ReEDS-Mexico: A Capacity Expansion Model of the Mexican Power System

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National Renewable Energy Laboratory

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Acknowledgments

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Nomenclature or List of Acronyms

AEO	Annual Energy Outlook
ATB	Annual Technology Baseline
BA	balancing area
CC	combined cycle
CT	combustion turbine
DOE	U.S. Department of Energy
DUPV	distributed utility PV
EIA	Energy Information Administration
ERCOT	Electric Reliability Council of Texas
GW	gigawatt
ICE	internal combustion engine
INEGI	National Institute of Statistics and Geography
MW	megawatt
NARIS	North American Renewable Integration Study
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Resource Database
OGS	oil/gas steam
PRODESEN	Programa de Desarrollo del Sistema Eléctrico Nacional
PV	photovoltaic
ReEDS	Regional Energy Deployment System
SENER	Secretaría de Energía for Mexico
TRG	techno-resource group
TWh	terrawatt-hour
UPV	utility PV
WIND	Wind Integration National Dataset

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Introduction

In recent years Mexico's power sector has undergone considerable reform that has significant potential to impact the future electricity mix (Alpizar–Castro and Rodríguez–Monroy 2016). Day-ahead and real-time trading in Mexico's power markets opened in early 2016. In addition to this reform, Mexico is striving to ensure that 35% of its electricity is generated from clean energy sources by 2024, 40% by 2035, and 50% by 2050 (Presidencia de la República 2016). These rapid changes in both the market and the generation mix create a need for robust tools that can help electricity sector stakeholders make informed decisions. The purpose of this report is to document the extension of the National Renewable Energy Laboratory's (NREL's) Regional Energy Deployment System (ReEDS) model (Eurek et al. 2016) to cover the Mexico power system. This extension, which we will refer to throughout this paper as ReEDS-Mexico, provides a model of the Mexico power sector using a system-wide, least-cost optimization framework.

The ReEDS model has been used extensively for U.S. electricity sector analysis such as quantifying the impacts of tax credit extensions on renewable generation deployment (Lantz et al. 2014; Mai et al. 2016), evaluating clean energy futures (Mignone et al. 2012), and creating visions for the future U.S. power system (Mai et al. 2012; DOE 2012, 2015; Cole et al. 2016).[1] In more recent years, ReEDS has been used to examine capacity expansion for clean energy in combined U.S. and Canada power sector scenarios (Beiter, Cole, and Steinberg 2017; Ibanez and Zinaman 2016; Martinez et al. 2013). For example, Beiter, Cole, and Steinberg (2017) examined the value of additional U.S.-Canada cross-border transmission.

ReEDS has been developed with an emphasis on issues related to renewable energy, and as such it has significant and unique modeling capabilities for handling renewable energy expansion and integration. The expansion of the ReEDS model to include Mexico creates a tool capable of examining the implications of a variety of scenarios of the evolution of the Mexico power system, and establishes an analytic resource for considering the long-term impacts of additional electricity sector interactions across the United States and Mexico. Additionally, the extension of the ReEDS model to Mexico creates a platform for modeling and analyzing the coordinated build-out of the U.S., Canada, and Mexico power sectors, which is the aim of the ongoing North American Renewable Integration Study (NARIS),[2] and we anticipate that the ReEDS-Mexico tool will be used as the foundation for much of the modeling work performed under NARIS.

This report serves primarily to document the extension of the ReEDS model to Mexico and includes initial results from the ReEDS-Mexico model that demonstrate the model's capability. The report is structured in a way to provide context to those already familiar with the U.S. power system. This report aims to provide information for representation of the Mexico power system within ReEDS and assumes that readers are already familiar with or will seek information about ReEDS functionalities provided by Eurek et al. (2016). For example, in Section 2 we compare the size of the Mexican power system with well-known portions of the U.S. power system. We also compare key metrics such as capacity, generation, capacity factor in Mexico with the

[1] See http://www.nrel.gov/analysis/reeds/related_pubs.html for a list of publications that have used the ReEDS model.
[2] See https://www.nrel.gov/analysis/naris.html.

Electric Reliability Council of Texas (ERCOT) or U.S. power system to provide context. All costs and prices in this report are expressed in terms of US dollars.

Mexico's Power System

As of 2015, Mexico had a total installed capacity of 68 GW with an annual generation of 310 TWh (SENER 2016). By way of comparison, the 2015 capacity in ERCOT was about 77 GW producing 347 TWh.[3] The respective capacity and generation mixes for Mexico are shown in Figure 1 and Figure 2. Although the Mexico power system is fossil-fuel dominated, it still receives a substantial share of capacity and energy from renewable energy resources. In 2015, renewable energy technologies accounted for 25% of capacity and 15% of energy provided to the system.

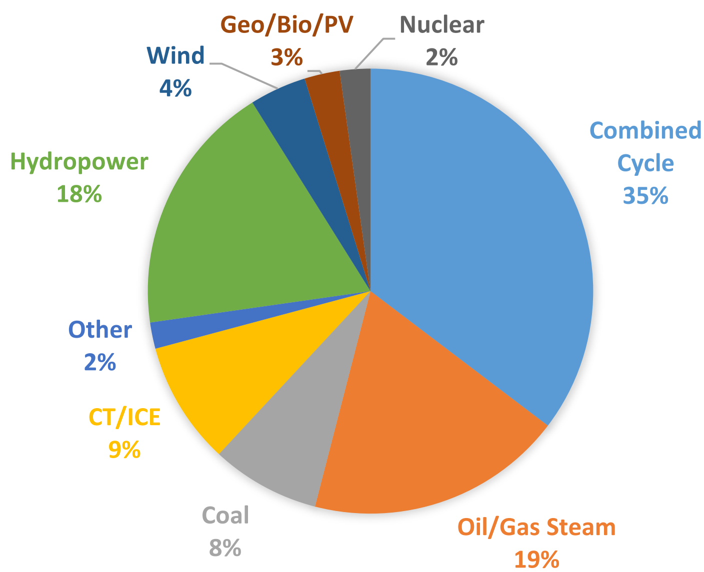

Figure 1. Mexico capacity mix in 2015 (SENER 2016).

[3] See http://www.ercot.com/content/wcm/lists/89475/ERCOT_Quick_Facts_33016.pdf.

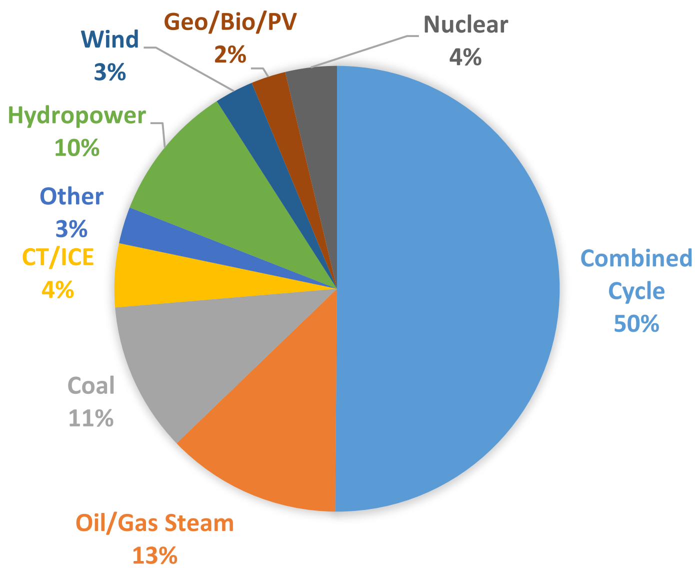

Figure 2. Mexico generation mix in 2015 (SENER 2016).

The capacity factors of the various resources is shown in Figure 3. The utilization for most technologies in Mexico are often higher than those in the U.S. despite Mexico having a higher reserve margin than many regions in the U.S. The higher capacity factors in Mexico are driven by a higher load factor[4] (77% in Mexico compared to 64% in US), where baseload units are utilized during more hours of the year, and by the higher share of peaking units in the generation mix such as combustion turbine (CT), internal combustion engine (ICE), and oil/gas steam (OGS) units.

[4] Load factor is the average load divided by the peak demand over a specific period of time. A lower load factor indicates that the peak demand is high relative to average load, while a high load factor indicates that the average load is closer to peak demand.

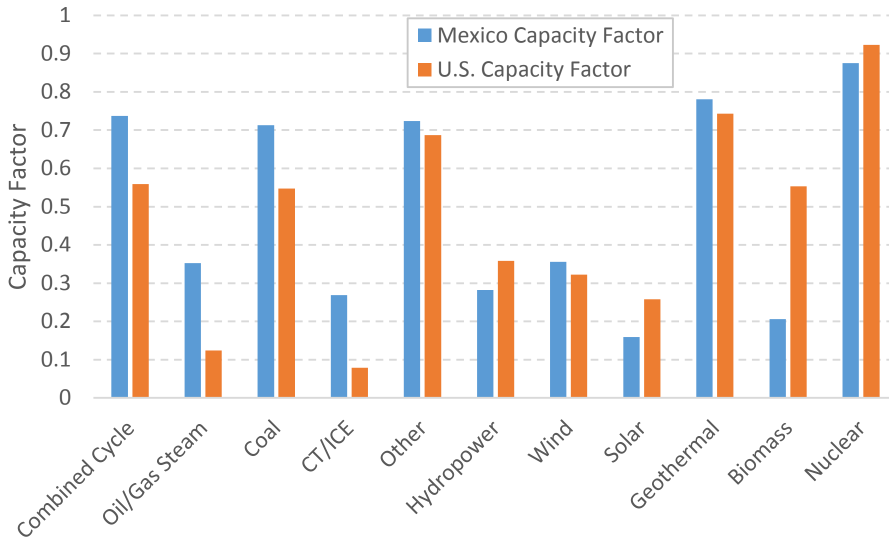

Figure 3. Capacity factor for 2015 for various Mexican electricity sector generation resources. The U.S. capacity factors for 2015 are provided for reference.

Methods

Input Assumptions and Model Structure

Fossil Fuel Prices

For this work we future Mexico natural gas prices assumptions are based on the trajectory from the 2017 Annual Energy Outlook (AEO) Reference Scenario (EIA 2017) for the West South Central census region (see Figure 4); however given that natural gas prices are typically higher in Mexico than they are in the U.S., the West South Central prices are inflated by 9% in derivation of the Mexico prices.[5] The AEO gas price trajectory is used as a price input. Actual natural gas prices in ReEDS are calculated endogenously based on the electricity sector natural gas demand determined by ReEDS. The census region includes a natural gas supply curve that adjusts the natural gas input price based on both regional and national demand (Cole, Medlock III, and Jani 2016). The coal and uranium price trajectories are from AEO 2017 Reference scenario and are also shown in Figure 4. Coal prices are also based on the West South Central census region, while uranium prices are the national values from the AEO 2017. Both coal and uranium prices are assumed to be fully inelastic.

[5] The 9% adder was calculated by comparing the EIA-reported Henry Hub prices to the exported natural gas prices for the years 2010-2015.

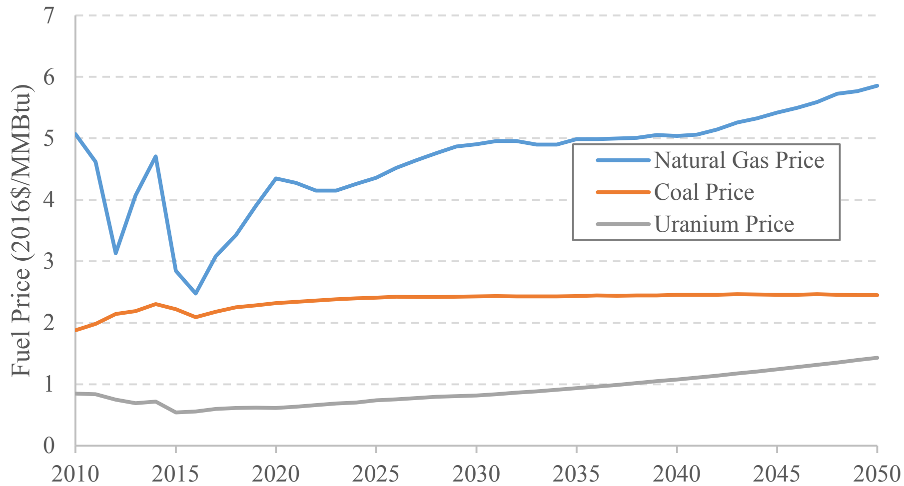

Figure 4. Fuel price trajectories used in ReEDS-Mexico

Demand Growth

For this work electricity sector demand growth is taken from the 2016 PRODESEN[6] (SENER 2016) and is shown in Figure 5. The PRODESEN only includes demand growth projections through 2030, so post-2030 values are extrapolated using the data from 2020-2030. This extrapolation results in a 2050 load that is 254% of the current system load with an average annual growth rate of around 2.7%. By contrast, the U.S. electricity demand from the AEO 2017 Reference case showed an average annual growth rate of 0.7%.

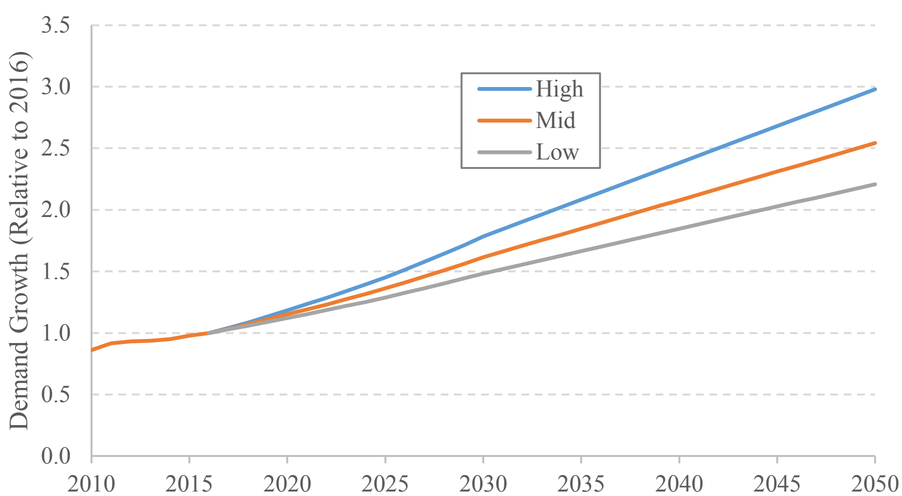

Figure 5. Demand growth trajectories used in the scenarios

[6] The Programa de Desarrollo del Sistema Eléctrico Nacional (PRODESEN) report is the electricity sector planning document produced annually by SENER for the Mexican power system.

Technology Cost and Performance

Technology cost and performance assumptions are taken from the 2017 Annual Technology Baseline (ATB) (NREL 2017). The cost projections in the Annual Technology Baseline are for U.S. based installations, but for the ReEDS-Mexico model we assume that these cost projections also apply to Mexico. Understanding the impact of capital cost differences of new generating units between the U.S. and Mexico is an area of future research.

Existing Fleet and Retirements

The existing fleet and retirements for conventional power plants are taken from the ABB Velocity Suite database (ABB 2017), which use age-based retirements unless an official retirement date has been announced. All other generator types use strictly age-based retirement schedules.

Policy Representation

The only power sector policy included in the ReEDS-Mexico model is the 35% clean energy target in 2024 (Presidencia de la República 2016). All renewable energy and nuclear technologies are counted toward the clean energy target, although the current version of the model does not allow new nuclear to be built in Mexico. The clean energy target is implemented according to the schedule shown in Figure 6. There are additional 2035 and 2050 targets specified by the Government of Mexico, but these longer-term targets are currently targets rather than mandated objectives that have to be achieved under law and thus are not included in the any of the modeled cases.

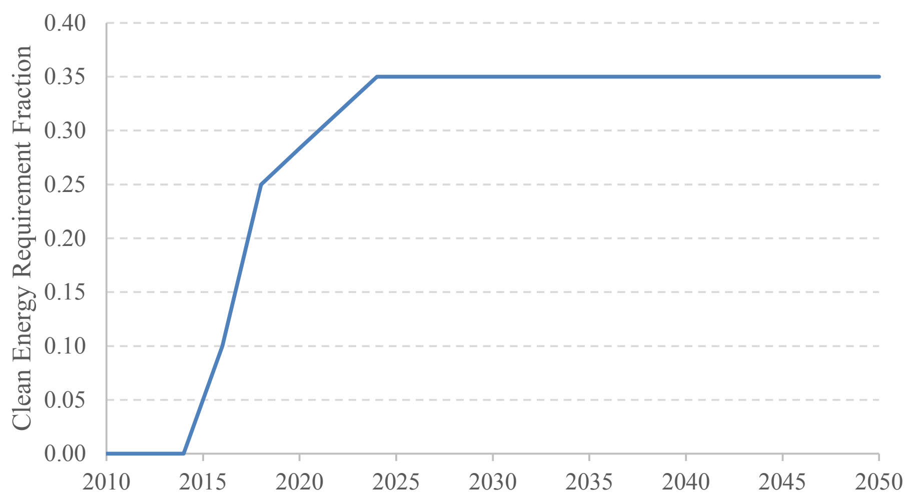

Figure 6. Fraction of total energy generation that must be met by clean energy sources.

Region Definitions

The regional representation of the Mexican power system used in ReEDS is shown in Figure 7. These regions were derived from the transmission regions specified in PRODESEN and shown in Figure 8 (specifics of the method are explained below). The ReEDS regions are defined such that the transmission control regions are matched to exactly one ReEDS balancing area (BA). This matching ensures that regional information in PRODESEN can largely be applied in ReEDS at its original level of aggregation. The structure of the BAs also preserves the alignment between transmission regions and control regions used by SENER. In two cases radial and low demand transmission regions were aggregated to a single ReEDS BA. The transmission regions of Cancún and Cozumel Island (#43 and #45 in Figure 8) were aggregated to a single BA. The three interconnected transmission regions in Baja California Sur include Villa Constitutción, La Paz, and Los Cabos (#50, #51, and #52 in Figure 8). The Mugelé transmission region (#53 in Figure 8) was not modeled as it is not currently interconnected with any other transmission regions. This mapping results in Mexico being represented in ReEDS as 49 model BAs, which match the 53 transmission regions from PRODESEN. In contrast to the U.S. and Canada BAs created in ReEDS, the PRODESEN transmission regions do not preserve administrative borders in Mexico and consequently the ReEDS-Mexico BAs are not a subset of Mexican states.

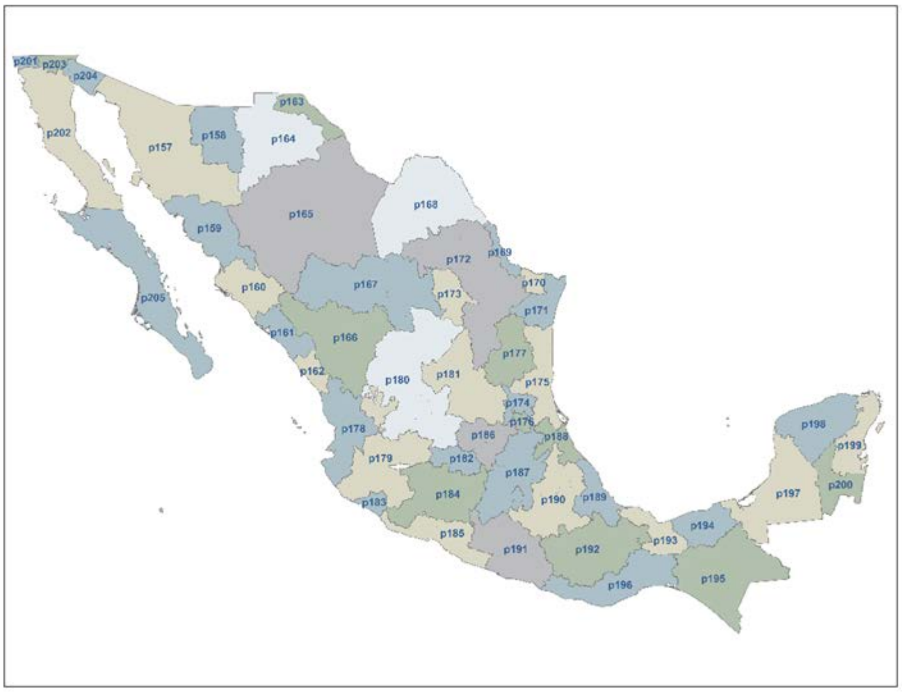

Figure 7. Map of Mexico PCA regions

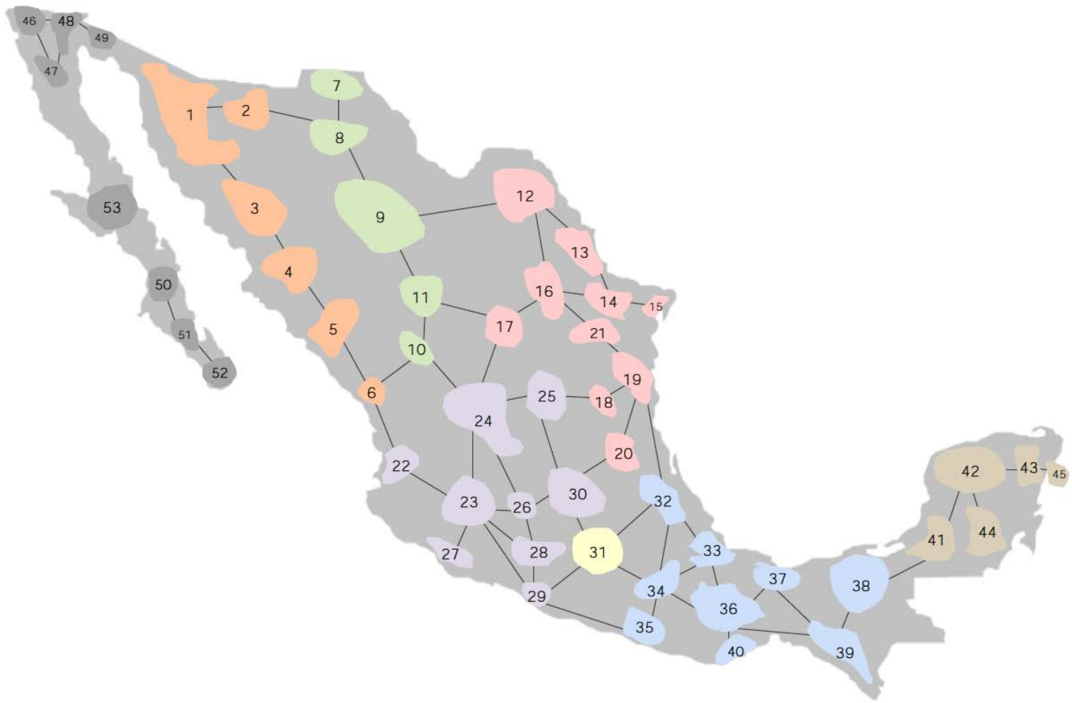

Figure 8. Transmission regions as defined in PRODESEN (SENER 2016).

As seen in Figure 7 and Figure 8, the PRODESEN regions do not have well-defined geographic boundaries, while ReEDS requires that its BAs cover the entirety of the country in order to properly represent the all renewable energy resources. In order to define the boundaries of the BAs, we used a combination of ABB network maps, National Institute of Statistics and Geography (INEGI) census data, and detailed maps in PRODESEN. The PRODESEN report included information about which substations were connected to interregional lines. The locations of these buses could be matched with those in the ABB electric transmission infrastructure database as well as detailed regional maps included in PRODESEN. These bus locations made it possible to confirm the geographic location of a BA and its known grid features. In order to define the ReEDS BAs, the region between substations known to belong to a specific region were interpolated based upon a combination of ABB network maps, INEGI census data, and PRODESEN maps. BA regions were created by aggregating the granular census sections, usually district level, such that known grid features and population centers of a transmission region remained intact.

Transmission Infrastructure

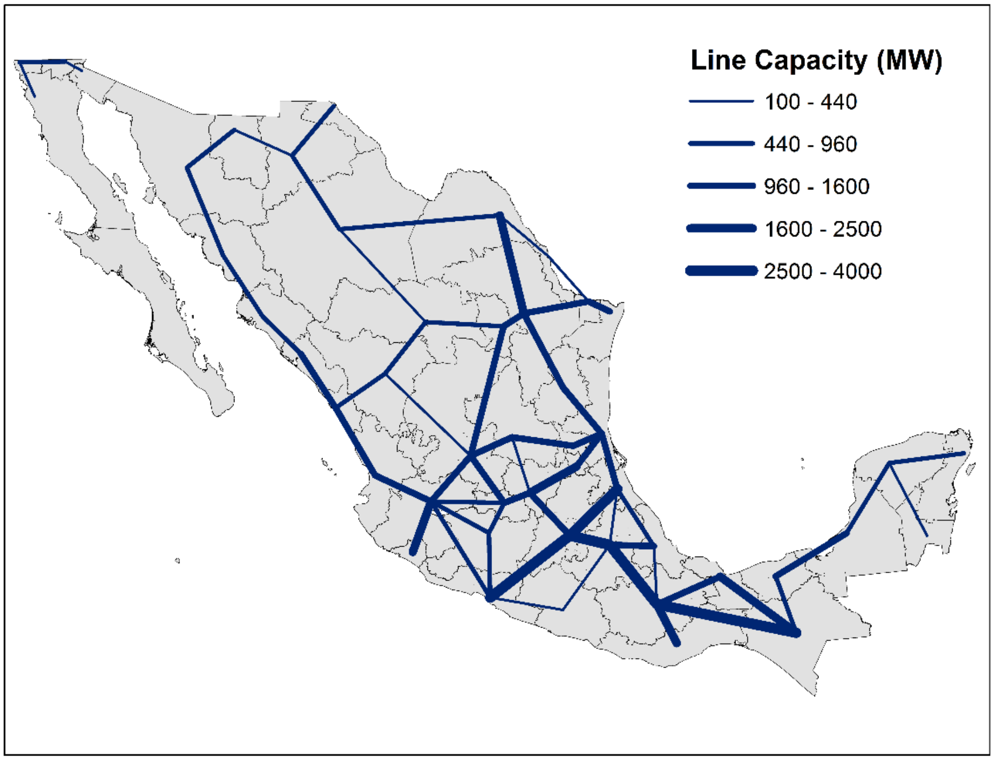

Figure 9. Map of existing transmission infrastructure

The existing transmission infrastructure is consistent with the network connections and transfer capacities specified in the 2016 PRODESEN. For cases where a ReEDS region forms a super set of transmission regions the internal transfer capacities were not considered, essentially assuming no intra-regional congestion. This assumption has limited impact effecting Baja California Sur and Cancún. Starting in 2022, transmission expansion is allowed along any existing transmission corridor. Prior to 2022, ReEDS may expand lines in accordance with a limited list of proposed transmission projects. The development costs for transmission are assumed to be the similar to those in the US (approximately $1,600/MW-mile in 2016$).

Load Profiles

ReEDS uses a 17-time-slice representation of the 8760 hours of the year to account for load and renewable resources variable profiles. The 17 time slices include one day from each season (winter, spring, summer, fall), four periods for each day (morning, afternoon, evening, and overnight), and one super-peak summer afternoon period. Hourly data are processed to create the 17-time-slice profile as described by Eurek et al. (2016). For Mexico, we use data from the 2016 PRODESEN report and PLEXOS model by SENER in the following way:

1 Hourly load data at the control region level (see figure 10) was obtained from the *Base de datos de demanda horaria para PIIRCE 2016-2030* which is released as part of PRODESEN. [7]

2 Using 2016 load participation factors from the equivalent PLEXOS model provided by SENER, the control region load profiles were disaggregated to each of the ReEDS regions.

3 The hourly disaggregated load data were mapped to the 16 non-peak time slices.

4 The top forty summer afternoon load hours in each BA were mapped to the peak time slice.

5 The load in each time slice is averaged to create the time slice representation.

Hourly load data was obtained from the *Base de datos de demanda horaria para PIIRCE 2016-2030* which is released as part of PRODESEN. This dataset includes 2015 hourly load profiles with growth projected out to 2030 for each of the 10 control regions, shown in Figure 10. In ReEDS we exclude the Mulegé control region as it is disconnected from the other transmission regions.

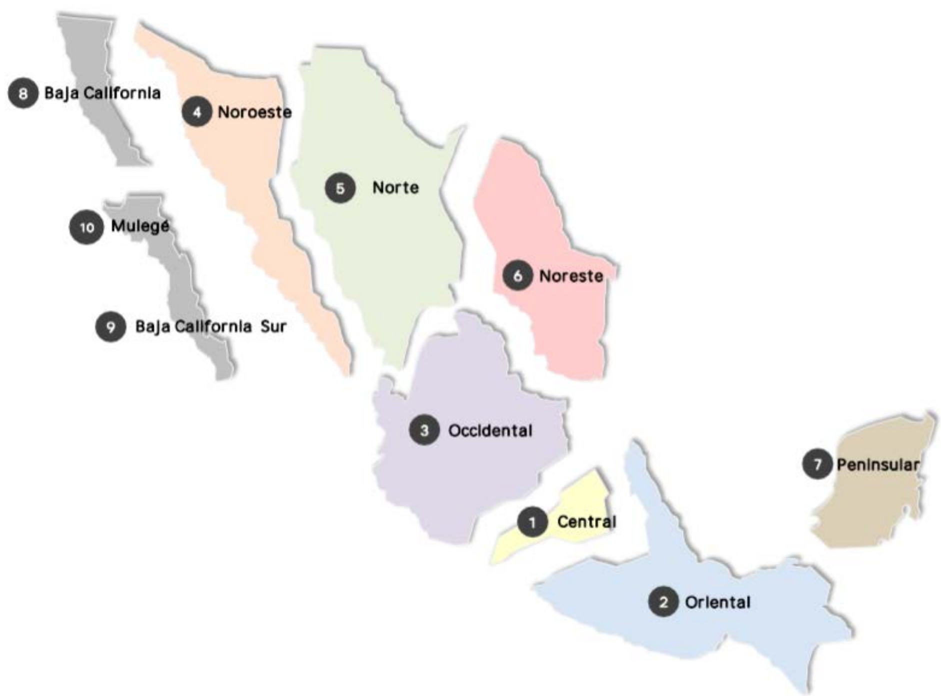

Figure 10 Map of Control Regions

[7] This dataset includes 2015 hourly load profiles with growth projected out to 2030

Wind Representation

Wind costs and performance projections align with values used in ATB 2017. The availability of wind resource, its quality, generation profile, and spur line costs are assessed by the reV tool. Modeled wind results use the meteorological and turbine power from NREL's Wind Integration National Dataset (WIND) Toolkit (Draxl et al. 2015). Existing Toolkit data providing coverage for northern Mexico was extended using NASA's MEERA-2 datasets to cover the remainder of Mexico. Wind resources are divided into 10 techno-resource groups (TRGs). The TRGs include the impacts of both the resource quality (e.g., average annual wind speed) as well as the turbine class (e.g., different hub levels) that is deployed in that region.[8] In total 2.07 TW of onshore wind resource is available for development in ReEDS (see Figure 11).

[8] See Appendix H of the Wind Vision report for more details of the TRGs (DOE 2015).

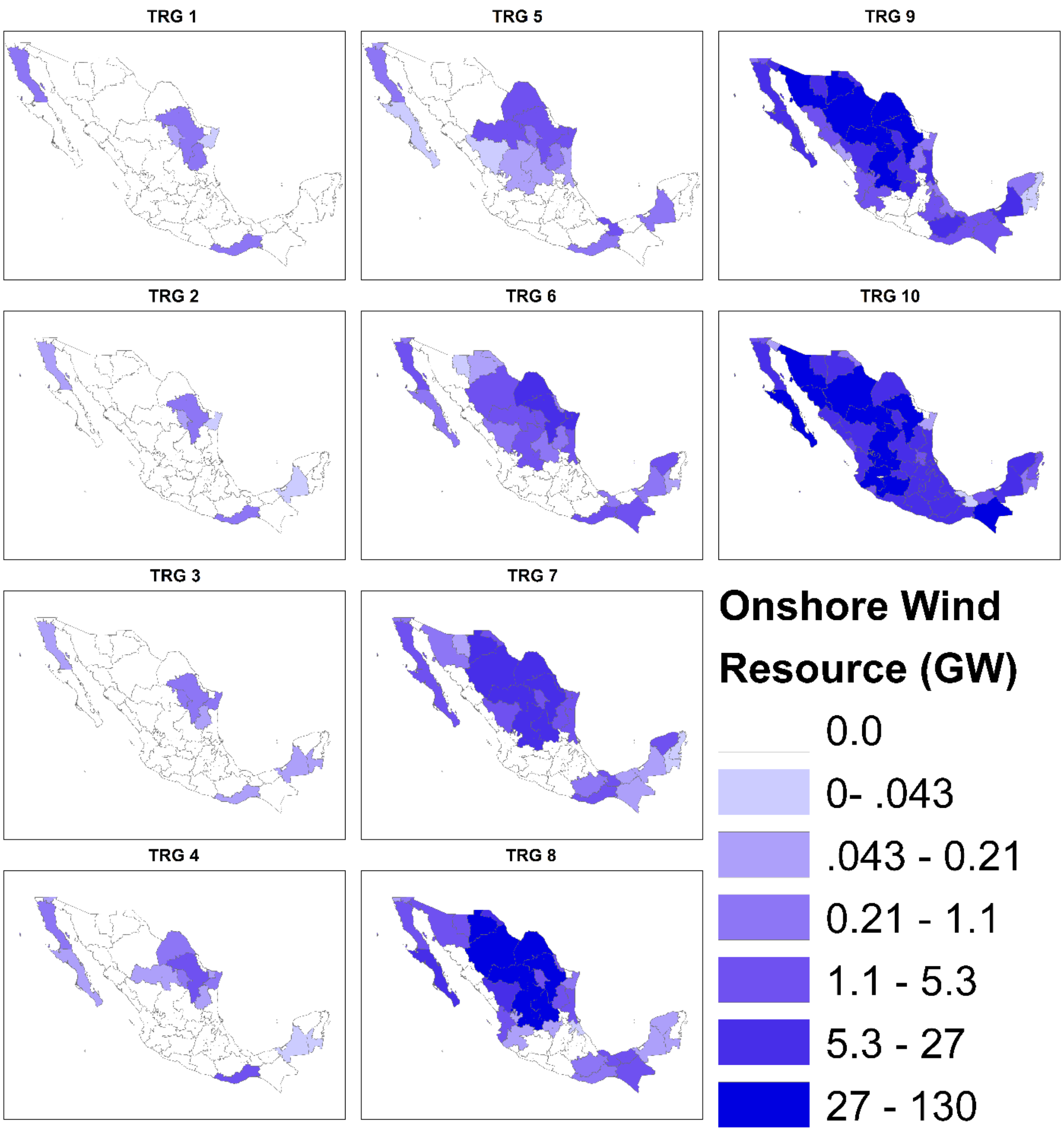

Figure 11. Onshore Wind Resource Map by TRG

Solar Representation

Utility-scale PV (UPV) and distributed utility-scale PV (DUPV) costs and performance are from ATB 2017. Solar insolation from NREL's National Solar Resource Database (NSRDB) 2.0 was processed using reV to assess resource supply and create hourly generation profiles. The PV resources were aggregated based on average annual solar radiation to nine resource classes (see Table 1). For Mexico there was a total resource of 17.7 TW of UPV with 411 GW of DUPV (see Figure 12 and Figure 13). Concentrating solar power and rooftop PV are not included in the current version of the ReEDS-Mexico model.

Table 1. UPV and DUPV Resource Classes

Class	kWh/m^2/day
1	3.0–3.5
2	3.5–4.0
3	4.0–4.5
4	4.5–5.0
5	5.0–5.5
6	5.5–6.0
7	6.0–6.5
8	6.5–7.0
9	7.0–7.5

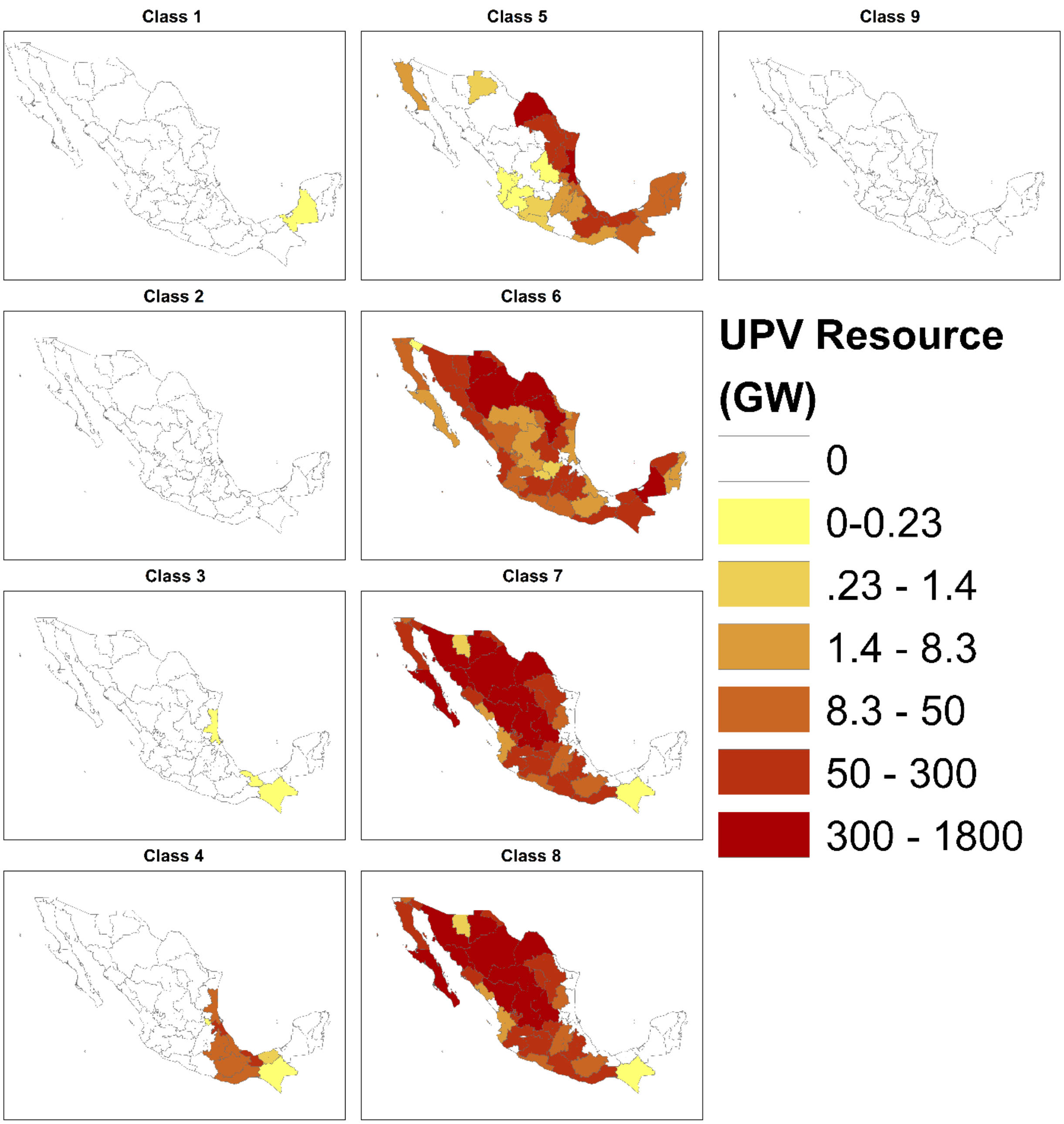

Figure 12. Utility PV (UPV) resource availability by resource class.

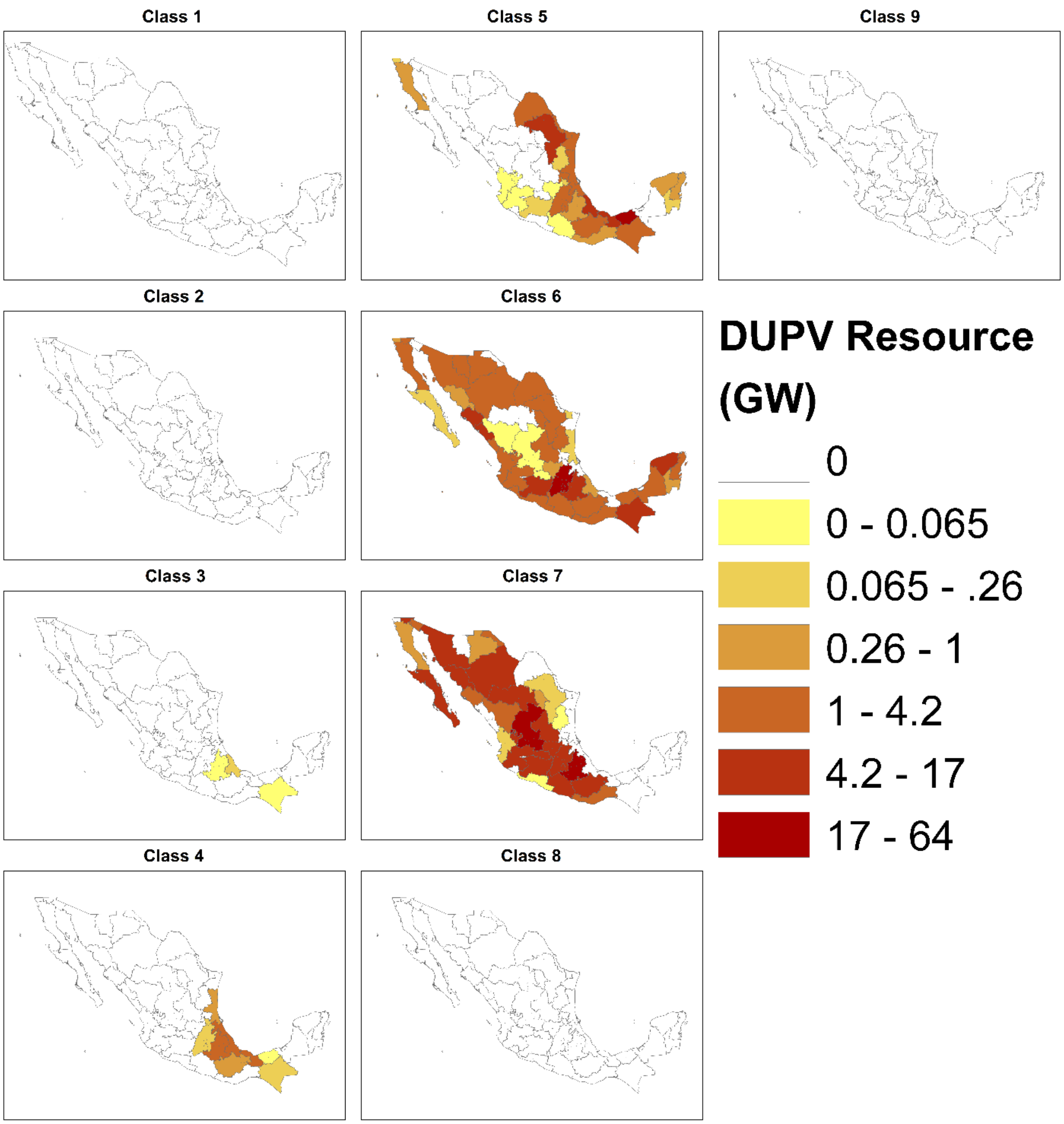

Figure 13. Distributed utility PV (DUPV) resource availability by resource class.

Description of Scenarios

As a demonstration of model capabilities we constructed five scenarios focusing on the impacts of demand growth and natural gas prices on the evolution of the Mexican power system. The demand growth cases align with the projections included in PRODESEN 2016 while the natural gas price scenarios align with the AEO 2017 scenarios.

Table 2. Brief description of scenarios analyzed in this report

Scenario Name	Scenario Description
Reference	PRODESEN Planning Case Demand Growth
High Load Growth	PRODESEN Low Demand Growth
Low Load Growth	PRODESEN High Demand Growth
High Natural Gas Price	AEO 2017 Low Oil & Gas Resource
Low Natural Gas Price	AEO 2017 High Oil & Gas Resource

Results

Reference Scenario Results

The Mexican power system capacity and generation results from the ReEDS-Mexico model are shown in Figure 14 and Figure 15, respectively. In the near-term (up to 2020), new capacity is primarily added to satisfy increasing demand and replace existing oil/gas steam units (just over 2/3 of the 2010 oil/gas steam capacity is projected to retire by 2020). The new capacity is mainly in the form of combined cycle (CC) natural gas power plants (~12 GW) and wind (~10.5 GW). Over the mid-term (up to 2036), the majority of new capacity additions still comes in the form of combined cycle and wind (~34 and 32 GW, respectively), but combustion turbines and PV get deployed in larger quantities (~17 GW each). Over the long term (up to 2050), PV growth rises driven by low capital costs (~60-65% lower capital compared to 2012) and PV becomes the largest renewable resource in capacity terms (~ 68 GW of PV vs. 47 GW of wind). In parallel, significant combustion turbine capacity is added in order to meet peak capacity and flexibility needs, resulting in similar levels of CC and CT capacity in 2050.

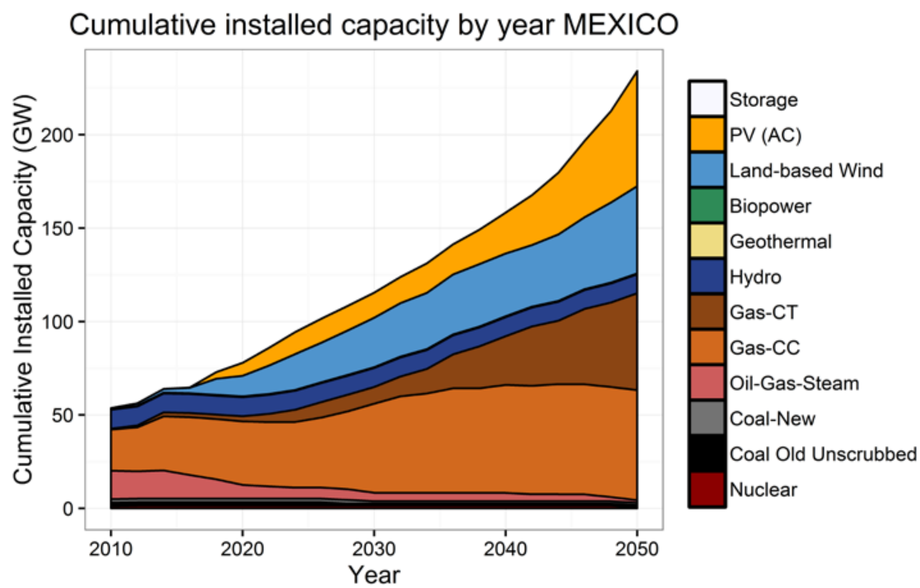

Figure 14. Mexican power system capacity mix from 2010-2050 under Reference scenario.

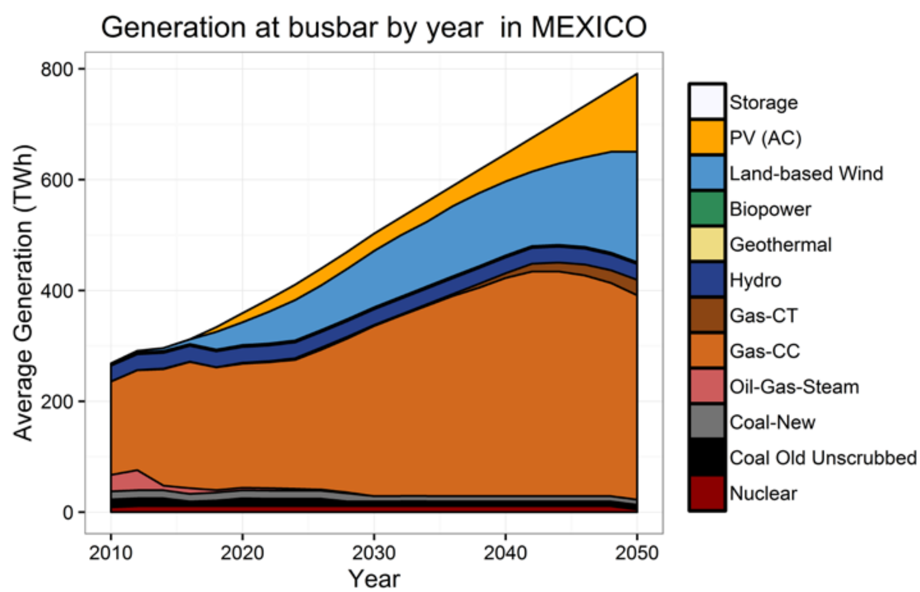

Figure 15. Mexican power system generation mix from 2010-2050 under Reference scenario.

The generation mix shows very high contribution of natural gas combined cycle units (~ 60% up to 2040s and declining to ~50% in 2050). This high contribution indicates the cost-effectiveness of natural gas per Reference scenario assumptions on natural gas prices. As we will discuss later under High and Low natural gas price scenarios, higher natural gas prices would reduce the cost competitiveness of natural gas combined cycle and increase the competitiveness of renewable generator options and vice versa.

The renewable energy additions under the Reference Scenario are influenced by the clean energy mandate. Total clean energy (renewable energy plus nuclear energy) hits the 35% requirement in 2024 and then is maintained at 35% throughout the mid-40s, when higher generation from both PV and wind leads to ~50% of clean energy in 2050, surpassing the 35% clean energy standard. The higher fraction of renewable generation in later years is mainly driven by lower capital costs for new PV.

By 2050 ReEDS adds an additional 14 GW of transmission capacity. The transmission additions (see Figure 16) appear to be closely related to the development of wind resources (Figure 17). There are significant transmission additions connecting the areas of high quality wind resources in North Eastern Mexico as well as in those on Oaxaca. PV builds seem to be concentrated in the southwest parts of Mexico and their generation seems to be mainly used locally under the Reference scenario (see Figure 18).

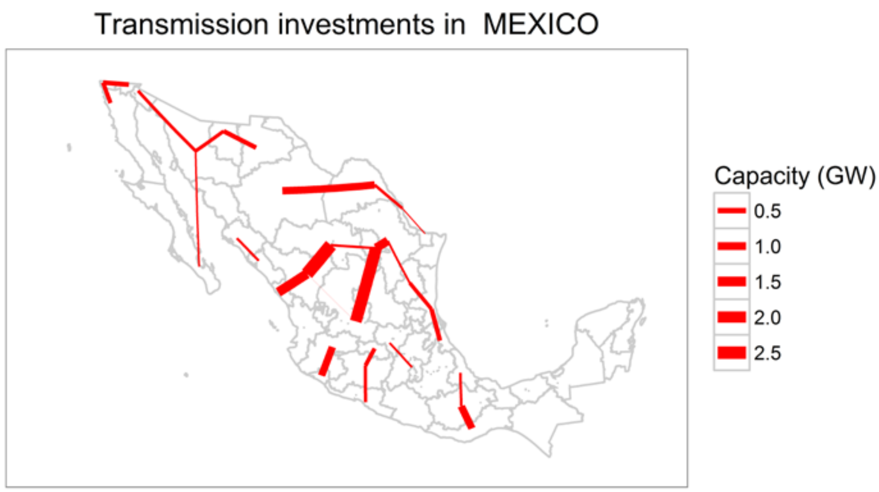

Figure 16. Transmission investments up to 2050 under Reference scenario

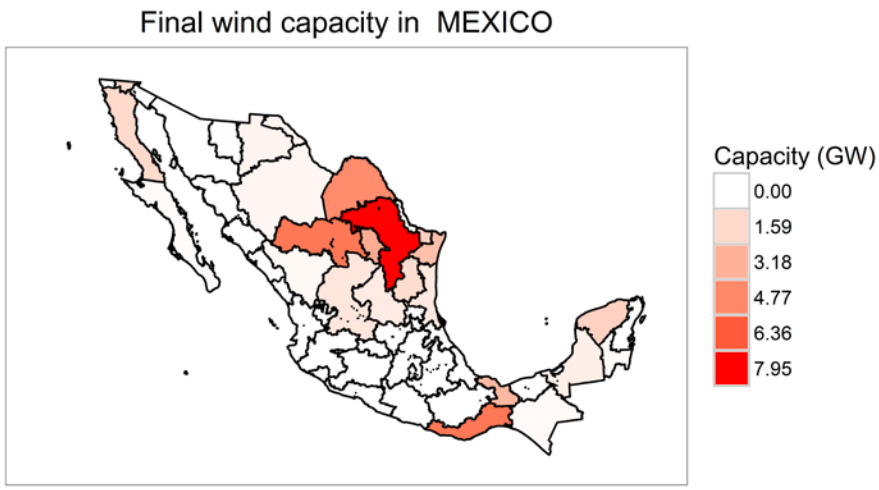

Figure 17. 2050 Wind capacity per region under Reference Scenario

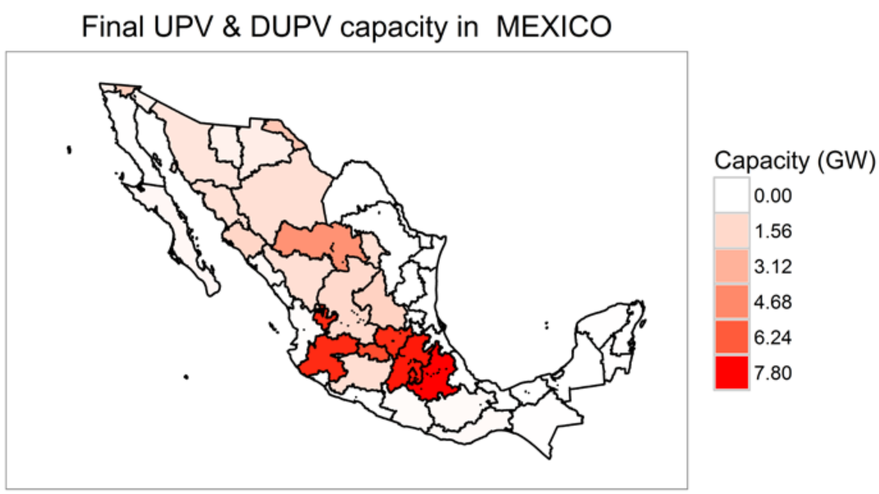

Figure 18. 2050 Wind capacity per region under Reference Scenario

Natural gas price sensitivities results

Given the significant contribution of natural gas generation in the generation mix under the reference scenario, we included high and low natural gas price sensitivities. In figure 18 below, we provide the generation mix for years 2020, 2036 and 2050 under all three natural gas price scenarios. In the short term, the generation mix is similar across scenarios. A slight replacement of coal generation by natural gas generation is observed under the Low Natural Gas Price scenario when it is compared against the other two. In the medium term, while the Low Natural Gas Price and Reference scenario generate clean energy at the mandated level, the High Natural Gas Price scenario exceeds the 2035 clean energy goal and renewable energy penetration is much higher due to improved relative economics compared to gas. Also, while the Low Natural Gas Price and Reference scenarios are characterized by similar amounts of gas generation, the mix of gas units generating is slightly different with higher contribution of CTs under the low gas price. With low gas prices, the lower capital costs of CTs relative to CCs were sufficient to offset the higher heat rates of CTs, increasing the CT deployment. Finally, in the long term we observe that the clean energy mandate of 35% is binding only under the Low Natural Gas Price scenario and both the Reference and High Natural Gas Price scenarios lead to much higher penetration of renewable energy technologies.

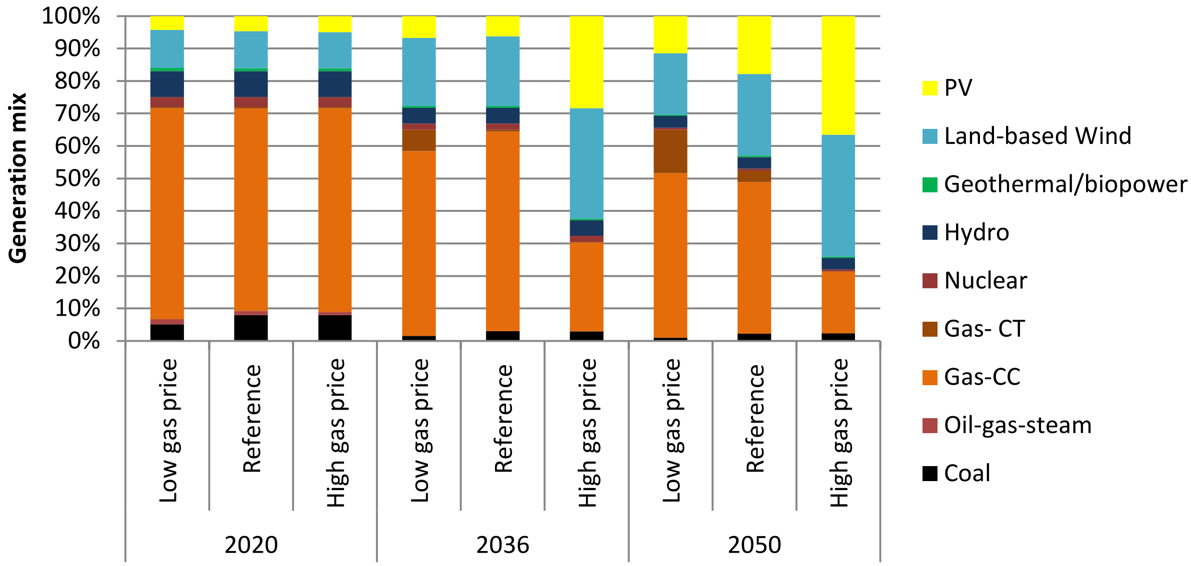

Figure 19. Generation mix for years 2020, 2036 and 2050 across the natural gas price scenarios

As demonstrated by the generation mix, across the three natural gas price scenarios, the levels of wind capacity span across a wide range: from 34.6 GW under Low Natural Gas Price scenario to 74.5 GW under the High Natural Gas Price scenario in 2050. The spatial distribution of the wind generation does not change significantly though: four out of the 49 regions used in ReEDS host ~50% of the capacity across all scenarios. In particular, those regions are Northeast parts of Mexico (PRODESEN transmission region names: Laguna, Rio Escondido and Monterrey) and Oaxaca (Ixtepec).

PV capacity increases more steeply from the level of ~40 GW under the Low Natural Gas Price scenario to ~142 GW under the High Natural Gas Price scenario. Approximately 60% of the capacity under Reference and High Natural Gas Price scenarios (~40% under Low Gas Price) is located in the southwest parts of Mexico (Guadalajara, Salamanca, Queretaro, Central, Puebla).

Therefore, transmission infrastructure also varies across scenarios (see Table 3) and would have to be significantly expanded to facilitate the high renewable penetration identified by the High Natural Gas price scenario. Transmission lines would have to be built to export excess renewable generation.

Table 3. Transmission investments across Natural Gas Price Scenarios

Cumulative transmission installations	Low Natural Gas Price	Reference	High Natural Gas Price
MW	11,753	13,637	65,017
MW-mile	1,724,198	1,973,159	8,437,139

Load Growth Sensitivities Results

Load growth is a highly uncertain assumption for developing economies such as Mexico. For that reason, we included two load growth sensitivities. In these three scenarios, the relative generation mix is very similar across all scenarios. However, the differences in the absolute magnitude of the generation has significant effects on the magnitude of CO_2 emissions from the power sector. The 35% clean energy mandate leads to quite different emission levels depending on the path of load growth. In particular, long-term emissions rise in all demand growth scenarios (see Figure 19) because of the increase in natural gas consumption driven by demand growth. High demand growth leads to 2050 CO_2 emissions that are ~18% higher than the mid-level demand, and the low demand growth leads to 12% lower emissions.

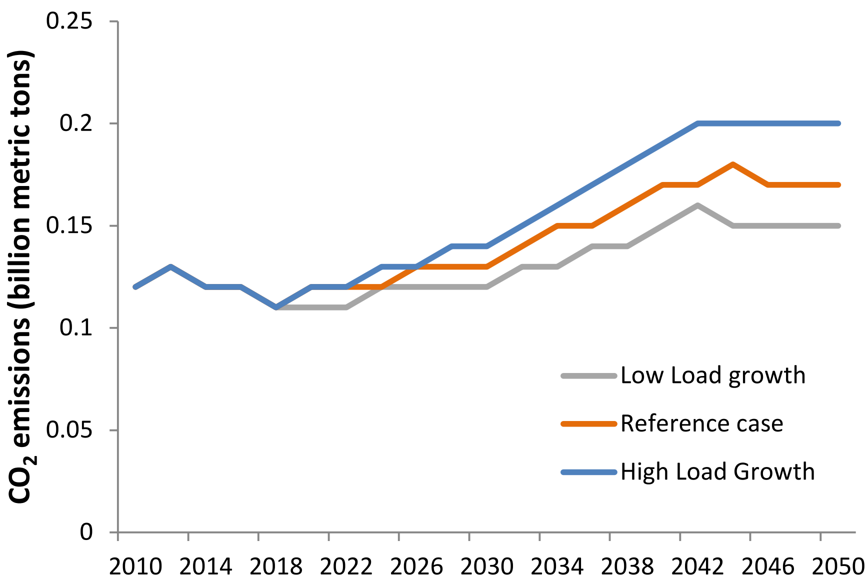

Figure 20. Burner-tip CO_2 emissions from the power sector across demand growth scenarios.

Similarly, the amount of installed capacity also varies according to the demand growth levels (see Figure 21). For example, wind capacity is ~12 GW higher in 2050 in the High Load Growth scenario compared to the Low Load Growth scenario while PV has ~34 GW of additional capacity.

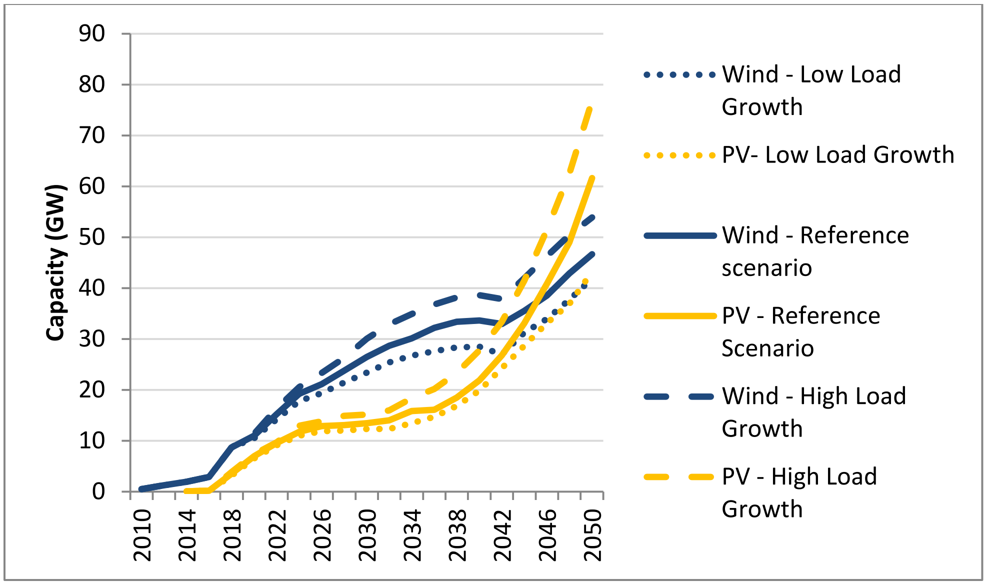

Figure 21. PV and wind capacity across Demand Growth Scenarios

Summary

This document details the development effort to construct an endogenous representation of the Mexican power system within the NREL ReEDS model. The results exhibit the new capabilities of ReEDS resulting from this development. The results reported demonstrate the new capability of ReEDS to conduct similar types of analyses as those that have been conducted for the U.S. and Canadian power systems e.g. *2016 Standard Scenarios Report: A U.S. Electricity Sector Outlook* or *Modeling the Value of Integrated U.S. and Canadian Power Sector Expansion*.

The development was largely centered around the updating and development of model data inputs built on the foundation of existing work by organizations in Mexico combined with the tools and capabilities previously developed as part of ReEDS. Significant updates include the physical representation of the Mexican power system, the development of new resource supply curves for Mexican regions, and the implementation of Mexico specific energy policies.

In our results we present a Reference scenario as well as to other load and gas growth sensitivities. Our Reference scenario projects the evolution of the Mexican power system with significant growth in natural gas and renewable energy, strongly driven by the Mexican clean energy policy.

This work provides a foundation for developing a capacity expansion model of the U.S., Canada, and Mexico, which will be the focus on the ongoing North American Renewable Integration Study. Within the NARIS, we plan to? extend the work presented here in order to consider the value and trade-offs of electricity exchange with the U.S. power sector.

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