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A prospective study of bioenergy use in Mexico

Jorge Islas[a], Fabio Manzini[a,*], Omar Masera[b]

[a]Centro de Investigación en Energía, Universidad Nacional Autónoma de México (CIE-UNAM), Aptdo. Postal 34, Temixco, 62580 Morelos, Mexico
[b]Centro de Investigaciones en Ecosistemas, Universidad Nacional Autónoma de México (CIECO-UNAM),
Antigua Carretera a Pátzcuaro No. 8701, Morelia 58190, Michoacán, México

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Abstract

Bioenergy is one of the renewable energy sources that can readily replace fossil fuels, while helping to reduce greenhouse gas emissions and promoting sustainable rural development. This paper analyses the feasibility of future scenarios based on moderate and high use of biofuels in the transportation and electricity generation sectors with the aim of determining their possible impact on the Mexican energy system. Similarly, it evaluates the efficient use of biofuels in the residential sector, particularly in the rural sub-sector. In this context, three scenarios are built within a time frame that goes from 2005 to 2030. In the base scenario, fossil fuels are assumed as the dominant source of energy, whereas in the two alternative scenarios moderate and high biofuel penetration diffusion curves are constructed and discussed on the basis of their technical and economical feasibility. Simulation results indicate that the use of ethanol, biodiesel and electricity obtained from primary biomass may account for 16.17% of the total energy consumed in the high scenario for all selected sectors. CO_2 emissions reduction—including the emissions saved from the reduction in the non-sustainable use of fuelwood in the rural residential sector—is equivalent to 87.44 million tons of CO_2 and would account for 17.84% of the CO_2 emitted by electricity supply and transportation sectors when the base case and the high scenario are compared by 2030.

Keywords: Biofuels; Bioenergy; Greenhouse gas mitigation; Mexican energy system

1. Introduction

Why should we develop bioenergy in a country that has oil? The use of biomass as a primary source of energy has been decreasing in Mexico since 1965, when it constituted 15.3% of the total primary energy supply. As of year 2005, this share represented only 5.3%. Meanwhile, the use of hydrocarbon fuels has been steadily increasing and accounted for 87.7% of the gross primary energy supply [1].

There are several reasons to increase the use of bioenergy in Mexico. On the one hand, the increasing reliance on fossil fuels is problematic. In 2007, the national proven reserves of hydrocarbon are enough to support the annual oil and gas production for 9.6 and 8.9 years, respectively [2,3]. The annual average growth rate of Mexico's energy-related non-biogenic CO_2 emissions is 4.3%, one of the highest in the world [4].

On the other hand, bioenergy has the potential to become a fundamental piece in a sustainable energy system, contributing not only to the country's energy diversification strategy but also to the appropriation of emerging energy technologies. It can contribute to the reduction of greenhouse gas emissions, the generation of new jobs in rural areas and the improvement of income distribution. Furthermore, the resulting substitution of

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Abbreviations: AAGR, average annual growth rate; BIGCC, biomass integrated gasification combined cycle; NGCC, natural gas-fired combined-cycle plants; CEST, condensing-extraction steam turbine; CDM, clean development mechanism; GDP, gross domestic product; EDB, Environmental Database; IEA, International Energy Agency; EPA, Environmental Protection Agency; ETBE, ethyl tertiary butyl ether; GHG, greenhouse gas; IGCC, integrated gasification combined cycle; IPCC, intergovernmental panel on climate change; LEAP, long-range energy alternatives planning system; MSW, municipal solid waste; MTBE, methyl tertiary butyl ether; MW, megawatt; PEMEX, Mexico's state-owned oil company; PJ, petajoule; PV, photovoltaic; SEI-B, Stockholm Environment Institute at Boston; USCS, US Country Studies program; VOME, vegetable oil methyl ester

*Corresponding author. Tel.: +52 55 5622 9704; fax: +52 55 5622 9791.
E-mail address: manzini@servidor.unam.mx (F. Manzini).

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current energy imports, mainly gasoline and diesel, is important for economic and national security reasons. The world's future bioenergy potential ranges from 94,000 [5] to 325,000 PJ/year [6]. The latter value represents up to 78% of total world primary energy consumption in 2004 [7]. As of year 2004, world bioenergy resources represented 11% of global primary energy consumption [7]. Ghilardi [8] suggests that 3035 PJ/year is a moderate value of the Mexican bioenergy potential whereas 4550 PJ/year is a high estimation. These figures represent 46% and 68% of the primary energy supply in Mexico in the year 2005, respectively.

A first and important step to solve this energy diversification problem was made by the Mexican Congress in April 2007 with the Law of Promotion and Development of Biofuels (Ley de Promoción y Desarrollo de los Bioenergéticos). This law was approved by the Congress and it is expected to be published and enacted in the same year [9]. It will provide a legal framework to foster the use of biofuels at the national level. At present there is another law initiative that has a broader application, the Law for the Promotion and Use of Renewable Energy Sources (Ley de Aprovechamiento de las Fuentes Renovables de Energía), which was approved by the Chamber of Deputies in December 2005. However, this initiative has been under debate at the Chamber of Senators since then and has not yet been ratified. This law would establish a legal framework to promote the massive use of renewable energy sources, particularly in the Mexican electricity sector [10].

The Brazilian example stands out as one of the most important international initiatives for the use of bioenergy. Brazil's Proalcool program began in 1975. Over the course of 14 years, 5000 million USD have been invested in bioenergy. Twenty-five years later, expenditures for gasoline imports have been reduced by 43,000 million USD and 700,000 new jobs have been created [11]. Currently, ethanol consumption in the Brazilian transportation sector represents 47% of gasoline consumption [12]. In the United States, bioenergy became the leading source of renewable energy and slightly surpassed hydroelectric production. It also contributed to 48% of the total renewable energy used and to 4% of the total energy produced in 2004. The Biomass Program of the US Department of Energy, launched in 2000, predicted that the role of bioenergy would eventually represent 5.75% of transportation fuels by 2010 and 30% of current petroleum consumption by 2030 [13]. Recently, the American "20 in 10 program", launched in January 2007, proposed that 15% of the transportation fuel demand would be satisfied with biofuels in 2017.

Other countries have seriously considered the massive use of bioenergy in the future. For instance, China [14], Germany [15], Austria [16] and Sweden [17] have set goals of 10–15% of their internal primary energy supply up to the year 2020. A special case is Vietnam where the contribution of bioenergy is high with 37.8% of the total energy consumption [18].

In a study made by Kumar [18], greenhouse gas mitigation potential of bioenergy technologies was calculated for Vietnam. In that study, penetration rates of biomass energy technologies are high, including the substitution of traditional cooking stoves with efficient biomass or biogas stoves at a high average annual penetration rate of 20%.

In this study, three different scenarios are created for electricity generation, transportation and residential sectors up to the year 2030. The hypotheses of such scenarios are based on the behavior of macroeconomic variables as well as specific hypotheses regarding the substitution of fossil fuels for biofuels. Particular assumptions are applied for each scenario and energy-consuming sector in order to simulate the annual growth of biofuel use. In the case of the residential sector, this assumption is related to the increasing use of more efficient wood-burning and biogas stoves. Furthermore, a profile of bioenergy consumption has been obtained for all sectors considered in each scenario. Finally, the corresponding amount of avoided CO_2 emissions is calculated using the IPCC emissions factors.

2. Methodology

2.1. The long-range energy alternatives planning system (LEAP) model

This study was done with the 1995 version of the LEAP model. This model, developed by the Stockholm Environment Institute at Boston (SEI-B), is a bottom-up-type accounting framework, which serves as a database and forecasting tool. It also allows the evaluation of the corresponding environmental emissions of different energy policies and technologies in energy consumption and supply (i.e. energy efficient use, fuel substitution and/or structure changes) [19].

Fig. 1 shows the LEAP structure integrated into 4 modules: energy scenarios, the Environmental Database

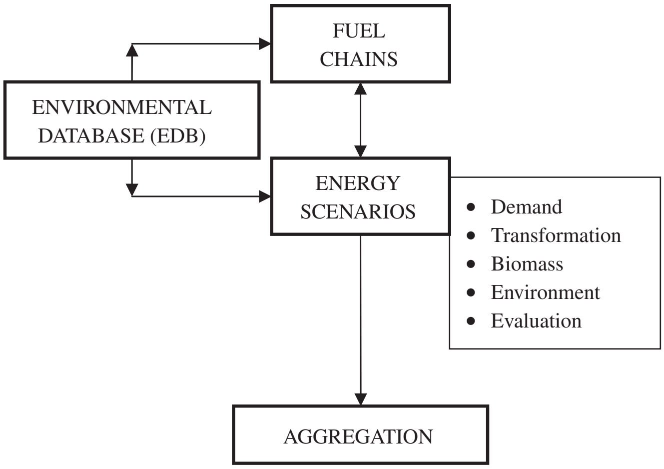

Fig. 1. LEAP's schematic structure.

(EDB) interface, the aggregation and the fuel chains. The energy scenarios module also consists of the following programs: demand, transformation, biomass, environment and evaluation. The EDB interface contains information on energy-related environmental loadings that can be used to calculate alternative energy scenarios. The aggregation module gathers area-level energy accounts and projections and then presents these data in multi-area results. The fuel chains module allows comparison of environmental impacts of specific fuel and technology choices.

Energy demand is calculated with the demand analysis program and based on data regarding the energy consumed by different Mexican end-use sectors as reported in the national energy balance [20]. The transformation program simulates the infrastructure of electricity generation and distribution, refinery and gas plants, including data on natural gas, oil and coke production. Once the energy requirements are calculated in the demand analysis program, then the primary supplies in the transformation program match the calculated energy demand.

Due to the fact that non-biogenic CO_2 emission factors depend on the carbon content of the fuel and they may vary from country to country, the CO_2 emission factors used in this study are those included in the EDB interface. The environment program uses the EDB in order to calculate the environmental impacts associated to the alternative scenarios. Emission factors represent average values gathered by the IPCC. Table 1 shows the CO_2 emission factors used in this study [19]. The biomass program incorporates land use data for the biomass supply assessment. The evaluation program is used to compare alternative scenarios.

It should be noted that in this study each sector's aggregation level are assigned by fuel types and according to our hypothesis they have the same average annual growth rate (AAGR) as the GDP, except for fuelwood which grows with population.

LEAP has been widely used as a model for simulating energy systems at country level. Examples of energy supply, demand and greenhouse gas mitigation studies are available for Mexico [21], China [22] and the US Country Studies program (USCS) [23]. LEAP has also been used for sector-level analysis: in electricity generation [24], transportation [25,26] and household [27]. Other studies about bioenergy scenarios have been reported for Vietnam [18] and Korea [28].

Table 1
Non-biogenic CO_2 emission factors from LEAP Environmental Database (EDB) [19]

CO_2 emission factor	kg/GJ
Coal	141.5
Fuel oil	73.7
Diesel	72.9
Natural gas	52.2
Gasoline	52.5
LPG	64.6
Kerosene	71.3

2.2. Scenario construction

Three scenarios are constructed for Mexico: a base or trend scenario and two alternative scenarios. All scenarios are based on previous studies formulated by Islas and Manzini [24,29,30].

2.2.1. Base scenario

In this scenario, fuels derived from oil and natural gas are assumed as the most-used options. Thus, in the power sector, all new capacity additions are based on natural gas-fired combined-cycle plants (CCNG). In the residential sector, liquefied petroleum gas is the most used fuel in the urban areas, while fuelwood is burned in the traditional manner in the rural areas. With regard to the transportation sector, gasoline and diesel are the most used fuels.

Due to the lack of recent data, 1996 was selected as the reference year. Mexico's 1996 energy balance is reproduced in LEAP's Demand and Transformation programs. In so doing, future energy demand of the following end-use sectors can be calculated: residential, commercial, services, agricultural, industrial, transportation and energy sector self-consumption. After this, and based on [21,30,31], the following assumptions are used: (i) Constant economic growth—gross domestic product (GDP) AAGR of 4%. (ii) Constant population growth—AAGR of 1.21% and 138 million inhabitants by year 2030 [32]. (iii) Constant end-use demand structure. (iv) Energy and electricity demand grows at 4% per year—same AAGR as the GDP [33]. (v) The installed power capacity increases by 5% up to the year 2007 [34]. (vi) After 2007, the installed power capacity grows at 3.4% per year. (vii) Three percent of the new electricity requirements is devoted to satisfy the peak power demand by diesel and natural gas-powered internal combustion engines.

Mexico's GDP AAGR of 4% is calculated considering its historical behavior: GDP grew at an average annual rate of 6% between 1965 and 1979, but it fell to 1.4% during the 1980s. Afterwards, in the 1990s, it grew at an AAGR of 3.4% and then reached 7% in year 2000. Thus, the 4% value chosen for this study is exactly the historical AAGR of Mexico's GDP between 1965 and 2000 [33]. Likewise, Mexico's electricity demand AAGR of 4% is calculated according to its historical behavior: electricity demand grew at an AAGR of 7.7% between 1966 and 1989, but it fell to 5.1% in the 1990s. From 1980 to 2000, the growth rate of electricity demand had always been greater than the GDP AAGR. However, and due to improvements in energy efficiency of end-use technologies and to effective energy savings programs, this difference has been decreasing. Hence, it is assumed that this tendency remains and reaches zero by 2012 and 0.8% below the GDP AAGR by the year 2030. The electricity demand AAGR is 4% between 1996 and 2030, identical to the assumed GDP

AAGR. According to this historical path, installed power capacity grew at an AAGR of 0.6% below the electricity demand AAGR from 1965 to 2000. Therefore, it is assumed that this capacity grows at an AAGR of 3.4% after year 2007. Table 2 shows the input data values for all macroeconomic variables in 1996 and their corresponding annual growth rates thereafter.

2.2.2. *Alternative bioenergy scenarios*

As previously mentioned, Mexico's technical bioenergy potential ranges from 3035 to 4550 PJ/year [8]. This potential is equivalent to 68% and 46% of the Mexican primary energy supplied in 2005 (6649 PJ), respectively [35]. Table 3 shows this potential classified by different type of bioenergy sources. Woodfuels contribute with up to 67% of this bioenergy potential, farming fuels with 32% and organic municipal solid wastes (MSW) with just 1%. As of year 2005, bioenergy use in Mexico amounted to 350 PJ and accounted for 12% and 8% of the estimated potential, respectively.

In the two alternative scenarios, the substitution of fossil fuels for biomass fuels is analyzed in all selected economic sectors. Thus, a moderate and high bioenergy penetration scenarios are simulated. Table 4 shows the biofuels and energy technologies that can replace fossil-fuel-based options in electricity generation—including cogeneration and electricity for self-supply purposes—traditional cook stoves in the residential sector, and diesel and gasoline in the transportation sector.

Fig. 2 provides the structure of the energy demand tree for all analyzed sectors in the alternative scenarios. It is important to note that energy required to meet the own power plants needs for public service, cogeneration and electricity self-supply are represented in LEAP model as an end use demand sector.

Furthermore, it is assumed that the diffusion of each biofuel-technology option has the classic S-shaped sigmoid curve. This growth curve is described in three phases: emerging, maturity and saturation.

The emerging phase is characterized by high average annual penetration rates that range from 30% to 50% owing to the process of innovation. When innovation is introduced, its adoption begins from almost zero. The penetration rate grows exponentially with the awareness of the new technology and the number of early adopters. In this paper the emerging phase is generally divided in two stages, both with high values, but in the second stage the diffusion rate decreases due to the high growth—in absolute terms—encountered in the middle of this emerging phase.

Table 3
Bioenergy resource potential in Mexico evaluated in 2004 [8]

Bioenergy sources	Energy potential (PJ/year)
Wood fuels	
From natural forests	997–1716
From forest plantations	450–1246
Residues from sawmills and forest extraction	71
Farming fuels	
From crop residues	863
From agro-industrial residues	202
From cattle residues	148
From energy crops	269
Municipal waste residues	35
Total	3035–4550

Table 4
Emerging and commercially available biofuel-energy technology options that allow fossil fuels to be substituted with biofuels

Biofuel	Energy technology	Substituted fuel/ technology
Commercially available		
Biogas from sanitary landfills	Gas turbines	Residual fuel oil in steam turbines
Forest and crop residues	Incinerators	Residual fuel oil in steam turbines
Any gasoline and ethanol blending	Flexible internal Combustion engines (ICE)	Gasoline ICE and Ethanol ICE only
Biodiesel	Diesel ICE	Diesel
Fuelwood	Efficient wood burning stoves	Traditional fuelwood stoves
Cattle residues	Biodigestors and biogas stoves	Traditional fuelwood stoves
Emerging		
Forest plantations, forest residues and bagasse	Biomass integrated gasification combined cycle (BIGCC)[a]	Natural gas combined cycle (NGCC)

[a] To be introduced in Mexico by 2010.

Table 2
Values of Mexican macroeconomic variables in 1996

Variable	Units	Value (1996)	AAGR
POB inhabitants[a]	10^6 inhabitants	92.040	1.21%
GDP[b]	Billions of current USD	332.5	4.0%
Installed power capacity[c]	MW	34,695	5% until 2007 3.4% after 2007

[a] CONAPO [32].
[b] INEGI [33].
[c] SENER [34].

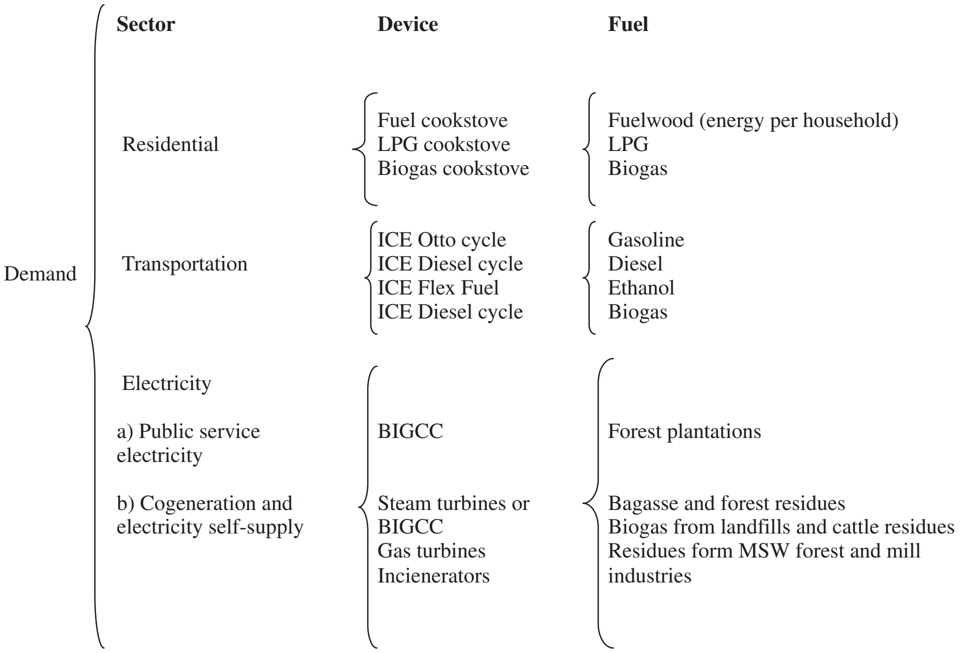

Fig. 2. Energy demand tree used in LEAP to simulate the alternative scenarios.

The emerging phase ends when selected biofuel-energy technology options cover from 6.5% to 9.5% of the fuels substituted in the base scenario.

Later, a maturity phase starts with lower average annual growth rates, usually from 18% to 22%. This phase is characterized by consolidation of the technology in the market. Therefore, in this paper the initial year may differ for each technology. For example, the maturity phase for biodiesel—diesel engine option begins in 2024, while energy plantations—biomass integrated gasification combined cycle (BIGCC) option does not reach its maturity phase before 2030.

Finally, the saturation phase starts when market penetration begins to level off at ‘‘full-market potential’’ [36]. Although in this phase technology adoption still grows, it slows its growing pace rapidly. In this study, it is assumed that none of the selected technologies reaches this phase.

During the emerging phase, most of the previously mentioned high AAGR are inspired by the successful experiences of countries that implemented various new renewable sources of energy. For example, Germany had an AAGR of 40% for PV generating systems from 1994 to 2004 [37] and wind energy in Spain grew at an AAGR of 60% between 1994 and 2004 [38].

High and moderate bioenergy scenarios assume that biofuels are introduced in electricity generation, transportation and residential sectors at different penetration rates, which reflect its diffusion during the emerging and maturity phases. Table 5 shows, for most cases, the emerging phase—divided in two stages and their corresponding

Table 5
Assumed AAGRs in the emerging and maturity phases of the considered biofuel—energy technology options up to the year 2030

	Emerging phase		Maturity phase
	1st stage	2nd stage	
Electricity generation			
Residues—incinerators	2005–2015	2016–2023	2024–2030
High scenario (%)	38.0	31.0	20.0
Moderate scenario (%)	30.0	22.0	17.0
Biogas from landfills and cattle residues—gas turbines	2005–2023		2024–2030
High scenario (%)	24.0		18.2
Moderate scenario (%)	18.0		16.0
Energy plantations—BIGCC	2015–2030		
High scenario (%)	38.0		
Moderate scenario (%)	31.4		
Bagasse—BIGCC	2010–2023	2024–2030	
High scenario (%)	30.0	20.8	
Moderate scenario (%)	24.0	18.4	
Transportation sector			
Ethanol—ICE	2005–2015	2016–2025	2026–2030
High scenario (%)	45.0	30.0	20.5
Moderate scenario (%)	40.0	30.0	13.0
Biodiesel—ICE	2005–2015	2016–2023	2024–2030
High scenario (%)	45	33	21
	2005–2015	2016–2026	2027–2030
Moderate scenario (%)	40	25	15
Residential sector			
Fuelwood—efficient cookstoves	2005–2015	2016–2025	2026–2030
High scenario (%)	50	35	21.7
Moderate scenario (%)	45	32	19.6

penetration rates—with the purpose to reflect its slowing pace after a quick start. These penetration rates are assumed to be feasible from a technical, economical and institutional point of view and are discussed in detail in Section 2.2.2.1.

2.2.2.1. Electricity generation assumptions. The integrated gasification combined cycle (IGCC)—originally developed to use mineral carbon as energy source—can also be used with fuelwood bagasse and forest residues in a process called BIGCC. This recent development has opened new possibilities for biofuels use. This study assumes the BIGCC option as an emerging energy technology that will be introduced by 2010. Corti [40] examined with favorable results the use of fuelwood and forest residues as input fuels in a BIGCC plant. A similar study made by Turn [41] and Larson [39] about using sugar cane bagasse as input fuels in BIGCC plants concluded with positive results. Other authors such as Dowaki [42] and Rhodes [43] made an economic analysis and calculations on carbon capture and storage using BIGCC and other gasification systems. With regard to the efficiencies of biomass gasifiers integrated with gas turbines, the values have been reported in the range of 35–40% when feeded with solid biomass [44]. Load factors vary according to biofuel availability, but BIGCC plants can perform as high as 80% [44].

In 2001, Larson [39] considered that biomass integrated-gasifier/gas turbine combined cycle (BIGCC) systems had doubled the electricity produced per unit of biomass in comparison to the conventional condensing–extraction steam turbine (CEST) systems. BIGCC systems were expected to achieve lower capital investment requirements per kilowatt of installed power capacity. More recently, Rhodes [43] carried out an analysis and considered feedstock cost, efficiency, capital cost and load factor. This analysis has shown that BIGCC systems are roughly cost-competitive with conventional technologies and can provide cost-effective emissions reductions.

On the other hand, current Mexican laws allow the generation of electricity to satisfy self-supply and cogeneration needs, particularly in the industrial activities. However, sugar cane bagasse has been the only source of biomass officially used for cogeneration of electricity and heat in the Mexican energy sector. As of year 2003, the energy sector's installed power capacity for self-supply purposes amounted to 2224 MW and generated 55 million GJ, which were equivalent to 49% and 43% of the national self-supplied power capacity and electricity generated in that year, respectively. It is worth to mention that 19% (428 MW) of this power capacity were bagasse-fuelled steam turbines, which generated 10% of the electricity supplied for self-consumption in the industrial branch in the same year.

This study assumes that it is technically and economically feasible for the power sector to generate electricity from fuelwood plantations through BIGCC by 2015. These plants have a capacity of up to 250 MW. Similarly, our scenarios assume that it is technically [44] and economically [9] feasible the implementation in cogeneration projects of BIGCC plants after year 2010. In the case of sugar cane bagasse, these projects operate with an average efficiency of 40% and a load factor of 60%. The problem that bagasse is not available year round is solved with a combination of bagasse and forest plantations as done by [45].

Finally, it is assumed that not only landfill, MSW and animal wastes biogas projects but also the utilization of cellulosic or other solid biomass residues for energy generation are feasible from an economic point of view. Biogas is used in modern gas or steam turbines cycles with an efficiency of 32% and a load factor of 60% [28]. Cellulosic or other solid biomass residues [46] are incinerated directly in a boiler, using the resulting superheated vapor in a conventional steam turbine and coupled to an electric generator. These plants operate with an efficiency of 36% and a load factor of 60%, which are average values for the analyzed period.

2.2.2.1.1. Energy plantations—BIGCC. In the high penetration scenario of forest plantations, the following assumptions are considered: (1) In order to avoid competence with natural forests and to promote a sustainable use, fuelwood fast-growing forest plantations such as Acacia and Eucalyptus need between 5 and 8 years from the mature to the clear-cut stages [39,42,43]. (2) Forest plantations will be fully mature to produce in 2015.

Hence, only the emerging phase has been analyzed between 2015 and 2030, where this biofuel-technology option would grow at an AAGR of 38%.

In the moderate penetration scenario, the technical assumptions are the same as those considered in the high scenario. Nevertheless, more stringent environmental laws are implemented in order to prevent land use changes, which slow down the development of forest plantations. Therefore, an AAGR of 31.4% has been considered.

2.2.2.1.2. Bagasse—BIGCC. In the high penetration scenario of bagasse, the following assumption is made: (1) As a result of the great ethanol demand in this scenario, sugar cane crops experience a big expansion. Therefore, energetically favorable bagasse is widely available for being exploited in BIGCC plants.

The emerging phase has been divided in two penetration stages: the first one corresponds to a rapid growing stage from 2010 to 2023 with an AAGR of 30%. In the second stage, the growth rate would decrease, but still remains high at an AAGR of 20.8%.

In constrast, the moderate scenario assumes the existence of a major barrier encountered in the lack of bagasse production. This barrier slows down the implementation of this option owing to the less economic incentives. As a result, the diffusion velocity of bagasse—BIGCC technology decreases in comparison with the high scenario and would lead to an AAGR of 24% during the first stage of the emerging phase between 2010 and 2023. Similarly, this decreasing path would be observed in the second stage, with an AAGR of 18.4% from 2024 to 2030.

2.2.2.1.3. Biomass residues—incinerators. The following assumptions are made in the high penetration scenario of biomass residues: (1) Sources of financing are available so that a national program on incinerators deployment can be fostered. (2) It has been implemented an efficient logistics system for biomass feedstock recollection. (3) National laws and standards have been adapted so that the establishment of distributed generation plants facilitates the installation of small plants (30 MW average), which are located near to the place where most of the resources are recollected.

Due to these positive factors, the following phases have been identified: an emerging phase, divided in two penetration stages, and the beginning of a maturity phase. During the first emerging stage, this technology option would have an AAGR of 38% between 2005 and 2015 whereas in the second emerging stage it would grow at an average annual rate of 31% from 2016 to 2023. This value is a lower but still high AAGR. The maturity phase would start in 2024, growing at an average annual rate of 20% until 2030.

In contrast, the moderate penetration scenario assumes the existence of two barriers associated to financing problems as well as to the lack of institutional conditions that limit the support of distributed generation. Hence, the diffusion velocity decreases and would lead to a first emerging stage with an AAGR of 30% between 2005 and 2015. During the second emerging stage, this biofuel-technology option would grow at an average annual rate of 22% from 2016 to 2023. The maturity phase would start in 2024, growing at an average annual rate of 17% until 2030.

2.2.2.1.4. Biogas from sanitary landfills. In the high penetration scenario, the following assumptions are made about the deployment of sanitary landfills for biogas production using MSW: (1) Financing schemes such as the clean developing mechanisms facilitate access to the deployment of this option. (2) State and Municipal legislations foster the deployment of sanitary landfills.

The emerging phase takes place for a long period so that the average annual rate would grow at 24% from 2005 to 2023. Then, the maturity phase would start in 2024, growing thereafter at an average annual rate of 18.2%.

On the contrary, the moderate scenario assumes that the flow of finance is not enough to support an important penetration of this option and the legal framework required to foster this technology develops slowly. Therefore, during the emerging phase the diffusion of this option would grow at an average annual rate of 18% from 2005 to 2023. The maturity phase would start in 2024, growing at an average annual rate of 16% up to the year 2030.

2.2.2.2. Transportation sector assumptions. Transportation sector has been the dominant energy consuming sector in Mexico since 1968, except for the 1983–1987 period. According to the 2005 National Energy Balance [1], sectors' energy consumption reached 1864 PJ and accounted for 45.7% of the final energy demand in Mexico in that year. Road transportation consumed 91% of these energy requirements, where gasoline and diesel together accounted for 64% and 24% of that share, respectively. In this work, it is assumed that ethanol and biodiesel are technically and economically viable options that can be massively introduced in the Mexican transportation sector. Furthermore, based on IEA's 2010 price forecast [47], it is assumed that both sugar cane-based ethanol and waste grease-based biodiesel are competitive with gasoline and diesel prices during the same period of time.

It is important to mention that the Brazilian experience has demonstrated—once large-scale production is reached—the economic competitiveness of ethanol from sugar cane when compared with international gasoline prices [11,48]. Additionally, Mexico's Law of Promotion and Development of Biofuels [9] seems to be the first step towards a massive use of biofuels in the transportation sector since it will enforce the implementation of programs for the promotion and development of ethanol and biodiesel production in the country.

2.2.2.2.1. Ethanol. Ethanol is the most widely used biofuel in the world. At present it is mostly derived from sugar cane and corn. There are at least three ways of expanding the use of ethanol in the transportation sector.

A first option is the use of ethanol in the production of ethyl tertiary butyl ether (ETBE), an oxygenating additive that is mixed with gasoline in proportions up to 15 vol%, as currently done in France, Spain and Germany. ETBE increases octane rating and reduces carbon monoxide and unburned hydrocarbon emissions. ETBE is composed by 48 vol% ethanol and 52 vol% isobutylene (a byproduct of oil refining). ETBE is an adequate substitute for methyl tertiary butyl ether (MTBE), an oxygenating additive that is currently prohibited in some US states because it is a "potential human carcinogen" as stated by US EPA [49].

A second option is the blending of anhydrous (dehydrated) ethanol with gasoline. In this case, anhydrous ethanol is also an oxygenating additive that increases octane rating. Currently, several countries blend anhydrous ethanol in proportions that range from 5 to 26 vol%.

The third option is the use of ethanol in its pure and undehydrated form as a transportation fuel in vehicles specially modified for this purpose. In Brazil, approximately 5 million of E100 vehicles have been sold since 1979. These sales reached a maximum of 76% of total vehicle sales in 1986, but had been declining since then. However, in 2003, a new technology was introduced and allowed the use of any blending of gasoline and ethanol. Vehicles with flex-fuel or "flexible" engines—which can automatically adjust to the combustion parameters of any gasoline–ethanol proportion—have been gaining an increasing share of the automotive market, particularly in the US and Brazil.

Mexico had the infrastructure to produce 66 million liters of ethanol in 2005, mostly for drink and health uses.

In order to build the high penetration scenario of ethanol production for transportation the following assumptions are made: (1) Ethanol production technology is commercially available. (2) Sugar industry has undertaken a partial transformation of sugar production to ethanol production. (3) There is an expansion of agricultural land dedicated to sugar cane crops for ethanol production. (4) The technical barrier related to the hygroscopic property of anhydrous ethanol has been removed by building infrastructure to continuously dehydrate ethanol. (5) PEMEX, the oil company that according to the law has the monopoly of oil sector in Mexico, has the obligation to blend anhydrous ethanol with gasoline, starting gradually with a 5% ethanol blending (E5). This blending is distributed in all country's big cities from 2005 and it will be in force at country level by 2010. Later, flex-fuel technology is introduced, allowing the use of up to 100% ethanol (E100) in internal combustion engines. (6) There are fiscal incentives and governmental subsidies to foster biofuels.

Therefore, the emerging phase would have an initial stage (from 2005 to 2015) characterized by an AAGR of 45%. Later, in a second stage of this emerging phase, ethanol production growth rate would be reduced to 30% until 2025. From 2026 the maturity phase of ethanol production would begin, growing at an average annual rate of 20.5% until 2030.

In the moderate scenario it is assumed that: (1) Problems derived from the hygroscopic property of anhydrous ethanol are not solved immediately. (2) PEMEX accepts to blend ethanol with gasoline by substituting MTBE for ETBE. This blending is distributed only in big urban centers (Mexico City, Guadalajara and Monterrey). (3) Later, due to a legal obligation, PEMEX starts to blend anhydrous ethanol with gasoline in 2020, reaching the whole country with a 5% (E5) blending in 2024. In 2025, a 10% (E10) blending is distributed in big cities, reaching the whole country in 2030. (4) There are serious restrictions to expand the agricultural land dedicated to sugar cane crops for ethanol production. (5) There are neither fiscal incentives nor subsidies to foster biofuels.

Hence, the emerging phase would have an initial stage (from 2005 to 2015) characterized by an AAGR of 40%. Later, in a second emerging stage, this average annual rate would grow at 30% from 2016 to 2025. In the maturity phase (starting after 2025) ethanol production would grow at an AAGR of 13% until 2030.

2.2.2.2.2. Biodiesel. Biodiesel, or vegetable oil methyl ester (VOME), is the second most commonly used liquid biofuel in the world. Biodiesel is derived from oleaginous plants (i.e. rapeseed, oil palm tree, soy or sunflower). It is produced through a transesterification reaction of vegetable oil and alcohol such as methanol or ethanol. Biodiesel can be used in its pure form or mixed with conventional diesel for use in conventional diesel engines [50].

In 2005, the production of biodiesel in Mexico was 0.25 PJ [51]. In order to build the high penetration scenario of biodiesel production, the following assumptions are made: (1) Biodiesel can use the same infrastructure than petro diesel so PEMEX is cooperative. (2) Diesel engines require only minor mechanical adjustments in order to use 100% biodiesel (B100). (3) There is an increasing rate on the expansion of the agricultural land dedicated to tropical vegetable oil-producing plants (i.e. oil palm tree) and temperate vegetable oil-producing plants (i.e. rapeseed and soy) as feedstock for biodiesel production. (4) There are fiscal incentives and governmental subsidies to foster biofuels.

In the high penetration scenario, biodiesel would expand rapidly at an AAGR of 45% from 2005 to 2015—the first stage of an emerging phase. Later, in a second and final stage, biodiesel production AAGR would be reduced to 33% from 2015 to 2023. The maturity phase of biodiesel production would start in 2023, growing at 21% annually until 2030.

In the moderate penetration scenario of biodiesel production, it is assumed that there is a restricted rate on the expansion of the agricultural land dedicated to tropical and temperate oil producing plants for biodiesel production, because there are not enough fiscal incentives and governmental subsidies to foster biodiesel.

Therefore, in the first stage of the emerging phase, biodiesel would expand at an AAGR of 40% from 2005 to 2015. Later, in a second stage, biodiesel production would grow at an average annual rate of 25% from 2016 to 2026. The maturity phase would start in 2027, growing at an average annual rate of 15% until 2030.

2.2.2.3. Residential sector. In the residential sector, particularly in rural subsector, the introduction of efficient woodfuel and biogas cooking stoves was analyzed.

Deforestation is a global phenomenon with increasingly serious ecological consequences. While the clandestine and indiscriminate felling of trees to obtain wood, and expansion of agriculture and cattle ranching are the principal causes of deforestation. The use of fuelwood for cooking, mainly in the rural subsector, also puts pressure on forests, contributing to their deterioration [52].

Our scenarios for decreasing the pressure from fuelwood harvesting on forests focus on alternatives to traditional methods for cooking and heating water in the rural sector. We focused on two variables: stove type and fuel type. It is assumed that the traditional open fires are replaced with efficient wood-burning cookstoves and biogas stoves [53]. Approximately one-fourth of Mexican population cooks with fuelwood on open fires. These devices are very inefficient and led to annual household cooking energy use of 257 PJ in year 2003 [54] (approximately 30% of Mexican residential consumption). Several models of efficient cookstoves have been disseminated in Mexico. A recent successful experience corresponds to the "Patsari" cookstove, a massive, multi-pot stove that results in 50% savings in fuelwood use compared with traditional open fires [54,55]. In this article, it is assumed that open fires are gradually replaced by efficient cookstoves with a net reduction of 50% in fuelwood use.

Wood-burning cookstove programs have had a minimal impact in Mexico to this date, as there has not been support from the government to launch large-scale initiatives. The total number of stoves disseminated in the last 15 years reaches less than 3000. This fact constrasts with the approximately 6 million households that used traditional fuelwood for cooking in 2003 [8].

In the high penetration scenario, it is assumed that there will be a change in government priorities leading to the launching of large-scale efficient cookstove programs. It is also assumed that the use of cattle residues to obtain biogas through a household biodigester in Mexico grows as fast as fuelwood cookstoves. This would represent 680,000 biodigesters–biogas cookstoves by year 2030, or 7% of rural households [30]. Biodigesters would be fed by 26% of available cattle residues (see Table 3).

In a high scenario, in order to estimate the penetration of fuelwood and biogas used in efficient cookstoves among rural population in Mexico, the following assumptions were made: (1) Due to governmental and national private sector support, there is a large-scale program to deploy efficient cookstoves, biogas cookstoves and biodigesters among rural population, similar to those introduced in China in the 1990s [56]. (2) The biogas is produced in a household biodigester with animal manure as feedstock. (3) Mexico achieves important international economic support as CDM projects to reduce GHG emissions and deforestation prevention, and from other humanitarian institutions for health and poverty alleviation noting that most people in Mexican rural areas live below poverty line.

The emerging phase is divided in two penetration stages. In the first emerging stage, the fuelwood and biogas cookstoves would diffuse with an AAGR of 50% between 2005 and 2015, then in a minor but still high second emerging stage at 35% AAGR from 2016 to 2025. The maturity phase would start in 2026, growing at an AAGR of 21.7% until 2030.

In a moderate scenario, the total number of cookstoves is approximately half the number of the high penetration scenario, due to the following assumption: There is not enough governmental and international support to promote these efficient wood and biogas cookstoves.

In the first stage of the emerging phase it is assumed that the use of efficient cookstoves and biogas cookstoves would grow at an average annual rate of 45% from 2005 to 2015. Later in a second stage from 2015 to 2025 both cookstoves would grow at lower but still high AAGR of 32%, and at the beginning of the maturity phase, from 2025 to 2030 at 19.6% AAGR.

3. Results

This section presents the results obtained from the simulation using the LEAP program as well as an assessment of the physical and environmental effects of the previously discussed alternative scenarios.

3.1. Electricity generation

In the high-penetration scenario, all four biomass-based energy-technology options for electricity generation (see Table 5) would reach an installed power capacity of 440 MW by 2015 and 16,987 MW by 2030. In terms of electricity generation, this capacity would produce 8.3 PJ in 2015 and 321.7 PJ in 2030.

Bioenergy input requirements would account for 0.8% and 18.2% of the total energy consumed in the electricity sector by 2015 and 2030, respectively. With regard to the avoided CO_2 emissions, they would represent 0.7% and 15.5% of the base scenario's emissions in 2015 and 2030. These figures would amount to 0.6 and 21.6 million tons by 2015 and 2030, respectively (see Table 6).

In the moderate scenario, all four biomass-based energy-technology options for electricity generation would reach an installed power capacity of 297 MW by year 2015 and 6697 MW by 2030. This power capacity may represent an annual electricity generation of 5.6 PJ in 2015 and 127 PJ in 2030. Bioenergy input requirements would account for 0.5% and 7.1% of the total energy consumed in this sector by 2015 and 2030, respectively. CO_2 emissions would be reduced by 0.4% and 6.1% with respect to the base scenario in years 2015 and 2030, respectively. This reduction would be equivalent to 0.3 million tons of avoided CO_2 by 2015 and 8.5 million tons by 2030 (see Table 6).

3.2. Transportation sector

3.2.1. Ethanol

In the high-penetration scenario, ethanol consumption would grow from 20.5 PJ in 2015 to 719.5 PJ in 2030. Ethanol's contribution would be 0.68% and 13.18% of the total energy used in the transportation sector by 2015 and 2030, respectively. The participation share of ethanol in the gasoline vehicle sector would be 1.27% in 2015 and 20% in 2030. The corresponding non-biogenic CO_2 avoided emissions would add up to 1.23 million tons in the year

Table 6
Results for the bioenergy scenarios in the electricity generation

Power sector and CHP producers	Moderate scenario		High scenario	
	2015	2030	2015	2030
Installed capacity (MW)	297	6697	440	16,987
Electricity production (PJ)	5.6	127	8.3	322
Bioenergy consumption (PJ)	15.3	332.5	23	855
Bioenergy input/total energy input (%)	0.5	7.1	0.8	18.2
Avoided non-biogenic CO_2 (million tons)	0.3	8.5	0.6	21.6
Avoided non-biogenic CO_2 (%)	0.4	6.1	0.7	15.5

Table 7
Energy consumption, GHG emissions and participation shares of ethanol used in transportation sector

Ethanol in transportation sector	Moderate scenario		High scenario	
	2015	2030	2015	2030
Bioenergy consumption (PJ)	14.5	367.3	20.5	719.5
Ethanol/total energy (%)	0.48	6.73	0.68	13.18
Ethanol/(ethanol + gasoline) (%)	0.80	10.19	1.27	20.00
Avoided non-biogenic CO_2 (million tons)	0.77	17.35	1.23	34.06
Avoided non-biogenic CO_2 (%)	0.80	10.19	1.27	20.00

2015 and 34.06 million tons of CO_2 in 2030. This reduction in CO_2 emissions would account for 1.27% and 20%, respectively, when compared with gasoline emissions (see Table 7).

In the moderate scenario, bioethanol consumption would reach 14.5 PJ in the year 2015 and 367.3 PJ in 2030 and would be equivalent to only 0.48% and 6.73% of total energy use in the transportation sector, respectively. The participation share of ethanol in the gasoline vehicle sector would be 0.80% in 2015 and 10.19% in 2030. With regard to the corresponding avoided non-biogenic CO_2 emissions, this scenario would add up to 0.77 million tons in the year 2015 and 17.35 million tons of CO_2 in 2030. These avoided emissions would represent a reduction of 0.80% and 10.19%in CO_2 levels, respectively, when compared with gasoline emissions (see Table 7).

3.2.2. *Biodiesel*

In the high penetration scenario, biodiesel consumption would grow from 10.3 PJ in 2015 to 381.9 PJ by 2030. Biodiesel's participation in the transportation sector would be 0.34% and 6.99% of the total energy consumed by diesel-fueled vehicles in 2015 and 2030, respectively. The participation share of biodiesel in the diesel vehicle sector would be 1.30% in 2015 and 26.91% in 2030. Additionally, the corresponding avoided CO_2 emissions would sum up to 0.72 million tons in 2015 and 25.60 million tons in 2030. This reduction in CO_2 emissions would account for 1.30% and 26.91%, respectively, when compared with diesel emissions (see Table 8).

In the moderate scenario, biodiesel consumption would reach 7.2 PJ in 2015 and 147.2 PJ in 2030 and would be equivalent to 0.24% and 2.70% of total energy used in the transportation sector, respectively. The contribution of biodiesel to the diesel vehicle sector would represent 0.92% and 10.37% of the participation share in 2015 and 2030. Total avoided CO_2 emissions would amount to 0.51 million tons in the year 2015 and 9.87 million tons in the year 2030, corresponding to a reduction in CO_2 emissions of 0.92% and 10.37.%, respectively, when compared with diesel emissions (see Table 8).

Table 8
Energy consumption, GHG emissions and participation shares of biodiesel used in transportation sector

Biodiesel in transportation sector	Moderate scenario		High scenario	
	2015	2030	2015	2030
Energy consumption (PJ)	7.2	147.2	10.3	381.9
Biodiesel/total energy (%)	0.24	2.70	0.34	6.99
Biodiesel/(biodiesel + remaining diesel) (%)	0.92	10.37	1.30	26.91
Avoided non-biogenic CO_2 (million tons)	0.51	9.87	0.72	25.60
Avoided non-biogenic CO_2 (%)	0.92	10.37	1.30	26.91

Table 9
Energy consumption, GHG emissions and participation shares of ethanol and biodiesel used in transportation sector

Biofuels in transportation sector	Moderate scenario		High scenario	
	2015	2030	2015	2030
Bioenergy consumption (PJ)	21.7	514.6	30.8	1101.4
Biofuels/total energy (%)	0.72	9.43	1.02	20.17
Biofuels/ (ethanol + gasoline) + (biodiesel + diesel) (%)	0.83	10.24	1.28	21.95
Avoided non-biogenic CO_2 (million tons)	1.27	27.18	1.95	59.65
Avoided non-biogenic CO_2 (%)	0.83	10.24	1.28	21.95

3.2.3. *Ethanol and biodiesel*

In the high penetration scenario, ethanol and biodiesel consumption would reach 30.8 PJ in 2015, increasing up to 1101.4 PJ in 2030. The contribution of these biofuels to the total amount of energy used by the transportation sector would be 1.02% in 2015 and 20.17% in 2030. Furthermore, biofuels would participate with 1.28% and 21.95% of the share in diesel and gasoline vehicle sectors by 2015 and 2030. Avoided emissions of non-biogenic CO_2 would amount to 1.95 million tons of CO_2 in 2015 and 59.65 million tons in 2030. This would represent a reduction of 1.28% and 21.95% by 2015 and 2030 (see Table 9).

In the moderate scenario, ethanol and biodiesel consumption would reach 21.7 PJ by 2015 and 514.6 PJ by 2030. The contribution of ethanol and biodiesel with respect to the total amount of energy used by the transportation sector would be 0.72% in 2015 and 9.43% in 2030. Additionally, the participation share of biofuels in diesel and gasoline vehicle sectors would be 0.83% in 2015 and 10.24% in 2030. Finally, avoided non-biogenic CO_2 emissions would be 1.28 million tons in 2015 and 27.22 million tons in 2030. These avoided emissions would account for a reduction in CO_2 levels of 0.83% and 10.24% in years 2015 and 2030 (see Table 9).

3.3. *Residential sector*

The proposed introduction of efficient wood-burning and biogas cookstoves developes into a large net reduction of fuelwood demand, therefore avoiding large emissions from deforestation and forest degradation.

Generally, estimates of the carbon mitigation potential depend on the fuelwood savings associated to the improved cookstoves, fuelwood type, geographical and climate conditions among other variables. Nevertheless, a conservative average carbon mitigation for fuelwood cookstoves was calculated for Mexico which is 0.5 tC/cookstove-year [57]. Assuming this average value as representative for all Mexican conditions, the total saved CO_2 in a high scenario would be approximately 0.12 million tons of CO_{2eq} by 2015 and 6.23 million tons of CO_{2eq} by 2030 (see Table 10). Additionally, the annual fuelwood consumption would be reduced 0.35% in comparison to the base scenario, resulting in 0.08 million tons of unconsumed fuelwood in year 2015. Afterwards, fuelwood consumption would reach a maximum in 2023 (see Fig. 3) and then would decrease progressively. Towards 2030 the reduction in fuelwood consumption would amount to 4.05 million tons and would be equivalent to savings of 15.87%. The number of efficient cookstoves introduced in 2015 would be 64,432 and 3,400,080 in 2030. Their consumption would change from 42.67 PJ in 2015 to 113.78 PJ in 2030, representing 13.89% and 36.60% of the total fuelwood used in residential sector, respectively. The rest of this fuelwood would be used in traditional cookstoves.

Table 10
Number of efficient wood-burning cookstoves, fuelwood savings and avoided carbon emissions in the residential sector

Residential sector	Moderate scenario		High scenario	
	2015	2030	2015	2030
Number of efficient wood burning cookstoves	45,193	1,776,102	63,432	3,400,080
Fuelwood savings (PJ)	0.78	30.62	1.09	58.6
Fuelwood savings (million tons)	0.05	2.11	0.08	4.05
Fuelwood savings (%)	0.25	8.29	0.35	15.87
Avoided emissions from the non-sustainable use of fuelwood (million tons of CO_{2eq})	0.08	3.26	0.12	6.23

In the moderate scenario, the total carbon emissions saved would be 0.08 million tons of CO_{2eq} in 2015 and 3.26 million tons of CO_{2eq} by 2030 (see Table 10). The annual fuelwood consumption would be 0.25% less than the consumption in the base scenario by the year 2015 and would total 0.05 million tons of fuelwood savings. Later, fuelwood consumption would reach a maximum in 2029 (see Fig. 3) and then would decrease progressively. In 2030, the consumption reduction with respect to the base scenario would be 2.11 million tons of fuelwood and would be equivalent to 8.29% savings. The number of efficient cookstoves introduced in 2015 would be 45,193 and 1,776,102 in 2030. Their consumption would change from 24.29 PJ in 2015 to 59.43 PJ in 2030, accounting for 7.9% and 17.55% of total fuelwood used in residential sector, respectively. The rest of this fuelwood would be used in traditional cookstoves.

3.4. General results

In the high penetration scenario, the use of biofuel–energy technology options in electricity generation, transportation and residential sectors would reach 55.9 PJ by 2015 and 2070 PJ by 2030 (see Fig. 4) and would be equivalent to 0.44% and 16.17% of the total consumed

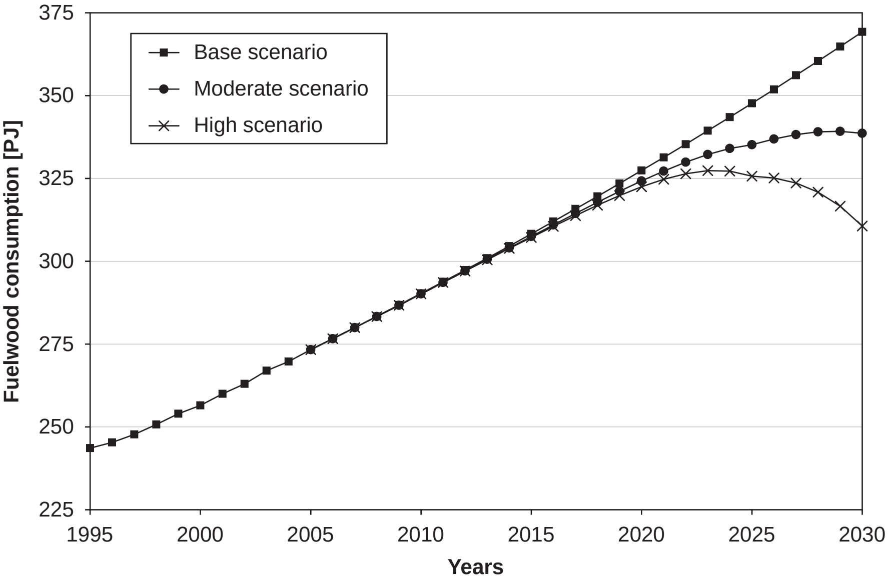

Fig. 3. Fuelwood consumption in base, moderate and high scenarios in the residential sector.

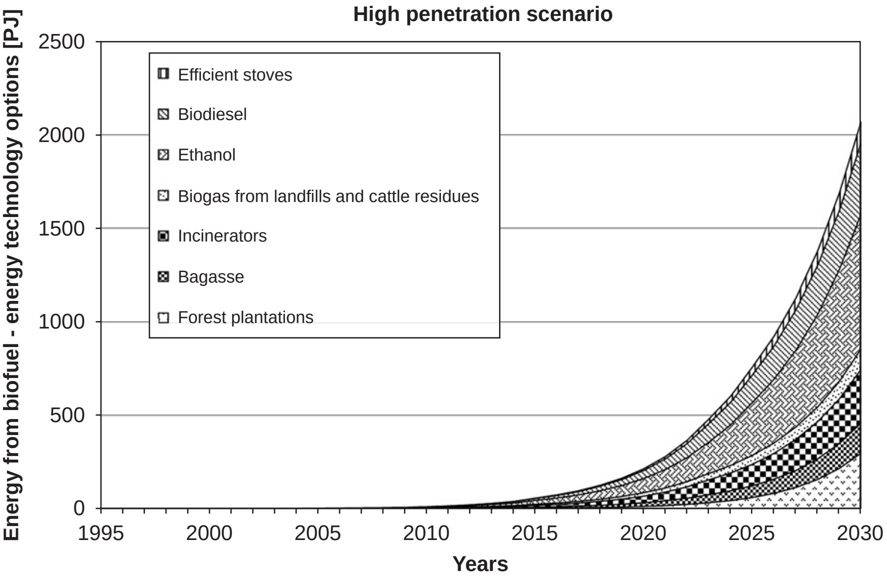

Fig. 4. Future penetration of biofuels in a high scenario in selected sectors.

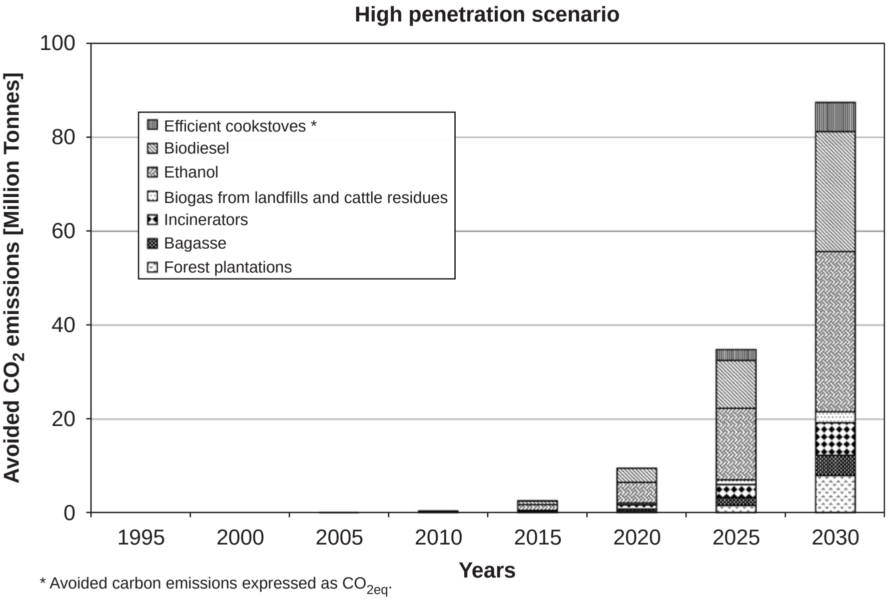

Fig. 5. Avoided CO_2 in a high scenario from selected sectors.

energy by these sectors, respectively. Furthermore, avoided CO_2 emissions from power generation, transportation and residential sectors would amount to 2.63 million tons of non-biogenic CO_2 by 2015 and 87.44 million tons of CO_2 by 2030 (see Fig. 5). These avoided emissions would account for 0.54% and 17.84% of the total CO_2 emitted by electricity generation and transportation sectors in the base scenario, respectively.

In the moderate scenario, the total estimated penetration of bioenergy in electricity generation, transportation and rural residential sectors would reach 38.5 PJ by 2015 and 906.5 PJ by 2030 and would be equivalent to 0.30% and 7.08% of the total consumed energy by these sectors, respectively. Additionally, the avoided CO_2 emissions from electricity generation, transportation sector and the avoided emissions from deforestation and forest degradation in the rural residential sector would total 1.7 million tons of CO_2 by 2015 and 38.98 million tons of CO_2 by 2030. These avoided emissions would account for 0.34% and 7.95% of the total emissions of electricity generation and transportation sectors in the base scenario, respectively.

4. Conclusions and recommendations

The present prospective study shows that the use of bioenergy in a high penetration scenario may be increased substantially in order to reach up to 16.17% of Mexico's total energy supply in electricity generation, transportation and rural residential sectors by 2030. Transportation sector is expected to be the major bioenergy consumer with up to 8.60% of the total energy consumed in all included sectors, followed by power generation (6.68%) and residential (0.89%) sectors. The use of fuelwood in traditional cookstoves may be equivalent to 17.84% of the total bioenergy participation in electricity generation, transportation and rural residential sectors.

When our calculations are analyzed by sector, they indicate that the participation of bioenergy in electricity generation (forest plantations, bagasse, biomass residues and biogas from sanitary landfills) may represent 15.45% of all electricity produced in 2030. Similarly, the participation of bioenergy (ethanol and biodiesel) in the transportation sector may represent 20.17% of the liquid fuels used in this sector. With regard to the rural residential sector, the saturation of the efficient cookstoves is only of 47%, which indicates that there is still a big substitution potential in this area.

Furthermore, the more intensive use of bioenergy, under the scenarios depicted in this paper, would help reduce up to 16.57% of the annual CO_2 emissions in electricity generation and transportation sector by 2030. The major reduction potential is found in transportation (12.17%), followed by electricity sector (4.40%).

The deployment of only 59% of the low estimated bioenergy potential (3050 PJ/year) may reduce as a much as 81.21 million tons of Mexico's CO_2 emissions in electricity generation and transportation sector by 2030 and would be equivalent to 18.3% and 16.9% of the 1990 [58] and 2002 [59] national CO_2 emissions, respectively. Carbon emissions saved through the utilization of efficient cookstoves in the rural residential sector would amount to 6.23 million tons of CO_{2eq} in 2030. This potential would be equivalent to 7.68% of total avoided emissions in electricity generation and transportation sector by 2030. What is more, it is equivalent to 12.25% of 2002 captured CO_2 in national managed forests (estimated in 50.85 million tons of CO_{2eq}) and enough to offset their net CO_2 emissions (estimated in 4.93 million tons of CO_{2eq}) [60].

These results point out that it is essential for the current energy system to evolve towards an ever-greater use of bioenergy as a substitute for fossil fuels in order to achieve environmental sustainability. Therefore, if Mexican bioenergy resources are not developed in a timely manner, Mexico would be losing the opportunity to diversify the country's energy system. At the same time, jobs would not be created, and the underdevelopment in rural areas and the social problems associated with poverty would remain for a long time. The use of bioenergy would allow Mexico to foster sustainable development strategies, particularly in the rural sector.

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