NET ZERO WORLD INITIATIVE

Accelerating Global Energy System Decarbonization

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

EXECUTIVE SUMMARY

Michael Kintner-Meyer, Guenter Conzelmann, Hyekyung Clarisse Kim, Nan Zhou, Paelina DeStephano, Siddarth Durga, Amgad Elgowainy, Bruce Hamilton, Amit Kanudia, Nina Khanna, Zarrar Khan, Page Kyle, Virginie Letschert, Wei Feng, Felipe Feijoo, Francisco Flores, George Giannakidis, Francisca Licandeo, Haewon McJeon, Timothy Reber, Daniella Rough, Michael Westphal, and Evelyn Wright

U.S. DEPARTMENT OF STATE

USAID FROM THE AMERICAN PEOPLE

U.S. DEPARTMENT OF ENERGY

USTDA U.S. TRADE AND DEVELOPMENT AGENCY

DFC U.S. International Development Finance Corporation

THE DEPARTMENT OF THE TREASURY

EXIM EXPORT-IMPORT BANK OF THE UNITED STATES

DEPARTMENT OF COMMERCE

MILLENNIUM CHALLENGE CORPORATION UNITED STATES OF AMERICA

NET ZERO WORLD INITIATIVE

Accelerating Global Energy System Decarbonization

Read the full report

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

EXECUTIVE SUMMARY

Michael Kintner-Meyer, Guenter Conzelmann, Hyekyung Clarisse Kim, Nan Zhou, Paelina DeStephano, Siddarth Durga, Amgad Elgowainy, Bruce Hamilton, Amit Kanudia, Nina Khanna, Zarrar Khan, Page Kyle, Virginie Letschert, Wei Feng, Felipe Feijoo, Francisco Flores, George Giannakidis, Francisca Licandeo, Haewon McJeon, Timothy Reber, Daniella Rough, Michael Westphal, and Evelyn Wright

Argonne NATIONAL LABORATORY

BERKELEY LAB
Bringing Science Solutions to the World

NREL
Transforming ENERGY

Pacific Northwest NATIONAL LABORATORY

Suggested Citation: Michael Kintner-Meyer, Guenter Conzelmann, Hyekyung Clarisse Kim, Nan Zhou, Paelina DeStephano, Siddarth Durga, Amgad Elgowainy, et al. 2022. *Preliminary Analysis of Decarbonization Pathways for Five Countries: The Net Zero World Initiative Report Series – 01: Executive Summary*. Richland, WA: Pacific Northwest National Laboratory. PNNL-SA-179337.

DISCLAIMER

PACIFIC NORTHWEST NATIONAL LABORATORY

operated by

BATTELLE

for the

UNITED STATES DEPARTMENT OF ENERGY

under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Axelandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <http://www.nits.org/about/form.aspx>
Online ordering: http://ntis.gov

This document was printed on recycled paper.
(8/2010)

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

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:**

- Efficiency improvements of all end-use sectors
- Fuel switching to clean energy carriers (electricity or hydrogen)
- Greening the electric power supply through large deployments of renewable energy technologies
- 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 Energy Secretariat of the Argentina Ministry of Economy 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

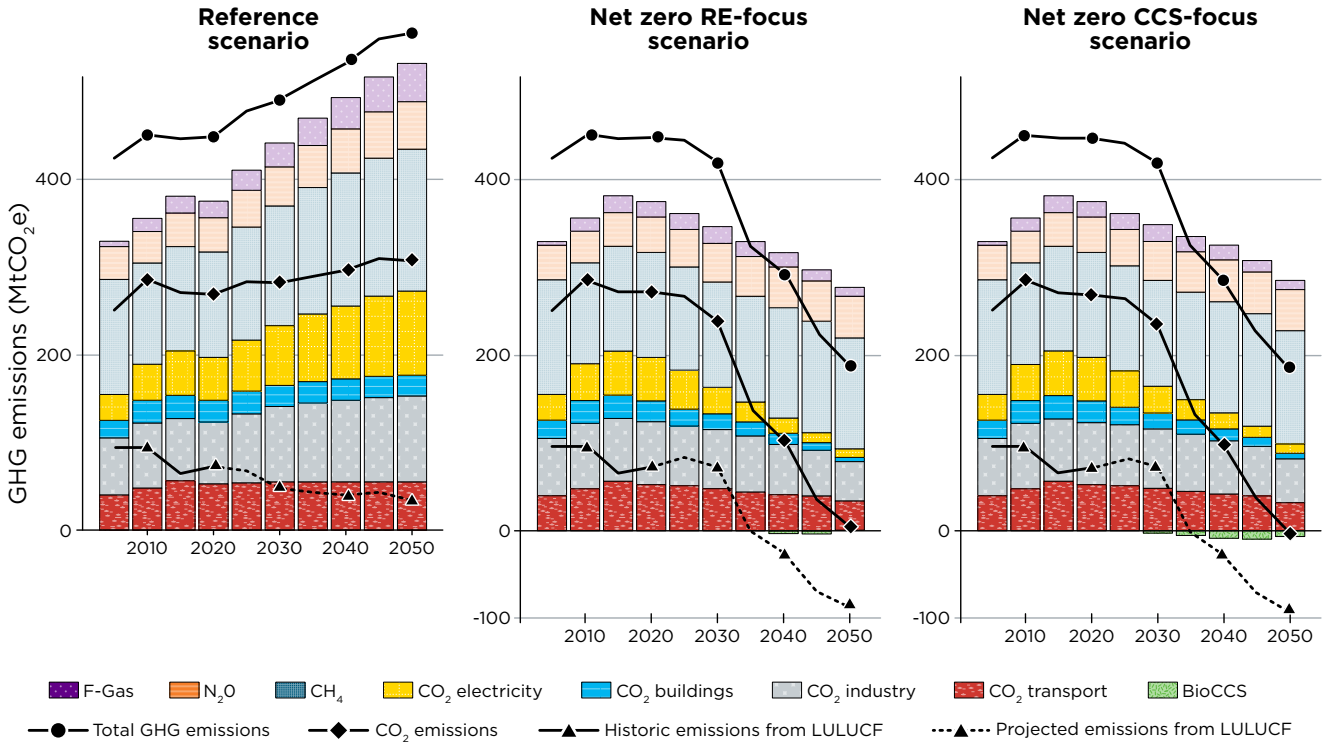


Figure ES-1. Argentina's emissions projections

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

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

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

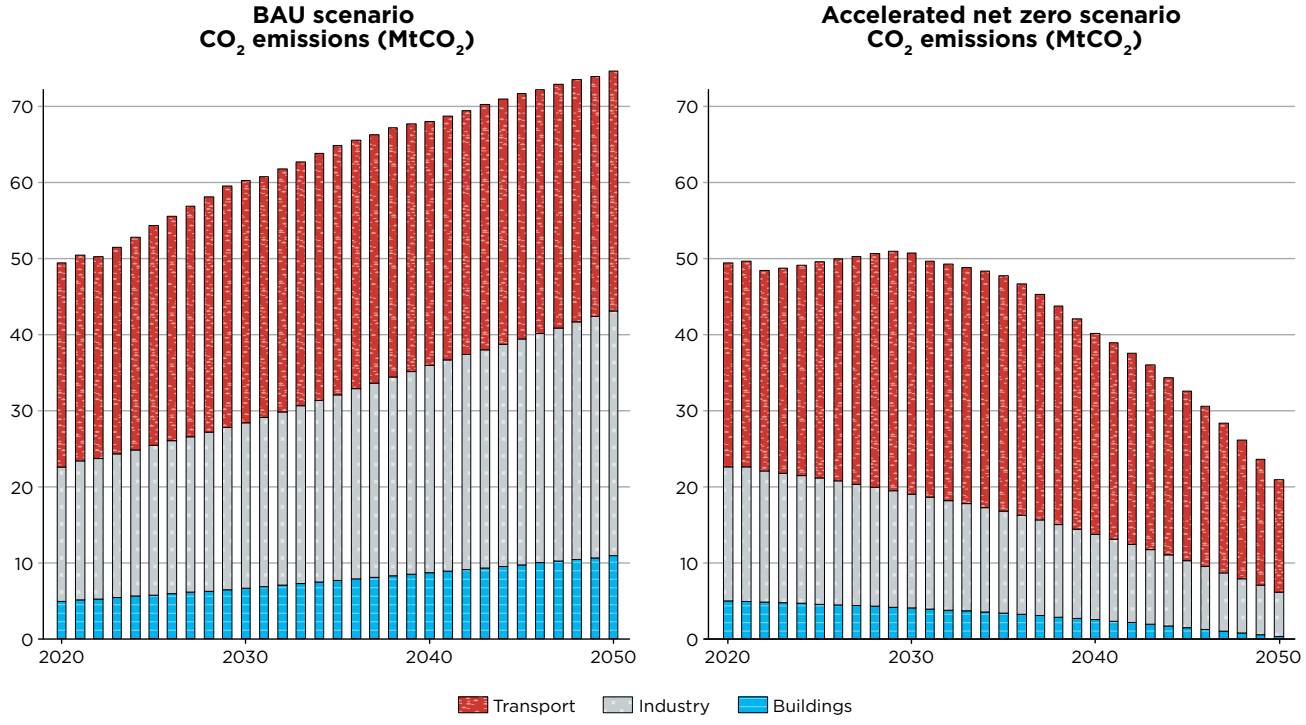


Figure ES-2. Chile's CO_2 emissions by sector, LEAP BAU and Accelerated Net Zero scenarios

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

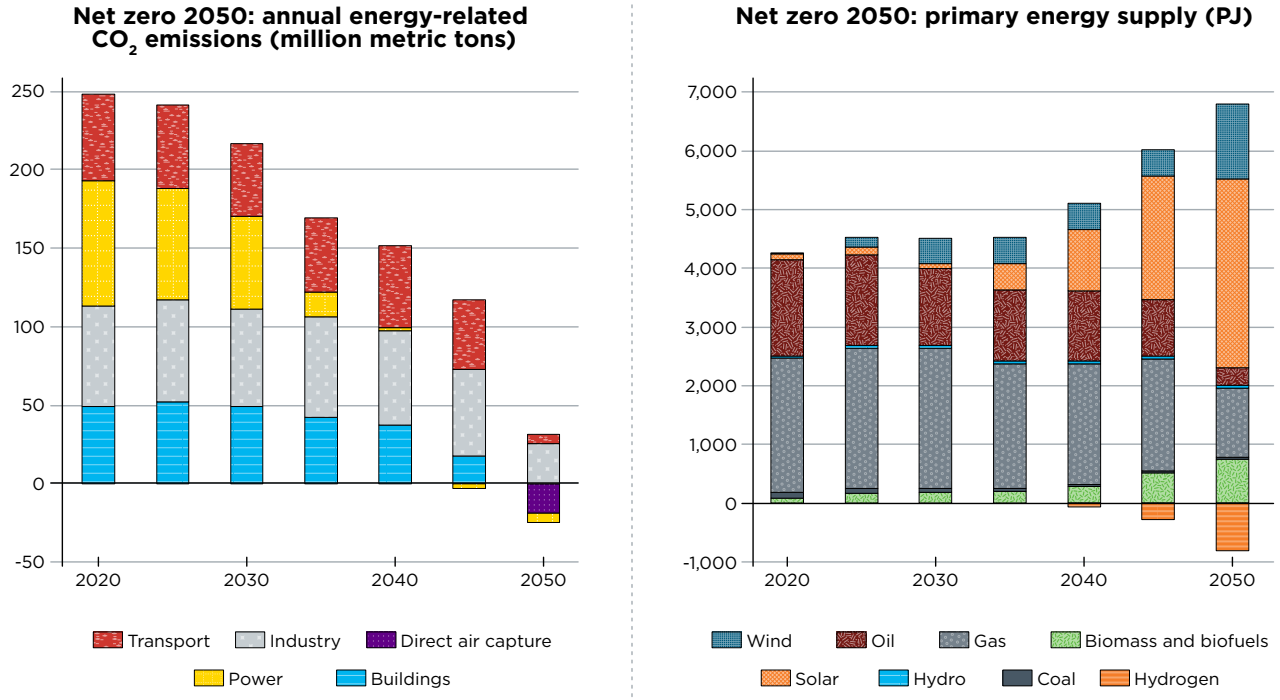


Figure ES-3. Egypt's emissions projections (left) and primary energy supply (right)

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

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 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[1] 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.

Pathway Results

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.

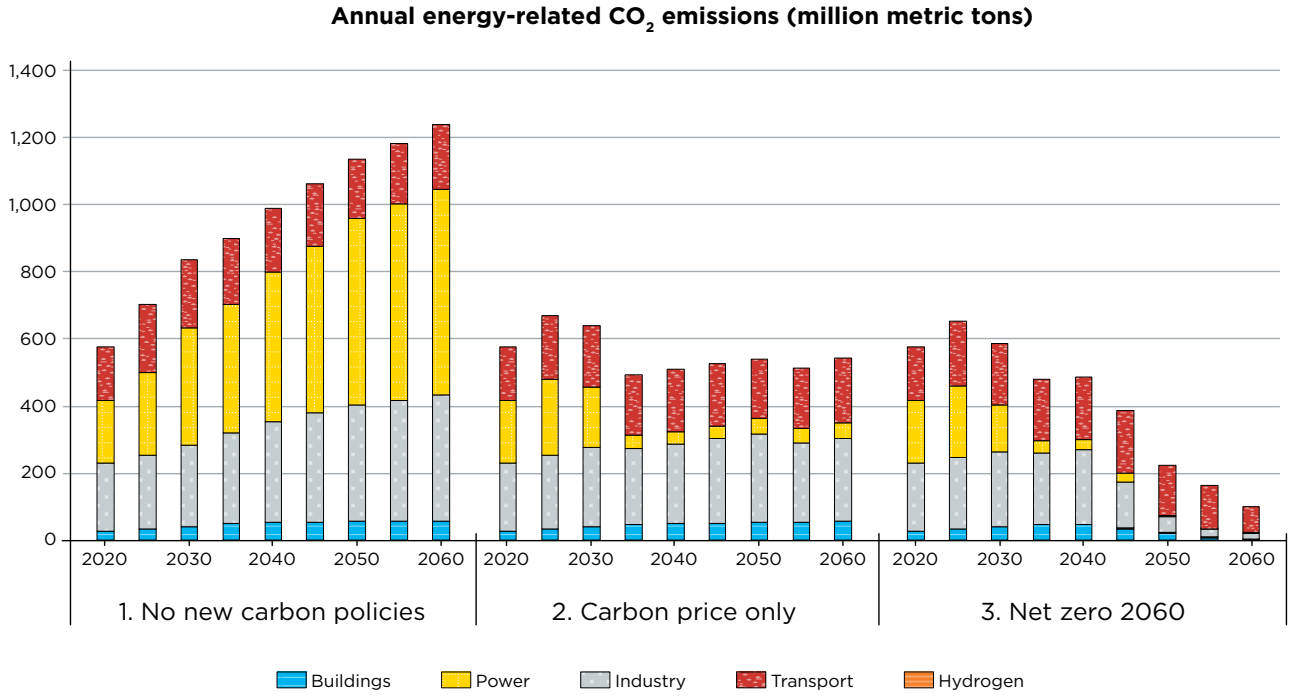
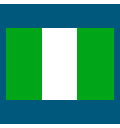


Figure ES-4. Indonesia's emissions projections

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

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).

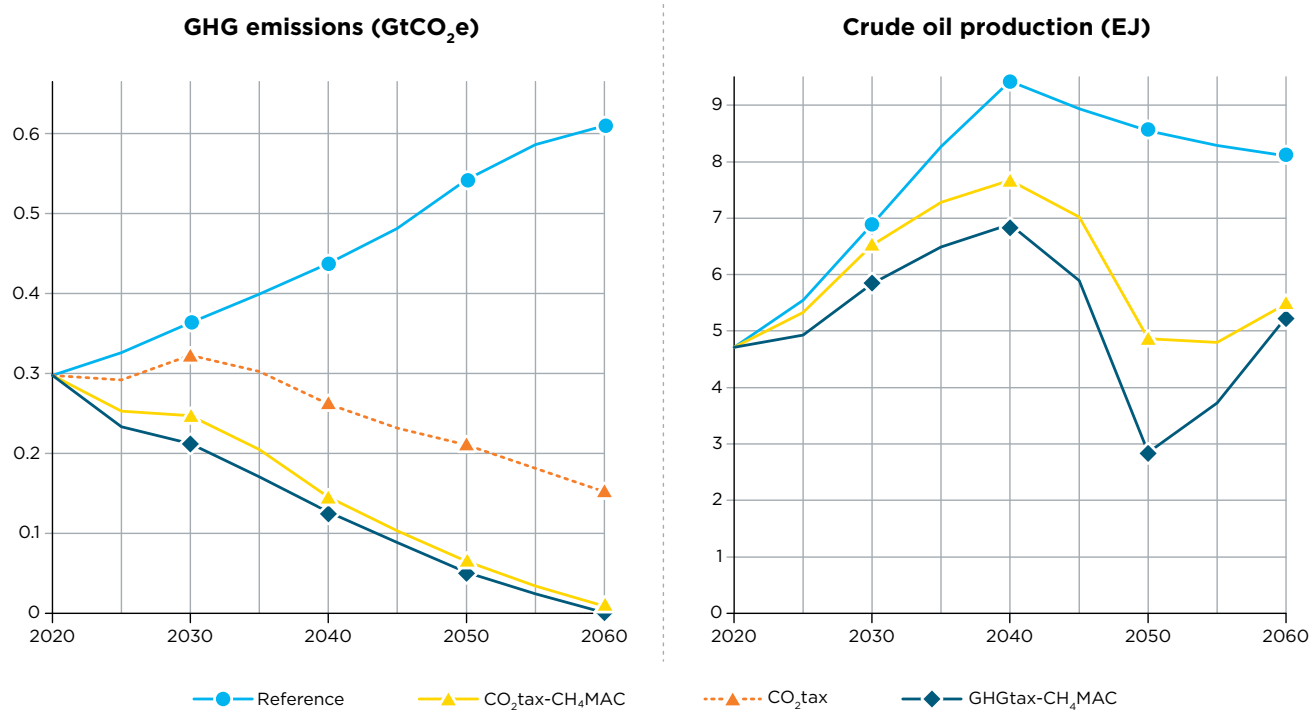


Figure ES-5. Nigeria's total in-scope GHG emissions by scenario, 2020–2060 (left) and crude oil production by scenario (right)

Pathway Results

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.

Argonne NATIONAL LABORATORY

BERKELEY LAB
Bringing Science Solutions to the World

NREL
Transforming ENERGY

Pacific Northwest
NATIONAL LABORATORY

USAID
FROM THE AMERICAN PEOPLE

U.S. DEPARTMENT OF ENERGY

USTDA
U.S. TRADE AND DEVELOPMENT AGENCY

DFC U.S. International Development Finance Corporation

EXIM EXPORT-IMPORT BANK OF THE UNITED STATES

MILLENNIUM CHALLENGE CORPORATION
UNITED STATES OF AMERICA

NET ZERO WORLD INITIATIVE

Pacific Northwest National Laboratory
902 Battelle Boulevard, Richland, WA 99354
1-888-375-7665 • www.pnnl.gov

PNNL prints on paper that contains recycled content.

Pacific Northwest National Laboratory (PNNL) is managed and operated by Battelle for the U.S. Department of Energy

PNNL-SA-179337 • November 2022