Mexico is ideally positioned to become a clean energy powerhouse given its world-class renewable energy resource potential and the low cost of renewable energy generation. Rapid growth in renewable energy deployment in Mexico could generate high levels of investment, increase energy access, reduce costs to consumers, and—together with other actions—improve the reliability and resilience of Mexico’s power system.

Mexico’s energy transition law established a target for meeting at least 35% of its electricity generation from clean energy sources by 2024. In 2021, Mexico generated 86.27 TWh or 26.7% of its electricity from clean energy resources. By 2024, electricity demand is expected to grow 12.7%.

Deploying renewable energies at scale would allow Mexico to meet its clean energy goals while increasing its energy security, attracting significant new investments, growing its national and regional economies, and creating new high-quality jobs. Renewable energy technologies are also the most cost-effective way to provide rural electrification solutions. Access to electricity enhances education, health, and other social services that improve quality of life for underserved communities. Clean energy generation in Mexico is also necessary to power the electrification of the transport sector, which would improve air quality.

Figure 1 shows that Mexico’s renewable resources are well distributed throughout the country. National technical potential includes 24,918 GW of solar photovoltaics, 3,669 GW of wind, 2.5 GW of conventional geothermal, and 1.2 GW of additional capacity from existing hydropower facilities.

Combining transmission planning with available renewable energy development in key regions can increase energy access, promote economic growth, and reduce electricity prices while increasing system reliability. Figure 2 shows the southeast region’s very strong potential to become Mexico’s most important clean energy hub, powering sustainable growth throughout the region and exporting clean energy capabilities to the rest of the country and to Central America.

The southeast technical potential includes 5,561 GW of solar PV, 744 GW of wind, an additional 272 MW from conventional geothermal, and the largest hydro resources in Mexico.

The U.S. National Renewable Energy Laboratory (NREL) conducted a 2024 renewable integration study for Mexico, utilizing planned project data from developers, and a regional production cost model of the Mexican power system over a 1-year period. The study looked at three different 2024 generation scenarios, focused mostly on wind and solar but including hydro repowering and geothermal projects from

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1 PRODESEN 2021
2 NREL’s estimate utilizing the National Solar Radiation Database, Wind Toolkit and the Renewable Energy data explorer for Mexico
3 Gutierrez Negrin, et al. 2021. Based only on hydrothermal resources at temperatures ≥150°C
4 Assumes a 10% gain from current facilities
The scenarios with higher accumulated variable renewable generation would result in other numerous benefits. For example, the cost of producing a kWh of electricity would be reduced with more renewable generation. Figure 4 shows that total production costs under the highest accumulated clean generation scenario would save US$1.1 billion, compared to business as usual. Mexico could also create US$17 billion in new investment opportunities and over 72,000 jobs under the highest accumulated renewable scenario.

In addition, emissions would grow more slowly with higher renewable generation. Figure 5 shows that producing a unit of electricity (kWh) in 2024 with higher amounts of accumulated clean generation would produce fewer CO₂, SO₂, and NOₓ emissions.

Higher accumulated renewables would reduce localized marginal prices. More deployment of renewables (Figure 6) in the ARE+ scenario exert a consistent downward pressure on wholesale energy prices (Figure 7), especially in the Yucatan Peninsula, where electricity inflows are constrained because of transmission.

Variable renewable energy curtailment is low in all scenarios, meaning that system constraints would not require renewable output to be reduced.

Finally, the study found that higher accumulated deployment of renewable energy has small but mostly beneficial impacts by reducing transmission congestion between regions.

Given the right mix of policies and technical measures, the country could attract large-scale investments and build a clean energy matrix that meets Mexico’s energy goals and provides social and economic benefits to its citizens. The following actions would enable Mexico to achieve its 35% clean energy target and promote the uptake of renewable energy for transport, buildings, and industry while reaping the economic, emissions, and reliability benefits noted above:

- Transmission expansion in areas of high resource potential
- Regional programs for renewable development
- Operational improvements that better integrate renewables and natural gas generation
- Expedited permitting
- Regulation to increase energy democratization and system reliability
- Creation of sustainable transportation programs that include charging infrastructure investments and grid integration measures.
MEXICO CLEAN ENERGY REPORT—APPENDIX
NORTH AMERICAN CLEAN ENERGY POWERHOUSE

April 2022
Contents of the Appendix

- Resource Potential
- Results of the 2024 Renewable Energy Integration Study
- Technology Chapters:
  - Wind
  - Solar
  - Geothermals
  - Hydro
  - Transportation
  - Green Hydrogen
- Transmission Grid
- Solutions for the Integration of Variable Generation Resources
- Summary of Benefits
Resource Potential
Mexico Has Abundant Renewable Energy Resources to Meet Its Energy Goals

• Mexico generated 86.27 TWh or 26.7% of its electricity from clean energy resources in 2021.

• To meet the 35% clean energy target in 2024, Mexico needs at least 128.83 TWh or 42.56 TWh of additional clean energy generation.

• National solar PV capacity potential is estimated at 24,918 GW.¹ This potential capacity could generate 50,196 TWh/yr or 137 times the 365 TWh estimated demand for Mexico in 2024.

• National wind capacity potential is estimated at 3,669 GW². This potential capacity could generate 5,759 TWh/yr or 15 times the 365 TWh estimated demand for Mexico in 2024.

• National additional conventional geothermal potential is estimated at 2.5 GW.²

• Additional hydropower potential from repowering existing plants is estimated at 1.2 GW.³

¹ NREL Renewable Energy Data Explorer. Exclusions: Urban areas, water/wetlands, protected areas
² Gutierrez Negrín et al, 2021. Based only on hydrothermal resources at temperatures ≥150°C
³ Assumes a 10% gain from current facilities. New construction was not considered given this project’s 2024 timeline
The southeast region of Mexico is rich with renewable resources to power sustainable growth and even export clean energy to the rest of the country and to Central America.

The southeast region of Mexico has:

- 5,561 GW of solar PV potential
- 744 GW of wind potential
- Additional 272 MW potential from conventional geothermal
- Largest hydro resources of Mexico.
Baja California Sur is an electrical islanded system with enough resources to transform its fossil fuel power system into a clean energy system.

Baja California Sur has:
- 743 GW of solar PV potential
- 516 GW of concentrating solar power potential
- 110 GW of wind potential
- 154 MW of conventional geothermal potential
- Pumped hydro potential for energy storage to assist the integration of variable renewable energy.
2024 Renewable Energy Integration Study
Methodology
NREL conducted a renewable energy integration study utilizing pipeline project data from developers in Mexico and Comisión Federal de Electricidad and applying a regional production cost model of the Mexican power system implemented in encoord's Scenario Analysis Interface for Energy Systems (SAInt). The study looked at three different generation 2024 scenarios over a 1-year period and included a 2020/2021 reference scenario that was validated against real market data published by the Centro Nacional de Control de Energía.

Four scenarios were explored for this study:
• REF: 2020/2021 reference scenario
• BAU [2024 business as usual]: 531 MW of internal combustion projects underway and 4,837\(^1\) MW of renewable projects that are carrying out or about to begin pre-commissioning tests
• ARE [accumulated renewable energy]: 2024 scenario with higher renewable energy penetration: +3,935 MW of renewable projects that are in more advanced stages of obtaining permits, financing, interconnection, or beginning construction
• ARE+ [2024 scenario with even greater renewable energy penetration]: +6,485 MW of projects that are in less advanced stages of permitting and obtaining financing and interconnection.

\(^1\) Includes 2,336 MW of new solar distributed generation capacity projected by 2024
Conclusions

• The more ambitious accelerated renewable energy scenario would achieve the 35% target while meeting demand and reserve requirements at all hours of the year. Mexico could attract US$17 billion of direct investment under the highest accumulated renewable scenario.

• The impacts of greater renewable energy penetrations vary geographically and depend on the assumptions made when defining the new installed generation capacity for each scenario.

• Variable renewable energy curtailment is low in all scenarios. However, maximum national instantaneous variable renewable energy penetrations range from 36% to 51% across the 2024 scenarios.

• Higher integrations of renewable energy (primarily wind and solar) provide the following benefits to the Mexican power system:
  • Lower production costs
  • Decrease in natural gas-fired electricity generation
  • Lower regional marginal electricity generation prices
  • Less fuel consumption (primarily natural gas)
  • Smaller increases in emissions between 2021 and 2024
  • Small impacts in transmission congestion, with the most congested interconnections generally seeing less congestion with more renewables.
The Highest Accumulated Renewable Generation Scenario Meets the 35% Clean Energy Goal

Renewable projects in the ARE and ARE+ scenarios would likely require that the current legal, regulatory, and electricity market frameworks remain and are equitably enforced.

Under the ARE+ scenario and if conditions are met, the existing planned renewable projects could achieve Mexico’s clean energy generation goal of 35% by 2024.

Under the BAU and ARE scenarios, clean energy generation reaches 27% and 30.2%, respectively, by 2024.

Estimated investment from renewable generation capacity could achieve US$8,357 million under the ARE scenario\(^1\) and additional US$8,790 million under the ARE+ scenario\(^1\).

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\(^1\) Estimates using data from ASOLMEX, AMDEE and CFE
Production costs (primarily due to lower gas consumption) are reduced with higher accumulated renewable energy generation.

Adding more renewables in the ARE and ARE+ scenarios save US$500 million and US$1,100 million in total costs, compared to the BAU scenario.

The total system costs in the ARE+ scenario are only 2% higher than the reference scenario, while total demand grows by almost 13%.
Summary Results of the 2024 Integration Study

Electricity demand is forecasted to increase 12.7%\(^1\) from 2021 to 2024. Emissions per kWh reflect significant system emission reductions as more renewables are added to the system.

\(^1\) Source: PRODESEN
Lower Regional Marginal Electricity Generation Prices are Achieved with Higher Accumulated Renewables

Higher deployment of renewables exerts a downward pressure on wholesale energy prices across the country, especially in the Yucatán Peninsula where electricity inflows are constrained because of transmission. Baja California Sur further substantiates this relationship: Increase in demand without deployment of renewables in Baja California Sur suggests that existing pressures will only lead to higher prices.
Summary Results of the 2024 Integration Study

- Variable Renewable Energy curtailment is low in all scenarios.
- Maximum national instantaneous VRE penetrations range from 36% to 51% across the 2024 scenarios.

### Summary Results of the 2024 Integration Study

- Variable Renewable Energy curtailment is low in all scenarios.
- Maximum national instantaneous VRE penetrations range from 36% to 51% across the 2024 scenarios.

### National Instantaneous Variable Renewable Generation Penetration

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>SOLAR PV</th>
<th>WIND</th>
<th>VRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFERENCE</td>
<td>0.04%</td>
<td>1.18%</td>
<td>0.78%</td>
</tr>
<tr>
<td>BAU</td>
<td>0.01%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>ARE</td>
<td>0.01%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>ARE+</td>
<td>0.45%</td>
<td>0.71%</td>
<td>0.60%</td>
</tr>
</tbody>
</table>

### Annual Percentage Curtailment Per Technology and for all VRE (PV + Wind)

- For BAU, solar PV curtailment is 0.01%, wind curtailment is 0.00%, and total VRE curtailment is 0.00%.
- For ARE, solar PV curtailment is 0.01%, wind curtailment is 0.01%, and total VRE curtailment is 0.01%.
- For ARE+, solar PV curtailment is 0.45%, wind curtailment is 0.71%, and total VRE curtailment is 0.60%.

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**MEXICO: NORTH AMERICAN CLEAN ENERGY POWERHOUSE**
Wind Technology
Resource Potential

- Cumulative installed capacity at end of 2021: 7,154 MW\(^1\)
- 8% of total electricity generation from wind in 2020\(^2\)
- Technical potential includes areas with average wind speeds of at least 3 m/s and excludes mountainous terrain, wetlands, and urban and protected areas
  - National: 3,670 GW
  - Northeast: 670 GW
  - Southeast: 744 GW
  - Baja California Sur: 110 GW.

\(^1\) AMDEE, Inventario Eólico 2021
\(^2\) GWEC, Global Wind Report 2021
# Deployment Scenarios

- **Business as usual (BAU) scenario:**
  860 MW of projects that are carrying out or about to begin pre-commissioning tests

- **Accumulated Renewable Energy deployment (ARE) scenario:**
  +1,705 MW of projects that are in more advanced stages of obtaining permits, financing, interconnection, or beginning construction

- **High Accumulated Renewable Energy deployment (ARE+) scenario:**
  +2,686 MW of projects that are in less advanced stages of permitting and obtaining financing and interconnection.

<table>
<thead>
<tr>
<th>State</th>
<th>Capacity (MW)</th>
<th>2021</th>
<th>Added by 2024</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current</td>
<td>BAU</td>
</tr>
<tr>
<td>Baja California</td>
<td>195</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Campeche</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Coahuila</td>
<td>397</td>
<td>348</td>
<td>444</td>
</tr>
<tr>
<td>Guanajuato</td>
<td>105</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jalisco</td>
<td>179</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td>Nuevo León</td>
<td>793</td>
<td>168</td>
<td>468</td>
</tr>
<tr>
<td>Oaxaca</td>
<td>2,758</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Queretaro</td>
<td></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Tamaulipas</td>
<td>1,715</td>
<td>198</td>
<td>315</td>
</tr>
<tr>
<td>Yucatán</td>
<td>244</td>
<td>0</td>
<td>1,128</td>
</tr>
<tr>
<td>Zacatecas</td>
<td>230</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>Others</td>
<td>538</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7,154</strong></td>
<td><strong>860</strong></td>
<td><strong>2,565</strong></td>
</tr>
</tbody>
</table>
In these scenarios, wind energy generation increases from 8.1% in the Reference to 12.5% in ARE+ and becomes the largest single source of clean electricity.

Overall, wind curtailments are quite low (approx. 1% or less) suggesting, for these scenarios, that wind is not introducing new transmission constraints or significantly impacting congestion.

With possible brief exceptions in some regions, wind and PV are operating at penetration levels in these scenarios that have been managed successfully in regional power systems around the world. Targeted upgrades, if any, in key areas may be sufficient to handle wind deployment at these levels.
Opportunities and Recommendations

Potential Benefits

- Local economic development can be supported by construction activities—including building foundations, erecting turbines, and commissioning—especially when using a local workforce, subcontractors, and materials (such as aggregate or concrete).
- Operations and maintenance jobs provide long-term employment opportunities in windy regions.
- Wind energy development can be sized to meet individual and community needs, from kW to MW scale, fostering electricity access and energy independence.
- Community ownership has played a key role historically in wind development in markets in Europe (Denmark and Germany) and in the early 2000s in the United States; community ownership has been demonstrated to bolster local economic benefits and foster project development that is consistent with community development goals. Community finance models have become more complex as the industry has matured but are still plausible, particularly when policy is designed to foster community ownership.

Keys to success

- Build on successful auctions of renewable capacity (Mexican Wind Energy Auctions have produced some of the lowest prices for wind energy globally).
- Avoid delays due to permitting and conflict with host communities with planning and stakeholder engagement.
- Work for policy and market certainty to encourage development and supply chain investments that benefit the domestic economy.

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* Jobs are extrapolated from U.S. labor intensities. Sources: DOE, United States Energy & Employment Report, 2021; NREL, Workforce and Economic Development Considerations from the O&M of Wind Power Plants, 2020
Solar Technologies
Utility Scale

Solar Technologies
Solar Capacity Installed and Resource Potential

- Cumulative utility scale capacity at the end of 2021: 6,160 MW\(^1\)
- 4.4% of total electricity generation from solar in 2021\(^2\)
- Technical PV potential nationally and key regions:
  - National: 24,918 GW
  - Southeast: 5,561 GW
  - Baja California Sur 743 GW
- Technical concentrating solar power potential in key regions:
  - North of Mexico: 8,310 GW
  - Southeast: 4,105 GW
  - Baja California Sur: 516 GW

\(^1\)Source: ASOLMEX
\(^2\)2020–2021 NREL Mexico SAInt production cost model validated with Centro Nacional de Control de Energía figures
Deployment Scenarios

- **Business as usual (BAU) scenario:**
  1,641 MW of projects that are carrying out or about to begin pre-commissioning tests

- **Accumulated Renewable Energy deployment (ARE) scenario:**
  +2,119 MW of projects that are in more advanced stages of obtaining permits, financing, interconnection, or beginning construction

- **High Accumulated Renewable Energy deployment (ARE+) scenario:**
  +3,580 MW of projects that are in less advanced stages of permitting and obtaining financing and interconnection.

### Utility Scale Capacity (MW)

<table>
<thead>
<tr>
<th>State</th>
<th>Current</th>
<th>BAU</th>
<th>ARE</th>
<th>ARE+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonora</td>
<td>1,326</td>
<td>199</td>
<td>409</td>
<td>619</td>
</tr>
<tr>
<td>Aguascalientes</td>
<td>907</td>
<td>295</td>
<td>395</td>
<td>395</td>
</tr>
<tr>
<td>Chihuahua</td>
<td>828</td>
<td>80</td>
<td>215</td>
<td>771</td>
</tr>
<tr>
<td>Coahuila</td>
<td>809</td>
<td>0</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Jalisco</td>
<td>385</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Guanajuato</td>
<td>314</td>
<td>30</td>
<td>141</td>
<td>141</td>
</tr>
<tr>
<td>Durango</td>
<td>295</td>
<td>0</td>
<td>0</td>
<td>300</td>
</tr>
<tr>
<td>Tlaxcala</td>
<td>220</td>
<td>217</td>
<td>317</td>
<td>567</td>
</tr>
<tr>
<td>San Luis Potosí</td>
<td>205</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Puebla</td>
<td>200</td>
<td>0</td>
<td>700</td>
<td>1,610</td>
</tr>
<tr>
<td>Zacatecas</td>
<td>165</td>
<td>150</td>
<td>220</td>
<td>920</td>
</tr>
<tr>
<td>Hidalgo</td>
<td>101</td>
<td>0</td>
<td>276</td>
<td>780</td>
</tr>
<tr>
<td>Veracruz</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Baja California Sur</td>
<td>83</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Morelos</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Yucatán</td>
<td>50</td>
<td>370</td>
<td>493</td>
<td>493</td>
</tr>
<tr>
<td>Baja California</td>
<td>47</td>
<td>0</td>
<td>49</td>
<td>119</td>
</tr>
<tr>
<td>Nuevo León</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Edo de México</td>
<td>21</td>
<td>0</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Campeche</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Other</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6,159</strong></td>
<td><strong>1,641</strong></td>
<td><strong>3,760</strong></td>
<td><strong>7,340</strong></td>
</tr>
</tbody>
</table>

1 Source: ASOLMEX 2021 Mexico’s solar capacity inventory
Production Cost Modeling Key Solar Results

- Solar energy generation increases from 4.4% in the reference scenario to 10% in ARE+, including distributed generation and becomes the second largest single source of clean electricity.

- Overall solar curtailments are quite low (approx. less than 0.5%) suggesting, for these scenarios, that solar is not introducing new transmission constraints or significantly impacting congestion.

- Solar deployment can follow wind transmission. Targeted grid upgrades, if any, for wind, will benefit solar as well because solar resources exist in all areas of the country.
Opportunities & Recommendations

Potential Benefits

- Solar potential in Mexico is six times larger than wind, and the technology complements wind generation very well.
- The solar industry has generated more than 70,000 jobs\(^1\) in Mexico. Because the solar resources are good in all of Mexico, the potential is for expanding O&M jobs and bringing economic and social benefits to all areas of the country.
- Solar distributed generation provides energy access and enhances education, health, and other social services for underserved communities at the lowest cost.
- Solar community ownership provides the opportunity to participate in—and benefit directly from—clean energy generation, even for people without the right siting for solar.

Keys to success

- Develop programs to attract large solar development in key regions.
- Enable institutional finance mechanisms for development of solar and wind projects.
- Avoid delays due to permitting and provide assistance with community consultations.
- Encourage technical knowledge sharing with Centro Nacional de Control de Energía and academia for better integration of variable renewable energy generation.
- Encourage development and supply chain investments that benefit the domestic economy.

\(^1\) Source ASOLMEX. Image Source: NREL picture library

* Jobs are extrapolated from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), SEMARNAT and Institute for Advanced Sustainability Studies (IASS). CO-BENEFITS for Energy Efficiency and Renewable Energy for Sustainable Development IN MEXICO, December 2019
Distributed Generation

Solar Technologies
Mexico Has Installed 2,015 MW of Distributed Generation—Mostly Solar as of December 2021

2,336 MW of solar DG capacity added for all scenarios BAU, ARE, and ARE+


<table>
<thead>
<tr>
<th>Capacity</th>
<th>Public installation price (USD/Wp) without IVA (Oct. 2021)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05</td>
<td>US$1.24/Wp</td>
</tr>
<tr>
<td>5–15</td>
<td>US$1.14/Wp</td>
</tr>
<tr>
<td>15–30</td>
<td>US$1.08/Wp</td>
</tr>
<tr>
<td>30–50</td>
<td>US$1.04/Wp</td>
</tr>
<tr>
<td>50–100</td>
<td>US$0.93/Wp</td>
</tr>
<tr>
<td>100–250</td>
<td>US$0.90/Wp</td>
</tr>
<tr>
<td>250–500</td>
<td>US$0.85/Wp</td>
</tr>
</tbody>
</table>

Distributed solar deployment in Mexico has grown exponentially, exceeding expectations. By 2024, an additional 2,336 MW of DG is forecast\(^1\). This new capacity could add 22,000 construction jobs and 1,000 O&M jobs.\(^2\)

Prices are at a competitive US$0.085/w for systems 250–500 kW—strong deployment among small businesses, small-medium enterprises, and high consumption users.

Additional federal and subnational policies could increase this growth.

\(^1\) Source. NREL dGen Mexico model  
\(^2\) Source: GIZ, SEMARNAT, IASS. CO-BENEFITS for Energy Efficiency and Renewable Energy for Sustainable Development in Mexico, December 2019
DG Can Provide Myriad Benefits to Mexico

**Technical**
- DG paired with smart inverters can provide grid support functions such as fault and voltage ride through and reactive power support
- DG paired with battery energy storage systems can relieve grid stress during times of high use by reducing peak energy demand
- DG paired with battery energy storage can increase resilience during power outages.

**Social**
- Cost-effective solution to electrifying rural and marginalized communities
- “Democratization” of energy as energy consumers have option to produce energy.

**Economic**
- Lowers energy costs for electricity customers, especially micro, small, and medium-sized businesses
- Enables productive uses (e.g., water pumping) for agricultural industries
- Provides job and investment opportunities for local communities across multiple sectors (e.g., construction, business services)
- Provides models (e.g., “bono solar”) that can repurpose ongoing electricity subsidies for some customers and reduce Treasury outlays.

**Environmental**
- Provides alternative to large-scale energy development in regions of ecological and cultural value
- Reduces CO₂ and air pollutant emissions from the power sector.
Recommended Actions for Government of Mexico to Support DG

- Reduce financial barriers to DG adoption through direct financial investments and expanded access to affordable financing
- Recalibrate interconnection procedures for DG
- Establish shared solar and virtual net metering regulations
- Consider expanding the current 500 kW capacity limit for DG
- Encourage maturation and quality of suppliers, materials, and labor
- Establish a clearly defined Comisión Federal de Electricidad role for DG
- Redirect tariff subsidies to support DG investments.
Geothermal
Current State and Potential

- Current installed capacity: **1006 MW**, Operating capacity: 948 MW
- Additional potential of **2,500 MW** for conventional geothermal
- 2% generation from geothermal in 2018
- Cerro Prieto is the **second largest field worldwide**
- Cerritos Colorado: 75 MW potential, **high development probability** in the near term
- **Comisión Federal de Electricidad** exploring **13 fields** with cumulative capacity of **448 MW**
- 97% geothermal capacity owned by **Comisión Federal de Electricidad**
Opportunities and Recommendations

• **Mexico’s Geothermal Law (enacted 2014) is working to spur new capacity and investments**
  - 14 private companies in different stages of exploration, with more than 500 MW of potential
  - However, the government has stopped renewing exploration permits for private projects
  - Current law could help increase deployment through public (Comisión Federal de Electricidad) and private capital.

• **Direct use and cascading for agro-industrial activities**
  - Benefits flow to remote and rural communities
  - Thermal energy can be used in agro-industrial settings for fish farming, greenhouse heating, food drying and processing, heat for industrial processes, and other uses
  - Simple technology, locally available
  - Government could support development through grants, revolving loan fund.
Emerging Technologies

- Nonconventional technologies could more than double Mexico’s potential
- Geothermal can be used to produce green hydrogen when there is an oversupply of electricity on the grid
  - This would increase the profitability of current geothermal plants
- Geothermal energy can be produced using wells currently or formerly used to extract oil and gas, extending their economic life
- Enhanced geothermal systems and closed-loop systems unlock resources that do not contain water naturally, which could enable using geothermal closer to population centers
  - Pilot projects exist in Mexico, the United States, and Europe
- Supercritical geothermal resources, which exist in Mexico, can produce up to ten times more power per well
- Newer, small-scale geothermal plants (some of which can be 3D-printed) can be used in small communities located in the volcanic areas in central Mexico
- The government of Mexico could consider continuing its investment in geothermal research through the CEMIE-Geo center, the GEMex project (researching EGS and supercritical resources), and Mexican innovators like Geokeri, a small Mexican company.
Hydropower
Hydro Has Grown, But Load Has Grown Faster

- Mexico’s hydropower has grown, but its load has grown faster—by almost 4x since 1990.\(^1\) As a result, hydropower’s contribution has dropped from 20% to 8% of annual generation.

- An additional 1.2 GW (~2.6 TWh/yr) of low-cost, flexible renewable power (and energy) may be realized by repowering the existing fleet.\(^2,3\)

- Repowering gains can be achieved with no additional land use and only marginal environmental and cost impacts.

- Economically feasible hydropower potential is believed to be twice current generation levels (27 GW or ~59 TWh/yr).\(^4\) Technical hydropower potential is estimated at 135 TWh/yr (4x current levels).\(^5\)

\(^{1}\) IEA 2022  
\(^{2}\) Assumes a 10% gain in power at repowered facilities (NREL ReEDS 2021)  
\(^{3}\) 2015 and News Mexico Electric Power 01/11/22  
\(^{4}\) 2018 IHA Hydropower Status Report  
\(^{5}\) Hydropower & Dams World Atlas and World Bank
Cross-Sector Challenges

• Mexico uses 76% of its water for agricultural purposes, exceeding both world (71%) and Organisation for Economic Co-operation and Development (48%) country averages.
• Water scarcity and uncertainty are issues that must be analyzed holistically by weighing the tradeoffs.

Opportunities

• Where development is necessary (e.g., new municipal or agricultural water needs), a multipurpose reservoir can address water uncertainty and seasonal scarcity while increasing the growing season and renewable generation.
• Irrigation modernization that includes in conduit (or in canal) generation benefits both farmers and the grid—reducing water use and increasing renewable generation.
• Adding generation to existing non-powered dams can increase renewable production with little environmental impact or additional land use.

Notes:
The new environmental thinking on hydropower includes “adding generation at non-powered dams to increase renewable generation; developing pumped storage capacity at existing dams” (U.S. Hydropower: Climate Solution and Conservation Challenge, Stanford University’s Uncommon Dialogue, 2020). One of the Joint Statement’s three Rs: Retrofit.
New Development: Pumped Storage Hydro

Pumped Storage Hydropower (PSH)

- Opportunities
  - Storage is key to cost-effective integration of variable renewable energy (e.g., wind and solar PV)
  - Pump-back PSH (adding the ability to pump water between existing reservoir pairs) can provide one of the most cost-effective forms of storage

- Considerations
  - Closed-loop PSH is more expensive than pump-back or new open loop development, but it reduces environmental impacts by using reservoirs isolated from natural waterways
  - For large grids with less than 50% renewables, shorter duration storage (2–4 hours) can be adequate. However, for electrically islanded systems like Baja California Sur, PSH may be valuable given the additional reliability benefits it provides (e.g., inertia).

Source: U.S. Department of Energy
Transport Electrification
Mexico Can Achieve Significant Air Quality, Energy Security, and Socioeconomic Benefits (e.g., Comisión Federal de Electricidad revenues) From the Electrification of Transportation

- 43% of (fossil fuel) energy
- 22% of greenhouse gas emissions
  - 97.5% from cars, buses, & trucks
- Major source of local pollution
- Low levels of electrification
- Mode share In 100 cities
  - public transit–49%
  - foot or bicycle–23%
  - private car–23% (Guerra et al. 18)
- Transport accounts for
  - 19.3% of household expenses.
Electric Mobility’s Potential Can Only Be Achieved With a Clean Energy Grid—Early Planning, Investment, and Regulation That Effectively Integrate Transportation and Charging Infrastructure With a Clean Energy Grid Would be Needed

Policies and programs can foster:
- Production of affordable electric vehicles, e.g., E-motorbikes
- Siting of charging infrastructure
- Replacement of long-distance road freight with rail
- Electrification of last-mile transport.

Benefits of electric mobility include:
- Cost-effectiveness after initial purchase
- Improved health of populations, particularly those closer to freight corridors.

Source: Wu, Bracho, Romero-Lankao 2022
The Electrification of Public Transport and Last-mile Freight are Feasible, Cost-effective, and Equitable Options That Can Improve Mobility for 70% of Mexicans

Cost-effectiveness and affordability

- 1 electric bus = 100 single occupancy EVs
- 1 bus = 40–80 people.

Electric public transit

- Reduced congestion and environmental impacts
- Improved public health
- Improved mobility.

Sources: ICM 2021a and 2021b

Mobile emissions in Mexico City are the most harmful to humans

Source: Romero-Lankao, Gilleran, Weigl, Holden, Neri, 2019
Green Hydrogen
Hydrogen (H₂) Importance

Global Significance

• As of early 2021, 30 countries, 50% of global gross domestic product, have decarbonization goals and H₂ road maps [1]
• Cross sector uses in transportation, agricultural, industry, and electricity.

Mexico

• Near-term, <2030, economic uses are public buses, long haul freight, and mining trucks [2]-[7]
• Leverages Mexico expertise in manufacturing to produce and use H₂ technologies

Colors of H₂ (carbon intensity and process for production)

• Gray H₂, steam-methane reforming of natural gas, most produced today
• Green H₂, produced entirely by renewable energy
  o the most viable near-term strategy is PEM (polymer exchange membrane) electrolysis using renewable electricity and water
• Blue H₂, produced by fossil fuels with carbon dioxide sequestered
• Green and blue H₂ are required for decarbonization targets.

What?
A versatile energy carrier that is increasingly seen as a requirement for decarbonizing hard-to-abate sectors.
Green H₂ in Mexico

Energy status and issues in Mexico:

- Imports 60% of H₂ \[^8\]
- Suffered fertilizer and petrochemical business outages including no ammonia (fertilizer) production in 2019 \[^9\],[^10]\)
- Demand in above two sectors to increase to 40% and 12% by 2025 \[^8\]
- Supply disruptions already affecting Mexican businesses.

Mexico has some of the best potential green hydrogen resources in Latin America.
Near Term Actions for H₂ in Mexico

1. Develop a national hydrogen road map to provide direction for industry and investors.
2. Aggressively develop renewable electricity resources so that Mexico is positioned for development of large-scale green hydrogen production.
3. Incentivize refueling infrastructure for freight trucks, public buses, and mining trucks.

Sends a signal of support to businesses and communities.

News excerpts around Mexico

• Launch of the new industry body—Mexican Hydrogen Association.[11]
• La Comisión Federal de Electricidad (CFE) informó que se encuentra impulsando un proyecto piloto de hidrógeno verde para poder producir energía eléctrica y reducir la dependencia de gas natural.[12]
• Mexican company Delicias Solar, SA de CV, […] powers a 75 MW hydrogen power plant with an estimated annual production of 4,425 tons.[13]
• Green hydrogen projects in Hidalgo, Baja California, and Chihuahua states.[11]
• Two projects with estimated investments of US$1.35bn in Durango and Guanajuato states.[11]


Transmission
How Transmission, Renewables Can Cut Electricity Costs

An efficient grid uses generators with low variable cost as much as possible; fuel and capacity contracts might preclude efficient operations, causing the public to pay more regardless of renewables.

Renewables have near-zero variable cost; as they grow, inefficient thermal units are used less, saving money on variable costs.

Efficient thermal units (low variable cost) are used about the same; units that are both efficient and flexible might be used even more.

Source for generator supply curve and system demand: SENER[1]
Path to Reduced Costs

With transmission to the best renewable energy zones, Mexico can get more MWh of clean energy generation for every peso of capital investment. This translates to lower capital costs and lower total cost per MWh.

If the variable cost savings are more than the capital costs of new renewables and the enabling transmission, end users could pay less for electricity.

Both emissions and the cost of electricity to businesses and individuals would fall, which can accelerate growth and help Mexico meet its climate commitments.

- From 2009 to 2013, Texas added 2,376-line miles of transmission for new renewables at a cost of US$7 billion.[2, 3]
- By the end of the build-out, transmission charges to customers increased 0.7 cents per kWh.
- By 2020, wind and solar increased to 26% of the Texas generation mix;[4] energy costs fell 0.8 cents per kWh from 2013 to 2020.
- Residential rates changed little from 2013 to 2020, while rates for the rest of the United States increased 1 cent per kWh.

<table>
<thead>
<tr>
<th>Energy cost</th>
<th>Transmission build-out period</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.00</td>
<td>$0.05</td>
</tr>
<tr>
<td>$0.05</td>
<td>$0.10</td>
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<tr>
<td>$0.10</td>
<td>$0.15</td>
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<tr>
<td>$0.15</td>
<td>$0.00</td>
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</tbody>
</table>

*Chart source: [5]*
Where High-Quality Renewables Are Most Concentrated

Mexico has several possible hubs where transmission could connect high-quality renewable energy zones.[6]

Geographic diversity of renewable energy zones would reduce integration costs.[7]

Construction employment for transmission and new renewables can quickly accelerate local economic growth.

Developing renewables in the North and South and increasing interconnections with the US and Central America could increase system reliability and resiliency, and provide opportunities for clean energy exports.
Challenges and Solutions for Dealing with Large Penetrations of Variable Renewable Energies (VRE)
Technical Challenges with Higher Inverter-based Resources
Technical Challenges with Higher Inverter-based Resources

**Challenges:**
- Frequency Stability (Lower System Inertia)
- Voltage Stability and Regulation
- System Protection
- Grid Forming capability
- Black Start capability
- Control system interactions and resonances
- Cybersecurity.


Options for Dealing with Variability and Uncertainty
Options for Dealing with Variability and Uncertainty

**Solutions:**
- Utilize geographic diversity
- Improve renewable resource and load forecasting
- Increase sharing among balancing authority areas
- Enhance VRE services
- Coordinate flexible loads (active demand response)
- Utilize flexible conventional generation
- Expand the transmission system
- Curtail excess VRE production
- Add electrical storage
- Interact with other energy carriers.


**Relative Economics of Integration Options**

<table>
<thead>
<tr>
<th>Type of Invention</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Involuntary Load Shedding</td>
<td>Upward Reserve and Dispatch</td>
</tr>
<tr>
<td>Flexibility Reserves</td>
<td>Increased Use of Economic Dispatch</td>
</tr>
<tr>
<td>SYSTEM OPERATION</td>
<td>SERVICES FROM VARIABLE RE</td>
</tr>
<tr>
<td>Cost</td>
<td>LOAD</td>
</tr>
<tr>
<td>Transmission Expansion</td>
<td>Residential Demand Response</td>
</tr>
<tr>
<td>Pumped Hydro Storage</td>
<td>CT and CCGT Gas Ramping</td>
</tr>
<tr>
<td>Transmission Reinforcement</td>
<td>Industrial &amp; Commercial Demand Response</td>
</tr>
<tr>
<td>Chemical Storage</td>
<td>Hydro Ramping</td>
</tr>
<tr>
<td>Thermal Storage</td>
<td>Advanced Network Management</td>
</tr>
<tr>
<td>Fuel Storage/Flexible Ramping</td>
<td></td>
</tr>
</tbody>
</table>

Option costs are system-dependent and evolving over time.
Work to Unify the Integration of Inverters and Synchronous Machines Could Help Mexico’s CENACE

This work is Co-led by NREL, Univ. of Washington, and EPRI

UNIFI is a forum to address fundamental challenges in seamless integration of grid-forming (GFM) technologies into power systems of the future

The forum conducts research and development, demo concepts at scale, author best practices and standards, and trains the next-generation workforce.

Learn more about UNIFI at: 
https://www.youtube.com/watch?v=g5ej82euGCM
The power industry is seeing a shift towards 100% clean energy goals and each region has a variety of resources to tap into to meet these goals.

One way to address these goals is increasing use of variable renewable energy like solar and wind.

The favorable economics of solar and wind are driving new installations and deployments.

There are two main challenges with integrating very high levels of solar and wind in power systems:

- The **inverter challenge** of adding more power electronics-based technologies and removing synchronous generators.
- The **balancing challenge** of maintaining the supply/demand balance at all time scales by increasing system flexibility.

These are solvable challenges that NREL is working together with various stakeholders to meet!
For More Information

Summary of Benefits for Mexico
Benefits from High Deployment of Renewables

Conclusions

• Achieving the 2024 target of 35% clean energy generation is feasible with the successful development of planned renewable projects. Some of the benefits from achieving this goal include:
  o Reduction of electricity production costs by US$1.1 billion over a business-as-usual scenario
  o Approximately US$17 billion of direct investment
  o Creation of upwards of 72,000 full-time jobs
  o Diversification of generation to more areas of the country and increased energy security
  o Increased air quality with the reduction of power sector emissions
  o Sustainable power for national and regional economic growth
  o Social benefits—cost-effective electrification of rural and underserved communities with low emissions and increased services such as health and education
  o Reduced transmission congestion in key areas
  o Clean energy export opportunities
  o Energy system and utility resilience
  o Powering the electrification of the transport sector with equitable solutions and lower emissions.