

Bioenergy in Mexico: Status and perspective

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Abstract: Mexico's government has introduced a Law on Climate Change that is unique worldwide; it establishes targets for greenhouse gases reductions at the same level of developed countries despite being an emerging country. This reform represents a crucial challenge for the electrical and transport sectors largely dependent on fossil energy since Mexico is the ninth-largest oil producer in the world. Local industry and academic sectors are called to lead the introduction of renewable energy sources, and particularly to enhance the share of energy from biomass in the local energy basket. Thus, this paper outlines the baseline on regulatory, energy, and carbon markets, and the scientific capacity to increase bioenergy utilization in Mexico. Furthermore, it opens a discussion about the steps forward with regard to sustainability and research needs, emphasizing some priorities and principles to develop a bioenergy system environmentally compatible in this country. © 2014 The Authors. *Biofuels, Bioproducts, Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

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Introduction

Mexico produced 9074 PJ total energy during 2012 according to the national energy databases:¹ 88.5% from fossil fuels, 6.8% from renewable energy sources (RES), 3.6% from coal, and 1.1% from nuclear plants. Around 56.9% of RES contribution came from biomass, followed by geothermal energy (21.4%), hydropower (18.5%), wind energy (2.1%), and solar energy (1.1%). Energy from biomass - also known as bioenergy has been identified as the highest potential renewable energy (2635 to 3771 PJ/year), and this RES research topic is increasingly explored by Mexican academia.² Bioenergy participation in the primary energy local supply has remained stagnant during the last decade, but it has been evidenced that its exploitation is undergoing challenges imposed by the new Mexican General Law for Climate Change adopted in May 2012, which aims to generate 35% of its energy needs from RES by 2024.² This law represents the core of the national strategy to move Mexico away from the fossil-fuels-dependent energy market, historically distinguished by important oil and natural gas reserves, but with strong refining capacity limitations and increasing fossil fuel imports needs. For instance, by 2011, Mexico was importing 21% natural gas,³ 50% gasoline, and 21% diesel.⁴ In the electrical sector, the overall target is to increase the installed capacity to 1, 2, 12, and 1.5 GW from biomass, geothermal, wind, and solar energy power, respectively,⁵ while the oil and coal percentage in the electrical matrix are gradually reduced.

Nevertheless, the bioenergy development in any region requires a higher level of analysis in order to determine the degree of contribution for each biomass source, suitable and sustainable technology, and barriers to overcome.⁶⁻⁹ All according to international standards and usual practices in this domain. In this context, the present study summarizes the current situation of bioenergy use in Mexico and its regulatory framework as a baseline for tackling the discussion of barriers and opportunities for new and improved bioenergy project implementation. Mexico has scientific capacity and research experience in diverse topics related to bioenergy production, and sound experience in placing Clean Development Mechanisms (CDM) in agricultural and waste management activities as decisive opportunities for bioenergy development. Both sectors are closely related to bioenergy through energy recovery from biogas and lignocellulosic biomass co-combustion.¹⁰

Current bioenergy status

Regulatory framework

Biomass energy use and its production in Mexico are considered in the recent general regulatory frame for RES. According the National Development Plan (NDP) formulated during the last presidential period (2006–2012), the definitive pathway for the penetration of RES in the national energy strategy recognizes and promotes four specific guidelines:¹¹⁻¹³

- (i) Energy is a resource related to human development in agreement with the United Nations Development Program.
- (ii) A power generation capacity increasing from 23 to 26% based on renewables: 17% from hydroelectric above 70 MW, and 3% and 6% through small hydroelectric and other renewables, respectively.
- (iii) Use of RES and biofuels in economically, environmentally, and socially responsible forms.
- (iv) A reduction in the national greenhouse gas (GHG) emissions, from 14 MtCO_{2eq} in 2006 to 28 MtCO_{2eq} in 2012, 261 MtCO_{2eq} in 2020 and 523 MtCO_{2eq} in 2030.

The latter was endorsed by the General Law for Climate Change. A pioneering initiative from the Mexican government; for the first time a Non-Annex I Country of the Kyoto Protocol has assumed GHG reductions goals at the same level as industrialized countries. This is a substantial difference with other climate change laws of emerging countries, particularly from the Latin American region, where policy tools for climate change adaptation and development of low-carbon strategies are structured following schemes of voluntary targets for GHG emissions reductions.¹⁴ Furthermore, the Mexican Law for Climate Change establishes a more stringent commitment that Nationally Appropriate Mitigation Actions (NAMAs) focused on the voluntary emission reduction goals implemented by other developing countries, and establishes that adaptation measures require the same level of priority as mitigation projects.^{15,16} Nevertheless, it is important to point out that Brazil, Colombia, Chile, and other Latin American countries reach substantial emissions reductions following the schema provided by NAMAs.

From a practicality point of view, the more important regulations in Mexico are established inside the Renewable Energy Sources Law, recently modified to include 'economic instruments' to finance the Energy Transition toward renewables.¹⁷ For instance, this law promoted the use 2% of ethanol in gasoline in the most important metropolitan areas of the country: Mexico, Monterrey, and



Guadalajara from the end of 2012.¹⁸ It also created a fund for the transition to renewable energy and clean technologies. The Technical Committee for the Fund administration decides on assigning and channeling credit, and other financing support options for project developers.

In spite of these significant advances, renewable energy policies need to be harmonized with existing regulations on conventional energy sources and the current conditions of the local energy markets, specifically in electricity, a state-integrated system with private investments for power generation exists.^{19,20} Activities considered accessible to private participation are:²¹

- (i) Self-supply and power co-generation in industrial facilities to supply own energy needs.
- (ii) Independent power production (IPP) at plants (>30 MW installed capacity) built and operated by private companies under a power purchase agreement with the Federal Electricity Commission (CFE) for its transmission and distribution.
- (iii) Small-scale generation (<30 MW) at power plants built and operated by private companies whose electricity is fully distributed by CFE.

However, the participation schemas in charge of CFE might be improved in other areas, as the transmission and distribution at small-production scale, since an important share of agricultural biomass and organic municipal wastes are preferentially intended for electricity production worldwide.^{10,22} Biomass projects focused on liquid and gaseous fuels would face barriers imposed by the structure of the fossil fuels market in Mexico, a country with enormous oil and gas natural reserves. The raw oil exportation compensated by gasoline and diesel importation, and the elevated contribution of fossil in the electrical matrix, open unique opportunities to offset carbon emissions and obtain carbon credits with bioenergy.

Bioenergy in the national energy market

In Mexico, the energy use of biomasses has decreased since 1965 when it constituted 15.3% of the total primary energy supply. Forest and agricultural wastes were predominant fuels for cooking in the past, when the rural population was equivalent to that settled in urban zones. Today, energy biomass contributes from 3.2 to 5.3% of total energy use, though its application is widely different. Modern biomass use includes around

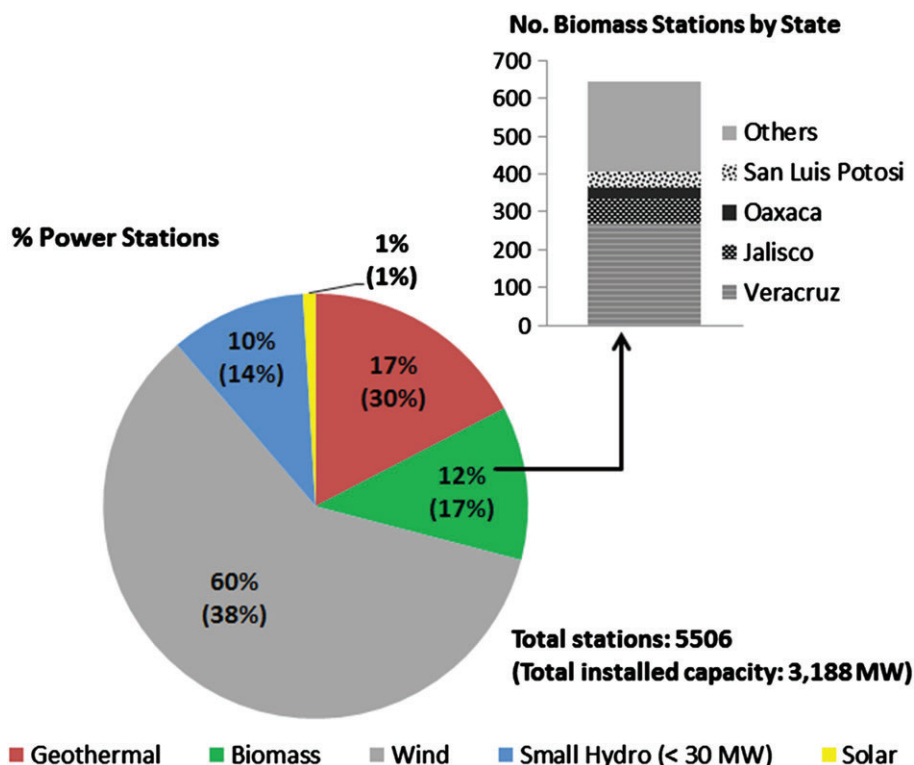


Figure 1. Participation of biomass and other renewable energy sources in Mexico's power generation. The percentage in parenthesis indicates the installed capacity for each RES (geothermal 958 MW, bioenergy 548 MW, wind 1,215 MW, small hydro 434 MW, solar 33 MW).



59 projects for power self-supply through combustion process using biogas and waste lignocellulosic biomass (e.g. sugarcane bagasse). Power installed capacity is close to 40 MW for biogas and the rest for sugarcane mills,²³ resulting in a total of 500 MW. These projects are mainly located in center and southern states of the country as depicted in Fig. 1. Nowadays, the sugarcane industry has the possibility to participate in the electrical and liquid fuels markets, placing electricity surplus on the grid and mixing ethanol with gasoline as previously mentioned.

Bioenergy portfolio and carbon markets influence

Mexico's bioenergy potential continues to be unexploited. Excluding current lands used for food agriculture (~21.7 million ha.), protected forest and non-arable mountain areas, lands suitable for energy agriculture have the potential to produce 2.6 to 3.7 EJ/year in Mexico.^{10,24} Cultivated biomass or crops specifically grown for energy production and agricultural residues mainly from maize, cereal, and sugarcane represent 77.9% of this potential, while processed residues

from sugarcane, *Jatropha curcas*, and palm oil are nearly 20.1%.²⁴ A previous analysis identified 15 states with the highest bioenergy potential along the country (Fig. 2). The main crops produced in these areas are corn, wheat, cotton, sorghum, and sugarcane.²⁵

Energy production using residual biomass might prove to be the best environmental and social option for the rural sector, better than the usual business involving animal feed and primitive cooking practices. Integrated waste management to generate a blended feedstock with equilibrated C/N/P composition reduces investment costs, and stabilizes biogas production in centralized regional anaerobic digesters. Besides, final digested matter is able to reduce inorganic fertilizers requirement, helping the farmers' family economy. For Mexico, the determinant is to reduce its energy related non-biogenic CO₂ emissions because these rise 4.3% yearly, one of the highest rates in the world.²⁶ However, there are public and private actions that reflect the country's commitment to this goal. For instance, biomass-to-biogas projects in rural and agro-industrial applications have placed Mexico as the second Latin American country (LAC) after Brazil, with more registered projects CDMs (Fig. 3), and the fifth host country worldwide receiving more carbon incomes by means of Certified Emissions Reductions (CERs) as showed in Fig. 4.²⁷ Data presented in Figs 3 and 4 should be carefully analyzed, because CDMs only guarantee GHG reductions by simple biogas flaring; it is highly probable that only a few projects recover energy biogas effectively.

The instability of carbon credits requires the implementation of green tags, preferential taxes, ease rural credits, and other economy tools to foster biogas as accessible renewable energy. US, German, Brazilian, and Malaysian studies stress the need for policies and subsidies to promote biogas utilization.^{28–31} A detailed typology for Mexican CDM bioenergy-based projects is shown in Fig. 5. In the AgBg capture group, swine and dairy farms have been the most active during the first application period of the Kyoto Protocol. Nevertheless, since 2008, LFBg for electricity and the application of sugarcane bagasse and other solid organic wastes for combined production of heat and power through co-combustion were privileged (ICoWB). In particular, CEMEX, the Mexican company leading the world's cement industry and the multinational PROACTIVA, which operates several municipal landfills along Mexico's territory, own nearly all of the grand-scale Mexican bioenergy CDM. Both industrial groups are seriously engaged in the use of bioenergy to obtain CERs by offsetting fossil carbon from the national grid. Recently,



Figure 2. Biomass energy potential by main states and municipalities (280,320 to 2 181 021 tons of dry matter per year). States (green) and their municipalities (brown) are indicated by numbers (state; municipality): (1) Baja California; Mexicali, (2) Sonora; Cajeme, Etchojoa, Navojoa, (3) Chihuahua; Cuahutemoc, (4) Sinaloa; Ahome, Angostura, Culiacan, Guasave, Navolato, Sinaloa, (5) Tamaulipas; El Mante, Matamoros, Reynosa, Rio Bravo, San Fernando, Valle Hermoso, (6) San Luis Potosi; Ciudad Valles, (7) Jalisco; La Barca, San Martín Hidalgo, (8) Guanajuato; Abasolo, Irapuato, Penjamo, Salamanca, Valle de Santiago, (9) Hidalgo; Cardonal, (10) Veracruz; Cosamaloapan de Carpio, Panuco, Tres Valles, (11) Oaxaca; Acatlan de Perez Figueroa, San Juan Bautista Tuxtepec, (12) Tabasco; Cardenas, (13) Chiapas; Venustiano Carranza, (14) Campeche; Hopelchen, (15) Quintana Roo; Othon P Blanco. Adapted from Valdez-Vazquez *et al.*²⁵

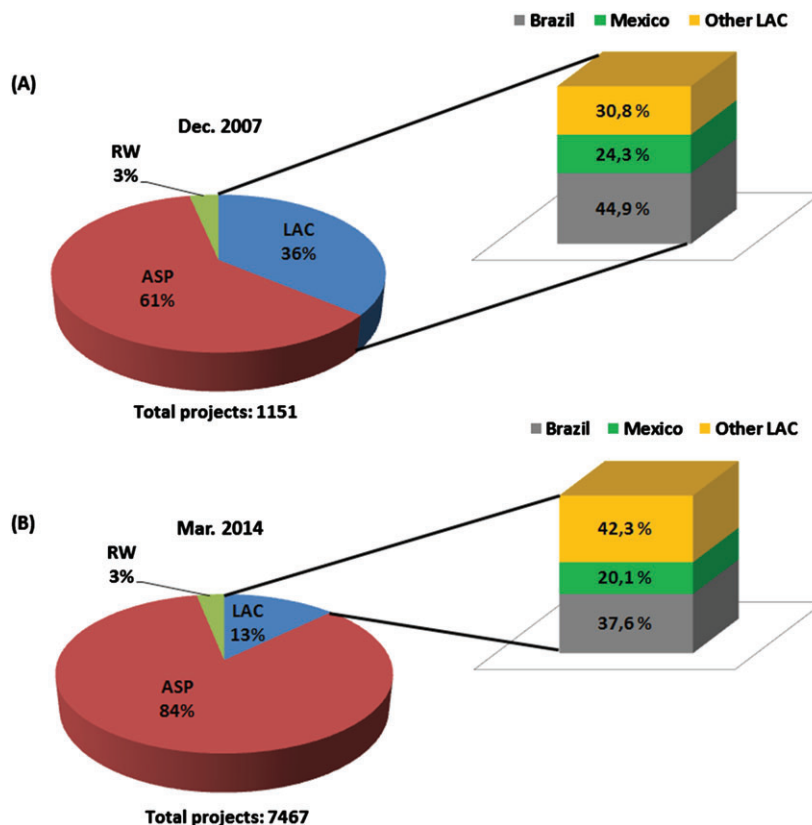


Figure 3. Evolution of CDM registration projects, World and Regional tendency. LAC, Latin-American Countries; ASP, Asia-Pacific Region; RW, Rest of the World.

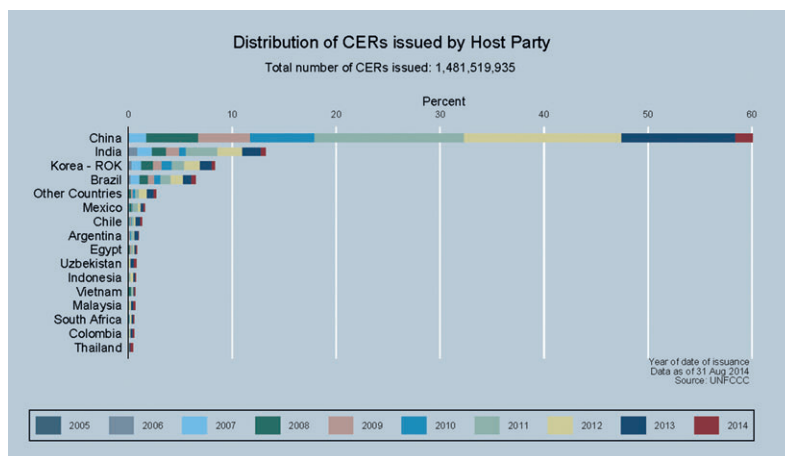


Figure 4. CERs issued by CDM activities (2005–2014). From original source <https://unfccc.int>

Ingenio Tres Valles, S.A., a company of the industrial group Piasa involved in milling of sugarcane, presented a CDM project with the capacity to reduce 46 728 tCO₂/year in a 40 MW combined heat and power (CHP) cogeneration system. These observations demonstrate, as endorsed

by Fig. 3, that Mexico is placing a lower number of CDM projects but with more effective energy recovery.

Currently, a consolidated inventory for bioenergy sources in Mexico is not available. However, cooperation among Mexico’s National Council for Science

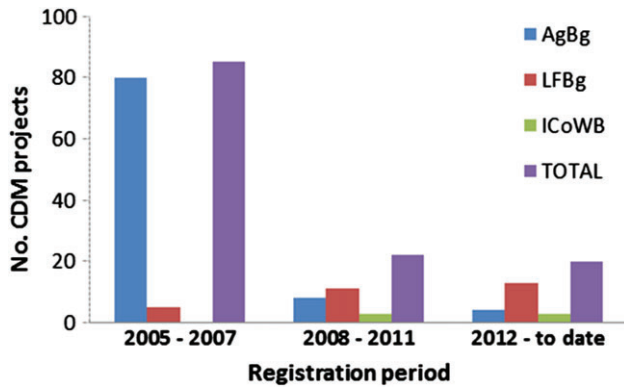


Figure 5. Typology for Mexico's Bio-energy CDM projects. Projects grouped in Agricultural Biogas (AgBg), Landfill Biogas (LFBg) and Industrial co-combustion of Waste Biomass (ICoWB). Adapted from <https://unfccc.int>

and Technology (CONACYT), the German Academic Exchange Service (DAAD), and the Institute of Environmental Technology and Energy Economics (Technical University of Hamburg) is searching to build a model to assess the sustainable biomass potential in Mexico. This model is the basis for investigating the impact of the regulatory framework, penetration strategies for energy biomass projects, and its potential contribution in compliance with GHG reductions targets.³² Mexico also

participates in the Methane Global Initiative project, that contributes to obtaining consolidated data about biogas energy potential, especially in the waste sector,³³ and places mitigation projects through biogas capture in the US carbon markets.

Actions for the bioenergy development in Mexico

Barriers and opportunities

Mexico is a net electricity and raw oil exporter and a big importer of refined liquid fuels. Its expectations regarding natural gas and coal reserves are to increase their exploitation for thermal power generation.² In 2006, 1.3 TWh was exported to the USA and 0.2 TWh to neighboring countries in Central America. By 2010, these electricity exports were doubled.³⁴ The lack of an energy strategy based on methodologies that evaluate RES feasibility in the short term and the natural markets tendency to consume the cheapest energy source, usually fossil fuels, inhibits RES promotion. Bioenergy is the most vulnerable RES to these barriers: bioenergy sources are diffuse producing small generation projects and their supply-chains are complex and vulnerable to fossil carbon inputs mainly associated to feedstock transport.³⁵ Consolidated national inventories of natural biomass sources are necessary as a starting

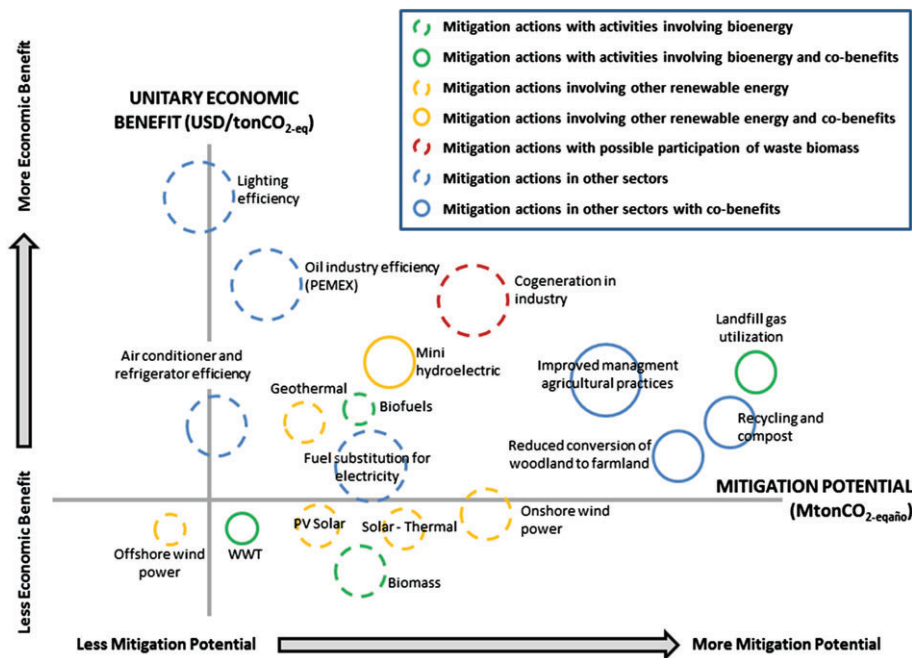


Figure 6. Matrix for the GHG emissions mitigation actions (2020–2050). The size of circles represents viability of projects given current conditions. Adapted from SEMARNAT 2013.



point for biofuels production planning, without risking food security and incorporating environmental safeguards.

In the electricity market, the mechanisms implemented to promote participation of the private sector in generation and transmission activities include a preferential rate of 65% in transmission services fee, designed to ensure a more efficient co-generation with renewable sources as regards the cost of transmitting conventional energy, and simplified procedures for interconnection to the electrical grid. Both initiatives would benefit small-scale electricity generation with agricultural biogas (20 to 500 KW) complementing the CDM's co-benefits.²

Additionally, the impact of the new Mexican Law for Climate Change on bioenergy projects as mitigation activities need to be evaluated. For instance, the matrix for mitigation actions presented in Fig. 6 unveils some opportunities for bioenergy-related activities, as well as some barriers and risks in relation to the law's targets achievement. Figure 6 also shows that viability of projects involving biogas recovery in waste-water treatment plants (WWT) and landfills is considered on a par with other renewables, and its implementation offers ancillary benefits for human health, protection of ecosystems, and social welfare as explicitly expressed by the Mexican agency on environment or evidenced through numerous LCA studies about biogas recovery from waste systems.^{16,36,37} Only mini-hydraulic power generation exceeds the viability of bioenergy projects between RES and produces similar economic benefits by tCO_{2e} reduced. Landfill biogas and liquid biofuels offer a greater economic benefit than other renewables; however biofuels production should be associated with public transportation for generating co-benefits and avoid promoting land-use changes because woodlands conservation has a higher mitigation potential. Waste biomass participation in cogeneration offers a direct and increased option to obtain simultaneous economic benefits and GHG emissions mitigation, although competition with recycling and composting reduces the effective biomass availability for energy uses.

In general, the GHG abatement potential in the waste sector was estimated in 26 MtCO_{2eq}, 10% the total estimated for 2020, and it might increase up to 17% in 2030. From this abatement potential, 51% corresponds to a well-consolidated mitigation portfolio, and about 6.9% is linked to landfill biogas use, municipal sanitation upgrading with biogas recovery, and agricultural residues management.¹⁶ Nowadays, the more important barrier for bioenergy development is the relative higher marginal costs of CO₂ abatement with regard to actions in other sectors. For liquid biofuels, the estimated cost ranges from 7 to 12 USD/tCO_{2e}, while for biogas and WWT upgrading is around

60 USD/tCO_{2e}. Presently, there are no biofuels production projects included in the first consolidated Mexican portfolio of mitigation activities, although a mitigation capacity for 15 MtCO_{2e} is projected in 2030 through biofuels use. From this perspective, only biogas landfill projects are competitive to date in the bioenergy sector due to the relatively cost neutral situation in this kind of mitigation action. Most GHG reductions in the waste sector before approval of the new Mexican Law for Climate Change, came from biogas landfill capture. This corresponds approximately to 4% (~51 MtCO_{2e}) of the total GHG emissions reductions in 2012.³⁸

National R&D contributions

World scientific research about RES has been mainly conducted (80%) by 12 to 14 countries.³⁹ From 1982 to 2012, almost 70.1% of the research publications in Mexico focused on biomass use as renewable energy, representing 1.1% of world research in this field. Energy reform allowed the creation of a fund to save the surplus over the GDP target (4.7%) based on the year 2013 for RES development.⁴⁰ Specifically, 10% of this fund will be used to finance projects in science, technology, and RES development, and another 10% in scholarships for human capital development through post-graduate formation.⁴⁰ A total of 390 bioenergy-scientific papers, including original research and review contributions, have been published in the period 2004–2013 by Mexican research groups according to the ISI Web of Knowledge compilation. Nearly 62.3% are specifically related to studies on the potential of different biomass sources and technologies for their valorization. Most of them deal with energy valorization of residual lignocellulosic biomasses (43.6%) and biomass from energy crops (37.1%). In addition, Mexico's location offers a high solar energy potential suitable for microalgae cultivation, and there is evident scientific interest to exploit it. Mexico generates the highest number of scientific publications in the LAC region about micro-algae application for wastewater bioremediation (Alexander MJ *et al.*, unpublished), as technological options for CO₂ capture from the cement industry,⁴¹ and as feedstock for third-generation biofuels and future biorefineries.⁴²

Environmentally compatible bioenergy: the step forward

The role of biomass in Mexico's sustainable energy future will depend on the choice of appropriate methodologies to harmonize policies and actions for bioenergy production and its use with environmental principles and social



welfare. New environmental and sustainable ways for bioenergy in Mexico require incorporating some notions into policies and actions to be implemented:

- (i) Bioenergy production systems are multifunctional.
- (ii) Bioenergy systems sustainability largely depends on the nexus with water resources (Bioenergy / Water Nexus).
- (iii) Life cycle perspective is committed to avoid a shift in impacts or their magnification along bioenergy supply-chains.
- (iv) Integration and co-evolution principles are essentials for bioenergy development.

Some guidelines about these four notions are given below, focusing particularly on future decisions that government, business, and academic stakeholders in Mexico would make to tackle this gap by defining their participation levels in the bioenergy national strategy.

Bioenergy systems are multifunctional

Lessons learned in other LACs more experienced in the development of cultivated bioenergy invite Mexico to understand the complexity of this kind of energy production. The economics and sustainability of 'cultivated biomass-to-fuels' depend on developing the ancillary potential of the waste agricultural biomass. For instance, in Colombia, palm oil mills and ethanol-sugarcane distilleries can be only for heating and powering auto-generation purposes without the option to plug in their electricity surplus to the interconnected national system.⁴³ This situation limits the autonomy of biofuels production and forces it to keep higher government subsidies over these activities. The origin of this policy perhaps is to protect hydropower participation (63%) in the Colombian electricity mix, unveiling the risk of predatory or inhibitory competition between RES when the regulatory framework is not harmonized with sustainability goals. As a consequence, important electricity surplus with potential to supply isolated rural communities is lost and the country is penalized with the highest electrical transmission losses in the LAC region (~15%).⁴⁴ On the other hand, the Brazilian model for electrical cogeneration might be more appropriate as a guideline, because in the rural electrification program 'Light for all' the priority is to give access to rural households diminishing transmission losses by incorporating small electricity sources in the interconnected grid. Thus, Brazil has required an evolution toward the smart grid concept showing the successful addition of renewable energy producers, mainly to generate energy valorization options

for agricultural waste biomass from its enormous sugar/bioethanol industry.⁴⁵ For this, Brazil has required solving technical gaps related to reliability and intermittence in the electrical supply when small sources get access in the system.^{46,47} Nowadays, the participation of energy from biomass in the Brazilian electrical matrix is estimated at 6.8%, and comes from the use of firewood, sugarcane bagasse, black-liquor and other primary sources. Independently of the virtues or defects of the adopted model, bioenergy systems could be observed as promoters of rural jobs, drivers of local economies, and key factors in the activities towards climate change mitigation.

Bioenergy-water nexus

In several ways the *raison d'être* of the bioenergy is to offset fossil fuels and their associated GHG emissions. However, the bioenergy supply-chain starting from cultivated crops is vulnerable to fostering dioxide carbon, nitrous oxide, and methane emissions by activities related to agricultural machinery use, biomass transport, and waste management. Sustainability of this kind of bioenergy requires minimizing this fossil participation and improving the performance of the water management in bioenergy activities.⁴⁸ Biofuels from crops are comparatively more intensive in freshwater use than fossil fuels.^{49,50} For instance, average water consumption in the oil fuels supply-chain (extraction and refining) is 0.19 m³/GJ, and 0.17 m³/GJ for synthetic fuels (gas to liquids or carbon to liquids).⁵¹ Meanwhile, the water consumption for biofuels (mainly as green water) is on average 190.5 and 181.1 m³/GJ in Brazil and the USA, based on sugarcane and corn as predominant feedstocks, respectively. Thus, the water footprint expressed as water consumed by the GJ equivalent of biofuel is drastically bigger than that for fossil fuels and this difference can increase dramatically in regions facing water scarcity and prolonged dryness periods.⁵² Furthermore, the biofuel industry produces highly polluted organic effluents during extraction and refining stages. A palm-oil mill generates effluents with organic loads between 30 and 90 g COD/m³, whereas the vinasses produced in the ethanol-sugarcane industry range from 20 to 65 g COD/m³. Consequently, waste-water treatment implementation focused on water reuse and energy recovery are two determinant aspects in the management of the bioenergy-water nexus in this kind of industry, as supported by the experience of palm-oil mills in Asia.⁵³

A comprehensive study of important aspects, such as the balance between invested energy in waste-water reuse and economy for pumping freshwater toward the crop plantations is crucial for each specific location.⁵⁴ On the other



hand, primary waste-water treatment could be focused on anaerobic processes, enabling biogas recovery as energy background to support industrial duties or to participate in decentralized energy grids with low transmission losses, as shown by experience in the sugarcane and palm-oil industries.^{55,56} An important share of this energy might be employed to provide enhanced waste-water treatment. In particular, reverse osmosis and other membrane technologies used for deep salts and ionic solids removal are big energy consumers,⁵⁷ but they are the more immediate option to protect soils during ferti-irrigation with reused water.

In the specific case for Mexico, reuse and fertilization using recycled water and sludge from the effluents treatment of bioenergy production systems and other sources, might be key factors to mitigating parasitic pathways of pollution and external energy use, and prevent deterioration of freshwater sources not distributed homogeneously along the territory. The Mexican National Water Commission (CONAGUA) states the distribution of natural water availability and reports that 69% of freshwater availability is concentrated in the southeast region, a low-density population region producing only 13% of GDP.⁵⁸ However, policies and actions to introduce E2 fuel (2% ethanol – 98% gasoline) point to the richest northern and central Mexico regions, which have less than 10% of national freshwater resources. Hence, Mexico is called to outline carefully the water supply for energy crops without depleting water resources in regions suffering from scarcity, and to generate bioenergy production ways for the poorest regions in the south. Mexico might take advantage of its experience in the management and implementation of irrigation districts, but risk putting freshwater resources under additional pressure. The aquifers overexploitation in Mexico is generalized, whereas the average freshwater extractions per year in the American continent is 3.2%, in Mexico reaches 15%.⁵⁹

Life cycle of bioenergy systems

Recent reviews claim the need for a comprehensive and reliable sustainability assessment for bioenergy systems in order to recommend how these productive systems should be implemented in a determined context, or how to improve the environmental performance of existing energy biomass projects.^{60,61} The predominant biorefining platforms in the LAC region are so far single biofuels refining units, without important energy and mass integration levels inside and outside the borders of the supply-chain. However, life cycle assessment (LCA) for integrated biorefining platforms has begun to be considered in different studies worldwide, showing the important role of effluents,

biogases, and waste biomass to close the energy and materials loops, thus avoiding costly chemical and fossil energy input.^{62,63} In developed countries, this perspective is being applied to evaluate the future performance of modern biorefining platforms based on micro-algal biomass,^{64,65} as well as grass and agricultural wastes as feedstock.^{37,66,67} Most of these studies are focused on determining the carbon footprint of bioenergy production systems. Primary energy demand, eutrophication, airborne emissions, and land use – in this order – are the other environmental impacts better covered in LCA studies.⁶⁰ Some LCA initiatives are also being implemented in the LAC region to study different routes of bioenergy production from micro-algal biomass.⁶⁸ The development of research capacity in the field of sustainability methodologies is a necessary step for guidance of the environmental compatibility of full-scale bioenergy initiatives.

Integration and coevolution principles

Transition to integrated biorefineries by replacing their oil analogs is not an immediate achievement.⁶⁹ Experiences in first-generation liquid biofuels and biogas from energy crops show that national coverage targets using this energy require planning and complete evaluation of the available proper lands for energy crops. Production limits need to be known and accepted to prevent unsustainable soils exploitation.^{70,71} Besides, commercial opportunities for biochemicals and bioenergy surplus from biorefineries directly depend on needs present in consolidated productive systems (coevolution), particularly as substitution products for traditional 'fossil chemicals' or raw materials for the petrochemical industry. The evolution of biorefining and autonomous bioenergy platforms definitely requires regional integration of several biomass sources to increase their productivity and stability. This notion is currently applied to biogas exploitation in other LACs. Chile and Argentina are starting new projects with well elaborated and reliable inventories of metanizable biomass.^{72,73} Mexico has the opportunity to replicate these by incorporating preferential use of organic wastes and agricultural residues over energy crops as feedstock for biogas production. This might avoid proliferation of single agricultural digesters without profitable energy potential.

Conclusions

The new Mexican General Law for Climate Change is in line with the international actions taken against the adverse effects of GHG emissions and sets out ambitious



reduction targets for an emerging country. In this view, the supply-chains development for biofuels and electricity from waste and energy crops under sustainability criteria represents the main challenge for the country. Bioenergy and the proven experience of Mexico to place projects in the CDM will play a determining role in the achievement of the practical purposes of this law. It is expected that bioenergy offsets a share of the fossil fuels participation within the Mexican energy matrix, with a major contribution of landfill biogas recovery. In Mexico, the first steps to implementing biofuel and bioenergy roadmaps are currently linked with the development of biomass inventories, the establishment of GHG mitigation potential through bioenergy actions, and the strengthening of the legal framework for renewables. A good practice in this task is to follow the models suggested by the International Energy Agency for bioenergy roadmaps,⁷⁴ particularly in issues related to (i) definition of technical choices for solid biomass, liquid biofuels, and biogas production and valorization; (ii) introduction of methodologies and sustainability criteria for bioenergy supply-chains use; and (iii) forecast of different medium- and long-term demand scenarios of biofuels versus land and water requirements. On the other hand, involvement of the Mexican Academia in this 'bioenergy wave' through their own technological solutions, technological transfer surveys, and design of sustainability guidelines has been decisive so far. Advances in microalgae research, biorefining, and other bioprocesses for energy generation promote the evolution of this sector, and take part in the actions to reduce the Mexico's energy fossil dependence in the next decades.

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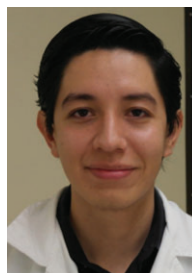
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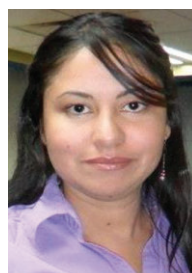
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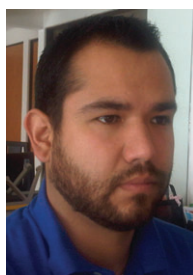
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