


Ea Energy Analyses

# Renewable energy in Mexico

Background report to the Mexican Renewable Energy Outlook, 2015

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Mikael Togeby and Aisma Vitina
Ea Energy Analyses
Frederiksholms Kanal 4, 3. th.
1220 Copenhagen K
Denmark
T:  +45 88 70 70 83
Email: info@eaea.dk
Web: www.eaea.dk

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# Foreword

This is a background report to be used in relation to the Mexican Renewable Energy Outlook, 2015. It has been developed with support from the Mexican-Danish Climate Change Mitigation and Energy Programme.

Input to this report has been gathered during three missions to Mexico (September to November 2015), and through dialogue with Efrain Villanueva Arcos, Luis Alfonso Muñozcano Alvarez, Daniela Pontes Hernández, Luis Gerardo Guerrero Gutierrez, Alain de los Angeles Ubaldo Higuera and Fidel Carrasco Gonzalez, Secretaria de Energia, SENER, as well as many other stakeholders. We would like to express our gratitude to Bloomberg for making information sources on renewable energy costs and policy in Mexico available. Also, gratitude for their valuable input and comments is hereby extended to Niels Bisgaard Pedersen, Danish Energy Agency, and Ulla Blatt Bendtsen, Mexican-Danish Climate Change Mitigation and Energy Programme.

Mikael Togeby
Ea Energy Analyses

# 1 Introduction

Renewable energy delivers 17% of the electricity generated in Mexico (2014). Hydro comprises 13% of the total power generation, followed by geothermal (2%) and wind power (2%), respectively. The introduction of Clean Energy Certificates (CEL) from 2018 will further increase the development of renewable energy. 'Clean energy' is defined as renewable energy, nuclear, Carbon Capture and Storage (CCS) and efficient cogeneration. At present, the main supply of electricity comes from gas (52%) and coal (25%).

In its INDC (Intended Nationally Determined Contribution) Mexico has published the goal of 22% reduction of greenhouse gasses compared to business-as-usual (BAU) by 2030. The BAU corresponds to emission of 973 $MtCO_2e$. Renewable energy will play a significant role in achieving this target.

Renewable energy has features that can be a challenge. These include the high investment costs and the variable nature of the generation as well as the issues related to system integration. In this background report, current and future cost for renewable energy is reviewed (chapter 2) and challenges and solutions related to system integration are described (chapter 3). Special importance has been given to reviewing the most recent international sources.

Furthermore, the concept of using model-based scenarios as part of long term planning is presented and discussed

# 2 Cost of renewable energy

This chapter will address the costs of renewable energy technologies. The focus will be on power generation technologies: onshore wind, utility-scale solar PV, geothermal, hydro and biomass. Distributed generation, as well as co-generation, and non-power generating technologies (e.g. biofuels) are beyond the scope of the current Background report.

The structure of this chapter is as follows: overview of the currently observed RE technology costs globally, within the American region, and in Mexico, followed by an overview of the projections of these costs towards 2030. Thereafter, a recommendation for representative planning values of RE technologies for Mexico for the 2015 – 2030 period will be provided. Finally, the chapter will conclude with an LCOE perspective.

## 2.1 Renewable energy technology cost overview

The following sub-sections will provide an overview of the main power-generation RE technology costs, with specific focus on the overnight capital costs. Other cost categories of the RE technologies reviewed will be addressed in the LCOE Perspective section of the report.

All cost data throughout this Chapter will be expressed in Mexican pesos, in real 2014 terms[1] (MXN 2014) – unless specified otherwise. The investment costs will be expressed in millions of Mexican pesos, in real 2014 terms per MW (M MXN 2014 / MW). Currency and inflation conversion assumptions are detailed in Appendix 2: Currency and inflation conversion assumptions.

### Land-based wind

Land-based wind has become a mature and largely standardized technology. The cost of wind power generation is determined by capital costs, capacity factor, operation and maintenance (O&M) costs, and financing costs. Capital costs and the capacity factor (expected power generation per unit of capacity) are typically the most influential factors affecting the cost of energy for wind power projects.

The wind turbine is the most significant cost category within capital costs, accounting for ca. 70% of the total capital costs, yet cost shares of up to 84%

[1] Currency and inflation conversions have been carried out by converting the origin currency (e.g. USD 2012) into MXN using the average annual exchange rate of that year (i.e. 2012 to obtain MXN 2012), and thereafter inflating it to MXN 2014 using the GDP deflators of the World Bank

(and higher) are also observed (IRENA, 2015). Table 1 provides an example of a capital cost breakdown for San Matias, a 20 MW wind farm in Mexico.

| Cost category | Cost sub-category | M MXN 2014 | Share |
|---|---|---|---|
| **Civil works and grid connection** | Civil works of wind turbines | 108.4 | 18.2% |
| | Measurement tower | 1.2 | 0.2% |
| | Construction costs | 4.1 | 0.7% |
| | Construction indirect costs | 14.8 | 2.5% |
| | Land rent | 2.3 | 0.4% |
| | ***Sub-total*** | 233.8 | 22.0% |
| **Wind turbines and installation** | Turbine price | 274.6 | 46.1% |
| | Transportation of the wind turbines | 30.2 | 5.1% |
| | Electrical infrastructure of wind turbines | 103.0 | 17.3% |
| | ***Sub-total*** | 304.8 | 68.5% |
| **Planning and management** | Management cost | 6.1 | 1.0% |
| | Administrative cost | 50.6 | 8.5% |
| | ***Sub-total*** | 56.8 | 9.5% |
| **Total cost** | | **595.3** | **100.0%** |

*Table 1: Capital cost breakdown for a 20 MW onshore wind farm in Mexico (M MXN 2014). Source: (IRENA, 2015)*

Significant regional differences exist in wind project costs, with China and India exhibiting the lowest cost levels. Factors influencing regional cost differences include material and labour costs, maturity of the industry, policy support frameworks, availability of financing etc., and there can also be major cost differences across projects within each country based on the characteristics of each individual project (IRENA, 2015). Table 2 provides an overview of the average total installed costs of new wind farms in selected OECD countries in 2013, including Mexico.

| | New capacity in 2013 (GW) | Cost (M MXN 2014 / MW) |
|---|---|---|
| **Australia** | 0.68 | 19.0 - 31.7 |

| | | |
|---|---|---|
| **Austria** | 0.37 | 32.0 |
| **Canada** | 1.6 | 30.5 |
| **France** | 0.73 | 27.5 |
| **Germany** | 2.95 | 26.6 |
| **Italy** | 0.45 | 32.6 |
| **Japan** | 0.05 | 38.6 |
| Mexico | **0.62** | **28.0** |
| **Netherlands** | 0.24 | 25.7 |
| **Norway** | 0.07 | 26.3 |
| **Portugal** | 0.31 | 25.2 |
| **Switzerland** | 0.01 | 38.6 |
| **United Kingdom** | 1.64 | 24.9 |
| **United States** | 1.13 | 22.0 |

*Table 2: Average total installed costs of new wind farms in selected OECD countries, 2013. Source: (IRENA, 2015)*

Within the American region, US and Brazil exhibit the lowest investment costs. Wind power industry is mature and very well-established in the US, whereas the successful rounds of competitive auctions in Brazil have resulted in significant decreases of capital expenditure and rate of return for developers in the past few years. Figure 1 provides an overview of land-based wind power project capital cost ranges in the American region based on analysis by the Bloomberg New Energy Finance (BNEF), and Mexico is deemed to exhibit investment costs in the middle range within the region.

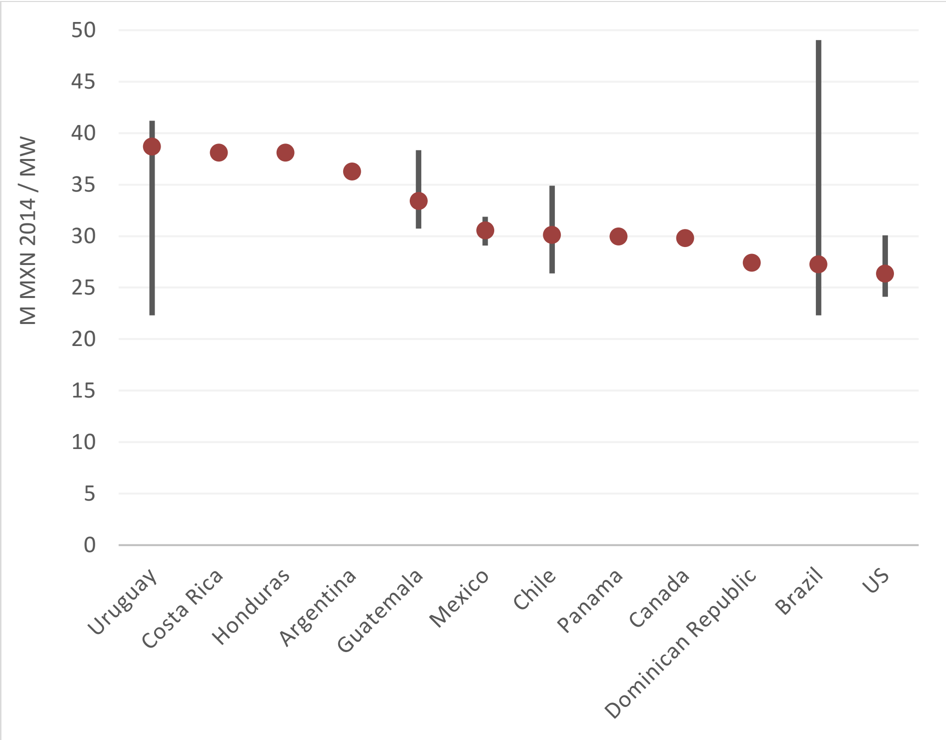



*Figure 1: Land-based wind capital cost ranges within selected countries (M MXN 2014 / MW). The tops and bottoms of the bars represent the High and the Low end of the cost range, with the red points indicating the average cost levels. Source: (BNEF, 2015).*

Figure 2 illustrates an overview of the identified sources providing estimates of capital costs of land-based wind power projects in Mexico.

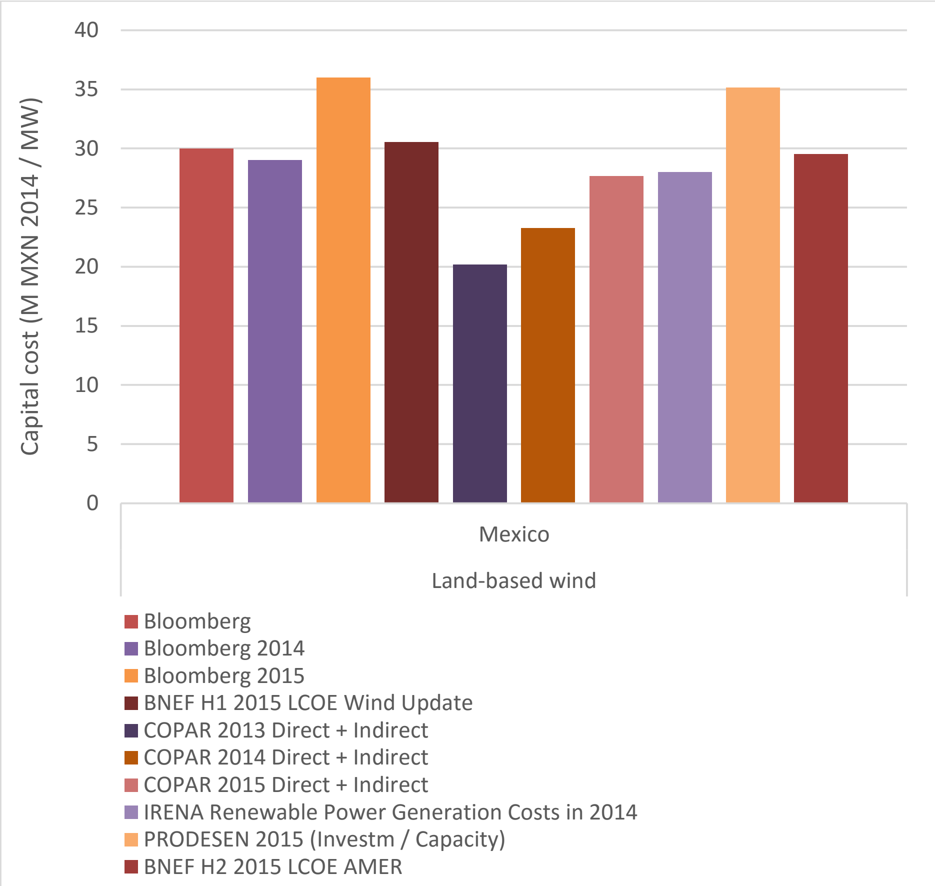



*Figure 2: Land-based wind capital cost overview in Mexico based on various sources. Sources: (Bloomberg, 2015), (BNEF, 2015), (CFE, 2013), (CFE, 2014), (CFE, 2015), (IRENA, 2015), (SENER, 2015)*
*Notes: Bloomberg is based on average across projects 2012 – 2015 in the Renewable Energy Projects database. Bloomberg 2014 and Bloomberg 2015 are based on very few projects (6 and 5, respectively) for the respective years in the same database.*
*COPAR 2015 cost differences have been affected by the USD/MXN exchange rate developments.*
*PRODESEN 2015 investment costs are based on the total investments per technology divided by the invested capacity.*

It should be noted that the investment cost estimates stated in COPAR publications are based on international sources. In addition, the highest capital cost estimate (Bloomberg 2015) is based on an average across 5 projects.

## Solar PV

Solar PV, especially the crystalline silicon-based, is already a fully mature technology, that nonetheless has continued exhibiting significant cost decreases over time. Solar PV installations can be divided into two broad components: the modules, and the balance-of-system elements (these include wiring, switches, a mounting system, and inverters). The modules have become largely standardized commodities, and their costs have exhibited a steep downwards trend for a number of years, as illustrated by Figure 3 (the 'Global Module Price Index' line).

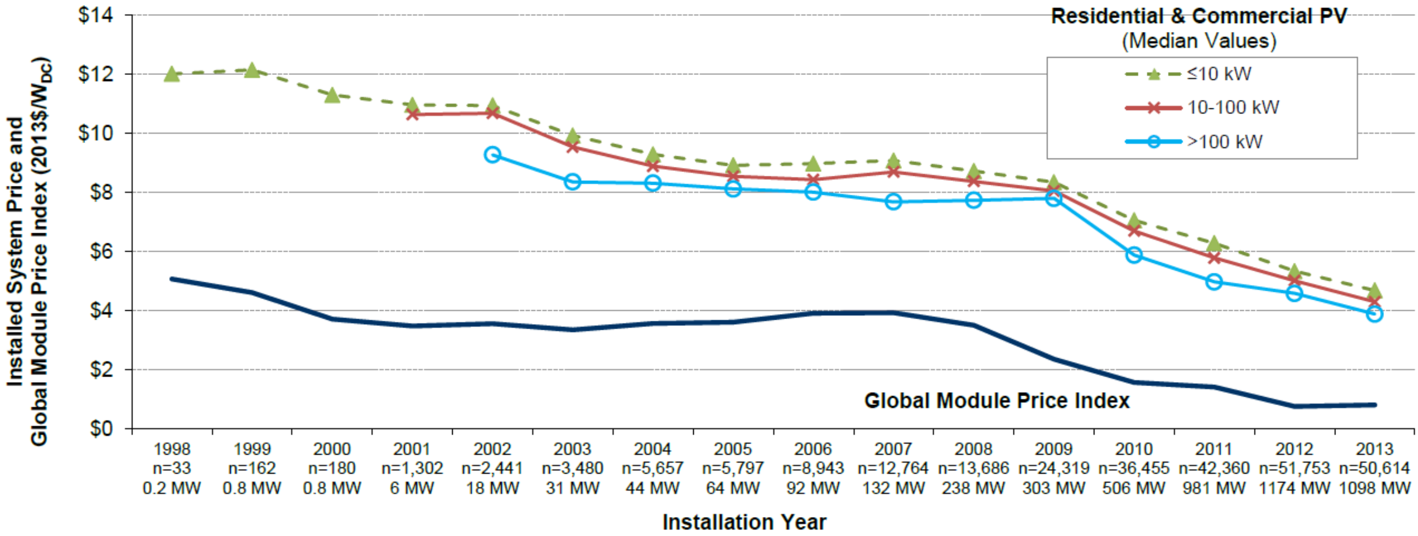



*Figure 3: Median Reported Installed Prices of Residential and Commercial PV Systems over Time (USD 2013 / $W_{DC}$). The Global Module Price Index is the average module selling price for the first buyer (P Mints SPV Market Research). Image source: (US DOE, 2014)*

Balance-of-system elements, on the other hand, are affected by a number of factors, such as different supply chains, local regulatory requirements, labour and permitting costs, financing mechanisms etc., resulting in a larger variation of their costs regionally. In the period 2011 to 2014, inverter cost decline of 29% and hardware cost decline of 20% were only accompanied by 1% decrease in the 'soft' balance-of-system costs: installation, engineering, procurement etc. (IRENA, 2015). One can observe the decreasing relative share of the module cost in the overall installed system price over time in Figure 3. Today the panels represents less than 25% of the total costs.

Figure 4 provides an overview of the capital costs for utility-scale solar PV installations globally and in Mexico. China and Germany exhibit the lowest cost level, whilst the US is close to the global average. (The costs in Mexico will be discussed in more detail later in the chapter.)

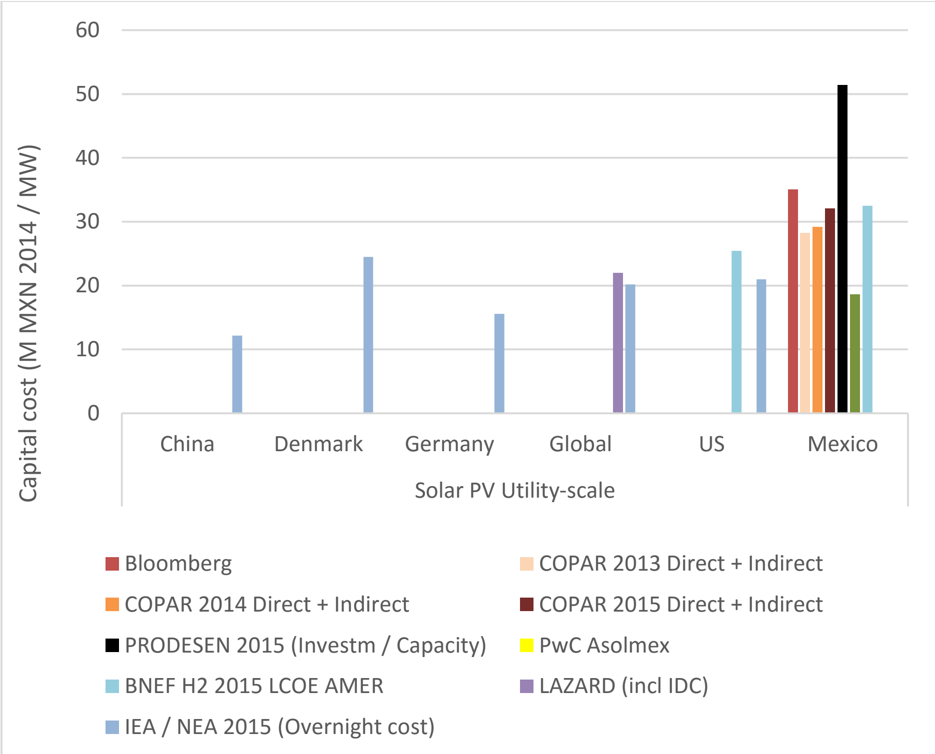



*Figure 4: Capital cost overview for utility-scale solar PV installations globally and in Mexico based on various sources. Sources: (Bloomberg, 2015), (CFE, 2013), (CFE, 2014), (CFE, 2015), (IEA, NEA and OECD, 2015), (Lazard, 2014), (SENER, 2015), (PwC, 2015), (BNEF, 2015)*
*Notes: Bloomberg is based on average across 6 projects 2011 – 2014 in the Renewable Energy Projects database.*
*COPAR 2015 cost differences have been affected by the USD/MXN exchange rate developments.*
*PRODESEN 2015 investment costs are based on the total investments per technology divided by the invested capacity.*

Figure 5 provides an overview of the investment cost ranges for utility-scale solar PV projects in the American region based on BNEF data. Central and South America is deemed to exhibit higher capital costs, whereas the US has reportedly reached the global best-case scenarios. In Brazil, the local content requirements increase the investment costs

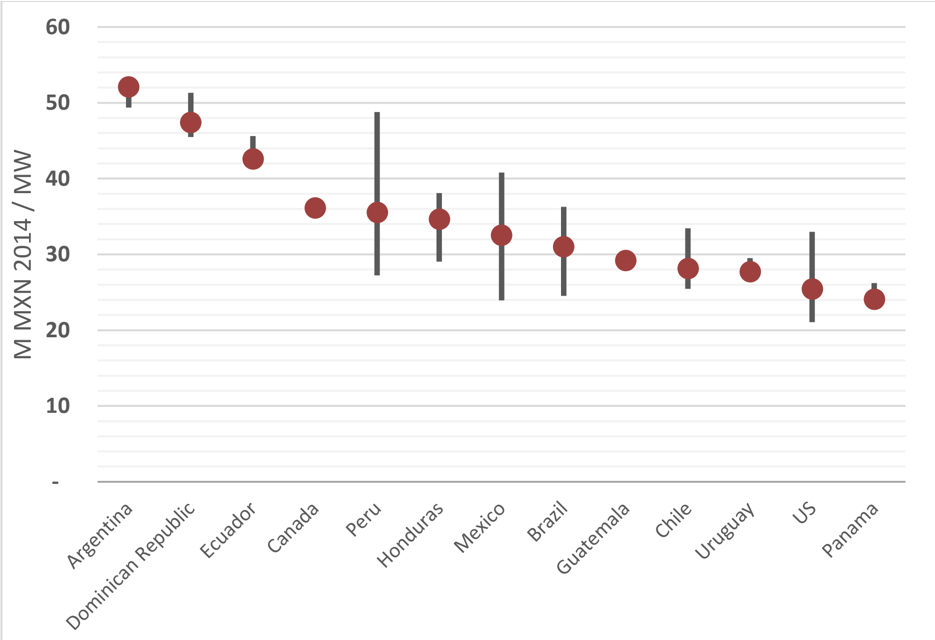



*Figure 5: Utility-scale solar PV capital cost ranges within selected countries (M MXN 2014 / MW). Source: (BNEF, 2015)*

Figure 6 illustrates an overview of the identified sources providing estimates of capital costs of utility-scale solar PV projects in Mexico.

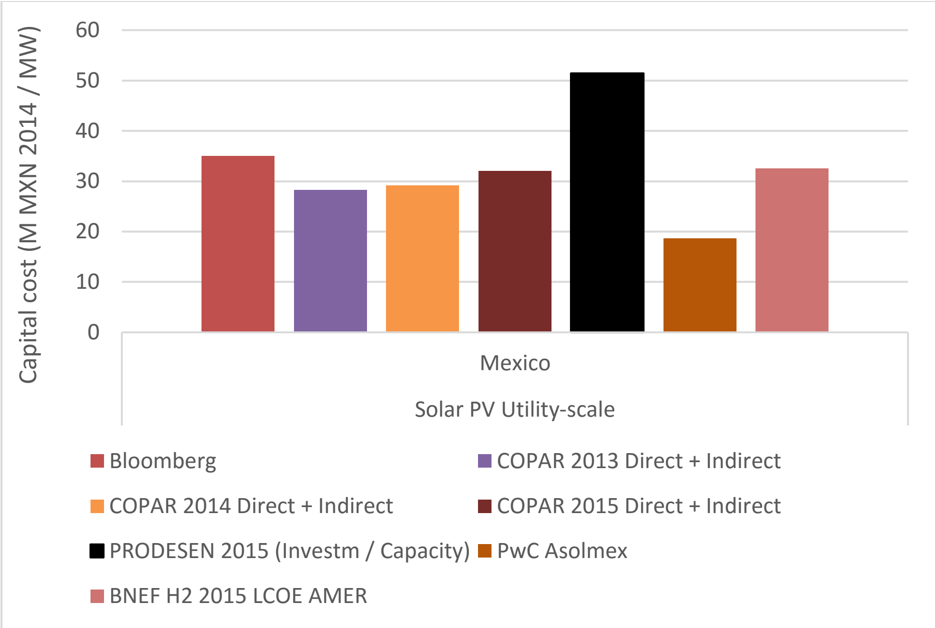
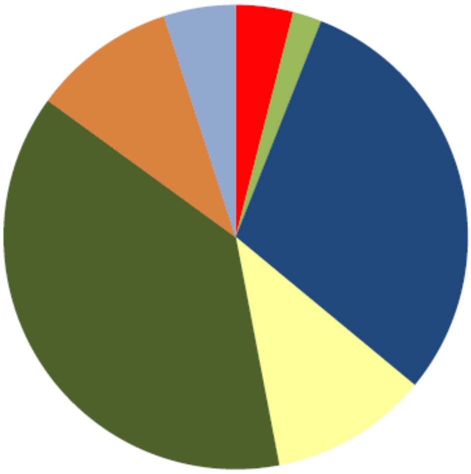



*Figure 6: Capital cost overview for solar PV utility-scale installations in Mexico based on various sources. Sources: (Bloomberg, 2015), (CFE, 2013), (CFE, 2014), (CFE, 2015), (SENER, 2015), (PwC, 2015), (BNEF, 2015)*
*Notes: Bloomberg is based on average across 6 projects 2011 – 2014 in the Renewable Energy Projects database.*
*COPAR 2015 cost differences have been affected by the USD/MXN exchange rate developments.*
*PRODESEN 2015 investment costs are based on the total investments per technology divided by the invested capacity.*

### Geothermal

The investment costs of geothermal power plants are highly site-specific, with the depth and individual characteristics of the geothermal resource (e.g. temperature) having considerable impact on the eventual costs of the project. Figure 7 provides a representative cost breakdown for a 20 MW geothermal project.



| | Cost (US millions) | US$/kW | % of Total |
|---|---|---|---|
| Site ("Establishment") Costs | $4 | $200 | 4% |
| Resource Exploration / Confirmation | $2 | $100 | 2% |
| Production / Injection Wells | $30 | $1,500 | 30% |
| Production / Injection System | $11 | $550 | 11% |
| Power Plant | $38 | $1,900 | 38% |
| Connection / Transmission | $10 | $500 | 10% |
| Administration / Management | $5 | $250 | 5% |
| | $100 | $5,000 | 100% |

*Figure 7: Representative cost breakdown for a 20 MW geothermal project (USD 2013). Image source: (Henneberger, 2013)*

Geothermal projects are characterized by high up-front costs, particularly in the exploration phase. Table 3 provides a more detailed overview of the different cost components in geothermal exploration phase.

| Study Type | Activity | Approximate cost in USD 2015 |
|---|---|---|
| **Geological** | Regional and structural geological survey of the area | 30,000 - 45,000 |
| **Geochemical** | Sampling of rock and fluids | 50,000 - 55,000 |
| **Geophysical** | Gravimetry Station | 100 - 150 |
| | Processing of Gravimetry Data | 5,000 - 6,000 |
| | TEM | 150 - 200 |
| | Processing of TEM Data | 3,000 - 3,500 |
| | MT | 1,500 - 2,000 |
| | Processing of MT Data | 9,000 - 10,000 |
| | Magnetometry | 100 - 150 |
| | Processing of Magnetometry Data | 5,000 - 6,000 |
| | Geophysical Report | 5,000 - 8,000 |
| **Drilling** | Gradient wells or smaller diameter (ø 1.5 a 7'') | 350,000 |
| | Slim production wells (ø 4.5 a 9'') | 1,500,000 |
| | Deep Exploratory (1,000 a 3,000 m) and Production well, (ø 3/8 a 20'') | 4,000,000 – 6,000,000 |

*Table 3: Approximate Costs of Geothermal Resources Exploration Phase (USD 2015). Source: SENER*

Figure 8 provides an overview of geothermal project investment costs globally and in Mexico. As noted earlier, these costs are highly site-specific, so a very wide range of capital costs have been reported. Based on information available for Mexico, it appears to exhibit a relatively low cost level as compared to other projects globally.

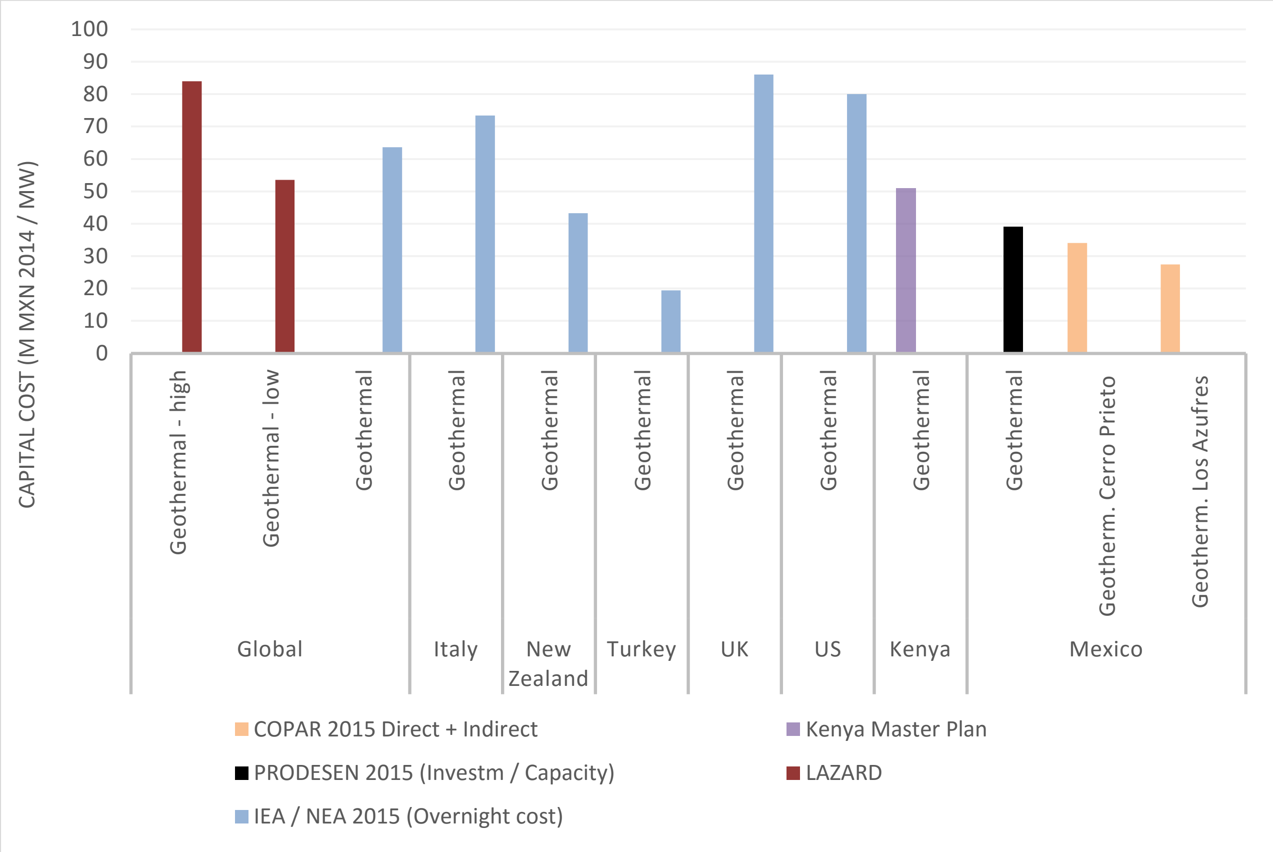



*Figure 8: Capital cost overview for geothermal projects globally and in Mexico based on various sources. Sources: (CFE, 2015), (IEA, NEA and OECD, 2015), (Kenya Ministry of Energy, 2013), (SENER, 2015), (Lazard, 2014)*

Figure 9 provides an overview of the geothermal project costs in Mexico. It should be noted that the data is based on 2 projects – Cerro Prieto and Los Azufres, and that different USD / MXN exchange rates affect the cost estimates if denominated in USD (as in e.g. COPAR publications).

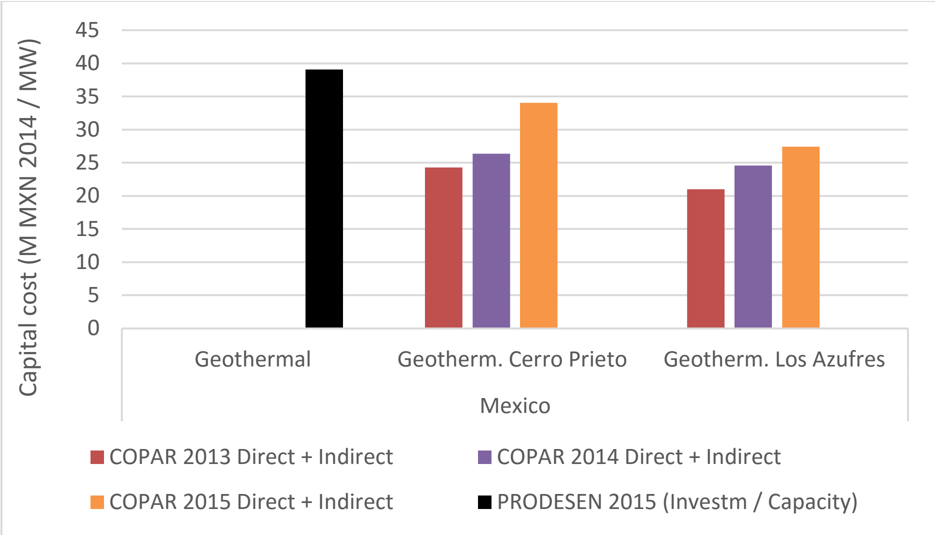



*Figure 9: Capital cost overview for geothermal projects in Mexico based on various sources. Sources: (CFE, 2013), (CFE, 2014), (CFE, 2015), (SENER, 2015).*
*COPAR 2015 cost differences have been affected by the USD/MXN exchange rate developments.*
*PRODESEN 2015 investment costs are based on the total investments per technology divided by the invested capacity.*

### Hydropower

Similar to geothermal projects, hydroelectric plants are also very site-specific (depending on size, the height of the water drop, flow rates etc.) resulting in a very wide range of costs. Hydropower is a capital-intensive technology involving long development and construction periods. In broad terms, the costs of a hydropower project can be separated into civil works (including infrastructure development) and the equipment cost. The civil works tend to represent the majority of costs for large hydropower projects, whereas the equipment costs can have a larger proportion of the total costs for smaller hydro projects (IRENA, 2015). An indication of cost breakdown for 2 large hydropower projects in the US and Brazil is provided in Figure 10.

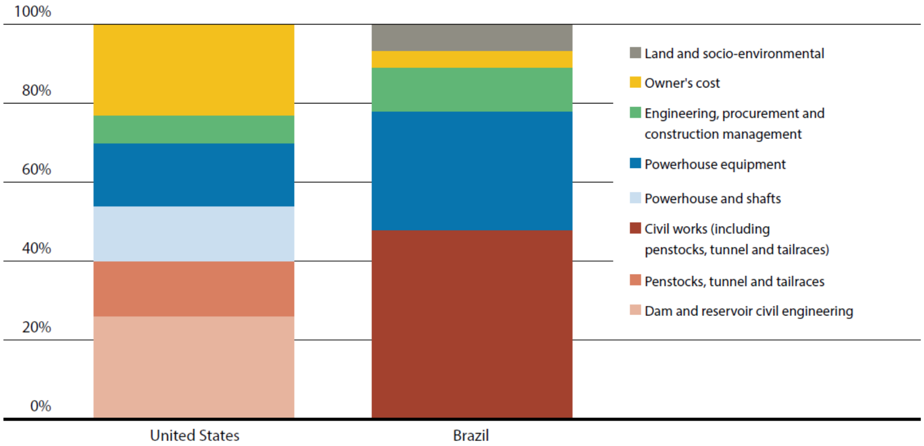



*Figure 10: Cost breakdown of an indicative 500 MW greenfield project in the United States and a 3 150 MW hydropower project in Brazil (%). Image source: (IRENA, 2015)*

The very wide range of investment costs for hydropower projects globally and by region is provided in Figure 11. The investment cost range for large hydropower projects is typically from 1 M USD / MW (13 M MXN 2014 / MW) to around M USD 3.5 / MW (45.5 M MXN 2014 / MW). The lowest total investment costs are found in India and China, whereas Caribbean and Central America are the regions with the highest cost levels. As a general rule, regions with significant remaining hydro potential will be able to deliver competitively-priced projects, whereas the opposite is true for regions where most of the hydropower potential has been already exploited (IRENA, 2015).

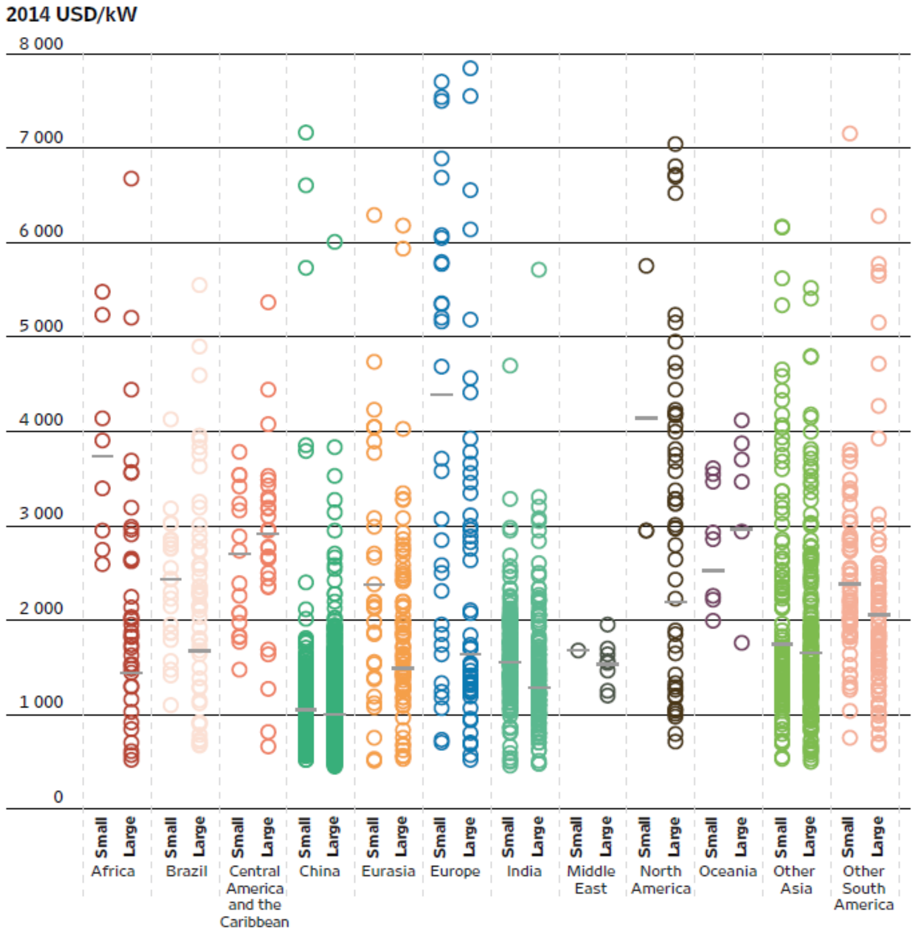



*Figure 11: Total installed cost ranges and capacity weighted averages for commissioned or proposed small and large hydropower projects by country/region (2014 USD / kW). Image source: (IRENA, 2015)*

Figure 12 provides an overview based on the latest data for hydro projects globally and in Mexico. The costs there appear to be in line with the investment costs in the region (Chile, Brazil, and the US).

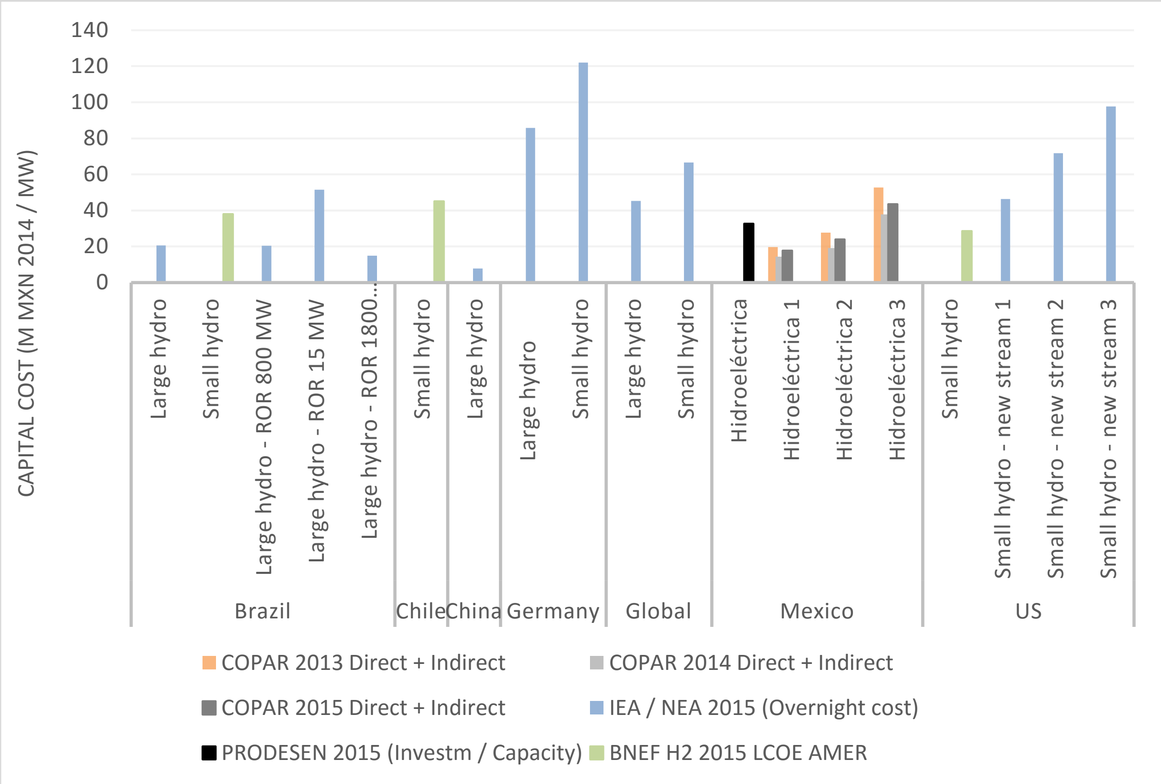



*Figure 12: Capital cost overview for geothermal projects globally and in Mexico based on various sources. Sources: (CFE, 2015), (IEA, NEA and OECD, 2015), (Kenya Ministry of Energy, 2013), (SENER, 2015), Data provided by SENER, (Lazard, 2014)*

## Bioenergy

The bioenergy category covers a wide range of power generation technologies, using a broad variety of biomass feedstocks. The technologies include direct combustion in stoker boilers, co-firing, anaerobic digestion for biogas production (and combustion), as well as combined heat and power. (Another subset of technologies commonly associated with bioenergy includes solid waste and landfill gas incineration.) The biomass feedstocks range from agricultural, forestry and industrial residues (e.g. black liquor at pulp and paper mills or bagasse at sugar mills), to wood waste, wood chips and pellets, to dedicated energy crops (e.g. bagasse, switchgrass, sorghum). (IRENA, 2015)

As a result of the wide range of technologies (and variations within a technology, e.g. in terms of its design complexity or emission controls), significant variations in capital costs exist, as illustrated by Figure 13.

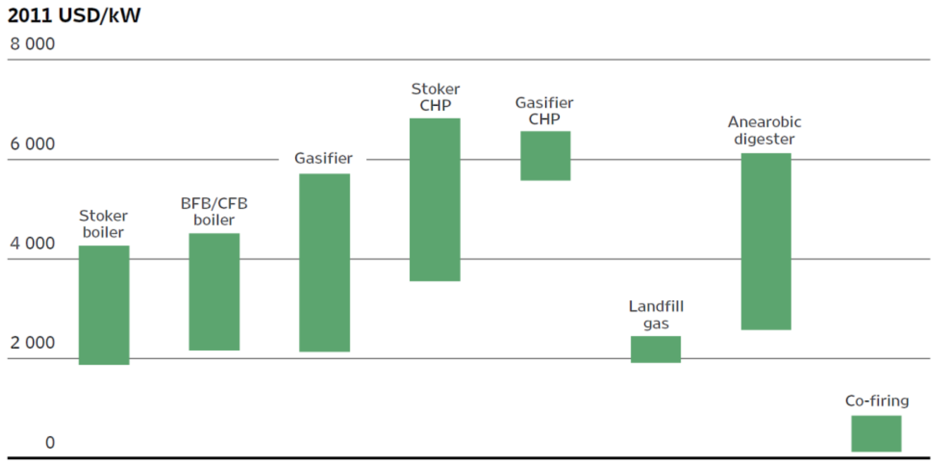



*Figure 13: Typical total installed capital costs of different biomass-fired electricity generation technologies in OECD countries (USD 2011 / kW). Illustration source: (IRENA, 2015).*
*Note: BFB = bubbling fluidised bed; CFB = circulating fluidised bed.*

The CHP technologies generally exhibit higher capital costs, yet their superior overall efficiency – and e.g. industrial uses – typically make them economically competitive for a wide range of applications. Waste incineration plants, in turn, exhibit higher investment costs as they need to ensure waste sorting functionality, as well as reduction of local pollutant emissions to an acceptable level (IRENA, 2015).

In terms of regional cost variations, developing countries tend to exhibit lower technology costs than e.g. OECD countries due to the less stringent environmental regulations and lower local content costs in the former. Based on analysis by IRENA, projects in Asia and South America generally tend to report lower investment costs, as illustrated by Figure 14.

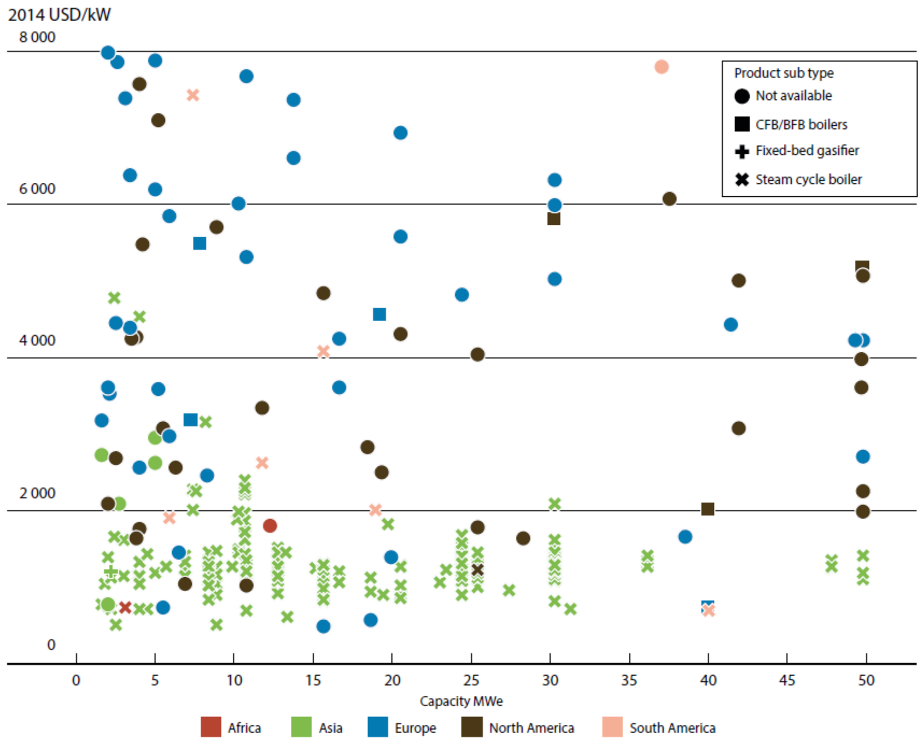



*Figure 14: Total installed costs of biomass-fired power generation technologies (USD 2014 / kW). Illustration source: (IRENA, 2015)*

In addition to the technological and regional cost differences, large variations in terms of infrastructure and grid connection costs exist, depending on the site and project specifics. Proportion of infrastructure costs as a part of total investment costs[2] can range between 1% and 58%, whilst grid connection costs can amount up to 41%, respectively (IRENA, 2015).

The bioenergy project investment costs for Mexico as estimated by PRODESEN 2015 appear to be in the lower range of the global and OECD reported costs – yet specific projects in some of the OECD countries, as well as the 'Low' estimates for non-OECD countries exhibit lower capital costs yet – as illustrated by Figure 15.

[2] Based on 12 project sample from Africa and India (IRENA, 2015)

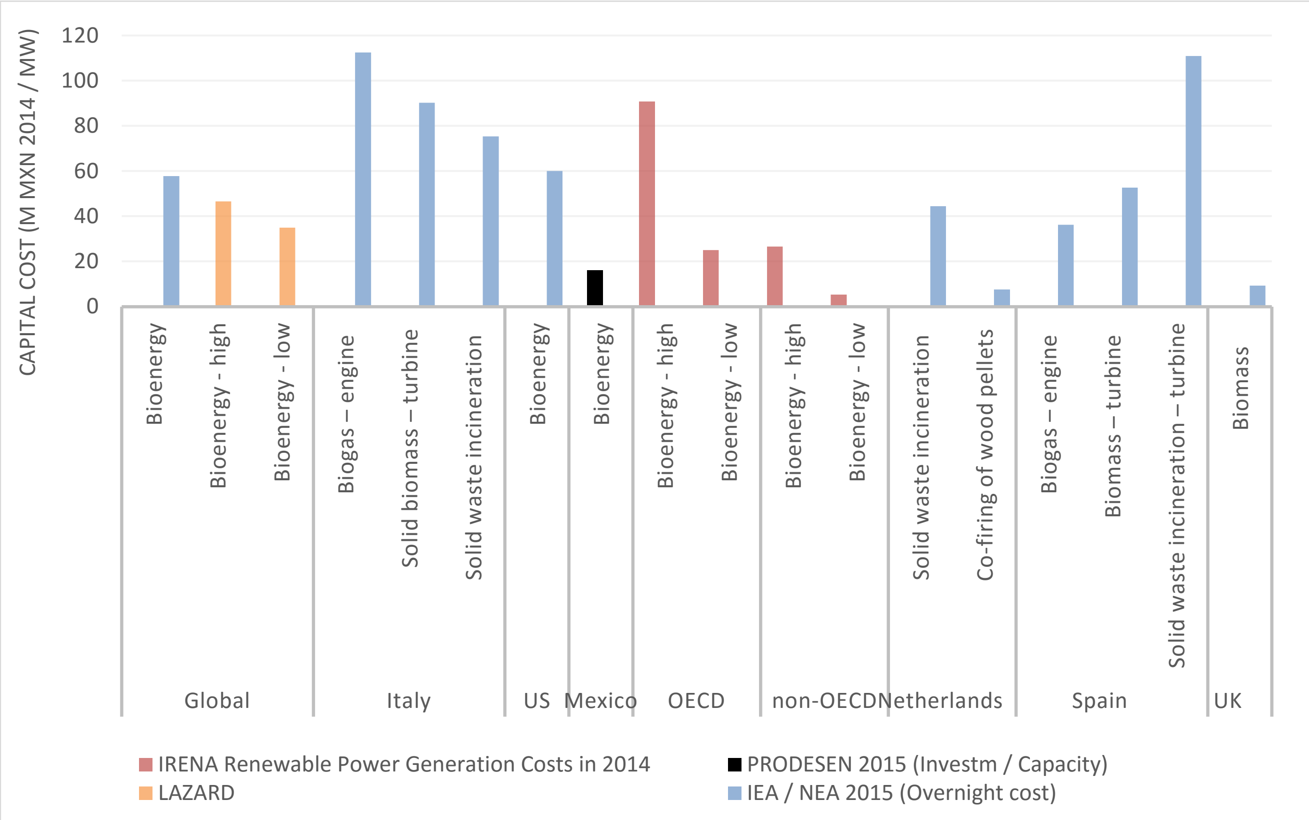



*Figure 15: Capital cost overview for bioenergy projects globally and in Mexico based on various sources. Sources: (IRENA, 2015), (SENER, 2015), (Lazard, 2014), (IEA, NEA and OECD, 2015)*

It should be noted, however, that a broad range of technologies has hereby been presented, thus any direct comparisons should be made with great caution.

## 2.2 Renewable energy technology cost projections 2015 – 2030

The purpose of this chapter is two-fold: first, to provide an overview of the latest technology cost projection pathways; and second, to identify a set of investment cost 'planning values' for these technologies that would be relevant for Mexico. Planning values in the context of this publication should be understood as technology-wide investment cost projections representative of a possible techno-economical environment in Mexico throughout the projection period – provided materialization of certain key assumptions and prerequisites (e.g. technological advancements, further possibilities for cost reductions along the technology supply chain, significant additional installed capacities of the technology globally etc.).

Planning values should **not** be interpreted as a prognosis for the investment costs of a specific, individual project at a given point in time. Planning values are neither necessarily direct extrapolation of the current costs and cost trends observed in Mexico, as the present cost levels might be affected by short-term factors (e.g. developer hesitation to progress projects due to upcoming changes in the support policies, and higher costs due to lacking economies of scale in the industry as a result) as opposed to systematic, technology-specific drivers.

### Land-based wind

Land-based wind technology is deemed to be largely mature, and breakthrough innovations are not considered the most likely sources of capital cost reductions. Instead, evolutionary, incremental innovations (e.g. lower drivetrain and nacelle costs, lower balance-of-plant and development costs etc.) are expected to continue to reduce costs in the future. Figure 13 provides an overview of land-based wind capital cost projections. (It should be noted, however, that some of the technological innovations – e.g. larger rotors and higher towers – are associated with an additional capital expenditure, whilst increasing annual energy production or allowing to utilize lower wind speed sites and give higher full load hours. As such, the investment costs are only one component in the wind power technology development pathway, and should be regarded jointly with other key parameters within levelized cost of energy (LCOE) framework – illustrated at the end of this chapter.)

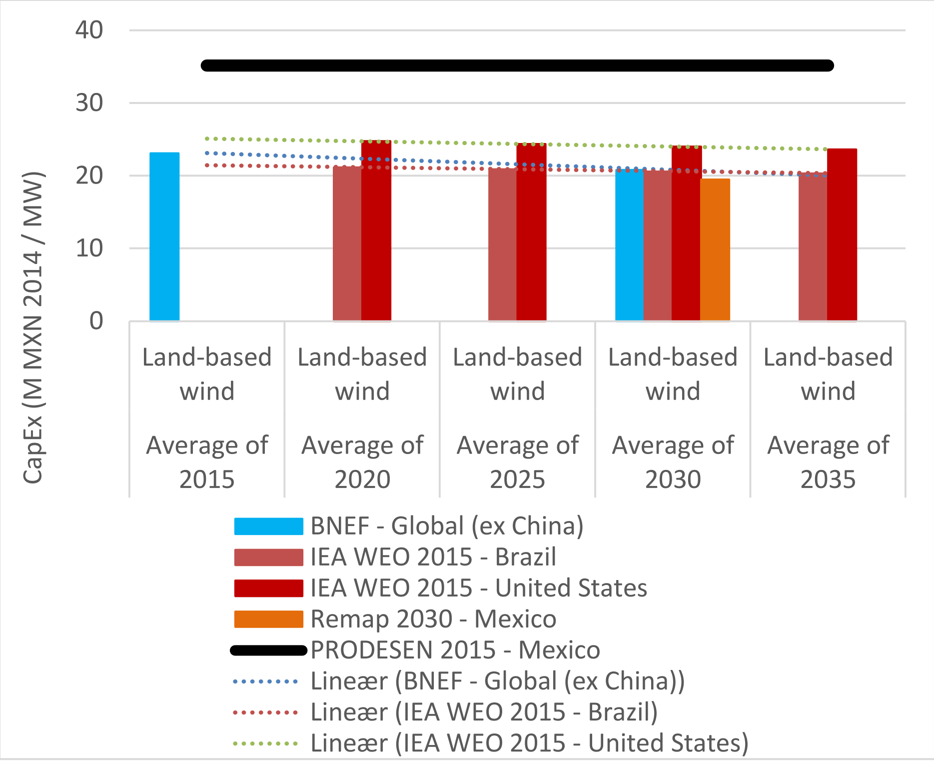



*Figure 16: Land-based wind capital cost projections based on various sources (M MXN 2014 / MW). Sources: (BNEF, 2015), (IEA, 2015), (IRENA, 2015), (SENER, 2015).*
*Note: Values for 2025 and 2030 have been linearly interpolated within the IEA WEO 2015 projections*

The investment cost projections appear to be largely in line with each other both in terms of the absolute cost levels, and the cost reduction trend (learning rate of 5 – 10% from 2015 to 2035). The convergence of wind power technology costs globally is likely to continue as industry matures and the installed capacities increase. Hence, the technology costs in Mexico are likely to converge closer to the global and regional (US and Brazil) costs levels in the foreseeable future. As such, cost level range between the 'Global excluding China' (as projected by BNEF) and the 'US' (as projected by the IEA WEO 2015) could be identified as appropriate for Mexico in the period towards 2030. I.e. 20.8 – 24 M MXN 2014 / MW, with a central value of 22.4 M MXN 2014 / MW.

### Solar PV

Continued decrease in solar PV capital costs is being projected despite the very rapid cost reductions observed for a number of years. The slowing rate of solar module cost reductions is projected to be compensated by the economies of scale and technological advancements enabled by continued capacity additions. Furthermore, optimisation of the balance-of-system costs is increasingly becoming a potential source of significant cost reductions, as the share of solar module costs in the total project costs is decreasing. Figure 14 provides an overview of the capital cost projections for utility-scale solar PV installations.

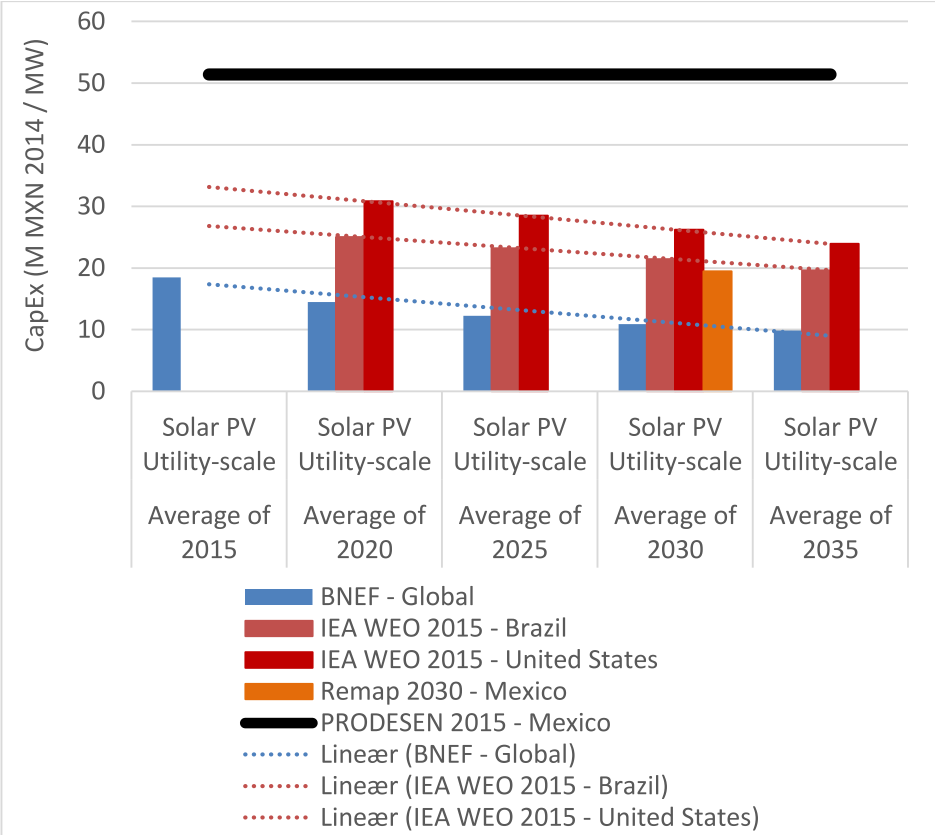



*Figure 17: Utility-scale solar PV capital cost projections based on various sources (M MXN 2014 / MW). Sources: (BNEF, 2015), (IEA, 2015), (IRENA, 2015), (SENER, 2015)*
*Note: Values for 2025 and 2030 have been linearly interpolated within the IEA WEO 2015 projections*

As can be seen from the graph, there is a wide range of expectations in relation to the development pathway of the solar PV investment costs in the future, albeit the downwards cost development trend appears to be fairly consistent across a number of projections.

Similar to wind power, the increasing commoditization of the industry is very likely to result in increasing convergence of the technology costs regionally and globally, with significant cost reductions anticipated towards 2030. The exact trend of cost developments is very difficult to anticipate, however, as many factors would affect its outcome. As such, the suggested planning value range for utility-scale solar PV installations for 2030 would be between the ambitious 'Global' (BNEF) and the more moderate 'Brazil' (IEA WEO 2015) estimate, i.e. 10.9 – 21.4 M MXN 2014 / MW, with a central value of 16.2 M MXN 2014 / MW.

### Geothermal

Geothermal technologies are deemed to be mature, and cost reduction potential projected therein is very limited, as illustrated by Figure 16.

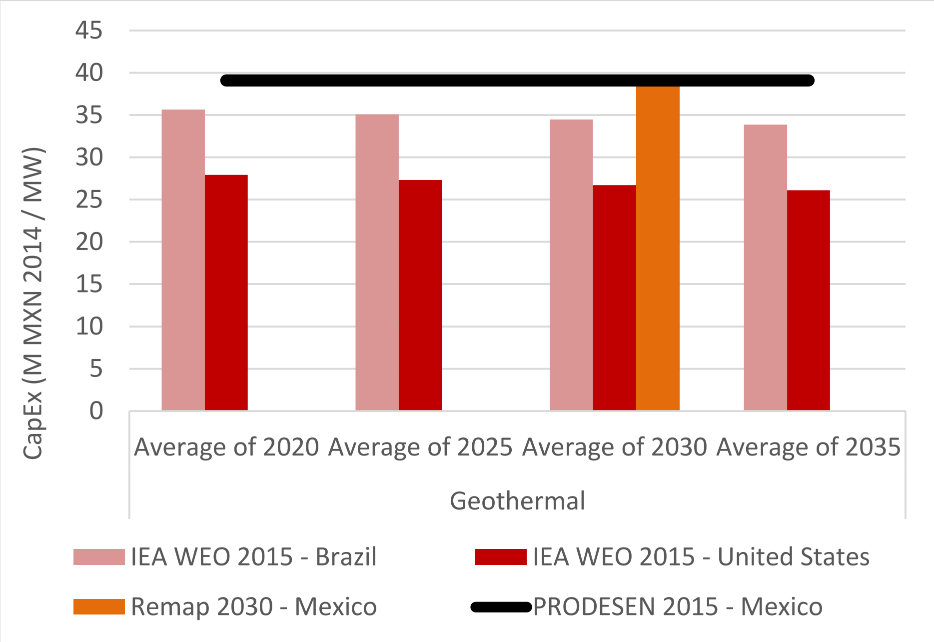



*Figure 18: Geothermal plant cost projections based on various sources. Sources: (IEA, 2015), (IRENA, 2015), (SENER, 2015)*
*Note: Values for 2025 and 2030 have been linearly interpolated within the IEA WEO 2015 projections*

For planning purposes, the investment costs for geothermal projects should be based on the individual project data to the extent possible due to the very site-specific nature of this energy source. In the absence of project-specific data, and in order to represent the diverse nature of geothermal projects, the planning values hereby recommended would be ranging from the lowest (IEA WEO 2015 US) to the highest (PRODESEN 2015) represented, i.e. 26.7 – 39.1 M MXN 2014 / MW, with a central value of 32.9 M MXN 2014 / MW for 2030.

### Hydropower

Hydropower is a mature technology, with limited cost reduction potential in most cases. Figure 15 provides an overview of the hydroelectric plant investment cost projections.

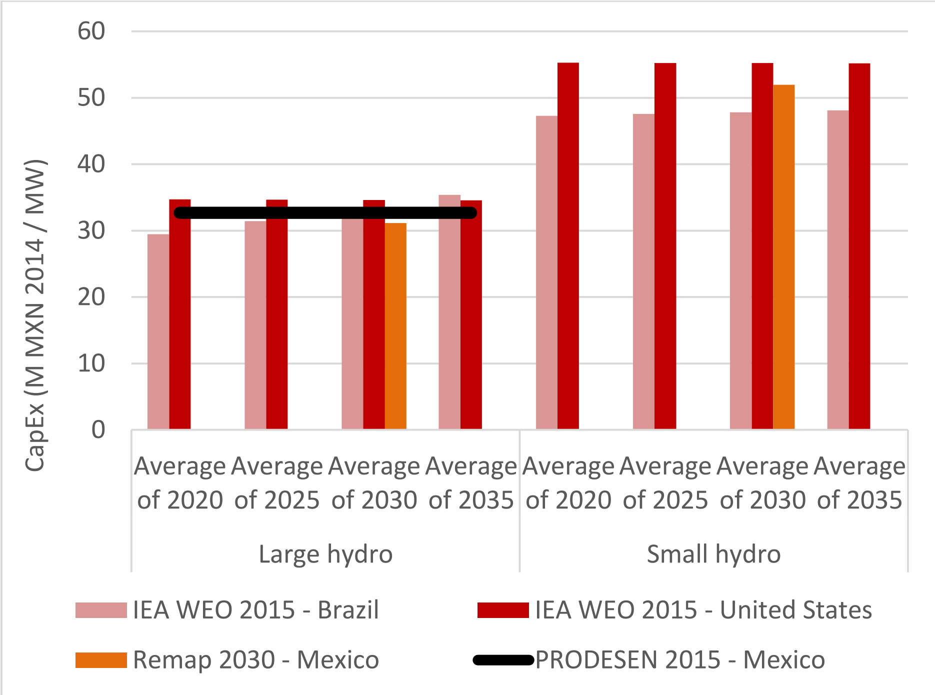



*Figure 19: Hydroelectric plant cost projections based on various sources. Sources: (IEA, 2015), (IRENA, 2015), (SENER, 2015)*
*Note: Values for 2025 and 2030 have been linearly interpolated within the IEA WEO 2015 projections*

As illustrated by the graph, the costs are projected to remain fairly constant over time. It should, however, be noted that the planning values for hydroelectric technology (large hydro in particular), similar to the geothermal projects, should be based on cost data for individual projects to the extent possible due to the very site-specific nature of this energy source. For small hydro power, it is hereby proposed to estimate the planning value investment cost range for Mexico between the IEA WEO 2015's 'Brazil' (47.8 M MXN 2014 / MW for 2030) and 'US' (55.2 M MXN 2014 / MW for 2030) projections, the two regional benchmarks. The central (average) planning value would therefore be 51.5 M MXN 2014 / MW, well in line with the REmap 2030's projections for 2030.

## Bioenergy

Investment cost projections for a number of biomass power generation technologies are provided in Figure 20. The technologies reviewed are all mature, and commercially available and therefore limited cost reduction potential is projected towards 2030.

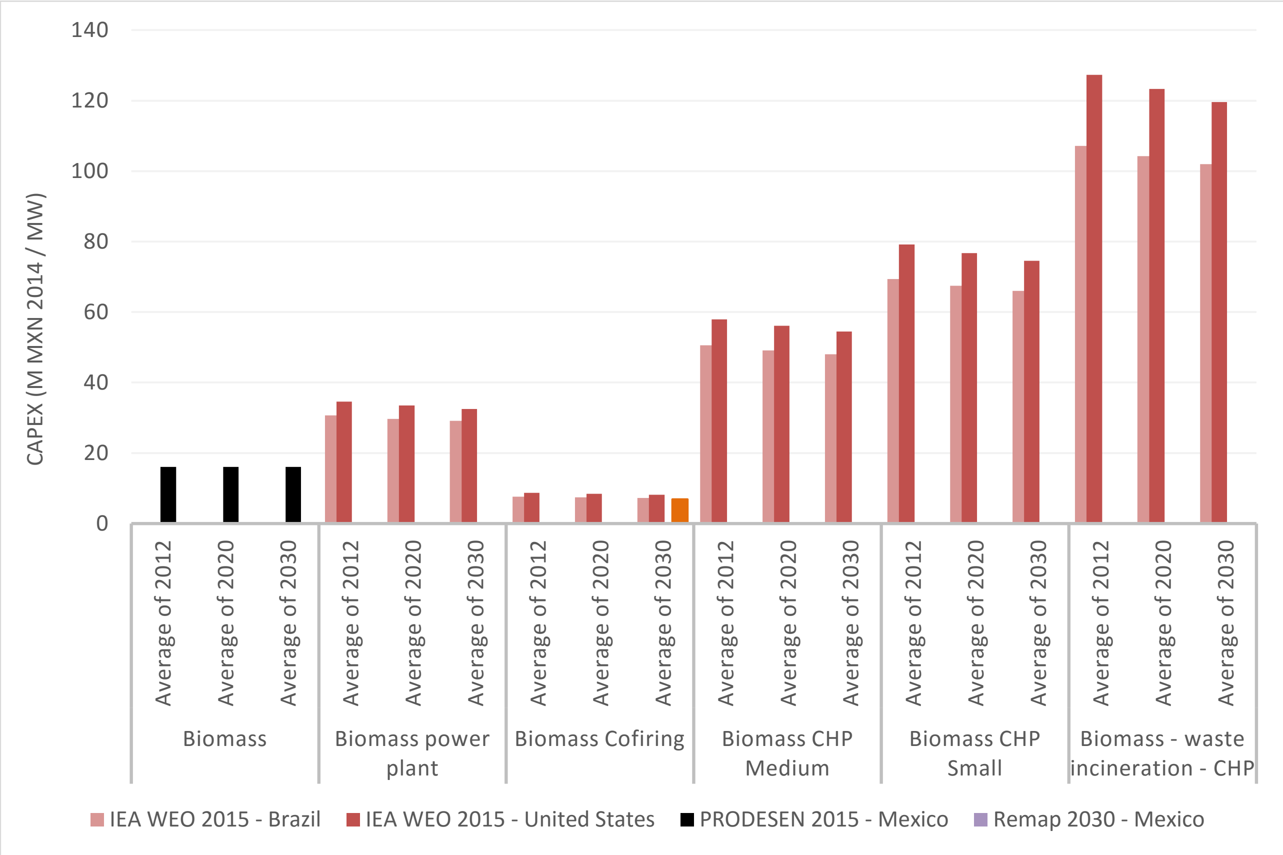



*Figure 20: Bioenergy plant cost projections based on various sources. Sources: (IEA, 2015), (IRENA, 2015), (SENER, 2015)*
*Note: Values for 2030 have been linearly interpolated within the IEA WEO 2015 projections*

Remap 2030 study for Mexico envisions a scenario with substantial power generation capacity additions arising from biomass co-firing in coal plants and combined heat and power plants in the manufacturing industry (IRENA, 2015). The exact bioenergy technology associated with the investment cost assumption used in the PRODESEN 2015 study has not been specified, yet the cost levels appear to be in between of the costs of co-firing and biomass power plant technologies.

## 2.3 LCOE Perspective

The focus of this analysis has been the capital costs, yet they are only one element in the cost of energy discussion. In order to represent the different energy technologies on a comparative basis, the planning values for 2030 (as prescribed earlier) will be applied in a levelized cost of energy (LCOE) perspective, with the other key inputs also represented. LCOE ranges will be represented for land-based wind, utility-scale solar PV, geothermal and small hydro technologies[1]. A spreadsheet-based cash flow model developed by the Energy Research Centre of the Netherlands (ECN) has been applied for the LCOE calculations, also used in the IEA Wind Task 26 – Cost of Wind Energy (IEA, 2015). Table 4 provides an overview of the LCOE assumptions used in the calculations, representing the central (and the ranges) of the planning values used to arrive at LCOE ranges for Mexico for 2030.

Additional assumptions include:

- Corporate tax rate of 30%
- Straight-line depreciation over 20-year period
- Loan duration of 10 years[2]
- Planning discount rate of 10%, in line with SENER methodology[3] (i.e. no representation of specific debt / equity financing structures and rates)
- No subsidies or support schemes
- Calculation made in real terms, i.e. no inflation has been applied
- No decommissioning costs
- No efficiency loss incorporated for solar PV

[1] LCOE ranges will not be estimated for large hydro, as these projects are too site-specific, and many other (e.g. environmental and social) factors need to be considered for a meaningful analysis. Biomass-fired technologies will neither be considered as the diversity of technologies, applications and fuels (and costs thereof) would require a more in-depth analysis, which is beyond the scope of the current Background Report.

[2] In line with (PwC, 2015)

[3] In line with (SENER, 2015)

| 2030 | Land-based wind | Solar PV | Geothermal | Small hydro |
|---|---|---|---|---|
| **Capital costs (M MXN 2014 / MW)** | 22.4 (20.8 – 24) | 16.2 (10.9 – 21.4) | 32.9 (26.7 – 39.1) | 51.5 (47.8 – 55.2) |
| **Capacity factor (%)** | 42.5 % (35 – 50 %)[1] | 23.5 % (20 – 27 %)[2] | 85 % (80 – 90 %)[3] | 40% (30 – 50%)[4] |
| **O & M costs per annum (MXN 2014 / kW)** | 560 (520 – 600)[5] | 254 (195 – 313)[6] | 1 055 (613 – 1 498)[7] | 726 (460 – 993)[8] |
| **Lifetime (years)[9]** | 20 (17.5 – 22.5) | 20 (17.5 – 22.5) | 25 (20 – 30) | 50 |
| **Discount rate (%)[10]** | 10% | 10% | 10% | 10% |
| **Construction period (years)[11]** | 1.5 | 1.5 | 3 | 4 |
| **Interest during construction (factor)[12]** | 1.08 | 1.08 | 1.12 | 1.22 |

*Table 4: Overview of the key LCOE inputs per technology for year 2030 – the central case (and the sensitivity range in parentheses)*

Figure 17 presents the resulting LCOE ranges, incorporating both the proposed capital cost planning values as per the table above, as well as the sensitivity of the LCOE to variation in the other key parameters.

[1] Based on COPAR 2015 (low) and current best sites in the US (high)
[2] Based on COPAR 2015 (low) and PwC Asolmex (high)
[3] Based on COPAR 2014 (central) and Lazard (range)
[4] Based on IEA WEO 2015 (range), central value averaged
[5] Based on (IEA, 2015) interpolated for 2030, Brazil for 'low', and US for 'high'
[6] Based on (IRENA, 2015) for 'low', and (IEA, 2015) 'Brazil' interpolated for 2030 for 'high'
[7] Based on (IEA, 2015) average between US and Brazil interpolated for 2030 for 'low', and the average from (CFE, 2015) for 'high'
[8] Based on (CFE, 2015) Chiapán for 'low' and (IEA, 2015) average between US and Brazil interpolated for 2030 for 'high'
[9] Based on (CitiGPS, 2013), (IEA, 2010), and COPAR 2015 (for hydro)
[10] In line with the planning discount rate in PRODESEN 2015. Loan duration assumed 10 years in line with (PwC, 2015)
[11] Based on IEA WEO 2015 and COPAR 2015 (for geothermal)
[12] Based on construction period, assuming linear investment profile, except for geothermal (investment profile and IDC factor from COPAR 2015 has been used)

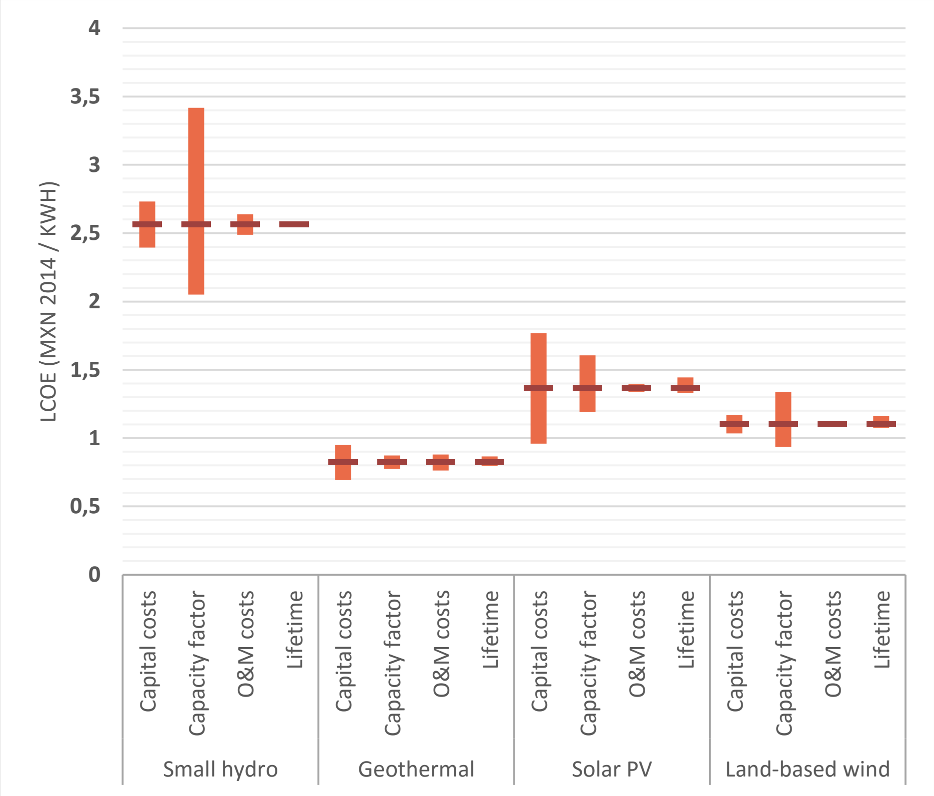



*Figure 21: LCOE ranges (bars) and LCOE average values (dashes) for the capital cost planning value ranges and central values, respectively, for Mexico for 2030*

These LCOE ranges represent both the different potential technology cost development pathway materializations towards 2030, as well as the potential variations in LCOE across different projects. Especially with regard to hydro and geothermal projects, large variations in the different cost components based on the specifics of each individual site could yield vastly different LCOE values. It should also be noted that the ranges represent single-parameter variation from the central case, whilst some of the parameter differences might be linked. E.g. higher capital cost for a wind power project (for turbines with larger rotors and / or taller towers) could yield higher capacity factor, with the net effect depending on the specific project.

Two main take-aways can be derived from the LCOE ranges obtained. First, capital costs and capacity factors are the most influential drivers of the LCOE for the technologies investigated (with the exception of geothermal, where the wide spread of O&M costs evaluated has a notable impact on the LCOE). The developments in these parameters in the future are likely to determine the viability of either technology. Secondly, land-based wind still appears to be generally less costly than solar PV in 2030, yet the project-specific factors (such as the capacity factor) could make solar PV cost-competitive with wind projects.

## 2.4 Implications for power system planning in Mexico

Accurate representation of technology characteristics and costs is of utmost importance for objective and trustworthy power system development planning studies. Inconsistencies in the inputs, especially in least-cost planning studies, lead to direct implications in the results, in terms of e.g. sub-optimal generation fleet composition or investment timeline. This is especially true for renewable energy sources (e.g. wind and solar PV) that, whilst being relatively mature technologies, still exhibit significant cost reductions (and performance improvements) that are projected to persist in the future.

The main focus of the current report has been renewable energy investment costs. Investment costs (as illustrated by the LCOE analysis) are one of the key determinants of the eventual cost of energy of a given technology, hence inconsistencies in the assumptions thereof can lead to significantly altered outcomes compared to an optimal least-cost power system development pathway.

Capacity factors are another crucial characteristic of wind and solar technologies, and, albeit they have not been a key focus area of the current report, a thorough review of the assumptions used in power system development planning could be recommended in order to accurately represent the potential of renewable energy in the future in Mexico.

The planning values (planning value ranges) brought forward by the current analysis could be either directly applied in the upcoming PRODESEN studies, or used as input for alternative. This would help provide a more accurate and nuanced representation of the latest developments of the renewable energy technology costs (and projections thereof), and their prospective impact on the optimal least-cost composition of the power system in Mexico in the future.

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# 3 System integration of renewable energy

The nature of the electricity system is such that the balance between demand and supply must be maintained second by second. The intermittent generation from renewable energy sources, like wind and solar, is driven by the meteorological conditions and must continuously be balanced by other generation.

Successful integration of wind and solar has been demonstrated in many countries, e.g. in Denmark, Germany and Spain – with 41%, 26% and 16% wind and solar in their systems (compared to yearly electricity demand), respectively. However, examples of less successful integration do also exist, e.g. from China, Ireland and Italy.

This chapter introduces key terms in system integration and summarise measures to improve the integration of wind and solar.

The term "system integration" of wind and solar covers two important issues:

- The costs associated with large-scale wind and solar generation, e.g. new transmission lines and start and stop costs for other generation. Also, balancing cost can be included here. Balancing services adress the lack of predictability.
- The value of the electricity generated by wind and solar. Large amount of generation, like wind and solar, can reduce the value of electricity generated. With good system integration, the value of the electricity generated can stay close to the average value.

All new generation affects the existing system, e.g. new efficient base load will also have impact on the performance of existing generators. However, the variable nature of generation from wind and solar – combined with the fact that these types of generation may be located far from demand centres - makes the system perspective especially important.

Typical cost for investment in transmission and distribution relating to renewable energy integration[1] can be between USD 2-13 / MWh (City, 2013). And

[1] It is clear that expansion of renewable energy requires expansion of grid capacity. However, it can be complicated to allocate the concrete investments to individual projects. Especially if the transmission grid investment is larger than the individual project and the resulting capacity can be used by many actors. Coordinated planning can help align transmission investments with the locations of renewable energy.

balancing cost[1] is typical in the range of USD 1-7 / MWh. In Denmark, the average cost of balancing wind power (2007-2013) has been USD 2.7 / MWh.

Good power system development practices must take the cost of integration (e.g. investment costs in new transmission lines, and the running costs for balancing) and the value of the electricity generated into account when planning for wind and solar. Focus on total system cost can be a way to balance transmission investments and location of new renewable sources.

Costs of alternative generation technologies (renewable as well as traditional) are often described by the levelized cost of electricity (LCOE) metric. The LCOE describes the costs of electricity per energy unit produced (e.g. MXN / kWh) – taking e.g. investment, variable costs, lifetime, full load hours and interest rate into account.

Comparing the LCOE of renewable energy and the typical electricity price (or the LCOE of other technologies) may not be enough to accurately establish whether an investment is attractive. The complete picture is only found when comparing the LCOE costs with the value of the generated electricity. With unsuccessful system integration, this value may by low. This is the case if the grid is weak and curtailment must take place to secure the balance in the local grid. The perspective here is national planning – not to be confused with the private investor perspective.

[1] Balancing cost represent the extra cost incurred by imbalances. Imbalances are defined as the deviation between the planned and the actual generation. In Denmark the Transmission System Operator (TSO) is in charge of activating up- and down-regulation to balance the system in real time. This is done based on the total imbalance in the system. After the day of operation these costs are distributed between the actors that have caused the imbalance. See case 3 in section 3.2.

**Merit order – optimal dispatch**

In effective electricity market systems, like the new Mexican market (with nodal pricing) or the existing markets in Europe (with price areas), a key feature is to secure optimal dispatch of all the possible generators. This is achieved by collecting bids about delivering electricity from potential generators. The bids describe the amount of electricity that is bid into the system and the price. The price would typically reflect the marginal cost of the generators.

Marginal cost for a fuel-based unit is the fuel price divided by the efficiency plus the variable O&M costs. For wind, solar and nuclear the marginal costs are close to zero. For hydro special considerations exist: Because the generation from hydro is limited by the inflow, these generators do not bid in with the marginal price (that is close to zero). They bid in in a way to maximise their income from the limited amount of water. The price they bid is called the water value.

Based on the bids for generation and the bids for demand, the market operator finds the solution with the lowest total costs. This will be the optimal dispatch, where the generators are activated in merit order (lowest marginal cost first) – respecting any limitation in the transmission grid.

When electricity is fed into the system from wind and solar (at low marginal price) other generators will reduce their generation. These generators will be removed from the list starting with those with the highest marginal costs.

In this way a market system can integrate wind and solar in an efficient way – without any explicit contract or agreement of doing so.

Hydro with reservoir as well as natural gas-based combined cycle plants have a special role in reacting to varying hourly prices – because of the good dynamic properties of these technologies.

## 3.1 Key terms in system integration

Value of generated electricity

The value of electricity generated is defined as the marginal cost of generation in a specific hour and a specific location. It is equal to the marginal cost at the most expensive generator (and should not be confused with the actual price paid to the generator or by the end-user). The marginal cost is a central planning property, both in centrally planned systems and in market based systems.

In PRODESEN the Mexican electricity system is studied in detail. The entire system is divided into 50 areas and the marginal price per area, per month is reported from, 2016 to 2032. In Figure 18, an example of these prices is given

(24 values for one area). Electricity generated in hour 13 has a value of US $ 48 per MWh, while electricity generated in hour 5 only has a value of US $ 37 per MWh. A traditional power plant could produce in the most expensive hours, while solar and wind generators produce when they can[1].

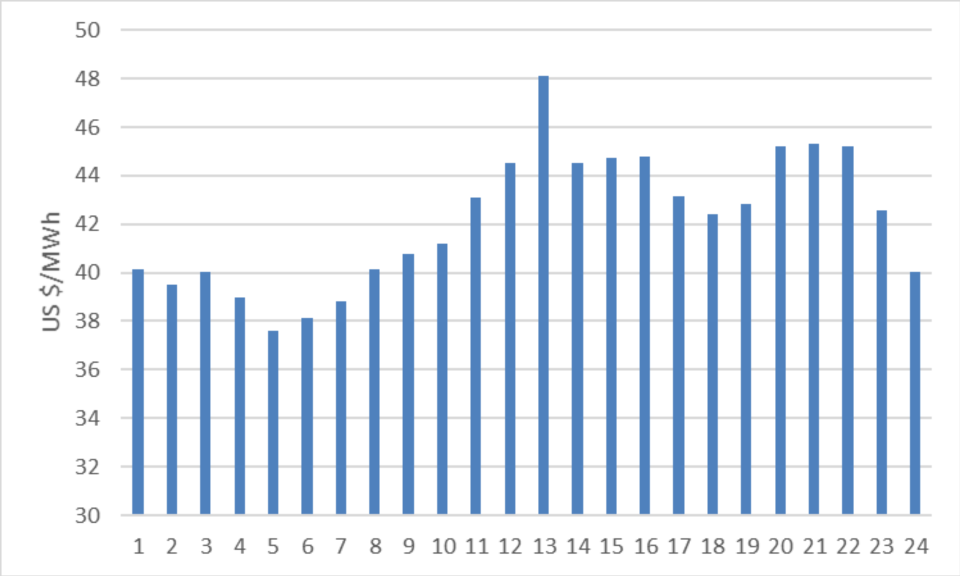


*Figure 22. Example of marginal prices from PRODESEN. Hourly data from area 1, Hermosillo, January 2016.*

How to measure system integration

With the planned expansion of variable renewable energy in Mexico, it is important to prepare for effective integration. This would ensure good value for the investments made, and avoid curtailment of renewable energy when the share of renewable energy in the power system increases.

The success of system integration can be measured in different ways, e.g.:

- Curtailment of generation: % of potential generation
- Price gap or value factor experienced by renewable energy: Measured as percentage difference in value of renewable-generated electricity compared to the average value.

Curtailment

Electricity is generated to meet electricity demand. In traditional electricity systems generation is managed to meet the varying demand based on the cost of generating electricity. This is also the case when large shares of wind and solar exist. However, in some cases the generation from these sources needs to be curtailed.

[1] All generators, traditional or renewable, can decide only to generate when the value of electricity is above the marginal cost for their specific plant. A peak plant may have a relatively high marginal cost and would only generate when the value was high. Wind and solar have low marginal cost and should generate when they can – and when there is a positive value for electricity.

If generation in a grid section threatens to exceed the demand plus the possible export to other areas, curtailment must take place to avoid overloading of lines. If the conventional power plants cannot reduce their output, wind and solar generation must be reduced. It is common practice for system operators to have control systems in place, so that e.g. selected large solar or wind parks can be curtailed if needed. Curtailment means loss of electricity generation (and economic costs associated with the fuel use, and extra GHG emissions arising from the generation that could have been replaced by the potential renewable generation). However, if the amount of curtailment is limited, this can be the least-cost option. In many countries with high shares of wind and solar generation, curtailment of wind power is in the order of 1%. This can be considered as a sign of effective integration.

Curtailment typically takes place during combination of high wind conditions and low demand. Also crucial is the available export capacity out of the area with wind and solar.

Critical examples exist with curtailment in the order of 15-30% of the potential wind generation. High curtailment rates existed in Italy (10% in 2009), but expansion of grid capacity resulted in drastically reduced curtailment (to 0.7% in 2014) – in a period with increasing wind capacity. Table 5 illustrates that it is possible to have between 5% and 41% of wind and solar (compared to yearly demand) without significant curtailment (less than 1% in the five out of six countries). Highest curtailment values are found in Ireland. Ireland is a relatively small system, and it is only weakly connected to the neighbouring main Great Britain system.

| | Denmark | Spain | Ireland | Germany | Italy | France | Mexico |
|---|---|---|---|---|---|---|---|
| Demand, TWh | 33 | 243 | 27 | 514 | 309 | 463 | 300 |
| Wind and PV, % of demand | 41% | 26% | 17% | 16% | 12% | 5% | 2% |
| Wind curtailment | 0.2% | <1.5% | 4.3% | 0.9% | 0.8% | 0% | n.a. |
| PV curtailment | 0% | <1.5% | - | 0.2% | 0% | 0% | n.a. |
| Wind capacity factor | 31% | 25% | 26% | 16% | 20% | 21% | 30% |
| PV capacity factor | 11% | 20% | - | 10% | 14% | 13% | 24% |
| Interconnector factor | 44% | 3% | 9% | 10% | 7% | 10% | 1.3% |

*Table 5. Examples of wind and solar generation and curtailment in six European countries. The interconnector factor is defined as the interconnector capacity to other (EU member) countries compared to the national generation capacity From: Ackermann et al, 2015, European Union, 2015, and PRODESEN, 2015.*

Model studies reviewed indicate that curtailment becomes relevant when generation exceeds a certain threshold: 25% in Egypt, 20% in Texas, and more than 22% in Estonia[1]. The actual threshold, e.g. for Mexico, is heavily dependent on the location of the generation and the expansion of transmission capacity.

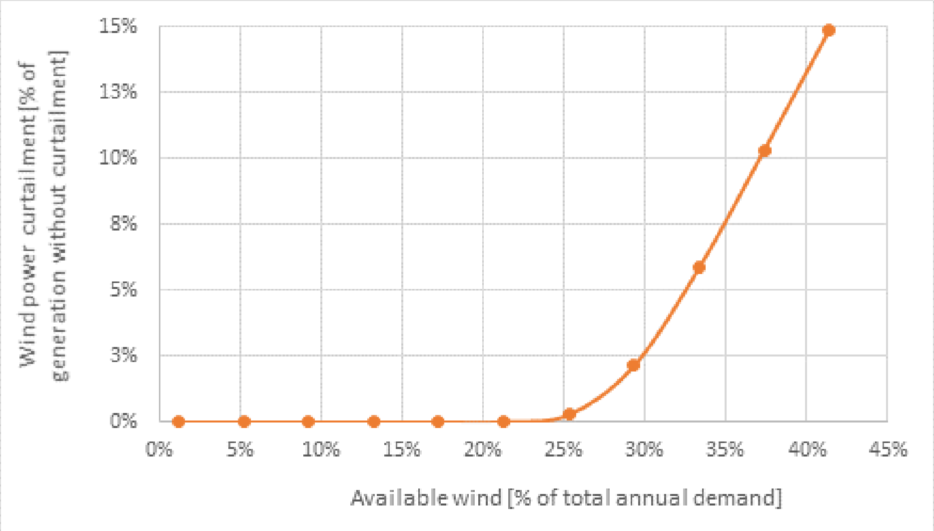


*Figure 23. Curtailment in the Egyptian system with increasing amount of wind power. Model study of the current system (no reinforcement of transmission capacity).*

Value of electricity

When significant wind and solar capacities are introduced in an area, the value of the generated electricity from these technologies will fall. The first installed capacity may replace expensive generation (e.g. oil-based), while cheaper generation may be replaced with additionally increased wind and solar generation.

How much the value will fall depends on the integration measures taken, e.g. new transmission capacity and increasing flexibility of traditional generation. The difference between the average value of electricity and the value of electricity generated by wind and solar can be used as a measurement of the successful integration: Small differences is an indicator of successful integration. If the value of electricity generated by wind and solar is much lower than the average value, then this is a sign of unsuccessful integration.

[1] Egypt: Draft model results by Ea Energy Analyses (2015). Texas: See page 377 in IEA (2015). Estonia: See Ea Energy Analyses (2010).

In Denmark, wind power has generated electricity 5-15% below average price, i.e. the value factors for wind power are 0.85 to 0.95 (2002-2014)[1]. The close location (including strong transmission capacity) to the large hydro capacities in Sweden and Norway is the major reason for the low price gap. However, model studies of system development suggest an increasing difference for the future.

Based on the expansion in Germany the following relation has been found for the value factor (Mueller, 2015):

$$Value\ factor = \frac{Wind\ (or\ solar)\ power\ realized\ price}{Average\ power\ price}$$

$For\ Wind$:
$Value\ Factor\ =\ 1.1 - 2.2\%\ \times\ W$

$For\ Solar$:
$Value\ Factor\ =\ 1.2 - 4.8\%\ \times\ S$,

$where$
$W\ =\ Market\ share\ for\ wind\ power$,
$S\ =\ Market\ share\ for\ solar\ power$

This is in line with the other studies: Solar starts out better (with higher value factor), but the reduction in value arising from increasing penetration is larger than that for wind. The smoothing out of the variation in higher for wind.

Today, Germany has 9% wind and 6% solar, and the value factors are: 0.86 and 0.98.

Hydro power generates 13% of the electricity in Mexico (2014). The interaction between wind, solar, and hydro is the main key to successful integration. The interaction between wind and solar, on the one hand, and the hydro on

[1] Note that this is referring to the value of the electricity generated. Not the cost of producing it. In general, the value of electricity generated from solar start with a positive price gap – because demand in general is higher during the day, where the PV's are producing. In IEA (2015, page 378) it is illustrated how the value of wind and solar develop – based on a model study about California. For small amount of wind and solar the value is US $ 88 per MWh for solar and US $ 65 Per MWh for wind. At 10% penetration the value is US $ 55 for both technologies, and for high penetrations solar is decreasing more than wind. The reason for the more stable value for wind can be that more smoothing take place for wind (across wind power at different places), while solar is more in sync. The reduction for wind at 10% penetration is equal to 15% price gap (assuming that the starting point of US $ 65 per MWh is close to the average value of electricity.

the other hand, can (as in Denmark) effectively take place through the market. The influence of wind and solar on the hourly market prices is the motivation for the owners of hydro resources to adapt their generation. No direct agreements are needed.

In addition, the fact that half of the Mexican electricity generation (2014) comes from natural gas-based combined cycle units is a good starting point for integration. These units have good dynamic properties (e.g. high ramping rates, short starting times and low minimum loads), which has a value in relation to large amount of wind and solar[1].

Decentral generation

PV technology can be scaled in any size. A significant share of global PV expansion comes as rooftop installations. In the REmap study 25% of the PV expansion is expected to be rooftop installations (7.5 GW out of 30 GW).

Rooftop PV often has capacities in the order of 1 – 10 kW. These installations can be used to cover the building's electricity demand and may in periods with high sun and little demand export the electricity to the local grid. If this takes place on a large scale, it can influence the operation of the grid, e.g. influence the voltage, or even lead to export of electricity from a low voltage grid to the higher voltage grid above this. This requires new procedures and may also require investment in new grid capacity or control equipment.

Because of the small capacity it is typically too expensive to introduce central control of such units. So they are operated as "must produce" units. Any adjustment of generation will be done on other units.

The Electricity Industry Law in Mexico defines distributed generation as units with capacity of less than 500 kW.

## 3.2 Measures to improve system integration

Electricity system in Mexico, as well as in most other countries, has not been developed with variable renewable energy in mind. Therefore, when a significant amount of variable renewable energy is introduced, it can be relevant to develop a number of activities to improve system integration. This can include many aspects, e.g.:

[1] In contrast, generation technologies like nuclear and large coal fired power plants are less dynamic and are often used as base load with little variation in output.

- Increased transmission capacity (in Mexico as well as to neighbouring countries)[1]
- Improved market function, with all generators producing according to marginal costs (reduce must-run and fixed payments). Optimal use of hydro with storage. Hourly and sub-hourly dispatch. The Mexican electricity market will start in January 2016 and has many of the features needed to motivate maximum flexibility from all generators, including prices that vary by the hour and locally (in the many P-nodes) (Bloomberg, 2015)
- Improved dynamic properties of traditional power plants. A number of low-cost improvements can be made on existing coal-based power plants to decrease minimum load, increase ramp rates and reduce start-up costs (see Danish Energy Agency, 2015, a). A review of five Mexican power plants describes the possibility to improve low load operation and increase ramp rates[2] (see Danish Energy Agency and Ramboll (2014)). Dynamic market prices will motivate generators to exhibit flexibility, also when designing new plants. Mexico has significant capacity in hydro and gas (56% of current generation capacity). These technologies are generally flexible and valuable assets in integrating wind and solar.
- Reducing the need for having traditional generators running for ancillary services like voltage, reactive power and inertia[3].
- Demand response (price-dependent electricity demand), e.g. with fuelshift in industry
- Improved procedures for real-time planning and operation of the electricity system near to the operational hour. This can include improved procedures to activate regulating power before the imbalances occur. A key feature is to utilise real-time measurements for demand, wind and solar generation to create a prognosis for the next hour's imbalance (see Danish Energy Agency, 2015, a).
- Activating new sources for balancing the system, including exchange with neighbouring countries, activating small generators and wind power (down regulation). This requires open and simple procedures, e.g. not to require bidders to give symmetrical bids (both up and down) and not to require bids to be active for long periods (an hour

[1] European Union has formulated it as a goal that each member state must have at least 10% interconnector capacity to other member countries in 2020. The 10% is defined as the interconnector capacity to other EU member states compared to the national generation capacity. For 2030 the goal is 15%. For Mexico the current interconnector capacity (865 MW to USA and Belize) is 1.3% of the installed generator capacity.

[2] The five plants are: 1200 MW TPP "Josè Lopez Portillo; 2778 MW TPP "Plutarco Elías Calles"; 1400 MW TPP "Carbón II"; 382 MW CCGT plant "San Lorenzo"; 591 MW CCGT plant "El Sauz".

[3] Denmark can today operate with medium wind speed without any central power plants running. In 15 hours on 2 September 2015 less than 12 MW of traditional (large) power plants were generating. The demand was between 2,800 and 4,800 MW in these hours. Investment in new units like VSC-HVDC interconnector, Synchronous Compensators and Static VAR compensator (SVC) makes this operation possible. Before these investments 3-6 power plants were needed online at all times. See Akhmatov et al (2007).

rather than a month). In the future electric vehicles may also be activated for demand response (intelligent charging).

Additional actions may be required to maintain secure system operation, e.g.:

- Control systems that enable curtailment of e.g. wind and solar generation. This can be relevant for selected units, e.g. over a certain capacity.

Parson et al. (2014) list best practise procedures that can be followed in studying the integration of wind and solar in Mexico. These include:

- Important to have access to historic wind and solar resource data to capture temporal and spatial diversity, which will be needed to correlate wind generation with solar generation and electric load.
- Important to collect basis data about system operation e.g., forced outage and generation by independent power producers; performance data and forecasts for small generators; load forecast errors and operational load; performance data for the conventional and hydropower generation fleet.
- Important to have planning models for assessing expansion scenarios for renewable and conventional generation and transmission.
- Important that the market design supports efficient integration of renewables, e.g. with short-term dispatch and unit commitment.
- Develop grid codes, e.g. so that requirements for wind turbines would include fault ride-through, provision of reactive power, and possibly automatic generation control, AGC.

The International Energy Agency, IEA, reviewed the flexibility of the Mexican electricity system (IEA, 2011). Examples of the identified challenges included:

- Limited interconnectors to neighbouring countries (865 MW DC).
- Internal connection between the four Mexican balancing areas is limited[1]

[1] The four synchronous areas are: The National Interconnected System (entire country, except Baja California). In peninsula of Baja California three system is operated: Baja California, Baja California Sur and Mulegé.

## Examples of measures that facilitate integration of renewable energy

**Case 1: Location of renewable generation**

For the initial expansion, it is value-adding to locate wind and solar units where the resources are best. However, with significant build-out of such generation, the value of the generated electricity tends to decrease. Therefore, locating additional generation in other places will have benefits:

- The value of the generated electricity may be higher. Investment in transmission may be reduced.
- With a certain distance to the high wind areas, a smoothing of the generation will take place. The generation from wind and solar in Mexico will be much more smooth and predictable than the generation from a single location., and therefore also easier to integrate in the power system

**Case 2: Low wind turbines**

A central design feature of wind turbines is the ratio between 1) hub height, 2) rotor diameter and 3) generator size. Low wind turbines have a relatively large rotor diameter compared to the generator capacity. A simplified representation of a conventional and a low wind turbine is shown in Figure 19. The low wind turbine has a lower cut-in speed and reaches its rated power generation capacity at a lower wind speed.

In some cases, it can be attractive to use low wind turbines. The generation from the low wind turbine is more stable (more full load hours) and the lower maximum generation reduces the generation in the hours with excess wind power (the less frequent high wind hours).

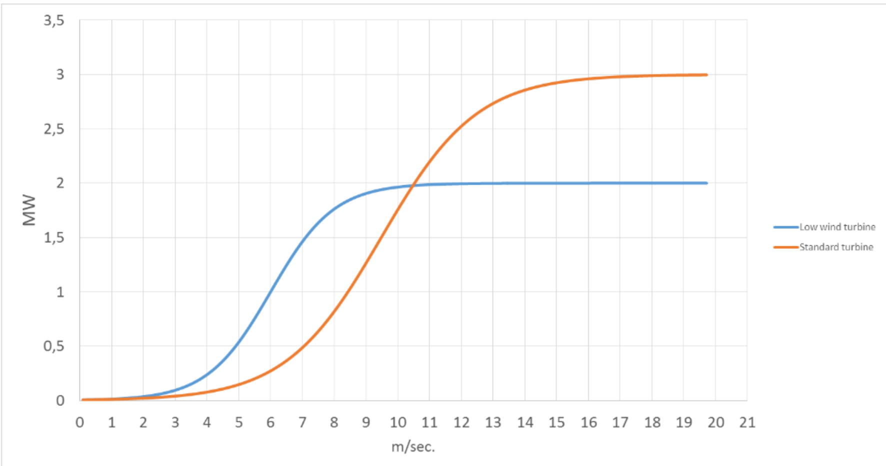


*Figure 24. Simplified power curve for a standard wind turbine and low wind turbine.*

Source: Product data from Vestas. See also Mueller (2015).

**Case 3: Procedure in relation to the activation of reserves**

The Danish electricity demand is 33 TWh/year with a peak demand of 6,200 MW. The installed wind power capacity in Denmark is 4.800 MW and solar is 620 MW. Interconnectors of 6,000 MW exist to the neighbouring countries (Sweden, Norway and Germany).

Automatic reserves (primary and secondary) are central to maintaining a stable electricity system. When a fault happens, e.g. loss of a power plant, the frequency and exchanges in the synchronous system will change, and the automatic reserves will instantaneously kick in and replace the missing generation. Manual reserves are then activated by the control room to release the primary and secondary reserves.

A common practice is to activate reserves "in real time", as the events occur. If the main drivers for imbalances are random and essentially unpredictable outages of generators, this is a relevant procedure.

As the installed wind power capacity in Denmark was increasing, however, Energinet.dk started developing a system to predict the imbalances. A system called Operational planning system, DPS, was created. The system collects data from numerous sources and presents a single curve for the operators in the TSO control room. The curve shows the predicted imbalance in the system.

The data used to collate the predicted imbalance in the system is as follows:

- Wind power. Each five minutes a new prognosis is produced. The frequent updating uses online measurements to correct the meteorological predictions (these are only updated each four hours). The online measurements represent a large sample of all the wind power units and are up-scaled to represent the entire generation.
- Solar power. A similar system is used to predict the power from the PV systems.
- Demand. Also for demand, the prognosis is frequently updated based on online measurements (of generation and import/export).
- Plans for the market participants. Detailed plans are received e.g. for all major generators. These plans have information about the expected generation in five minute intervals[1].

The predicted imbalance curve will cover the next 12 hours. When significant imbalances are foreseen, the control room operators will:

- Discuss with neighbouring TSO's if imbalances can be exchanged (at no cost), e.g. if Sweden has a positive balance and West Denmark a negative balance – and if transmission capacity is available, the two imbalances can offset each other. This also applies to the exchange between the two Danish areas (DK1 and DK2, West and East – that are a part of two different synchronous systems).

- Activate tertiary reserves (regulating power) to outweigh the expected imbalance. This is done from a common Nordic system (with bids from four countries), the NOIS list.

The traditional procedures for activating reserves can be called reactive, while the Energinet.dk approach can be called proactive. *In popular terms the new procedure can be described as "driving looking through the front window" in contrast to "driving looking in the rear view mirror".*

[1] This is in contrast to the spot market, Nord Pool Spot, which operates with hourly values.

**Case 4: System-wide and regional need for reserves**

The Danish TSO, Energinet.dk, reports that the introduction of 4,800 MW wind and 600 MW solar power *has not yet influenced the amount of planned reserves used in the system.* To understand this statement a simple presentation for the basic framework of having reserves is presented.

*A small islanded system*

In an isolated system the largest unit may be 600 MW. Such a system (based on the N-1 principle) would need to have 600 MW primary reserve, no secondary reserve[1] and 600 MW of tertiary reserve. If the tertiary reserve can be activated within 15 minutes, then this system can withstand one big fault – and after 15 minutes another one. If two large faults occur with less than 15 minutes apart, the reserves would not be able to manage the lack of generation and load shedding must be activated (e.g. with under frequency relays).

*A two-area system*

Imagine a system with two equally large areas A and B. The largest fault is still 600 MW. Based on the above principle, the total amount of primary reserve must be 600 MW and this could be divided equally to each of the two areas (2 x 300 MW). The secondary reserve must be 600 MW in each system (assuming that each system has a unit of this size). Each system may also need 600 MW of tertiary reserves.

*UCTE – reserves, wind and solar*

The UCTE is a large synchronous system, from Denmark in North, to Portugal in the South/West and Italy in the South: 2,300 TWh, 400,000 MW peak load, 100,000 MW wind and 72,000 MW solar. In this system 3,000 MW is considered at the dimensioning error. West Denmark must cover a fraction of this, computed as the fraction of demand: 23 MW as primary reserve.

In West Denmark the dimensioning error is 600 MW, so this is also the required amount of tertiary reserve. For tertiary reserve (regulating power), the situation is that there typically is a large surplus of this. The hydro power in the other Nordic countries typically has a large unused capacity. Depending on the expected operation and availability of the cross-border transmission capacity, Energinet.dk may reserve capacity for the tertiary reserve. Typically, Energinet.dk reserves 200-300 MW upregulation and no downregulation (Denmark, West, 2014-2015).

The dimensioning error represents a sudden incident. In a fraction of a second 3,000 MW (UCTE) generation can be lost, e.g. if a short circuit isolates a power plant from the grid (In Denmark the dimension fault is 600 MW).

Energinet.dk highlights that the introduction of wind and solar power has not increased the need for reserves in UCTE or Denmark. In Denmark wind and solar is 5,400 MW, and in UCTE it is in the order of 172,000 MW.

The background is that prognosis errors from wind and solar may be large on a day-ahead perspective, but will gradually be reduced as the time is approaching the operating hour and second. The hour-ahead error will be much smaller than the day-ahead error. And, below the hour-ahead the actual (and partly un-predicted) generation from wind and solar will influence the frequency and the flow on the interconnectors. Thereby reserves will be activated and balance will be re-established.

So, despite the large size of the wind and solar capacity the sudden (unpredicted) change in output is still considered smaller than 3,000 MW (the dimensioning error) on UCTE scale.

On a day-ahead scale the typical forecast error for wind power in Denmark is in the order of 20% (Mean Absolute Percentage Error, MAPE); however, this is continuously reduced as the time is approaching the operating second. While the output from a single wind farm may change rapidly, the aggregated output from a large area as UCTE (2,500 km from North to South) will develop quite smoothly. With continuously expanding capacity of wind and solar, at some point this will result in extra need for reserves. However, UCTE is not at this point, yet.

## 3.3 Possible actions in relation to system integration

Possible actions:

- The future Renewable Energy Outlook (REO) could report on system integration. Together with information about the power generated from renewable sources the year before, information about curtailment and the realised price gap / value factor could be reported. Price information will be available from market systems going forward. Renewable generation must be recorded per P-node to compute the price gap.
- Evaluate possible expansion of transmission capacity – both internal and in relation to the neighbouring countries – in light of the expansion of renewable energy.
- Secure that market systems as well as procedures for ancillary services are efficient and support the flexibility of the system

[1] The purpose of the secondary reserve is to locate in which control area the fault has occurred. With only one control area, there is no need for the secondary reserve.

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# Appendix 1: Model-based energy scenarios

*In this text, "model-based energy scenarios" refers to computer-generated results describing potential developments of the electricity system in a country or a region.*

Computer models as tools

Using computer models to describe potential futures has an analytical purpose. The idea is not that the computer should make policy choices. Instead, the results from a group of scenarios will help in qualifying the political discussion.

Electricity systems are large systems where interactions take place through synchronous AC systems, e.g. covering distances of more than 2,000 km (e.g. from West Denmark to Portugal). The balance between demand and generation must be maintained at the level of microseconds and extra input of electricity at one point must be balanced by reducing generation elsewhere. These features make it relevant to study the impact of new technologies like wind and solar power in models covering large areas, e.g. large synchronous areas.


*Figure 25. Transparency requires that all input data is published and can be reviewed, and that methods are documented and are easy to understand. If this is fulfilled, results can be fully understood.*

With a transparent set-up the discussion can change from "for or against" a certain technology, to a discussion about the assumptions. If parties can agree on the assumptions (including input data) and understand the methods, then reaching a consensus on the results is realistic.

Input data

Input data includes data about future values, e.g. the future cost of fuels, the future investment costs of technologies, including generation technologies like wind power, PV and nuclear power. Such data may be debated and important sources can be *technology catalogues* e.g. from the International Energy Agency, U.S. Energy Information Administration or the Danish Energy Agency[1]. See also chapter 2.

| Technology type | Available (Year) | CAPEX incl. IDC ($M\$/MW_{el}$) | Fixed O&M ($\$1000/MW_{el}$) | Variable O&M ($\$/MWh_{el}$) | Efficiency (%) | Technical lifetime (Years) |
|---|---|---|---|---|---|---|
| Steam Coal – Subcritical | 2020-2034 | 1.8 | 45 | 3.8 | 35% | 30 |
| Steam Coal – Subcritical | 2035- | 1.8 | 45 | 3.8 | 35% | 30 |
| Steam Coal – Supercritical | 2020-2034 | 2.2 | 63 | 5.3 | 40% | 30 |
| Steam Coal – Supercritical | 2035- | 2.2 | 63 | 5.3 | 40% | 30 |
| CCGT | 2020-2034 | 0.8 | 25 | 2.1 | 59% | 30 |
| CCGT | 2035- | 0.8 | 25 | 2.1 | 61% | 30 |
| Gas turbine | 2020-2034 | 0.4 | 20 | 1.7 | 38% | 30 |
| Gas turbine | 2035- | 0.4 | 20 | 1.7 | 40% | 30 |
| Geothermal | 2020- | 4.3 | 43 | 3.1 | | 30 |
| Medium Speed Diesel (MSD) Engine | 2020- | 1.6 | 22 | 1.8 | 45% | 30 |
| Low Speed Diesel (LSD) Engine | 2020- | 2.4 | 10 | 0.8 | 46% | 30 |
| Nuclear | 2020- | 5.7 | 140 | 0.0 | 33% | 60 |
| Solar PV | 2020-2034 | 1.9 | 24 | 2.0 | | 25 |
| Solar PV | 2035- | 1.5 | 23 | 1.9 | | 25 |
| Wind – onshore | 2020-2034 | 1.5 | 22 | 3.7 | | 20 |
| Wind – onshore | 2035- | 1.4 | 21 | 3.5 | | 20 |

*Table 6. Example of technology data about future investment costs etc. from IEA. Data used for the 2014 Master Plan for Eastern African Power Pool. Note that variable fuel cost for e.g. coal or natural gas units typical is in the order of US $ 50-100 per* $MWh_{el}$*. In this perspective, the shown O&M costs are relatively small.*

Future data about fuel and technology costs are intrinsically uncertain and it can be relevant to use scenarios to show the impact of alternative values, e.g. with higher and lower values. Such sensitivity analyses can illustrate the robustness of results.

Methods: Optimal dispatch and optimal investments

The need to balance electricity system in short time scale and the possibility to import and export electricity over long distances makes the dispatch problem suitable for model studies. Optimal dispatch of generation in large systems with limited transmission capacity requires the use of computer models.

[1] IEA, Technology roadmaps: www.iea.org/roadmaps/
IEA, World Energy Outlook: www.worldenergyoutlook.org/
Future investment costs: www.worldenergyoutlook.org/weomodel/investmentcosts/
U.S. Energy Information Administration (EIA):
www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/updated_capcost.pdf
Danish technology catalogue: www.ens.dk/node/2252
Irena Mexico study. See page 92 for technology costs:
www.irena.org/DocumentDownloads/Publications/IRENA_REmap_Mexico_report_2015.pdf

Optimal dispatch is well defined: if the marginal generation costs are known for each generator, one solution will have the lowest total costs. The marginal cost of traditional power plants is defined as the fuel price divided by the efficiency. Wind and solar power have high investment cost, but their marginal generation costs are close to zero. These technologies will produce when the sun is shining or the wind is blowing[1]. Hydro plants with reservoir also have a low marginal cost. However, the optimal dispatch of such hydro plants must consider that the units are restricted by the inflow of water. Optimal dispatch of hydropower means optimal use of the available water across a longer period, e.g. a year. The optimal use of hydropower is to optimise (maximise) the value of the electricity generated.

In the simplest set-up, each hour is considered independently, start-up and stop costs are ignored. These costs could be included in the modelling to make the dispatch more realistic, since power plants that are running in one hour are likely to continue generation in the next hour. Using such *unit commitment costs* will increase computer time and the more detailed dispatch is often not needed in studies of future situations as the change in the total annual system costs may not change significantly. Simulation to be used in the daily operation can be more detailed than in future scenario analyses. In future scenario analyses, unit commitment may not be applied and representative weeks can be included instead of the full number of hours of each year (8760).

Scenarios may include model-based investments in generation and transmission. Model-based investment may take place in a simplified way, e.g. the model may invest if the annualised costs of investments is less that the benefit in the same year. The set-up can be called myopic because the future use of the investment is not included.

Scenarios

Scenarios can be defined to support the political discussion. They are not meant as predictions, but as possible futures. Models are simplifications of real life and the absolute results may not always be accurate. However, the difference between two scenarios may be more accurate, e.g. changing an input parameter will produce differences both in dispatch as well as investments.

[1] In situations with large *must produce* generation the electricity price may be negative and it is relevant to curtail wind and solar.

The reference may be a frozen policy scenario: all framework is ‘as today’. Any planned change is ignored. Alternatively, it may include expected changes in the framework. In Figure 26, a set-up with 21 scenario is illustrated. In this case all scenarios are one-step away from the reference (one parameter is changed). In this way, it is easy to analyse even a large number of scenarios. In other studies, scenarios must be analysed is steps (see Figure 26).

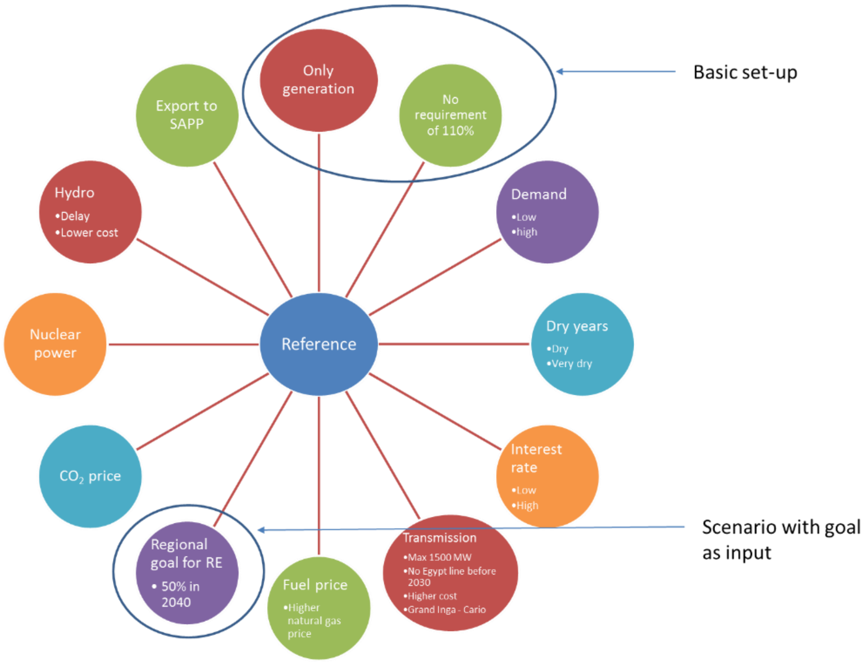


*Figure 26. A reference and 20 alternative scenarios:*
*17 parameter variations (e.g. demand, hydro inflow or interest rate)*
*1 goal scenario (50% renewable energy in 2040).*
*2 basic variations (Only generation, where no investment in transmission takes place, and No 110%, where the requirement that each country should have local generation capacity corre-sponding to minimum 110% of the peak demand, is removed).*

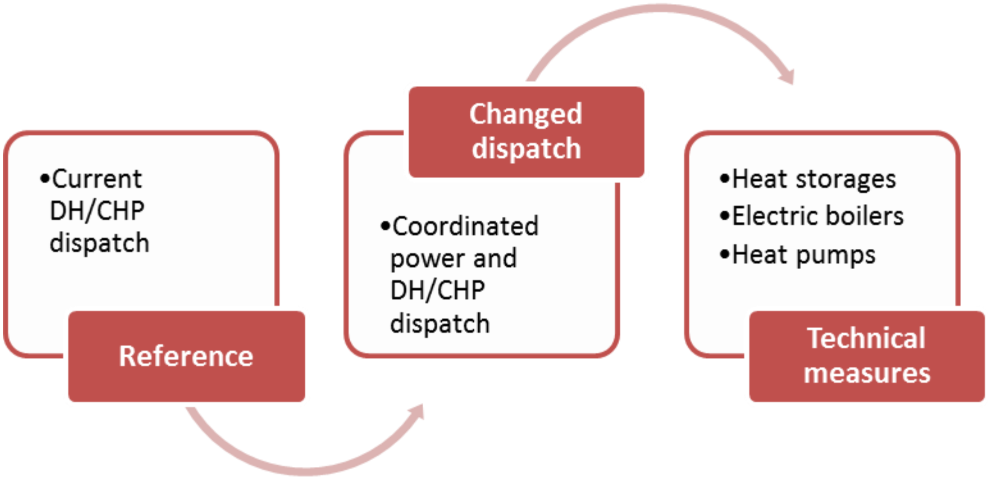


*Figure 27. A two-step approach of the design of five scenarios: Reference can be compared to Changed dispatch and this can be compared to three scenarios where one technical measure is introduced. The current dispatch reference includes some specific tariffs that do not represent the marginal cost of the plants.*

Results

Model results may include:

- Electricity generated (MWh). This may be per generator for each hour. These results can be aggregated per type of technology (coal, wind, solar, etc.) and to yearly values.
- Investment (MW) in generation and transmission. Investment may be shown per area, per type of technology or may be aggregated.
- Economic data, e.g. operating costs (fuel and maintenance), unit commitment costs, investment costs. Data may be shown per type of market participants (e.g. end-users, generators and TSO). In addition, externalities can be included.

Discussion

The model-based scenario results have been used in many studies. The benefit of this approach is more detailed analyses. The value of a specific technology, e.g. wind power, is described for the specific location and with a specific capacity. Other approaches, such as the levelized cost of electricity, LCOE, compare technologies in more general terms.

Distribution of costs and benefits can be illustrated with the models, e.g. across countries or regions or between end-users and generators.

Goal-driven scenarios can illustrate the total costs of e.g. requiring a certain amount of renewable energy or a specific reduction of $CO_2$ emissions.

In this text, the focus has been on model-based scenarios. Please note that the scenario technique can be used in many ways. In some cases scenarios are used to describe possible futures in a qualitative way, see ENTSO-E (2015), Danish Energy Agency (2014) and EcoGrid (2009).

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www.entsoe.eu/publications/system-development-reports/adequacy-forecasts/Pages/default.aspx

Examples of scenario studies:
ea-energianalyse.dk/themes/modellering_af_energisystemer.html
www.ea-energianalyse.dk/themes/energy_scenarios.html

# Appendix 2: Currency and inflation conversion assumptions

| Year | Average annual exchange rate[1] (USD / MXN) | Mexico Inflation, GDP deflator[2] (annual %) | Mexico annual deflator (re-based to 2014) | COPAR exchange rate[3] (USD / MXN) | Average annual exchange rate[4] (EUR / MXN) |
|---|---|---|---|---|---|
| 2010 | 12.64 | 4.49 | 0.87 | | |
| 2011 | 12.43 | 5.29 | 0.90 | | |
| 2012 | 13.16 | 3.27 | 0.95 | | |
| 2013 | 12.76 | 1.74 | 0.98 | 12.90 | 16.96 |
| 2014 | 13.31 | 3.56 | 1.00 | 12.60 | 17.66 |
| 2015 | 15.59 | 2.87 | 1.04 | 13.00 | 17.51 |

Currency and inflation conversions have been carried out by converting the origin currency (e.g. USD 2012) into MXN using the average annual exchange rate of that year (i.e. 2012 to obtain MXN 2012), and thereafter inflating it to MXN 2014 using the GDP deflators of the World Bank.

Assumption of start-of-the-year currency values has been made. E.g. to arrive at MXN 2014 from MXN 2013, the deflator for 2013 has been used.

[1] Source: http://www.usforex.com/forex-tools/historical-rate-tools/yearly-average-rates
[2] Source: World Development Indicators 14/10/2015: http://data.worldbank.org/data-catalog/world-development-indicators. For 2015: http://www.inflation.eu/inflation-rates/mexico/historic-inflation/cpi-inflation-mexico-2015.aspx
[3] Source: (CFE, 2013), (CFE, 2014), (CFE, 2015)
[4] Source: https://www.ecb.europa.eu/stats/exchange/eurofxref/html/eurofxref-graph-mxn.en.html