Modeling Approach and Scenario Definitions

The Nigerian Government partners requested that the Net Zero World Initiative evaluate options for developing a carbon market in Nigeria, which is viewed as a prerequisite for implementing Nigeria's Energy Transition Plan and facilitating investment in net-zero technologies and interventions. The Net Zero World Initiative team developed scenarios to help address two questions: (1) What are the costs, benefits, and impacts of various carbon market frameworks and trading schemes in Nigeria? (2) How can such a market accelerate progress toward net-zero implementation by driving investment toward lower emission technologies and practices?

Nigeria's energy system was represented using an initial GCAM implementation with a targeted focus on carbon market scenarios to help inform and guide the implementation of the Energy Transition Plan. An initial set of scenarios was developed to explore how different strategies for addressing GHG emissions in carbon market design would influence the effectiveness of the market and would affect Nigeria's competitiveness in global oil markets. Because of the large contribution of methane from oil and gas production to the national GHG emissions, scenarios were explored with different methane treatments in the abatement strategies:

- Reference case
- Economy-wide zero CO_2 by 2060 with abatement of CH_4 (CO_2tax-CH_4MAC scenario)
- Same as the second scenario but with no CH_4 abatement (CO_2tax scenario)
- Same as the second scenario with CH_4 taxes added (GHGtax-CH_4MAC scenario).

Pathway Results

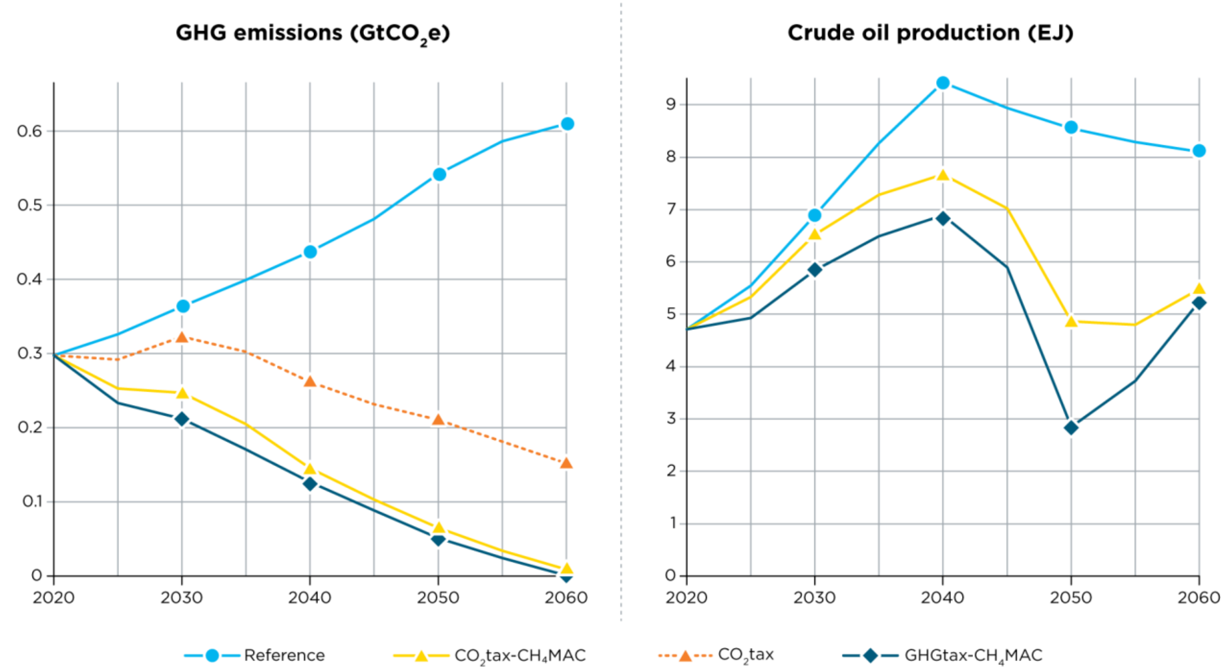

Figure ES-5. Nigeria's total in-scope GHG emissions by scenario, 2020–2060 (left) and crude oil production by scenario (right)

1. Power sector investments needed to reach net zero could double compared to the reference scenario. Much of this new power generation will be solar technologies, while new natural gas power generation with CCS may also significantly contribute to reducing carbon emissions. Carbon pricing can accelerate retirement of existing conventional natural gas generators.
2. In the modeled scenarios, negative emissions from biomass with CCS are important for reaching net zero by 2060.
3. Definition of carbon markets rules significantly influence the emission outcomes and domestic crude-oil competitiveness. For example, exempting oil and gas sector methane emissions from the GHG abatement efforts keeps overall emissions above net zero to 2060, while coupling the CO_2 abatement policies with methane abatement incentives allows emissions mitigation target to be reached. This is illustrated in Figure ES-5 above and further described in the body of the report.

Initial modeling activities for Nigeria explored emissions impacts and domestic crude oil market feedbacks as a function of different carbon market designs. These activities revealed that the specifics and scope of the market rules are important to achieving a desired emissions outcome. In follow-on work, additional analyses may (1) focus on regionally specific market rules and implementation that include fugitive methane and CO_2 emissions and (2) consider Nigeria's interest in methane capture commercialization efforts and 30% renewable energy targets by 2030. Furthermore, economic analyses could be undertaken to study the domestic and geopolitical conditions under which continuing natural gas investments might become stranded assets.

Next Steps

These *preliminary findings* from the initial modeling activities point directionally to key sectoral and/or technological opportunities for accelerating clean energy transitions and for use of key policy mechanisms that are country- and region-specific. Follow-on work in Phase II will be planned and conducted in collaboration with the country governments and technical partners to provide greater sectoral and investment detail and more targeted analyses to inform key priority net-zero pathway and policy issues for each country.

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1 Introduction and Objectives

The Net Zero World Initiative leverages expertise across U.S. government agencies and the U.S. Department of Energy's national laboratories, in partnership with other governments and philanthropies, to accelerate the decarbonization of global energy systems. This whole-of-government approach supports countries committed to raising their climate ambitions by cocreating and implementing highly tailored, actionable technical and investment strategies that put just and sustainable net-zero solutions within reach. The Net Zero World Initiative enables country partners to harness the convening power and technical expertise of U.S. and international industry, think tanks, and technical institutions. The initiative pursues the following objectives:

- **Develop and support ambitious technical, market, and investment strategies for clean energy transformation.** The Net Zero World Initiative collaborates with partners to develop country-specific technical and investment plans detailing the crosscutting planning and deployment strategies needed at the national, regional, and local levels.
- **Deliver holistic support for immediate and sustained transformative projects that maximize overall impact for the region**. The Net Zero World Initiative supports the development of cross-sector project pipelines and infrastructure modernization plans for partnering with the private sector and developing robust research, development, demonstration, and deployment partnerships to quickly advance technologies from research to implementation.
- **Foster exchange among U.S. leaders and countries to support peer-to-peer learning and confidence building**. The Net Zero World Initiative supports exchanges among U.S. states and cities, business leaders, and across countries to inform technical and investment plans and key design and implementation measures, and to enable peer-to-peer learning, tailored replication of successes, and confidence building. The initiative also provides implementation support for workforce development programs, with particular emphasis on gender equity and the inclusion of underrepresented groups.

As a first step toward these objectives, the Net Zero World Initiative reached out to five partner countries—Argentina, Chile, Egypt, Indonesia, and Nigeria—to identify priorities for cooperation and to initiate collaboration on energy system modeling and techno-economic analyses of net-zero pathways and key analysis issues and questions of greatest interest to each country. Core strengths of the U.S. national laboratory system were mobilized to codevelop energy system-wide modeling activities with in-country partners and to address high-priority climate/energy policy questions and decarbonization strategies of high interest for each country.

Phase I modeling activities were conducted from late July 2022 to September 2022 in partnership with in-country technical partners. This report summarizes the early outcomes of the Phase I energy system-wide modeling activities for each country. *The results presented here are preliminary and indicative*. In Phase II, modeling work will incorporate further in-country prioritization of specific technical and policy questions. Those questions will then be analyzed with the support and expertise of the DOE national laboratories. Phase II results will be jointly interpreted and summarized.

For more information about the models used for the Phase I modeling activities, see Appendix A.

2 Argentina: Preliminary Modeling Results

The overarching goal for the Argentina modeling work is to support the Government of Argentina in developing Argentina's energy system decarbonization pathways. These pathways support a resilient and sustainable energy system that enables and accelerates the transition toward Argentina's net-zero emissions goal. Previous modeling efforts developed by Fundación Bariloche applied the Low Emissions Analysis Platform (LEAP) modeling framework and other energy system-wide models (for example, IMACLIM, FABLE, and MESSAGE). The initial modeling work presented in this report was developed based on published data, studies, and in consideration of early discussions with the Government of Argentina in mid-2022 to identify priority mitigation measures for scenario development.

In the work reported here, the Net Zero World Initiative team used the Global Change Analysis Model (GCAM), which can analyze both human (socioeconomic) and earth system (climate) dynamics in a global framework, and which includes considerations of Argentina's complex economic situation and diverse climatic regions. Early scenarios focused on accelerated deployment of existing technologies and measures that can improve the energy efficiency in buildings, increase the share of variable renewable energy, and create negative emissions to offset continued use of fossil fuels and hard-to-abate sectors. This analysis included indicators that represent economic, environmental, and social benefits.

2.1 Overview: Emissions and Energy Situation

The most recent official emissions inventory by sector and subsector was published in Argentina's third biennial update report in 2019.[2] It reported total national GHG emissions of 364 $MtCO_2e$. The projected emissions scenario for the country shows that the national economy reaches 592 $MtCO_2e$ in 2030 if transformation actions are not implemented (SAyDS 2015). To reach its nationally determined contribution (NDC) commitments of 349 $MtCO_2e$ by 2030, Argentina needs to reduce its emissions by 40%, or 243 $MtCO_2e$, by 2030. According to Argentina's current target, all levers for the energy sector combined could result in 109.9 $MtCO_2e$ in 2030, which represents 46% of the total reductions required in the national economy by 2030. The major sources of GHG emissions are the energy and transportation sectors, which account for 53% of the total GHG emissions in the second biennial update report (193 $MtCO_2e$), followed by agriculture, forestry, and other land use at 37%, as presented in Figure 1.

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[2] "Argentina. Biennial update report (BUR). BUR 3," UN Climate Change, https://unfccc.int/documents/201965.

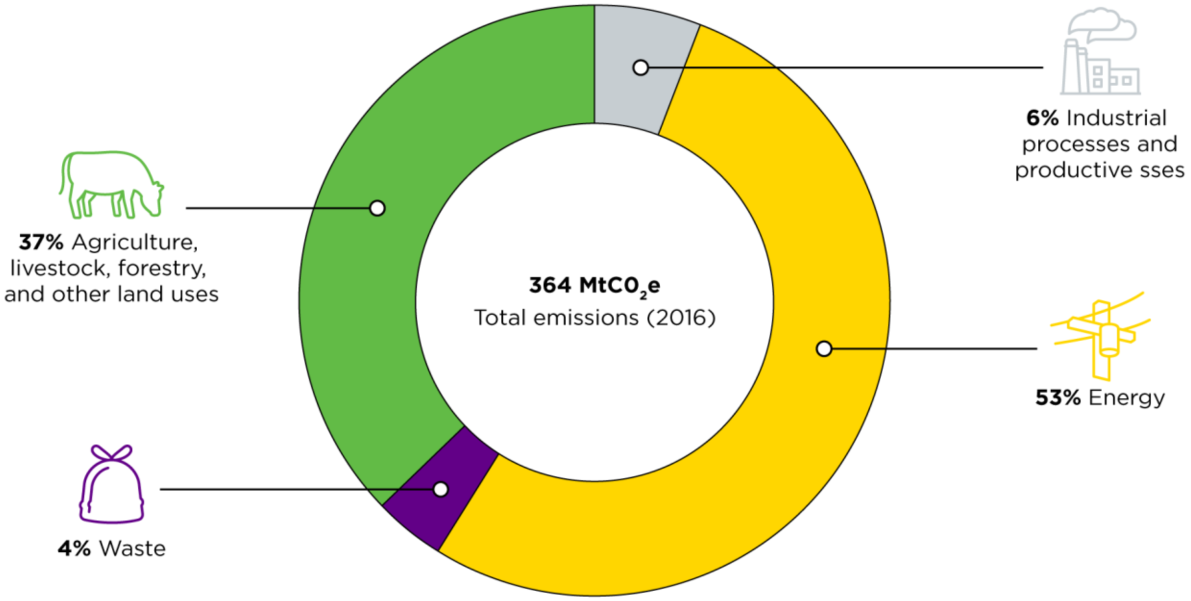

Figure 1. Greenhouse gas inventory for Argentina

Source: Ministry of Environment and Sustainable Development 2019

From the energy sector perspective, transport, electricity, and heat production have been the largest emitting sectors in Argentina since 1990. As can been seen in Figure 2, emissions from fuel combustion as reported using IEA's energy balances and the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines, have shown marked increases since 2002, especially for the electricity and heat producers, as natural gas from the Vaca Muerta reserve has taken a progressively more predominant role in the energy sector.

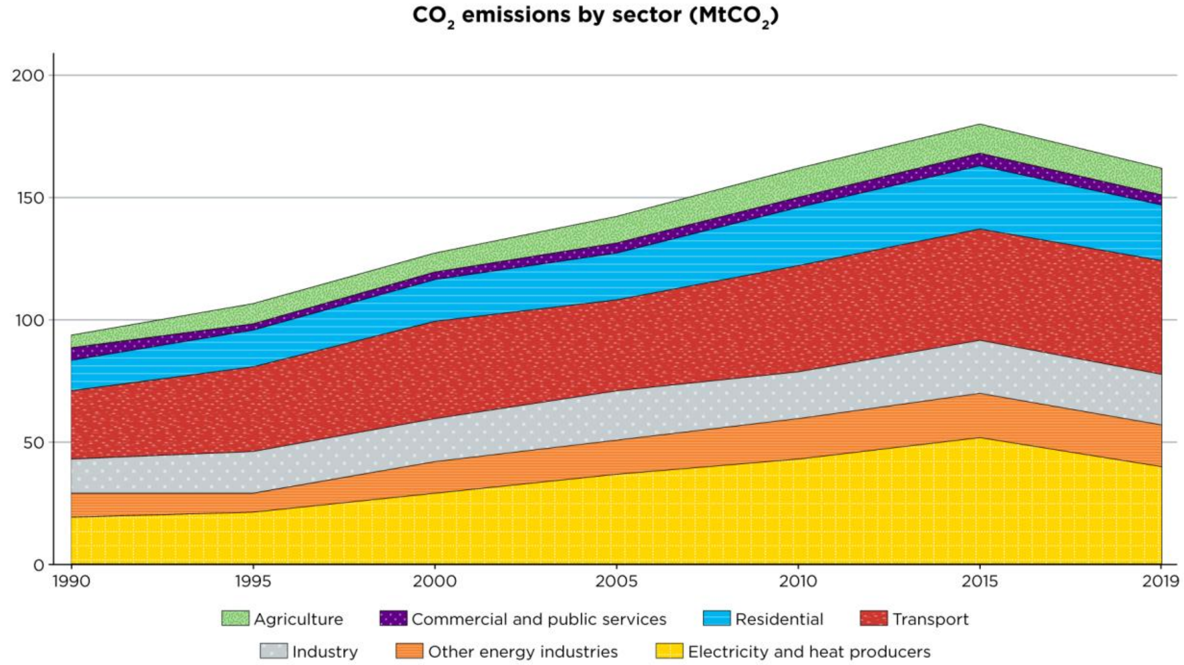

Figure 2. CO_2 emissions from fuel combustion by sector, 1990–2019

Sources: IEA Energy Statistics Data Browser (https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=ARGENTINA&fuel=Energy%20supply&indicator=TESbySource, accessed October 2022)

When looking at CO_2 emissions by energy source, natural gas represents the largest source of CO_2, at 93 $MtCO_2$, or 57% of the total emissions in 2019. Oil is close behind, representing 40% of total emissions by energy source, as presented in Figure 3. Both natural gas and oil are sourced from the Vaca Muerta reserve, the world's second-largest shale gas reserve and the fourth-largest shale oil reserve, which the Government of Argentina plans to continue exploiting into the foreseeable future. This fact represents an important challenge for reaching net-zero targets and justifies the relevance of including carbon management (capture, utilization, and storage) as a critical component of all net-zero scenarios.

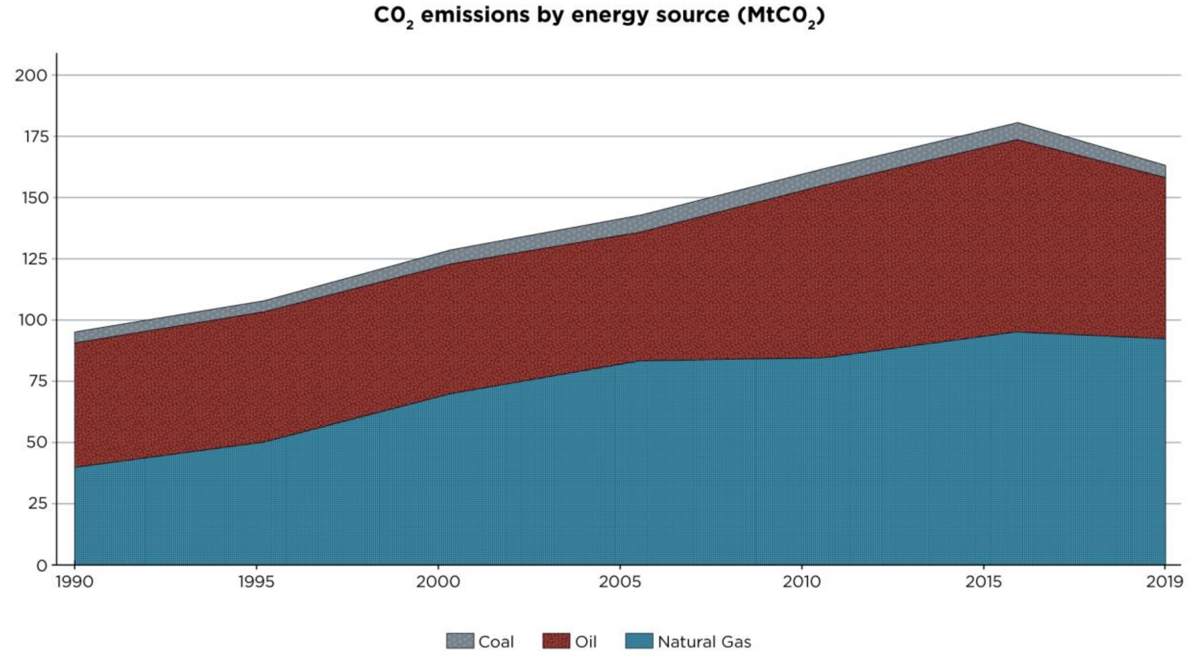

Figure 3. CO_2 emissions by energy source, 1990–2019

Source: IEA Energy Statistics Data Browser (https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=ARGENTINA&fuel=Energy%20supply&indicator=TESbySource, accessed October 2022)

The CO_2 emissions distribution by energy source are aligned with Argentina's energy supply profile, which consists predominantly of natural gas, which represented 54% of the total energy supply in 2019 (Figure 4). Oil was the second-largest contributor, representing 33% of total energy supply in 2019.

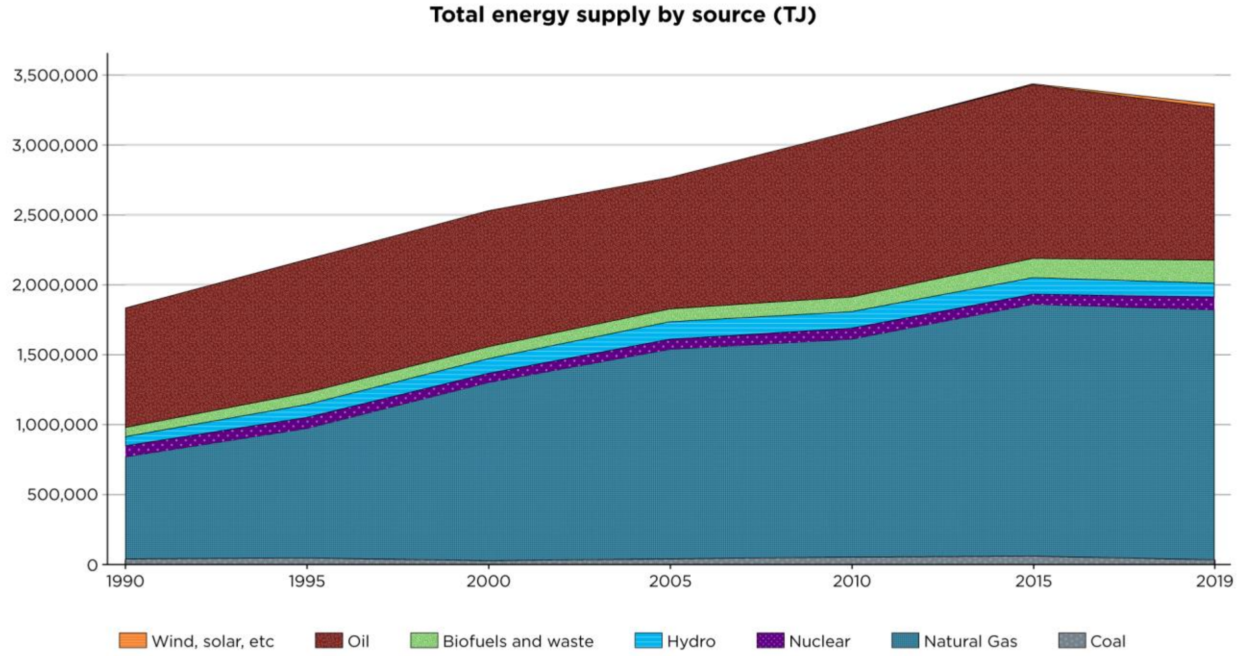

Figure 4. Total energy supply by source, 1990–2019

Source: IEA Energy Statistics Data Browser (https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=ARGENTINA&fuel=Energy%20supply&indicator=TESbySource, accessed October 2022)

When looking at electricity generation by source, natural gas plays an even larger role, representing 61% of the total generation in 2020. However, as can be seen in Figure 5, wind and solar are beginning to take a more predominant role in electricity generation over the last few years, representing 6% and 1% of total supply, respectively, in 2020.

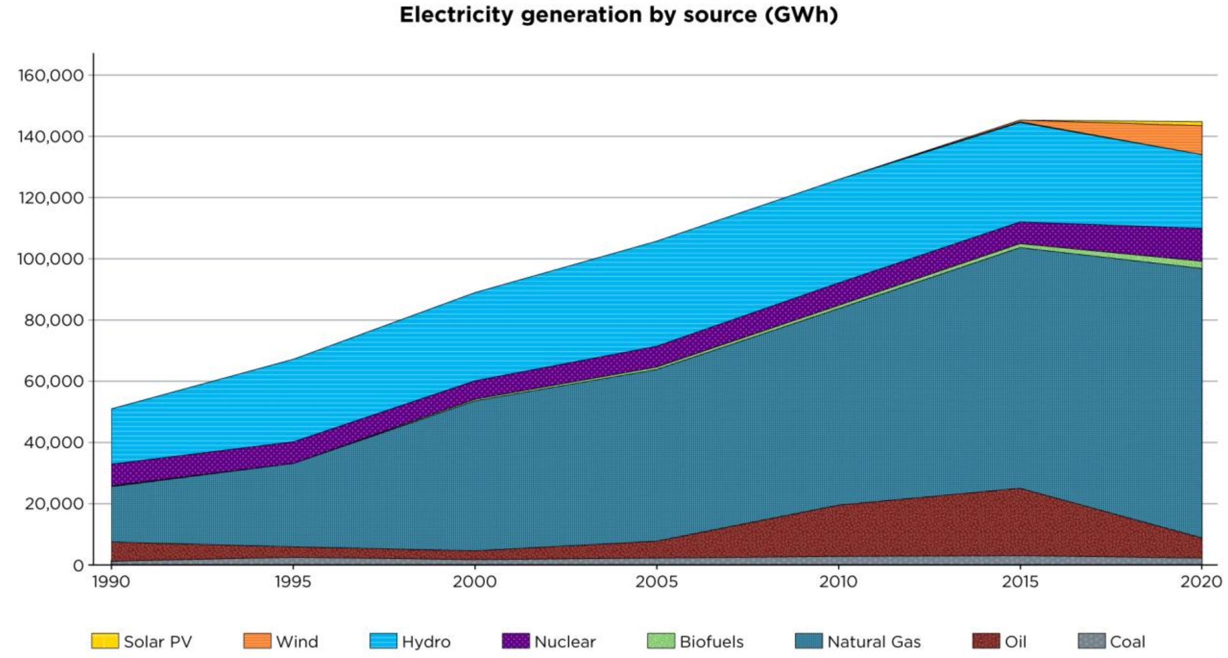

Figure 5. Electricity generation by source, 1990–2020

Source: IEA Energy Statistics Data Browser (https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=ARGENTINA&fuel=Energy%20supply&indicator=TESbySource, accessed October 2022)

The transportation sector has the largest final consumption of all sectors; it represented 32% of total final consumption in 2019. The residential and industrial sectors are close behind with 24% each, as presented in Figure 68. These figures demonstrate the high potential for reductions from energy efficiency measures in these three sectors, as presented later in the modeling results.

However, when looking at electricity consumption alone, the industrial sector consumes the largest share of total electricity consumption (40% in 2019), and the residential sector (34% in 2019) is close behind, as shown in Figure 7.

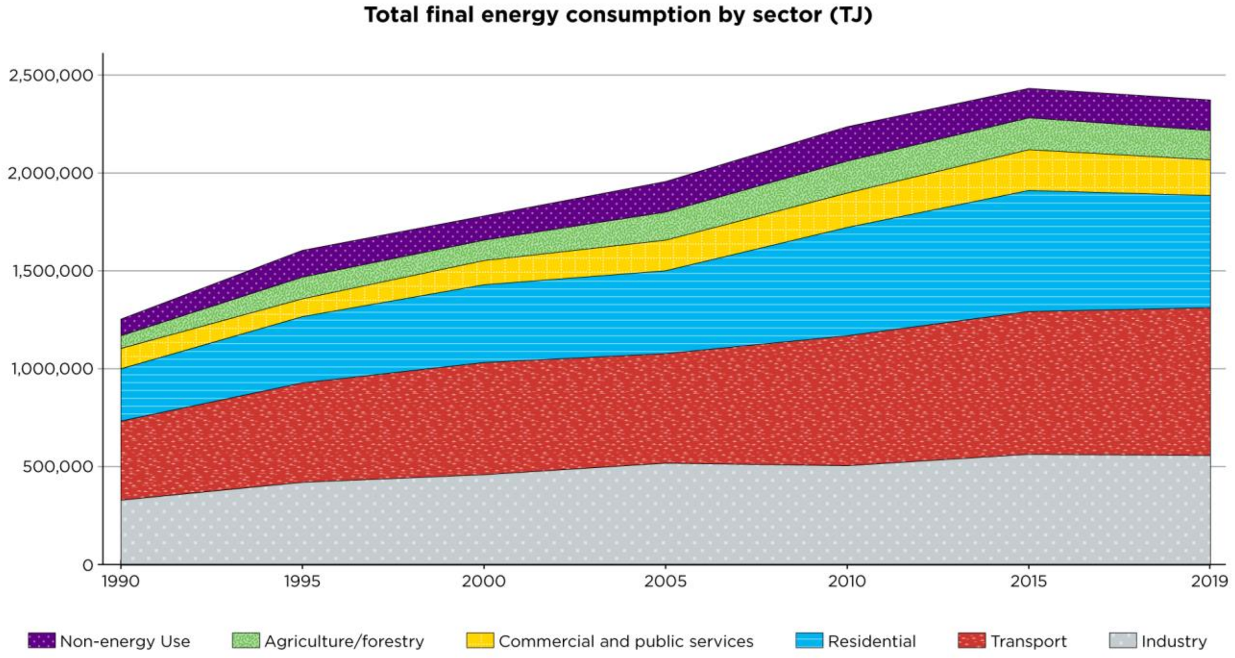

Figure 6. Total final consumption by sector, 1990–2019

Source: IEA Energy Statistics Data Browser (https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=ARGENTINA&fuel=Energy%20supply&indicator=TESbySource, accessed October 2022)

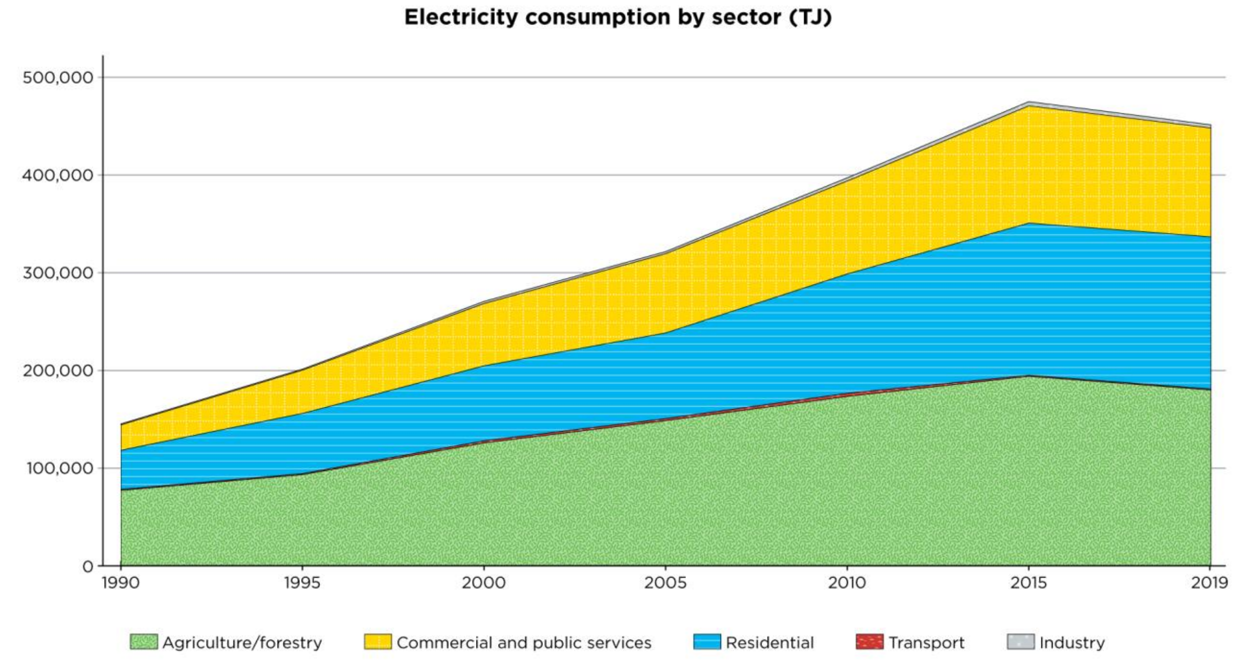

Figure 7. Electricity consumption by sector, 1990–2019

Source: IEA Energy Statistics Data Browser (https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=ARGENTINA&fuel=Energy%20supply&indicator=TESbySource, accessed October 2022)

2.2 Government Goals regarding Decarbonization

Argentina’s second NDC was submitted in December 2020 and updated in November 2021 to increase the GHG emission goal and add an adaptation component. The updated unconditional target is to not exceed 349 $MtCO_2e$ GHG emissions in 2030, a goal that is 27.7% higher than in the one in the first NDC submitted in 2016, where the original target for 2030 was 483 $MtCO_2e$ (unconditional), or 369 $MtCO_2e$ (conditional on international support). Argentina is currently preparing its long-term strategy (LTS) for submission to the U.N. Framework Convention on Climate Change (UNFCCC) and is aiming at carbon neutrality by 2050.

The Climate Action Tracker notes that due to the financial crisis in Argentina, climate has remained a secondary priority to economic recovery, especially during the COVID-19 pandemic. In earlier conversations with government counterparts and commitments taken in 2021, natural gas exploitation and exports are seen as a means to transition to renewables and create market opportunities to support economic recovery.

2.3 Preliminary Phase I Modeling Results

The Net Zero World Initiative team used GCAM version 6.0 to explore net-zero CO_2 pathways for Argentina. The net-zero scenarios modeled included Argentina’s economy-wide target for 2030 as laid out in its NDC (349 $MtCO_2e$). From 2030 to 2050, the net-zero scenarios included a linear constraint on net CO_2 emissions of 0 in 2050, across both fossil fuel and industry emissions and land use change emissions. Two net-zero scenarios are presented in this report: the first is a carbon capture and storage (CCS) scenario, where there is a greater share of natural gas-powered electricity generation with CCS in the electricity mix, and the second is a high renewable energy scenario that incorporates a greater contribution of renewable energy as part of the net-zero strategy.

The RE-Focus scenario represents the situation where new electricity generation from natural gas with CCS in the power sector is less than conventional natural gas electricity generation in the historical period, while the CCS-Focus scenario allows for scale-up of new natural gas electricity generation with CCS capacity. Although CCS can be used in both scenarios, we assume that more CO2 storage is available due to lower costs of storage in the CCS-focus scenario, such that the total amount sequestered in 2050 is 57 $MtCO_2$, compared to 30 $MtCO_2$ for the RE-focus scenario.

The estimates for negative emissions from land use change (≈90 $MtCO_2$ in 2050) were incorporated from the Deep Decarbonization Pathways study for Argentina (Lallana et al. 2021), and additional negative emissions measures were then modeled to reach net zero. To prevent carbon leakage, which refers to a shift of carbon-intensive activities to other regions of the world, both scenarios assume the rest of the world follows a similar timeline for net-zero decarbonization.

Argentina Insight 1: The preliminary modeling illustrates the importance of negative emissions, especially in the land sector, to balance continued positive emissions.

Figure 8 shows the economy-wide greenhouse gas (GHG) emissions by sector and by GHG for the two net-zero scenarios (RE-Focus and CCS-Focus), as well as a Reference (no new policy) scenario. In the Reference scenario without any new climate policy, Argentina is expected to continue the rapid growth in emissions through 2050. However, the two net-zero scenarios result in large GHG reductions (≈380 $MtCO_2e$ reduction in total GHG emissions) in 2050 compared to the Reference scenario. Most of the reduction (180 $MtCO_2$) comes from fossil fuel and industrial emission reduction, which represents a projected 66% reduction in CO_2 compared to the Reference scenario in 2050 and a 55% reduction compared to 2015 levels. The Net Zero CCS-Focus scenario shows marginally more negative emissions from bioenergy with CCS, but both scenarios rely on the reduction of the positive emissions through increased renewable energy and reduced fossil-based generation. Both scenarios assume a robust and sustained land sink in Argentina, that is, negative land use, land-use change and forestry (LULUCF) emissions through, for example reforestation. Otherwise, more dramatic decreases in fossil fuel use and industry emissions would be needed to reach net-zero CO_2 emissions. The land use change-related emissions are shown as the green lines in Figure 8. In the figure, solid lines represent historical emissions, and dotted lines represent future projections.

It should also be noted that the emissions constraint in the model applies only to CO_2 emissions. Other greenhouse gases such as fluorinated gases, nitrous oxide, and methane are included in the model and shown in Figure 8 but they were not considered in the overall net-zero scenarios and targets. Also, much of these non-CO_2 emissions are attributed to non-energy sources, such as livestock and agricultural activities.

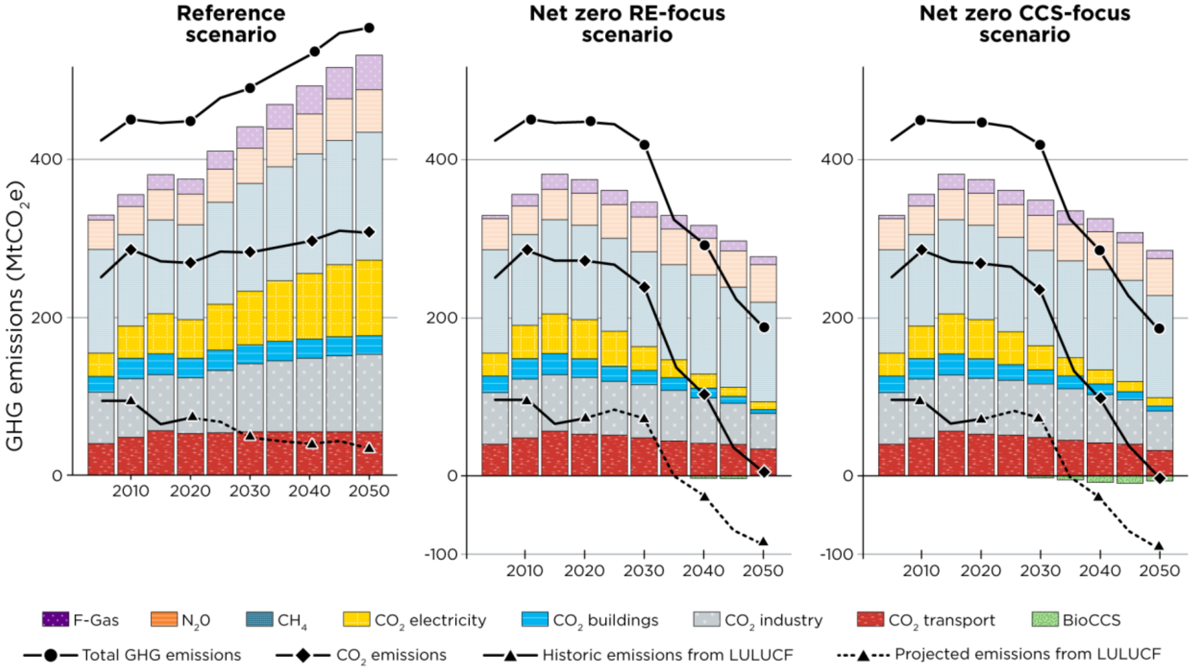

Figure 8. Argentina's emissions projections

Argentina Insight 2: A net-zero emissions pathway in Argentina would result in significant reductions in energy consumption (both primary and final).

The net-zero scenarios result in decreases in primary energy consumption of 25% (1.47 EJ) for the Net Zero CCS-Focus scenario and 31% (1.83 EJ) for the Net Zero RE-Focus scenario relative to the Reference scenario (Figure 912). Likewise, the net-zero scenarios result in decreases in final energy consumption of 22% (0.94 EJ) in the Net Zero RE-Focus scenario and 19% (0.81 EJ) in the Net Zero CCS-Focus scenario relative to the Reference scenario, with key contributions coming from the buildings, industrial and transportation sectors (Figure 10**Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**12).

These decreases highlight the importance of energy efficiency and fuel switching (e.g., electrification of transportation and electric heating of buildings) for decarbonization. Argentina's spending on energy subsidies, which are among the highest in Latin American, were 2.3% of gross domestic product (GDP) in 2021 ($11 billion) (IMF 2022), and utility bills in Argentina have been highly subsidized for over a decade. From the perspective of energy consumers, these two facts have resulted in low incentives to implement energy efficiency measures. However, the Government of Argentina is currently restructuring the energy tariffs, which will reduce the subsidies for the higher income bracket and thus create more favorable conditions for energy efficiency measures in the future. Government-backed energy efficiency programs in the lower economic brackets that will continue to be subsidized could also have a favorable return on investment, thus significantly reducing the amount of subsidies paid by the government and providing long-term cost savings.

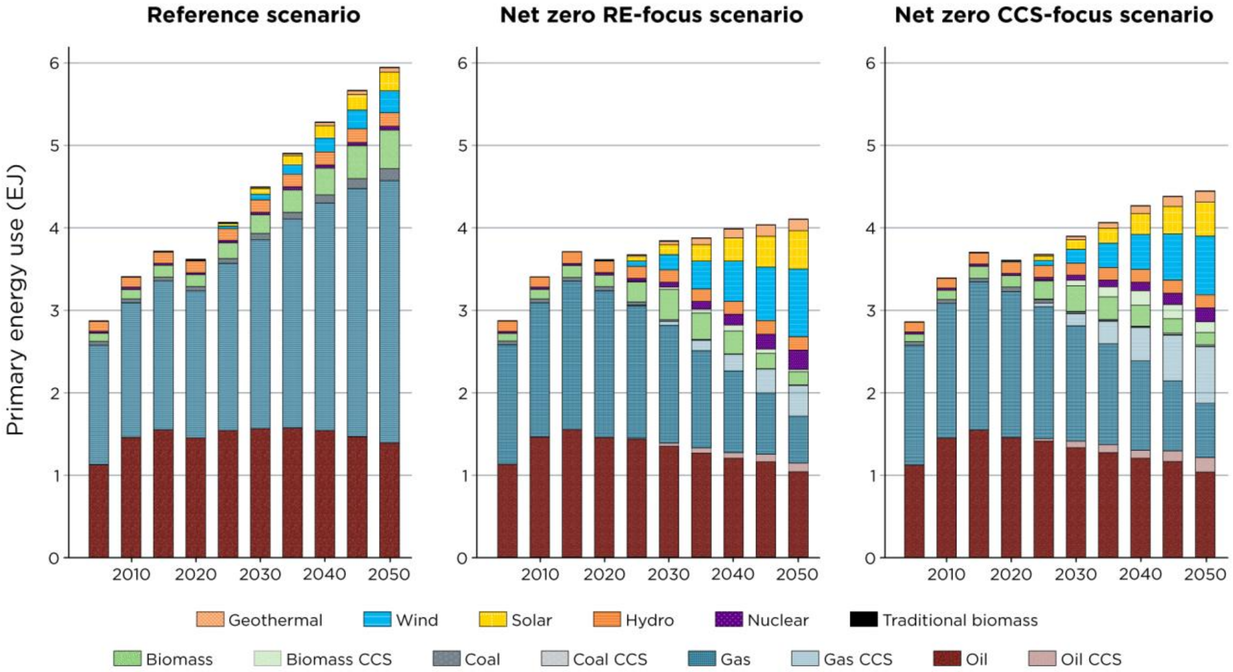

Figure 9. Argentina's primary energy projections

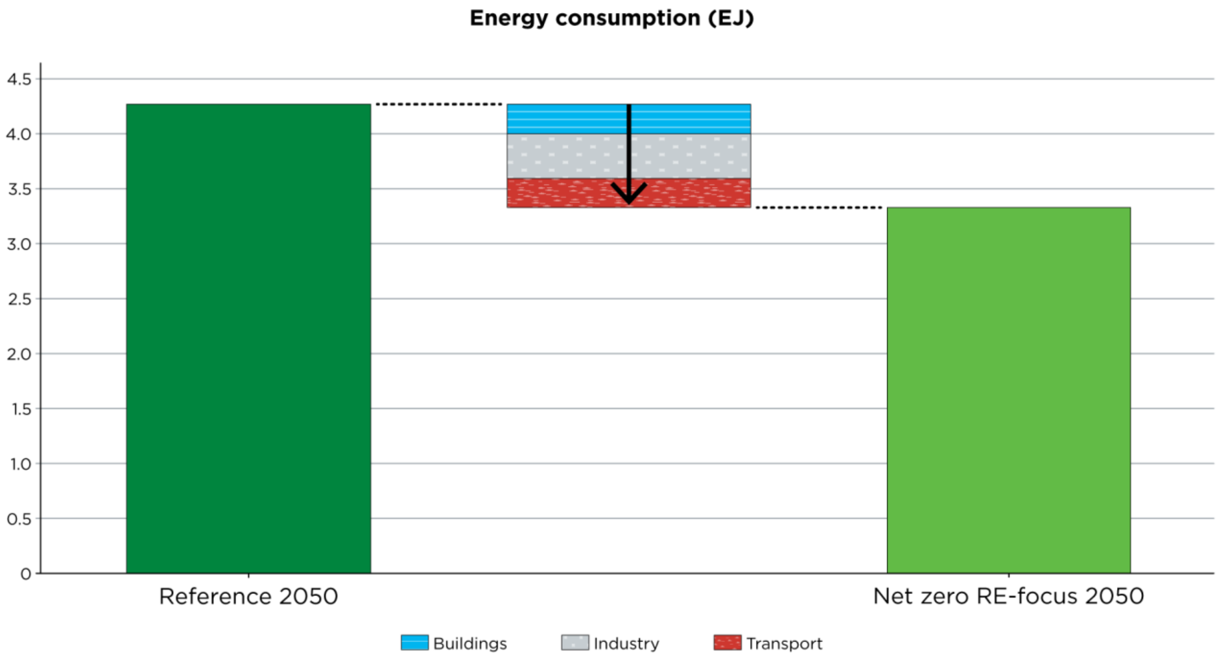

Figure 10. Argentina's sectoral end-use energy reductions (Net Zero RE-Focus scenario)

2.3.1 Sector Highlights

Argentina Insight 3: Power sector decarbonization is a key pillar of a net-zero transition in Argentina.

Overall, the generation of electricity is expected to increase significantly because of population growth rates and the electrification of transportation, buildings, and industry. The share of natural gas for electricity generation declines from 50% in 2050 (Reference) to 18% (Net Zero CCS-Focus scenario) and 11% (Net Zero RE-Focus scenario); virtually all of this decline is due to natural gas with CCS in the net-zero scenarios. In the Net Zero CCS-Focus scenario, the total installed capacity of gas generators is expected to increase, but essentially all gas generation capacity is equipped with CCS technology by 2050. There is an increasing share of variable renewable energy (wind and solar) in 2050 in the Net Zero CCS-Focus scenario (53%) and Net Zero RE-Focus scenario (60%) compared to the Reference case (29%). The Net Zero CCS-Focus scenario relies on CCS to remove emissions for 23% of electricity generation in 2050 (Figure 11). As can be seen in Figure 11, Argentina's electricity generation can almost entirely be decarbonized with a diversified contribution of renewable energy generation (geothermal, wind, solar, and hydropower), nuclear, and CCS coupled with all fossil fuel generation (hatched bars).

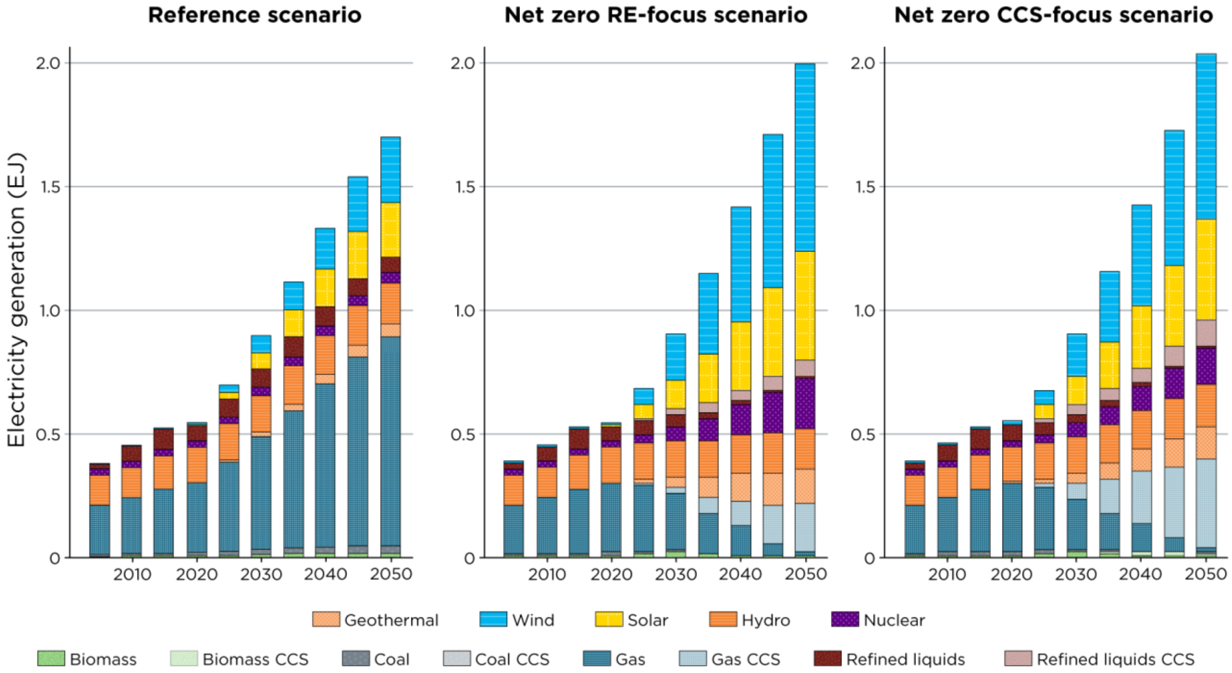

Figure 11. Argentina's electricity generation by technology

Though variable renewable energy has lower operating costs (e.g., fuel costs) than fossil fuel generation, the transition to low-carbon electricity will require new capital investments. For the RE-Focus scenario, average annual capital investments are estimated to be $8.7 billion from 2021 to 2050. For the Net Zero CCS-Focus scenario, average annual capital investments are estimated to be $8.1 billion from 2021 to 2050 (Figure 12). This represents an *additional* annual average capital investment of $4.1 to $4.7 billion from 2021 to 2050 (compared with the Reference scenario). These additional investments for the net-zero scenarios would be offset wholly or in part, by the large avoided social costs, such as reductions in air pollution. And these investments can be translated into employment and economic development opportunities related to creating a new clean energy economy.

The estimated cumulative capacity expansion through 2050 is 155 GW for the Net Zero CCS-Focus scenario, 164 GW for the Net Zero RE-Focus scenario, and 99 GW for the Reference scenario. These projections represent increases of double to more than quadruple the current electric generation capacity of 42 GW in 2020 (Castillo et al. 2021). Figure 13 15shows the new capacity additions over a 5-year period.

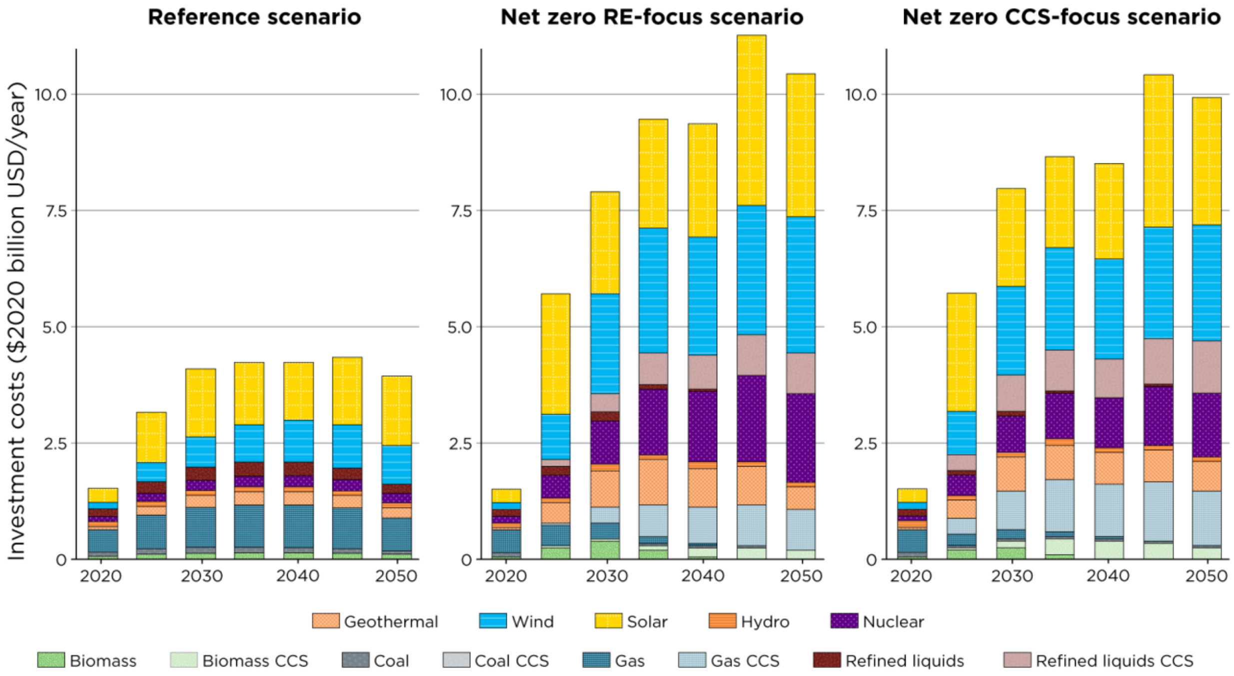

Figure 12. Argentina's electric generation annual investments

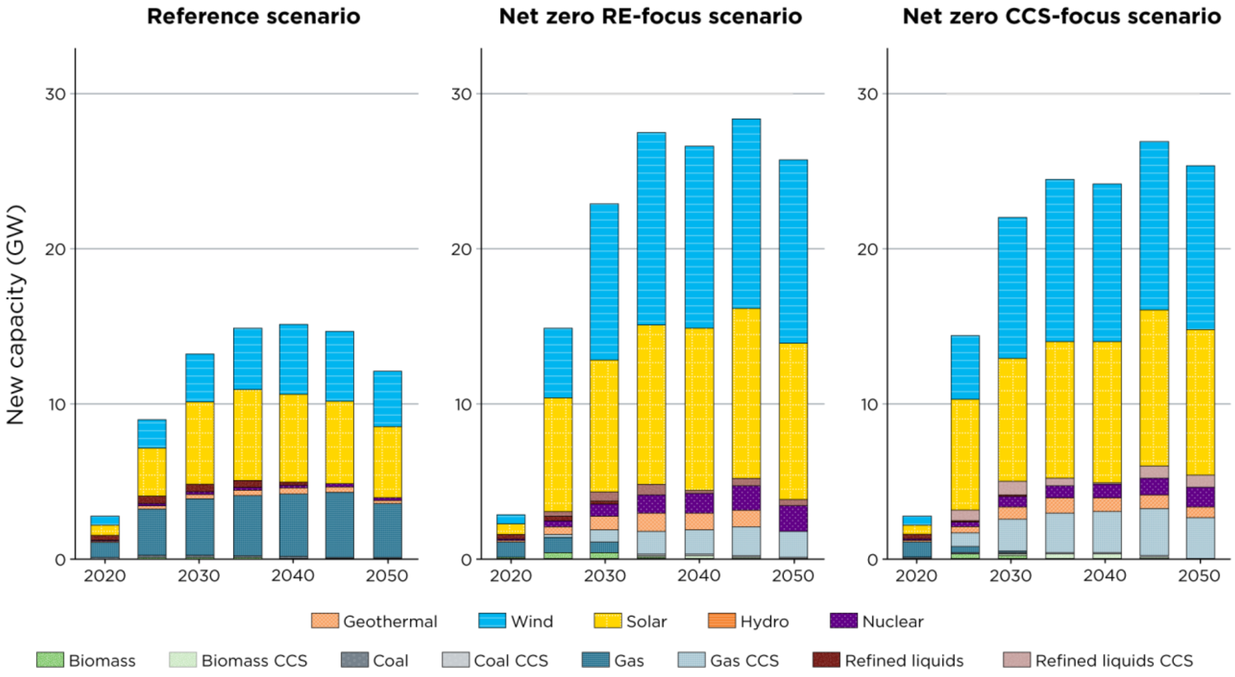

Figure 13. Argentina's new electric capacity additions over 5-year periods

2.3.2 Technology Highlights

Argentina Insight 4: CCS can be an important part of the strategy to achieve net-zero emissions by 2050 in Argentina.

In 2050, 57 $MtCO_2$ is sequestered under the Net Zero CCS-Focus scenario and 30 $MtCO_2$ is sequestered in the Net Zero RE-Focus scenario (Figure 14). About 80% of the sequestration is attributed to the electricity sector and the remainder to industry. CCS could provide up to 43% of the total emissions reductions.

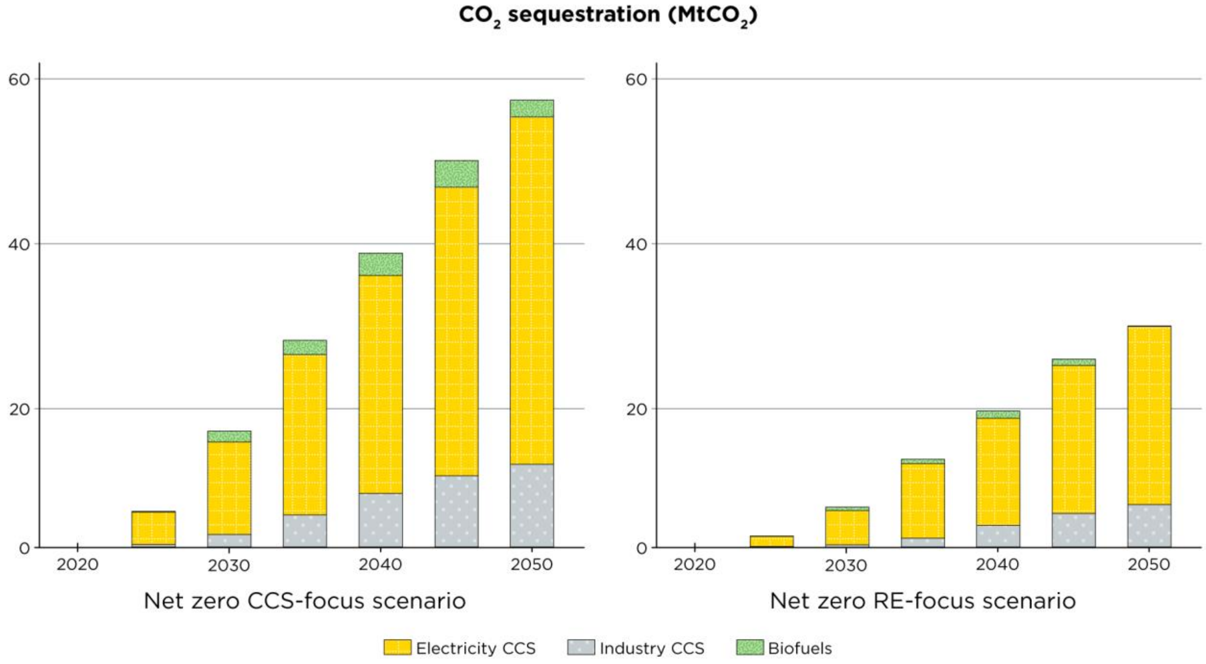

Figure 14. Argentina's sequestered CO_2

2.4 Lessons Learned from the Modeling and Potential Value of Results

Preliminary modeling research indicates the following implications for achieving Argentina's net-zero emission target under the net-zero scenarios:

- *Positive emissions from continued utilization of fossil fuels could be balanced with negative emissions to reach net-zero targets*. Argentina's economy-wide decarbonization was modeled to support the development of a resilient and sustainable energy system that enables and accelerates the transition toward Argentina's net-zero emissions target. Such a transition could include accelerated deployment of low-carbon technologies and measures that could improve energy efficiency in buildings, industry, and transport. Furthermore, it would involve removal of excess CO_2 from hard-to-decarbonize sectors via CCS and nature-based solutions. Such a net-zero pathway could provide Argentina with clean energy it needs while maximizing benefits to the environment, job creation, and social development.

- *Energy efficiency is a key pillar for achieving the net-zero emissions target*. A highly efficient energy system combined with fuel switching and electrification could support the net-zero target by helping to reduce at least 25% of total primary energy consumption by 2050. This finding highlights the importance of energy efficiency measures and fuel switching for decarbonization. A reduction in energy consumption associated with decarbonizing activities would allow the Government of Argentina to spend less on energy subsidies and shift fiscal resources to other priorities.
- *Power sector decarbonization will be key for developing net-zero energy foundations for Argentina*. The power grid could transition from conventional natural gas plants to a greater share of renewable generation and natural gas with CCS to build a sustainable electric supply system and to achieve the net-zero emissions target. Rapid scale-up of renewable energy will be needed with significant investments in the power sector. Such a transition would require *additional* annual average capital investments ranging from $4.1 billion to $4.7 billion per year from 2021 to 2050 (compared with the Reference scenario) and could generate a net economic benefit when considering the avoided social costs, such as climate-related damages and air pollution.
- *CCS technologies can help achieve Argentina's net-zero emissions target*. The analysis indicates that using domestic natural gas resources coupled with targeted CCS can offset 30–57 $MtCO_2$ emissions that would otherwise have been emitted. The largest opportunities exist in the power sector, followed by the industrial sector.

3 Chile: Preliminary Modeling Results

The Government of Chile is targeting a net-zero economy by 2050 and exploring additional decarbonization and sustainable development goals in their long-term strategy (LTS) (Gobeirno de Chile 2021) and long-term energy planning (PELP).[3] The PELP (Ministerio de Energía 2021a) is a multiyear process spearheaded by the Chilean Ministry of Energy that applies modeling to develop future energy generation profiles with climate change considerations. It guides the national transmission expansion planning led by the National Energy Commission and has been used to explore decarbonization pathways in Chile's LTS. The Low-Emissions Analysis Platform (LEAP) forms the backbone of the PELP energy modeling, which defines scenarios according to policy goals and provides a general view of the resource and infrastructure needs, as well as socioeconomic, territorial, and environmental impacts.

Based on technical collaboration areas identified by the Ministry of Energy, the Net Zero World Initiative team worked closely with the Ministry of Energy to build on and supplement their existing LEAP models and analyses. LEAP capabilities were applied to build a national-level model that aggregates the highly detailed 15-region LEAP model used by the Ministry of Energy, enabling the evaluation of national policy and technology scenarios, and highlighting supply-demand linkages. An integrated representation of the power sector was created within the overall LEAP framework, which obviates the need for exogenous power system simulations, and detailed end-use technology information was used to evaluate additional technical opportunities in the industry, transport, and buildings sectors.

To complement the work with the Ministry of Energy, the Net Zero World Initiative team applied GCAM in collaboration with researchers at Pontificia Universidad Católica de Valparaíso. GCAM was used to model potential pathways to reach the GHG emissions target set forth in the LTS while adopting some assumptions from the PELP. This work provides additional insights into decarbonization pathways and areas of national interest such as clean hydrogen developments. The GCAM model provides additional insights into the uncertainties of carbon land sinks and its contribution to the net-zero goal as well as impacts of water scarcity.

LEAP and GCAM offer complementary approaches to modeling decarbonization pathways for Chile. LEAP offers detailed insights into technological and policy changes at the end-use demand level with integrated supply modeling to track the national energy and environmental impacts, while GCAM models the demand-supply equilibrium to meet decarbonization goals. Due to time constraints, the two models were not integrated for the analysis reported here. Model runs were conducted separately based on different targets, assumptions, and model structures.

3.1 Overview: Emissions and Energy Situation

Currently, most GHG emissions in Chile are from the energy sector, and, specifically, coal-based electricity production and diesel-based land transportation. Chile benefits from vast solar and wind energy resources but faces the challenge that most of this renewable energy potential is concentrated in the north and south of the country, while the population is concentrated in the

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[3] Available at: https://cambioclimatico.mma.gob.cl/wp-content/uploads/2021/11/ECLP-LIVIANO.pdf

center of the country in and around the capital city of Santiago.[4] Thus, developing advanced transmission, storage, and grid flexibility capacities will be key to decarbonizing electricity production in Chile. Expanding renewable electricity generation from its current level of 43% is particularly important given that electrification underlies 80% of the emissions mitigation measures proposed in Chile's carbon neutrality scenario, on which its updated NDC and LTS is based (Gobeirno de Chile 2021) (**Error! Reference source not found.**Figure 15**Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**). One key measure is green[5] hydrogen; Chile aims to become a global green hydrogen exporter, providing "the cheapest green hydrogen on the planet," as articulated in the National Green Hydrogen Strategy (Ministerio de Energía 2020b). Maintained and increased carbon sinks also play a large role in Chile's strategy for achieving carbon neutrality. More broadly, Chile's LTS emphasizes crosscutting pillars tied to sustainability and justice, including the sustainable development goals, a just transition, water security, gender equality and equity, cost-efficiency, nature-based solutions, and considering local and traditional knowledge.

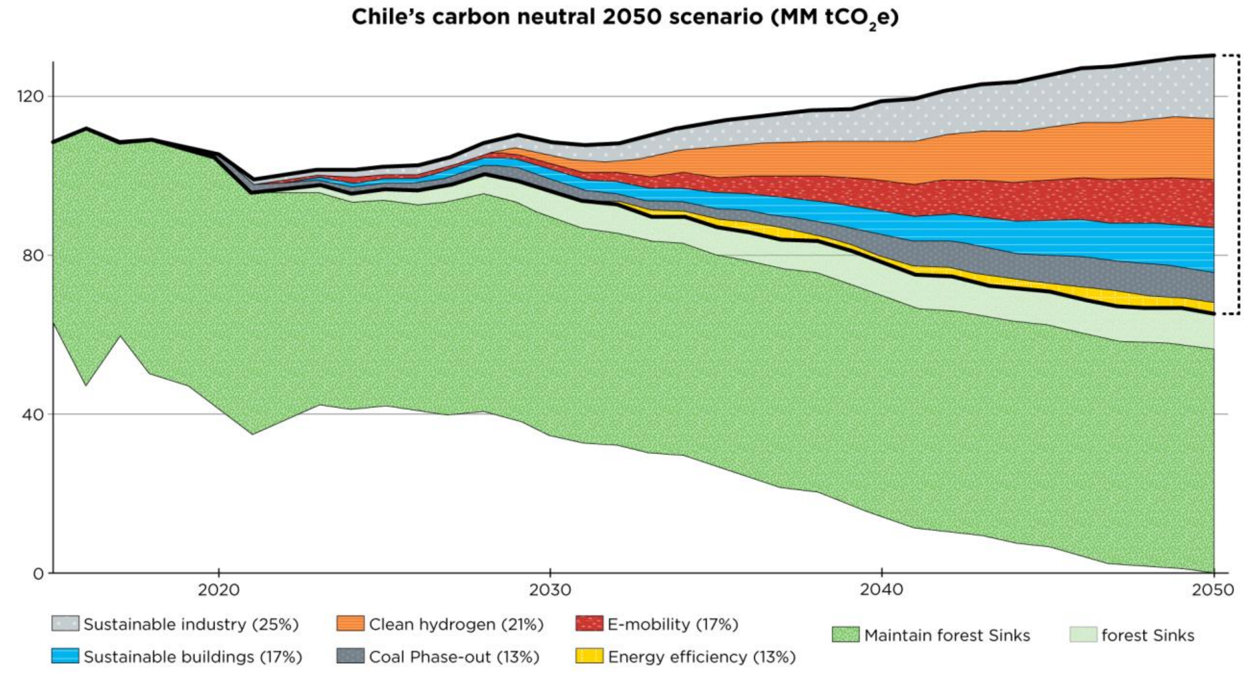

Figure 15. Chile's emissions trajectory for representative Carbon Neutral 2050 scenario

Source: Adapted from Ministerio de Energía 2020a

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[4] Under Chile's PELP process, which was established 2016, the Ministry of Energy must develop a long-term energy planning process for at least 30 years for different energy scenarios of the generation and consumption expansion. The second PELP process began in December 2020, for 2023–2027 (Ministerio de Energía 2021a/2020a).

[5] *Green* hydrogen is the preferred term of hydrogen generated from renewable energy resources. Others refer to it as *clean* hydrogen.

Figure 16 through **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.** show Chile's historical emissions by sector, total energy supply by resource, and final energy consumption (historical).

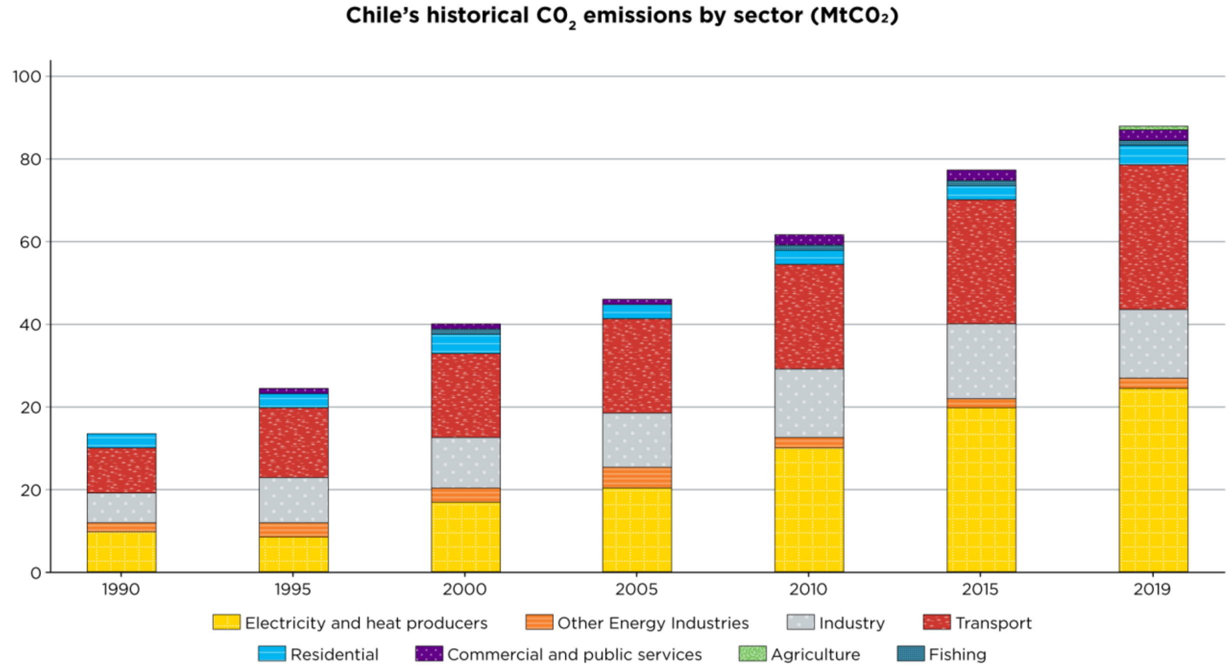

Figure 16. Chile's historical emissions by sector (IEA 2020)

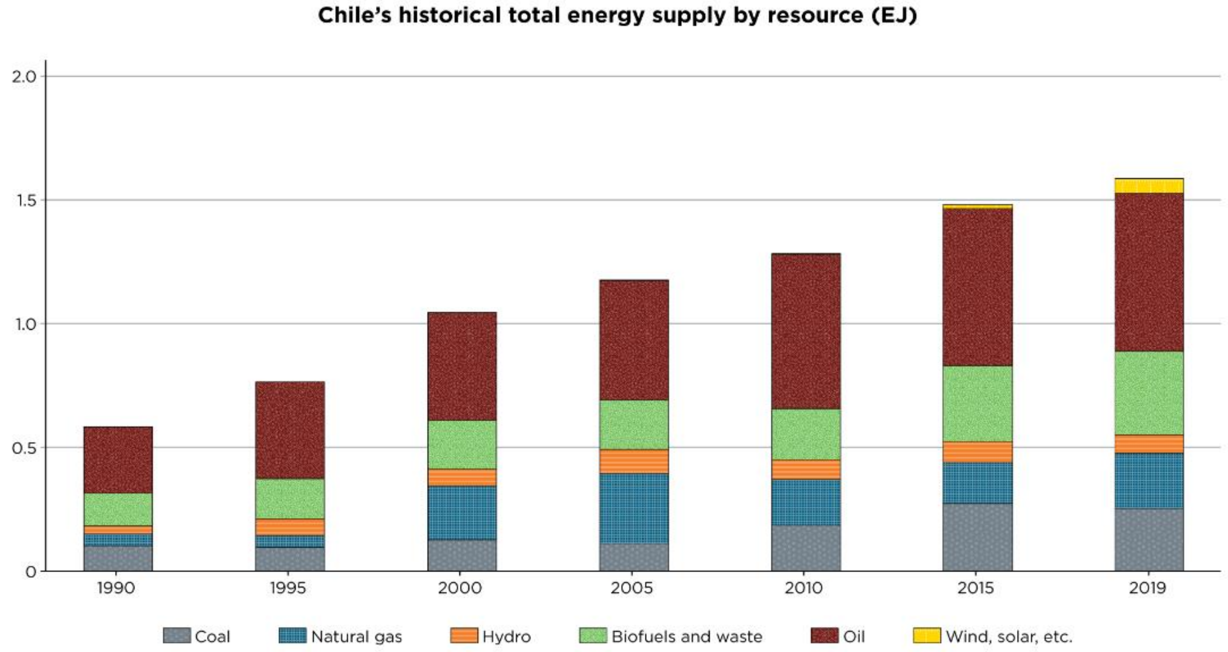

Figure 17. Chile's historical total energy supply by resource (IEA 2020)

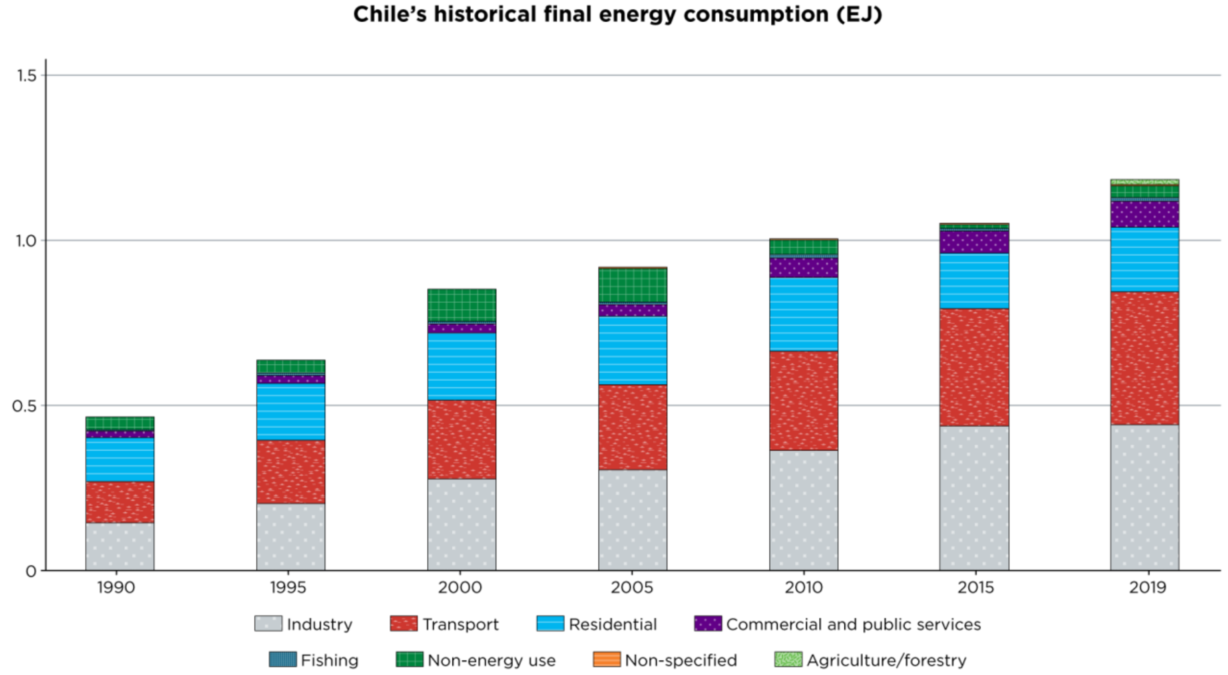

Figure 18. Chile's historical final energy consumption (IEA 2020)

3.2 Government Goals regarding Decarbonization

Chile's updated NDC has increased ambitions in all its components. The NDC update, which was submitted in 2020, was developed in parallel with the new climate change law (Ley Marco de Cambio *Climático (N°21455, 2022)*,[6] of June 2022, which establishes Chile's carbon neutrality commitment by 2050, along with other long-term objectives and actions toward a low-carbon economy. The updated NDC incorporates important pillars on social justice and sustainable development, which are called to guide the implementation of the new components and commitments. Building on its NDC, Chile submitted an LTS targeting a net-zero economy for 2050 (Gobeirno de Chile 2021). Based on current laws, Chile aims to achieve its GHG-neutral target by implementing policies that lead to a sustainable reduction of GHG emissions, and by increasing and maintaining its natural carbon sinks, which are estimated to be 65 $MtCO_2e$ in 2050 and to contribute to 50% of the emissions reduction required to achieve the 2050 net-zero target. The net-zero target covers all sectors (economy-wide) and gasses, and it defines end-use sector specific targets.

In addition to the NDC update, Chile has also developed the national green hydrogen strategy (Ministerio de Energía 2020b) as well as updated its electromobility strategy (Ministerio de Energía 2021b). For clean hydrogen, Chile aims to develop an electrolysis capacity of 5 GW by 2025 growing to 25 GW by 2030 and to be among the main clean hydrogen exporters by 2040. These strategies and targets are aligned with the updated NDC regarding the ambitious goals for hydrogen. For instance, 71% of freight transport demand is expected to be supplied by clean hydrogen by 2050. Regarding the electro-mobility strategy (Ministerio de Energía 2021b), the main goal establishes that by 2035, 100% of new sales in urban public transport, light and medium vehicles, and large mobile machinery will be zero emissions; by 2040, 100% of small mobile machinery sales will be zero emissions; and by 2045, 100% of freight transport and intercity buses will be zero emissions.

Nationally, various policy mechanisms have been identified to support the hydrogen and electro-mobility targets, some of which are not yet finalized. Chile's LTS also sets electric sector decarbonization goals of 80% renewable electricity generation by 2030 and 100% zero-emission generation by 2050. National policies further support power sector decarbonization. In a public-private agreement with energy companies, Chile has committed to retiring the eighteen coal-fired power plants (65% of the current coal-fired capacity) by 2025 and phasing out coal-based generation by 2040, though more ambitious timetables are under discussion and are modeled in Chile's PELP (Ministerio de Energía 2021a, 2020a). Between June 2019 and October 2022, eight coal units have already been retired.

3.3 Phase I Modeling Results

The Chilean Ministry of Energy currently uses LEAP for their scenario development and energy planning, alongside additional engineering models for the power sector and energy distribution. Chile's LEAP model represents 15 geographical regions of the country. It projects emission reductions resulting from user-defined technology turnover and captures energy efficiency

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[6] "Ley Marco de Cambio Climático," Ministerio del Medio Ambiente, https://www.bcn.cl/leychile/navegar?idNorma=1177286.

improvements and fuel switching mechanisms. Outputs from the energy model are manually transferred to a sophisticated electric sector model (AMEBA[7]), and additional agent-based and S-curve models are used for energy demand.

The Ministry of Energy team expressed interest in collaborating with the Net Zero World Initiative across various aspects of the modeling work, including optimization, improved understanding of seasonality (impacts of climate change), improved processes for linking LEAP with power system simulations, and expanded capabilities to cover industry, mining, and shipping, as well as cost projections within LEAP.

Based on the interests articulated by the Ministry of Energy, the Net Zero World Initiative team constructed a national-level LEAP model that builds on Chile's rich 15-region LEAP model and used it to assess technical potential for accelerating energy demand reductions in Chile's pathways toward 2050 carbon neutrality. The national-level aggregation enables the development of national policy and technology scenarios while capturing regional constraints through calibrated inputs. It also allows integration of energy demand and supply sectors within one framework to easily evaluate the impacts of power sector scenarios on CO_2 emissions and primary energy consumption.

In close collaboration with the Ministry of Energy, the Net Zero World Initiative team evaluated technical potential for demand reduction and introduction of alternative fuels or technologies across sectors of interest: industry (including mining), transportation (including shipping), and buildings. By working closely with teams from the Ministry of Energy, parameters of sectoral end-use technologies such as market shares and energy efficiencies were evaluated in developing and refining the scenarios, and detailed technology and policy assumptions were vetted by the Ministry of Energy team. Additional interests articulated by the Chilean Ministry of Energy can be addressed in future phases of modeling.

The LEAP model was *not* used to estimate cost-effectiveness of any measures using cost-benefit criteria. Rather, the demand modeling efforts were focused on quantifying and highlighting the technical potential in the demand sectors for future policy considerations. The LEAP framework can help identify remaining technical potential without specific cost constraints for each specific segment of the industry, transportation, and buildings sectors, and it can help highlight gaps between existing efficient and clean technologies and the best available technologies or practices. The bottom-up end-use nature of the LEAP framework provides energy and environmental results at the detailed end-use level, such as the impact of sectoral policies and technological transitions toward low-temperature heat electrification for industrial processes, freight electrification through battery electric and hydrogen fuel cell vehicles, and building envelope improvements to reduce heating and cooling loads.

Future energy demands were adopted from the PELP activities with the respective sectoral growth assumptions. Gross domestic product (GDP) projection was not used in the model to estimate future energy consumption. Rather, the model is based on PELP growth projections such as population, building floorspace, physical tons of industrial production, and vehicle stock

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[7] Details on AMEBA can be found at https://www.spec.cl/AmebaCloud/

that are aligned with Chile's projections. Future demand assumptions are kept constant across scenarios. The national LEAP modeling analysis for Chile examines a business-as-usual (BAU) case and a net-zero scenario described below, and it identifies opportunities for energy-related CO_2 emission reductions within each sector, in addition to the options already considered in the PELP (Ministerio de Energía 2021a, 2020a).[8] The two main scenarios are aligned with, and build on, the existing scenarios developed as part of the PELP process for 2023–2027:

- **Business-as-Usual (BAU) scenario**: This baseline scenario is consistent with the base cases used in recent PELP studies that consider the impact of all existing policies such as the NDCs, Chile's national electro-mobility strategy (Ministerio de Energía 2021b), and its energy efficiency law,[9] but the scenario assumes no significant future policy-induced technological changes.
- **Accelerated Net Zero scenario:** This scenario builds on the 2023–2027 PELP Accelerated Energy Transition scenario by evaluating additional sector actions that could be undertaken within each demand sector to further reduce energy demand and related CO_2 emissions, including new or aggressive energy efficiency improvement and additional electrification. This scenario includes scale-up of renewable energy resources.

Chile Insight 1: There is significant technical potential to reduce carbon in the demand sectors through accelerated energy efficiency improvements, electrification, and new zero-carbon fuel adoption. Cumulative measures can bend the emissions trajectory to reinforce and even surpass Chile's LTS targets by 2050. Cost feasibility of these measures will be examined in future phases of the study.

Significant CO_2 emission reduction potential is technically feasible through aggressive energy efficiency improvements, increased electrification, and additional new zero-carbon fuels that are not currently considered in the current PELP (Ministerio de Energía 2021a). These include solar heat for low-temperature applications and waste heat recovery technologies replacing fossil-based fuel. Under the BAU scenario, sectoral CO_2 emissions across all demand sectors are estimated to continue to increase through 2050, particularly in the industry and buildings sectors (BAU scenario, Figure 19**Error! Reference source not found.**). When applying aggressive energy efficiency and electrification measures and introducing new zero-carbon fuels (Net Zero scenario, Figure 19**Error! Reference source not found.**), buildings and industry emissions have the potential to decline rapidly beyond 2030. Buildings CO_2 emissions could decline to zero by 2050 with 100% electrification and clean grid assumptions. Industrial sectors have the potential of reductions across all types of fossil fuels with greater electrification and increasing hydrogen adoption, as well as reduced energy demand from efficiency improvements approaching global best practice benchmarks, resulting in 65% lower CO_2 in 2050 compared to 2020. Transportation

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[8] The Ministry of Energy expressed interest in modeling costs within LEAP to understand cost options of different scenarios. Due to the time required for data collection, cost optimization was not included in the Phase I modeling effort; however, this can be undertaken in the next phase of modeling.

[9] "President Piñera Enacts Energy Efficiency Law in the Los Lagos Region," Chile Ministry of Energy, February 8, 2021. https://energia.gob.cl/noticias/nacional/presidente-pinera-promulga-ley-de-eficiencia-energetica-en-la-region-de-los-lagos.

sector CO_2 emissions could continue to increase before 2030 under both scenarios due to activity growth, followed by a decline after 2030 due to efficiency gains, rapid electrification and hydrogen use beyond 2030 (especially in freight), including sustainable aviation fuel in later years. Under aggressive energy efficiency and clean fuels assumptions in the LEAP Net Zero scenario, total CO_2 emissions trajectory has the technical potential to reach as low as 20 $MtCO_2$ by 2050.

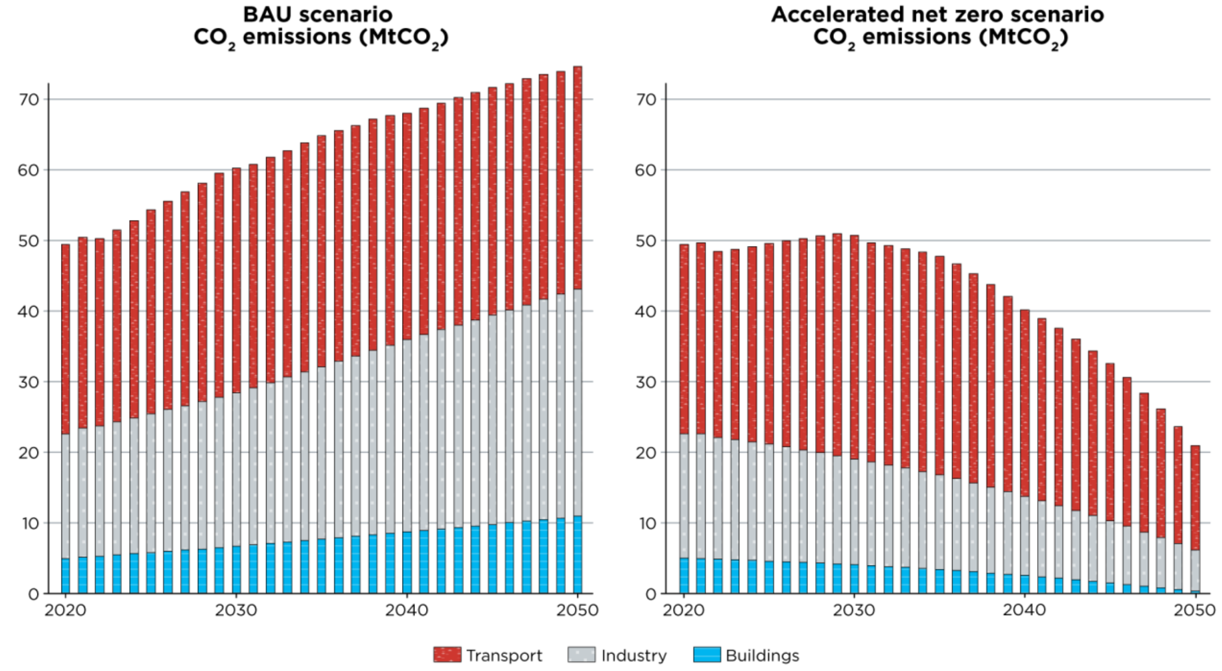

Figure 19. Chile's CO_2 emissions by sector, LEAP BAU (left) and Accelerated Net Zero scenarios (right)

Chile Insight 2: Natural gas and petroleum products remain in 2050 under the Accelerated Net Zero scenario but with lowered total primary energy demand and much less diesel.

Primary energy consumption is expected to grow, albeit at different paces, under both scenarios. By 2050, primary energy consumption is 38% higher than 2020 levels under the BAU scenario, but just 12% higher under the Accelerated Net Zero scenario (Figure 20**Error! Reference source not found.**). Solar and wind grow rapidly with continued reliance on hydropower in the power sector alongside coal phaseout under both scenarios, but at very different paces. Despite significant reductions in diesel under the Accelerated Net Zero scenario, petroleum products, including diesel, gasoline and jet kerosene remain the most-consumed fossil fuels in 2050 with a combined share of 18%. Natural gas grows under both scenarios, and biomass continues to play an important role in the energy system, particularly for the industrial sector, with 10% share of total primary energy consumption by 2050.

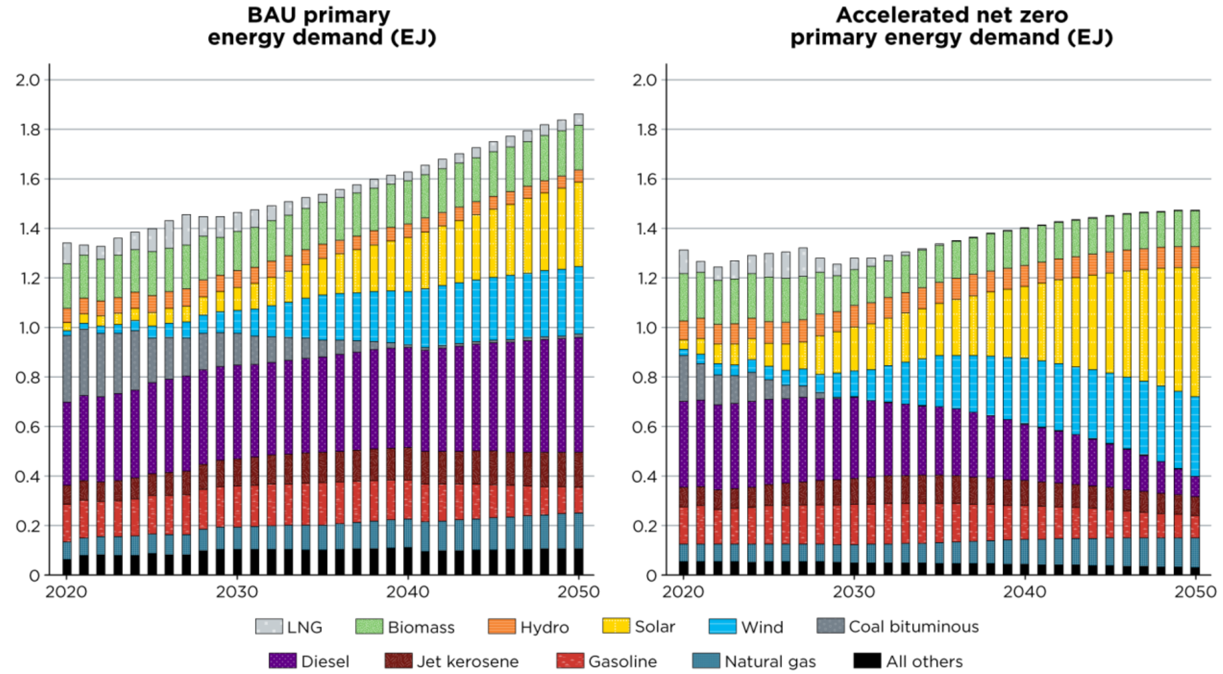

Figure 20. Chile’s primary energy consumption by fuel BAU (left) and LEAP Accelerated Net Zero scenarios (right)

“All others” include geothermal power, liquefied petroleum gas, kerosene, and coke.

Under the Accelerated Net Zero scenario, diesel is likely to be nearly eliminated in both the industrial sector (primarily from copper and other light industries) and the transportation sector (primarily from passenger road), with a remaining share of only 6% by 2050, compared to 24% under the BAU scenario (Figure 21**Error! Reference source not found.**). Additional reductions in gasoline and jet kerosene result from increased road electrification and a shift to clean hydrogen used in sustainable aviation fuel. Natural gas could be phased out in buildings with electrification and has the potential to be nearly phased out in industry, but it gains some use as a transition fuel in maritime transportation, where the potential for electrification remains limited.

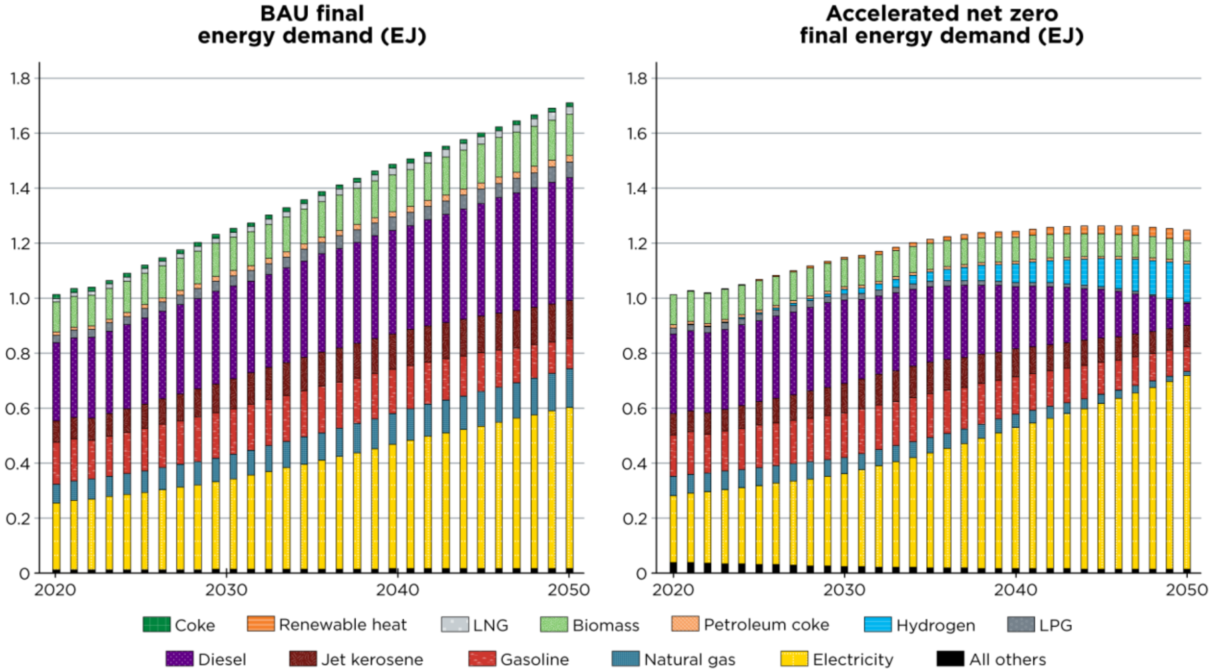

Figure 21. Chile's final energy demand by fuel, LEAP BAU (left) and Accelerated Net Zero scenarios (right)

"All others" includes coal, coal gas, kerosene, and municipal solid waste. International bunker fuel use is excluded from this analysis.

Chile Insight 3: Electricity demand growth in the highly electrified Accelerated Net Zero scenario is tempered by energy demand reductions and efficiency gains, and it is complemented by zero-carbon fuels.

Overall electrification levels are estimated to be similar before 2030 in both scenarios, but they occur at a faster rate after 2030 in the Net Zero scenario. By 2050, 56% overall electrification could be achieved with 195 terawatt-hours (TWh) of demand under the Accelerated Net Zero scenario as a result of both faster fuel-switching and lower levels of total energy demand; only 36% overall electrification (166 TWh) is achieved under the BAU scenario. New nonfossil alternative fuels such as renewable heat and hydrogen are also estimated to emerge in the Net Zero scenario, and they account for 3% and 11% shares, respectively, in 2050. Concurrently, renewables increase significantly, exceeding 250 TWh by 2050 in the Net Zero scenario.

3.3.1 High-Resolution Demand-Side Results

3.3.1.1 Transportation Sector

Chile Insight 4: Efficiency improvements and additional efficiency gains through electrification reduce transportation’s energy demand and emissions despite rising mobility activity, but the maritime and aviation subsectors are harder to decarbonize with lower emissions reductions.

Total final energy demand in the transportation sector continues to rise under the Reference scenario, but it peaks and declines to 11% below 2020 levels by 2050 under the Accelerated Net Zero scenario (Figure 22). This significant reduction in energy end-use consumption is realized despite a *2.5-fold increase in road transportation activity*. Under the Net Zero scenario, energy demand growth slows notably after 2030 as electrification begins to accelerate across all modes of road transport. This has dual benefits of contributing to (1) significant energy efficiency gains for all types of passenger and freight vehicles, and (2) decarbonization with an increasingly clean power sector. By 2050, road transport is 36% electrified with additional hydrogen share of 17%. For freight road transport, 100% of demand is met by battery electric vehicle (EV) technologies for light-duty trucks and a mix of battery electric and hydrogen fuel cell vehicle technologies for medium and heavy-duty trucks by 2050. Electrification also reduces passenger diesel consumption by 75% by 2050 compared to the BAU scenario. In passenger transport, full motorcycle electrification by 2050 is considered to further reduce gasoline consumption.

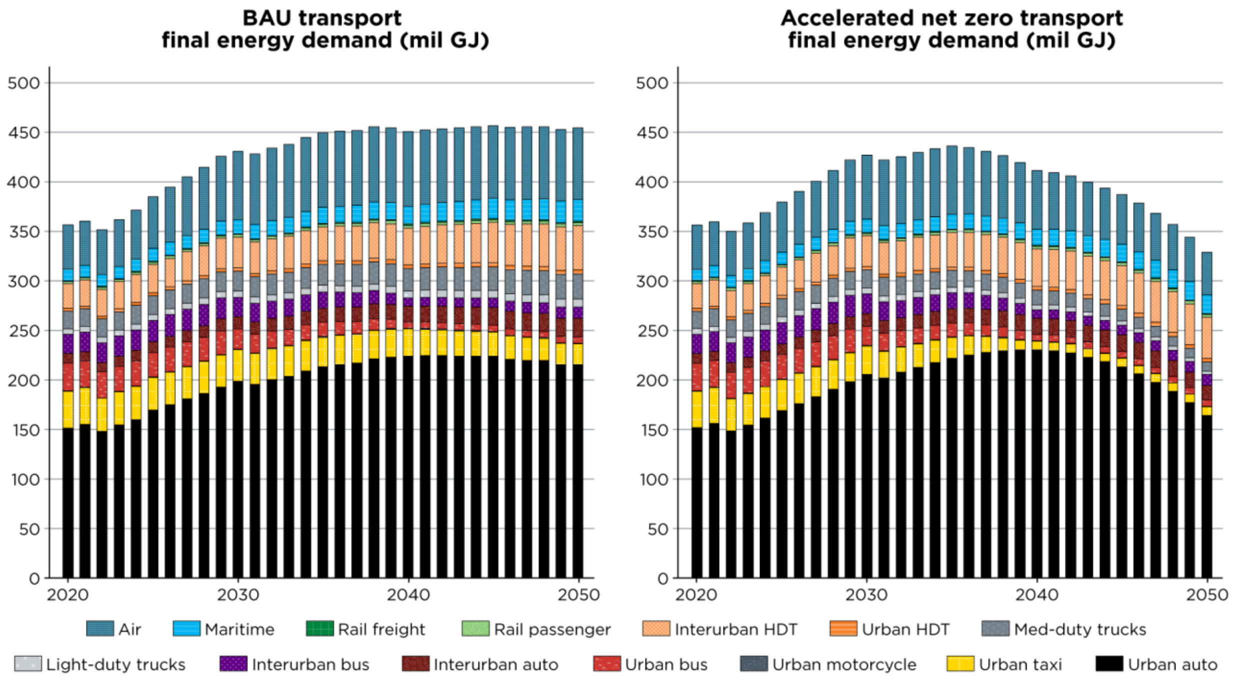

Figure 22. Chile’s transportation final energy demand in LEAP BAU (left) and Accelerated Net Zero scenarios (right)

Mobility efficiency improvements can play an additional role in emissions reductions. For example, road freight energy demand is further reduced by logistics improvements such as improved loading and dispatch optimization that reduces freight activity compared to the BAU scenario (IEA 2017). Additional reductions in maritime, rail, and air transport through energy efficiency measures such as performance optimization for rail and design improvements for ships and aircraft are included (Sharmina et al. 2020). For the harder-to-decarbonize modes of maritime and aviation, alternatives such as compressed natural gas for shipping and clean hydrogen for commercial aircraft help further reduce transport CO_2 emissions by 40% compared to 2020 levels under certain assumptions.

3.3.1.2 Industrial Sector

Chile Insight 5: Industrial decarbonization is possible through increased the adoption of electrotechnologies for specific process heating applications and the use of zero-carbon fuels for high-temperature applications.

Increased adoption of electrotechnologies when coupled with low-carbon electricity may have significant carbon reduction potential in the industrial sector, including industrial heat pumps to provide low-to-medium process heat (up to 165°Celsius) and electric boilers to electrify steam production (Schlosser et al. 2020; Schoeneberger 2022). Other electrotechnologies, such as electrical resistance heating, inductive heating, electric arcs, and infrared heating can provide process heating at a higher temperature for specific industrial processes (Rightor, Whitlock, and Elliott 2020). For the Chilean industry, the steel industry (through adoption of electric arc furnaces), the food and beverage industry, and other lower-temperature industries could be considered good candidates to apply electrification efforts. Under the Net Zero scenario, industry electrification can increase from 32% in 2020 to 41% by 2030 and 62% by 2050 (Figure 23**Error! Reference source not found.**), led by the copper industry and other industry segments (food, beverage, and textile) with low-temperature applications). Increased adoption of electrotechnologies indicates an increase in total electricity demand for the entire industrial sector, which grows from about 43 TWh in 2020 to 119 TWh in 2050.

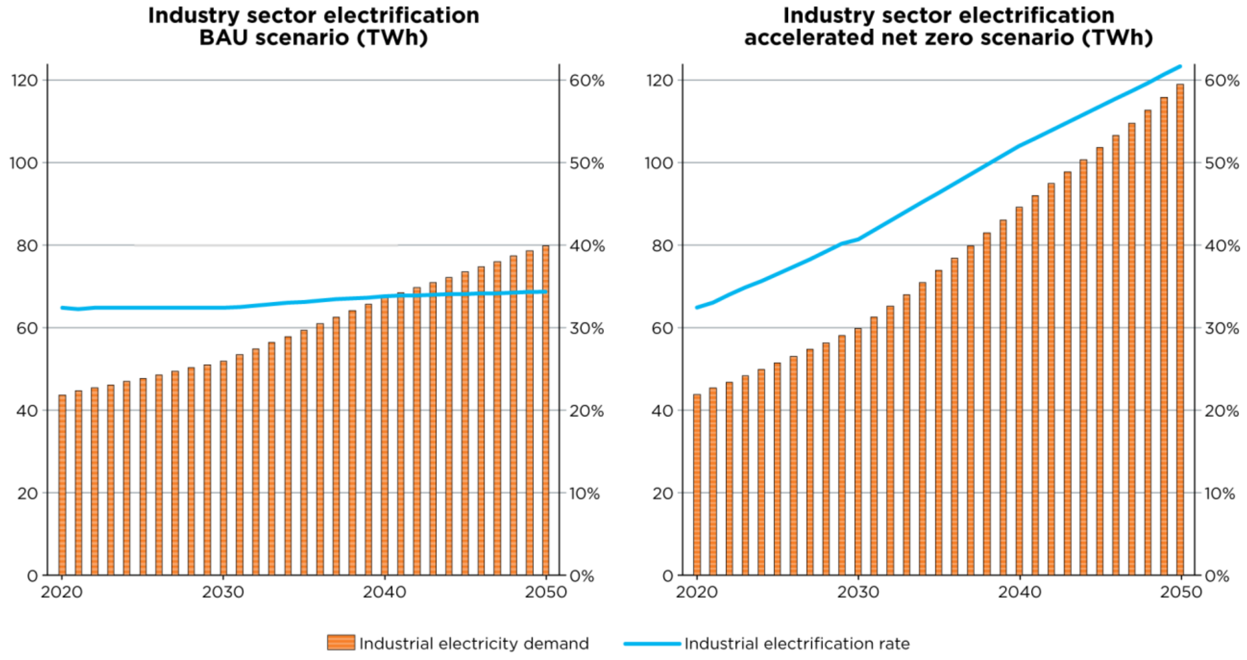

Figure 23. Chile's industrial sector electrification in LEAP BAU (left) and Accelerated Net Zero scenarios (right)

High-temperature applications, if fueled with zero-carbon fuels (bio-based or clean hydrogen), offer additional emission reduction potential. Under the Net Zero scenario, industrial sector fuel inputs are assumed to become more diversified and much less reliant on fossil fuels. Clean hydrogen can be used as a chemical feedstock in the ironmaking process to replace the use of metallurgical coal (for coke making) and can be injected as a fuel in cement production. Hydrogen consumption in industry begins to increase after 2030 and it account for about 9% of total industry final energy demand by 2050. Municipal solid waste, while not zero-carbon, can provide a lower-carbon fuel substitution to the petroleum coke currently used in the cement industry. Renewable heating technology, such as concentrated solar that can provide temperatures close to 1,000°C, is an emerging technology that has the potential to provide higher-temperature heat for industry.

3.3.1.3 Buildings Sector

Chile Insight 6: Buildings sector energy demand and GHG emissions are significantly reduced in the Net Zero scenario through stringent energy efficiency measures, appliance standards, and scale-up of net-zero buildings. Sector transformation is technically possible through electrification of traditional fossil fuel-based technologies.

The buildings sector is modeled using Chile's four key climate regions of the North, Central, South, and Far South to capture regional climatic characteristics. With continued population and economic growth, Chile's total building stock is expected to grow in the LEAP BAU scenario driven by (1) per capita living floor space growth in the residential sector and (2) per employee workspace growth in the commercial and public buildings sectors. Alongside this activity growth, final energy demand from commercial and residential buildings also grows, primarily due to thermal comfort requirements and increased use of home appliances.

In the BAU scenario, the new building annual energy use intensities nearly double for the residential sector, increasing by 44, 47, 42 kWh/m^2 from 2020 to 2050 in the North, Central, and South/Far South climate regions, respectively, and increases by 35, 30, 29 kWh/m^2 in the commercial sector. By applying stringent energy efficiency measures and appliance standards to reduce building energy demand and scale up net-zero energy buildings, the energy use intensity for residential and commercial sectors can be significantly reduced across all four climate regions, with reductions of 36, 40, 52 kWh/m^2 for residential, and 50, 53, 52 kWh/m^2 for the commercial sector for the North, Central, and South/Far South climate regions respectively.

Figure 24**Error! Reference source not found.** shows that the buildings sector's total energy demand in the BAU grows from 150 GJ in 2020 to 414 GJ in 2050; however, with energy-efficient buildings and appliances, *the final energy demand remains nearly flat* at 178 GJ in 2050 in the Net Zero scenario. Space heating demonstrates greater saving potentials through improved building envelope thermal integrity and heating electrification. In terms of CO_2 emission impacts, buildings sector emissions reaches almost zero by 2050 (as shown in Figure 1925 due to energy efficiency measures and electrification of heating, cooking and water heating that were formerly fossil fuel-based.

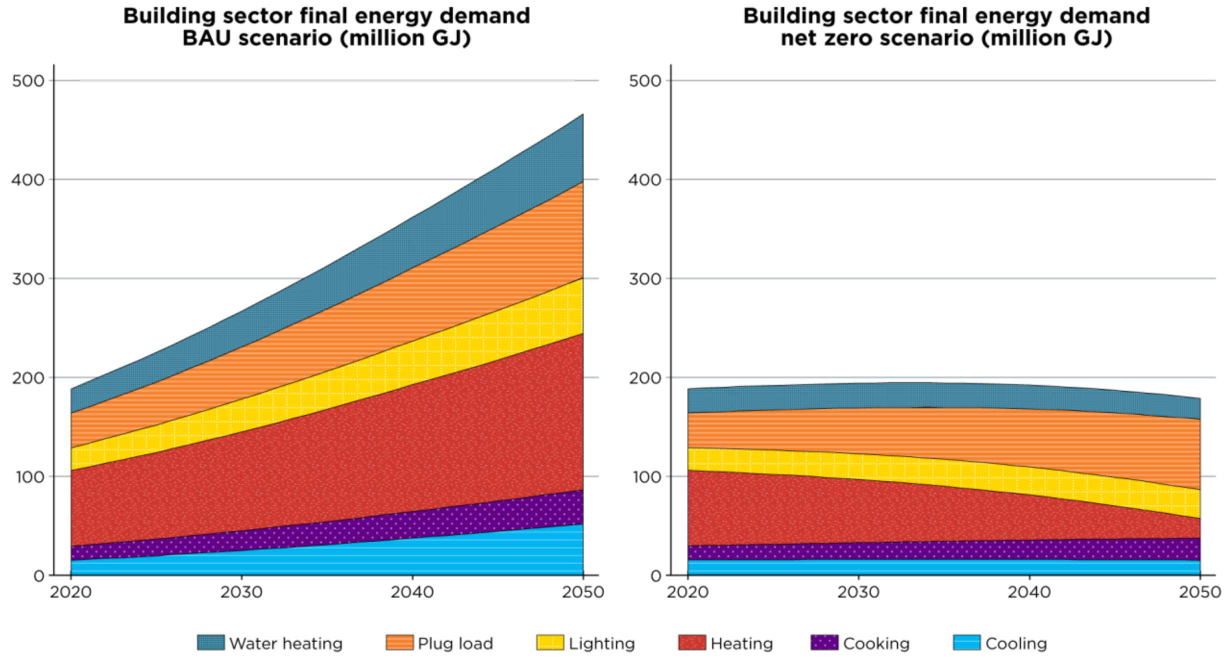

Figure 24. Chile's buildings sector final energy demand in BAU (left) and Net Zero scenarios (right)

Figure 25 shows the increasing role of electrification in the building sector under aggressive electrification assumptions. Electricity share of final energy demand increases from 45% to nearly 100% by 2050 under the Net Zero scenario. The total electrification phases out all fossil-based fuels (natural gas, fuel oil, and liquefied petroleum gas), which together accounted for 40% of building energy demand in 2020. As a key existing fuel for heating in the Central and South regions, biomass consumption declines slowly with the electrification of heating under the Net Zero scenario.

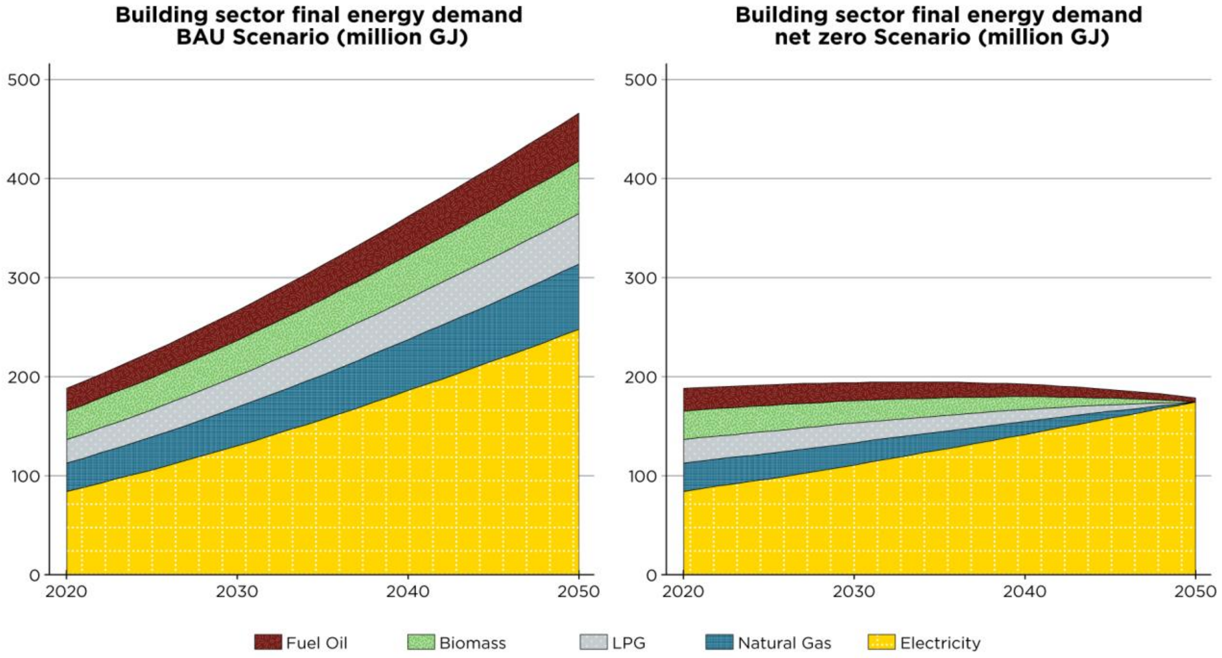

Figure 25. Chile's building sector final energy demand by fuel in BAU (left) and Net Zero (right) scenarios

A comprehensive table of energy efficiency and fuel switching measures by demand sectors is provided in Table B-1 in Appendix B.

3.3.2 Supply-Side Options for High-Demand Scenarios

In addition to LEAP, GCAM modeling was applied to integrate cost, technology, and socioeconomic assumptions from the PELP (Ministerio de Energía 2021a, 2020a) and to explore two pathways to decarbonization representing different technology focuses. Both pathways constrain all GHGs to meet Chile's positive emission goal of 65 $MtCO_2e$ in the LTS carbon neutrality scenario (Gobeirno de Chile 2021). They also model Chile's 2040 coal phaseout agreement, the national electro-mobility strategy (Ministerio de Energía 2021b), and key cost assumptions from the hydrogen strategy (Ministerio de Energía 2020b). The first decarbonization scenario, Net Zero RE-Focus, explores a focus on renewable energy where low-cost solar and wind energy support end-use electrification and biomass is largely limited to the buildings sector. These renewable cost assumptions are taken from the PELP low-cost case, and they exclude the use of CCS to align with Chile's internal modeling. The second decarbonization scenario, the Net Zero CCS-Focus scenario, is less constrained, with CCS playing a role throughout the economy. It serves as a useful counterpoint to explore how the adoption of CCS could change emissions and energy use throughout the economy. These scenarios are contrasted against a BAU scenario where emissions are unconstrained without any emission reduction measures. This scenario serves as a reference scenario for comparison reasons. It assumes the continued use of coal fired electricity generation recognizing that commitments for coal plant retirement through 2025 exist.

Chile Insight 7: Full implementation of the 2040 coal generation phaseout and the national electro-mobility strategy result in steep emissions reductions in both net-zero scenarios and in Chile nearly reaching the LTS goal by 2035.

The simultaneous phase out of coal generation and scale up in wind and solar technologies are essential contributors to the CO_2 emission reductions with immediate impacts in the scenarios, nearly meeting the GHG goals by 2035 (see Figure 26). Overall similar GHG reduction trajectories across the two reduction scenarios with slightly lower GHG emission in 2050 for the CCS-Focus scenario by adopting small contributions of Biomass with CCS contribution in the later years resulting in negative emissions. The sufficiency of available biomass feedstock will need to be further analyzed in follow-on work.

The Net Zero CCS-Focus scenario has smaller CO_2 reductions in industry (16%), buildings (43%), and transportation (11%) emissions than the Net Zero RE-Focus scenario. The large scale-up in wind and solar technology in the Net Zero RE-Focus scenario induces higher levels of electrification compared to the CCS-Focus scenario. In both scenarios, transportation emissions are strongly reduced (67% under the Net Zero CCS-Focus scenario and 71% under the Net Zero RE-Focus scenario) compared to the BAU case, showing the influence of the national electro-mobility strategy (Ministerio de Energía 2021b) in decarbonizing the transportation sector.

Figure 26 shows emission trajectories for the three scenarios investigated.

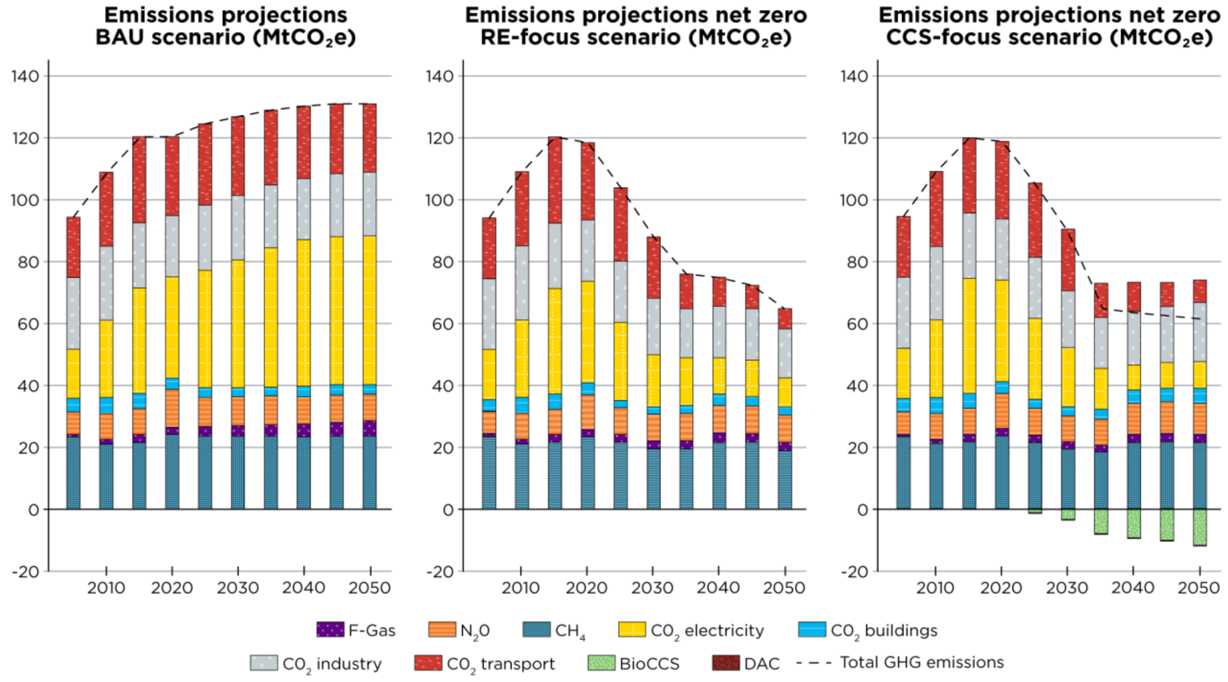

Figure 26. Chile's emissions trajectories

DAC is direct air capture technology, which extracts CO_2 directly from the atmosphere.

Chile Insight 8: Decarbonizing the electric sector can be a cost-effective way to meet Chile's emission targets. Investments for large increases in clean electric generation are required

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Comparisons of both decarbonization scenarios to the BAU scenario emphasize that decarbonizing the electric sector is a cost-effective way to meet Chile's emission targets, with overall emissions decreasing to ≈65 $MtCO_2e$ for the decarbonization scenarios. In the GCAM decarbonization pathways, emission reductions in the electric sector underpin Chile's progress toward its emission target. Under Chile's coal phaseout, which is modeled in the decarbonization scenarios, coal is largely replaced by wind and solar. In the Net Zero CCS-Focus scenario, fossil fuels make up a slightly larger share than in the Net Zero RE-Focus scenario (0.100 EJ opposed to 0.035 EJ in 2050). Unabated gas-powered generation remains in both scenarios, balancing the surge in intermittent generation. The Net Zero RE-Focus scenario has higher electricity generation overall (an additional 0.1 EJ by 2050), reflecting the heightened economy-wide electrification that occurs when CCS is not available.

Figure 27 shows the electricity generation for the three scenarios investigated.

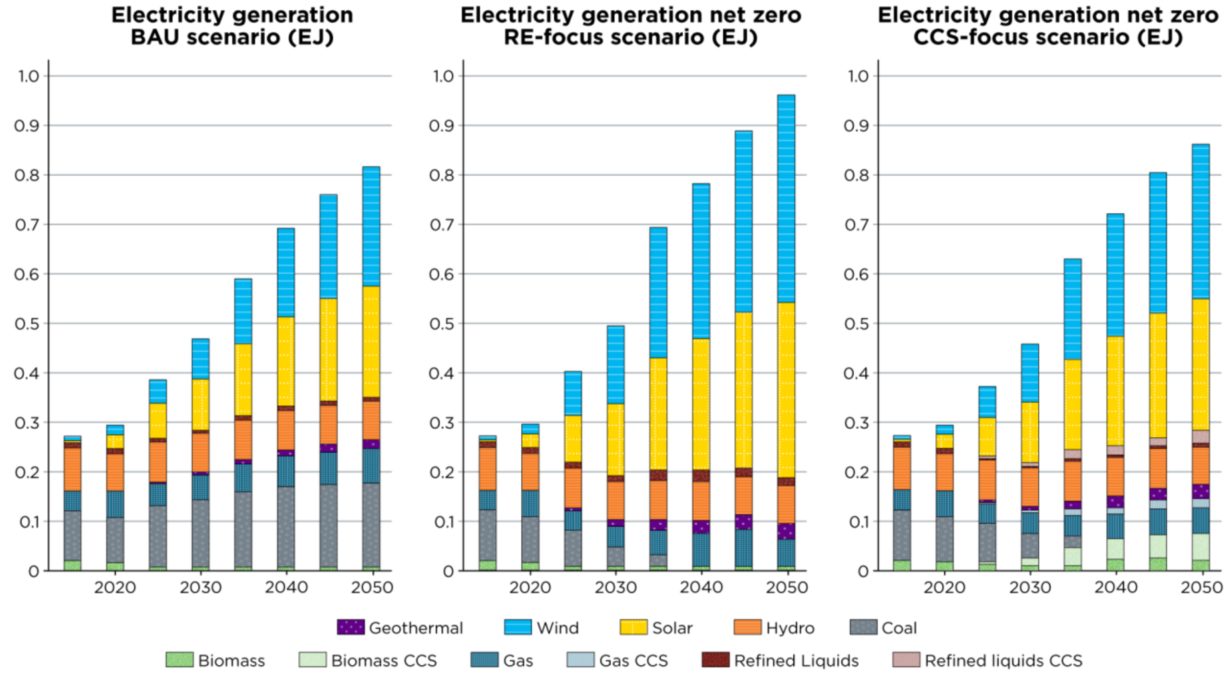

Figure 27. Chile's electric generation trajectories

Across scenarios, Chile continues to see capacity additions and commensurate investment in the electric sector. In the BAU scenario, approximately $67 billion is invested from 2020 to 2050, with spending dominated by investments in coal and solar. In the Net Zero RE-Focus scenario, low-cost renewable assumptions keep investment costs to $72 billion, and spending on solar ($23 billion) and wind ($21 billion) nearly doubles the BAU scenario. The Net Zero CCS-Focus scenario totals $94 billion, with investments in renewables matching the Net Zero RE-Focus scenario and investments in new bioenergy with CCS capacity totaling $27 billion. Figure 28 shows the cumulative investments in the electric sector by generation technology. It should be noted that the cost for Biomass with CCS technology represents high uncertainties as the cost for the removal and storage system can vary widely. The large investment of Biomass with CCS compared to the natural gas with CCS may be considered very optimistic and needs to be further analyzed in follow-on work.

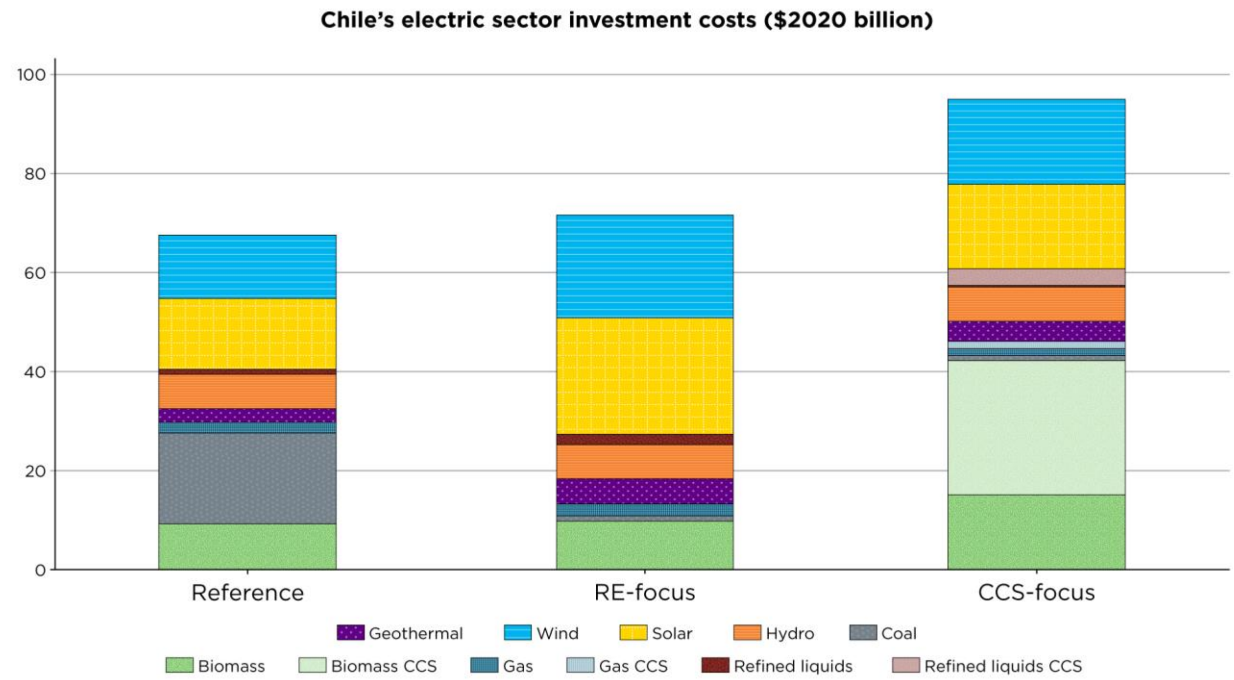

Figure 28. Chile's electric sector investment costs, 2020–2050

3.3.2.1 Technology Highlights: Hydrogen

Chile's interest in clean hydrogen provides a key element of the country's decarbonization strategy. Its hydrogen strategy (Ministerio de Energía 2020b) was modeled in GCAM with an optimistic assumption that cost parity with fossil-fueled vehicles (trucks, buses, mining machinery) could be reached by 2035. Further assumptions included continuing cost reductions in electrolyzer technologies over the projection horizon. Given these assumptions, an increase in hydrogen consumption could be significant (233% under the Net Zero CCS-Focus scenario and 144% under the Net Zero RE-Focus scenario). Additional inroads of hydrogen, though small, are likely in the industrial sector with cement and other heat applications by 2050. Hydrogen use may almost double in the Net Zero CCS-Focus scenario (0.034 EJ), partly because of low-emission hydrogen production from natural gas coupled with CCS technology.

Figure 29 shows the estimated hydrogen consumptions for three scenarios investigated

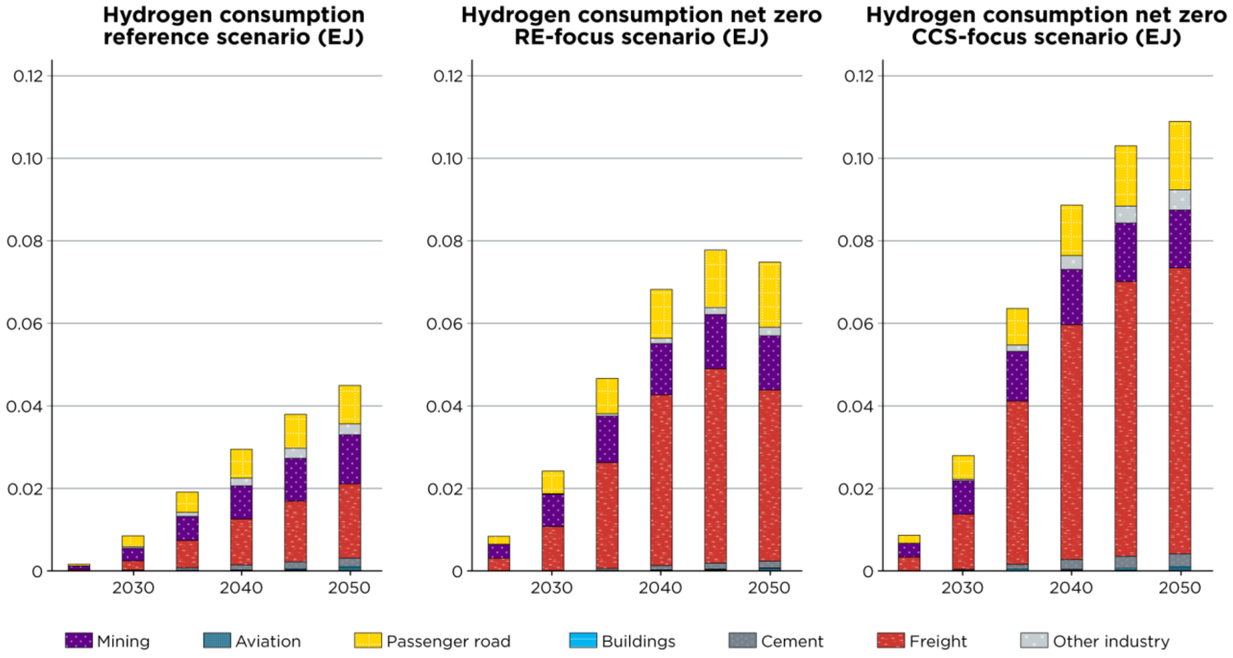

Figure 29. Chile's estimated hydrogen consumption

3.3.2.2 Technology Highlights: Carbon Capture and Storage

CCS technology is not currently operating in Chile, so the future of CCS is somewhat uncertain and useful to explore as a separate scenario. In the Net Zero CCS-Focus scenario, CCS is largely confined to the electric sector, where it can achieve negative emissions when paired with biomass. These negative emissions allow Chile to reach its emissions target several years early, thus lowering cumulative emissions but slowing decarbonization in other sectors and prolonging the use of fossil fuels. In the Net Zero CCS-Focus scenario, CCS also plays a role in industry and hydrogen production, playing a small role in hard-to-decarbonize industrial production processes. Figure 30 shows estimated potential of CCS technology in sectors for the CCS-Focus scenario.

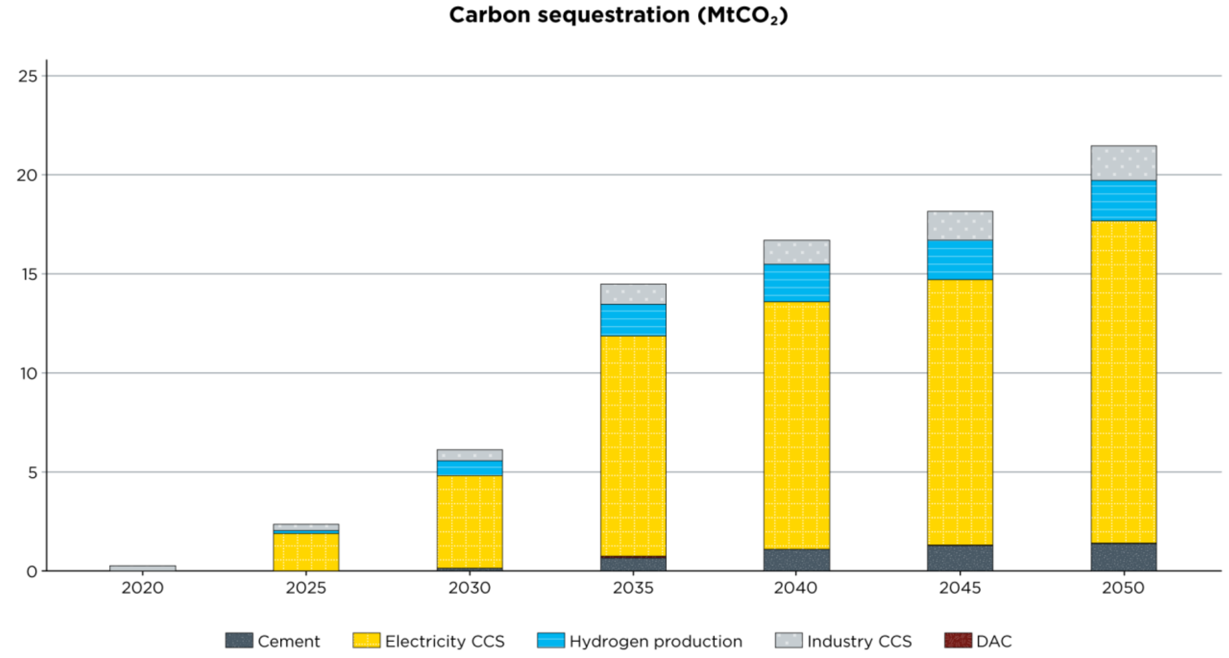

Figure 30. Chile's CCS potential for the Net Zero CCS-Focus scenario

3.4 Lessons Learned from the Modeling and Potential Value of Results

The high-resolution demand analysis for Chile modeled in LEAP indicates significant CO_2 emission reduction potential by applying aggressive energy efficiency improvements along with additional electrification and alternative fuels not currently considered in the PELP (Ministerio de Energía 2021a), including renewable heat and municipal solid waste use in industry and liquid natural gas for shipping. These measures lead to a rapid decline of emissions from the industrial, transportation, and buildings sectors that allow Chile to exceed 2050 targets in its LTS (Gobeirno de Chile 2021). The analysis for Chile identifies the significant potential of existing commercialized technologies while recognizing that this potential will require a host of supporting factors to overcome deployment barriers. GCAM results suggest that, in the absence of demand reduction measures, CCS and hydrogen deployment could offset a high-demand emissions trajectory requiring additional infrastructure investments. Additionally, GCAM scenarios illustrate strong sectoral policies for electro-mobility, coal phaseout, and hydrogen could bring the LTS target within reach.

4 Egypt: Preliminary Modeling Results

Building on several recent memoranda of understanding with major companies to build pilot projects and explore the potential of electrifying ammonia production via clean hydrogen production, and leveraging a recent report by the Oxford Institute for Energy Studies on Egypt's low-carbon hydrogen development prospects that primarily examined the domestic market for hydrogen (Habib and Ouki 2021), we focused our scenario analyses on Egypt's potential for renewable power expansion and its utilization for clean ammonia/hydrogen exports. Our goal was to build on these recent developments and provide new strategic insights by analyzing opportunities related to clean ammonia/hydrogen production and exports. Using an optimization model that represents global energy markets allowed us to explore market opportunities for Egypt to export ammonia/hydrogen into international clean fuels markets. Global and regional market size and price dynamics for ammonia/hydrogen commodities were modeled to reveal insights into Egypt's competitiveness in emerging regional and global clean fuel markets. Egypt's ammonia/hydrogen potential would allow Egypt not only to decarbonize its energy sector but also contribute to the decarbonization of other countries by exporting clean energy to the global markets.

4.1 Overview: Emissions and Energy Situation

Egypt is the second-largest country in Africa, with a population of ≈104 million people spread over a narrow band of its ≈1 million km^2 inhabited area around the Nile River that runs south to north, ending in the Mediterranean Sea. Egypt's GDP is approximately $363 billion (54% services, 34% industry, and 12% agriculture). Imports are ≈20% of its GDP, and exports are ≈9%.[10]

The United States is the third-largest foreign investor in Egypt, with $1.37 billion invested in 2019, trailing only the UK and Belgium, with $6.8 and $2.2 billion invested in 2019 respectively. The total (cumulative) stock of U.S. foreign direct investment is nearly $24 billion, with $20 billion concentrated in the oil and gas sector. Overall, nearly 75% of Egypt's foreign direct investment goes to the oil and gas sector.

As shown in Figure 31, Egypt consumed over 1,000 TWh, or 3,600 petajoules (PJ), of primary energy in 2021, 57% of which was natural gas, 37% petroleum oil, 1% coal, and 5% renewables (hydropower, wind, and solar), with electricity generation being the major consumer of natural gas. Electricity production in Egypt exceeded 200 TWh in 2021, with 76% of the generation being sourced from natural gas, 14% from petroleum oil, 7% hydropower, 2% wind and 1% solar.[11] Thus, the total share of renewable power generation in Egypt is ≈10%. However, the total renewable power generation resources in Egypt exceed 90 GW (≈55 GW solar and ≈35 GW wind),[12] more than the entire current generation capacity of 60 GW.

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[10] "Egypt GDP: Composition by Sector," https://www.indexmundi.com/egypt/gdp_composition_by_sector.html. Accessed October 2022.

[11] "Egypt: Energy Country Profile," Our World in Data, by Hannah Ritchie and Max Roser, https://ourworldindata.org/energy/country/egypt. Accessed October 2022.

[12] Presentation by Rehab Bedar, Egypt, at the International Atomic Energy Agency, April 20–22, 2022.

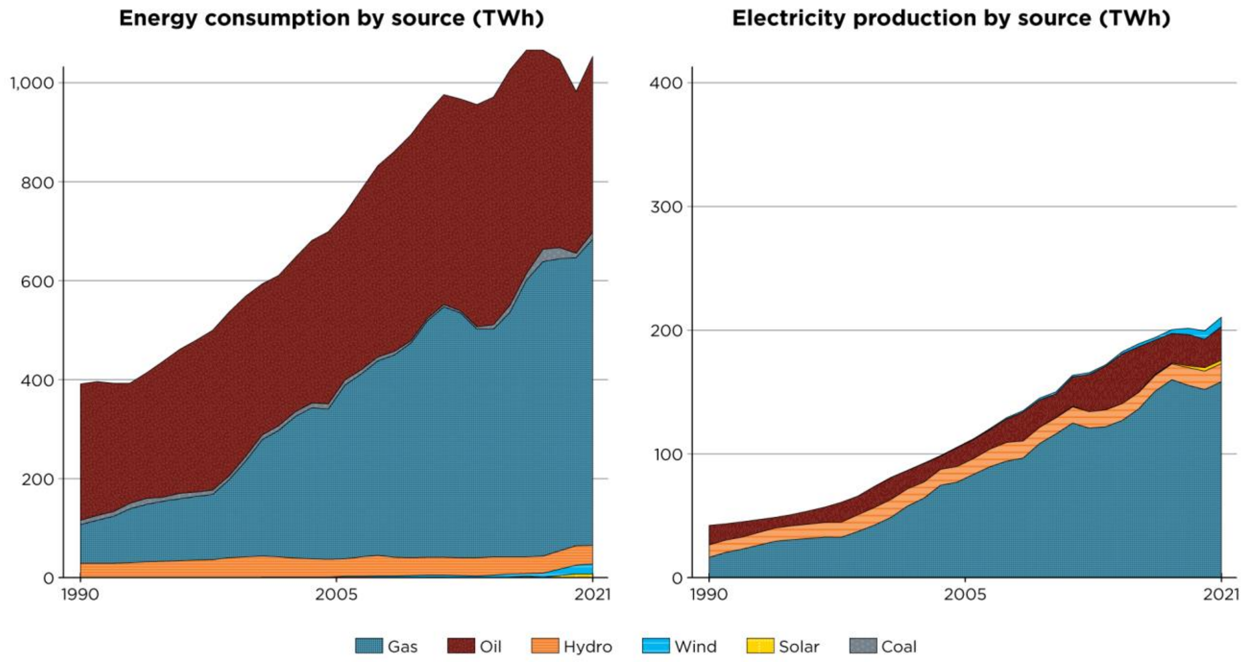

Figure 31. Egypt's historical primary energy consumption and electricity production by fuel

In 2018, Egypt emitted ≈250 million metric tons (MMT) of fossil CO_2 (Crippa et al. 2019). That year, the power sector contributed 40%, the transportation sector 20%, the industrial sector 15%, the buildings sector 5%, and 20% came from all other remaining sectors (Figure 32). In addition to CO_2, Egypt emitted ≈70 MMT of CO_{2e} in the form of methane emissions.

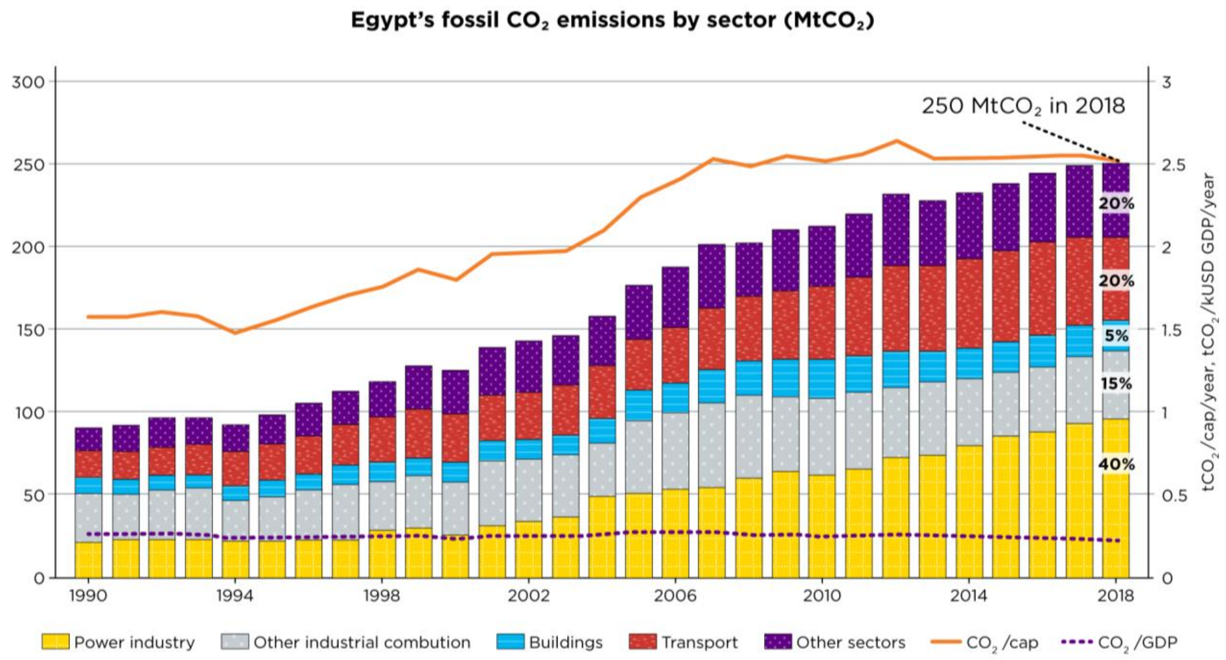

Figure 32. Egypt's fossil CO_2 emissions by sector

The above overview suggests Egypt has significant potential for decarbonization across sectors due to its large renewable resources and opportunities for methane emissions mitigation, CCS, and buildings efficiency gains. In particular, the renewable electricity potential could potentially extend beyond decarbonization of the power sector to decarbonization of the transportation and industrial applications via direct and indirect electrification. For example, Egypt recently deployed the world's largest solar power generation plant with 1.9 GW capacity in Benban of the Aswan Governorate.[13] Further deployment of renewable power generation provides the potential for clean energy production (e.g., clean hydrogen and ammonia) to decarbonize other energy sectors as well as the potential to export these clean energy carriers to global markets.

4.2 Government Goals regarding Decarbonization

Egypt is party to the Paris Agreement of 2015 and has submitted an NDC. However, the NDC does not include any specific GHG mitigation targets and all mitigation action is conditional on receipt of international aid. Mitigation focus areas vary by sector and include end-use energy efficiency, renewable energy, more efficient fossil fuel technologies, nuclear power generation, switching transportation modes, and energy subsidy reforms.[14]

More recently, Egypt announced several memoranda of understanding with major companies to explore the potential of electrifying ammonia production via clean hydrogen production. Notably, Egypt announced an initial phase of a project to produce 300,000 tons of green

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[13] "Giant Solar Park in the Desert Jump Starts Egypt's Renewables Push," Reuters, by Aidan Lewis, December 17, 2019, https://www.reuters.com/article/us-egypt-solar/giant-solar-park-in-the-desert-jump-starts-egypts-renewables-push-idUSKBN1YL1WS.

[14] Egypt, "Climate Policy Tracker, https://climatepolicytracker.org/countries/egypt/. Accessed October 2022.

ammonia annually in the region around Ein Sokhna, with a plan to ramp up ammonia production to 1.5 million tons per year.[15] The project will rely on green power supply to split water into hydrogen and oxygen via electrolysis.[16] A recent report on Egypt's low-carbon hydrogen development prospects (Habib and Ouki 2021) suggests concerns about future natural gas supplies lead to opportunities for clean hydrogen via electrolysis. The study suggests this low-carbon hydrogen strategy should start in the near term.

The Net Zero World Initiative can provide significant technical and investment support for Egypt to explore the various opportunities to decarbonize its economy and grow its energy sector using renewable and low-carbon technologies. In particular, the initiative can support advanced, next generation technology deployment and building on a joint research program of the U.S. Agency for International Development work and the U.S. Department of State by establishing a joint technology analysis, testing, and validation partnerships with Egypt's technical institutions and U.S. national laboratories. Such partnerships will support Egypt's priorities for energy sector decarbonization, including expansion of renewable power, buildings energy efficiency, clean hydrogen and ammonia production, methane emissions mitigation, and CCS.

4.3 Preliminary Phase I Modeling Results

The analysis was conducted in the 27-region global TIMES[17] Integrated Assessment Model. TIMES is a full-sector cost-optimization modeling framework that integrates assumptions across fuel, technology, and policy uncertainties to understand how the entire energy system responds to different incentives, explore the technology and market risks of policy options, and develop strategies to mitigate these risks. We focused our scenario analysis on Egypt's future hydrogen export potential, as this can expand on recent modeling efforts and provide additional strategic insights. Application of the TIMES Integrated Assessment Model was particularly valuable for exploring market opportunities to export hydrogen in a decarbonizing world, as it allows users to derive the global and regional market size and price of hydrogen endogenously and explicitly.

Egypt was broken out as its own region in the global model. A core Net Zero scenario and several sensitivity cases included a global cumulative energy-related carbon emissions constraint consistent with a 50% chance of maximum warming of 1.5°C. All regions were also required to individually achieve net-zero emissions (defined as 3% of 2019 emissions) by 2050. Biomass with CCS and direct air capture were available as negative emissions technologies. Additionally, a Reference case (No New Carbon Policies scenario) was run, in which recent historical trends in energy production and consumption are continued. All scenarios were driven by the IPCC Shared Socioeconomic Pathways (SSP2) GDP and population projections.

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[15] Egypt, Total Energies Sign MoU to Produce 300K Tons of Green Ammonia in Sokhna Region," Egypt Today, https://www.egypttoday.com/Article/3/115745/Egypt-Total-Energies-sign-MoU-to-produce-300K-tons-of. Accessed October 2022.

[16] In fact, Egypt is one of the leading countries that produced clean ammonia in the early 1960s using hydropower from the Aswan Dam to electrolyze water and produce clean hydrogen, which was combined with nitrogen from air in a Haber-Bosch process to synthesize green ammonia (this plant was recently retired).

[17] TIMES is The Integrated MARKAL-EFOM System. For more information, see https://iea-etsap.org/index.php/etsap-tools/model-generators/times.

Egypt Insight 1: In the Net Zero scenario, emissions decrease gradually into the 2040s as the power sector decarbonizes before meeting the net-zero target in 2050 with the buildings and light-duty vehicle sectors fully electrified. CCS, as well as advanced direct air capture technology, may become necessary to offset remaining emissions from industry and transportation.

Figure 33 shows the annual energy-related CO_2 emissions in the Net Zero scenario. Emissions level off in the 2020s and decrease gradually into the 2040s before the net-zero target is met in 2050. The power sector is first to decarbonize, with additions of wind and solar beginning in the mid-2020s and gas beginning with CCS in the mid-2030s. Electrification of light-duty vehicles begins in the mid-2020s, and they are fully electrified by 2050, along with all end-use loads in the buildings sector. Industry and heavy vehicles and aviation are slowest to decarbonize, with remaining emissions in these sectors being offset by CCS and direct air capture in 2050.

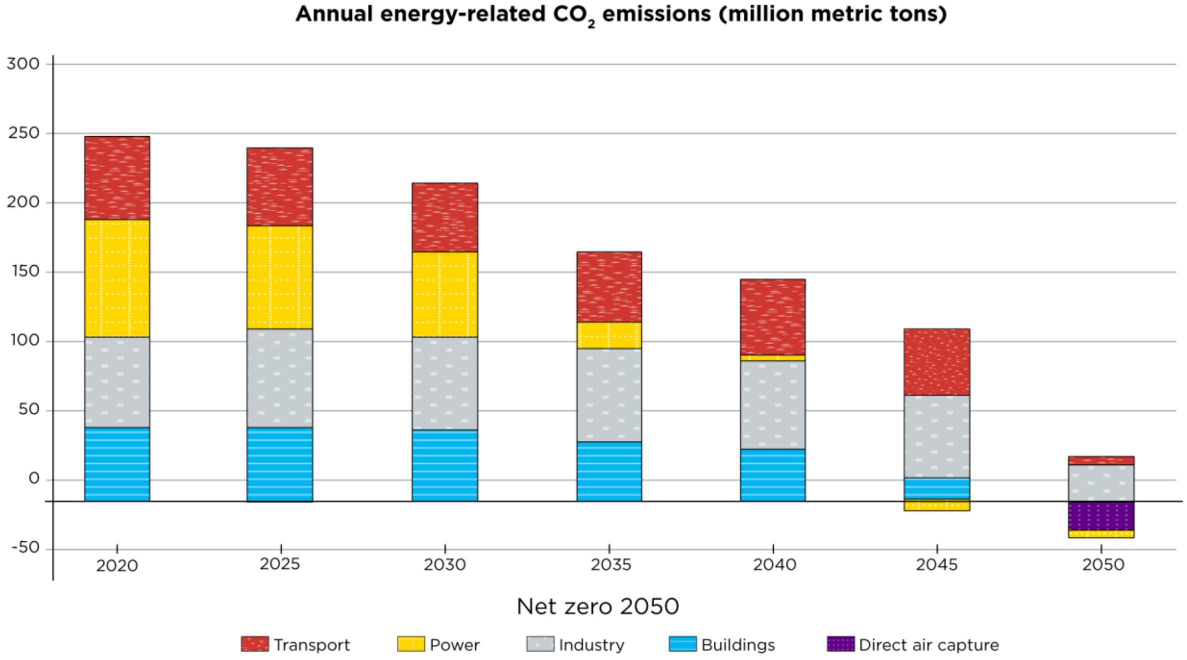

Figure 33. Egypt’s emission projections

Egypt Insight 2: Under the Net Zero scenario, Egypt's primary energy mix shifts significantly to renewables (solar and wind) for meeting both the domestic clean energy needs, as well as for exporting clean hydrogen. Gas consumption drops by about half with the remaining gas used in the industry and power sectors, much of it with CCS, as well as noncombustion chemical feedstocks. Almost 60% of final energy consumption comes from clean electricity and hydrogen.

Figure 34 illustrates Egypt's primary energy supply in the Net Zero scenario and clearly shows the share of renewables increasing from around 6% in 2020 to more than 75% by 2050. Oil consumption decreases by ≈80%, and most of the remaining consumption is for noncombustion feedstock uses, along with some continued combustion in heavy and nonroad vehicles. Gas consumption is cut roughly in half, with remaining use in industry and power, much of it with CCS, as well as for noncombustion chemical feedstocks. Hydrogen exports begin in 2040.

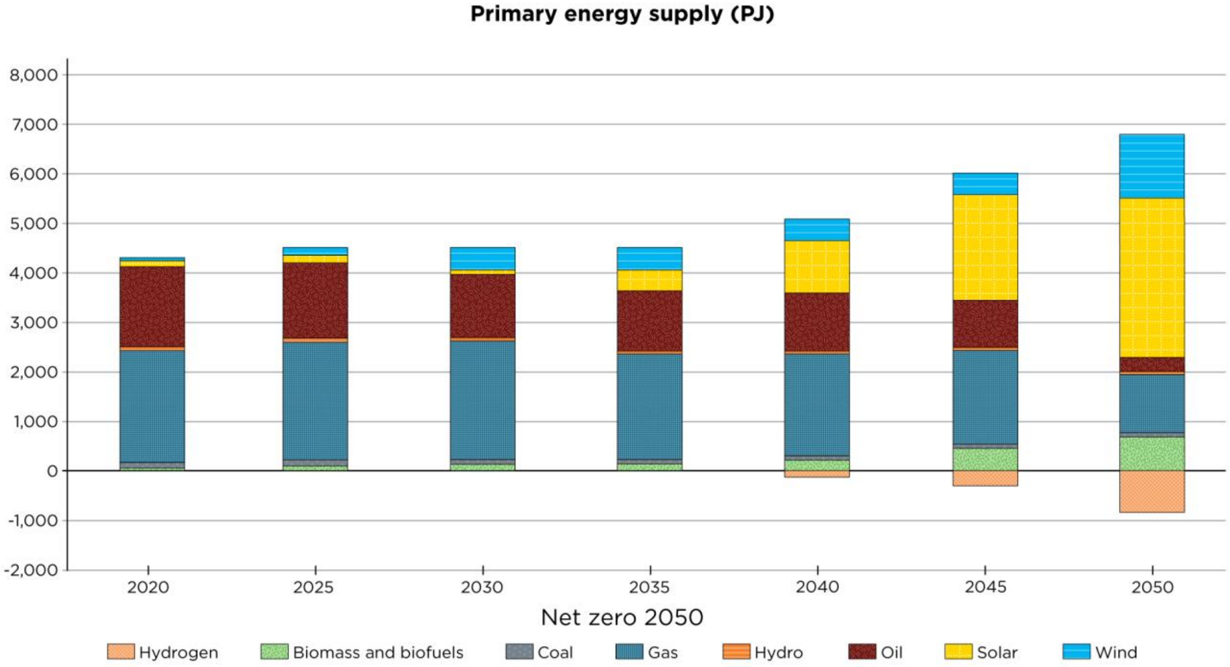

Figure 34. Egypt's primary energy supply

The share of electricity in final energy consumption (Figure 35 more than doubles from 18% in 2020 to 47% by 2050, as buildings, industry, and additional transport modes are electrified. There is also growing of use of modern solid biomass and hydrogen in industry. The main use of biomass is as alternative fuel in the cement industry and as input to other industries (mainly sugar factories). Hydrogen use begins in 2035 and grows to nearly a quarter of industrial fuel by 2050, where it is used in the iron and steel industry, for heat production in the cement and ceramics industry, and in other industries. There is also some use of hydrogen for heavy and nonroad transport. Oil combustion is nearly phased out by 2050.

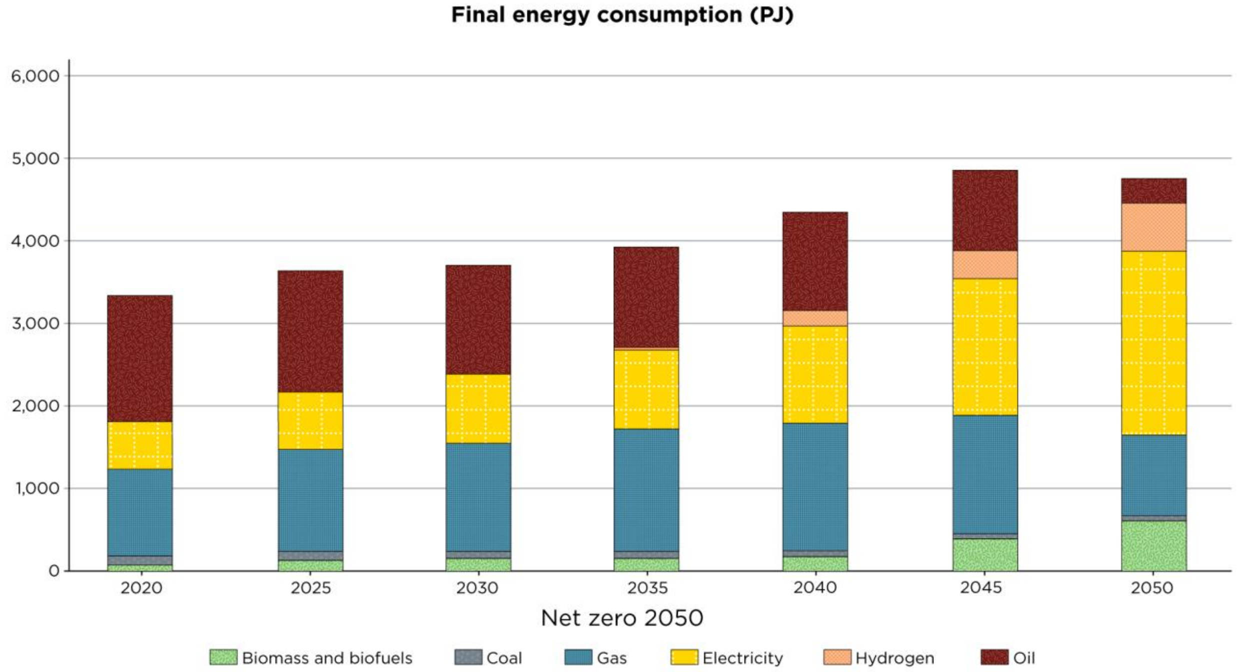

Figure 35. Egypt's final energy

4.3.1 Sector Highlights: Electricity Demand and Supply

Drilling into electricity consumption by sector, Figure 36 46shows the increasing use of electricity after 2035 in the Net Zero scenario for buildings, industry, transport, and for hydrogen production. Both buildings and industrial use more than triple from 2020 to 2050, and EV charging becomes about 15% of final end-use loads. Hydrogen electrolysis becomes a major user of electricity in the 2040s, growing to nearly the size of all building, industrial, and transportation loads combined, for domestic use and increasingly for export.

Figure 37 shows the sources of electricity supply. Most load growth is met by wind and, after 2035, by large increases in solar. Uncontrolled natural gas use is rapidly phased down, reaching only 10% of supply by 2035 and zero by 2050. Some production from gas with CCS continues. However, with the tight net-zero targets that were analyzed, the residual emissions from gas with CCS become costly to offset once 2050 arrives. Without the domestic potential for bioenergy with carbon capture and storage (BECCS) and land use offsets, as modeled here, Egypt would need to get all negative emissions from costly direct air capture (DAC) using hydrogen for the heat source. The tiny sliver of BECCS for power generation uses imported biomass for dispatchable zero-emissions power. Additional opportunities to offset remaining emissions would allow more gas with CCS in the net-zero mix.

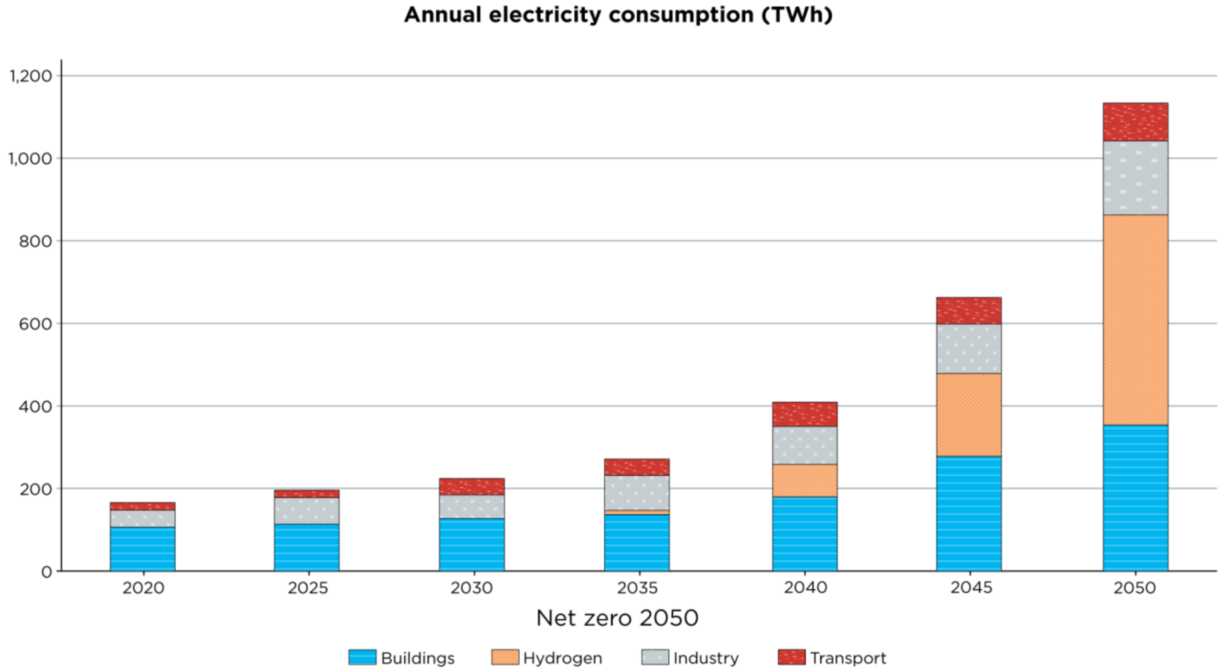

Figure 36. Egypt’s electricity consumption by sector

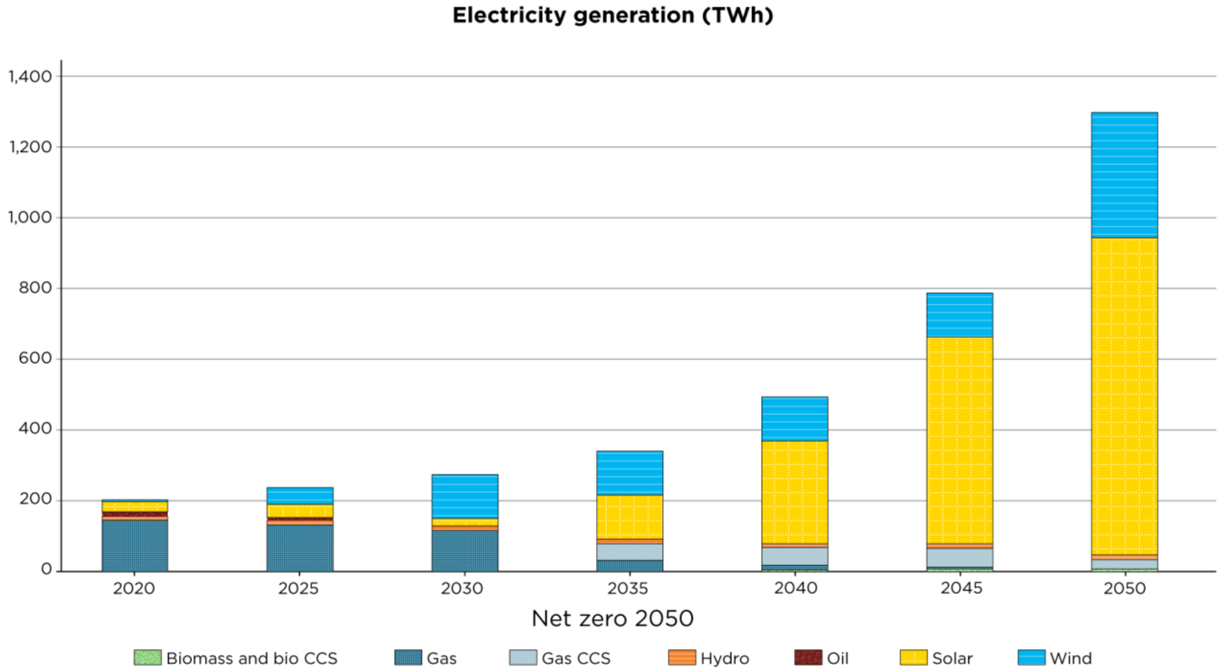

Figure 37. Egypt’s electricity generation mix

4.3.2 Technology Highlights: Hydrogen Market Opportunities

Egypt Insight 3: Egypt has substantial renewable resources in the form of solar and wind energy. These can be rapidly deployed and scaled up to decarbonize the power sector while also providing the potential to produce clean ammonia/hydrogen for the export markets. Our analysis assumes exports in the form of ammonia until 2040 with the potential for clean hydrogen exports thereafter as the scale of production increases and the delivery infrastructure develops. Early interest and investments in ammonia/hydrogen pilot projects and a hydrogen investment target policy can provide a solid foundation for continuing hydrogen industry development and scale-up of production.

Egypt has the potential for market opportunities in the export of hydrogen, due to its rich renewable resources and proximity to European markets. This section explores sensitivities around the core Net Zero scenario discussed above that impact Egypt's export market potential and competitiveness in a decarbonizing global economy. In all these scenarios, Egypt was assumed to have a 20% cost advantage in shipping hydrogen to Europe (via ammonia)—relative to generic long-distance global trade—and a 40% cost advantage after an assumed pipeline construction in 2040.[18] We also assumed local net-zero policies within importing regions require all internationally traded ammonia/hydrogen to be sourced from renewable electrolysis.

We explored one supply side and one demand side sensitivity, and each impacted Egypt's export potential. We also consider a Hydrogen Investment Targets scenario that set an explicit rate of hydrogen capacity development. The sensitivities are as follows:

- **High Cost of Capital scenario:** This scenario examines the sensitivity of Egypt's potential role as a clean hydrogen producer and exporter to the cost of financing for power sector projects. In this case, the cost of capital in Egypt's power sector is increased from 10% in the core Net Zero scenario to 16% in the sensitivity, increasing the cost of renewable electricity.
- **Low Global Hydrogen Demand (High CCS) scenario:** In this scenario, greater access worldwide to CCS storage potential reduces the global demand for hydrogen trade, as regions are able to offset more local emissions. Also, regions with strong biomass supplies engage in local hydrogen production from biomass with CCS, a negative emissions technology that further reduces their demand for hydrogen imports. In this sensitivity, for example, the EU28 region switches from being a net hydrogen importer in the Net Zero scenario to being a hydrogen exporter.
- **Hydrogen Investment Targets scenario:** In the real world, new industries take time and supported demonstration and investment to scale to maturity—time that is not represented within these initial model runs. To explore real-world policies that could lay the foundation for the growth of the Egyptian hydrogen industry, this scenario sets a hydrogen investment target policy that calls for 15 GW of electrolyzer capacity by 2030 and 52 GW by 2040.

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[18] Cost assumptions were based on analysis provided by Wang et al. (2021).

Figure 38 shows the production (left panel) and exports (right panel) of hydrogen in the core Net Zero scenario and each sensitivity. All production shown is via electrolysis using renewable electricity.

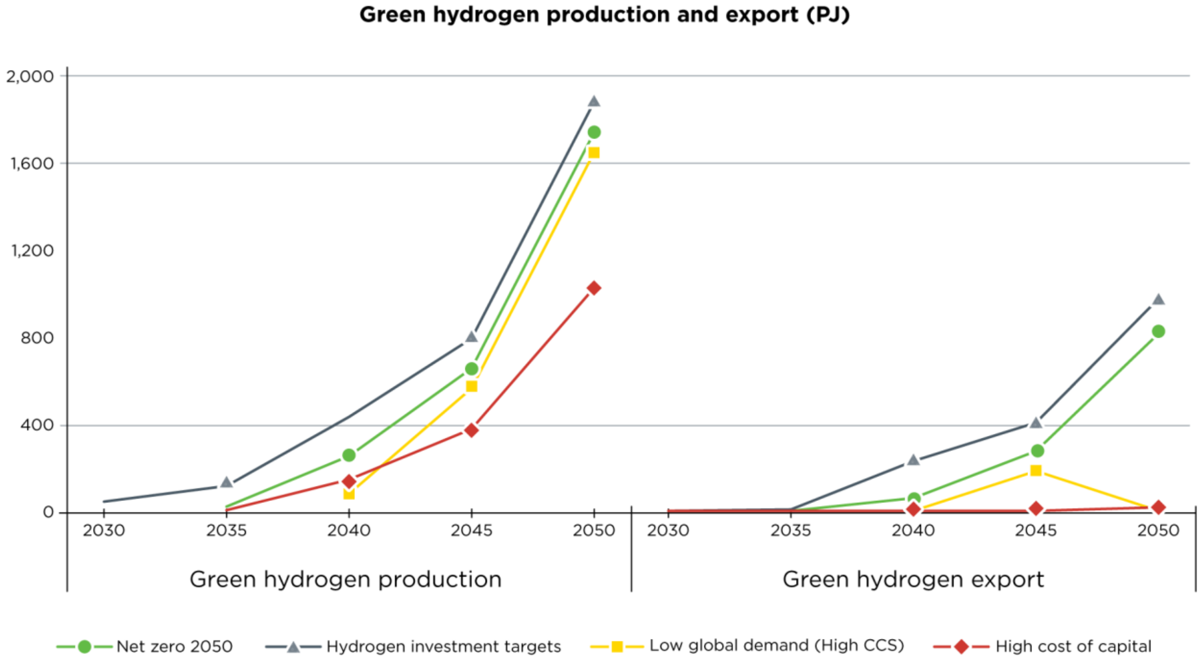

Figure 38. Egypt’s hydrogen production and exports

In the Net Zero scenario, Egyptian hydrogen production begins in 2035 and reaches ≈250 PJ of hydrogen annually by 2040, scaling up to nearly 1,800 PJ by 2050. Exports begin in 2040 and grow rapidly to reach nearly half of production by 2050. The rest is used domestically for industry, for transport, and for generating heat for direct air capture of CO_2 with CCS.

In the Hydrogen Investment Targets sensitivity, production begins in 2030, modestly accelerating hydrogen capacity development in the 2030s before roughly tracking the maturing development in the core Net Zero scenario in later years. These results suggest these target levels are appropriate to stimulate industry development. In the Hydrogen Investment Targets sensitivity, exports begin at demonstration levels in 2030, reach half of domestic production by 2040, or about quadruple the levels in the core Net Zero scenario, and then mature at a similar level in 2050.

Increasing the cost of capital (High Cost of Capital sensitivity) delays the development of the hydrogen industry. By 2040, hydrogen production is only 135 PJ, and none is exported. Although Egypt is producing nearly 1,000 PJ for domestic use by 2050, it does not become an exporter. When potential importing regions have greater access to CCS storage potential, they demand less imported hydrogen (Low H2 Demand sensitivity). In this sensitivity, development of Egypt’s hydrogen industry is delayed, but by 2050, Egypt is producing almost as much as in the core Net Zero scenario. However, in this case, the hydrogen is entirely used domestically, much of it as a heat source for direct air capture, reducing the mitigation burden for hard-to-decarbonize uses in transportation and industry.

4.4 Lessons Learned from the Modeling and Potential Value of Results

Egypt has the potential to become an international player in the clean fuels markets by exporting clean hydrogen from ammonia due to its rich renewable resources and proximity to European markets. Under such a scenario, Egypt not only moves toward its own decarbonization goals but also contributes to the decarbonization of importing countries. Our analysis for Egypt shows how the cost of project financing, variations in global and regional ammonia demand, and targeted clean hydrogen and renewable energy investments can drive Egypt’s competitiveness in the emerging regional and global clean fuels markets, and how these investments and potential credits from the international trade of clean energy could shape the future of Egypt’s energy infrastructure. Future analysis could explore how local decarbonization and energy security policies in potential importing regions could affect Egypt’s export potential and competitiveness.

5 Indonesia: Preliminary Modeling Results

During initial meetings in April 2022, the Ministry of Energy and Mineral Resources (ESDM) of the Republic of Indonesia confirmed the priority need for Net Zero World Initiative tools, analysis, and capacity building assistance related to energy system-wide decarbonization assessment. In response to this need, the initiative team developed an advanced analysis framework that applies two widely used energy system models—LEAP and TIMES—in an integrated manner to provide greater demand-side understanding and modeling capabilities while integrating price/cost-based modeling and multisector optimization capabilities. The framework also includes the VEDA online platform,[19] which is used to facilitate remote collaboration on model inputs, scenario development, and results review among modelers, country experts, and other stakeholders. This state-of-the-art energy system decarbonization assessment framework enables local modelers, country energy system experts, and other stakeholders to collaborate on country-driven energy system-wide decarbonization analyses at the city to national levels and thus inform decision-making on priority decarbonization actions, enabling policies, and financing mechanisms.

Additionally, ESDM requested that Net Zero World Initiative's collaboration in net-zero emissions pathway analysis leverage the country's net-zero emissions road map to 2060 (IEA 2022), prioritize implementation actions that create green jobs, help implement EV programs, and include capacity building support. ESDM also expressed interest in initiative's cooperation focused on advancing diesel displacement with efficient and clean minigrids, energy transition road map development for island sites, design and implementation support for targeted electro-mobility programs, and advancement of energy efficiency and renewable energy technologies for residential buildings. Based on discussions with ESDM experts, the Net Zero World Initiative team designed model runs to build on existing in-country modeling efforts, use strategic targets outlined in the Indonesian government's road map to net-zero emissions in the energy sector (IEA 2022), and apply an advanced analysis framework to evaluate supply- and demand-side actions and identify robust technology and investment strategies.

The energy system-wide modeling for Indonesia was designed to prioritize demand side actions (energy efficiency and transport electrification) and identify feedback effects on projected electricity demand and load shapes. The electric load forecasts were used as input to a separate power sector analysis to be published in a different document, in which a Net Zero World Initiative cross-lab team applied power sector capacity expansion and production cost models to evaluate the abatement costs of different investment strategies designed to speed coal-fired generation decommissioning, expedite the deployment of renewable energy in Indonesia, and provide input to the development of technical and investment plans to support clean energy transition.

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[19] For more information on VEDA, see https://iea-etsap.org/index.php/etsap-tools/data-handling-shells/veda.

5.1 Overview: Emissions and Energy Situation

Total energy supply in Indonesia increased from around 6,500 PJ in 2000 to almost 10,400 PJ in 2021 (IEA 2022). Figure 39 displays total energy supply by source in Indonesia for that period.

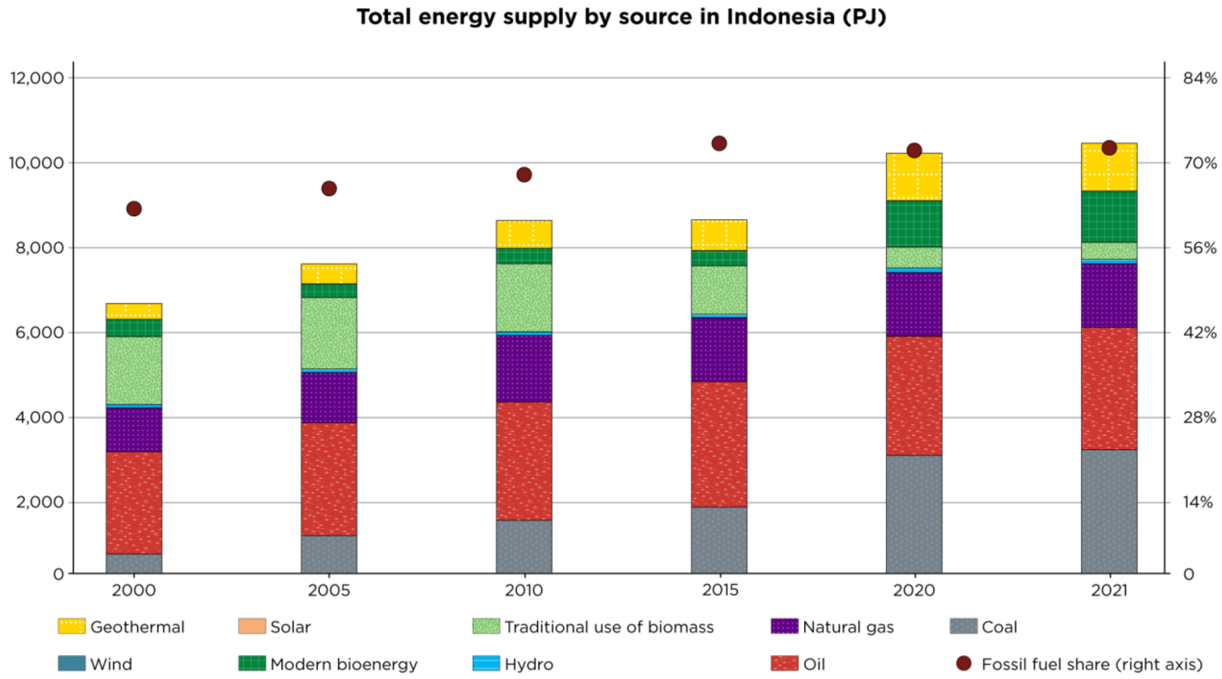

Figure 39. Indonesia’s total energy supply by source in Indonesia, 2000–2021 (IEA 2022)

Over the 2000–2021 period, Indonesia’s CO_2 emissions from the energy sector more than doubled, with total energy sector emissions being around 600 million tons of carbon dioxide (Mt CO_2) in 2021 (Figure 40). About 40% of total CO_2 emissions in 2021 were from the power sector, while transportation and industry each accounted for around 25% of total emissions (IEA 2022).

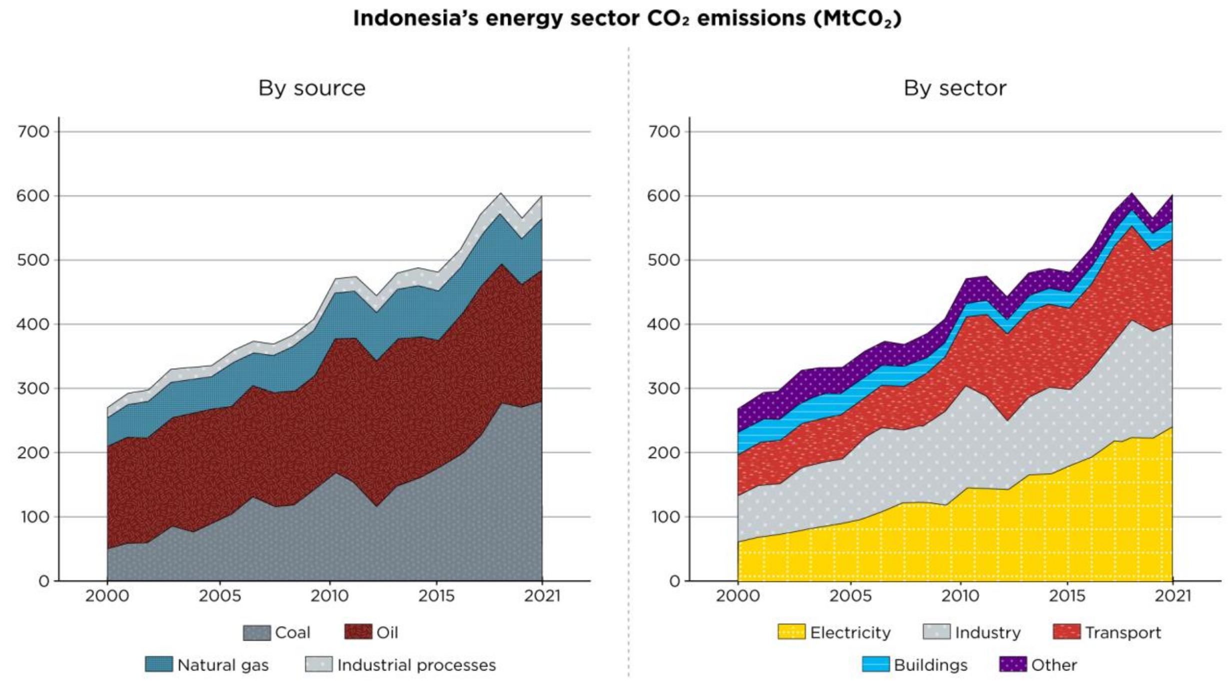

Figure 40. Indonesia's energy sector CO_2 emissions, 2000–2021 (IEA 2022)

5.2 Government Goals regarding Decarbonization

In its updated NDC,[20] which was submitted to the UNFCCC in July 2021, Indonesia states its aim to reduce GHG emissions by 29% (voluntarily) or 41% (with international support) compared to the BAU scenario by 2030. To achieve the latter, the Indonesian government estimates it will need $322.86 billion in climate finance (Suroso et al. 2022.). Indonesia's enhanced NDC in 2022 (Government of Indonesia 2022) is slightly increased to an unconditional target of 31.89% and a conditional target of 43.20%. In its LTS (Republic of Indonesia 2021), the country set pathways to achieve national development objectives, considering the balance between emission reduction, economic growth, justice, and climate resilience.

At the 2021 U.N. Climate Change Conference, COP26, Indonesia announced its ambitious objective to reach net-zero emissions by 2060 and signed the Global Coal to Clean Power Transition Statement,[21] committing to rapidly scale up technologies and policies in this decade to achieve a transition away from unabated coal power generation in the 2040s (or as soon as possible thereafter) provided the country receives additional international financial and technical assistance.

Recognizing the importance of collective action and inclusive collaboration among major developed countries and emerging economies around the world, Indonesia included a Sustainable

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[20] "NDC Registry," UN Climate Change Conference, https://unfccc.int/NDCREG.

[21] "Global Coal to Clean Power Transition Statement," November 4, 2021, https://ukcop26.org/global-coal-to-clean-power-transition-statement/.

Energy Transition as one of three main pillars to focus on during its G20 Presidency.[22] At the request of the Government of Indonesia, ESDM and the IEA worked collaboratively to model net-zero pathways for Indonesia's energy sector and produced a road map to achieve Indonesia's net-zero target (IEA 2022). While the intended outcome of this collaborative IEA effort was to produce a report for a net-zero pathway, the intended outcome of the collaborative Net Zero World Initiative efforts is to establish and apply an energy system-wide decarbonization assessment platform. This platform will enable local modelers, country energy system experts, and other stakeholders to (1) collaborate on country-driven energy system-wide decarbonization and investment analyses at the city to the national level and (2) inform decision-making on priority decarbonization actions, enabling policies, and financing mechanisms. The Net Zero World Initiative's collaboration with ESDM will start with capacity building assistance on the use of the initiative's decarbonization platform to enable the country to perform analyses required to prioritize mitigation actions—in collaboration with the initiative.

in September 2022, at the G20 Energy Transitions Ministerial Meeting, ESDM and IEA signed a joint high-level statement that sets out a shared vision of Indonesia's path to net zero, drawing on findings reported in *An Energy Sector Roadmap to Net Zero Emissions in Indonesia* (Goodson and Spencer 2022). It specifies three near-term pillars—efficiency, renewables, and electrification—noting that:

> Energy efficiency, renewables in the electricity sector, and the electrification of transport need to be kick-started now. To 2030, these three levers provide around 80% of the emissions reductions from the energy sector needed to put Indonesia on the road to net-zero emissions. The technologies for efficiency, electrification and renewables are commercially available and cost-effective, provided that the right policies are put in place.

As detailed below, the Net Zero World Initiative's energy system-wide decarbonization assessment seeks to provide insights to prioritize demand-side action, with a focus on efficiency programs and vehicle electrification.

5.3 Preliminary Phase I Modeling Results

Building on the IEA Announced Pledges Scenario (APS), the Net Zero World Initiative team applied its expertise in LEAP and TIMES to create a framework that will enable ESDM to continue using LEAP while benefiting from robust price/cost-based pathway modeling capabilities provided by the TIMES optimization modeling engine.

Three core scenarios were used:

- **No New Carbon Policies scenario:** In this scenario, recent historical trends in energy production and consumption are continued, and progress toward net-zero goals is fully delayed. Current policies, including minimum energy efficiency performance standards and biodiesel share requirements, have been incorporated. Other national goals and targets that

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[22] "Indonesia's G20 Presidency: Recover Together Recover Stronger: Priority Issues," https://g20.org/g20-presidency-of-indonesia/#priorities.

are nonbinding policy, including renewable electricity targets, have not. Thus, this scenario can be interpreted as a “worst case” of limited progress on climate goals. It was modeled with a combination of LEAP and TIMES as BAU.

- **Carbon Price Only scenario:** Here, the only new carbon policy is the carbon price used in the IEA APS scenario. The carbon price starts at $2/metric ton in 2020 and then rises to $40/ton in 2030 and $160/ton in 2050. The price is applied to all emissions, not just power and heavy industry. This policy is a proxy for moderate ongoing progress on recent commitments. This scenario was modeled in TIMES only, where the carbon price induces fuel switching and changes in end-use technology selection.
- **Net Zero 2060 scenario:** This scenario is based on the IEA APS scenario. The energy-related emissions target for 2060, drawn from the APS scenario, is 100 MMT. The scenario includes measures in all sectors, including end-use efficiency and demand reduction through building codes, electrification and fuel switching, incorporation of renewable energy and CCS, and hydrogen production and utilization. In TIMES, the IEA APS carbon price is included on emissions in all sectors. This scenario was modeled with a combination of LEAP and TIMES. Another variation on this scenario, modeled in TIMES only, is discussed in the Technology Highlights section below5.3.265.

All scenarios use population, GDP, and energy service demand projections consistent with the IEA APS scenario.

In the No New Carbon Policies scenario, energy-related CO_2 emissions continue to grow, nearly doubling by 2060 (Figure 41). The fastest growth takes place in the power sector, where emissions more than triple by 2060, as rapidly growing demand for power is met largely by a combination of coal and gas. Industrial emissions also grow, more than doubling from 2020 to 2060. Transportation sector emissions are flat, even as transportation demand rapidly increases, because EVs become cost competitive even without new carbon policies, and light-duty and light commercial truck fleets are electrified beginning in the 2030s. Direct emissions in the buildings sector remain modest, but buildings are a primary source of rapid growth in electricity demand, along with EVs.

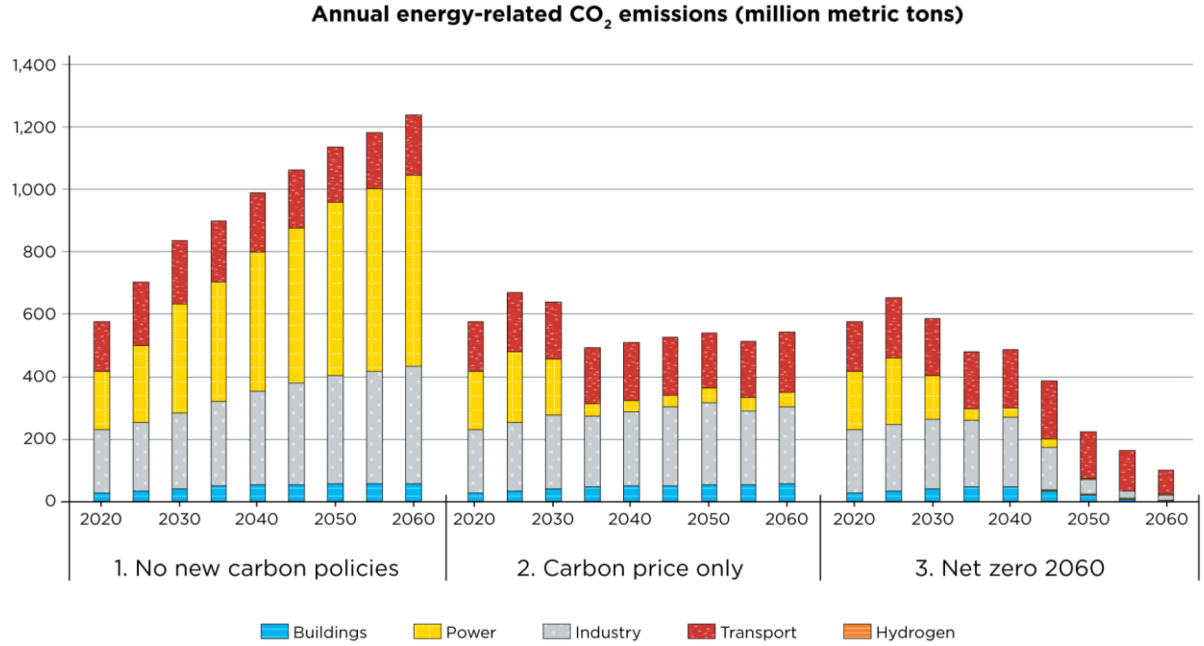


Figure 41. Indonesia's emission projections

Indonesia Insight 1: Carbon pricing may lead to early actions toward net-zero goals, but additional policies are needed after 2030 to achieve net-zero.

In the Carbon Price Only scenario, emissions peak in the late 2020s, fall to around 500 MT/year in 2035, and remain roughly flat thereafter. The largest reductions occur in the power sector, where the carbon price induces a phasedown of coal-fired power; use of CCS on many gas plants; and the addition of solar, hydropower, and geothermal production. The carbon price also reduces industrial sector emissions growth by inducing a shift from coal to gas use for high- and low-temperature heat. Industrial emissions increase 80% by 2050 before stabilizing and beginning to decrease.

Indonesia Insight 2: Reaching net zero requires full electrification of the buildings sector, an accelerated phaseout of fossil fuels in industry along with a scale-up of renewables, electrification of most of the transportation sector, and CCS for the remaining emissions.

In the Net Zero 2060 scenario, emissions reductions continue beyond 2035 and reach the net-zero target of 100 MT/year in 2060. Buildings sector uses are completely electrified by 2060. The phasedown of coal in industry is accelerated, and natural gas use is largely replaced after 2050 by electricity, biomass, and hydrogen. About three-quarters of remaining emissions are from petroleum products used in hard-to-electrify transportation applications, including aviation, shipping, and heavy-duty trucking. The remainder are small amounts of oil and gas consumption in the industry, mining, and energy sectors, along with residual emissions from gas-fired power production with CCS.

Primary energy supply doubles from 2020 to 2060 in the No New Carbon Policies scenario, with coal supply doubling, natural gas more than quadrupling, and oil growing by about 30% (Figure 42). With no firm policies to support renewable development, these fossil sources outcompete renewable supplies, and the share of renewables in primary energy falls from 19% in 2020 to 7% in 2060, as the inefficient use of traditional biomass is phased out. The addition of a carbon price in the Carbon Price Only scenario shifts the competitive balance, bringing additional geothermal, hydroelectric, and solar resources online, and bringing the renewable share to nearly one-quarter by 2060. Natural gas largely replaces coal use by 2060, and it contributes more than half of primary energy supply in 2060.

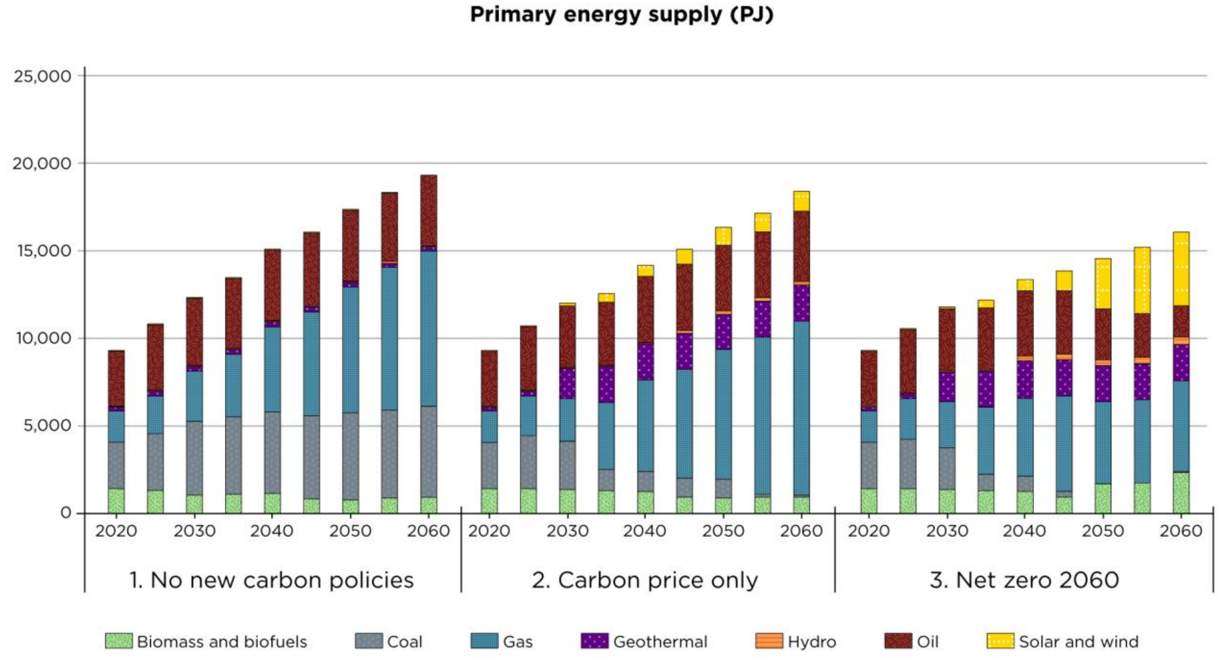


Figure 42. Indonesia's primary energy supply projections

Indonesia Insight 3: Under a net-zero scenario, renewables scale up rapidly to almost 60% of primary energy supply and solar accounts for nearly half of all renewables in 2060. Coal ramps down quickly after 2030 and is phased out by 2050. Most remaining natural gas is used for hydrogen production and electricity generation with CCS, as well as noncombustion feedstocks.

In the Net Zero 2060 scenario, the renewable share reaches 57% in 2060. Solar makes up nearly half of renewable energy supplies; biomass and biofuels, geothermal, and modest additional hydroelectric development make up most of the rest. Natural gas remains nearly one-third of primary energy. By 2050, nearly three-quarters of this natural gas is used for hydrogen and electricity production with CCS, and another 10% is used for noncombustion feedstock use.

Indonesia Insight 4: Moving toward net zero accelerates the electrification of various end-use sectors and supercharges the already strong growth in national electricity demand, particularly in the later years, despite the deployment of a range of energy efficiency measures.

One of the most prominent features of the Indonesian energy system is how quickly energy demands, and particularly electricity demands, are growing (Figure 43). In the No New Carbon Policies scenario, annual electricity consumption doubles by 2035 and then doubles again by 2060. Initially, the bulk of demand growth occurs in the buildings sector, where increasing incomes lead to a rapid increase in deployment of electricity-consuming devices. This growth is driven by the underlying assumptions in the IEA APS scenario that projects the stock of household air conditioners to grow as much as 36-fold from 2020 to 2060—from less than one in ten households to an average of around two per household. Industrial use of electricity also continues to grow, and, after 2030, electrification of light-duty vehicles, including scooters, cars, and light commercial trucks, becomes another rapidly growing load. Electricity load growth is similar in the Carbon Price Only scenario, which does not include increases in energy efficiency performance standards and where the carbon price does not induce end-use efficiency improvement.

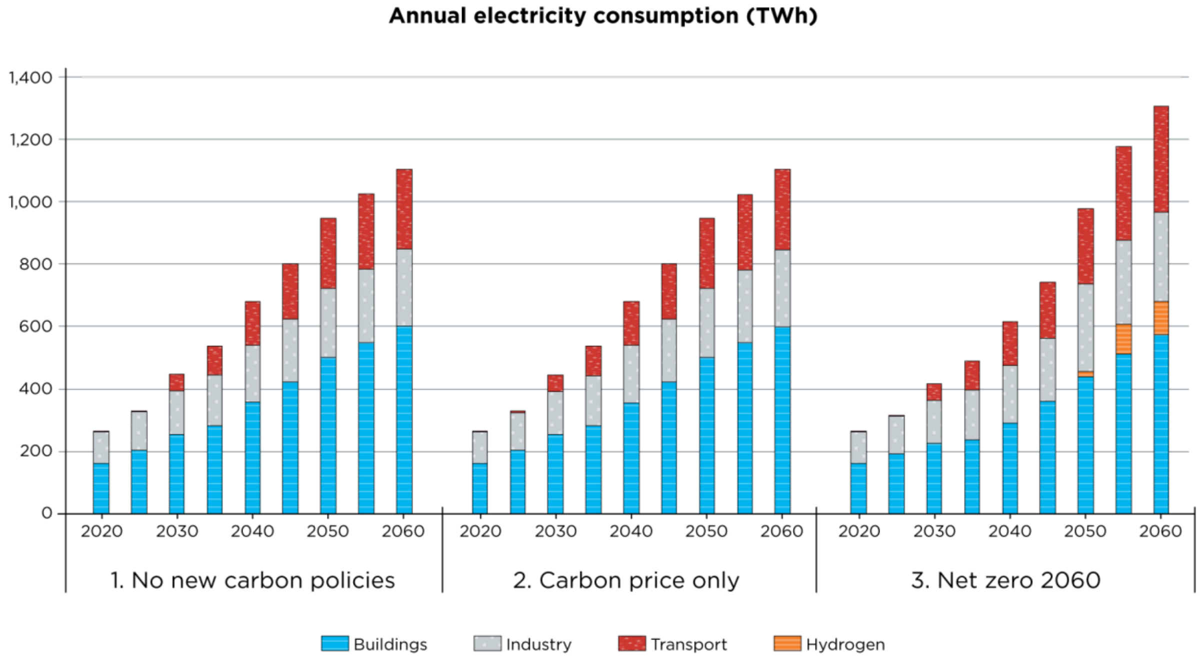


Figure 43. Indonesia's electricity consumption by sector

The energy efficiency policies and measures in the Net Zero scenario reduce electricity load growth relative to the other scenarios until the mid-2040s, when increased electrification of building loads, especially cooking and water heating, pushes load growth higher. (These policies and measures are discussed in the Sector Highlights section, Section 5.3.1) After 2050, hydrogen production becomes a significant new electricity load, along with partial electrification of additional transport modes.

Indonesia Insight 5: Achieving a near zero-carbon electricity grid requires tapping Indonesia's abundant renewable resources, including geothermal, hydropower, and especially solar. Significant grid storage is also needed to reliably operate Indonesia's grid.

Figure 44 shows the electricity generation mix in our three core scenarios. In the No New Carbon Policies scenario, coal construction continues through the 2020s, but new load growth is increasingly met by gas along with small additions of renewables. When a carbon price is added (Carbon Price Only scenario), coal generation is phased down after 2030, and load growth is met with a mix of gas with CCS, geothermal, hydropower, and solar, with renewables making up just under half of the generation mix by 2060. In the Net Zero 2060 scenario, the economy-wide net-zero target is too stringent to allow the residual emissions from gas with CCS, and the renewable shares reaches nearly 95% by 2050. Geothermal and hydropower resources are utilized, along with small amounts of wind and biomass, but the major generation source is Indonesia's rich solar resource.

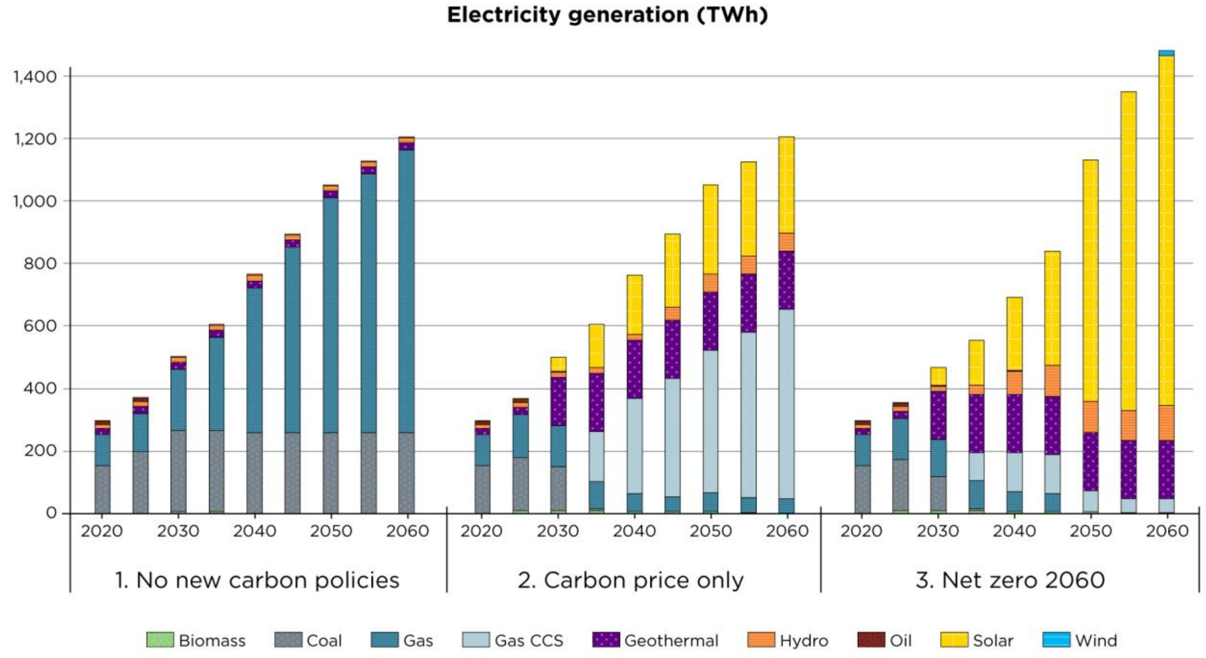


Figure 44. Indonesia's electricity generation projections

Figure 45 shows the corresponding capacity mix. Meeting loads with solar does require having substantially greater total capacity than using resources that have higher capacity factors. In the Carbon Price Only scenario, the solar capacity reaches nearly half the total capacity by 2050 despite contributing only about one-quarter of total generation. In the Net Zero 2060 scenario, substantial investments in grid-scale battery storage are needed to utilize solar for evening loads from 2045 onward.

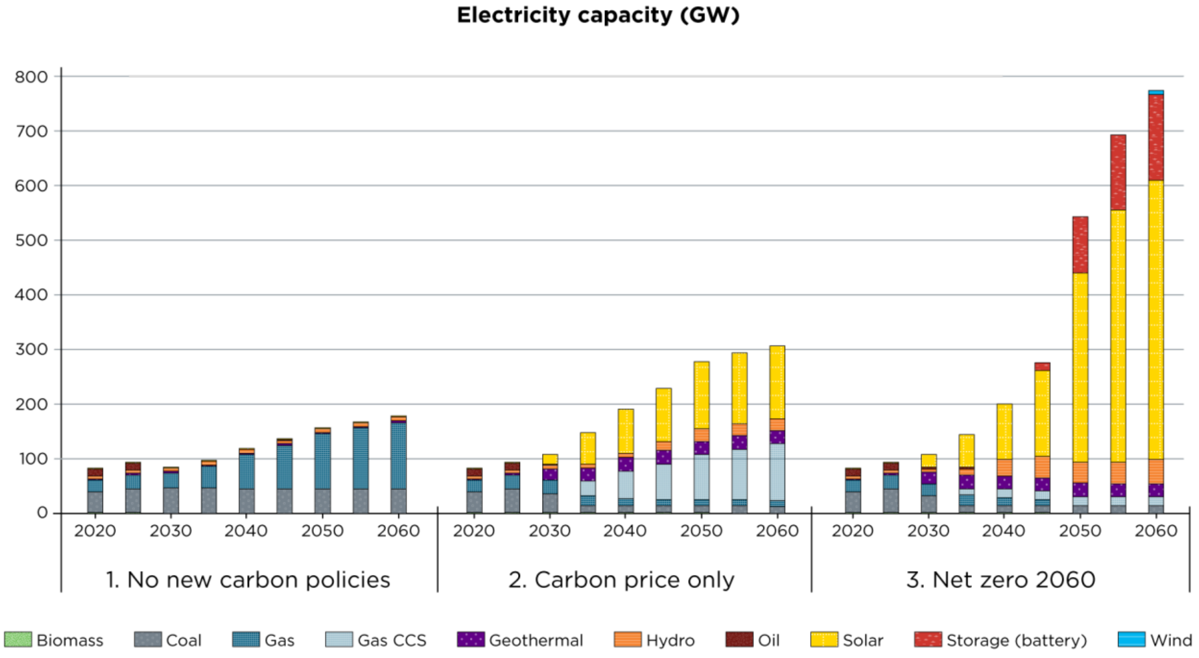


Figure 45. Indonesia's electricity capacity projections

It should be noted that all scenarios in this initial analysis represented the Indonesian electricity system as a single grid. Further analysis is needed to investigate the costs, investment needs, and investment timing to connect renewable resources to load centers.

Indonesia Insight 6: Total final energy consumption changes very little with decarbonization, but the composition shifts toward carbon-free sources, including clean electricity and hydrogen.

In the No New Carbon Policies scenario, coal use doubles from 2020 to 2060, primarily for high- and low-temperature heat in industry. Gas use in industry also doubles for a mix of high and low temperature heat, feedstock, and other uses (Figure 46). Petroleum consumption rises into the mid-2030s and then stabilizes, as lighter-duty transport modes are increasingly electrified. Traditional biomass use for cooking is fully phased out by the mid-2030s, and modern biomass energy is increasingly consumed for high-temperature heat in industry, along with increased use for biofuels production. In the Carbon Price Only scenario, gas replaces coal in industry by 2050, resulting in a quadrupling of overall gas use by 2060.

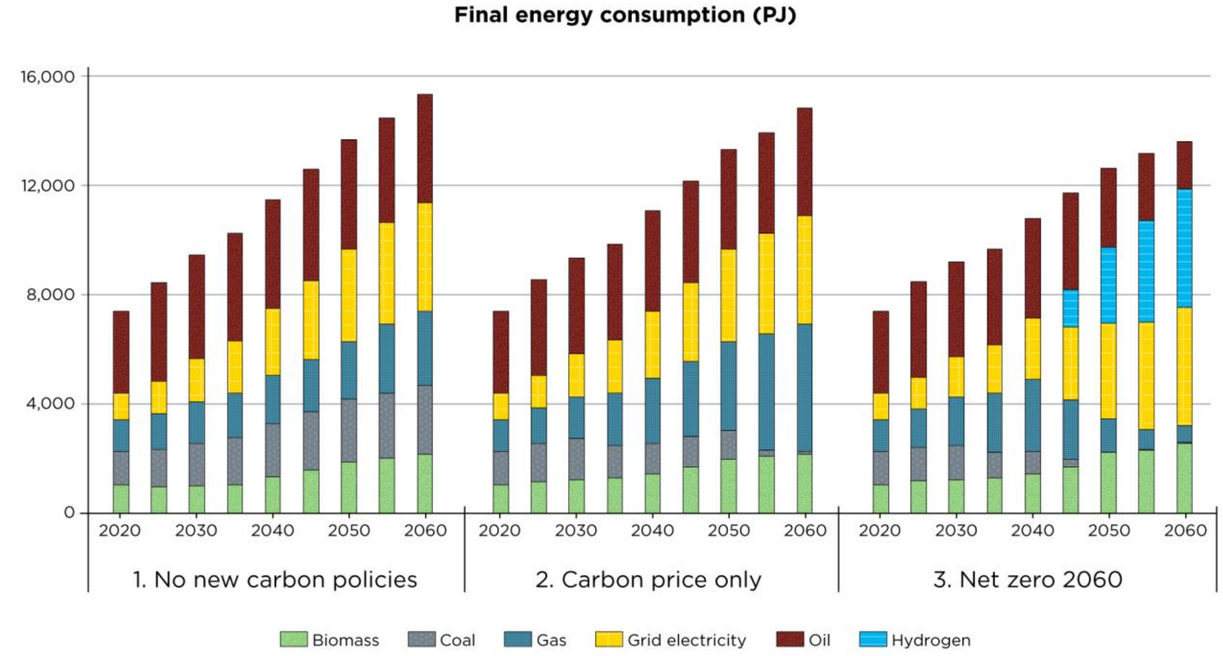


Figure 46. Indonesia's final energy consumption projections

In the Net Zero 2060 scenario, hydrogen begins to replace coal and gas use in industry in the mid-2040s. A combination of hydrogen, biofuels, and electrification displace petroleum use in aviation, shipping, buses, and heavy trucking.

Indonesia Insight 7: Investments in end-use efficiency are key to keeping the cost of meeting Net Zero goals down.

The difference in annual energy system costs (Figure 47) between the Net Zero 2060 and No New Carbon Policies scenarios is less than 1% until the mid-2040s, as the savings from energy efficiency and decreased consumption of fossil fuels balance out higher investments in low-carbon resources. The lower system costs in the 2020s are primarily driven by building code changes that reduce investments in air conditioning equipment and the electricity to run it. By the mid-2040s, demands for investment in low-carbon energy supplies—especially renewables, storage, and hydrogen production—drive the increase in system cost higher, with costs reaching 9% above the No New Carbon Policies scenario in 2050 and 20% in 2060. The next section, Sector Highlights, and the Technology Highlights section explore early demand-side investments that can help mitigate these supply-side investment costs.

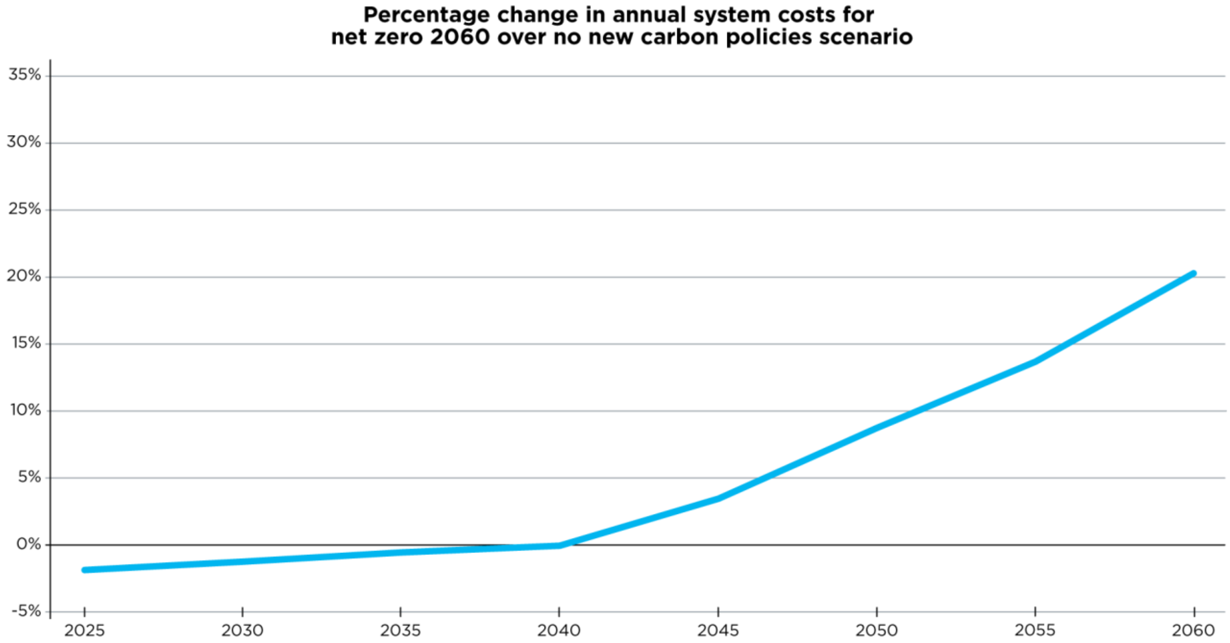


Figure 47. Indonesia's difference in annual system costs from No New Carbon Policies scenario

These are initial estimates of costs, and some important investment requirements are not included in this analysis. In particular, because of Indonesia's island geography, with load centers often being distant from renewable resource locations, detailed analysis of transmission, distribution, and grid management infrastructure investment requirements is crucial. The costs required for building code improvements were also not included in this initial assessment. Future analysis will assess these costs.

5.3.1 Sector Highlights

5.3.1.1 Transportation Sector

Indonesia Insight 8: Energy efficiency measures can cut transportation's final energy demand in half.

Under the BAU scenario, final energy demand in the transportation sector increases by 2% annually, driven by population, increased ownership of passenger vehicles, and miles traveled. In the Net Zero 2060 scenario, transportation's final energy demand is flattened by energy efficiency improvements across all technologies considering operation and vehicle improvements in key transport modes (Figure 48). Most notably, passenger vehicle efficiency improves by 2% every year, while road freight activity is reduced by 10% by 2050, assuming logistics improvements such as improved loading and dispatch optimization that reduce freight activity compared to the BAU scenario. Electrification of all road vehicle types further reduces final energy demand through efficiency gains from switching from fossil fuel to EVs.

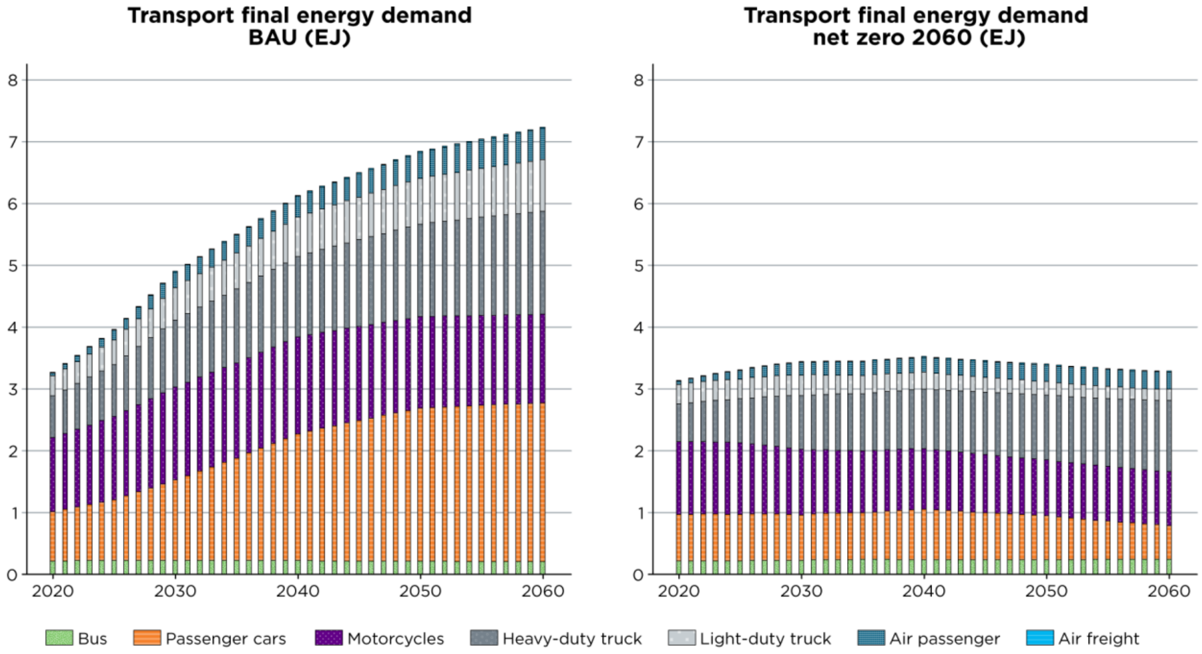


Figure 48. Indonesia's transportation final energy demand projections

5.3.1.2 Industrial Sector

Indonesia Insight 9: Energy efficiency can cut industrial energy consumption by almost two-thirds.

In the Net Zero 2060 scenario, the industrial sector final energy demand grows much more slowly than the BAU scenario, increasing at 1.2% per year on average instead of 3.5% per year in the BAU scenario. By 2060, total industrial final energy demand reaches about 3.4 EJ, which is 61% lower than the level in the BAU scenario (Figure 49). This reduction is due to a combination of improvements in (1) energy efficiency, particularly in the iron/steel, and cement industries, as well as (2) material efficiency, including lightweight materials, material substitution, and increased reuse and recycling. By 2060, the iron/steel and chemicals industries remain the largest energy-consuming industries, representing 14% and 18% of the total industrial final energy use respectively. The contribution from the nonmetallic industry (e.g., cement) declines from 17% in 2020 to 7% by 2060.

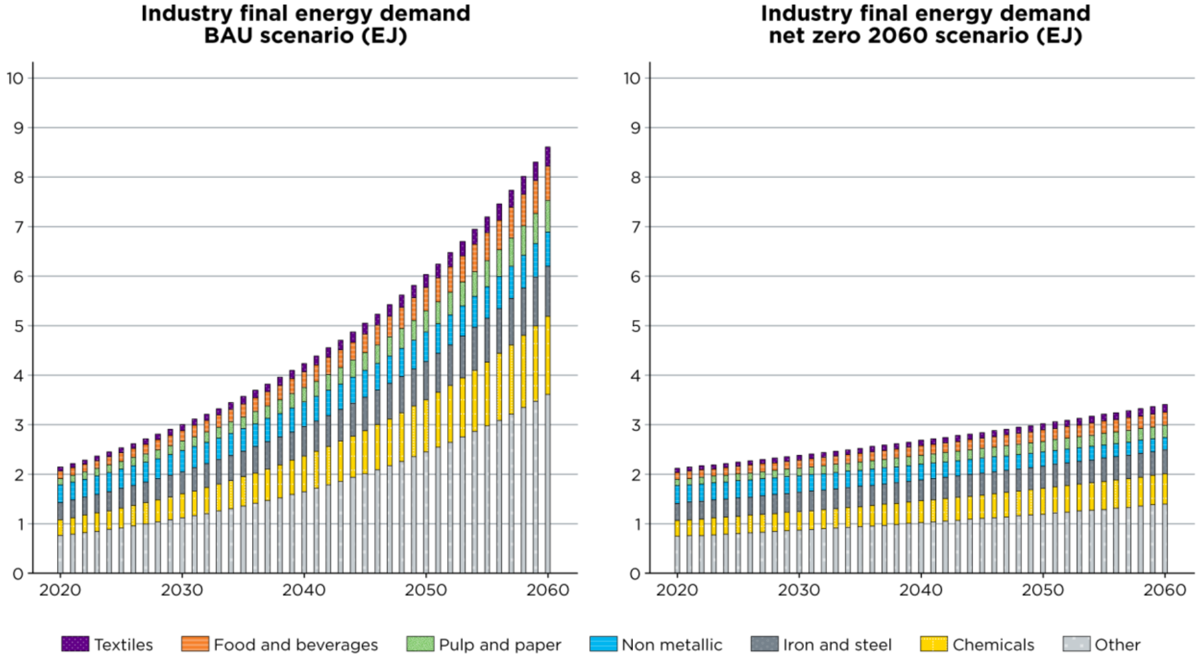


Figure 49. Indonesia's industrial final energy demand projections

5.3.1.3 Buildings Sector

With increasing incomes and standards of living, cooling demand in the Indonesian buildings sector is expected to grow tenfold from 2020 to 2060 if no further policy action is taken. The LEAP-TIMES Net Zero scenario considers various strategies to mitigate this demand by 40%–50%:

- **Improved equipment efficiency (reductions of 24% in residential and 21% in commercial applications):** High-efficiency room air conditioners using inverter technology and optimized centralized heating, ventilation, and air conditioning (HVAC) system efficiency can be deployed in residential and commercial buildings. Also, smart controls can intelligently manage cooling system setpoints and adjust cooling operation conditions based on building occupancy and using free cooling opportunities.
- **Reduction of cooling load through integrative building design (reductions of 14% in residential and 28% in commercial applications):** Combining multiple passive design strategies can enhance building performance, utilize natural resources, and reduce energy demand. Smart fenestration systems can effectively shade solar radiation and reduce heat transfer into buildings. Operable windows and openings can bring in natural ventilation and reduce building needs for mechanical cooling.
- **Urban-scale solutions to reduce cooling load (reductions of 20% in residential and 7% in commercial applications):** Urban-scale solutions can mitigate urban heat island effects and reduce the impacts on building cooling energy demand. Urban heat island effects can result in rising outdoor environment temperatures and can create hot surfaces such as roads and pavements, which can in turn enhance heat transfer from outdoor to indoor environments

and increase building cooling loads. Hot outdoor environments can also increase cooling energy demand by decreasing overall efficiency of HVAC systems. Studies (Cao et al. 2015) have shown that using cool surfaces and pavements can effectively reduce urban heat island effects and decrease outdoor air temperatures by 0.5°C–1.0°C. Green vegetation and sustainable urban planning can also mitigate urban heat island effects.

- **Demand flexibility (5%–10% savings):** Demand flexibility refers to controlling building equipment operations based on power grid signals. Demand flexibility often includes two types: load reduction and load shifting. Load reduction means buildings can cut off some loads (i.e., changing the air conditioning setpoint) when not needed or when the power grid sends peak load reduction signals. Load shifting refers to displacing some building equipment operations from one time period to another. Shifting load can enable equipment to operate in a period with low-carbon electricity from the power grid. Also, it can be financially attractive for occupants because of low electricity tariffs or incentives.

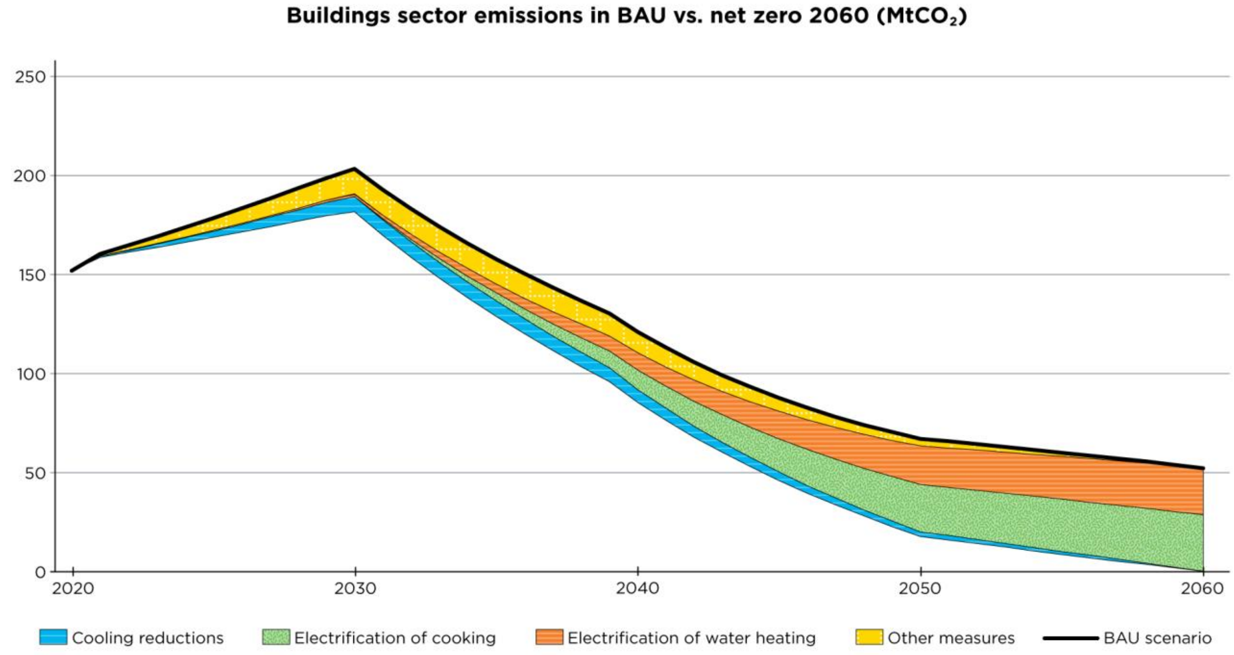
Indonesia Insight 10: Building efficiency measures can significantly reduce buildings sector consumption, lower system peak load, decrease grid storage requirements, and lead to significant savings.

Considering buildings and appliance lifetimes and stock turnovers, the energy efficiency measures avoid 13 TWh/year in 2030 and 130 TWh/year of electricity consumption by 2060 (or 16% of total building electricity demand), and 68 TWh and 62 TWh, respectively, are saved in residential and commercial buildings. By 2030, these translate into an annual reduction of 7.5 Mt CO_2 in the rapidly decarbonizing grid of the IEA APS scenario.

As described in earlier studies (McNeil, Karali, and Letschert 2019; Letschert et al. 2020), cooling has a very high coincidence and correlation with peak demand. The TIMES-LEAP model estimates 13% of peak demand is due to cooling in 2030 and that doubles to nearly 27% by 2060. These investments in cooling efficiency and load reduction avoid as much as 6% of peak demand by 2030 and 15% by 2060. As the grid decarbonizes in the Net Zero 2060 scenario, grid battery storage is increasingly needed to use excess daytime solar energy to meet evening peak loads. Cooling efficiency and load reduction decreases grid battery capacity requirements 30 GW by 2050. These power sector savings amount to roughly $1 billion per year of investment in the power sector in 2030, growing to over $10 billion per year by 2050. Building energy consumers save $4 billion–$5 billion per year in electricity costs in 2030, rising to $15 billion–$25 billion per year in 2050 in the No New Carbon Policies and Net Zero 2060 scenarios.

To achieve deeper decarbonization of the demand sectors, the models consider full electrification of end uses, such as water heating and cooking, as a key strategy to reduce emissions from the buildings sector. By 2060, liquefied petroleum gas use is replaced by 100% by electricity. In addition, a reduction of final energy consumption is achieved through efficient cooking (25%) and efficient water heating (33%). These measures allow building carbon emissions to peak in 2030 and decline to near zero by 2060, a difference of nearly 52 Mt/year from the BAU by 2060.

Figure 50 illustrates the contributions of these measures to decarbonize the buildings sector. Building on the IEA APS scenario, the LEAP analysis assumes that the power sector is decarbonized by 2060 under both BAU and net-zero scenarios. As a result, building emissions peak in 2030 and reach net zero by 2060.



Emissions shown here include direct emissions from fossil fuel use and indirect emissions from electricity use. Emissions from electricity generation are largely driven by APS decarbonization targets

Figure 50. Indonesia's emissions reduction measures for the buildings sector in LEAP BAU versus net-zero scenarios

5.3.2 Technology Highlights: Vehicle Electrification and Impacts of Charging Strategies

Indonesia is projected to experience rapidly growing demand for car travel. In its *Energy Sector Roadmap to Net Zero Emissions in Indonesia* (IEA 2022), the IEA projects the passenger car fleet in Indonesia will grow from around 11 million vehicles today to nearly 60 million in 2060.

Because of this rapid growth as EVs become globally cost-competitive, Indonesia has the opportunity to electrify the light-duty vehicle fleet much faster than countries with less growth in their vehicle fleets, because a much greater share of vehicles will be new purchases each year. Avoiding development of a legacy fossil fleet provides an opportunity to avoid a rapid increase in transport-related CO_2 emissions and to better insulate Indonesia from volatile world oil prices.

As EVs become cost-competitive with internal combustion engine vehicles, consumer uptake of EVs will depend on vehicle availability, sufficiency of charging infrastructure, and consumer attitudes and preferences—all factors that are exogenously determined in an energy system-wide analysis scenario. We project EVs making up 40% of new car sales by 2030 and internal combustion engine car sales ending by the mid-2040s in all scenarios. Electrification of two- and three-wheelers and a rapidly growing fleet of light commercial (delivery) trucks occur over a similar time frame.

If electrification proceeds at the pace envisioned in these scenarios, EV charging could represent nearly 20% of total annual electricity consumption by 2035, and more than one quarter by 2050. But the real impact on the electric grid comes from charge timing. The power draw of a typical slow home EV charger is roughly 10 times the average peak Indonesian household demand by 2030, so even a few million EVs, if plugged in simultaneously when drivers arrive home in the evening, would substantially increase the evening peak load. A smart charging system that incentivizes and facilitates charging when electricity is cheapest will be essential to integrate EVs onto the decarbonizing grid.

This section presents two variations on the Net Zero 2060 scenario. Both assume charging is sensitive to time-of-day electricity price signals and avoid charging during the evening peak. The scenarios differ in the degree of responsiveness to real-time pricing and drivers' access to smart vehicle chargers.

Our core Net Zero 2060 scenario, depicted in the sections above, assumes smart chargers are widely available to Indonesians at places of work, study, recreation, commerce, and other daytime destinations, and that these charging systems successfully incentivize drivers to plug vehicles in to real-time cost-responsive chargers that optimize charging time to utilize the lowest cost electricity available each day. In this scenario, we assume 75% of charging is available to be cost-optimized across the day and a minimum of only 25% must occur while vehicles are plugged in at home overnight.

The other scenario, 75% Nighttime Charging, reverses these percentages and assumes drivers primarily charge vehicles at home. The charging system—perhaps using a simple time-of-day rate—postpones charging until after the evening peak. A minimum of 75% of charging is cost-optimized overnight and only 25% may take place during daytime hours.

Indonesia Insight 11: Incentivizing day-time EV charging enables more solar power on the system early in the transition phase and eventually leads to significantly lower grid storage needs and costs.

Figure 51 and Figure 52 show the hourly load curve for a typical day (negative portion of the graphs) and the power supply sources meeting the load (positive portion) for two years (2030 and 2050) under the Net Zero scenario. In 2030, as the EV fleet ramps up and the electricity generation mix transitions toward a greater share of renewables, the load shapes and generation mixes are very similar. The evening load peak, driven by residential demands, is still prominent, and in both scenarios, more than half of charging occurs during nighttime hours. Loads are served by a mix of base-loaded coal and geothermal, with flexible gas and hydropower following the load. However, even this early, the ability to incentivize daytime charging when solar production exceeds demand leads to nearly twice as much solar capacity on the system. With ready access to grid-responsive daytime charging, solar can be economically built faster because it can be better utilized, and solar and EV fleets grow together. It should be noted that daytime charging may require additional charging infrastructure deployment (assuming EVs are parked at different locations during the day and at night) at public parking spaces and places of work.

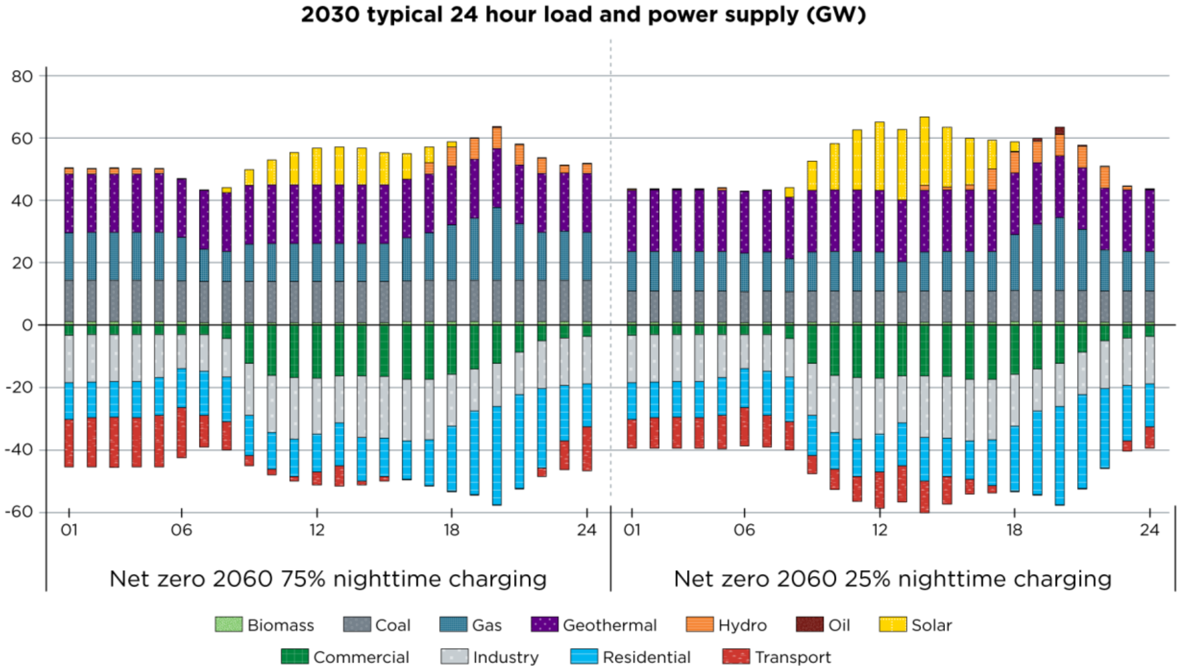


Figure 51. Indonesia's 2030 load profiles (negative) and power supply (positive) for Net Zero 2060 scenarios with fixed 75% nighttime charging (left) and flexible daytime charging (right)

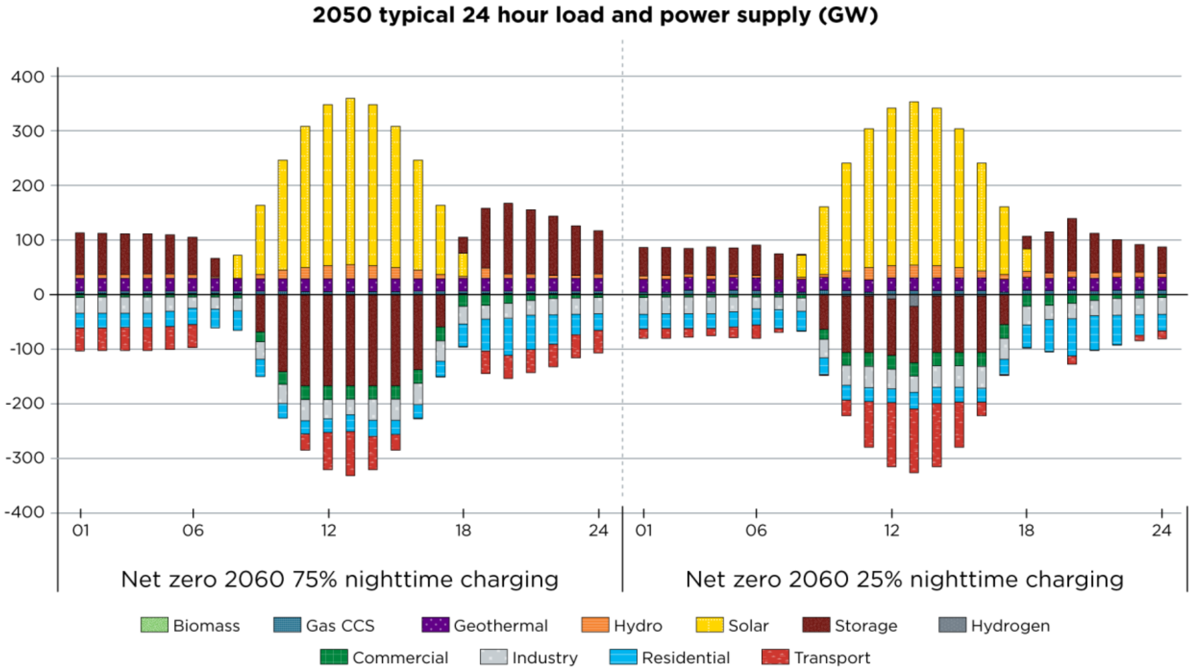


Figure 52. Indonesia's 2050 load profiles (negative) and power supply (positive) for Net Zero 2060 scenarios with fixed 75% nighttime charging (left) and flexible daytime charging (right)

By 2050, solar is a predominantly low-carbon resource and midday solar production overshadows other resources including geothermal, hydropower, and gas with CCS. Grid-scale battery storage is needed to utilize this energy to meet evening peaks. EV charging loads are now almost as large as industrial or residential loads and shifting charge timing to use solar energy is an economic opportunity for the system. The 25% nighttime charging scenario requires 60 GW less storage by 2050 than the 75% nighttime charging scenario. This translates into annual electricity cost savings for vehicle charging reaching 10% by 2050.

5.4 Lessons Learned from the Modeling and Potential Value of Results

To meet its net-zero goals, Indonesia faces the challenge of building a low-carbon electric grid while loads are rapidly growing. The LEAP-TIMES analysis conducted for Indonesia highlighted ways that early demand-side action could help make overcoming this challenge more achievable and affordable. Mobilizing investments in cost-effective energy efficiency options, developing building codes and practices that reduce fast-growing cooling loads, and facilitating load shifting, particularly for EV charging, are early investments that could make a net-zero electricity supply more achievable and affordable by mid-century.

6 Nigeria: Preliminary Modeling Results

Energy system-wide modeling for Nigeria was conducted by SEforALL[23] and McKinsey as part of development of the current Nigeria Energy Transition Plan (ETP).[24] It identifies key sectoral actions and pathways, including high-level estimates of required investment, for achieving net-zero goals by 2060. Because initial high-level system-wide modeling has already been completed as part of the ETP, Nigerian Government partners of Net Zero World Initiative expressed a desire to collaborate with the initiative in analyses that focus more on implementation than general planning scenarios.

In response to the country's interests, the Net Zero World Initiative's analysis activities build on and complement the ETP in the following ways:

- Work directly with Nigerian Government counterparts to build local capacity for design and execution of similar net-zero technical and investment modeling efforts in-country.
- Demonstrate ways to structure modeling and analysis at a greater level of granularity than currently applied in the ETP, including the development of specific pathways and investment options to implement measures as proposed in the ETP.

Specifically, the Nigerian Government partners requested that the Net Zero World Initiative initially focus on *evaluating options for developing a carbon market* in Nigeria, which is viewed as a prerequisite for implementing the ETP and facilitating investment in net-zero technologies and interventions. Initial Net Zero World Initiative modeling and analysis thus aims to answer key questions about (1) costs, benefits, and impacts of various carbon market frameworks and trading schemes in Nigeria and (2) how such a market can accelerate progress toward net-zero implementation by driving investment toward lower emission technologies and practices.

A preliminary energy system-wide modeling framework was developed using GCAM. It allows analysts to explore the interactions and trade-offs between the energy system and other human and environmental systems, providing insights that are complementary to the assessment already conducted for the ETP. Continued and targeted analysis work is expected in future phases of the technical collaboration.

6.1 Overview: Emissions and Energy Situation

Nigeria has adopted ambitious plans for net-zero energy transitions and established an Inter-ministerial Energy Transition Implementation Working Group chaired by the Vice President and comprised of several key ministers including the Ministers for Environment, Power, Finance, Works & Housing, Petroleum Resources, and Foreign Affairs to drive implementation. A dedicated secretariat for the Working Group, the Energy Transition Office within the Office of the Vice President, is tasked with leading planning and implementation of Nigeria's energy transition in the coming years. In February 2022, the Government of Nigeria formally adopted

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[23] Sustainable Energy for All (SEforALL) is a multistakeholder collaboration of international governments, private sector, and civil society. It was launched by the United Nations in 2011 and has the goal of driving global action to achieve universal sustainable energy access by 2030.

[24] "Nigeria Energy Transition Plan," https://energytransition.gov.ng/.

its official ETP, which outlines key sector goals and high-level investment needs to achieve transformation of the energy system that goes beyond Nigeria's current NDC to achieve net-zero emissions by 2060. Within this context, the Net Zero World Initiative is working with the Government of Nigeria and the Energy Transition Office to build on the ETP by (1) translating high-level sectoral visions outlined in the ETP into focused technical and investment plans to achieve least-cost implementation of specific ETP actions and (2) providing a platform for technical collaboration between the Government of Nigeria and the U.S. government to inform and drive implementation of those technical and investment plans and key actions.

Estimates of Nigeria's total GHG emissions vary but range from about 275 Mt CO_2e (ETP) to about 347 Mt CO_2e (Figure 53) (Nigeria 2021). The current ETP covers five key sectors accounting for ≈65% of emissions: power, cooking, oil and gas, transport, and industry. Land use and forestry and agriculture and waste are not covered in the ETP, but they are addressed in Nigeria's 2050 LTS (Nigeria Federal Ministry of Environment 2021). Notably, fugitive methane emissions—from oil and gas production and industry as well as agriculture—are a major contributor to Nigeria's total GHG emissions but is not fully addressed in the ETP and represents a significant opportunity for Nigeria to reduce overall emissions.

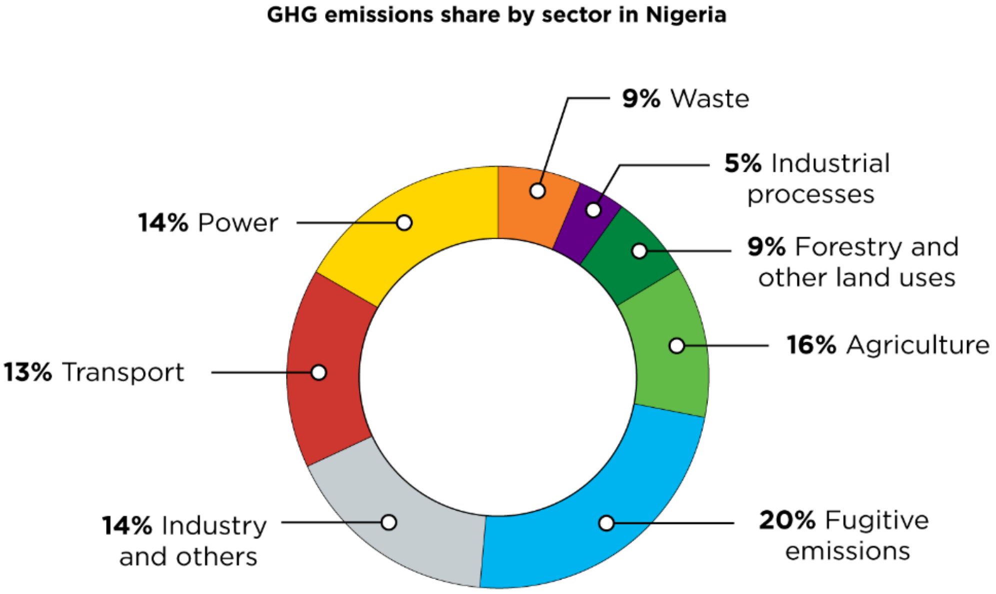

Figure 53. Nigeria's sectoral contribution to total GHG emissions in Nigeria

Source: Recreated from Nigeria NDC Update 2021

As shown in Figure 54 and Figure 55, Nigeria's total primary energy consumption has grown consistently over the past three decades. This growth in energy consumption can be attributed to both population and economic growth. Over that same time, the makeup of primary energy supply has remained largely unchanged, with biomass and waste burning (primarily for cooking and residential home use) being the largest primary energy use. Biomass and waste burning are followed by oil and natural gas, primarily for transportation fuels and electricity generation. Contributions from renewable resources such as wind and solar are negligible, though some hydropower is currently utilized. Overall, power, buildings, and oil and gas sectors account for most of Nigeria's GHG emissions, as illustrated in Figure 56 and discussed next in Section 6.2.

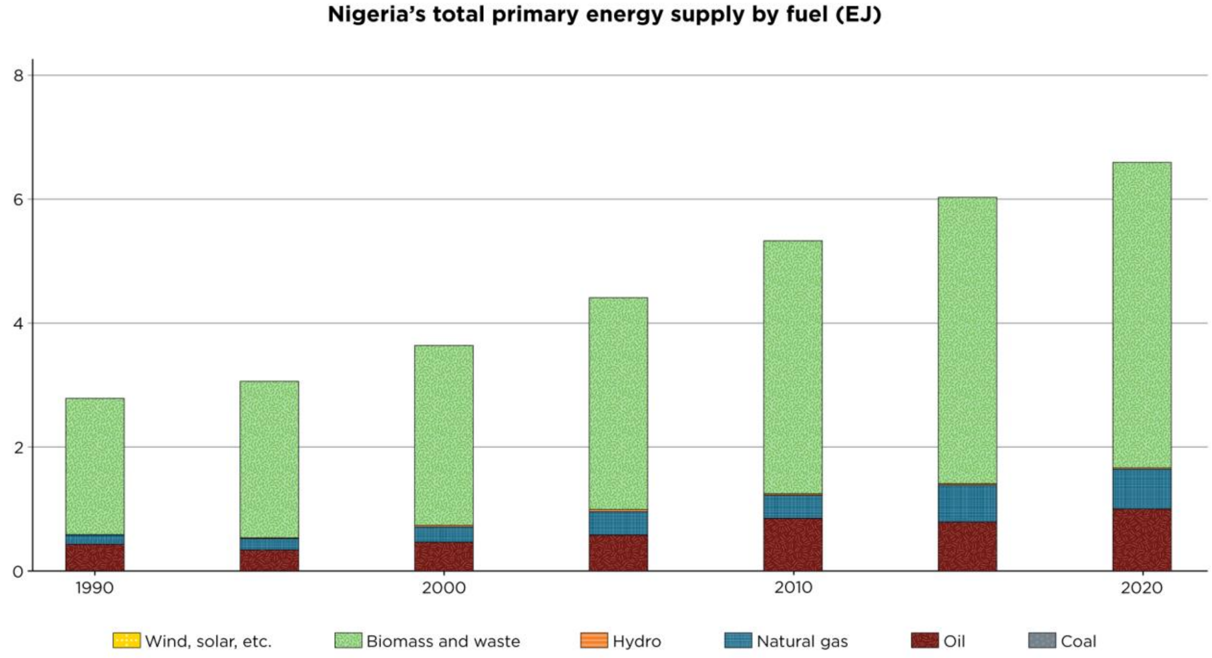

Figure 54. Nigeria's total primary energy supply by fuel

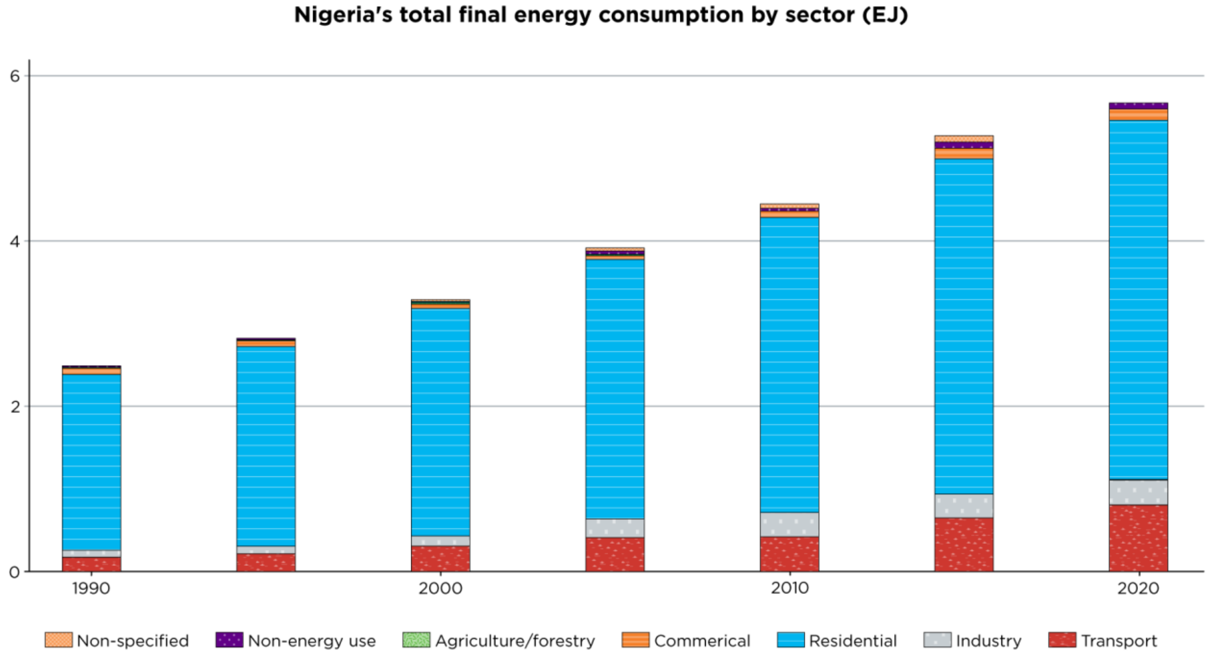

Figure 55. Nigeria's total final energy consumption by sector

6.2 Preliminary Phase I Modeling Results

The analysis for Nigeria presented in this report is based on a set of simulations performed with GCAM, a global integrated assessment model of energy, agriculture, land use, hydrology, and atmosphere. The specific version of the model used here was modified to include Nigeria as a model region, and additional revisions were designed to improve the data used for the model's historical calibration and to assure consistency with Nigeria's ETP in the future projections. With these modifications and revisions, GCAM can be used to analyze the impact of individual technology and policy futures in the context of the ETP.

The starting point for this analysis is the Reference scenario, in which Nigeria's population and GDP grow as prescribed by the ETP. Across the whole economy, emissions increase in most sectors as economic growth outpaces technological improvement (Figure 56a). Though the emissions intensity of electricity generation falls by over 50% from 2020 to 2060 due to improvements in efficiency of natural gas power generation and deployment of wind and solar, total electricity generation increases fivefold during this time (Figure 56b). While most of the generation is supplied by thermoelectric plants fueled by natural gas and liquid fuels, solar accounts for the largest shares of capacity (Figure 56c) and capital investment (Figure 56d). The growth in solar is driven by generally favorable economics of the technology, due in part to the decentralized nature of the grid—this model outcome is not driven by efforts to reduce GHG emissions.

Throughout the rest of the economy, oil and gas-related GHG emissions increase despite deployment of technologies that reduce methane leakage and despite an assumed phaseout of gas flaring by 2030. Residential sector emissions remain relatively stable due to the increase in service demand being offset by the phaseout of primary solid biomass fuels for water heating and cooking by 2050, which reduces methane emissions from incomplete fuel combustion. Similarly, transportation sector emissions remain stable due to technological improvements in vehicles, electrification of a portion of the vehicle fleet, and improvements in roads which translate to improved vehicle fuel economy. In the industrial sector, natural gas replaces biomass as the dominant fuel, driving a nearly fourfold increase in industrial sector GHG emissions.

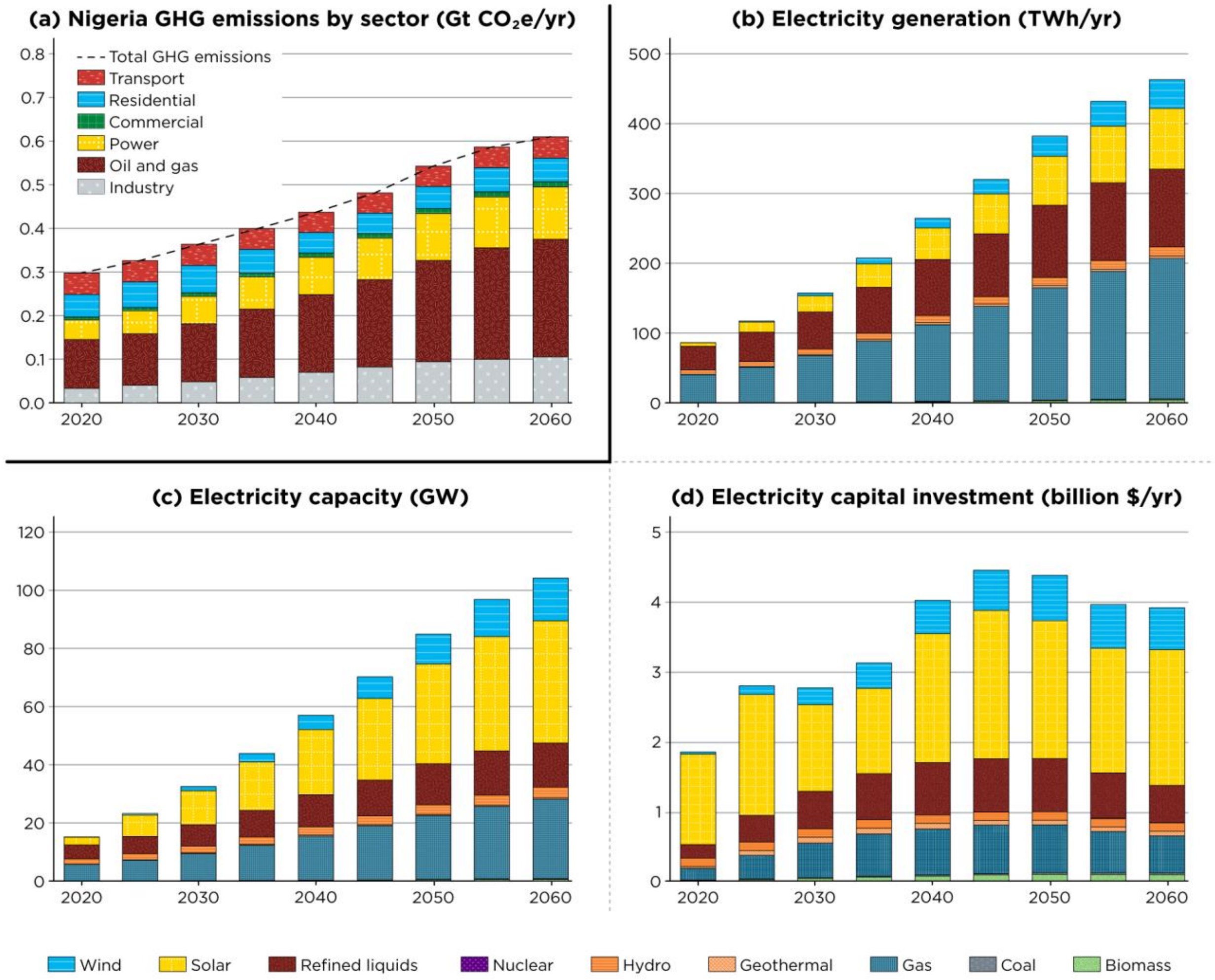

Figure 56. Nigeria's key indicators for the Reference scenario, 2020–2060: (a) Nigeria GHG emissions by sector (Gt CO_2e/yr), where the dotted line indicates total GHG emissions, (b) electricity generation (TWh/yr), (c) electricity capacity (GW), and (d) electricity capital investment (billion $2020/yr)

Nigeria Insight 1: Negative emissions from biomass with CCS is important under net-zero assumptions.

Figure 57 shows the same summary indicators as Figure 56 but for a representative scenario that approaches net-zero GHG emissions from the energy system by 2060, departing from the Reference scenario starting in the 2025 model time period. In the final years under this scenario, negative emissions realized by bioenergy with CO_2 capture and storage, or BECCS, offset the remaining positive emissions, mostly from the industrial sector, where several processes such as cement manufacturing are difficult to decarbonize (Figure 57a). In the Reference scenario, liquid fuels (e.g., liquefied petroleum gas) account for about 12% of buildings sector final energy consumption from 2050 to 2060, this share is only 3% in the ZeroBy2060 scenario. Electricity may become the dominant fuel in transportation starting in 2050.

Nigeria Insight 2: Natural gas with CCS may be a significant contributor to reaching net-zero.

In the power sector, wind and solar account for 70% of the electric generation capacity in 2060, but there is an important contribution from natural gas with CCS, which accounts for about 25% of capacity and 40% of generation (Figure 57b and Figure 57c). This technology choice reflects the favorable economics of natural gas in Nigeria, particularly compared with coal or biomass, in providing stable, dispatchable electric generation.

Nigeria Insight 3: Under a net-zero scenario, power sector investments double compared to the Reference scenario.

As Figure 57d shows, Nigeria's electric sector capital investment from 2050 to 2060 is almost $10 billion per year, or twice the level seen in the Reference scenario, and solar accounts for the majority of investments. Note that these figures only represent capital investment in power generation, and do not include infrastructure for electricity transmission and distribution, nor CO_2 transport and injection.

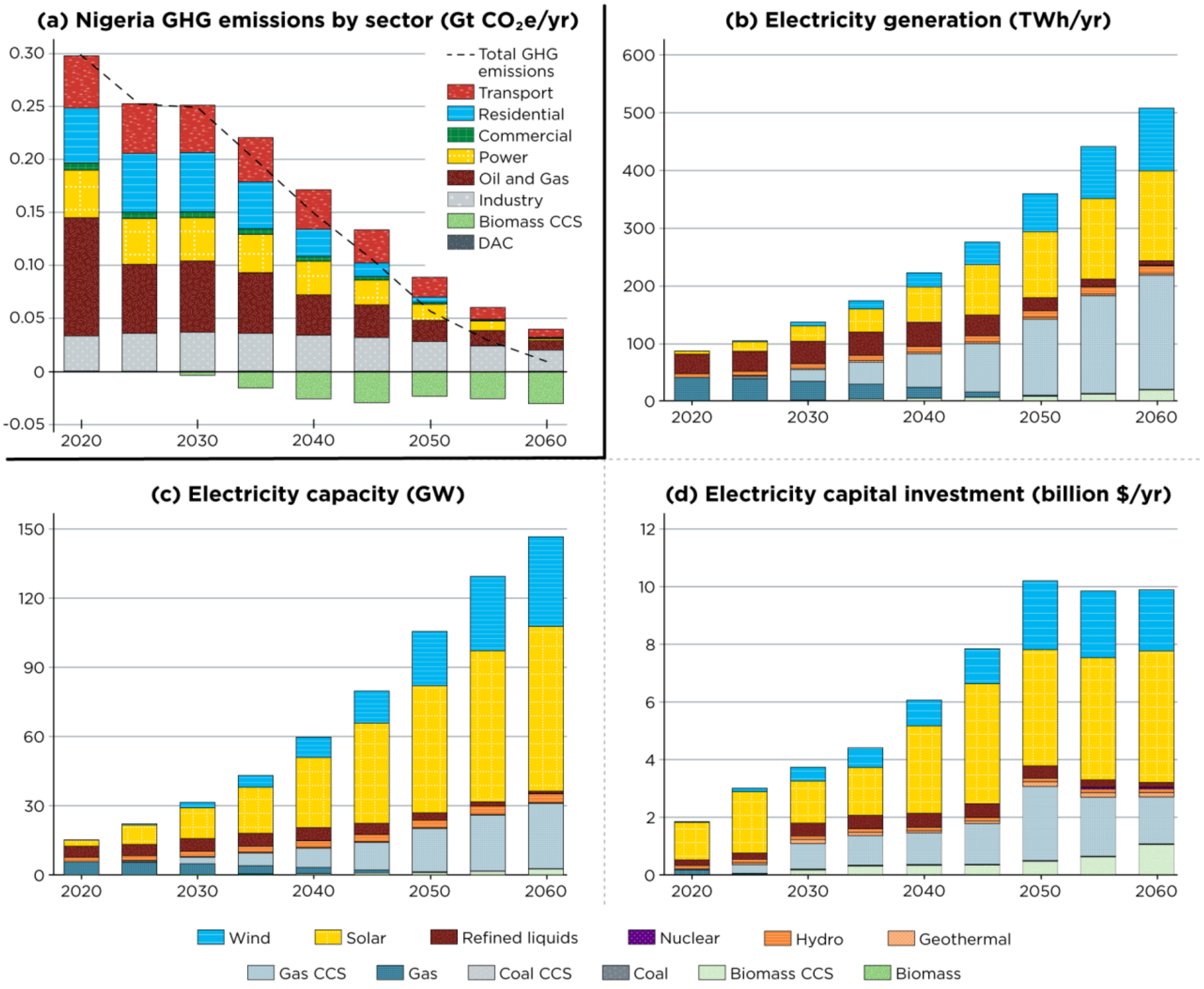

Figure 57. Nigeria's key indicators for a scenario with zero net GHG emissions by 2060, 2020–2060: (a) GHG emissions by sector (Gt CO_2e/yr), where the dotted line indicates total GHG emissions, (b) electricity generation (TWh/yr), (c) electricity capacity (GW), and (d) electricity capital investment (billion $2020/yr)

Nigeria Insight 4: Definition of carbon market rules significantly influence the emission outcomes and domestic crude-oil competitiveness

In this analysis, GCAM was used to gain insights into emission and market impacts of different carbon market rules. One of GCAM's strengths is the ease and flexibility of defining alternate scenarios. For instance, if a carbon market were defined as a power sector-specific cap-and-trade mechanism, we could explore questions such as:

- To what extent would a power sector cap-and-trade scheme drive consumers to shift away from electricity consumption or delay the electrification of transportation and buildings sectors?

- Within the power sector, if off-grid generators (i.e., diesel powered gensets) were exempt from the cap-and-trade scheme, to what extent would customers prefer nonqualifying technology, and thus, bypass the policy intent.

To demonstrate the flexibility of GCAM to assess emission outcomes based on market rules, the four following scenarios were explored:

- **Reference scenario:** No emission mitigation policy (CO_2 or CH_4)
- **CO_2tax-CH_4MAC scenario:** Economy-wide zero CO_2 by 2060 (driven by CO_2 tax) with CH_4 abatement incentives
- **CO_2tax scenario:** Economy-wide zero CO_2 by 2060 (driven by CO_2 tax) with no consideration of CH_4 abatement
- **GHGtax-CH_4MAC scenario:** Economy-wide zero CO_2 by 2060 (driven by CO_2 tax) with CH_4 abatement incentives and CH_4 taxes.

The CO_2tax-CH_4MAC scenario implicitly assumes mechanisms exist to incentivize oil and gas producers to reduce methane emissions, but producers are not taxed for methane emissions. By contrast, the CO_2tax scenario only has methane abatement to the extent that it is economically profitable (i.e., sold as a commodity), and zero economic value is assigned to the mitigation of emissions. The GHGtax-CH_4MAC scenario builds on the CO_2tax-CH_4MAC scenario by also pricing methane emissions, which tends to increase the costs of producing oil and gas according to any remaining (i.e., unabated) methane emissions.

Figure 58 (left panel) demonstrates that completely exempting oil and gas sector methane emissions from the GHG abatement efforts (CO_2tax) keeps whole-system emissions above net zero to 2060. Coupling the CO_2 abatement policy with revenue-neutral methane abatement incentives that do not increase net oil production costs (CO_2tax-CH_4MAC) allows the emissions mitigation target to be achieved. Taxing any remaining oil and gas sector methane emissions that were not lowered in response to the methane abatement incentives reduces the total GHG emissions by only a small amount (GHGtax-CH_4MAC, Figure 58, left panel); however, the consequent increase in production cost may lead to reduced demand in the global oil market(Figure 58, right panel). It should be noted that regardless of the carbon market option analyzed and the resulting carbon tax, the domestic crude oil production may still grow through 2045 because of global market conditions.

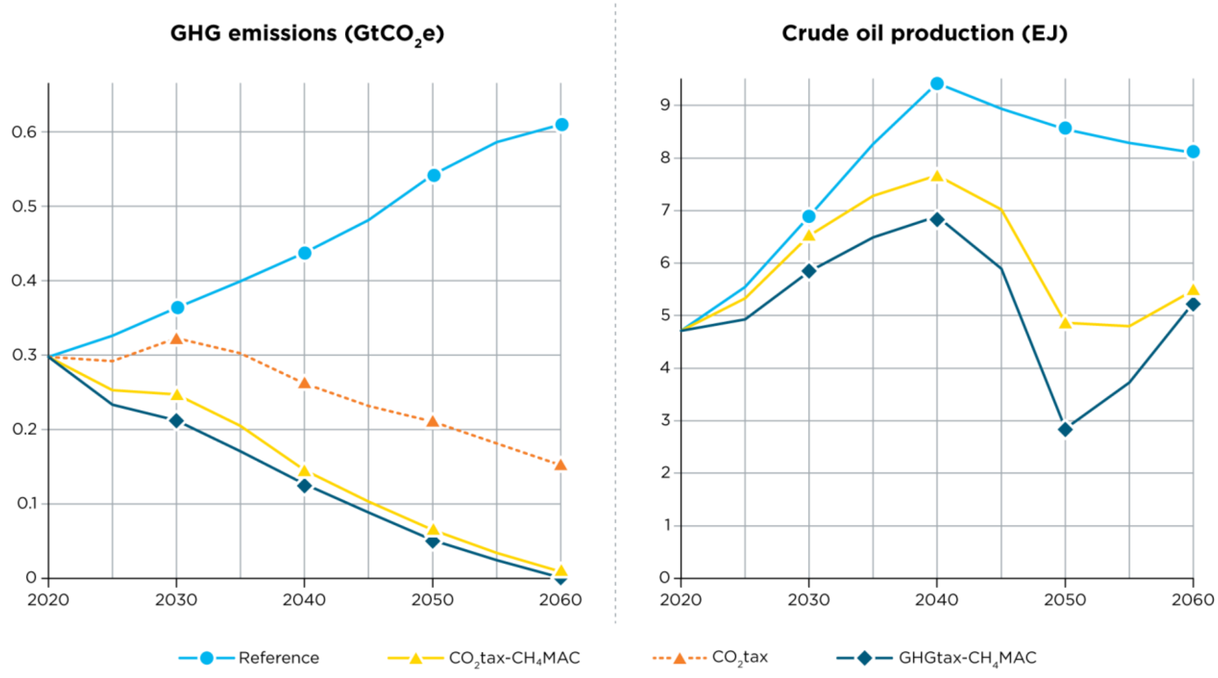

Figure 58. Nigeria's total in-scope GHG emissions by scenario, 2020–2060 (left) and crude oil production by scenario (right)

6.3 Lessons Learned from the Modeling and Potential Value of Results

Initial modeling results for Nigeria demonstrate the varying emission outcomes and domestic oil production market response of four different carbon market scenarios. GCAM offers flexibility to explore additional and subnationally defined carbon market rules and economic feedback on the Nigerian oil and gas sector and the overall economy. In follow-on work, additional analyses could focus on the regionally defined market rules and implementation that includes fugitive methane and CO_2 emissions. Future work might also consider Nigeria's interest in methane capture commercialization efforts and 30% renewable goals for 2030. Furthermore, economic analyses could be undertaken to reveal the domestic and geopolitical conditions under which continuing natural gas investments may become stranded assets.

7 Synthesis and Key Insights

The modeling of decarbonization pathways of our five partner countries is meant to establish an analytical foundation for, and to build trusted partnerships among, U.S. modelers and in-country Net Zero World Initiative partners and government representatives. The initial results and insights we report here—as part of Phase I of this work by the initiative—provide the basis for discussion among initiative partners to identify future stages of analysis that could expand on the system-wide analysis approach or drill more deeply into targeted sectoral analyses of high-value.

To nurture cross-fertilization of lessoned learned among all Net Zero World Initiative member countries, we summarized our preliminary results of the Phase I modeling activities into a single report—rather than into five individual reports. Though each country has a different energy system legacy, different resources bases, and different perspectives on possible pathway options and technological solutions that reflect that each country's value systems, the insights drawn from the modeling reported here point to several commonalities in our Phase I findings:

1. National decarbonization strategies are determined by each country's existing energy infrastructure, the national and subnational resources available, and the national preferences and valuations of advancing strategic energy system outcomes.
2. Four essential mechanisms drive carbon reduction to varying degrees in each country:
    A. Efficiency improvements of all end-use sectors
    B. Fuel switching to clean energy carriers (electricity or hydrogen)
    C. Greening the electric power supply through large deployment of renewable energy technologies
    D. Carbon capture and storage (CCS) of remaining fossil-based systems.
3. Energy efficiency is a high priority, particularly in high GDP-growth countries in the transportation, buildings, and industrial sectors.
4. Wind and solar will not only meet load growth requirements—it will also replace fossil-based electricity generation capacity (primarily coal).
5. Hydrogen is of interest for future study as an energy carrier for some countries.
6. Remaining fossil-based energy systems may require CCS technology for some countries.

Furthermore, the results generated by the TIMES and GCAM teams estimated time-dependent investments needed for each decarbonization pathway. The investment needs are large, but they will generate significant economy-wide co-benefits by reducing air pollution and creating opportunities for new workforce development and economic revitalization. Furthermore, benefits may extend to reduced vulnerability of energy supply disruptions and potentially overall higher energy system reliability. More quantitative sector-specific investment requirements are expected to be generated from the existing model results in our Phase II modeling work.

8 Next Steps

The Net Zero World Initiative will transition from Phase I modeling and analysis activities to Phase II activities. The latter will offer opportunities to explore additional national policy options and decarbonization strategies through energy system-wide modeling and analysis as well as by focusing on deeper sectoral questions that either emerged during the Phase I activities or may be of high interest to a partner country.

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Appendix A. Models Used in Phase I

GCAM

The Global Change Analysis Model (GCAM 6.0) is an integrated assessment model that links the world's energy, water, and land use systems with a simple climate model. It has been used in every Intergovernmental Panel on Climate Change (IPCC) report to provide global emission projections, and it is designed to assess climate change policies and technology strategies for the globe over long time scales. GCAM runs in 5-year time steps from 2005 to 2100, and it accounts for all major GHGs and all sectors of the economy. There are 32 geopolitical regions in the energy and economy module and 384 land regions in the agriculture and land use module. The model tracks emissions and atmospheric concentrations of GHGs, carbonaceous aerosols, sulfur dioxide, and reactive gases and provides estimates of the associated climate impacts, such as global mean temperature rise. GCAM can incorporate emissions pricing and constraints in conjunction with the numerous technology options including solar, wind, nuclear, and CCS. The model has been widely used to explore the effect of technology and policy on climate change and the cost of mitigating climate change.

The energy system in GCAM contains detailed representations of extractions of depletable primary resources such as coal, natural gas, oil, and uranium as well as renewable sources such as bioenergy, hydropower, solar, wind and geothermal. GCAM also includes representations of the transformation processes that convert these resources into secondary energy carriers, which are ultimately used to provide goods and services demanded by end users. Secondary energy carriers include refined liquids, refined gas, coal, commercial bioenergy, hydrogen, and electricity. Each secondary energy carrier can be produced with any number of primary energy sources, depending on the available technologies for that carrier. The choice of which primary energy source to use depends on the cost of producing each secondary energy carrier. Finally, these carriers are then used in buildings, industry, and transportation sectors. Similarly, the choice of which secondary energy carrier to use in end-use sectors depends on technology availability and price.

Additional information can be found at https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model. And documentation of GCAM can be found on GitHub at https://github.com/JGCRI/gcam-core/releases.

LEAP

The Low Emissions Analysis Platform (LEAP) is designed for integrated energy planning over a 20- to 50-year time horizon. It focuses on energy systems and the co-benefits of policy action on climate mitigation and air pollution, and it is widely used for NDCs, climate communications and strategy, national and regional planning, and cross-country analysis. Starter data sets are available for many countries; some additional inputs require information on macroeconomic drivers, energy activity drivers, technology or fuel mix, and energy intensities. LEAP provides projections throughout the entire energy system, from resource extraction and production to energy consumption, emissions, resource availability and investment requirements. For the electric power sector, the model includes optimization and least-cost expansion and dispatch capabilities with modeling of subannual time-slices down to seasonal, daily, and hourly intervals. User-defined indicators can be constructed and calculated in the model to evaluate job and economic impacts. Additionally, the Integrated Benefits Calculator extension allows for translation of national-scale emissions scenarios into estimates of health (mortality), ecosystem (crop loss), and climate (temperature change) impacts. Recent development efforts include LEAP integration with NEMO (the Next Energy Model system for Optimization) tool, which can enable least-cost optimization of energy supply and demand, and modeling of energy storage, renewable energy targets, and emission constraints.

Because LEAP is designed to be an energy planning tool, it provides a complete decision support system that includes data management processes and tools for visualization and stakeholder engagement, including charts, tables, maps, and reports that are produced by the software. It is freely available to governments, nonprofits, and academics in low and lower-middle income countries, and at low-cost licensing to higher-middle income countries. It is free to all students. The Net Zero World Initiative's LEAP modeling effort provides a unique physical driver approach and detailed end-use technology resolution that can be used to support specific policy development, such as codes and standards.

Information, updates, and downloads are available at leap.sei.org.

TIMES

TIMES is a full sector cost-optimization model that integrates assumptions across fuel, technology, and policy uncertainties to understand how the entire energy system responds to different incentives, explore the technology and market risks facing policies, and develop strategies to mitigate these risks. TIMES determines least-cost investment pathways and energy system operation to meet exogenously projected energy service demands, subject to various energy system and environmental constraints. It is a flexible and modular framework where energy commodity flows are represented in a fully customizable Reference Energy System from primary energy extraction through conversion and production and to end use. Technologies are easily added, removed, or represented at different resolutions. Users specify the time periods, regional and sectoral coverage, and coverage of air pollutants. For the electric power sector, demand is modeled through seasonal and daily time-slices, and least-cost generation investments that meet the electric load profile are also identified. TIMES can compute impacts on jobs, human health, and land and water with user-defined factors linking them to the energy sector investments and operations.

In addition to a sophisticated desktop user interface, the TIMES model has a cloud-based version for effective remote collaboration where teams around the globe can view the same model and results and collaborate in real time. TIMES source code is downloadable from GitHub and the cloud-based online system (VEDA) is available through an annual license. Additional information can be found at:

- TIMES: https://iea-etsap.org/index.php/etsap-tools/model-generators/times
- Desktop User Interface: https://iea-etsap.org/index.php/etsap-tools/data-handling-shells/veda
- TIMES Cloud: https://vedaonline.cloud.

Appendix B. Chile's LEAP Net Zero Scenario CO_2 Reduction Contributions and Mitigation Measures

Table B-1. Chile's LEAP Net Zero Scenario CO_2 Reduction Contributions and Mitigation Measures by Demand Sector

Sector	2020 Total CO_2 Emissions ($MtCO_2$)	Net Zero Scenario Mitigation Measures Modeled	2050 Direct CO_2 Reduction Contribution, Relative to BAU Scenario ($MtCO_2$)
Transportation	**24.6**		**17.0**
Road passenger	17.3	• Efficiency gains from accelerated electrification in urban and interurban autos (60% by 2050), taxis (100% by 2050), and buses (100% by 2050) based on PELP Electrification scenario • Additional efficiency gains from electrification (90% by 2050) of motorcycles	6.7
Road freight	3.7	• Efficiency gains from accelerated electrification (100% by 2050) of light-duty trucks based on PELP Electrification scenario • 70% electric and 30% hydrogen shares for medium-duty trucks by 2050 based on Ministry of Energy discussion • 83% hydrogen and 17% electric shares for heavy-duty trucks by 2050 based on Ministry of Energy discussion	5.9
Railway	0.05	• 1%/year average energy efficiency improvement for interurban rail based on international trends	0.03
Maritime	0.45	• 20% fuel share for liquefied natural gas by 2050, as a commercially available alternative to displace diesel and fuel oil shares	0.27
Air	3.1	• 78% hydrogen fuel share by 2050 based on Ministry of Energy and PELP analysis	4.1
Industry	**17.6**		**26.3**
Copper	6.0	• 0.5%/yr energy efficiency improvement in concentrating, leaching, and pyrometallurgy processes, 2020–2050	8.4

Sector	2020 Total CO_2 Emissions ($MtCO_2$)	Net Zero Scenario Mitigation Measures Modeled	2050 Direct CO_2 Reduction Contribution, Relative to BAU Scenario ($MtCO_2$)
		• 0.9%/yr process energy efficiency improvement in hydrometallurgy process, 2020–2050 • Increased share of electricity in energy use for copper concentrates production, from 40% in 2020 to 85% by 2050 • Reduced shares of diesel and natural gas; increased share of electricity and hydrogen in refined copper production to 75% and 15%, respectively, by 2050	
Cement	1.1	• Increased thermal energy efficiency of ≈1%/yr • Reduced fuel share of pet coke from 87% in 2020 to 30% by 2050 • Increased share of municipal solid wastes, biomass, and hydrogen to 40%, 10%, and 20% by 2050 respectively • Improved clinker-to-cement ratio (0.6 by 2050)	1.3
Steel	2.1	• Increased adoption of waste heat recovery in blast furnaces, coking, and basic oxygen furnace (BOF) • Increased energy efficiency in blast furnace-basic oxygen furnace (1%/yr), electric arc furnaces (2%/yr), and steel rolling (0.4%/yr) processes through 2050 • Increased scrap-based EAF production share, to 45% by 2050 • Increased production share of green hydrogen direct reduced iron-electric arc furnace technology, to 15% by 2050 • Reduced coke consumption and increased green hydrogen as a chemical reduction agent • Increased hydrogen share to 15% in blast furnace-BOF process energy use by 2050	1.5

Sector	2020 Total CO_2 Emissions ($MtCO_2$)	Net Zero Scenario Mitigation Measures Modeled	2050 Direct CO_2 Reduction Contribution, Relative to BAU Scenario ($MtCO_2$)
Pulp and paper	1.2	• Improved energy efficiency (both specific heat and electricity requirements) in virgin pulp making, of ≈1%/yr on average • Improved electrical energy efficiency in thermomechanical pulp making of 0.6%/yr on average • Improved thermal energy efficiency in papermaking process of 1.5%/yr on average • Improved electrical energy efficiency in papermaking process of 0.3%/yr on average • Phaseout of natural gas, diesel, and liquefied natural gas in chemical pulp-making by 2050; reduced shares of fuel oil to 3% by 2050; increased share of biogas and renewable heat to 7% and 10% respectively by 2050 • Reduced share of fuel oil to 6% by 2050 and increased share of renewable heat to 10% by 2050 in papermaking process	1.0
Other industry and mining	7.3	• Improved economic energy intensity of other industries and other mining sectors of 0.4%/ yr • Increased use of electricity through adoption of electrotechnologies (e.g., electric boilers and industrial heat pumps) and expansion of electricity end uses in industry • Increased use of renewable heat (e.g., solar and geothermal) and hydrogen to 12% each, reducing the shares of natural gas and diesel	14.2
Building	**5.0**		**10.6**
Electrification of heating	2.7	• Integrative, passive building design for 70% heating load reduction (better insulation and air tightness) • Improved energy efficiency (heat pump coefficient of performance=3) • Demand flexibility load shedding (5%–10%)	5.2

Sector	**2020 Total CO_2 Emissions ($MtCO_2$)**	**Net Zero Scenario Mitigation Measures Modeled**	**2050 Direct CO_2 Reduction Contribution, Relative to BAU Scenario ($MtCO_2$)**
Electrification of cooking	0.8	• 25% cooking final energy saving • Achievement of 100% electrification • Demand flexibility load shedding (5%–10%)	1.9
Water heating	1.4	• 30% in residential building and 20% in commercial buildings • Achievement of 100% domestic hot water electrification • Demand flexibility load shedding (5%–10%)	3.5
Lighting	Electricity only, no direct CO_2	• Energy efficiency gains (40% residential and 20% commercial) • Demand flexibility load shedding (5%–10%)	Electricity only, no direct CO_2
Cooling	Electricity only, no direct CO_2	• Mitigation of urban heat island effect (10% residential and 7% commercial) • Integrative, passive building design (14% residential and 28% commercial) • Cooling energy savings through technology and system efficiency (24% residential and 21% commercial) • Demand flexibility load shedding (5%–10%)	Electricity only, no direct CO_2
Fans	Electricity only, no direct CO_2	• Energy efficiency gains (30% residential and 40% commercial) • Demand flexibility load shedding (5%–10%)	Electricity only, no direct CO_2
Plug load	Electricity only, no direct CO_2	• Energy efficiency gains (30% residential and 40% commercial) • Demand flexibility load shedding (5%–10%)	Electricity only, no direct CO_2

Bunker fuel use is not reported for transportation.

Some totals may not be equal to the sum of the separate figures due to rounding.

CO_2 reported is from direct fossil fuel consumption and does not include CO_2 from electricity consumption. Electricity CO_2 is reported separately for the power sector and is not allocated to the demand sectors in the current analysis.

NET ZERO WORLD INITIATIVE

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