# 55.3 Energy Storage at utility scale as an enabler for $CO_2$ Mitigation

## Appendix A

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SECRETARÍA DE MEDIO AMBIENTE Y RECURSOS NATURALES
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Technology Roadmap and Mitigation Potential of Utility-scale Electricity Storage in Mexico

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# Appendix A – Detailed input data and assumptions

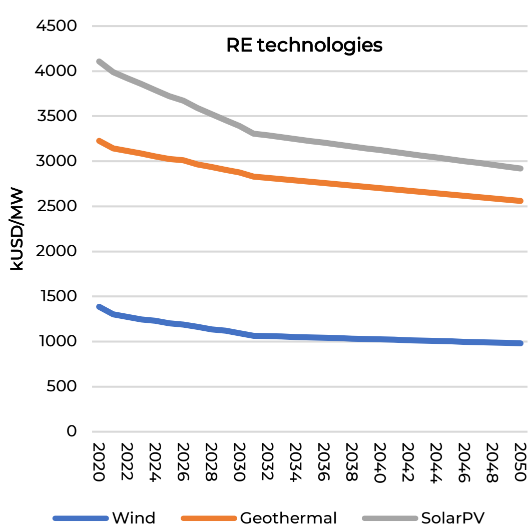
## Technology costs and learning rates

Table A.1 and Figure A.1 contain key technical and financial data for power generation technologies available for investment. All financial terms are in 2018 USD.

Table A.1. Power generation technologies. The investment cost for wind, solar and Li-Ion follow a learning curve as described in Figure A.1. *CAPEX is described both in kUSD/MW and kUSD/MWh

| Technology Type | CAPEX | Fixed O&M | Variable O&M | Efficiency | Economical lifetime |
|---|---|---|---|---|---|
| Units | (kUSD/MW) | (USD/kW/year) | (USD/MWh) | (%) | (years) |
| Biomass Sugar Cane | 2012 | 44.12 | 3.92 | 35.64 | 30 |
| Biomass Wood Waste | 2012 | 44.12 | 3.92 | 35.64 | 30 |
| Biomass Biogas | 3017 | 33.44 | 3.18 | 42.35 | 25 |
| Combined Cycle Gas turbine | 960 | 15.69 | 2.76 | 49.45 | 30 |
| Cogeneration Sugar Cane | 2012 | 44.12 | 3.92 | 35.64 | 30 |
| Cogeneration Biogas | 2765 | 62.35 | 8.09 | 42.35 | 25 |
| Cogeneration Diesel | 800 | 5 | 4.7 | 22.50 | 30 |
| Cogeneration Natural Gas | 777.21 | 15.69 | 2.76 | 48.65 | 30 |
| Engine Fuel oil | 3017 | 33.44 | 3.18 | 42.35 | 25 |
| Engine Diesel | 3017 | 33.44 | 3.18 | 42.35 | 25 |
| Engine Natural Gas | 3017 | 33.44 | 3.18 | 42.35 | 25 |
| Wind | See X | 37.5 | | 100.00 | 25 |
| Geothermal | See X | 82.28 | 0.05 | 100.00 | 30 |
| Hydro run-of-river | 1900 | 30.34 | | 100.00 | 40 |

| Technology Type | CAPEX | Fixed O&M | Variable O&M | Efficiency | Economical lifetime |
|---|---|---|---|---|---|
| Hydro reservoir | 1900 | 17.92 | | 100.00 | 40 |
| Coal Fluidized bed | 1415 | 34.03 | 2.45 | 30.00 | 40 |
| Nuclear | 3924 | 99.45 | 2.38 | 34.62 | 40 |
| Solar PV | See X | 10.5 | | 10.00 | 30 |
| Gas Turbine Natural Gas | 800 | 5 | 4.7 | 40.91 | 30 |
| Gast Turbine Diesel | 800 | 5 | 4.7 | 40.91 | 30 |
| Battery Li-ion | See X | 0.6 | 2 | 95.00 | 25 |
| Pumped Hydro Storage* | 840/23 | 15.4 | 2 | 80 | 60 |



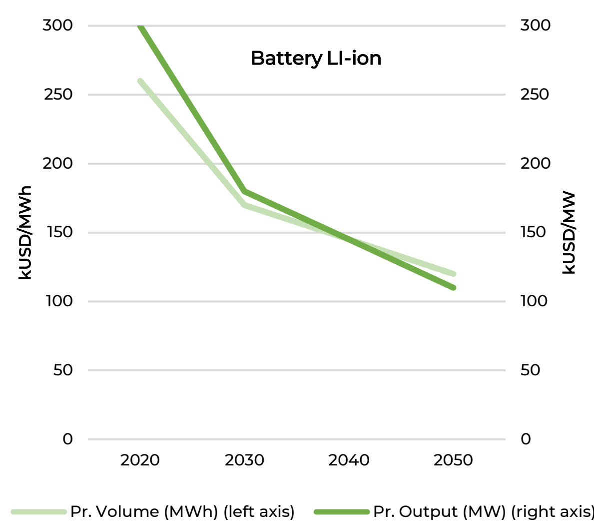




**Figure A.1.** Investment costs of wind, solar and geothermal (left) and Li-Ion Batteries (right).

Due to geographical constraints, investments in hydropower, geothermal, coal power, nuclear power and biomass from sugar cane are only allowed in certain regions according to Table A.2, based on resource availability. Pumped hydro storage is only allowed in regions with existing hydro dams.

Table A.2. Technologies that are geographically limited. The technologies listed are only available in the below regions. Sources: SENER (2018) and SENER-CFE (2018).

| Hydro run-of-river | Hydro Reservoir | Geothermal | Coal fluidized bed | Nuclear | Biomass sugar cane/Cogeneration Sugar cane |
|---|---|---|---|---|---|
| Culiacan | Veracruz | Aguascalientes | Rio Escondido | Hermosillo | Campeche |
| Guadalajara | Grijalva | Carapan | | Huasteca | Guadalajara |
| Tabasco | Acapulco | Chihuahua | | Veracruz | Manzanillo |
| Grijalva | Chihuahua | Durango | | La Paz | Puebla |
| Tabasco | Tepic | Ensenada | | | Temascal |
| Tijuana | | Grijalva | | | |
| Poza_Rica | | Guadalajara | | | |
| Veracruz | | Mexicali | | | |
| Mazatlan | | Obregón | | | |
| Central | | Poza Rica | | | |
| Hermosillo | | Puebla | | | |
| Puebla | | Querétaro | | | |
| | | Salamanca | | | |
| | | Tepic | | | |

# Wind and solar potential

The wind resource potential in each transmission region has been identified by using the Mexican Renewable Energy Atlas AZEL (SENER, CFE, 2018), where the available potential, in terms of maximum installed capacity, has been identified as well as the capacity factor associated to it, using the so-called "Scenario 2" of the Atlas (see Figure A.2). The hourly profiles have been estimated through re-analysis data of Merra-2 (Renewables.ninja, 2017) by using wind speed time-series at a height of 100 m and the power curve from the latest Vestas wind turbine (3MW) as well as micro-localization defined in AZEL for siting the wind farms, ensuring the consistency between the capacity factor reported in AZEL and the one estimated through re-analysis data.

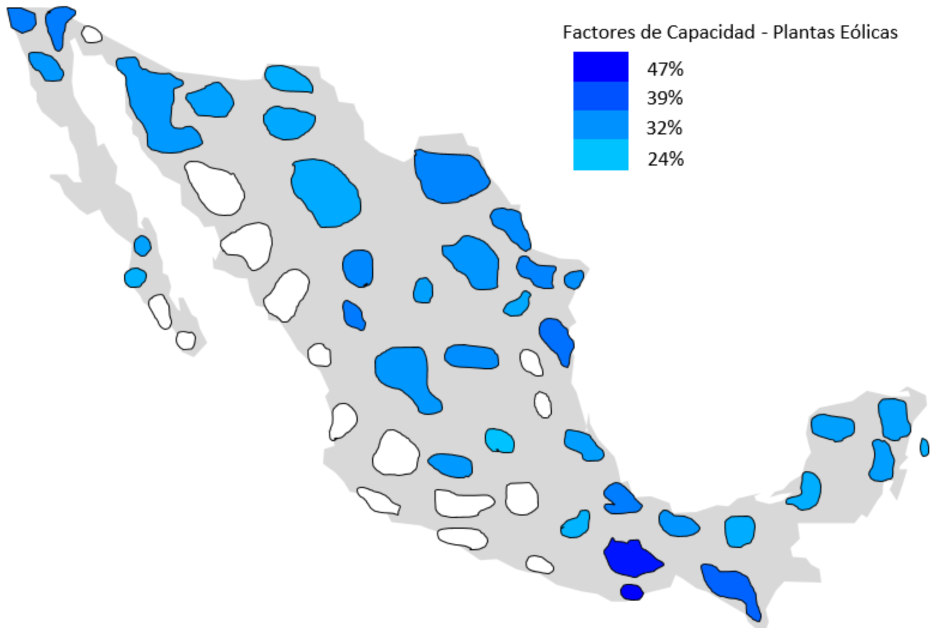



Figure A.2. Wind capacity factor per region

The capacity factor for solar PV in Mexico as well as the maximum installed capacity that could be potentially achieved in the "Scenario 2" of the Mexican RE Atlas AZEL were fed into the Balmorel model (see Figure A.3). The hourly profiles were estimated by re-analysis data of Merra-2 by using satellite data on global irradiation and temperature (Renewables.ninja, 2017).

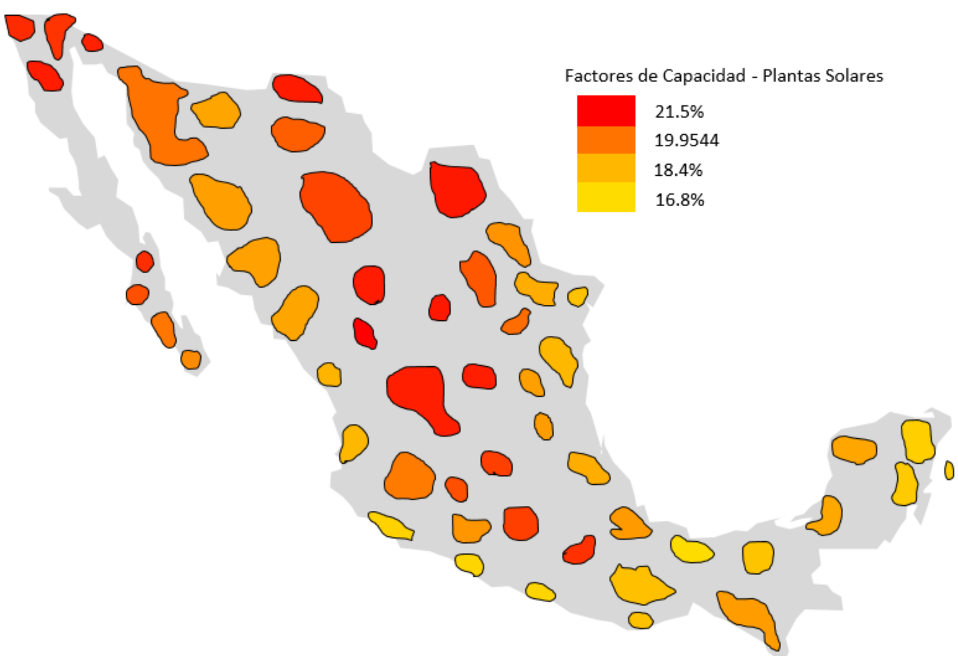



Figure A.3. Solar capacity factor per region

Table A.3. Full load hours (FLH) and capacity factor per transmission region for wind, solar (existing capacity). Note that small hydro has region specific FLHs while large hydro generators have plant specific information.

| | Wind (FLH) | Solar (FLH) | Wind (Cap) | Solar (Cap) |
|---|---|---|---|---|
| Hermosillo | 2,705 | 1,748 | 31% | 20% |
| Nacozari | 2,605 | 1,655 | 30% | 19% |
| Obregón | - | 1,667 | - | 19% |
| Los Mochis | - | 1,664 | - | 19% |
| Culiacán | - | 1,656 | - | 19% |
| Mazatlán | - | 1,615 | - | 18% |
| Juárez | 2,432 | 1,860 | 28% | 21% |
| Moctezuma | 2,503 | 1,780 | 29% | 20% |
| Chihuahua | 2,487 | 1,815 | 28% | 21% |
| Durango | 3,047 | 1,886 | 35% | 22% |
| Laguna | 2,897 | 1,858 | 33% | 21% |
| Río Escondido | 2,926 | 1,863 | 33% | 21% |
| Nuevo Laredo | 2,864 | 1,694 | 33% | 19% |
| Reynosa | 2,935 | 1,637 | 34% | 19% |
| Matamoros | 2,815 | 1,578 | 32% | 18% |
| Monterrey | 2,739 | 1,792 | 31% | 20% |
| Saltillo | 2,609 | 1,863 | 30% | 21% |
| Valles | - | 1,666 | - | 19% |
| Huasteca | 3,149 | 1,606 | 36% | 18% |
| Tamazunchale | - | 1,673 | - | 19% |
| Güémez | 2,508 | 1,760 | 29% | 20% |
| Tepic | - | 1,606 | - | 18% |
| Guadalajara | - | 1,737 | - | 20% |
| Aguascalientes | 2,720 | 1,856 | 31% | 21% |
| San Luis Potosí | 2,831 | 1,856 | 32% | 21% |
| Salamanca | 2,695 | 1,800 | 31% | 21% |
| Manzanillo | - | 1,520 | - | 17% |
| Carapán | - | 1,689 | - | 19% |
| Lázaro Cárdenas | - | 1,508 | - | 17% |
| Querétaro | 2,144 | 1,821 | 24% | 21% |
| Central | - | 1,821 | - | 21% |
| Poza Rica | 2,624 | 1,634 | 30% | 19% |
| Veracruz | 3,025 | 1,679 | 35% | 19% |
| Puebla | 2,343 | 1,836 | 27% | 21% |
| Acapulco | - | 1,504 | - | 17% |
| Temascal | 3,942 | 1,583 | 45% | 18% |
| Coatzacoalcos | 2,758 | 1,472 | 31% | 17% |
| Tabasco | 2,458 | 1,571 | 28% | 18% |

| | Wind (FLH) | Solar (FLH) | Wind (Cap) | Solar (Cap) |
|---|---|---|---|---|
| Grijalva | 3,277 | 1,673 | 37% | 19% |
| Ixtepec | 4,095 | 1,578 | 47% | 18% |
| Campeche | 2,433 | 1,646 | 28% | 19% |
| Mérida | 2,609 | 1,653 | 30% | 19% |
| Cancún | 2,597 | 1,531 | 30% | 17% |
| Chetumal | 2,638 | 1,548 | 30% | 18% |
| Cozumel | 2,425 | 1,537 | 28% | 18% |
| Tijuana | 3,021 | 1,843 | 34% | 21% |
| Ensenada | 2,714 | 1,858 | 31% | 21% |
| Mexicali | 3,021 | 1,833 | 34% | 21% |
| San Luis Río Colorado | - | 1,854 | - | 21% |
| Villa Constitución | 2,387 | 1,800 | 27% | 21% |
| La Paz | - | 1,743 | - | 20% |
| Los Cabos | - | 1,707 | - | 19% |
| Mulegé | 2,594 | 1,840 | 30% | 21% |

# Fuel prices

Fuel prices in the model are based on (SENER, 2019) with individual prices per regions. After 2030, fuel prices are kept constant. The projection of diverse fuel prices is shown for the Central region in Figure A.4. The fuel prices for coal, natural gas, fuel oil and light oil differ by region as shown, for natural gas and fuel oil, in Figure A.5

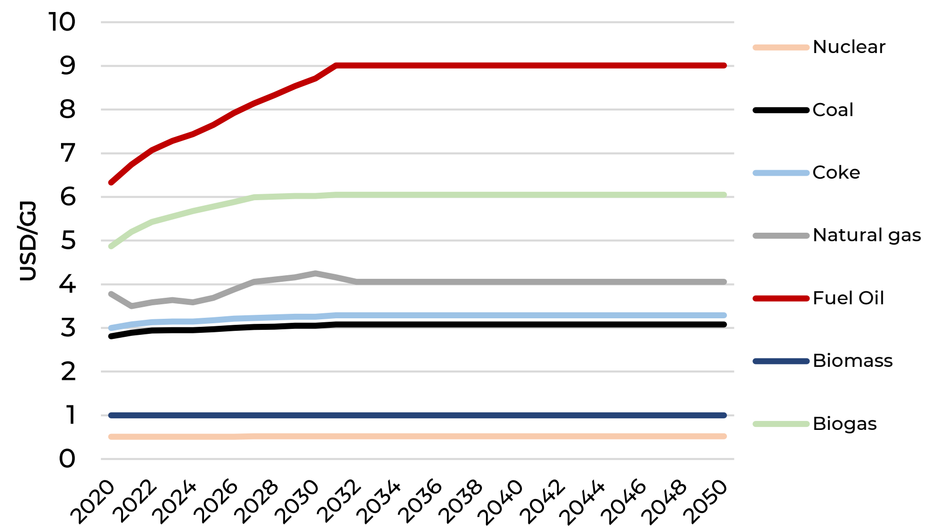



Figure A.4. Fuel price projections in the Central region 2020-2050, including fuel transport costs towards the region. Fuel prices are assumed to be constant after 2030. Fuel prices are taken from Prodesen 2019-2033 and fuel transport cost from Prodesen 2018-2032.

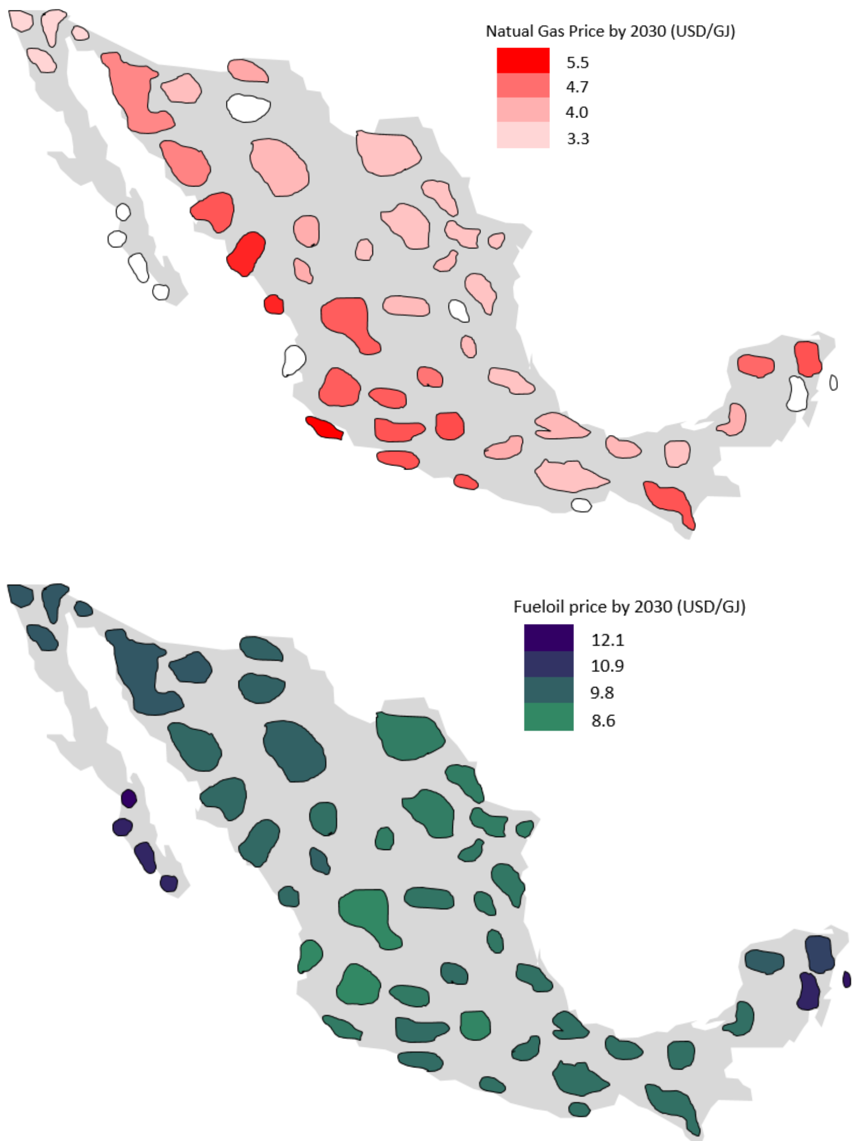



Figure A.5. Estimated Natural gas (top) and fuel oil (bottom) prices by 2030, adapted from Prodesen 2019-2033 (fuel price) and Prodesen 2018-2032 (fuel transmission/transport cost). The areas in white reflect that it is not predicted to have natural gas fuel availability by 2030.

# Transmission system

The starting point of the interconnected grid within Mexico is all existing and committed interconnectors. In the Balmorel model used in this report, the country is divided into 53 transmission regions, which are equivalent to the PRODESEN regions. These regions are connected through a transmission grid of existing and committed interconnectors, as well as the possibility to expand it through endogenous optimization of the transmission capacity.

Committed interconnectors are projects that are under construction or projects that are decided and financed or are planned with a very high likelihood of being realized. The table below shows a list of existing and committed interconnectors as found in (SENER, 2019). These committed interconnection projects and their net transmission capacities will be considered as firm capacity just as existing interconnectors, after being operational.

Table A.4. Existing and committed interconnectors (MW). "Online" is the year when the committed projects are expected to be operational.

| To/From | From/To | Existing * | Committed ** | Online |
|---|---|---|---|---|
| | | (MW) | (MW) | (Year) |
| Acapulco | Puebla | 300 | | |
| Aguascalientes | Salamanca | 880 | | |
| Nacozari | Hermosillo | 975 | | |
| Nacozari | Moctezuma | 400 | | |
| Cancun | Cozumel | 48 | 146 | 2021 |
| Carapan | Salamanca | 700 | | |
| Chihuahua | Laguna | 330 | | |
| Coatzacoalcos | Temascal | 1,750 | | |
| Culiacan | Los_Mochis | 890 | 810 | 2019 |
| Durango | Aguascalientes | 300 | | |
| Durango | Mazatlan | 640 | | |
| Grijalva | Coatzacoalcos | 2,100 | | |
| Grijalva | Tabasco | 1,450 | | |
| Grijalva | Temascal | 2,800 | | |
| Guadalajara | Aguascalientes | 1,000 | | |
| Guadalajara | Carapan | 700 | | |
| Guadalajara | Lazaro_Cardenas | 580 | | |
| Guadalajara | Salamanca | 700 | | |
| Guemez | Monterrey | 1,500 | 300 | 2019 |
| Hermosillo | Obregon | 980 | 280 | 2018 |
| Huasteca | Guemez | 1,700 | 100 | 2019 |
| Huasteca | Tamazunchale | 1,200 | | |
| Huasteca | Valles | 1,050 | | |
| Huasteca | Poza_Rica | 1,875 | | |
| Ixtepec | Temascal | 2,500 | | |
| Juarez | Moctezuma | 640 | 325 | |
| Laguna | Durango | 550 | | |
| Laguna | Saltillo | 550 | | |
| La_Paz | Los_Cabos | 200 | | |
| Lazaro_Cardenas | Acapulco | 350 | | |

| To/From | From/To | Existing * | Committed ** | Online |
|---|---|---|---|---|
| Lazaro_Cardenas | Carapan | 720 | | |
| Lazaro_Cardenas | Central | 2,900 | | |
| Campeche | Chetumal | 140 | | |
| Campeche | Merida | 850 | | |
| Manzanillo | Guadalajara | 3000 | | |
| Matamoros | Reynosa | 1,400 | | |
| Mazatlan | Culiacan | 1,450 | | |
| Mazatlan | Tepic | 1,380 | | |
| Merida | Cancun | 825 | | |
| Merida | Chetumal | 135 | | |
| Mexicali | San_Luis_Rio_Colorado | 390 | | |
| Moctezuma | Chihuahua | 640 | 175 | 2019 |
| Monterrey | Saltillo | 1,500 | 100 | 2019 |
| Obregon | Los_Mochis | 680 | 550 | 2019 |
| Poza_Rica | Central | 4,100 | | |
| Poza_Rica | Puebla | 310 | | |
| Puebla | Central | 3,000 | 2,500 | 2022 |
| Queretaro | San_Luis_Potosi | 425 | | |
| Queretaro | Central | 1,800 | | |
| Reynosa | Monterrey | 2,060 | 750 | 2022 |
| Reynosa | Nuevo_Laredo | 140 | | |
| Rio_Escondido | Chihuahua | 450 | | |
| Rio_Escondido | Monterrey | 2,100 | | |
| Rio_Escondido | Nuevo_Laredo | 400 | | |
| Salamanca | Queretaro | 1,600 | | |
| Saltillo | Aguascalientes | 1,290 | 210 | 2019 |
| San_Luis_Potosi | Aguascalientes | 1,300 | | |
| Tabasco | Campeche | 1,200 | | |
| Tamazunchale | Queretaro | 1,780 | | |
| Temascal | Puebla | 3,000 | | |
| Tepic | Guadalajara | 1,178 | | |
| Tijuana | Ensenada | 255 | | |
| Tijuana | Mexicali | 520 | 480 | 2022 |
| Valles | San_Luis_Potosi | 1,500 | | |
| Veracruz | Poza_Rica | 750 | | |
| Veracruz | Puebla | 1,100 | | |
| Veracruz | Temascal | 350 | | |
| Villa_Constitucion | La_Paz | 80 | 760 | 2023 |
| Mulege | Villa_Constitucion | | 180 | 2023 |

* Existing in 2017
** Capacity additional to the existing capacity

The figure below shows a map of Mexico with all existing (upper) and committed interconnectors (lower).

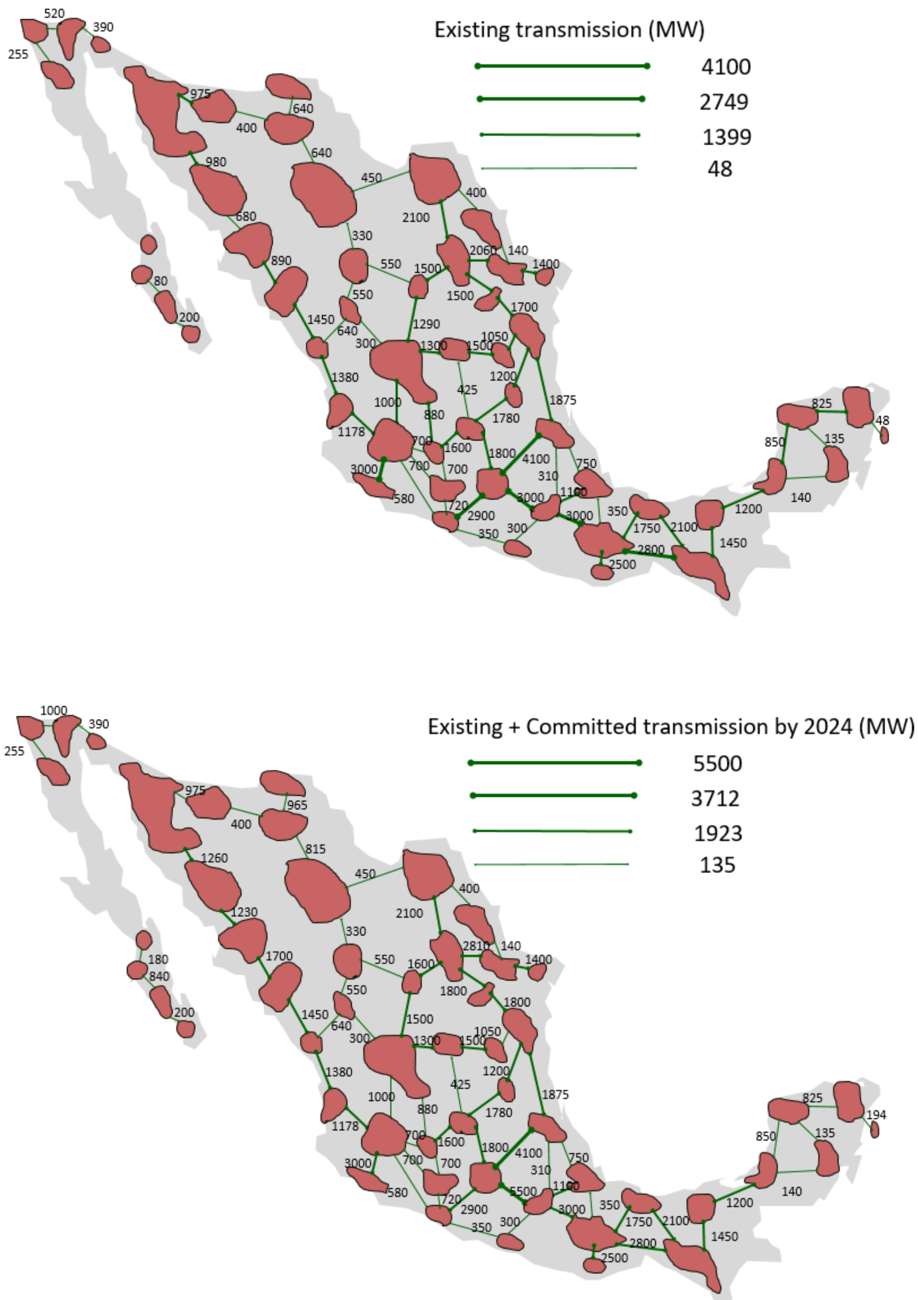



Figure A.6. Existing (2017, top) and Existing + committed (bottom) interconnectors in Mexico (MW).