MEXICO: NORTH AMERICAN CLEAN ENERGY POWERHOUSE

Photo from ASOLMEX

Mexico Clean Energy Report—Executive Summary

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%.[1]

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.

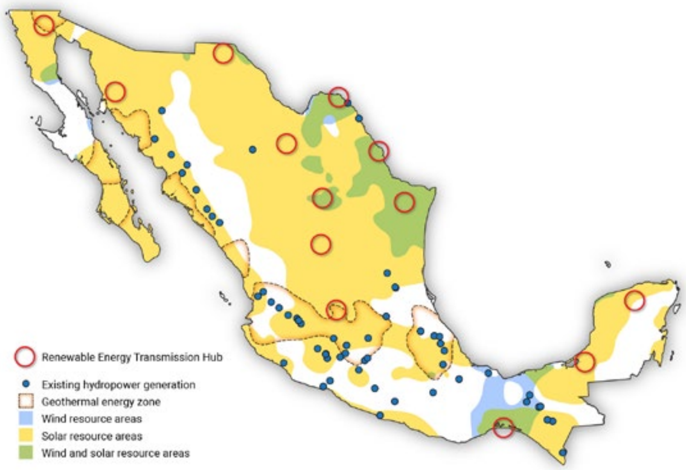

Figure 1. Map of Mexico with areas of highest potential for solar, wind, geothermal and hydro technical potential called out

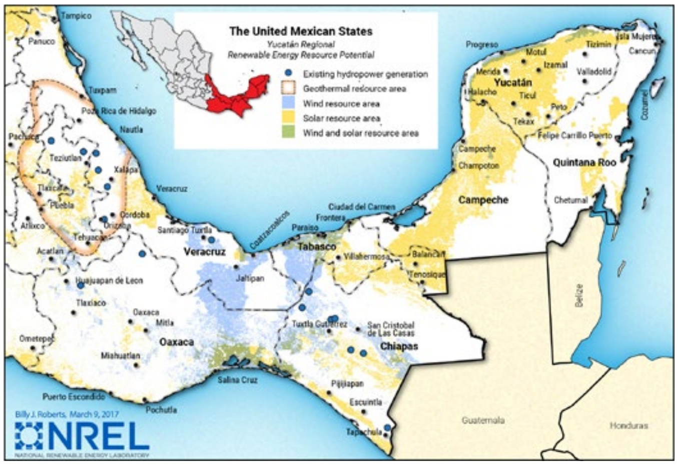

Figure 2. Map of Southeast Mexico with areas of highest renewable potential

Mexico's large and diverse renewable energy resource base could support significant growth in clean generation capacity. **Figure 1** shows that Mexico's renewable resources are well distributed throughout the country. National technical potential includes 24,918 GW[2] of solar photovoltaics, 3,669 GW[2] of wind, 2.5 GW[3] of conventional geothermal, and 1.2 GW[4] 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

[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 Negrín, et al, 2021. Based only on hydrothermal resources at temperatures ≥150°C
[4] Assumes a 10% gain from current facilities

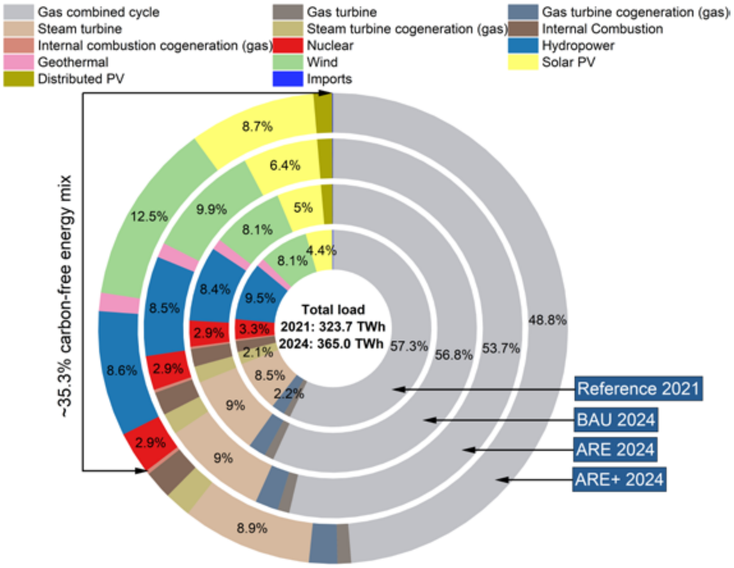

Figure 3. Percentage of annual generation mix by technology and scenario, including business as usual (BAU), accelerated renewable energy (ARE), and accelerated renewable energy plus (ARE+) compared to the reference scenario

CFE (Comisión Federal de Electricidad). The study utilized a 2020–2021 reference scenario that was recently validated against figures from the CENACE (Centro Nacional de Control de Energía). The three 2024 study scenarios were:

- A business as usual (BAU) scenario that includes 531 MW of internal combustion projects currently underway and 4,837 MW[5] of renewable projects that are being carried out or are about to begin pre-commissioning tests.
- An accelerated renewable energy (ARE) deployment scenario that adds 3,935 MW from renewable projects that are in more advanced stages of obtaining permits, financing, interconnection, or are beginning construction.
- An accelerated renewable energy plus (ARE+) scenario that increase additional 6,485 MW from renewable projects that are in less advanced stages of permitting and obtaining financing and interconnection.

Note that the private sector renewable projects in the ARE and ARE+ scenarios would have a very low probability of completion if changes are made to the current legal, regulatory, and electricity market frameworks that create significant barriers to market entry.

While meeting demand and reserve requirements at all hours of the year, the study found that the more ambitious accelerated renewable energy scenario would be sufficient to meet the 35% target (**Figure 3**).

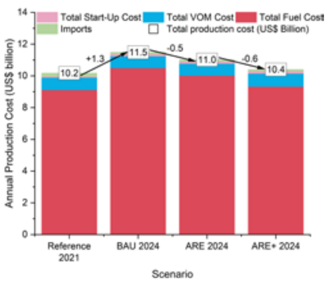

Figure 4. Annual production cost for each type of cost. (VOM is variable operations and maintenance.)

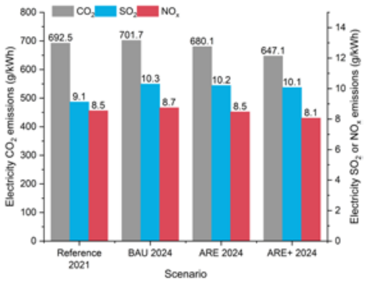

Figure 5. Annual emissions per unit of demand (kWh)

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 CO_2, SO_2, and NO_x, emissions.

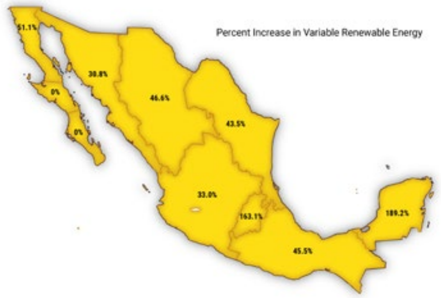

Figure 6. Percentage increase in variable renewable energy generation, ARE+ compared to BAU

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.

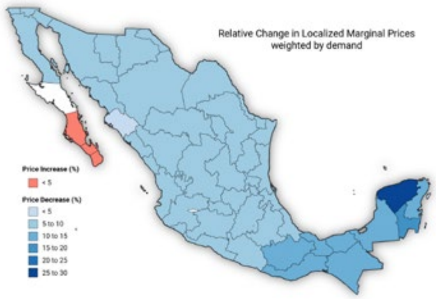

Figure 7. Regional change in localized marginal prices (LMP), ARE+ compared to BAU

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.

[5] Source ASOLMEX. Includes 2,015 MW of distributed generation; Source AMDEE

U.S. DEPARTMENT OF ENERGY

NREL Transforming ENERGY

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
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MEXICO CLEAN ENERGY REPORT—APPENDIX

NORTH AMERICAN CLEAN ENERGY POWERHOUSE

April 2022

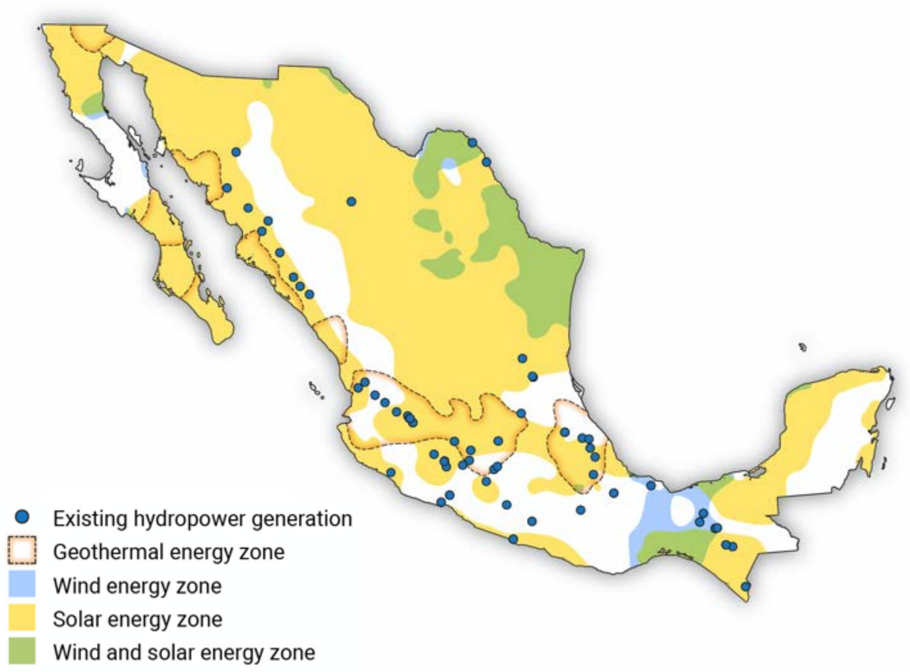
U.S. DEPARTMENT OF ENERGY

NREL Transforming ENERGY

Contents of the Appendix

Resource Potential

Mexico Has Abundant Renewable Energy Resources to Meet Its Energy Goals



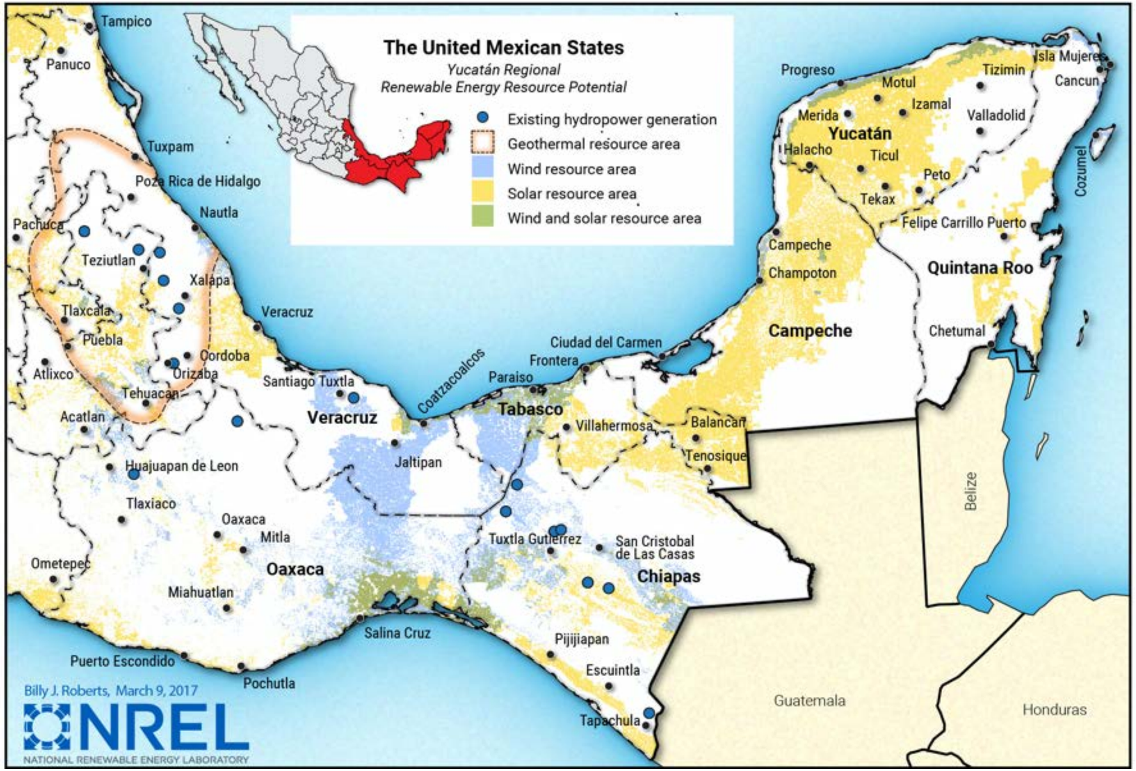
- Mexico generated 86.27 TWh or 26.7% of its electricity from clean energy resources in 2021.
- To meet the 35% clean energy target in 2024, Mexico needs at least 128.83 TWh or 42.56 TWh of additional clean energy generation.
- National solar PV capacity potential is estimated at 24,918 GW.[1] This potential 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 GW[1]. This potential capacity could generate 5,759 TWh/yr or 15 times the 365TWh 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:

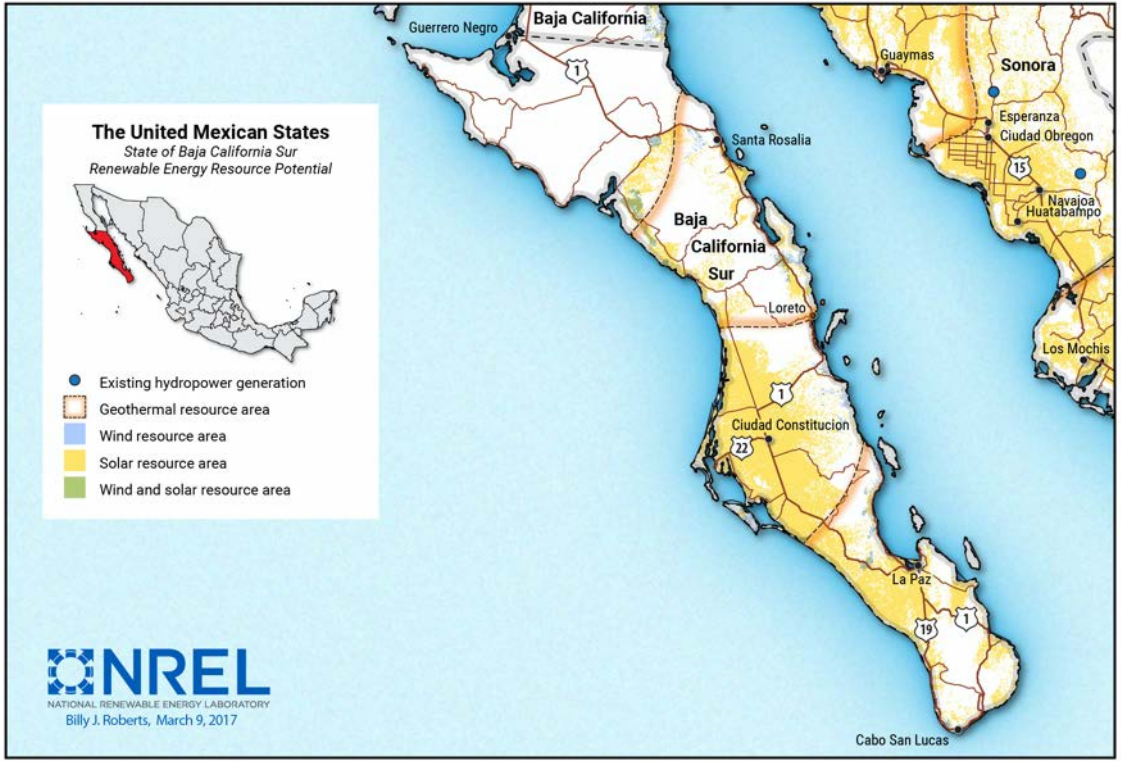
- 5,561 GW of solar PV potential
- 744 GW of wind potential
- Additional 272 MW potential from conventional geothermal
- Largest hydro resources of Mexico.



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 for the 2024 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.

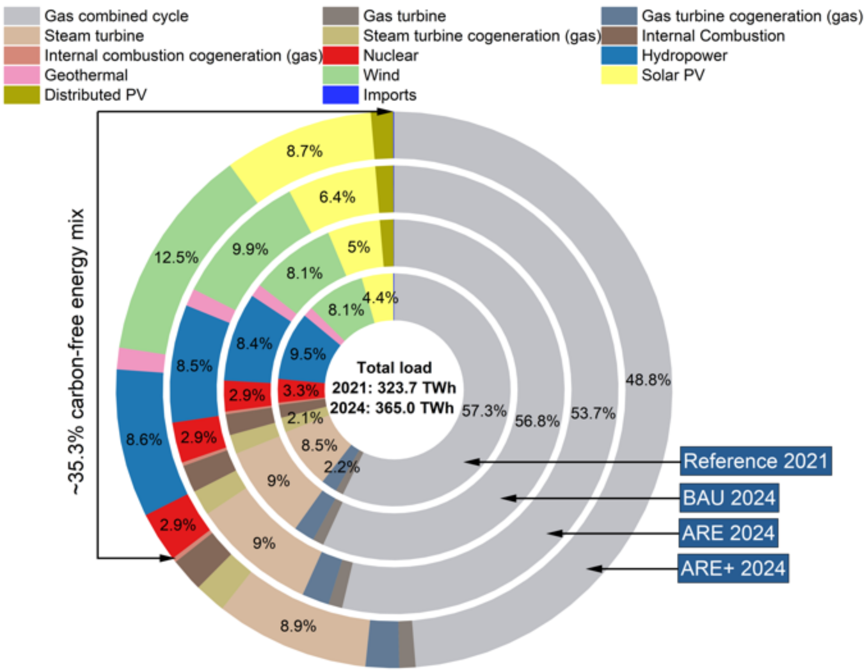
[1] *Includes 2,336 MW of new solar distributed generation capacity projected by 2024*

Summary Results of the 2024 Integration Study

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



Comparison of Generation Participation by Technology

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]

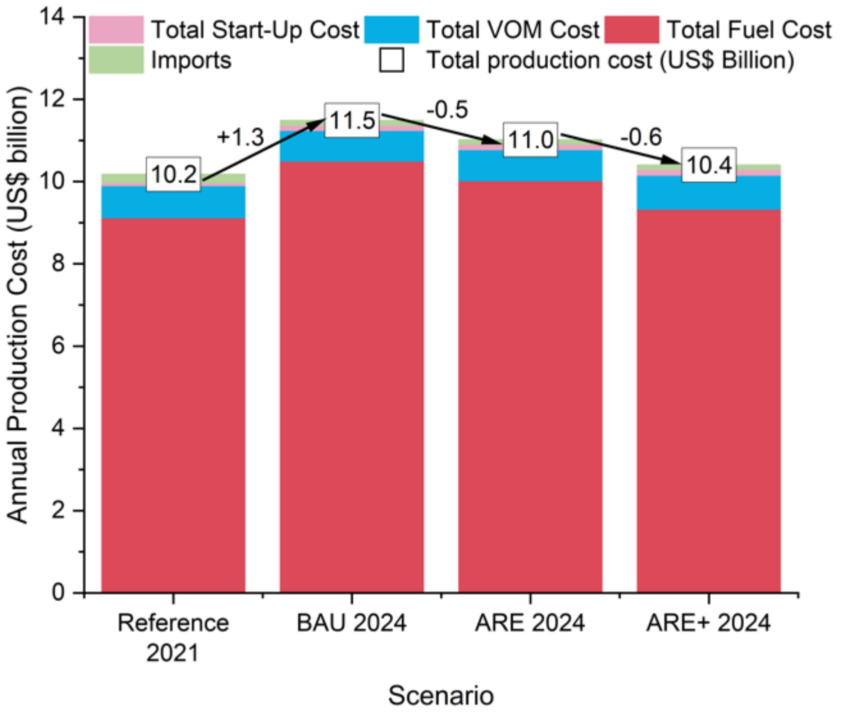
[1] *Estimates using data from ASOLMEX, AMDEE and CFE*

Lower Production Costs are Achieved with Increased Renewable Energy Generation

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%.

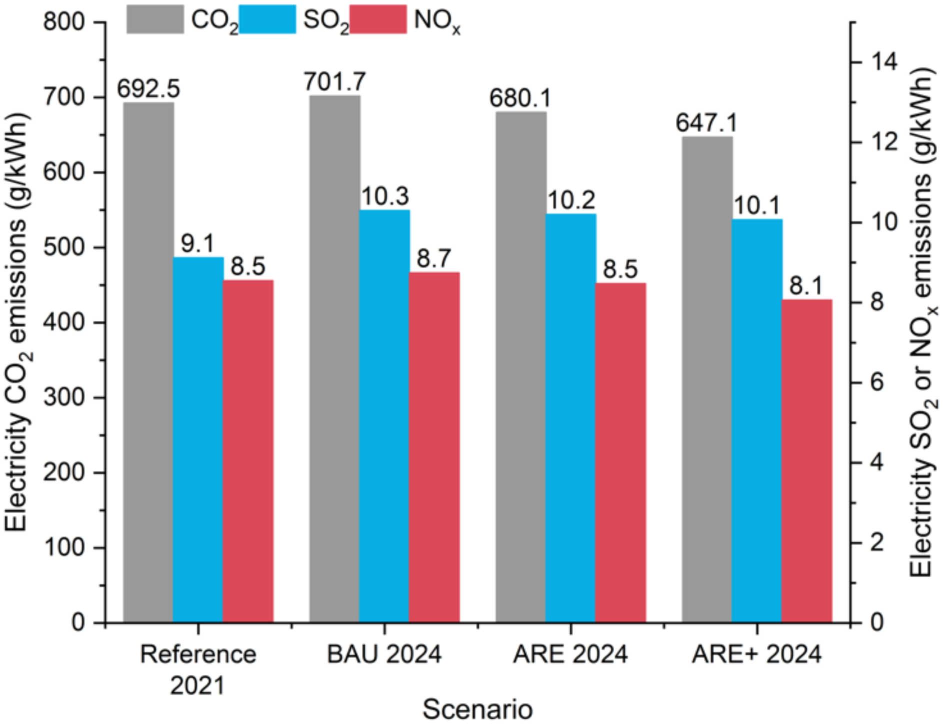


Annual Production Cost for Each Type of Cost

Summary Results of the 2024 Integration Study

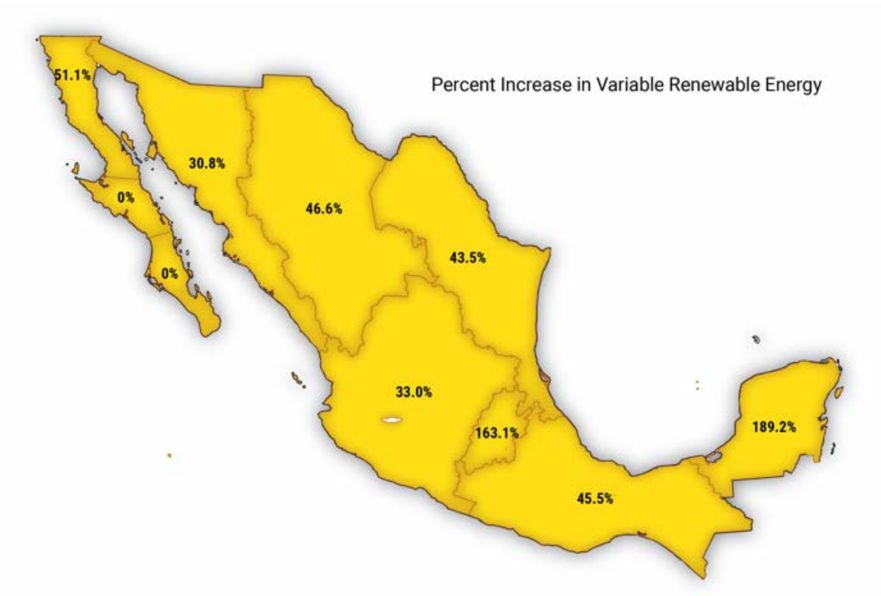
Electricity demand is forecasted to increase 12.7%[1] from 2021 to 2024. Emissions per kWh reflect significant system emission reductions as more renewables are added to the system.

[1] *Source: PRODESEN*

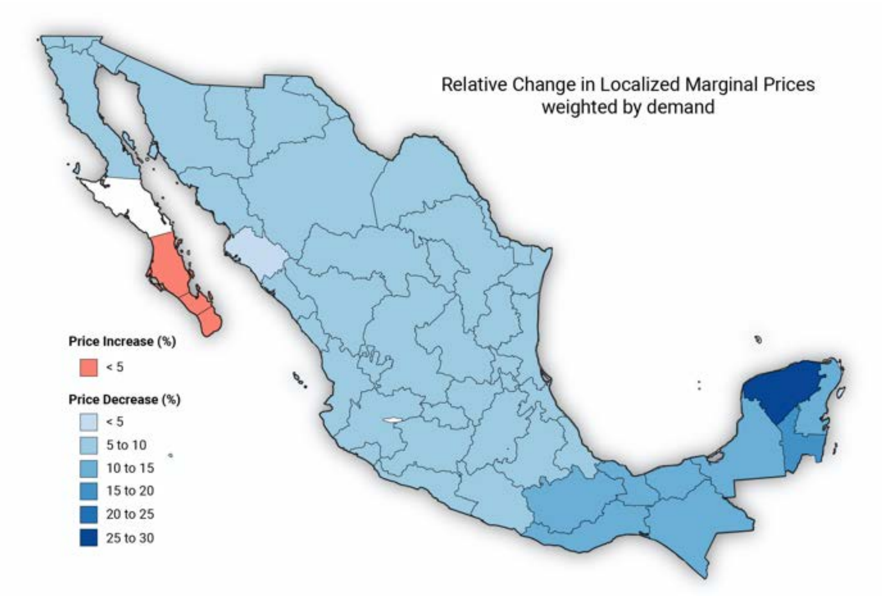


Comparison of Emissions per Unit of Demand Under the Different Scenarios

Lower Regional Marginal Electricity Generation Prices are Achieved with Higher Accumulated Renewables



Percentage Increase in Variable Renewable Energy Generation



Regional Change in Localized Marginal Prices

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.

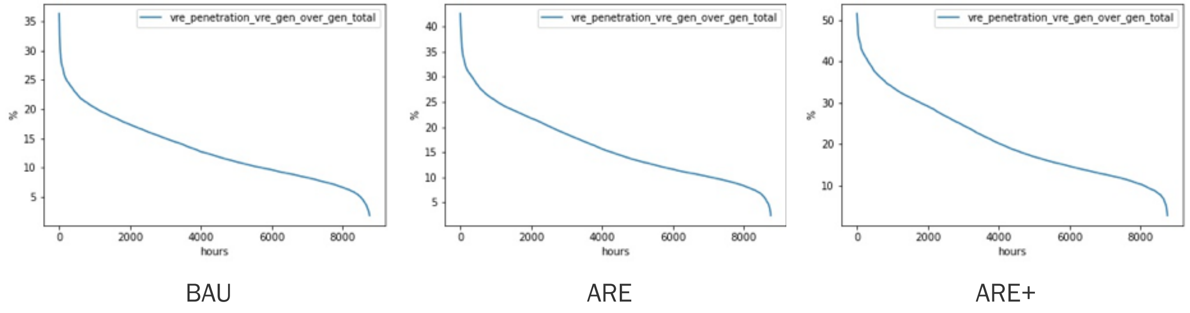
Summary Results of the 2024 Integration Study

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

SCENARIO	SOLAR PV	WIND	VRE
REFERENCE	0.04%	1.18%	0.78%
BAU	0.01%	0.00%	0.00%
ARE	0.01%	0.01%	0.01%
ARE+	0.45%	0.71%	0.60%

- 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



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*

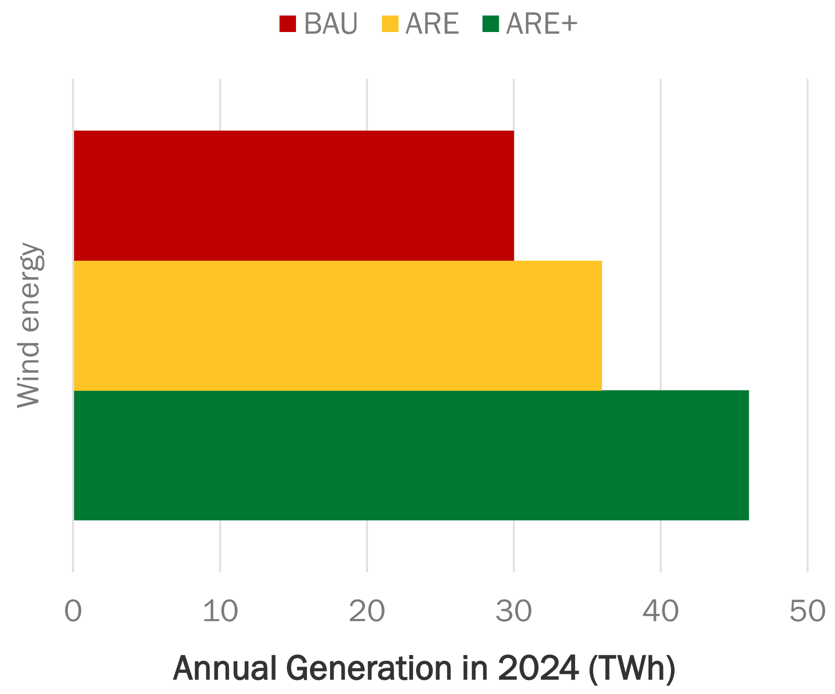
Deployment Scenarios

State	Capacity (MW)			
	2021	Added by 2024		
	Current	BAU	ARE	ARE+
Baja California	195	50	50	50
Campeche	0	0	0	110
Coahuila	397	348	444	444
Guanajuato	105	0	0	63
Jalisco	179	0	64	64
Nuevo León	793	168	468	718
Oaxaca	2,758	0	0	300
Queretaro		30	30	30
Tamaulipas	1,715	198	315	1,086
Yucatán	244	0	1,128	2,317
Zacatecas	230	66	66	66
Others	538	0	0	0
Total	**7,154**	860	**2,565**	**5,251**

- **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.

Production Cost Modeling Key Wind Results

- 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.

* 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

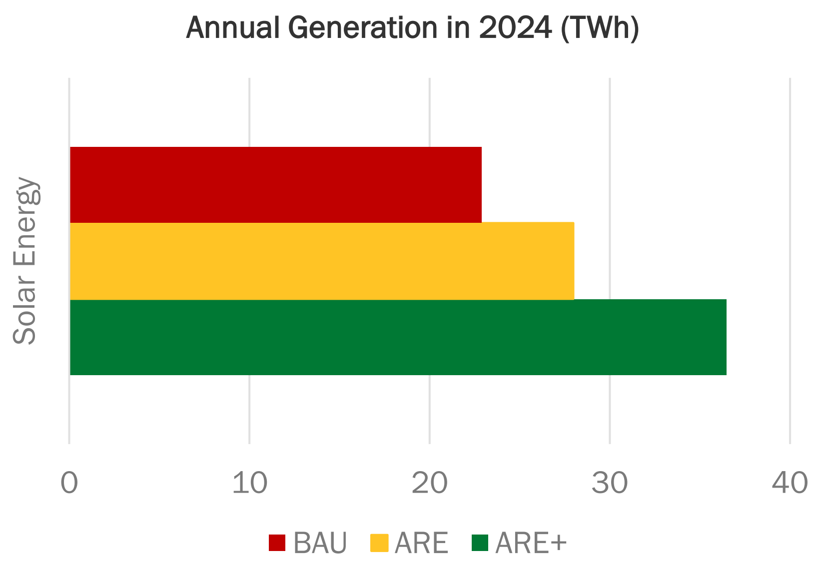
- **Business as usual (BAU) scenario:**
  1,641 MW of projects that are carrying out or about to begin pre-commissioning tests
- **Accumulated Renewable Energy deployment (ARE) scenario:**
  +2,119 MW of projects that are in more advanced stages of obtaining permits, financing, interconnection, or beginning 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.

State	Utility Scale Capacity (MW)			
	2021[1]	Added by 2024		
	Current	BAU	ARE	ARE+
Sonora	1,326	199	409	619
Aguascalientes	907	295	395	395
Chihuahua	828	80	215	771
Coahuila	809	0	150	150
Jalisco	385	0	0	0
Guanajuato	314	30	141	141
Durango	295	0	0	300
Tlaxcala	220	217	317	567
San Luis Potosí	205	300	300	300
Puebla	200	0	700	1,610
Zacatecas	165	150	220	920
Hidalgo	101	0	276	780
Veracruz	100	0	0	0
Baja California Sur	83	0	0	0
Morelos	70	0	0	0
Yucatán	50	370	493	493
Baja California	47	0	49	119
Nuevo León	30	0	0	0
Edo de México	21	0	95	95
Campeche	0	0	0	80
Other	3	0	0	0
Total	6,159	1,641	3,760	7,340

[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.



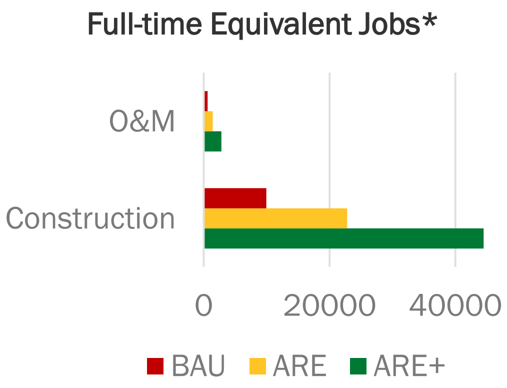
Opportunities & Recommendations

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.



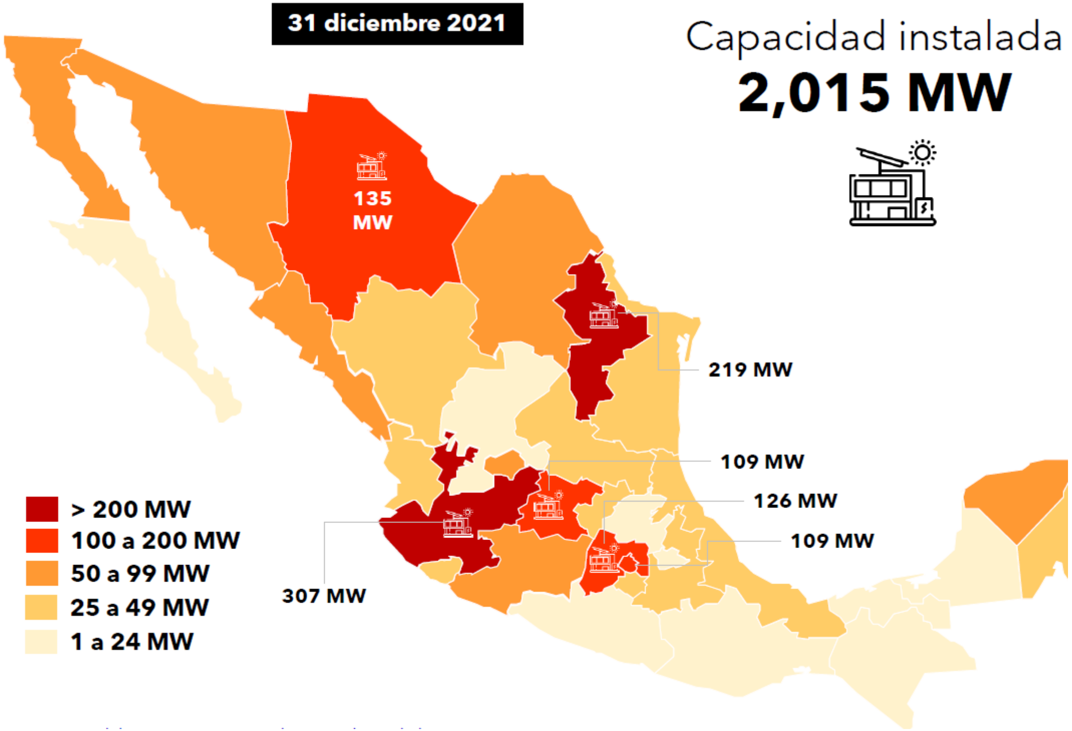
* Jobs are extrapolated from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), SEMARNAT and Institute for Advanced Sustainability Studies (IASS). CO-BENEFITS for Energy Efficiency and Renewable Energy for Sustainable Development IN MEXICO, December 2019

[1] Source ASOLMEX. Image Source: NREL picture library

Distributed Generation

Solar Technologies

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



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

Source. Asolmex, ANES, AMIF, GIZ. 2021. "Monitor de información commercial e índice de precios de generación solar distribuida en México." Presentation for Solar Power México. www.monitordepreciosgsd.com

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

Source. ASOLMEX.a 2021 . "Inventario Solar 2021._ Presentation

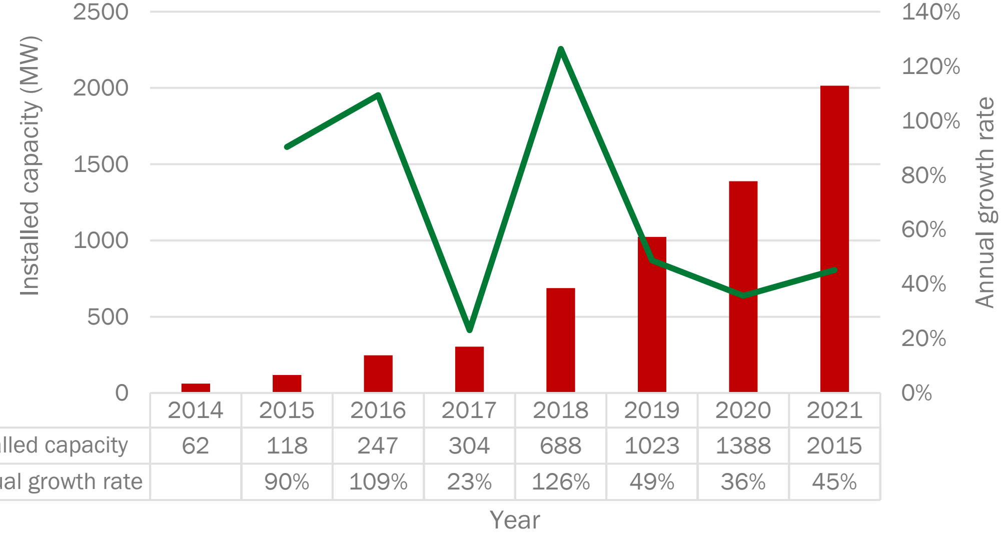
Distributed solar deployment in Mexico has grown exponentially, exceeding expectations. By 2024, an additional 2,336 MW of DG is forecast[1]. This new capacity could add 22,000 construction jobs and 1,000 O&M jobs.[2]

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

Distributed Generation Deployment in Mexico (2014-2021)



	2014	2015	2016	2017	2018	2019	2020	2021
Installed capacity	62	118	247	304	688	1023	1388	2015
Annual growth rate		90%	109%	23%	126%	49%	36%	45%

Source. Zinaman, O., Aznar, A., Flores-Espino, F. Garza, A. 2018. The Status and Outlook of Distributed Generation Public Policy in Mexico. https://www.nrel.gov/docs/fy18osti/71469.pdf

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 CO_2 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.

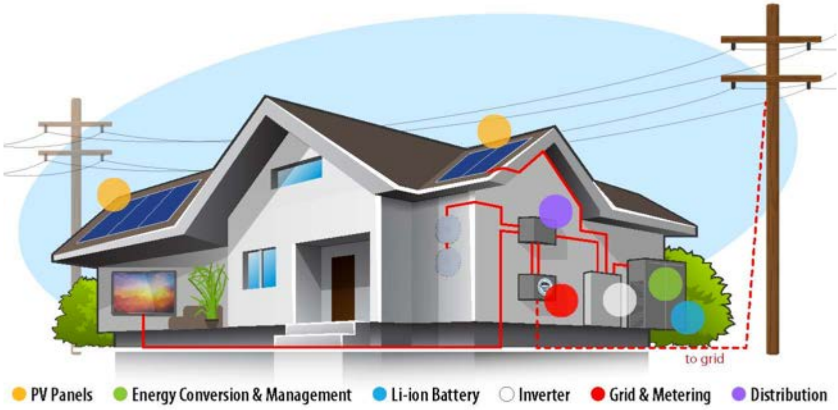
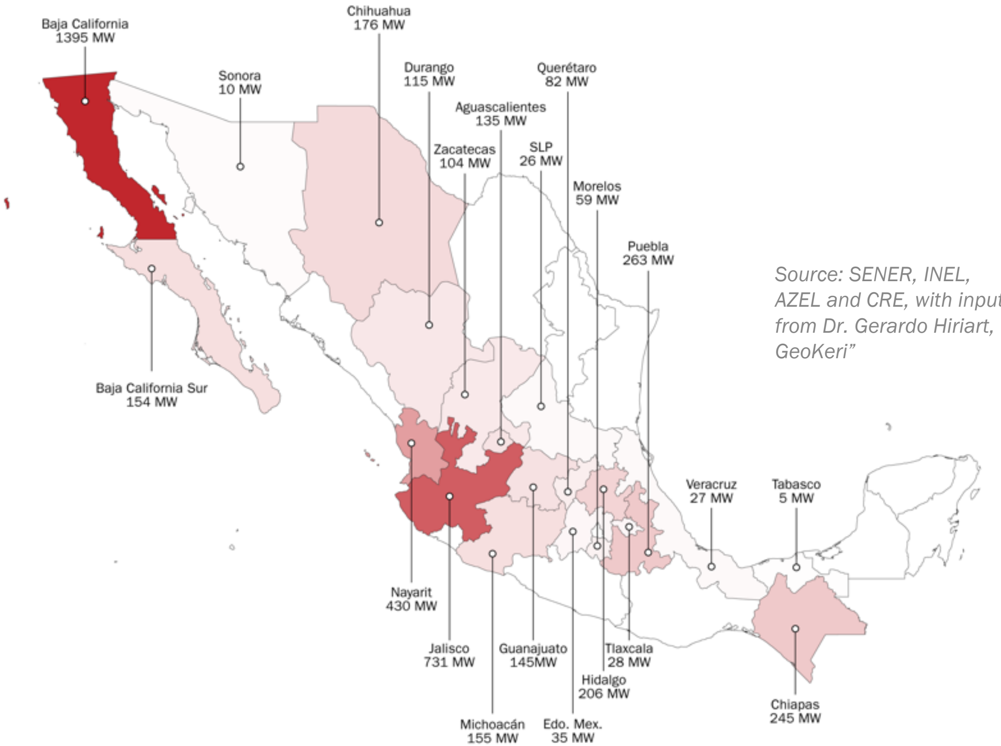


Image from NREL

Geothermal

Current State and Potential

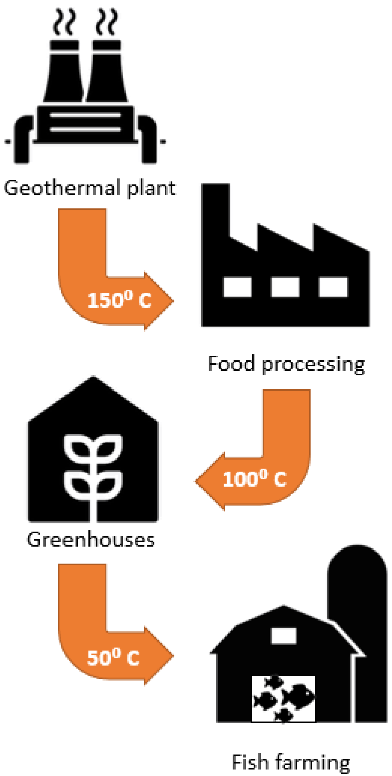
- Current installed capacity: **1006 MW,** Operating capacity: 948 MW
- Additional potential of **2,500 MW** for conventional geothermal
- 2% generation from geothermal in 2018
- Cerro Prieto is the **second largest field worldwide**
- Cerritos Colorado: 75 MW potential, **high development probability** 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



Source: SENER, INEL, AZEL and CRE, with input from Dr. Gerardo Hiriart, GeoKeri"

Opportunities and Recommendations

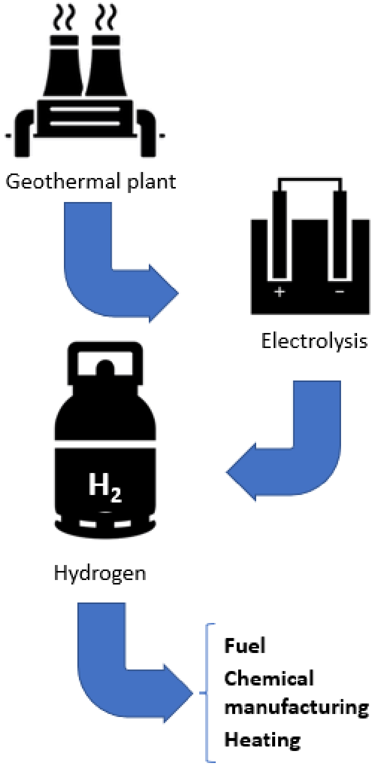
- **Mexico's Geothermal Law (enacted 2014) is working to spur new capacity and investments**
  - 14 private companies in different stages of exploration, with more than 500 MW of potential
  - However, the government has stopped renewing exploration permits for private projects
  - Current law could 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.



Geothermal cascading for agricultural uses
Geothermal Energy by Vectors Point, Factory by iconsphere, Greenhouse by Deemak Daksina, Fish by Adrien Coquet, and Farm by Bonegolem; all from from NounProject.com

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.



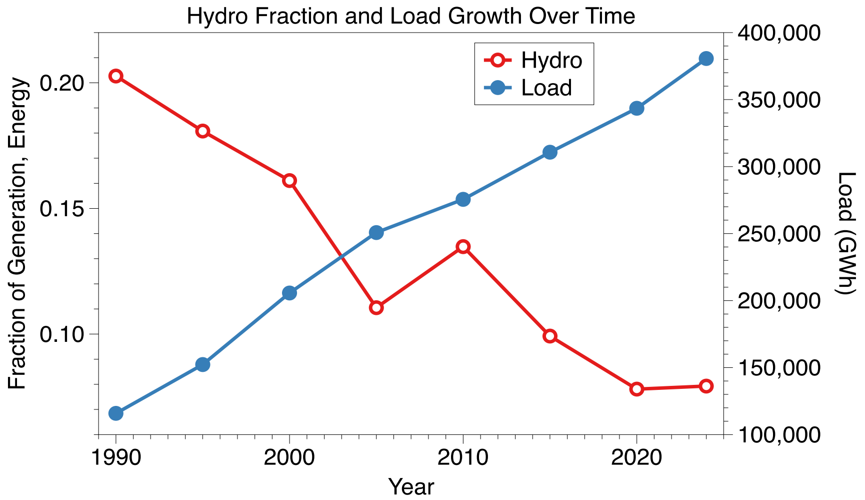
Green hydrogen production from geothermal energy

Geothermal Energy by Vectors Point, Electrolysis by Steinar Hillersøy Dyvik, and Gas Cylinder by SHAHAREA; all from NounProject.com

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 Hydropower Opportunities

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.

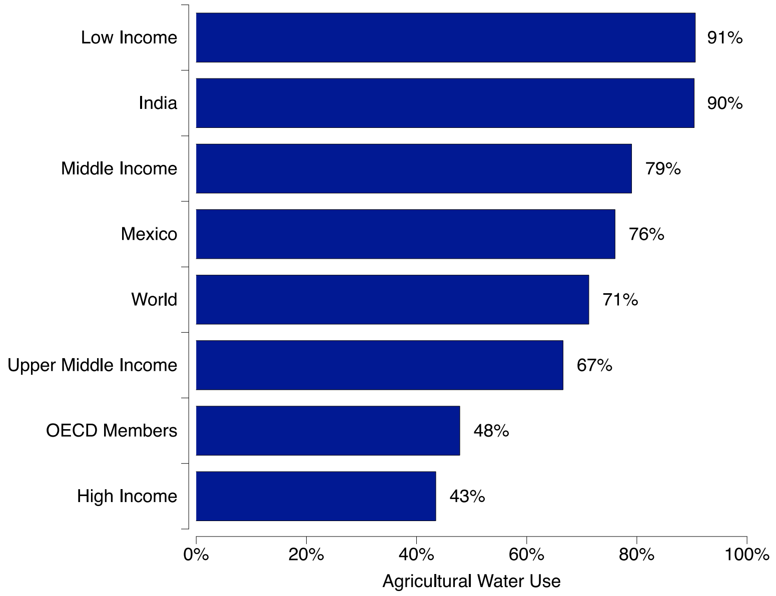
Opportunities

- 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.

Agricultural water as a share of total water withdrawals, 2017

Agricultural water withdrawals as a percentage of total water withdrawals (which is the sum water used for agricultural, industry, and domestic purposes). Agricultural water is defined as the annual quantity of self-supplied water withdrawn for irrigation, livestock, and aquacultural purposes.

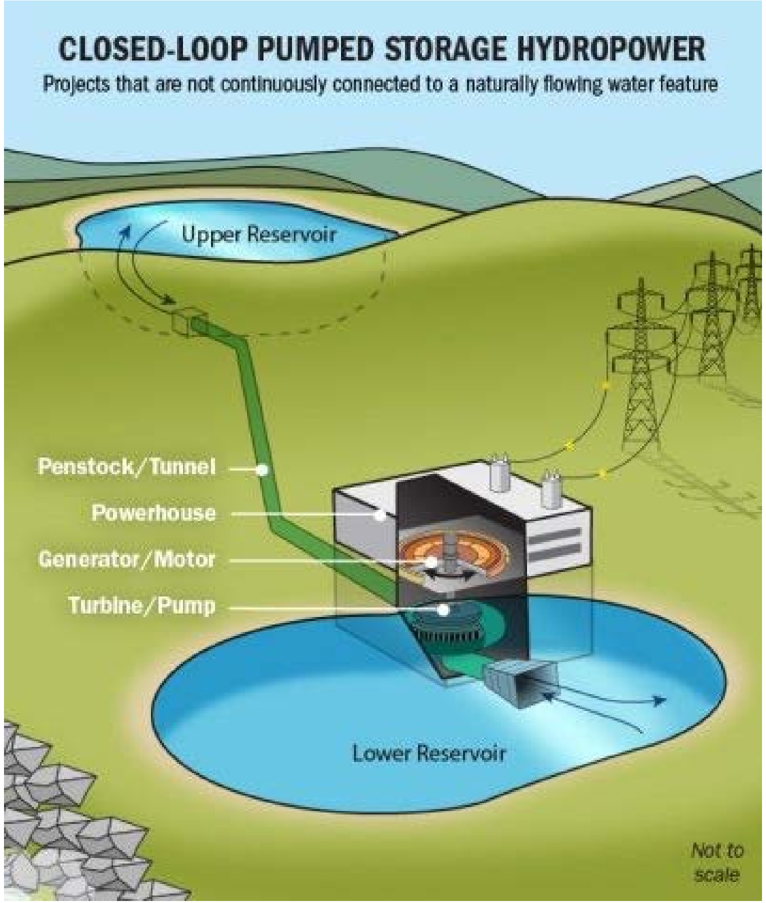


Source: Food and Agricultural Organization of the United Nations (via World Bank) OurWorldData.org/water-access-resources-sanitation

New Development: Pumped Storage Hydro

Pumped Storage Hydropower (PSH)

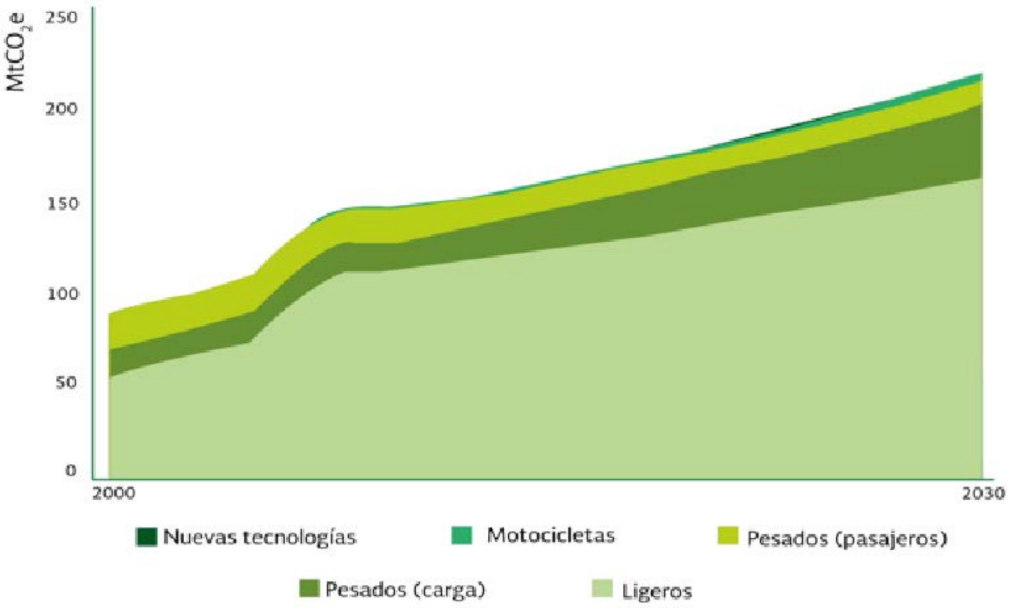
- Opportunities
  - Storage is key to cost-effective integration of variable renewable energy (e.g., wind and solar PV)
  - Pump-back PSH (adding the ability to pump water between existing reservoir pairs) can provide one of the most cost-effective forms of storage
- Considerations
  - Closed-loop PSH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



Mexico Transportation Road Emissions by Vehicle Type, Total and Projected, 2000–2030

Source: Wu, Bracho, Romero-Lankao 2022, Image by INECC, 2018

- 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

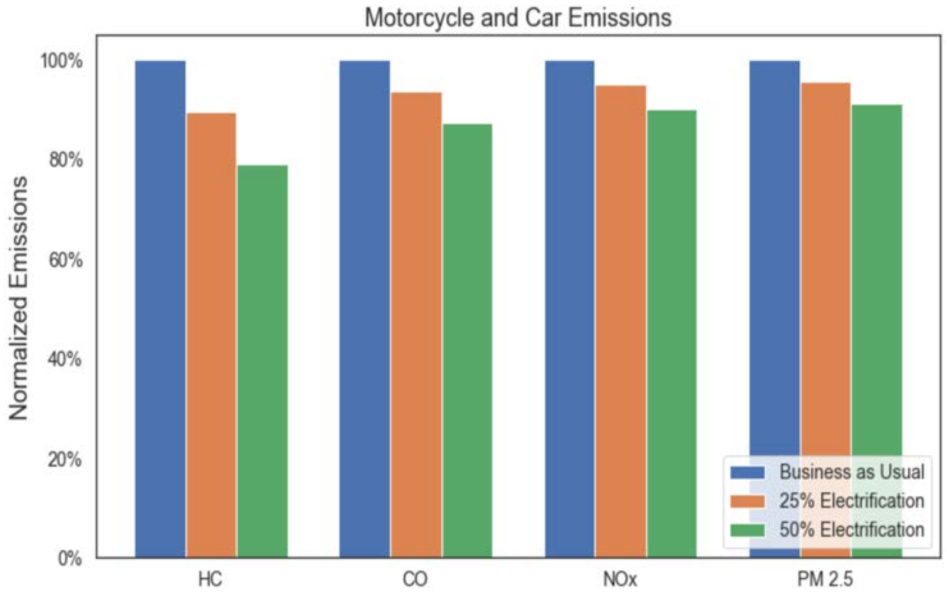
Policies and programs can foster:

- 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 bar chart shows normalized emissions benefits from motorcycles and cars in Mexico City for cases with electrification of 0%, 25%, and 50% motorcycle kilometers travelled.

Source: Romero-Lankao, Gilleran, Weigl, Holden, Neri, 2019

The Electrification of Public Transport and Last-mile Freight are Feasible, Cost-effective, and Equitable Options That Can Improve Mobility for 70% of Mexicans

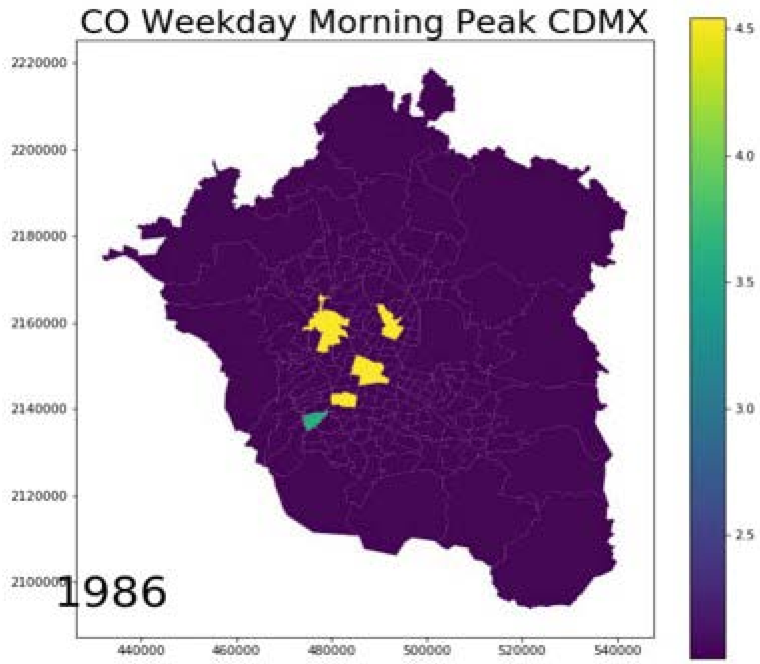
Cost-effectiveness and affordability

- 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 (H_2) Importance

Global Significance

- As of early 2021, 30 countries, 50% of global gross domestic product, have decarbonization goals and H_2 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 H_2 technologies

Colors of H_2 (carbon intensity and process for production)

- Gray H_2, steam-methane reforming of natural gas, most produced today
- Green H_2, produced entirely by renewable energy
    - the most viable near-term strategy is PEM (polymer exchange membrane) electrolysis using renewable electricity and water
- Blue H_2, produced by fossil fuels with carbon dioxide sequestered
- Green and blue H_2 are required for decarbonization targets.

What?

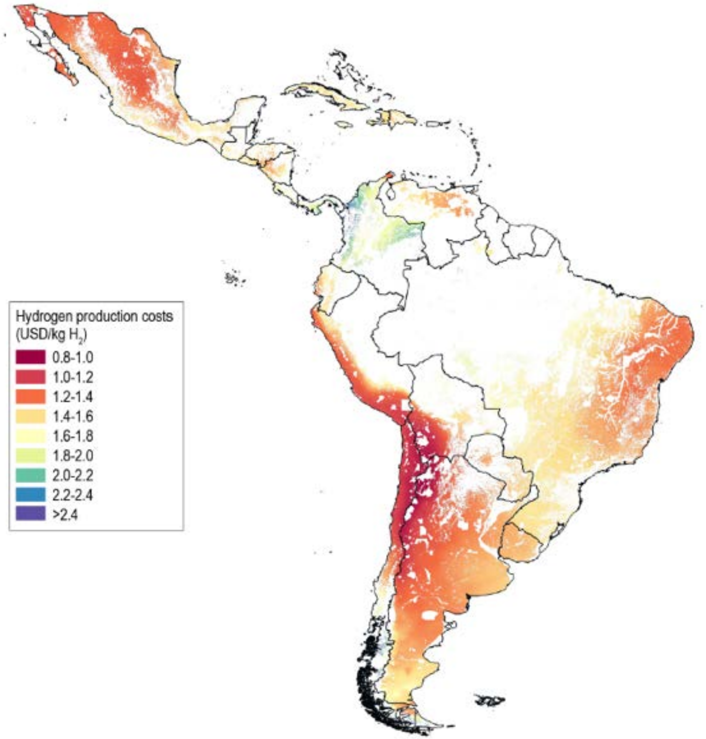
A versatile energy carrier that is increasingly seen as a requirement for decarbonizing hard-to-abate sectors.

Green H_2 in Mexico

Energy status and issues in Mexico:

- Imports 60% of H_2 [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.



Levelized cost of hydrogen production via electrolysis powered by hybrid solar PV and onshore wind, Latin America, 2050 [9]

Near Term Actions for H_2 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]

H2 References

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6. HINICIO, “Hidrogeno verde en Mexico: el potencial de la transformacion Tomo VI: An lisis de la cadena de valor local y del potencial de exportaci n de hidr geno verde,” Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Oct. 2021.
7. HINICIO, “Green Hydrogen in Mexico: towards a decarbonization of the economy Volume VII: Results Integration and General Recommendations,” Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Oct. 2021. [Online]. Available: https://www.energypartnership.mx/fileadmin/user_upload/mexico/media_elements/reports/Hydrogen_EP_volume_VII.pdf
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9. IEA, “Hydrogen in Latin America,” Paris, 2021. [Online]. Available: https://www.iea.org/reports/hydrogen-in-latin-america
10. C. Lenten, “Mexico Seeking to Join Latin American Peers in Hydrogen Push,” Apr. 2021. https://www.naturalgasintel.com/mexico-seeking-to-join-latin-american-peers-in-hydrogen-push/
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12. https://www.elfinanciero.com.mx/nacional/2022/01/20/cfe-busca-subirse-al-barco-del-hidrogeno-verde/
13. https://www.pv-magazine.com/2021/03/09/green-hydrogen-projects-proliferate-in-chile-mexico-uruguay/

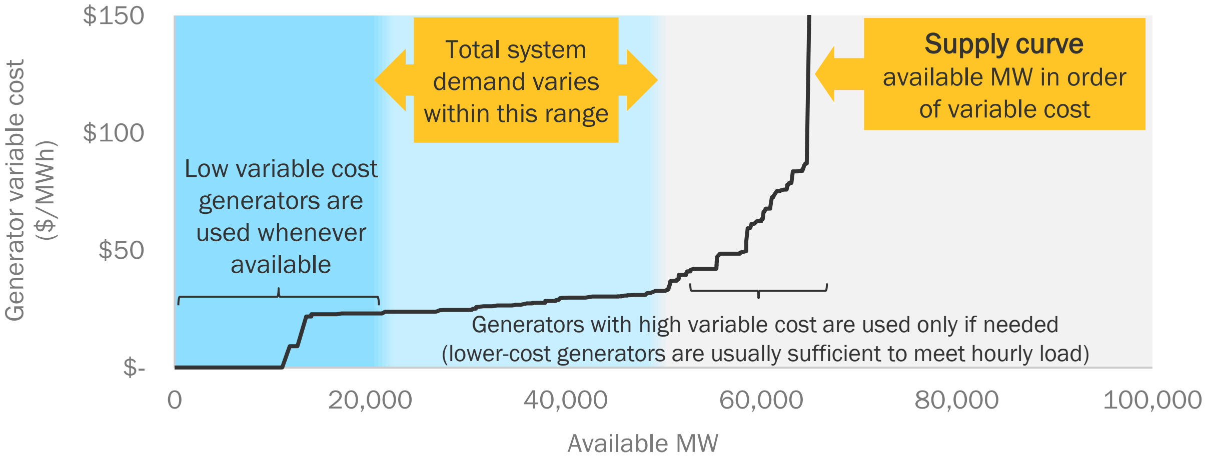
Transmission

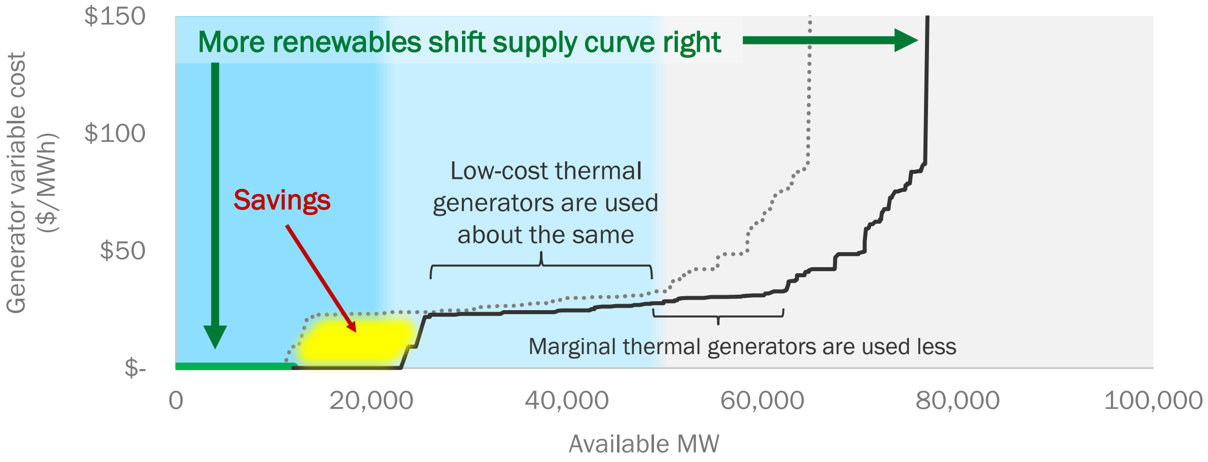
How Transmission, Renewables Can Cut Electricity Costs

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.

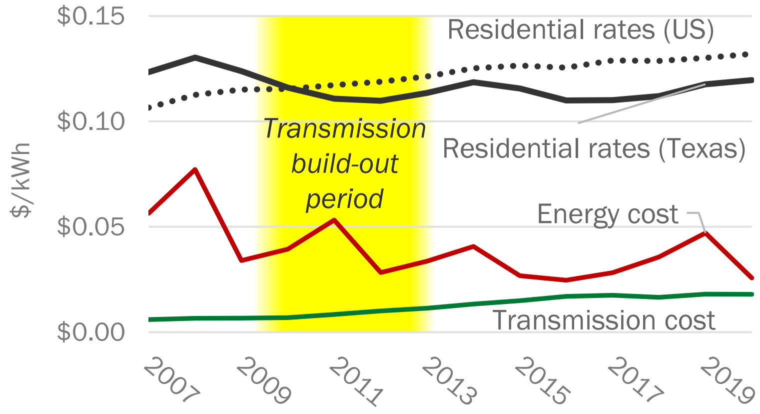


Chart source: [5]

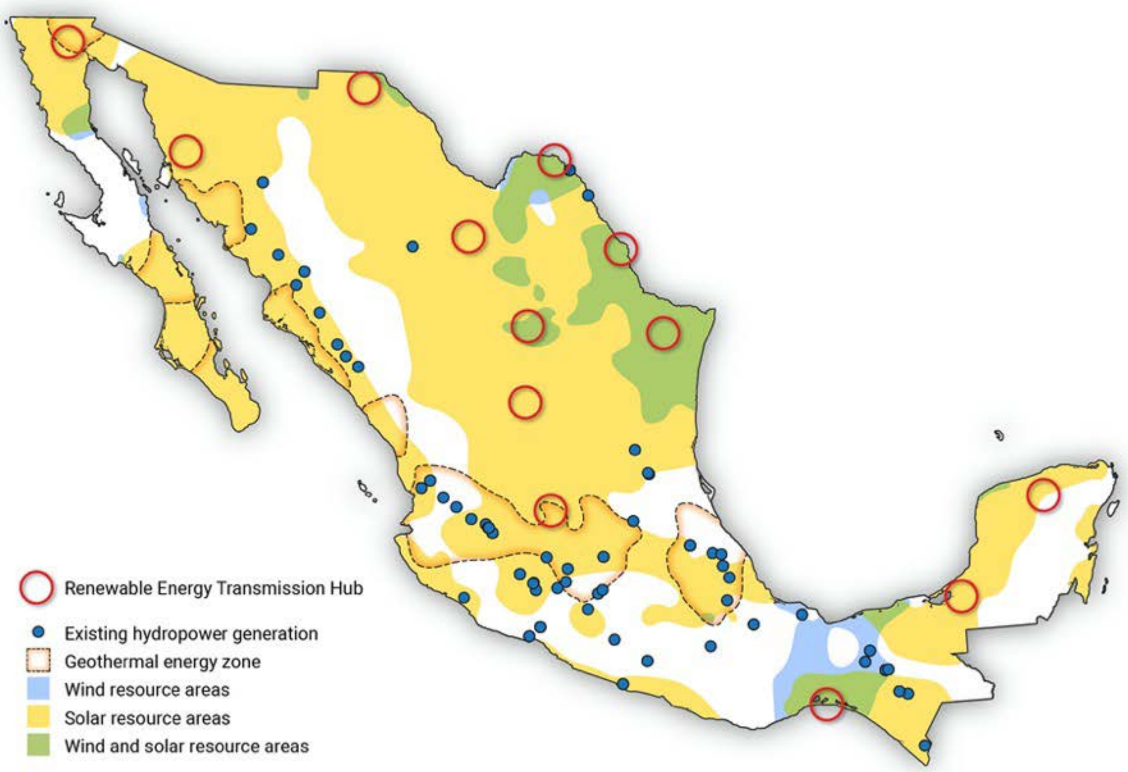
Where High-Quality Renewables Are Most Concentrated

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

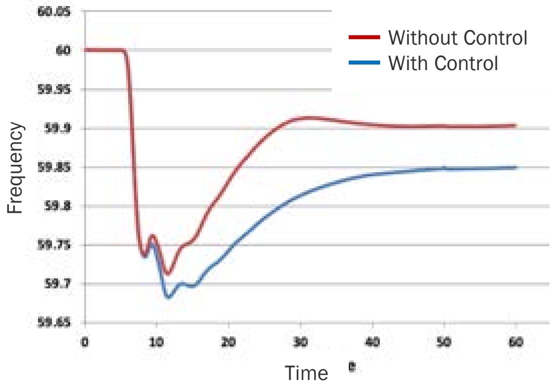
Challenges:

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

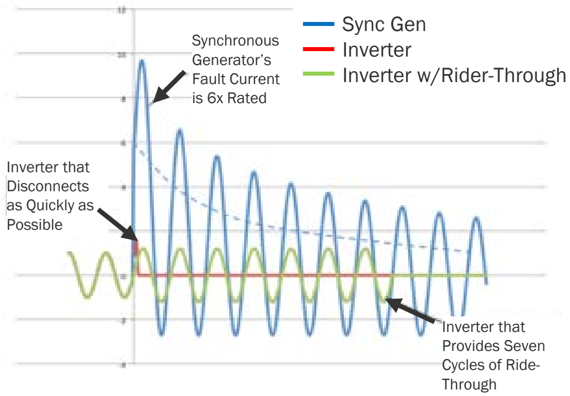
Source: *B. Kroposki et al., "Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," http://ieeexplore.ieee.org/document/7866938/*

Source: *Blackstart of Power Grids with Inverter- Based Resources, H. Jain, G. Seo, E. Lockhart, V. Gevorgian, B. Kroposki, 2020 IEEE Power and Energy General Meeting: https://www.nrel.gov/docs/fy20osti/75327.pdf*

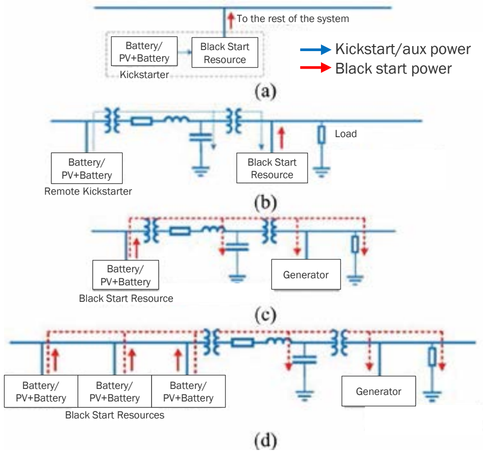
Stability



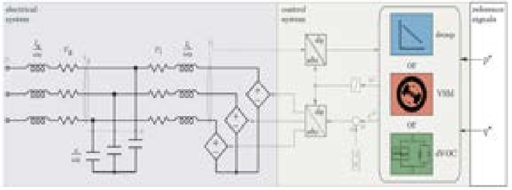
Protection



Grid-forming/Blackstart



Control system interactions and resonances



Options for Dealing with Variability and Uncertainty

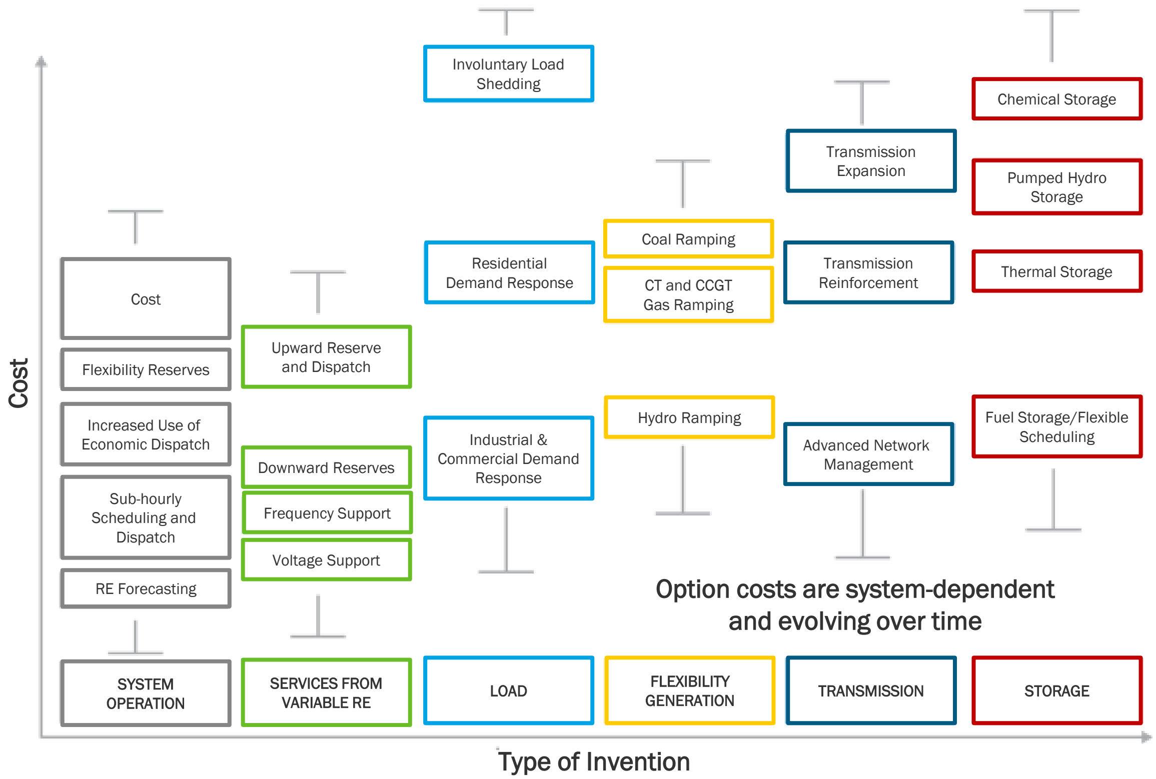
Options for Dealing with Variability and Uncertainty

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.

Source: Impact of Flexibility Options on Grid Economic Carrying Capacity of Solar and Wind: Three Case Studies, P. Denholm, J. Novacheck, J. Jorgenson, and M. O'Connell, National Renewable Energy Laboratory, NREL/TP-6A20-66854, December 2016, *https://www.nrel.gov/docs/fy17osti/66854.pdf*

Relative Economics of Integration Options



Work to Unify the Integration of Inverters and Synchronous Machines Could Help Mexico's CENACE

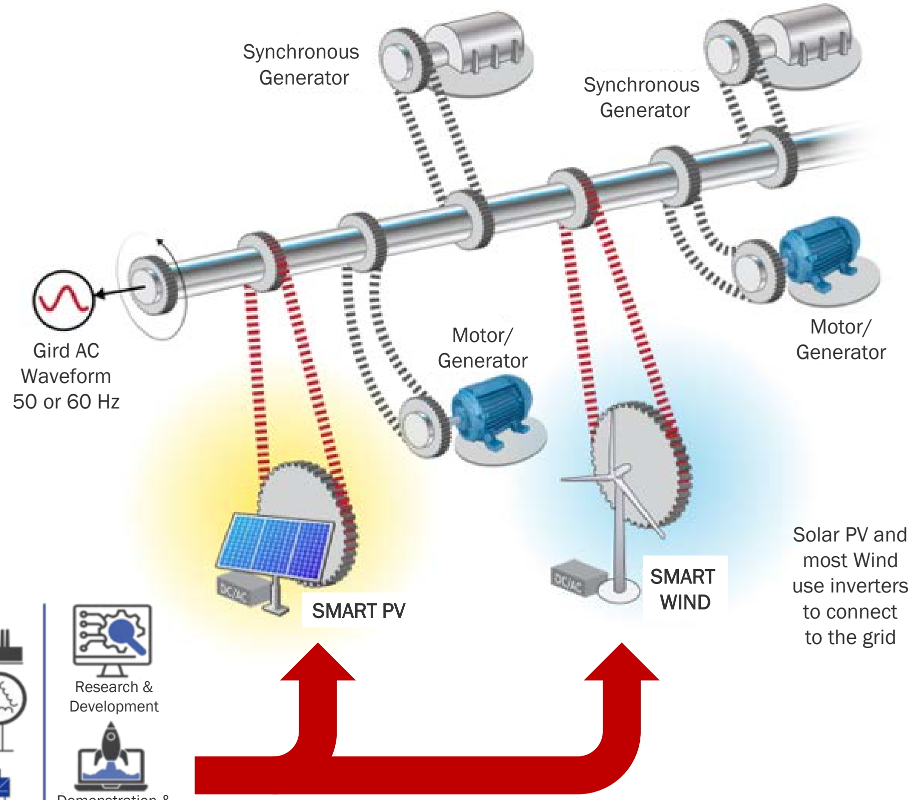
This work is Co-led by NREL, Univ. of Washington, and EPRI

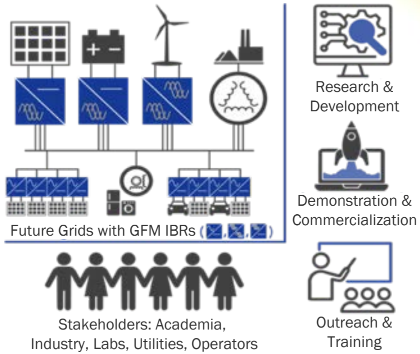
UNIFI is a forum to address fundamental challenges in seamless integration of grid-forming (GFM) technologies into power systems of the future

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

unifi consortium
universal interoperability for grid-forming inverters

Learn more about UNIFI at:
https://www.youtube.com/watch?v=g5ej82euGCM





Need inverter-based resources to provide essential reliability services

Summary

- 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

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

MEXICO: NORTH AMERICAN CLEAN ENERGY POWERHOUSE

Authors: Riccardo Bracho (NREL), José Alvarez (encoord), Alexandra Aznar (NREL), Carlo Brancucci (encoord), Gregory Brinkman (NREL), Aubryn Cooperman (NREL), Francisco Flores-Espino (NREL), Will Frazier (encoord), Chris Gearhart (NREL), Omar José Guerra Fernández (NREL), David Hurlbut (NREL), Amanda Kolker (NREL), Ben Kroposki (NREL), Eric Lantz (NREL), Galen Maclaurin (NREL), Billy Roberts (NREL), Patricia Romero Lankao (NREL), Genevieve Saur (NREL), Greg Stark (NREL), and Haiku Sky (NREL)

Guidance and Technical Support: Ron Benioff, Adam Warren, Daniel Laird, Al LiVecchi, Paul Denholm, Doug Arent, Andrea Watson, Peter Green, Johney Green, Juan Torres, Craig Turchi, Jeffrey Logan, Nate Blair, Brian Curtiss, Jennifer Kurtz, Cindi Edgley, and Gian Porro

Communications Team: Britton Marchese and Christopher Schwing

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