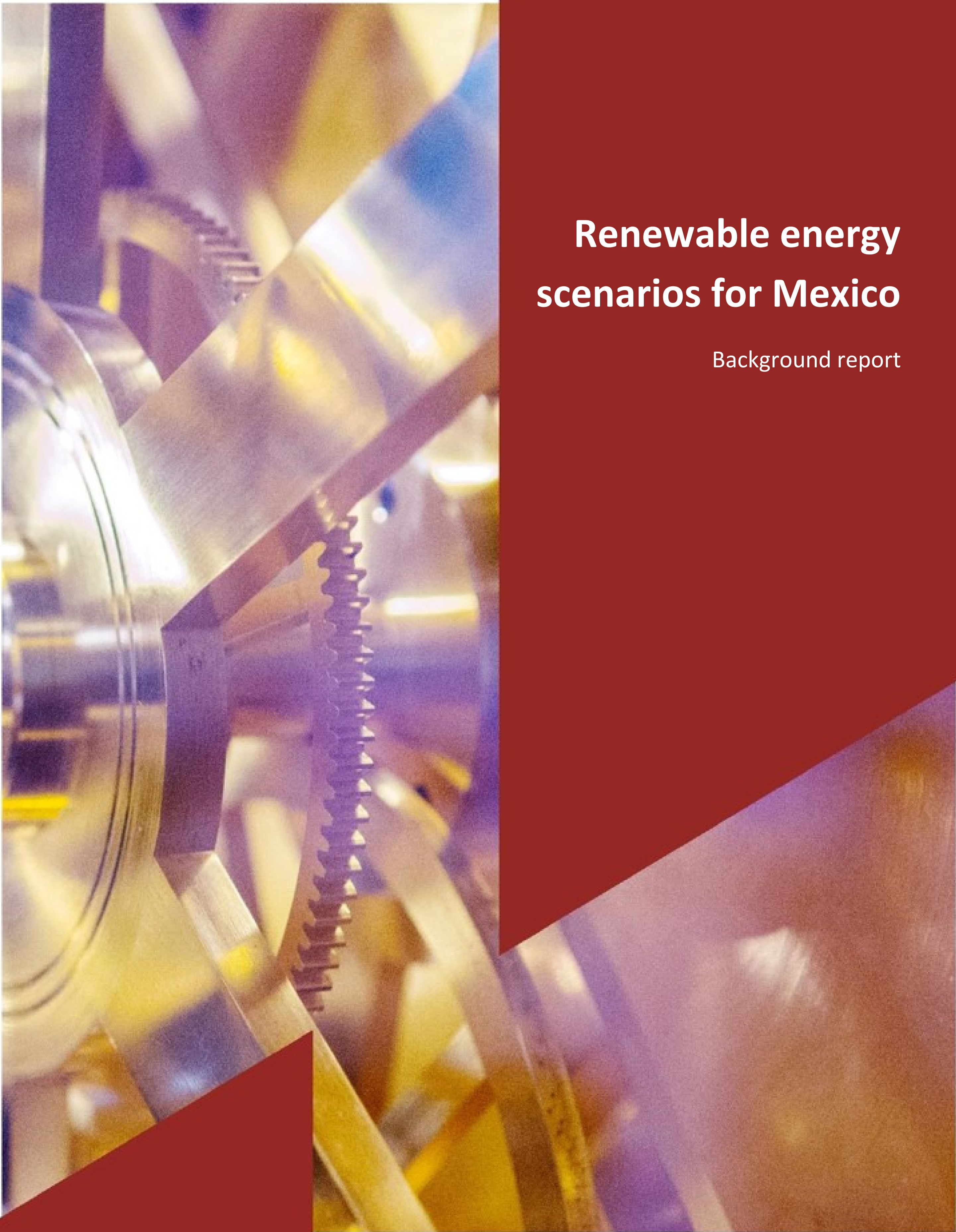

Renewable energy scenarios for Mexico

Background report

Ea Energy Analyses

November 2016

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Foreword

This Background Report relates to the Mexican Renewable Energy Outlook, 2016 and has been developed in close cooperation with Department of General Planning, SENER, the UNAM/SIMISE team and the Danish Energy Agency. The activity has been supported by the Mexican-Danish Climate Change Mitigation and Energy Programme.

The central analyses are based on the Balmorel model, which has been populated with detailed data for the current Mexican electricity system and the expected future developments.

A separate Data Report is available providing a detailed overview of all the input data and assumptions employed in the modelling and analysis.

Mikael Togeby

Acknowledgements

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1 Introduction

Mexico has ambitious goals for expanding the share of clean energy. Clean energy (*energía limpia*) in the Mexican context is defined as renewable energy, nuclear and efficient industrial cogeneration. The goals are formulated as share of clean energy compared to the total electricity generation.

The current analysis indicate that the planned expansion of clean energy will make it possible to maintain the CO_2 emissions from the electricity sector at their current level, even with the expected increase in electricity demand.

In the North American Climate, Clean Energy and Environment Partnership (Canada, USA and Mexico) coordination on efforts for CO_2 reductions is being discussed. This can be done in many ways, e.g. with a common market for renewable energy certificates or a common market for CO_2. Such common markets can help equalise the marginal costs of renewable energy expansion or CO_2 emission reductions across the three countries and achieve these goals at the lowest (regional) cost.

In this perspective, it is relevant to investigate the costs of decreasing the Mexican CO_2 emissions even beyond the current plans. The extra reduction could be "exported" to other countries, if a common framework were to be established.

Mexico has taxes on fossil fuels: from USD 0.33 to USD 2.66 per tonne CO_2. From 2015, emission reporting has started for all emissions above 25,000 tonnes CO_2 (National Emissions Registry System, RENE) and regulation for an emission trading system (ETS) is expected by year 2018 (SEMARNAT, 2016). An ETS simulation exercise is under way with 50 participants, including companies from the power sector.

International coordination mechanisms already exist in other countries:

- Renewable energy certificate system between Norway and Sweden (NVE, 2016)
- The EU-wide CO_2 cap-and-trade system (28 EU countries and 3 non-EU countries)[1]. The EU system has shown low CO_2 prices since 2009. There has been a surplus of CO_2 quotas since the start of the economic crisis. The current price is USD 7 per tonne CO_2.

[1] See: ec.europa.eu/clima/policies/ets/index_en.htm

- The Regional Greenhouse Gas Initiative (RGGI) covers the US states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont to cap and reduce CO_2 emissions from the power sector.
- California has a Cap-And-Trade Program. Current prices are in the range of USD 12 per tonne of CO_2.

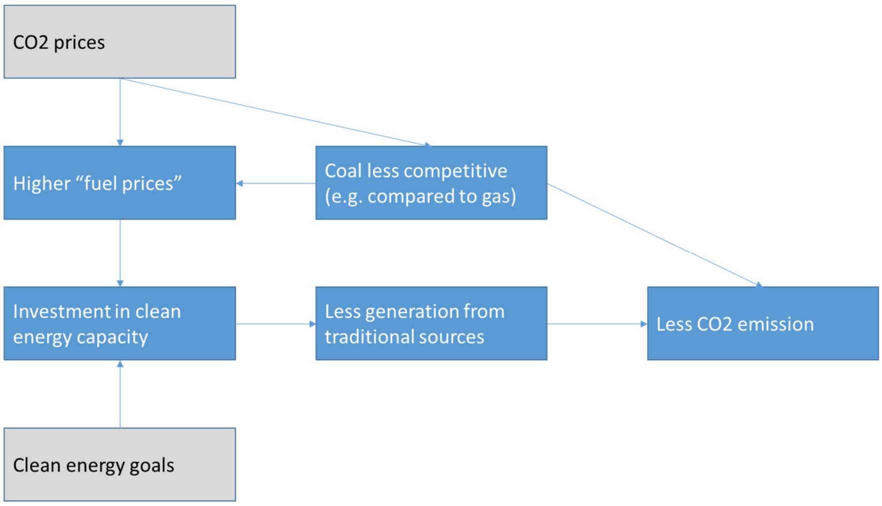

Figure 1. Simplified mechanisms from two different policy instruments.

Mechanisms to impact CO_2 emissions

Setting goals for clean energy and using auctions to promote investment in clean energy will reduce the Mexican CO_2 emission. There will be less conventional generation (coal, oil, natural gas) because of the increased generation from the clean energy (see Figure 1). Clean energy, like wind and solar, has low marginal costs and are prioritised in the market over the conventional energy.

Imposing a CO_2 target or price on all generators will have a comparable impact, but some of the mechanisms differ. A CO_2 restriction or tax will increase the cost of conventional generation, thereby increasing market prices and consequently increasing the incentive for investment in clean energy. Compared to a setup with clean energy goals, a CO_2 price setup will put more pressure on heavy-emitting fuels like coal and oil (see Figure 1).

With a cap on CO_2 emissions, the price of CO_2 can be found via auctions. The share of clean energy will not be known at the outset, as clean energy is only one of several ways to reduce emissions. Similarly, with clean energy goals, the CO_2 emission levels are not pre-defined[2].

Research questions

In this report, it is studied how clean energy goals and CO_2 prices can be used to motivate CO_2 reductions in Mexico. The questions include:

- What difference (on generation capacity, technologies and total costs) would it make to use CO_2 targets instead of clean energy goals?
    - Two scenarios with the same CO_2 emission level will be compared:
        - The current clean energy goals
        - A theoretical case with a CO_2 restriction equal to the CO_2 emissions of the clean energy goals scenario
    - A CO_2 cap is expected to give lower total costs – but is the cost differences substantial?
- How is the electricity system expected to develop (in terms of installed capacity, generation and total costs) if the CO_2 emission level were to be decreased even more than can be achieved with the current clean energy goals?
    - Three scenarios with increasing CO_2 reduction will be compared to the scenarios with the current clean energy goals.
        - How much more expensive will it be to reduce the CO_2 emission with 20 or 50% - compared to the current policy?

The questions will be answered based on detailed model studies of the Mexican electricity system.

Markets for CO_2 and forecast of prices

The most developed market for CO_2 prices is the Emission trading system (ETS) in the EU, which covers 28 countries and was introduced in 2005. The ETS covers the power generation sector and large industries, while other sectors like transportation and agriculture are not in included in the system yet. The system is based on the issuance of a certain number of free quotas, which is gradually reduced. The emission quotas can then be bought and sold by the market participants. The long-term target price was more than USD 55 per ton. Historically, initial prices were

[2] In the Balmorel model a restriction can be applied for the share of clean energy or the CO_2 emissions. The model will then operate the system and invest in new capacity so that the restrictions are met at the lowest possible costs. In this process the model estimates *a shadow price* to find the optimal solution. The shadow price can be interpreted as the equivalent of a tax that should be added to fuels, to realise the required (low) emission level, or the subsidy given to clean energy to reach the clean energy goal. The model has five cost categories: Fuel costs, fixed and variable O&M costs and capital cost for generation and transmission. Adding a restriction will increase the total costs – the sum of these five elements.

around 25 EUR/ton, but the economic crisis in 2008 lead to a situation with oversupply of quotas and low prices. Political agreement between the member countries about reduction of the number of quota cannot yet be reached.

Currently Certified Emission Reductions are traded around USD 7 per tonne. The oversupply is gradually being reduced and it is expected that price will increase over time.

The IEA recently published its forecast for CO_2 prices in the European Union under the New Policies Scenario ranging from 20 to 50 USD/tonne in 2020 and 2040 respectively. It is foreseen that this level of penalisation of fossil fuels will also hit North American markets. Regional CO_2 markets will most likely only become more widespread when the global ambitions towards climate change are increased, and in that case CO_2 prices will be considerably higher, according to estimations of the IEA. (IEA 2016, c)

1.1 The Balmorel model

Electricity systems have the unique feature that demand and generation must always balance. This is well known and many procedures have been developed to match the daily variation of the electricity demand with generation that gives the lowest possible total costs.

With new generation sources, like wind and solar power, finding the optimal dispatch can be a challenge. The variation in e.g. wind power generation can induce many new combinations of optimal dispatch and development of transmission capacity can be important.

The Balmorel model is an advanced tool to optimise the operation and the development of large electricity systems. It is a *fundamental* model where each individual power plant is described (at least with capacity, fuel type and efficiency) and the hourly electricity demand is an input. The model optimises the generation, taking into account the available transmission capacity.

The model can also invest in least-cost expansion of the system. It can *simultaneously* add both generation and transmission capacity. This is done based on a catalogue describing investment costs (and other key information) for the different possibilities.

The model is deterministic and assumes *full foresight.* All information is available for the optimisation e.g. hourly demand, hydro inflow, wind and solar profiles. Also, availability of power plants is known. These assumptions make it possible to solve the optimisation problem within a few hours of computer time – even with a very detailed representation of the Mexican system, e.g. with 53 transmission regions.

The model is open source and has been used in many countries, including 17 European, 14 African as well as in China, Vietnam and Indonesia. See www.eaea.dk/balmorel for more information and examples of use of the model.

2 Scenarios

A number of scenarios have been developed for these analyses. All scenarios span from 2015 to 2050 and results are computed for every five years.

The scenarios include:

- Unrestricted: Least-cost expansion – with no clean energy or CO_2 goals. Investment in coal is allowed in this scenario. It is a hypothetical scenario, only used to find the cost and other impacts of having clean energy or CO_2 goals.
- Main: The clean energy goals as formulated in the Mexican energy and climate laws are fulfilled. See Figure 2. New coal-based capacity cannot be added, as this is not in line with current policy.
- CO_2 Target. This scenario has the same CO_2 emissions as the Main scenario, but this is achieved with a CO_2 cap. The purpose is to compare the differences of using clean energy goals and CO_2 goals.
- Three CO_2 price scenarios with increased ambitions in decreasing the CO_2 emission. These are Full, 2/3 and 1/3. The level for the high CO_2 price scenario (Full) is inspired by the analyses of existing and future CO_2 price systems in Canada. In the Full scenario, a CO_2 price of USD 75 per tonne is introduced gradually between 2020 and 2040. See Figure 3. In these scenarios, the goals for clean energy are not included.

The Full scenario is a relatively aggressive scenario. In IEA New Policies Scenario, the CO_2 prices for 2020, 2030 and 2040 are similar to the 2/3 scenario: USD 22, 37 and 50 per tonne, respectively.

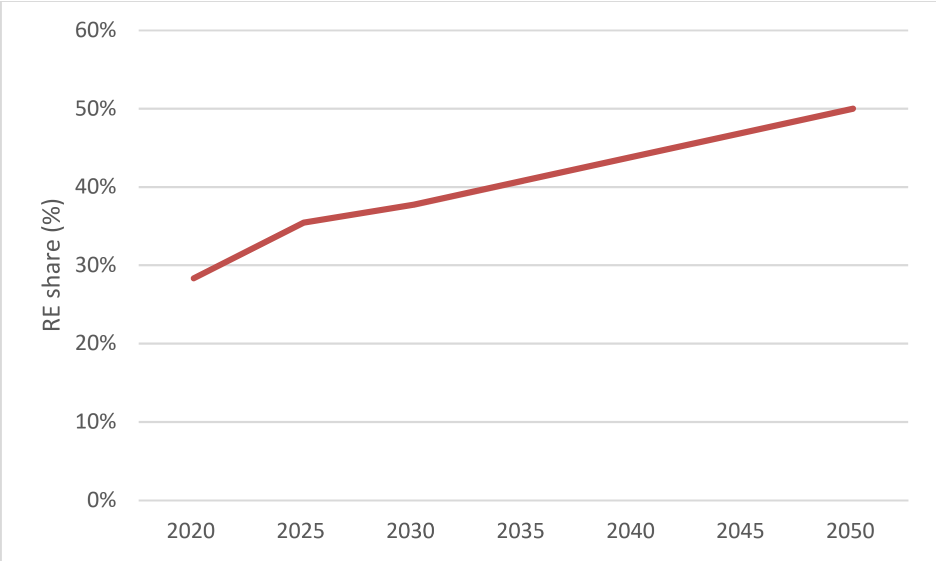

Figure 2. Clean energy goals for Mexico. Share of total electricity generation.

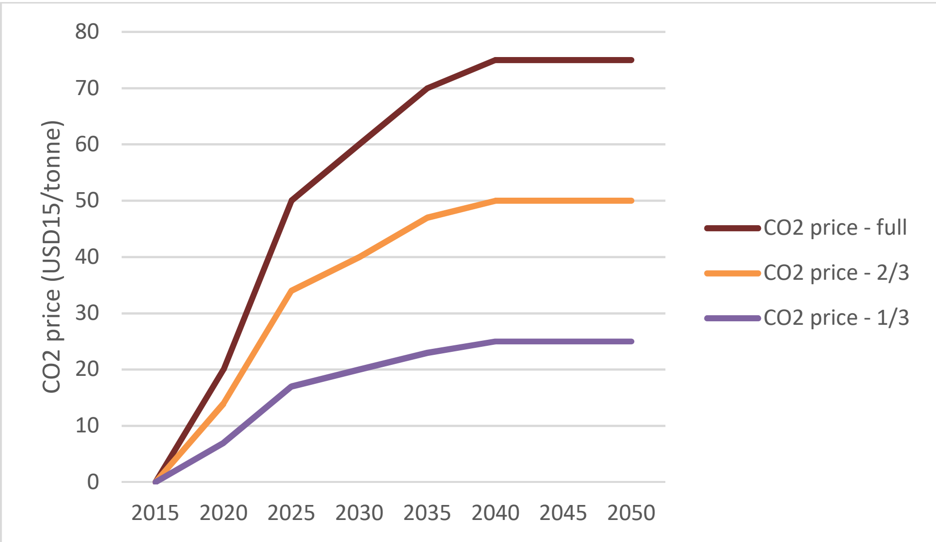

Figure 3. Three sets of CO_2 prices.

3 Data and assumptions

In this section, key parameters for the model analyses will be presented. A complete overview and details of the input data and assumptions can be found in the accompanying Data Report. See Ea Energy Analyses (2016, b)

Demand

The starting point for analyses of the Mexican electricity system is the electricity demand. The hourly demand is used as input for each of the 53 transmission regions.

The prognosis for the development until 2030 has been taken from PRODESEN 2016, and extrapolated until 2050 by assuming an absolute annual growth level consistent with the one projected for the end of the period in PRODESEN 2016, i.e. period 2020-2030. This result is a decrease in the *relative* yearly growth. See Figure 4.

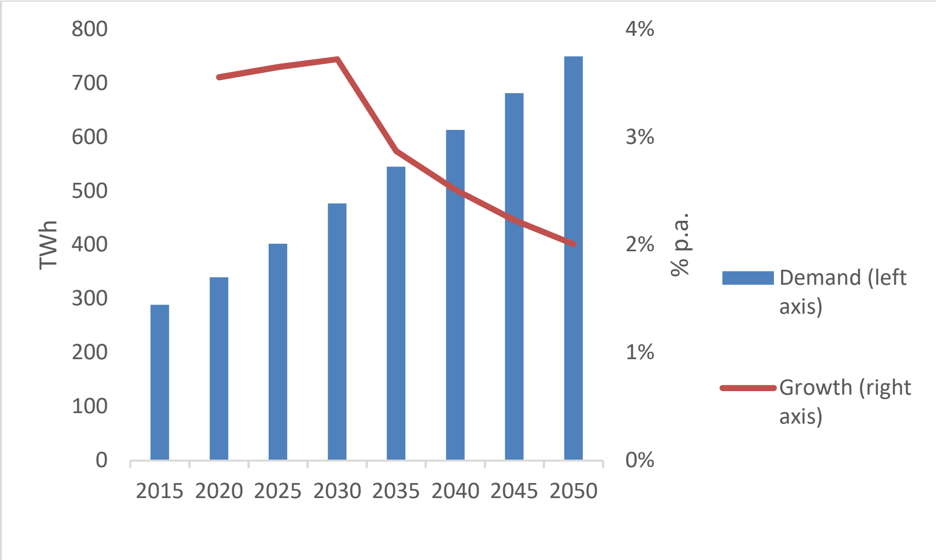

Figure 4. Electricity demand projection modelled (TWh), and the corresponding annual growth rate (% per annum).

In year 2000 the electricity demand in Mexico was in the order of 200 TWh, and in 1990 around 115 TWh. In 1990 more than half of the generation was based on oil (IEA, 2016, b), see Figure 5.

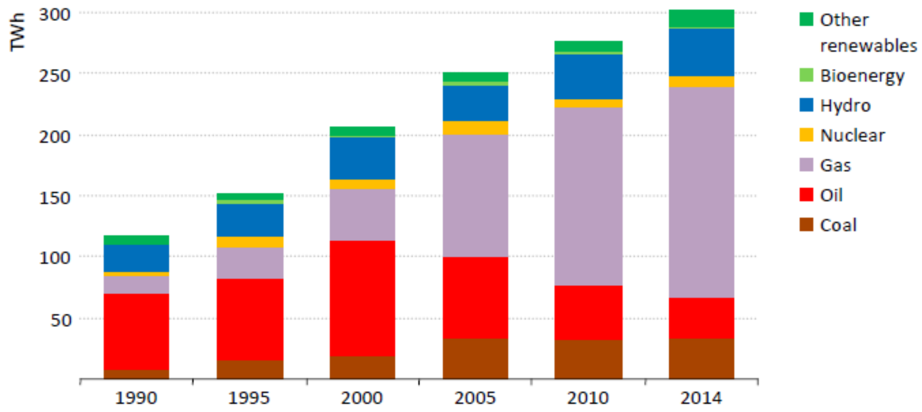

Figure 5. Historical electricity generation in Mexico by fuel type, TWh

Existing generators

The Balmorel model has been populated with information about each individual power plant (e.g. fuel, capacity and efficiency) and uses this to compute the marginal costs of generating power from each plant. Marginal costs are used to compute the optimal dispatch – taking into account the transmission capacity constraints between regions. Optimal dispatch is defined as the allocation of generation that gives the lowest total system cost. The existing capacity in 2015 is shown in Table 1.

Fuel	Units	Capacity (MW)
Natural gas	176	26 422
Hydro	74	12 468
Fuel oil	81	11 675
Coal	6	5 378
Wind	33	2 946
Light oil	81	1 517
Nuclear	1	1 510
Geothermal	14	926
Coke	2	580
Cogeneration	8	572
Solar	9	57
Total	**481**	**64 051**

Table 1. Existing generation capacity (2015)

Planned additional generation capacity

The planned expansion of generation (PRODESEN, 2016) for natural gas- and oil-based generators until year 2020, and industrial cogeneration, geothermal and hydro until 2030 is included in all scenarios. See Table 2. For Baja California, it has been assumed, in contrast to PRODESEN, that no natural gas will be available.

The planned investments in the transmission system until 2021 are included.

MW	2020	2025	2030	Total
Natural gas	17 283			17 283
Oil	261			261
Cogeneration	3 011	4 034		7 045
Hydro	342	3 869	281	4 492
Geothermal	336	441	118	895

Table 2. Exogenous additions to the generation capacity represented in the model

Model-based investments

The model will invest in new generation and transmission capacity when and where it is economically attractive. This is done based on a catalogue of all potential technologies available for new investments. The model will invest in clean energy (renewable energy, e.g. wind and solar, and nuclear) if it will be economically attractive, or in order to fulfil clean energy goals.

The competitiveness of wind and solar is improving over time because the investment costs are assumed to decrease and fuel costs are increasing, see Figure 6 and Figure 7. The investment costs can be compared e.g. to those of nuclear (USD 6,281 per kW) or natural gas technologies (CCGT: USD 875 per kW).

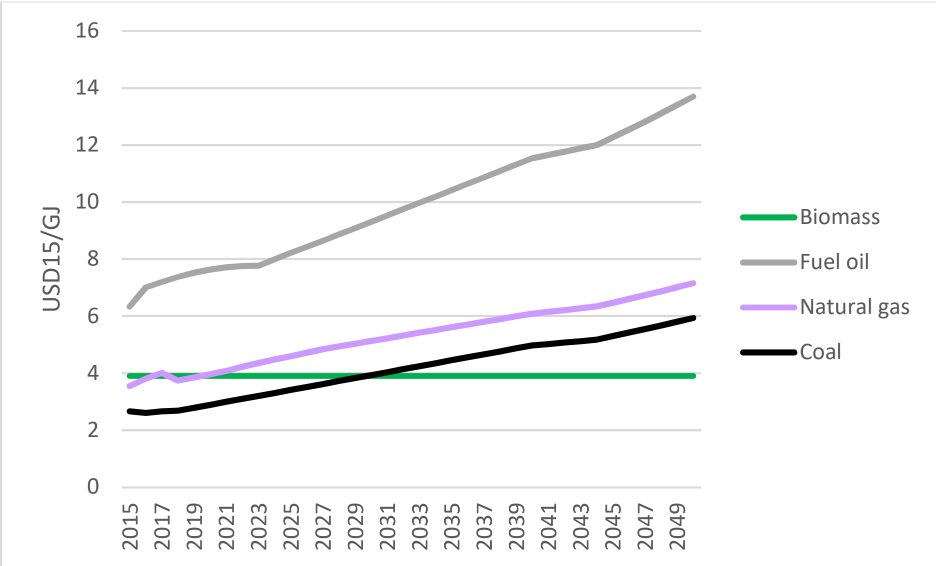

Figure 6. Fuel price development projection represented in the model, USD 2015/GJ

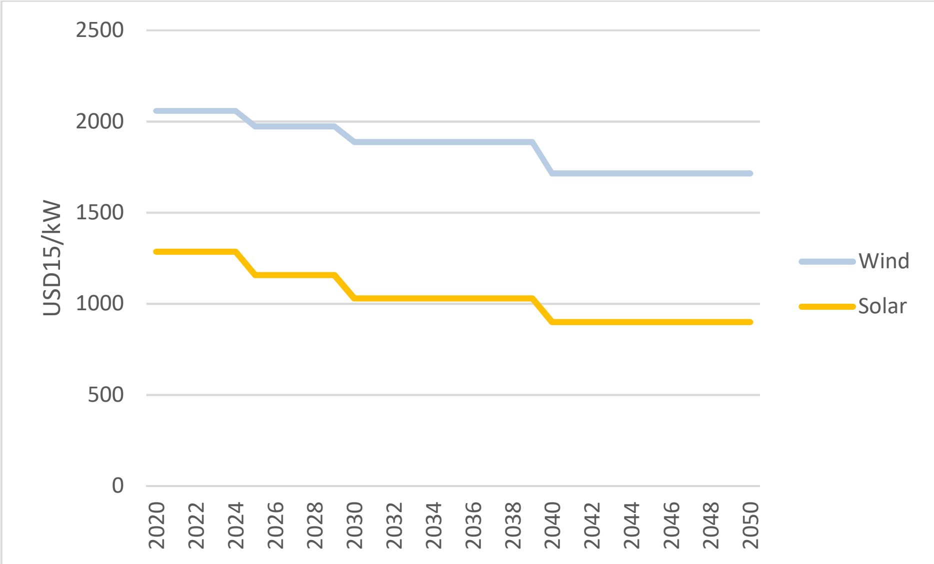

Figure 7. Investment cost development projections for land-based wind and utility-scale solar PV plants represented in the model. The wind power technology represented is based on Low Cut-In wind turbines (LCI), characterised by 20% higher investment costs compared to conventional wind turbines, but higher generation per MW installed (FLHs).

Wind and solar

Detailed data about the wind and solar resource has been used (Hahmann, 2016). See Figure 8 to Figure 11.

For each of the 53 transmission regions wind (m/s) and solar data (W/m²) has been obtained from the *Wind Atlas of Mexico* project[3]. The project has data from 2006 to 2015, and 2013 has been selected because this year was close to the average wind speed for the period (a 'normal wind year'). The data is from metrological simulations that have been down-scaled to produce mesoscale results (5 x 5 km). The results are preliminary and will be further developed and refined by use of data from a set of new wind masts.

The detailed information about wind and solar resource (hourly values for 53 locations) is important to correctly describe the *smoothening effect,* where e.g. the strong variation of wind at a specific site is getting smoother, as generation from a larger area is aggregated. E.g. while the lowest wind speed at a specific location typically is close to zero, the lowest average wind speed for all regions is 21% of the maximum.

[3] See: Hahmann et al (2016).

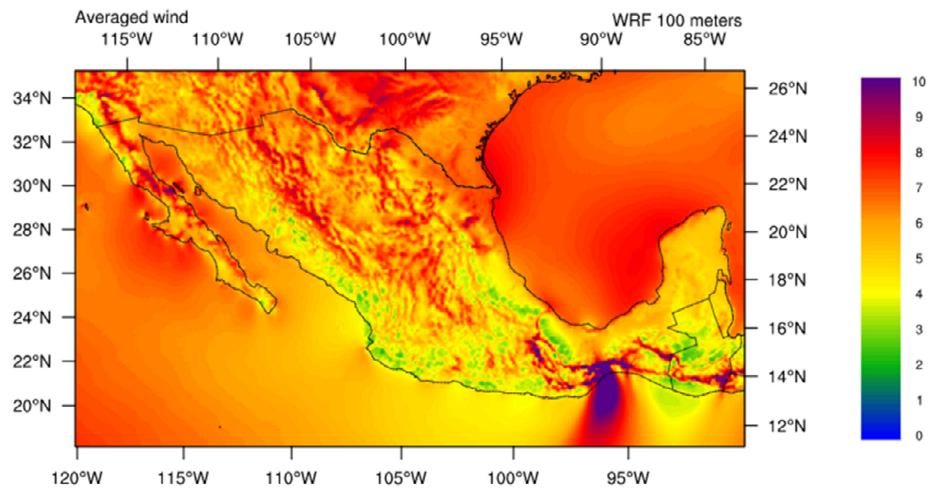

Figure 8. Average wind speed in 2013 (m/s).

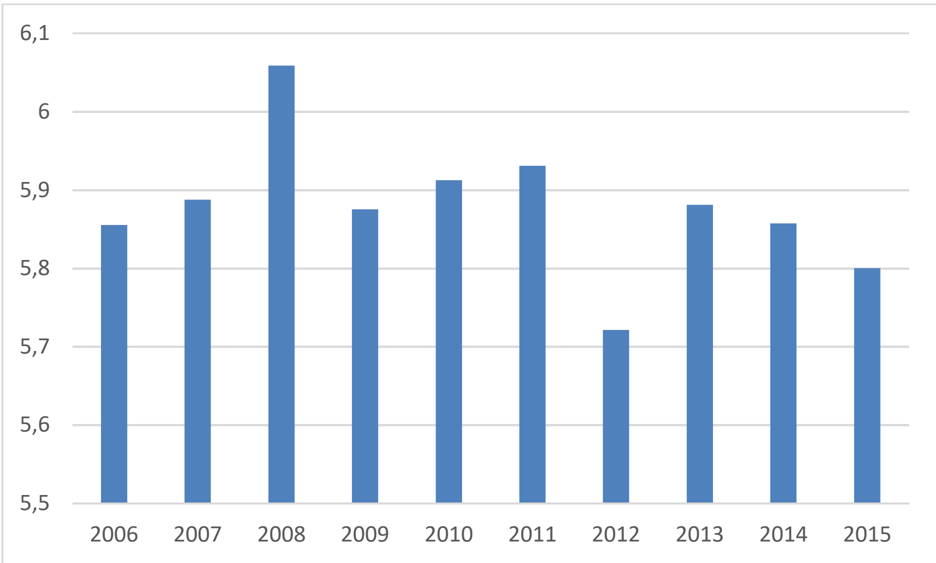

Figure 9. Variation in yearly average wind speed in Mexico (m/s, in 100 meters' height, average of all 5 x 5 km cells).

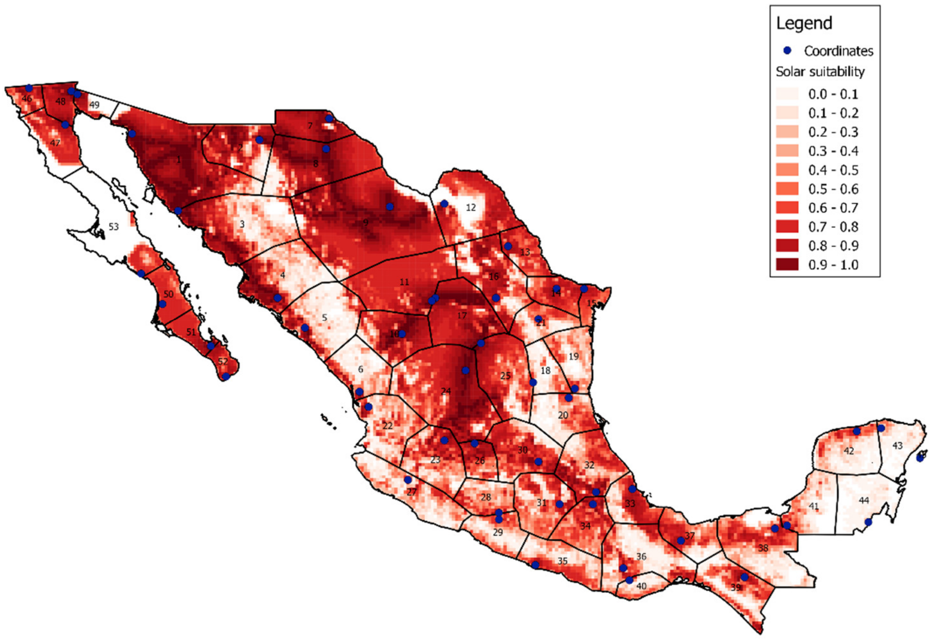

Figure 10. Location of coordinates for the solar time series (blue dots). The solar suitability map. IRENA (2015) has computed solar suitability based on the irradiance, as well as information about distance to grid, population density, topography, land cover and protected areas. The selected locations have the highest suitability indexes per region.

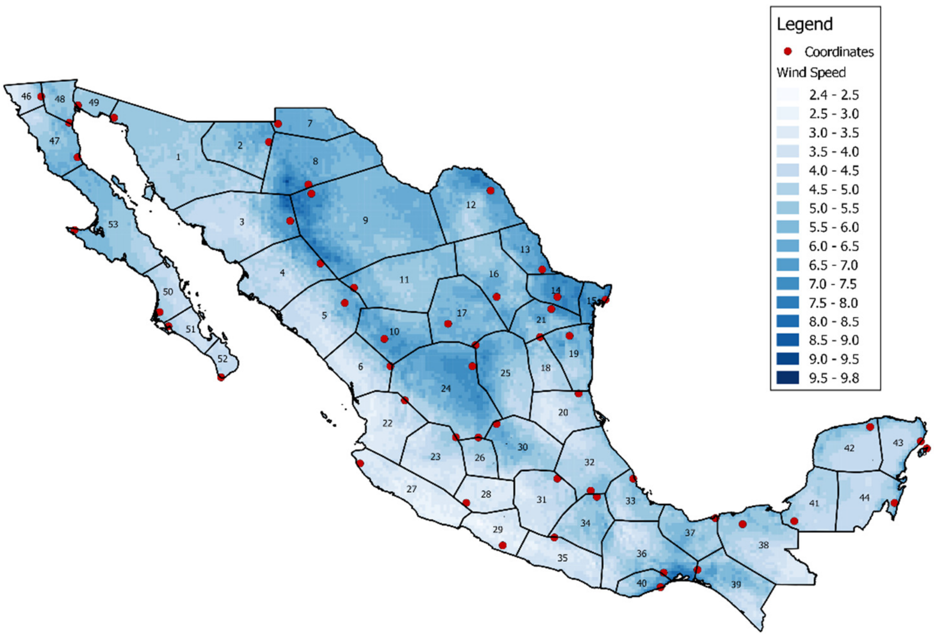

Figure 11. Location of coordinates for wind time series (red dots). IRENA data is used to find the location within each region corresponding to the 90th percentile of the highest average wind speed within each region.

Further development

The model is covering Mexico, and does not yet have a representation of the neighbouring countries. In a later stage, the neighbouring countries and the possible import/export will be included.

The current description of the maximum renewable energy potential per region is simplified and should be improved to find the accurate regional distribution of the generation expansion. Also, the description of candidate investment projects for geothermal, cogeneration and hydro should be improved. The costs for these technologies are very individual and site-specific. For the period after 2030, simplified, generic investment costs have been allocated to these three technologies. Information about industrial heat demand is limited, so the model does not invest in cogeneration after 2030. A more detailed representation of biomass should be implemented in the model, including fuel prices per biomass type and updated investments costs for biomass power plants. Restrictions about the use of water in hydro plants should be added.

Global trends in costs of and deployment of renewable energy

Global investments in renewables-based generating capacity comprised USD 288 billion or 70% of total generation investment and over two-and-a-half times that of new fossil fuel capacity in 2015. Renewables investment has remained stable since 2011, but will generate one-third more electricity on an annualised basis thanks to technological progress and unit cost reductions.

In 2015, global renewable electricity capacity growth reached an all-time record at 153 gigawatts (GW), thanks to record additions in both onshore wind (63 GW) and solar PV (49 GW).

The record deployment was accompanied by continued generation cost reductions, with announced record-low long-term remuneration prices ranging from USD 30 to 50 per MWh for both onshore wind and solar PV plants. These projects are expected to become operational over the medium term in markets as diverse as North America, Latin America, Middle East, and North Africa. Recent tender results in Europe for large-scale offshore wind projects indicate possible 40% to 50% cost reductions for new plants by 2021. Recently a Danish tender for a large off-shore wind farm offered a record low price of USD 55 per MWh.

These prices signal a clear acceleration in cost reductions, increasing the affordability and improving the attractiveness of renewables among policy-makers and investors.

The IEA expects onshore wind generation costs to decrease by a further 15% on average by 2021, while utility-scale solar PV costs are anticipated to decline by 25%. These trends are underpinned by a combination of sustained policy support, technology progress and expansion into newer markets with better renewable resources. In addition, improved financing conditions play a particularly important role, driven by the expanding use of long-term power purchase agreements (PPAs) awarded through price competitive public or private tenders, including government-backed auction systems.

China remains the global leader of renewable energy expansion, representing close to 40% of growth. In 2021, more than one-third of global cumulative solar PV and onshore wind capacity are expected to be located in China.

India's solar PV capacity is forecast to grow eight-fold supported by ambitious government targets and competitive auctions, where contract prices have already declined by a factor of two since 2014

Solar PV and onshore wind together represent 75% of global renewable electricity capacity growth over the medium-term. Solar PV leads providing almost 40% of global additions while onshore wind is the largest source of new renewable electricity generation. Hydropower growth slows because fewer large-scale conventional projects are expected to be commissioned in China and in Brazil while some projects are delayed in various developing countries.

Offshore wind capacity is forecast to triple over the forecast period led by deployment in Europe but with China's capacity also scaling-up fast. These developments are complemented by modest growth in concentrated solar thermal (China and Morocco), geothermal (Indonesia and Turkey) and ocean (France and Korea) technologies.

The share of renewables in overall electricity generation will rise from over 23% in 2015 to almost 28% in 2021. (IEA 2016,d)

4 Comparing two policy instruments

In this chapter, we will illustrate two policy cases:

- The impact of the clean energy goals. This will be done by comparing the Unrestricted scenario with the Main scenario.
- The impact of clean energy goals vis-à-vis CO_2 goals. This will be done by comparing the Main scenario (with clean energy goals) with the CO_2 target scenario, a scenario with a CO_2 cap, limiting the CO_2 emissions to those obtained in the Main scenario. A CO_2 target can in reality be reached by quotas, a CO_2 price or a CO_2 tax on all fuels.

The results will be described in MW (capacity), GWh (generation) and USD (total system costs).

Emissions

The Main scenario and the CO_2 target scenario have significantly lower CO_2 emission levels[4] compared to the Unrestricted scenario.

In the Unrestricted scenario, the model can invest in coal-based generation, and it does use this possibility to a limited extent (350 MW in 2020 growing to 1,300 MW in 2050). Coal is cheaper than natural gas, but the investment costs for the power plants are higher.

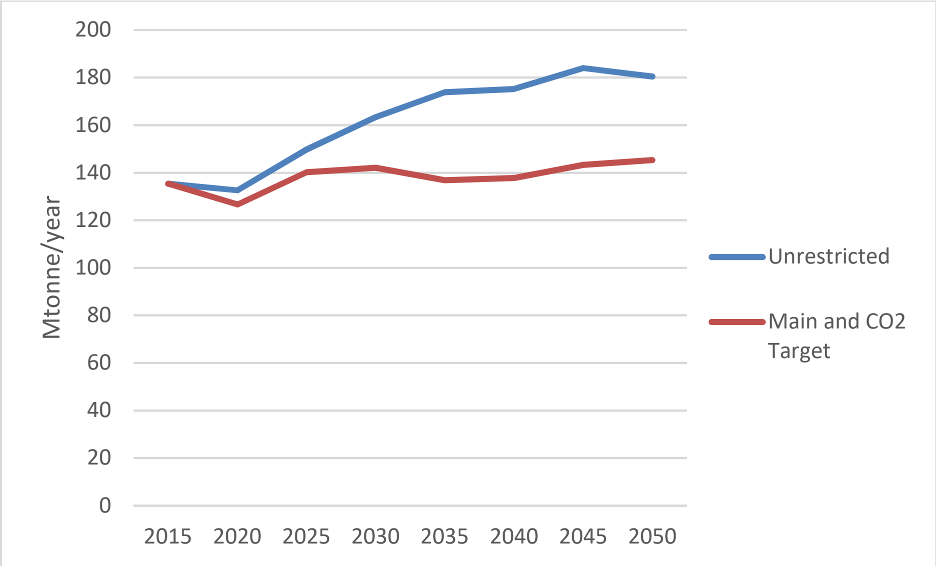

Figure 12. CO_2 emission in three scenarios, modelling results

[4] The total CO_2 emission from all sectors in Mexico was 431 Mtonne in 2014 (IEA, 2016b). INECC (2016) indicated a total net emission of 492 Mtonne for 2013. The emissions in the Unrestricted scenarios can be compared to the INDC business-as-usual scenario: This has an emission from the power sector of 202 Mtonne in 2030, which is significantly more than in our Unrestricted scenario. The unconditional goal of 139 Mtonne is close to the result in the Main scenario.

CO_2 price

By implementing a CO_2 restriction in the model, a CO_2 shadow price is automatically calculated by the model. This price represents the CO_2 price that is necessary to obtain the same CO_2 emissions as imposed by the CO_2 cap. In the CO_2 target scenario, the CO_2 emissions are capped at the same level as those in the Main scenario. The resulting CO_2 shadow price is compared to the CO_2 prices (used in the following chapter) in Figure 13. The shadow price of the CO_2 target scenario is close to the one used in the 1/3 CO_2 price scenario.

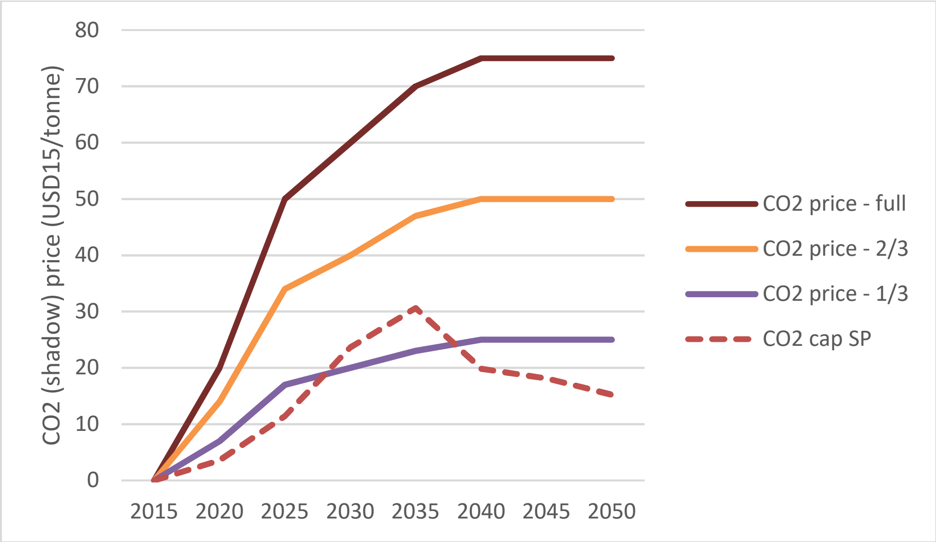

Figure 13. The CO_2 prices in the CO_2 target scenario (red dashed line) and the prices used in the scenarios modelling more ambitious environmental goals.

Clean energy

It can be seen from Figure 14 that only the Main fulfils the clean energy goals. The CO_2 target scenario has identical CO_2 emissions, but achieves this target with less coal and oil, and more natural gas – and less renewable energy. This mechanism is clearest in the years 2025 and 2030. After these years, there is very little oil and coal in the Main scenario.

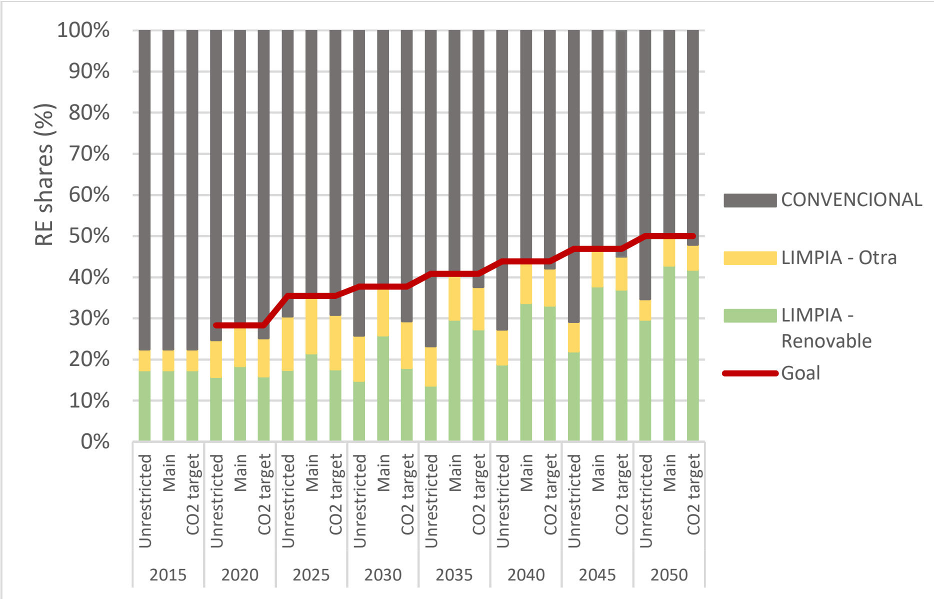

Figure 14. Share of clean energy in the three scenarios, modelling results.

The CO_2 emissions are the same in the Main and the CO_2 target scenario. However, the way this has been achieved is different as is seen in Figure 15. In the CO_2 target scenario, the natural gas-based generation has overtaken generation from coal and oil. Therefore, less clean energy is needed to fulfil the CO_2 target.

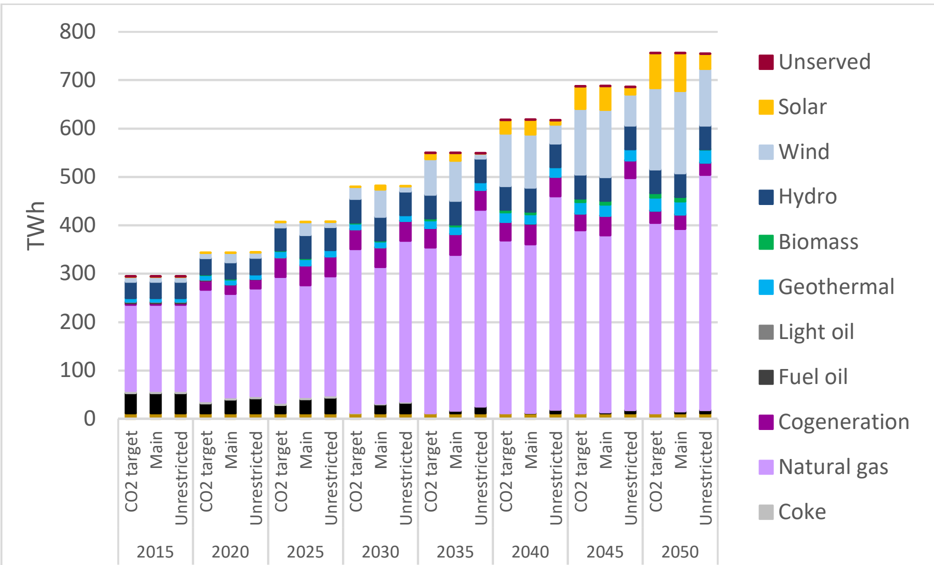

Figure 15. Generation in Main and CO_2 Target. Selected years.

Total costs

Using CO_2 quotas or pricing to realise the same emission level as would be achieved with the clean energy goals, will reduce the overall mitigation costs. The extra cost in realising the CO_2 emission reduction is lower in the first years, e.g. USD 350 million per year in 2030 – or 1.5% lower total system costs (on an annualised basis). After 2040 the CO_2 target scenario becomes more expensive. The (expensive) investment realised in the first part of the period in the Main scenario reduces the cost in the later part of the studied period, see Figure 16.

Expressed in net present value (with 10% interest) the Main scenario is USD 2,229 million more expensive than the Unrestricted scenario, and the CO_2 Target scenario is USD 1,472 million more expensive than the Unrestricted scenario. The CO_2 Target is USD 1,357 million cheaper than the Main scenario.

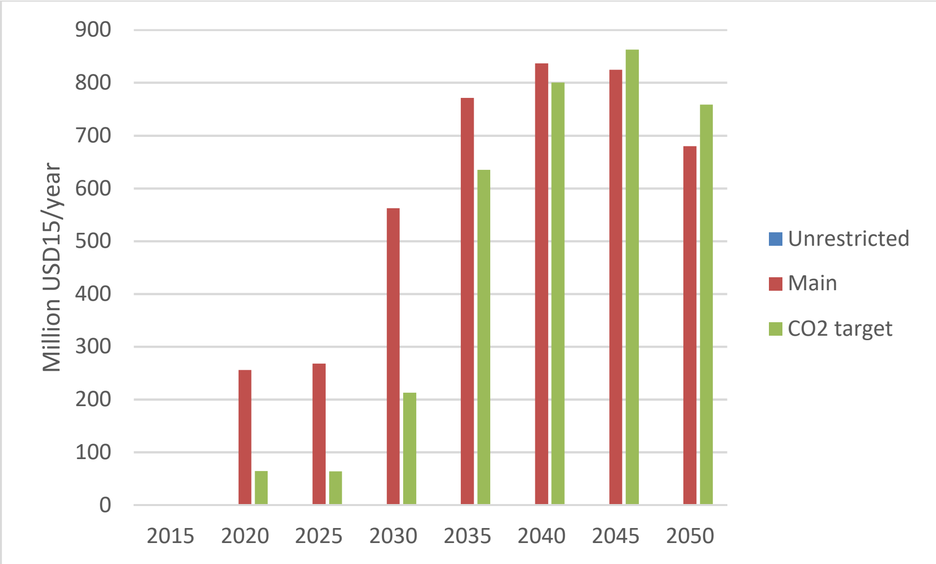

Figure 16. The total annualised cost compared to the Unrestricted scenario.

Generation capacity

In the CO_2 target scenario, the investment in new generation (compared to Main) focusses more on natural gas (e.g. 3,267 MW more in 2030) and less on wind and solar (3,028 MW less wind and 164 MW less solar). The difference in capacity is reduced in the following years as can be seen Figure 17.

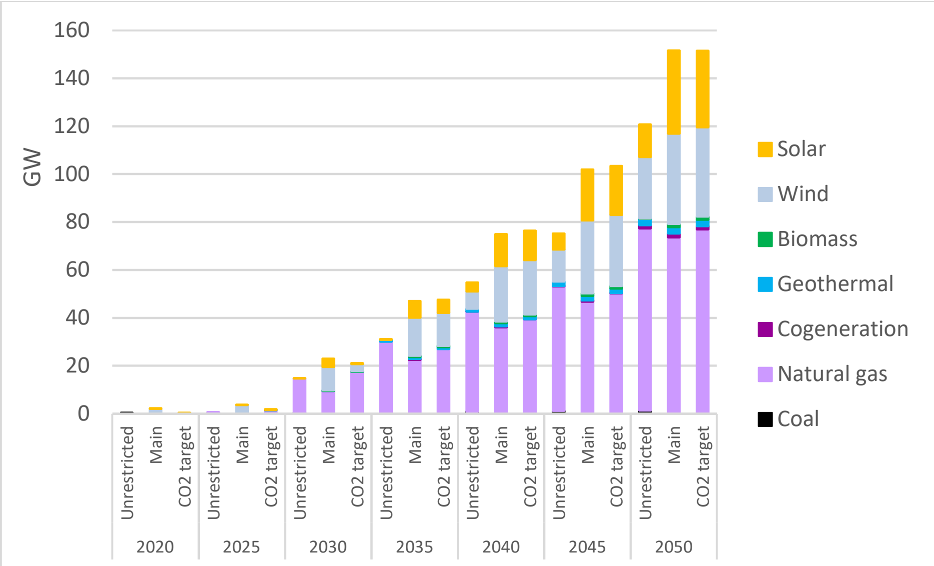

Figure 17. Model-based investment in new generation capacity across scenarios, GW.

5 Can Mexico be even more ambitious?

In this chapter, we will investigate if and how Mexico could reduce CO_2 emissions even more than planned with the current clean energy goals (e.g. 50% reduction compared to the Main scenario in 2050). *How much more expensive is it to reduce CO_2 emission beyond the current plans?*

The results are presented in technical terms (MW, GWh) as well as economical terms. Also, there will be focus on the operational aspects: Can the system integrate the high shares of renewable energy. See Figure 3 (Chapter 2) for the three sets of CO_2 prices used to simulate future ambition levels on reducing CO_2 emission. The three price profiles end at USD 75, 50 and 25 per ton, for Full 2/3 and 1/3, respectively. This is well above current CO_2 prices in e.g. EU or California.

Emissions

Based on the power demand projection assumptions used in the analysis, the electricity demand grows by 160% between 2015 and 2050. Even with this growth, the CO_2 emissions are reduced in all CO_2 scenarios, except the Main scenario, where a marginal increase can be found. The CO_2 scenarios result in significant reductions compared to the Main scenario. The three levels of CO_2 prices tested are all more aggressive than the current Clean energy goals as was implemented in the Main scenario. See Figure 18.

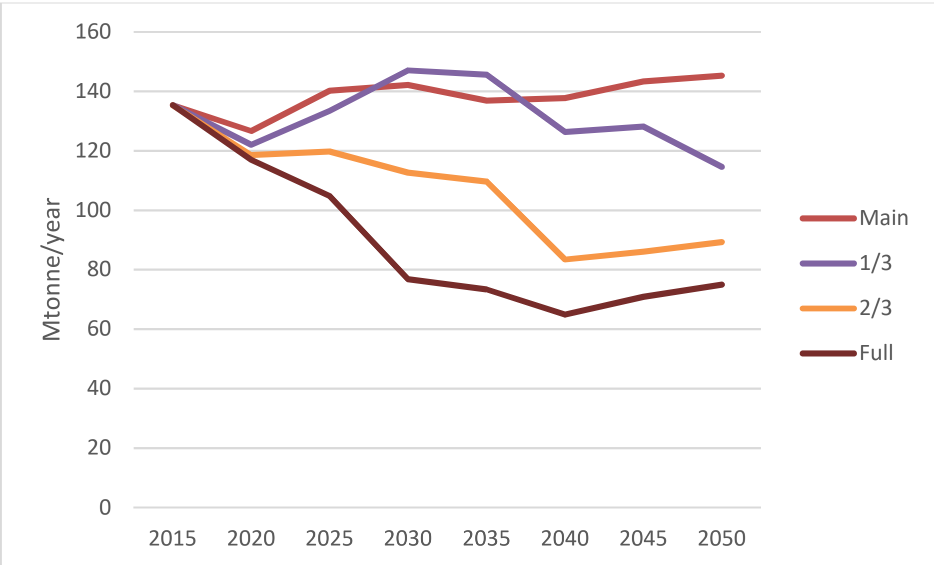

Figure 18. CO_2 emission in the four scenarios tested, modelling results.

New generation capacity

The CO_2 reductions are possible because of massive investment in new generation capacity. As illustrated in Figure 19, new generation capacity in the Main scenario is comprised of natural gas, wind and solar. The CO_2 price scenarios have more wind and solar and less natural gas.

The model could also have invested in nuclear, coal with CCS and diesel, but none of these technologies are found to be economically attractive.

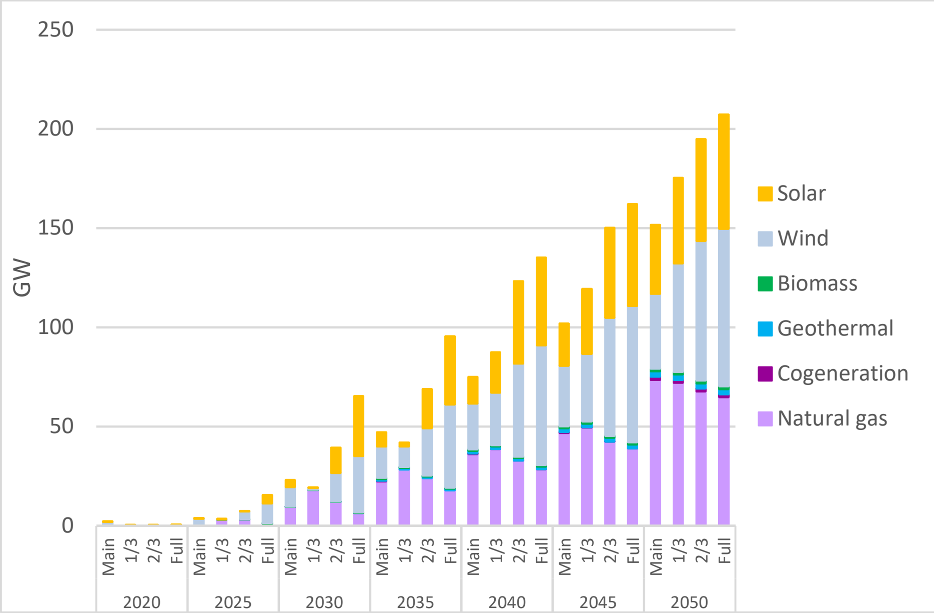

Figure 19. Model-based investment in new generation capacity, GW.

New transmission capacity

With more wind and solar energy in the system, the need for transmission increases. Table 3 illustrates the investments in transmission capacity. With more wind and solar, more transmission capacity is needed.

The model invests in transmission capacity when it is economically attractive: E.g. when the reduction in total costs is higher than the needed investment (expressed as annual costs). Transmission may have other purposes, like securing the operation of the grid, but in the Balmorel model it is only the transport of electricity that is in focus.

		Main	1/3	2/3	Full
Acapulco	Puebla	93	123	166	126
	Temascal	352	510	577	549
Aguascalientes	Durango	0	0	653	398
	Guadalajara	0	0	0	98
	Salamanca	0	0	334	954
	San_Luis_Potosi	0	0	47	0
Cancun	Merida	267	14	0	0
Carapan	Guadalajara	0	0	0	154
Central	Puebla	0	3,487	6,851	9,445
	Queretaro	792	2,376	4,635	5,896
Chihuahua	Laguna	0	0	0	151
Coatzacoalcos	Temascal	0	0	0	124
Culiacan	Los_Mochis	256	796	1,549	1,968
	Mazatlan	249	477	1,076	1,375
Durango	Mazatlan	0	0	481	398
Ensenada	Mexicali	81	311	769	1,121
	Tijuana	1,508	1,732	1,713	1,891
Grijalva	Tabasco	739	815	1,677	1,799
	Temascal	23	19	275	1,116
Guadalajara	Tepic	0	0	134	577
Hermosillo	Nacozari	48	0	122	93
Huasteca	Monterrey	0	0	698	2,114
	Poza_Rica	0	0	120	1,596
	Valles	0	0	0	63
Los_Mochis	Obregon	0	0	13	265
Matamoros	Reynosa	0	2,332	3,168	3,408
Mexicali	San_Luis_Rio_Colorado	0	0	50	262
Moctezuma	Nacozari	31	0	176	190
Monterrey	Saltillo	0	0	188	1,970
Nuevo_Laredo	Reynosa	0	127	651	778
Poza_Rica	Veracruz	16	314	1,150	2,674
Puebla	Temascal	887	5,251	9,683	12,182
Queretaro	Salamanca	0	0	170	382
	San_Luis_Potosi	1,768	6,425	9,016	10,265
	Tamazunchale	76	156	76	0
Temascal	Veracruz	969	1,257	2,096	3,666
Total		**8,155**	**26,522**	**48,314**	**68,049**

Table 3. New transmission capacity (MW). For simplicity, the capacity is only shown for the end year (2050).

In the CO_2 price scenarios in the first years, oil and coal are generating less, and natural gas more. In later years, natural gas is also reduced and more renewable energy is introduced, see Figure 20.

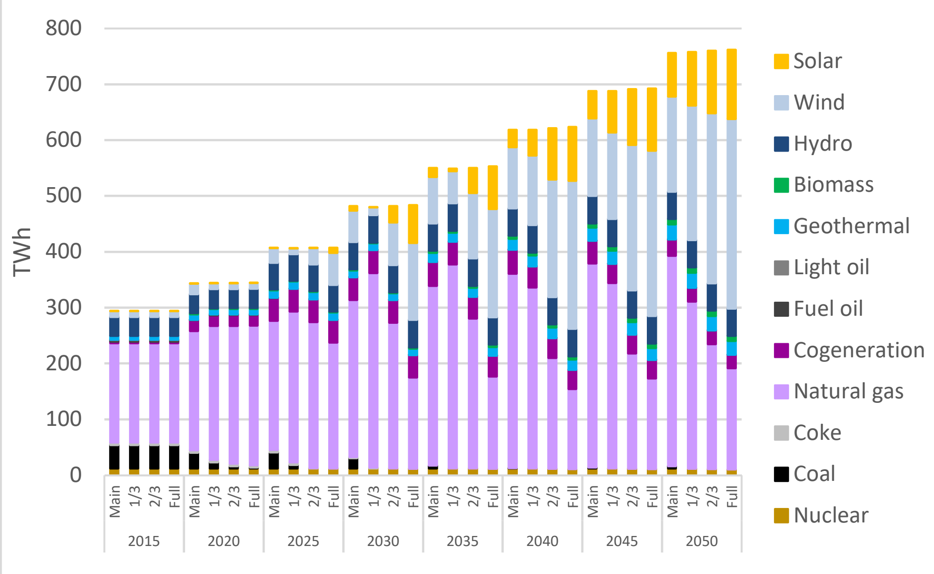

Figure 20. Generation in Main and the three CO_2 price scenarios, TWh.

Economy

More wind and solar means less fuel costs, but higher capital costs. As illustrated in Figure 21, the additional costs in the Full CO2 price scenario (compared to Main) reach USD 4,000 million per year in 2040, corresponding up to 10% of the total costs.

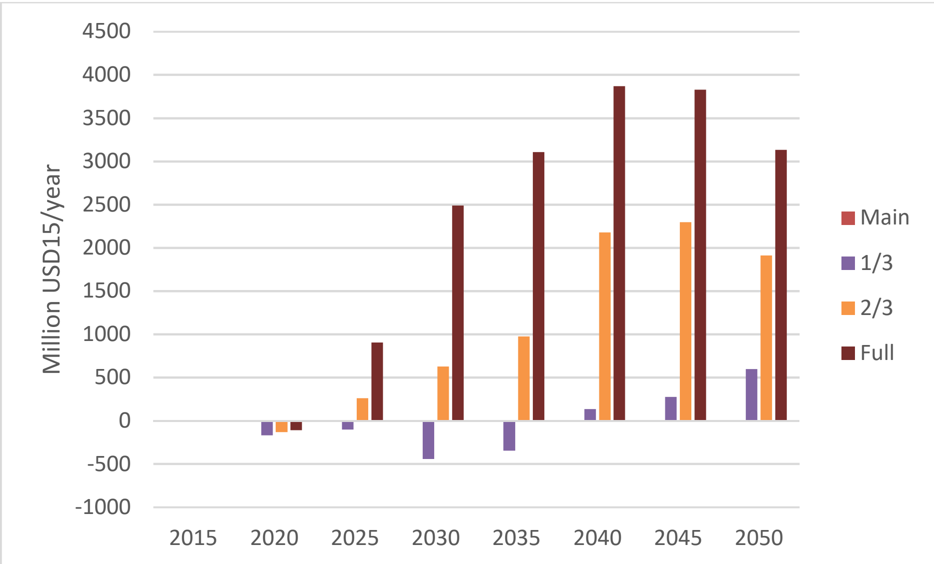

Figure 21. Difference in total economy in the three CO_2 scenarios compared to Main.

Figure 22 illustrates how the cost of reducing the CO_2 emissions beyond the Main scenario is increasing. For example, a 20% reduction can be achieved at an additional cost of about 2%. A 50% reduction would increase the cost about 11% in 2030 and 6% in 2050.

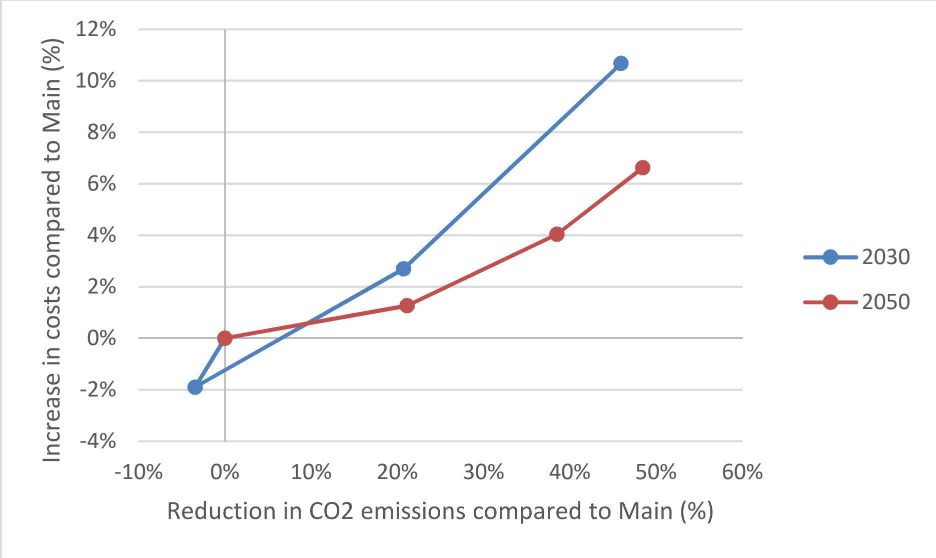

Figure 22. Increase in total costs compared to the Main scenario. The three points with reductions corresponds to the scenarios 1/3, 2/3 and Full.

Clean energy

In the Main scenario, the goals for Clean energy are met in all years, 2020 – 2050. The 2/3 CO_2 price scenarios is exceeding the goal from 2030, and the Full scenarios from 2025.

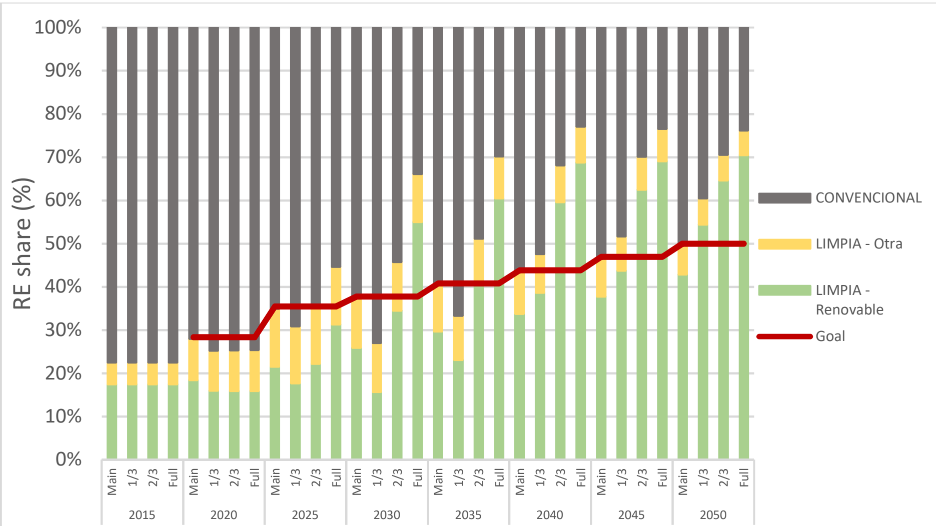

Figure 23. The share of Clean energy in the four scenarios.

Efficient integration of wind and solar

In systems with large share of wind and solar, there is a risk of curtailment of wind and solar and of spillage of hydro. The general picture is that the large share of wind and solar can be efficiently integrated in the Mexican system. Only minimal amounts of curtailment occur towards the end of the projections period. For the Full scenario, the curtailment is highest but remains under 2%. The values reported are national averages and larger relative amounts can be found in specific transmission areas.

In all the other scenarios and years, much less curtailment takes place. Solar and hydro power generation is not curtailed to any significant degree. See Figure 24. Note that the model has invested optimally in both generation and in transmission, so the described curtailment can be called *economically optimal curtailment.*

Curtailment can be reduced in several ways that have not been included in the current model: e.g. investment in pumped hydro, flexibility in the conventional generation sources, demand response (extra demand, e.g. to industrial use, when prices are low) and import/export to neighbouring countries.

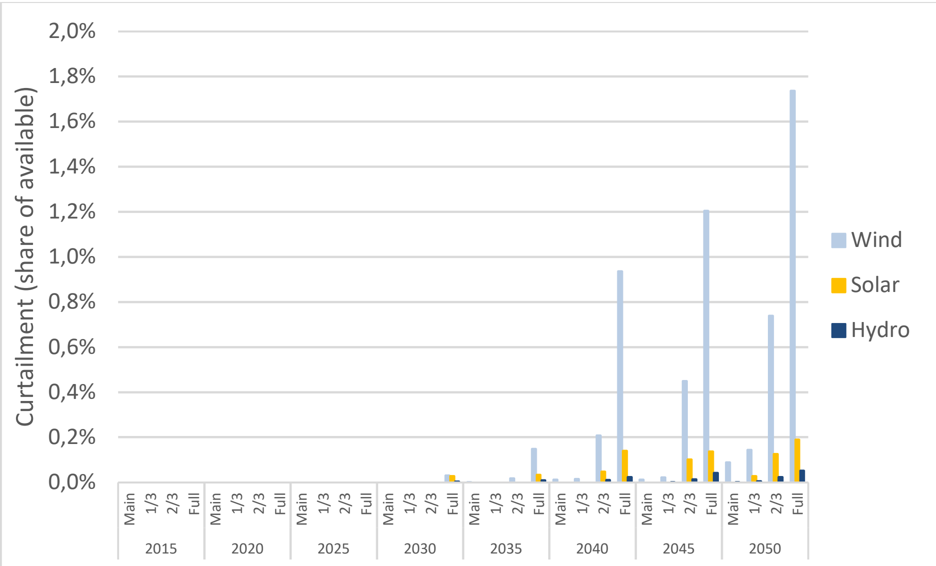

Figure 24. Curtailment of wind, solar and hydro, share of possible generation (%).

6 Discussion

The development of the Mexican electricity system has been studied from the current state and until year 2050. Least-cost model-based investment simulations have been used to illustrate a number of possible futures. It is well understood that the input data projections for towards year 2050 are subject to a high degree of uncertainty. The purpose has not been to predict the future, but rather to illustrate important aspects and possibilities for the Mexican electricity system.

The electricity sector in Mexico only represents 26-32% of the current net greenhouse gas emission, but is expected to be the sector that contributes the most to the reduction indicated in the Intended Nationally Determined Contributions (INDC) for 2030: Both in absolute terms (63 Mtonne) and relatively (31%). In the INDC the reduction is in relation to a business-as-usual scenario.

6.1 Clean energy goals vs. CO_2 target

Different combinations of policy instruments can be used to reduce CO_2 emission. Two scenarios have been compared in the current study: The Main scenario with the Mexican clean energy goals implemented (i.e. 35% in 2024 and 50% in 2050) and a CO_2 Target scenario, where a CO_2 target (and implicitly a CO_2 shadow price) has been included.

The results illustrate that using the CO_2 target reduces the total costs with 1.5% compared to the clean energy goals. This is done by reducing the use of oil and coal. More natural gas and less wind and solar are being used in power generation, while the emissions are the same. The needed CO_2 price to realise this development peaks at USD 30 per tonne in 2035.

A CO_2 goal system can also be applied for other sectors, e.g. process energy in industry, and this could improve the coordination between the sectors. The EU ETS system has this feature.

In practice, Mexico does not need to choose between clean energy goals or CO_2 targets/prices. Many types of policy instruments can be combined. Many of the results and cost reductions in the CO_2 price scenarios can be obtained, e.g. by putting restrictions on the use of oil and coal for power generation, e.g. via a tax or a regulation.

6.2 Further reduction of CO_2 emissions

Three alternative developments with decreased CO_2 emissions (compared to the current clean energy goals) have been studied. The increased ambitions have been implemented by testing three scenarios with relatively high CO_2 prices. The levels have been inspired by Canadian analyses. The highest CO_2 price development ('Full' CO2 price scenario) ends up at USD 75/tonne in 2050. The two other alternative scenarios feature CO2 prices that are 1/3 and 2/3 of this, respectively.

The 1/3 scenario is close to the Main scenario, so in popular terms the 2/3 has the double ambition (in shadow price) compared to the Main scenario – and the Full has three times higher ambition.

Large potentials

The three alternatives will lead to significant CO_2 reductions from the electricity sector – 21%, 39% and 48% compared to the Main scenario (in 2050), respectively. The maximum reduction in emissions from the electricity sector compared to Main is 65 Mtonne/year in 2030 (Full CO_2 price scenario). This can be compared to the difference between the unconditional and the conditional goals in the Mexican INDC: 146 Mtonne/year. The electricity sector can make a significant contribution in the overall Mexican CO_2 reduction.

This reduction has been achieved mainly by deploying more wind and solar energy – at the expense of natural gas. In 2050 the three scenarios have 54%, 65% and 70% renewable energy shares (1/3, 2/3 and Full respectively) and 6% other clean energy. Wind and solar represent 44%, 55% and 61% of the total generation in 2050, respectively.

Efficient integration

The simulations indicate that it is possible to operate the Mexican electricity system with these high levels of variable renewable energy. The Mexican system is relatively flexible with its large share of natural gas-based generation. Also, the dispatchable hydro generation capacity helps making the system flexible. The small amount of curtailment (less than 2%) indicates an efficient integration of wind and solar in the system. Part of the reason for this is that all economic investment in transmission has been included which will contribute to accommodating the variable renewable energy.

Curtailment can be reduced further, e.g. with investment in pumped hydro and other measures that have not been included in the analyses, like demand response and interchange with neighbouring countries.

Increases in total costs

The total costs for generating electricity will go up, when the CO_2 emission are reduced. In relative terms the costs of reducing the CO_2 emission with 20% will increase the total costs with less than 2%. Reducing CO_2 emission with 50% will increase the total costs with 6-11%.

It is a political decision whether these increases in cost are worth the result (lower emission). The analyses indicate how emission reduction can be achieved most efficiently, other things being equal.

Policy instruments can be combined

Many policy instruments can be used – and often they are used in combination, e.g. the EU have goals for CO2, share of renewable energy as well as separate instruments to promote energy efficiency. Combination of instruments may lead to some overlapping (and extra costs), but can also give a more robust development, since progress is secured by several instruments.

International coordination

An international CO_2 trading system can coordinate the effort to reduce CO_2 emission.

The Emission Trading System (ETS) in the European Union is covering 28 member states and the system includes the power sector and industry. There is currently an oversupply of quotas, and the price is lower than expected (and needed to promote renewable energy): USD 7 per ton. The low economic growth is a major reason for the oversupply.

The EU also has goals for renewable energy and energy efficiency. The goals overlap (e.g. the expansion of renewable energy has increased the oversupply of quotas), but gives a degree of robustness to the development.

The implementation of an international emission trading system in Mexico requires thorough preparation and could include a stepwise approach where the trading system could first be introduced in the most emission-heavy sectors – like power production and heavy industry. This is in line with the ETS simulation exercise under preparation.

Summary

Major findings in this report include:

- *It is possible to operate the Mexican electricity system with very high share of wind and solar, e.g. 61% in 2050. This result is obtained with an optimal investment in transmission capacity – along with the investment in generation capacity. Only minimal curtailment (less than*

2%) of wind power takes place. Investment in pumped hydro may reduce the amount of curtailment.

- *The use of the clean energy goals has a significant impact on the CO_2 emission.*
- *Alternative policy instruments, like CO_2 targets or prices, can have similar impact at a lower total cost or larger CO_2 reductions at the same cost. However, the difference in total costs is computed to be in the order of 1% - so this is not extensive.*
- *Scenarios with high and very high CO_2 prices have been studied which result in further reduction of the Mexican emissions from the electricity sector. The increase in total costs compared to the implementation of clean energy goals is about 2 % for a 20% emission reduction and, for 50% emission reduction; the cost increase is ca. 11% in the medium-term and 6% towards the end of the period.*
- *Development of the policy instruments can reduce the total costs, e.g. with more international coordination and exchange of power. Increased transmission capacity to neighbouring countries will help in the integration of more variable generation.*

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