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Towards a low-carbon electric power system in Mexico

Genice Grande-Acosta, Jorge Islas-Samperio *

Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Priv. Xochicalco s/n, Col. Centro, 62580, Temixco, Morelos, Mexico

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A B S T R A C T

The energy sector is one of the largest sources of Greenhouse Gas (GHG) emissions in Mexico and the World due to the intensive use of fossil fuels. This article is developed on and examines from an environmental and economical approach an alternative scenario towards a Mexican Low Carbon Electric Power System, by analyzing 36 GHG mitigation options on the electric demand side, namely −23 for an energy-efficient use and 4 for distributed generation, across the residential, commercial, public, industrial and energy sectors and, 9 options of electric power generation with Renewable Energy Sources (RES) on the electric power supply side. Our results reveal that, regarding the GHG baseline, towards 2020, this alternative scenario minimizes 33% of the GHG emissions, and towards 2035 these emissions are dramatically minimized at 79%. Furthermore, results also show that there is a possibility to reach a GHG peak in the electric power industry in very few years with this alternative scenario. Moreover, it is found that this alternative scenario will entail no cost in the analyzed period; on the contrary, it creates a global economic benefit of over 8000 MUSD, where 74% is related to the application of the mitigation options in the electric demand sectors and the remaining 26% comes from RES technologies in the electric power supply. Results show that the implementation of this alternative scenario requires an incremental investment of almost than 2 Billion USD/year within the analysis period. Lastly, it is shown that national goals for the electric power sector that have been recently established in the General Climate Change Law, the Energy Transition Law as well as the proposed Intended Nationally Determined Contribution in the Paris COP21 Agreements are feasible for achievement in this alternative scenario.

Introduction

Since 1990, greenhouse gas (GHG) emissions from the electric power sector worldwide have increased at a yearly rate of 2.7% reaching, in 2011, 12,954 $MtCO_2e$, which amounted to 41% of the total GHG emissions derived from energy use (IEA, 2013a). Taking these trends into account, it is forecast that these emissions from the electric power sector worldwide will keep on growing alarmingly towards year 2035 until it reaches 19,123 $MtCO_2e$ (IEA, 2013b).

In this context, the utilization of Renewable Energy Sources (RES) for electric power generation becomes an important factor for the uncoupling of electric power generation and GHG emissions. Nonetheless, electric power technologies based on RES, although these may be at diverse technological and commercial maturity stages (Grubb et al., 2008), face significant barriers for its wide usage, such as recognizing negative externalities from fossil fuels and establishing appropriate financial sources and mechanisms to allow a widespread use of the RES in electric power systems. Therefore, it is essential to use other feasible mitigation options, both from the technical and economic standpoint to achieve significant GHG reductions in the electric power system, such as energy savings and an efficient use of energy. To a large extent, the originality of this article lays in showing that a mitigation option portfolio including intensive measures for energy savings and energy efficient use (EEU) and distributed generation (DG) based on solar energy in the electric power demand and, RES in the electric power supply is a solution with economic benefits to establish low-carbon electric power systems.

On the other hand, in a national context, it must be noted that Mexico is one of leader countries in the world that has Climate Change Law that enabled establishing an institutional framework to set goals

Abbreviations: AC, Air conditioning; AS, Agricultural sector; AAGR, Average annual growth rate; AUEC, Average unit electricity consumption; BAU, Business as usual; CFL, Compact fluorescent lamps; COP21, Twenty-first meeting of the Conference of the Parties of the United Nations Framework Convention on Climate Change; CS, Commercial sector; DG, Distributed generation; EEU, Energy efficient use; GHG, Greenhouse gas; GW, Giga-watt; GWp, Giga-watt peak; HS, Oil and Gas sector; INDC, Intended Nationally Determined Contribution; IPVS, Interconnected photovoltaic systems; IS, Industrial sector; kW, Kilo-watt; kWh, Kilo-watt hour; kWp, Kilo-watt peak; LEAP, Long-range Energy Alternatives Planning System; LGCC, General Climate Change Law; MUSD, Millions of U.S. Dollars; $MtCO_{2e}$, Million ton of equivalent carbon dioxide; MW, Mega-watt; MWp, Mega-watt peak; PS, Public sector; PV, Photovoltaic; RES, Renewable Energy Sources; RS, Residential sector; TS, Transportation sector; TWh, Tera-watt hour; USD, U.S. Dollars.

* Corresponding author.
E-mail addresses: gkga@ier.unam.mx (G. Grande-Acosta), jis@ier.unam.mx (J. Islas-Samperio).

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and foster plans, programs and mechanisms that favor GHG mitigation and the adaptation to climate change in Mexico. This law was recently enacted in 2012 and named the General Climate Change Law (LGCC) (DOF, 2012) establishing three ambitious and volunteer goals specially to minimize GHG emissions in the medium and long term. The first one aims to minimizing national GHG emissions in 30% by 2020 against the current base line; the second one, and the most relevant for this article, provides for that by 2024, the percentage of electric power generation with clean energies must be 35%, while the third one sets a 50% national GHG emission reduction goal by 2050 against GHG emissions in 2000.

More recently, in the framework of the international negotiations of the Conference of the Parties of the United Nations Framework Convention on Climate Change during its twenty-first meeting (COP21), Mexico presented its Intended Nationally Determined Contributions (INDC) to minimize GHG, by establishing, on the one hand, an unconditioned goal to reduce 22% its GHG emissions by 2030 against the current base line and, on the other hand, a conditioned goal to reduce 36% its GHG emissions in that same year if a global agreement is to be reached to ensure the financial support and technology transfer to enforce mitigation actions in developing countries (Gobierno de la República, México, 2014). Regarding the electric power sector, the INDC for Mexico established that for the unconditioned goal, the Mexican electric power sector achieves a 31% GHG reduction against its GHG emission sector base line (SEMARNAT, 2015). The goals set under the LGCC and the INDC of the Mexican government for the electric power sector are, furthermore, framed in a new institutional context derived from the most recent Mexican energy sector reform (Alpizar and Rodríguez, 2016), especially with the new Energy Transition Law (DOF, 2015) which established a minimum number of clean energy involvement in electric power generation, namely: 25% in 2018, 30% in 2021 and 35% in 2024.

Before these important mitigation goals and the legal provisions to establish clean energy involvement goals, reliable and accurate data is required to develop a GHG mitigation action portfolio that is deemed feasible in Mexico to achieve them. This article addressed this issue focusing on the Mexican electric sector, which is responsible for 24% of the total GHG emissions due to the use of energy in Mexico. For this purpose, this article shows the development of an alternative scenario for the Mexican electric sector based on an intense use of EEU and DG on the electric power demand side and RES on the electric power supply, which is critical to attain a cost effective low-carbon scenario that is aligned with the national GHG reduction goals. Several studies were developed mitigation scenarios for the electric power sector in Mexico, focusing on the electric power supply mainly from RES (Manzini et al., 2001; Islas et al., 2003, 2004a, 2004b; Santoyo et al., 2014; Vidal et al., 2015) and, this way, EEU and DG mitigation options have been overlooked for the electric power demand. Very few studies in Mexico (McKinsey and Centro Mario Molina, 2009; Johnson et al., 2010; Martínez and Sheinbaum, 2016) include GHG mitigation options, both on the electric power demand and supply. However, the EEU and DG are not explored in an exhaustive way in the electric power demand as mitigation options; accordingly, the potential in the mitigation options for the electric demand have not been properly taken into account to develop more ambitious GHG mitigation scenarios in the electric power sector and, this way, to make them feasible from a technical and economical approach.

The current situation in the Mexican electric power sector

The Mexican electric power sector, according to the world's trend, has characterized over the last decades for the prevalence of fossil fuels as energy input which amounted to 82% (SENER, 2015a). This has caused a significant GHG emission contribution that reached 127 $MtCO_2e$ (INECC, 2015), which represented, as stated above, about 24% of the national GHG emissions (522 $MtCO_2e$) from combustion of energy fuels and over 19% of the global emissions in Mexico (665 $MtCO_2e$) (INECC, 2015). Accordingly, if this country is pursuing a route to significantly reduce its GHG emissions, the electric power sect must be de-carbonized.

Table 1 shows data about the total installed capacity based on RES in Mexico for the electric power generation in 2014 (SENER, 2015b) and the maximum and minimum values of the RES potential, which has been reported in several studies (CFE, 2010; CONUEE, 2011; CRE, 2011; García et al., 2015; Islas et al., 2013; NREL, 2003; SENER and IIE, 2011; SENER, 2012a, 2013). According to this table, this trend towards a predominant use of fossil fuels and low participation of RES in the electric power sector seems paradoxical when we know that Mexico has an important RES potential.

On the other hand, since the beginning of the 1990s, especially through the implementation of The National Commission for Energy Savings (Comisión Nacional para el Ahorro de la Energía) (today CONUEE — Comisión Nacional para el Uso Eficiente de la Energía), EEU has been part of national energy policies and in the context of national commitments and targets for climate change and the reduction of proven national oil reserves, it appears that EEU policies in Mexico will become more important. To date the Mexican Ministry of Energy through the CONUEE has issued 27 EEU standards of which 22 impact the consumption of electricity (CONUEE, 2016). This article takes into account 23 EEU options which 8 are Mexican standards and 4 DG (distributed generation) solar energy based options and try to show that all these options imply an important reduction of electric power demand which may significantly reduce the consumption of fossil fuels for electricity generation. Even more, this article is seeking to prove the technical and economic feasibility of low-carbon scenarios in the electric power systems based on an intensive use of EEU and DG based on renewable energy in the demand side and the use of RES power plants in electricity supply. The method used to prove this feasibility is the development of scenarios and the global cost-benefit analysis of an alternative scenario against the base scenario. This research may be a benchmark for national studies conducted in other countries

General methodology

To develop this work the following steps are made:

- First and foremost, the reference year is established as 2010, since in this year there are enough data to duly represent the electricity demand and the power supply in Mexico to develop the business as usual (BAU) scenario and the low-carbon alternative scenario, for a forecast period of 25 years.
- Secondly, the BAU scenario is created by following the official forecast to develop the electric demand and the power supply (mainly based in combined cycle and coal plants) in Mexico.
- Thirdly, the low-carbon alternative scenario is created based in two main components. On the one hand, by representing intense GHG mitigation actions on the electric demand side, with the implementation of 27 emission mitigation options, out of which, 23 are related to EEU and 4 are related to DG. On the other hand, with GHG mitigation actions on the power supply considering 9 RES-based technologies.
- Finally, a cost-benefit analysis is conducted to define the economic viability of the low-carbon scenario in relation to the BAU scenario.

All of this is simulated in LEAP software (Heaps, 2008), which is an accounting bottom-up model, where a draw between the electric demand and the generation supply is an unavoidable condition to simulate in an adequate way for the whole analysis period (Grande, 2013).

Table 1
Installed capacity of RES-based plants and national potential in Mexico.
Source: Own data based on CFE (2010), CONUEE (2011), CRE (2011), García et al. (2015), Islas et al. (2013), NREL (2003), SENER and IIE (2011), SENER (2012a, 2013, 2015b).

Generation technology	Total (MW) in June 2015	National potential (MW)	Reference
Hydropower plants	12,454	49,750 – 52,600	CFE (2010), CONUEE (2011), SENER (2015b)
Geothermal plants	899	9686–13,110	CRE (2011), SENER (2015b)
Wind power farms	2760	44,350–70,000	NREL (2003), SENER and IIE (2011), SENER (2015b)
Biomass	208[a]	9183–13,472	Islas et al. (2013), García et al. (2015), SENER (2015b)
Biogas	62	898–140	SENER (2012a, 2015b)
Solar	114[b]	650,000 GWh	SENER (2013, 2015b)
Total	16,497		

[a] It includes sugar cane bagasse-based plants.
[b] It refers to PV plants.

Establishing the reference year and building the BAU scenario

The establishment of the reference year and the BAU scenario were conducted based on the followings two components:

1) On the electric power demand side, based on official data (SENER, 2007, 2010, 2011, 2012b), the electric power consumption in 2010 is represented in seven sectors, namely: industrial (IS), residential (RS), commercial (CS), public (PS), oil and gas* (HS), transport (TS) and agriculture (AS) and, on the other hand, once this representation is conducted, an electric power consumption forecast is addressed on these sectors, based on official prospective.
2) On the electric power supply side, based on official data (CFE, 2011a, 2011b; SENER, 2007, 2010, 2011, 2012b), the reference year is represented and then the electric power supply forecast is made to satisfy the electric power demand from the consumption sectors in the whole analysis period. At this point, with information based on CFE (2011c) and EIA (2011), the costs related to investment, fuels, operation and maintenance of the BAU scenario capacity expansion are taken into account in the LEAP model.

Development of the low-carbon scenario

The development of the alternative low-carbon (LC) scenario was conducted in the following two stages:

1) During the first stage, 23 EEU options are included in the demand sectors consisting of actions for a more efficient electric power consumption, such as the replacement of inefficient equipment (e.g. Efficient refrigeration in the residential sector, efficient motors in the industrial sector), enforcement of efficiency standards (e.g. Efficient lighting in the residential sector), best practices for process optimization (e.g. adjustments to minimize electric power consumption across the several compression system components in the oil and gas sector) and the establishment of co-generation plants, inter alia. There are 4 DG options too, based on interconnected photovoltaic systems (IPVS) across several sectors, which minimizes the electric power consumption from the grid. Table 2 describes the 27 options considered in this article that have an impact on the electric power demand, by consumption sector and end use, and shows the improvement in energy efficiency in percentage terms. Tables 3 and 4 present the main assumptions for these options in terms of number of conventional equipment, average unit electricity consumption (AUEC), electricity consumption of grid in BAU scenario, number of replaced equipment, AUEC, and electricity avoided of grid in LC scenario.
2) In stage two, once the electric power demand is obtained due to the application of the 23 mentioned options, an electric power supply expansion scenario based on a predominant use of RES utilization technologies is constructed to meet the adjusted electric power demand. This low-carbon electric power supply was established by taking the energy potential of RES in the country (see Table 1) as well as the main replacement of combined cycle and carbon power plants under the BAU scenario. Table 5 shows the main options and hypothesis about RES to construct the alternative scenario for the electric power supply.

* As part of the analysis methodology, this intermediate consumption sector was considered as a final electric power consumption sector.

Economic calculation model

A cost benefit (CB) model is used to estimate the overall costs and benefits of the analyzed options in the LC scenario in relation to BAU scenario according to the following general equation:

$$CB_{LC-BAU} = IC_{LC-BAU} + O\&MC_{LC-BAU} + EC_{LC-BAU} \quad (1)$$

where:

$IC_{LC\text{-}BAU}$ Overall incremental investment costs for all alternative options in the LC scenario in present value.
$O\&MC_{LC\text{-}BAU}$ Overall incremental costs of operation and maintenance for all alternative options in the LC scenario in present value.
$EC_{LC\text{-}BAU}$ Overall avoided costs of energy for all alternative options in the LC scenario in present value.

with

$$IC_{LC-BAU} = \sum_{i=1}^{Op}\sum_{y=1}^{P}\frac{IC_{LC-BAU\,isy}}{(1+r)^y} \quad (2)$$

where

$IC_{LC\text{-}BAUisy}$ Annual incremental investment costs in relation to the implementation of the alternative option *i* in the sector *s* for any year *y* in the period *p*. This specific information is provided by Islas et al. (2016).
y year;
r discount rate (10%);
P analyzed period (25 years);
s residential, public, industrial, transport and oil and gas sectors, and electric power generation sector;
Op Number of alternative options in the LC scenario (36 alternative options).

$$O\&MC_{LC-BAU} = \sum_{i=1}^{Op}\sum_{y=1}^{P}\frac{O\&MC_{LC-BAU\,isy}}{(1+r)^y} \quad (3)$$

where

$O\&MC_{LC\text{-}BAUisy}$ Annual cumulative incremental costs of operation and maintenance (O&M) for the alternative option *i* in the sector *s* accumulated in the year *y* in the period p. This specific information is provided in a registered database in the Mexican Copyrights Office with the number 03-2016-091310364300-01 (see Islas et al., 2016).

Table 2
Options for the efficient use of electric power and distributed generation under the low-carbon scenario.
Source: Own data based on Islas et al. (2013).

Sector	End use	Option ID[a]	Option	Description
Residential	Lighting	EEU-RS-ELB	Efficient light bulbs	100% of incandescent bulbs are replaced with compact fluorescent lamps (CFL) towards 2035. As of the first year of the analyzed period, the use of incandescent light bulbs of 100 W or more is forbidden. 7.6 million incandescent light bulbs are replaced annually. The application of NOM-028-ENER-2010 standard is strengthened.
	Refrigeration	EEU-RS-ER	Efficient refrigerators-RS	Replacement of the total refrigerators number within the analysis period with efficient refrigerators meeting NOM-015-ENER-2012 standard.
	Space conditioning	EEU-RS-EACTI	Efficient air conditioning and thermal insulation-RS	Replacement of 100% inefficient air conditioning (AC) systems and devices with efficient ones, along with the implementation of thermal insulation in roofs. The application of NOM-023-ENER-2010 and NOM-018-ENER-2011 standards are strengthened.
	Use of electric power	DG-RS-IPVS	Interconnected photovoltaic systems-RS	All high consumption users in tariff 1 install an IPVS by 2035. A monthly average consumption of 353 kWh and the installation of 1 kWp IPVS is considered; therefore, 667 MWp of end capacity in the period are expected.
Commercial	Lighting	EEU-CS-EL	Efficient lighting-CS	Replacement of 100% existing lamps (38.5 million in the reference year) by efficient lamps in 2035. The application of NOM-028-ENER-2010 standard is strengthened.
	Air conditioning	EEU-CS-EACTI	Efficient air conditioning and thermal insulation-CS	Air conditioning equipment replacement with more efficient and thermal insulation is considered. Overall, more than half a million of inefficient equipment are replaced by 2035. The application of NOM-023-ENER-2010 and NOM-018-ENER-2011 standards are strengthened.
Public	Public lighting	EEU-PS-LPL	LED public lighting	100% of the existing lamps of the public lighting nationwide are replaced with light-emitting diode (LED) lamps towards 2035. This option complies with the NOM-031-ENER-2012 standard.
		DG-PS-PLIPVS	Public lighting with IPVS	3.8 GWp of distributed photovoltaic systems with a capacity of 2.6 kWp, are connected to the electric power grid in nationwide by 2035 to cover, under a net metering scheme, the public lighting.
	Municipal pumping	DG-PS-MPIPVS	Municipal pumping sytems with IPVS	1.2 GWp of distributed photovoltaic systems with a capacity of 2.6 kWp, are connected to the electric power grid in nationwide by 2035 to supply electric power to the grid during sunstroke hours nationwide to cover, under a net metering scheme, the municipal pumping systems.
Industrial	Motors	EEU-IS-EM	Efficient motors	It is estimated that there are currently 1.4 million motors in the country and 5 million towards 2035. 100% of the inefficient motors in the BAU scenario are replaced with more efficient ones in the analyzed period. The application of NOM-016-ENER-2010 standard is strengthened.
	Pumps, fans, compressors	EEU-IS-SD	Speed variators	This option considers the application of variable speed drives in the pumps, fans and compressors.
	Compressors	EEU-IS-AC	Air compressors	This option assumes that by repairing leaks in air compression systems, savings of 9716 GWh would be obtained by the end of the analyzed period.
	Chillers	EEU-IS-EC	Efficient chillers-IS	It is estimated that there are currently 1.7 million chillers in this sector and there will be 6.5 million by 2035. 100% of these equipment will be replaced with more efficient chillers within the analyzed period, thus, savings of 4679 GWh will be obtained by the end of the period.
	Lighting	EEU-IS-EL	Efficient lighting-IS	It is estimated that there are currently 49.1 million lamps in this sector and there will be 181.2 million by 2035. 100% replacement with more efficient lamps is considered by the end of the analysis period. The application of NOM-028-ENER-2010 standard is strengthened.
	Electric furnaces and heaters	EEU-IS-EEFH	Efficient electric furnaces and heaters	This option considers that is possible the use of more efficient electric furnaces and heaters in this sector.
	Iron and steel, aluminum, glass and paper industries	EEU-IS-MR	Material recycling	An average 27% increase is considered in the use of recycled materials. 2274 GWh are reached in electric power savings by 2035.
	Electric power consumption	EEU-IS-CG	Co-generation-IS	It is considered that 8454 MW of cogeneration is fully implemented in this sector by 2035.
		DG-IS-IPVS	Interconnected photovoltaic systems-IS	12 GWp of photovoltaic systems in distributed generation, are installed and connected to the grid, under a net metering scheme, by 2035.
Oil and gas	Compressors	EEU-HS-CRO	Compression ratio optimization	This option consists in the installation of transducers at compressor ports and the computerized review of suction and compression cycles in 390 existing compression systems towards 2035. This option represents 42 GWh annual savings.
		EEU-HS-CVA	Compressor valve adjustment	It consists in adjusting the suction pressure valve, the return valve and backpressure valve to minimize the return and feed to the compressor in 390 existing compression systems towards 2035. Annual 42 GWh savings are also obtained.
		EEU-HS-GCSR	Gas compression system resizing	Gas compression systems are deemed resized to minimize losses. This is applicable to all compression systems included towards 2035. This represents up to 28 GWh/year in electric power savings.
		EEU-HS-FCVA	Free cylinder volume adjustment	It consists in making a manual or automated free cylinder volume adjustment so as to run at its highest capacity in 390 existing compressors systems. 28 GWh/year in electric power savings are obtained.
		EEU-HS-CCOA	Compressor cylinder opening adjustment	It consists in making a cylinder opening adjustment at a minimum value to optimize the compressor efficiency. 28 GWh/year in electric power savings are obtained.
		EEU-HS-IISC	Intra and inter stage coolers	It consists in the implementation of coolers at the compressor use stages to improve the compressor efficiency. 56 GWh/year are saved with this action.
	Heating steam heaters and systems	EEU-HS-IOSMIEE	Introduction of on-site metering to improve energy efficiency	Supervision, control and data acquisition software utilization to meter on site so as to increase the energy efficiency at this sector's thermal processes. 5 GWh/year savings in electric power are achieved in this sector with this action.
		EEU-HS-PCP	Pipe cleaning with pigging	It consists of conducting 390 pipe cleaning projects towards 2035. 3 GWh/year savings in electric power in the sector are considered.

Table 2 (*continued*)

Sector	End use	Option ID[a]	Option	Description
	Gas production	EEU-HS-ONGPS	Optimization of gas production Systems	This is the implementation of optimization measures in gas production (e.g. inspection of the piping network, optimizing flow to minimize pressure drop and compressor feed). 7 GWh/year are saved in electric power with this action in the sector.

[a] EEU = Energy-Efficient Use, DG = Distributed Generation.

$$EC_{LC-BAU} = \sum_{i=1}^{Op} \sum_{y=1}^{P} \frac{EC_{LC-BAU\,isye}}{(1+r)^y} \tag{4}$$

where

$EC_{LC\text{-}BAUisy}$ Annual cumulative costs of energy savings (fossil fuel or electricity) for the alternative option i in the sector s in the year y in the period p; electricity when the option i in the sector s is an option of electric power demand side and, fossil fuel (fuel oil, diesel, natural gas and coal) when the option i is an option of electric power supply side. This specific information is provided by Islas et al. (2016).

In order to calculate the mitigation cost for each alternative option the following calculation is used:

$$MC_{LC-BAUis} = \frac{TC_{LC-BAUis}}{GHG_{LC-BAUis}} \tag{6}$$

where

$TC_{LC\text{-}BAUis}$ Total incremental costs for the alternative option i of the sector s in the LC scenario in present value.

$GHG_{LC\text{-}BAUis}$ Total Greenhouse gases emissions mitigated by the implementation of the alternative option i of the sector s in the LC scenario.

with

$$TC_{LC-BAUis} = \sum_{y=1}^{P} \left(\frac{IC_{LC-BAU\,isy}}{(1+r)^y} + \frac{O\&MC_{LC-BAU\,isy}}{(1+r)^y} + \frac{EC_{LC-BAU\,isye}}{(1+r)^y} \right) \tag{7}$$

$$GHG_{LC-BAUis} = ES_{LC-BAUise} * EF_e \tag{8}$$

where

$ES_{LC\text{-}BAUise}$ Cumulative energy savings in the analyzed period related to the implementation of alternative option i of the sector s. The energy savings e is electricity when the option i in the sector s is an option of the electric power demand side and, fossil fuel (fuel oil, diesel, natural gas and coal) when the option i is an option of the electric power supply side. This specific information is provided by Islas et al. (2016).

EF_e GHG emission factor of energy e.

Table 3
Main assumptions of the options for the efficient use of electric power under the low-carbon scenario.
Source: Own data based on Islas et al. (2013).

ID option	BAU scenario				LC scenario				Percentage efficiency improvement of the AUEC (%)
	Number of conventional equipment/ system/process (thousand)		AUEC[a] (kWh/year)	AAGR[a] (%)	Number of replaced equipment/ system/process (thousand)		AUEC (kWh/year)	AAGR (%)	
	2010	2035			2011	2035			
EEU-RS ELB	154,546	190,121	117	0.8	7392	190,121	33	14.5	72
EEU-RS-ER	24,661	49,539	828	2.8	1000	49,539	372	17.7	55
EEU-RS-EACTI	10,841	21,102	1638	2.7	1000	21,102	983	13.5	40
EEU-CS-EL	38,467	142,575	500	5.4	2500	142,575	435	18.4	13
EEU-CS-EACTI	138	500	7518	5.3	50	500	4511	10.1	40
EEU-PS-LPL	4620	12,616	963	4.1	32	12,616	490	28.2	49
EEU-IS-EM	1462	4975	48,131	5	51	4975	44,509	21	8
EEU-IS-SV	687	2338	54,464	5	24	2338	43,571	21	20
EEU-IS-AC	278	945	51,346	5	10	945	41,077	21.1	20
EEU-IS-EC	1770	6500	3006	5.3	62	6500	2254	21.4	25
EEU-IS-EL	49,822	181,182	202	5.3	1727	181,182	176	21.4	13
EEU-IS-EEFH	1.6	5.7	9,091,560	5.3	0.1	5.7	8,000,573	18.3	12
EEU-IS-MR	5500[b]	10,706[b]	708	2.7	3100[b]	10,706[b]	496	5.3	30
EEU-IS-CG	107,824	392,125	[c]	5.3	110.8	67,390	[c]	30.6	17
EEU-HS-CRO	390	390	711,710	0	390	390	604,953	0	15
EEU-HS-CVA	390	390	711,710	0	390	390	604,953	0	15
EEU-HS-GCSR	893	893	310,825	0	893	893	279,743	0	10
EEU-HS-FCVA	390	390	711,710	0	390	390	640,539	0	10
EEU-HS-CCOA	390	390	711,710	0	390	390	640,539	0	10
EEU-HS-IISC	893	893	310,825	0	893	893	248,660	0	20
EEU-HS-IOSMIEE	350	350	310,623	0	350	350	295,091	0	5
EEU-HS-PCP	390	390	278,764	0	390	390	270,401	0	3
EEU-HS-ONGPS	450	450	289,914	0	450	450	275,419	0	5

[a] AAGR = Average Annual Growth Rate, AUEC = Average Unit Electricity Consumption.
[b] Values in tones of production in the iron and steel, aluminum, glass and paper industries.
[c] Refers to energy consumption to grid, and not applicable in this option.

Table 4
Main assumptions of the options for distributed generation under the low-carbon scenario.
Source: Own data based on Islas et al. (2013).

ID option	BAU scenario			LC scenario					Percentage of electricity avoided of grid (%)
	Electricity consumption of grid in the sectorial base line (GWh)		AAGR (%)	Electricity avoided of grid (GWh)		AAGR (%)	New installed capacity (MW)		
	2010	2035		2011	2035		2011	2035	
DG-RS-IPVS	1723	2827	2.0	7.5	1006	21.6	5.0	667	35.6
DG-PS-PLIPVS	4583	12,514	4.1	15.8	6179	27.0	9.4	3773	49.4
DG-PS-MPIPVS	3140	8575	4.1	27.8	2069	18.8	16.7	1246	24.1
DG-IS-IPVS	107,824	392,125	5.3	1.1	24,646	49.3	0.6	12,058	6.3

Results

BAU scenario

The current official projections were reproduced appropriately in the BAU scenario (see Fig. 1). In this scenario according to our results, electric power demand in Mexico shows an accelerated annual growth of 4.9% in average and by the end of the analysis period reaches 663 TWh, which represents 3.3 times the electric power demand in 2010 (199 TWh). This growth is fostered by the industrial and commercial sector demand developing at an annual growth rate of 5.3%, followed by the residential sector (4.6%) and the oil and gas and the transportation sectors with the same annual growth of 3.6%. Lastly, the agricultural sector has the lowest dynamism, since its electric power demand is expected to grow at 1.8%/year (Fig. 1).

To meet the electric power demand under this scenario, the preferred technologies under the BAU scenario, according to the Mexican official prospective, gas combined cycle and coal power plants which capacity has an average annual growth from 5.3% and 6.1%, respectively. On the contrary, the capacity of fuel oil-based thermal power plants will decrease 3.1%/year in average (Fig. 2).

Regarding technologies based in renewable energy, power plants capacity (including low scale ones) show an average annual growth of 3.1% where geothermal, wind power and solar power plants have an annual average capacity increase of about 7.5%, a growth that is insufficient for RES involvement to become significant in electric power generation. Lastly, the nuclear technology capacity grows at an annual rate of 0.7%, due to the repowering of the existing units.

The described supply scenario leads to electric power inputs on the supply side for 5662 PJ in 2035, where 88% (5019 PJ) come from fossil fuels (natural gas, coal, fuel oil, diesel and petroleum coke), which represent a growth of 270% against the one in 2010. This scenario is expanded mainly to gas and coal based against the use of fuel oil, which has a high GHG emission and pollutant factor, due to the scheduled shutdown, throughout the period, of steam-based plants based on this oil by-product. Regardless of this replacement, forecast trends for the fuel consumption structure in the electric power sector have a significant impact on the GHG emission volume (Fig. 3), which amount to 334.4 $MtCO_{2e}$ in 2035, a 284% higher figure against the number in 2010. Gas will be more involved in emission volume, from 47% to 59% of the total number. A similar trend results in coal emissions, which overall GHG emission involvement will go from 25% to 38% (Fig. 3). Lastly, the GHG emission ratio from fuel oil will decrease significantly, since 2010 amounts to 27% to 1% in 2035%, while diesel and petroleum coke involvement in global GHG emissions go from 1% to 3% by the end of this period.

Table 5
RES options selected for the low-carbon scenario.
Source: Own data based on Islas et al. (2013).

Option ID[a]	RES option for the electrical supply	Main hypothesis
RES-BGAS	Biogas	The highest estimated potential in SENER (2012a) of 1.4 GW is reached by 2035.
RES-BIOMW	Biomass from waste	Plants with capacities of 25, 35 and 50 MW using waste from the forest and rainforest sustainable management are installed, and 8.25 GW is reached by 2035.
RES-BIOMEP	Biomass from energy plantations	Plants with capacities of 25, 35 and 50 MW using biomass from energy plantations are installed as of 2020, and 1.2 GW is reached.
RES-WIND	Wind power	A total Wind power capacity of 20 GW is installed in the analyzed period.
RES-GEO	Geothermal plants	A total of 12.4 GW is installed by 2035 of this technology.
RES-HYDROG	Power plant >30 MW	The installation of additional 17.4 GW hydro power plants is considered where the 35% of this capacity (mostly peak capacity) is used to manage the intermittence from wind power and PV plants and in this way to adjust the electricity demand curve and the electric power supply.
RES-HYDROS	Small power plants <30 MW	In 2035 4.4 GW of small power plants are utilized.
RES-SPV	Solar PV	4 GW in PV plants are reached nationwide in 2035.
RES-STH	Solar Thermal	1.1 GW of solar thermal power plants with 15% storage is reached in 2035, mainly in desert areas in the northern area of the country.

[a] RES = Renewable Energy Sources.

Low-carbon scenario

Electric power demand

The impact of EEU and DG options that have been considered in the electrical demand sector may be seen in Fig. 4. From these options, the annual growth average of the overall electric power demand will go from 4.9% under the trend scenario to 2.9% under the low-carbon scenario. As you may see, the six options contributing more significantly to the electric power demand reduction are co-generation, speed variators, IPVS and efficient motors in the industrial sector as well as efficient refrigerators and light bulbs in the residential sector.

Electric power supply

To satisfy the adjusted electrical demand of the low-carbon scenario, the electrical supply is constructed considering the use of renewable sources in a predominant way. PV centrals grow at an annual rate of 67% to reach a total of 4000 MW in 2035. Wind power plants show a significant annual growth of 41% amounting to a total of 20,085 MW in 2035. As for geothermal plants, an annual increase of 11% is estimated, which represents an installed capacity of about 13,000 MW by the end of the analyzed period. On the other hand, solar thermal plants that will start spreading as of the first decade of the analyzed period and

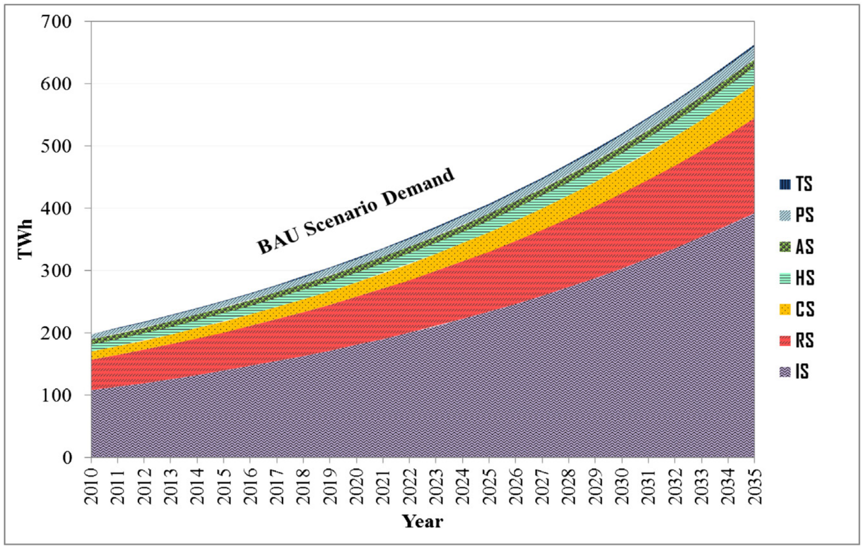

Fig. 1. Electric power demand in Mexico by sector in the BAU scenario according to official projections.
Source: Own data based on SENER (2007, 2010, 2011, 2012b).

will reach 1000 MW, which entails an annual increase in capacity of 20% (Fig. 5).

As for hydroelectricity plants (including low scale ones), these will have an annual average capacity growth of 4%, adding up to 29,452 MW by the end of the period. Likewise, the use of biomass will have an annual average growth of 18%, which results in a total installed capacity of 9435 MW by 2035; especially, due to the utilization of biomass waste from the sustainable management of forests and rainforests. Lastly, it must be noted that, under this low-carbon scenario, an installation of 1228 MW from electric power generation systems from municipal solid waste (MSW) and livestock waste biogas will be taken into account, with an average annual growth rate of 31%.

Cost-benefit and GHG emission reduction analysis

The cost-benefit analysis results for each EEU, DG and RES options described in the section above are shown in Fig. 6. Axis Y represents the mitigation cost and axis X represents GHG emissions accumulated in the analysis period derived from the implementation of every option and sorted from a lower to a higher cost. As you may see, most of the EEU options and RES entail negative costs, i.e., economic benefits are obtained when applied, while solar options, both distributed and centrals have the higher costs but a significant volume of GHG emission reduction.

From all options, efficient lighting in residential sector is the action with the highest economic benefit and an important GHG reduction, the second best option is the efficient electric furnaces and heaters in the industrial sector with also an important GHG reduction, and the third, is the adjustment of the free cylinder volume option in the Oil and Gas sector but with a very low volume of GHG reduction. While the higher cost options are IPVS in the industry sector, street lighting with IPVS and the utility pumping with IPVS in the public sector, these three options have an important GHG reduction but high costs.

The Table 6 shows the low-carbon scenario results in global benefits of about $8524 MUSD throughout the 25-year period, out of which, 74%

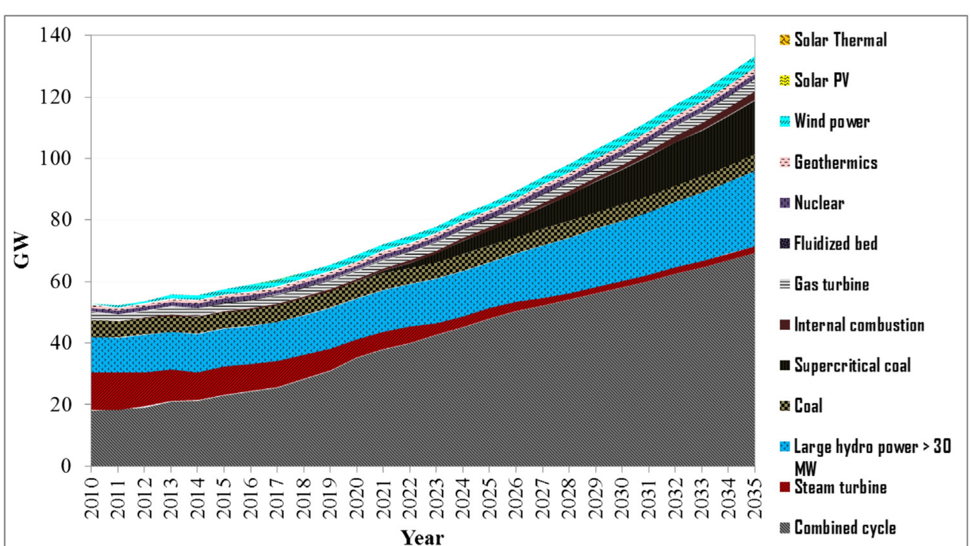

Fig. 2. Capacity by generation technology in the BAU scenario according to official projections.
Source: Own data based on CFE (2011a, 2011b), SENER (2007, 2010, 2011, 2012b).

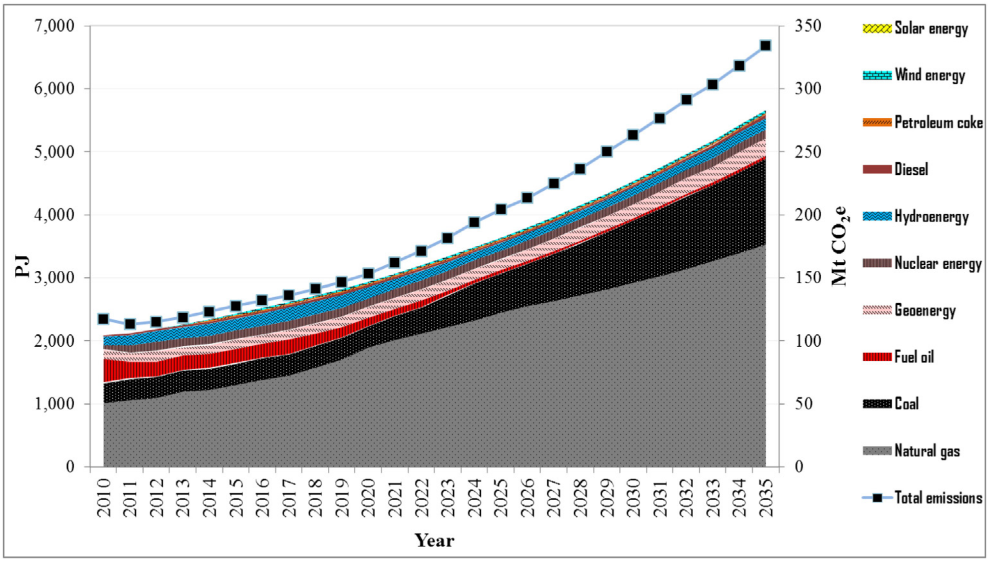

Fig. 3. Consumption from the Mexican electric power sector by energy source and GHG emissions in the BAU scenario.
Source: Own data.

will be generated from the electric power demand side where EEU and DG options are put in place and the remaining 16% is obtained from the electric power supply side with the implementation of renewable energy power plants. However, this scenario entails a significant total investment cost of about $48,970 MUSD in the analysis period and, in this item, RES options for electric power supply amount to a little more than half those costs and the remaining from the EEU and DG options on the electric power demand; therefore, the aspiration of achieving a low-carbon electric power system, just like the one stated in this article represents huge funding challenges. While the total operation and maintenance represents savings in the amount of $4353 MUSD, it must be noted that these benefits are focused on RES options in the electric power supply and these type of benefits are relatively low in EEU and DG options on the electric power demand side. We must highlight that by putting this scenario in place, there will be also important benefits, such as fuel savings of about $53,141 MUSD, where 57% come from the electric power demand and the remaining 43% from the electric power supply.

Regarding GHG emissions, the low carbon scenario implementation means, on the one hand, an accumulated reduction of 2526 $MtCO_2e$ in the electricity generation during the analysis period, which represents a 50% reduction of the accumulated GHG emissions for the BAU scenario and, on the other hand, that the electricity generation has, by 2035, annual emissions for 71 $MtCO_2e$, which means a 79% reduction related to the annual emissions of the BAU scenario for 2035. Moreover, if the low-carbon scenario is pursuit, GHG emissions by 2035 from the electricity generation will be 40% less than in 2010, which consolidates the path towards stabilizing GHG emissions in the Mexican electricity generation (Fig. 7).

In terms of the goal under the LGCC of achieving 35% of the electric power generation with clean energy by 2024, the low-carbon scenario would achieve it since 59% of the electricity generation comes from

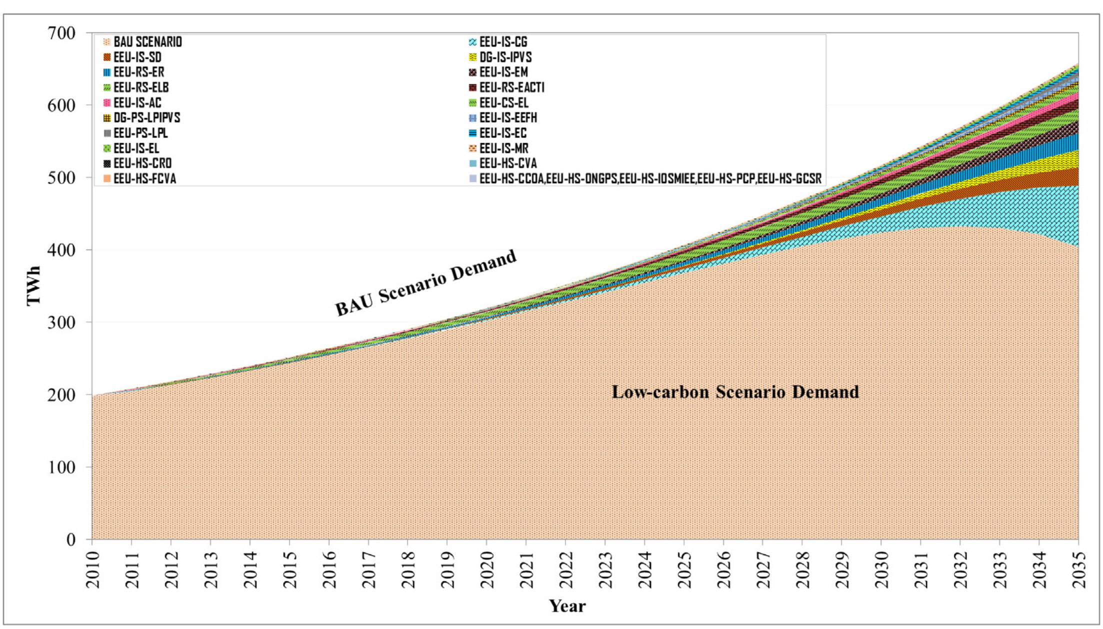

Fig. 4. EEU and DG option contribution to reduce the electricity demand in the Low Carbon scenario.
Source: Own data.

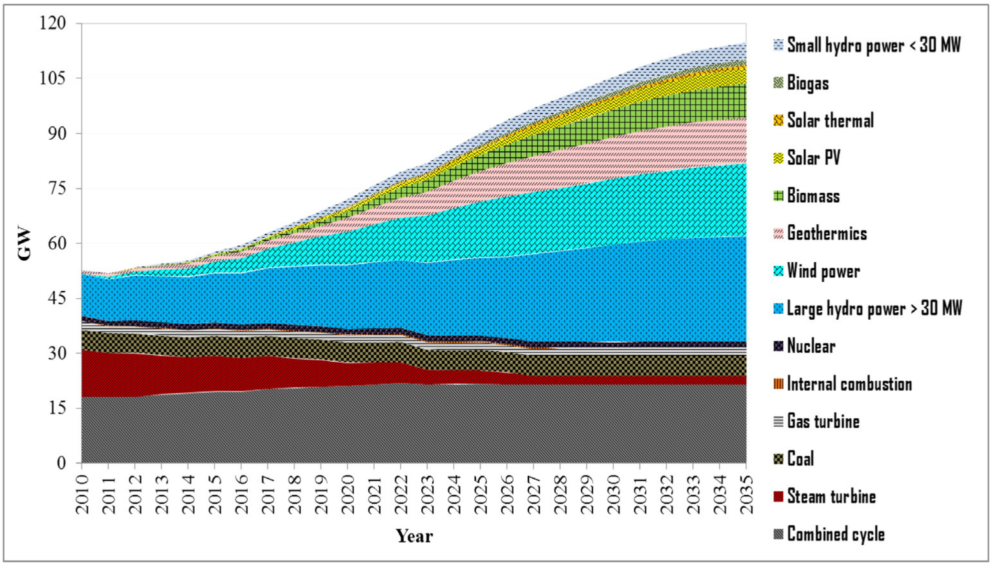

Fig. 5. Capacity by type of generation technology in the electric power supply in the low-carbon scenario.
Source: Own data.

renewable energies in that year. Likewise, the objective of minimizing the electric power sector GHG emissions in 31% against a base line set to meet the unconditioned INDC in Mexico in this sector, is achieved under the low-carbon scenario, since GHG emissions are minimized in 67% against GHG emissions in the BAU scenario. Lastly, the goals under the most recent Energy Transition Law of a minimum share of clean energies for electric power generation that would be 25% for 2018, 30% for 2021 and 35% for 2024 are achieved in this alternative scenario, since energy generation from renewable energies is 43% in 2018, 51.3% in 2021 and 59% in 2024.

As stated above, the implementation of this low-carbon scenario would entail incremental investment costs, according to our results, on the order of $48,970 million dollars (MUSD) throughout the 25 years of the analysis period (equivalent to an annual incremental investment cost of around $2000 MUSD) which are divided by $23,715 MUSD due to the implementation of EEU and DG options on the electric demand side and $25,255 MUSD due to the implementation of RES technologies in the electric power supply, i.e., an incremental investment of almost 1 Billion USD per year, both on the electric demand and supply sides.

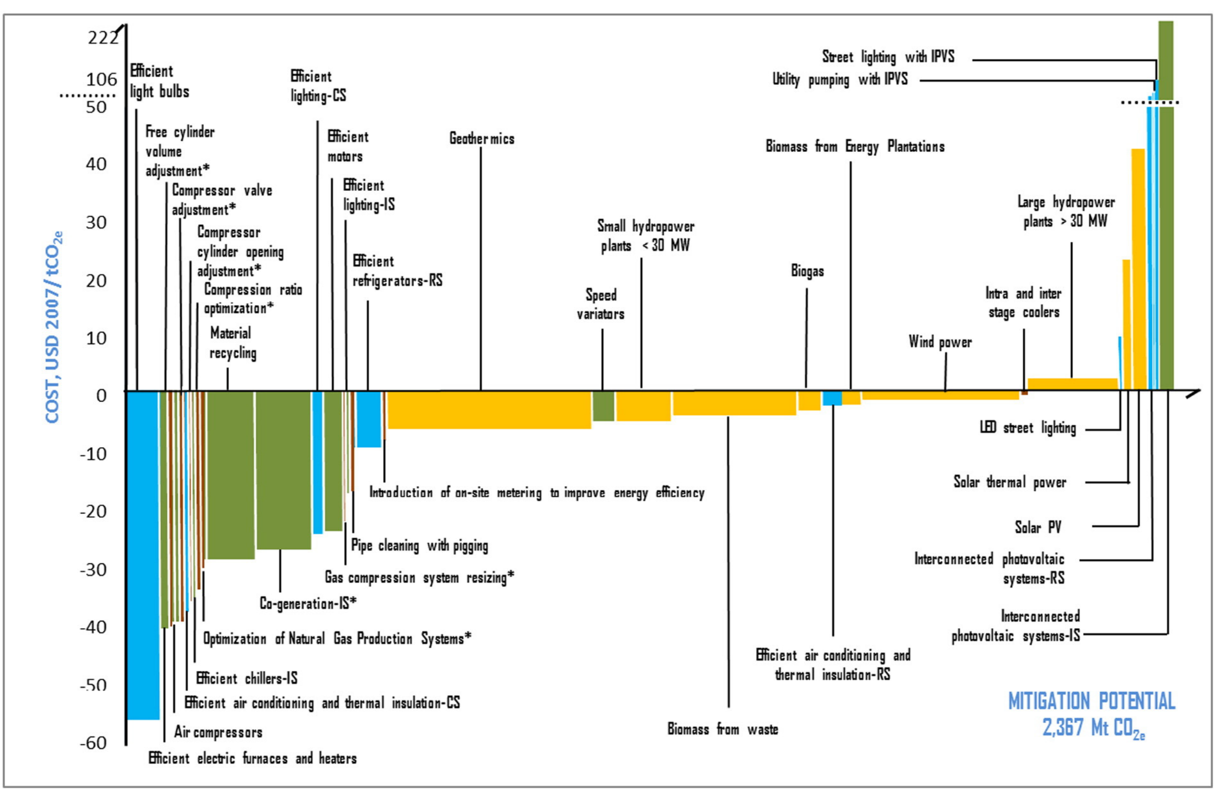

Fig. 6. Mitigation costs curve for EEU, DG and RES options in the low carbon scenario for the Mexican electric power system.
Source: Own data.

Table 6
Cost-benefit and saved emissions by type of option and sector in the low-carbon scenario.
Source: Own data.

	Sector	Type of option	Investment cost (MUSD2007)	O&M cost (MUSD2007)	Fuel cost (MUSD2007)	Total cost-benefit (MUSD)	Saved emissions ($MtCO_2e$)
Demand		EEU	$635	$0	−$1496	−$861	32
	Oil and gas	EEU	$185	$42	−$564	−$337	13
	Industrial	DG	$9928	$99	−$1200	$8827	40
		EEU	$4182	$32	−$15,167	−$10,954	445
	Public	DG	$2855	$0	−$660	$2196	18
		EEU	$537	$0	−$416	$121	12
	Residential	DG	$420	$2	−$168	$254	2
		EEU	$4973	$0	−$10,521	−$5548	201
	Demand subtotal		$23,715	$175	−$30,192	−$6301	763
Supply	Electric power generation	E-RES	$25,255	−$4528	−$22,949	−$2223	1763
	Supply subtotal		$25,255	−$4528	−$22,949	−$2223	1763
	Global		$48,970	−$4353	−$53,141	−$8524	2526

EEU = Energy-Efficient Use options, DG = Renewable distributed generation options.

Conclusions

Under the BAU scenario conditions, the amount of the required energy in México is 5662 PJ in 2035 that is higher at 270% in relation to the one in 2010. According to this trend, the GHG emissions reach 334.4 $MtCO_2e$ in 2035 with a 284% increase against 2010. These emissions come mainly from the use of gas in the first place, and it is followed by coal.

The GHG emission reduction in the electricity generation under the low-carbon scenario comes from two components –the application of 27 mitigation options from the electrical demand side, out of which 23 are EEU and 4 are DG, and are implemented across the several electricity final consumption sectors, including the oil and gas sector and, on the other hand, the expansion of the RES in the electricity supply side. This portfolio of options offers a potential of emission reduction equal to 2526 $MtCO_2e$ in the analysis period (762 $MtCO_2e$ related to the EEU and DG options on the electrical demand side and 1763 $MtCO_2e$ from RES on the electric power supply side), equal to 50% accumulated emissions in the BAU scenario in the analysis period.

According to our estimations made, in the low-carbon emission scenario, a 63% of the electricity generation from RES may be achieved towards 2035 on the electric supply side. Under this scenario, EEU options, at most, will yield benefits. However, DG options entails costs, but with a significant potential to mitigate GHG emissions. On the electric power supply side, both hydroelectricity and solar technologies (thermal and PV) entail mitigation costs and the highest ones are found in the two solar technologies. However, the remaining options yield benefits. All mitigation actions under the low-carbon scenario altogether cause benefits in the amount of $53,141 MUSD to exceed costs for $48,970 MUSD, so that a low-carbon scenario at no cost is created with a net economic benefit in the amount of $8524 MUSD.

Results show that the low-carbon scenario is also well aligned with the national goals for the electric power sector established under the LGCC, the Mexican INDC and those under the most recent Energy Transition Law, since the low-carbon scenario exceeds them. Results show that it is also possible to reach a GHG emission peak in the Mexican electric power sector within a short period if the low-carbon scenario is implemented.

However, results show that the main constraint to implement this scenario is the funding, since the incremental investment is in the ballpark of the required 2000 MUSD/year for its implementation; accordingly, it is essential to define the objective of obtaining higher

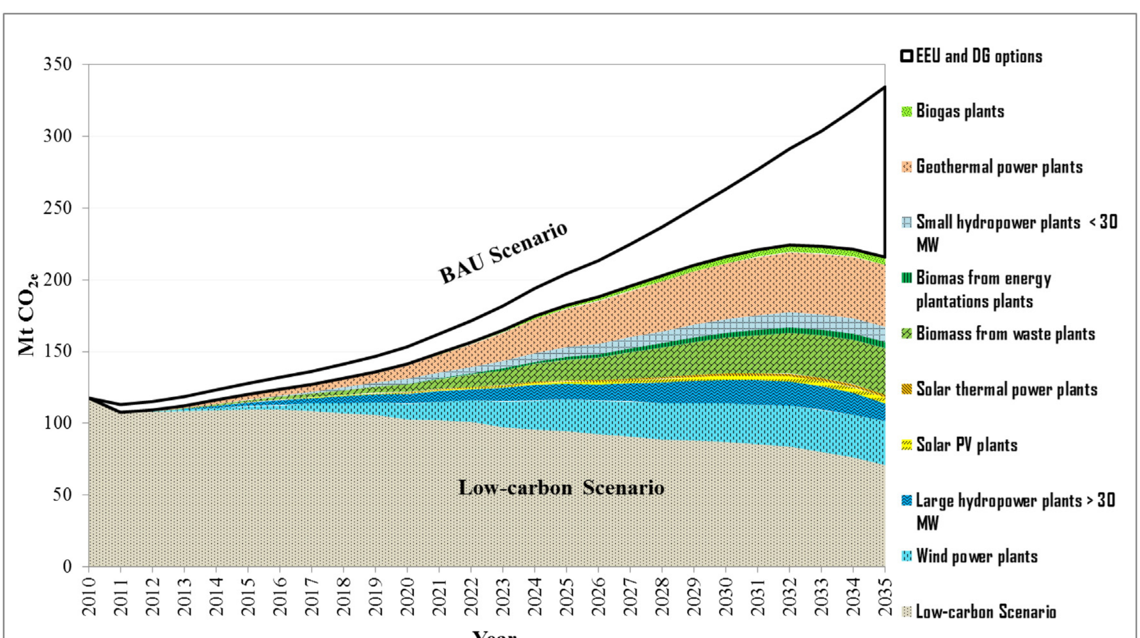

Fig. 7. Reduction emissions with RES, EEU and DG options, 2010–2035.
Source: Own data.

sources of funding, both domestic and international, and to create appropriate funding mechanisms for each type of mitigation action. More particularly, for concentrated solar thermal power and PV technologies, it is crucial to set mechanisms and incentives to support a larger scale dissemination thereof.

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