Waste-to-Energy in Mexico

Technical potential for biogas production and greenhouse gas mitigation from the anaerobic digestion of municipal solid waste

Master Thesis of Víctor Mediavilla Merchán

EnRes
Programa Aprovechamiento Energético de Residuos Urbanos en México
(Converting Solid Urban Waste into Energy in Mexico)

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Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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Commissioned by:	German Federal Ministry for Economic Cooperation and Development (BMZ) Ministerio Federal de Cooperación Económica y Desarrollo (BMZ) de Alemania

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Design:	Leticia Llamas De la Torre, Mexico
Publication date:	March, 2018

“In solid waste management there is no ‘away’. When ‘throwing away’ waste, system complexities and the integrated nature of materials and pollution are quickly apparent […] Solving one problem often introduces a new one, and if not well executed, the new problem is often of greater cost and complexity.”

What a waste: a global review of solid waste management
Daniel Hoornweg and Perinaz Bhada-Tata, 2012

This thesis would not have been possible without the experience and knowledge acquired during the internship of six months in Mexico City with the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Specially thanks to my colleagues from the Project ENRES, who supported me during and after that period.

Besides, I would like to thank the main supervisor from the University of Utrecht, Wina Graus, and the guest supervisor from the Technical University of Berlin, Celia Hahn, for their attention and guidance during this period. As well, I want to thank to the second reader of this thesis, Daniela Thrän, and to the colleagues that helped me to check out this report.

Last, but not least, I want to thank to my parents for their financial and moral support during this Master's degree.

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The generation of waste has been historically a source of environmental disturbance that triggered the development of technologies to minimize it. The anaerobic digestion of municipal solid waste has emerged in the last decades as a feasible solution. Its effectiveness to stabilize the waste and the added value of providing biogas during the process makes it an attractive solution. In Mexico, the implementation of these facilities is still at a preliminary stage, but it could contribute to facing the multiple problems derived from the disposal of solid waste in sanitary landfills and dumpsites, such as methane emissions that contribute to climate change.

This case study provides an insight to the technical and the country-specific limitations to deploy the potential for biogas production. The energy that this biofuel could produce is estimated in the range of 25-29 PJ per year that could substitute the use of fossil fuels to meet the energy demand of the country. The energy output varies according to the use given to the biogas: cogeneration of heat and power, injection to the natural gas network or feeding gas-powered vehicles.

Besides, this could have a direct effect on the emission of greenhouse gases to the atmosphere: between 1.4 and 1.9 Mt $CO_{2\text{-eq}}$ per year could be saved by using biogas. Additionally, this mitigation would be larger due to the diversion of 14 million tons of organic waste from being disposed: 11.7 Mt $CO_{2\text{-eq}}$ per year. This implies a positive contribution towards meeting the commitments made by Mexico to reduce its carbon intensity. The Nationally Determined Contributions implies a reduction of 28% of the greenhouse gas emissions from the waste sector for 2030 in comparison with the baseline. If this mitigation potential is deployed, up to 87% of the internationally compromised targets could be achieved.

To conclude, a review is made of the existing policies in Mexico and in other countries to enhance the implementation of anaerobic digestion technologies to treat municipal solid waste.

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ACRONYMS AND SYMBOLS

AD	Anaerobic digestion
BAU	Business as usual scenario
CH_4	Methane
CLO	Compost-like output
CO_2	Carbon dioxide
EPA	Environmental Protection Agency (USA)
GDP	Gross domestic product
GHG	Greenhouse gas
IEA	International Energy Agency
IMTA	Mexican Institute of Water Technology
INEGI	Mexican National Institute of Statistics and Geography
IPCC	Intergovernmental Panel on Climate Change
kt CO_{2-eq}	Thousand ton of carbon dioxide equivalent
kWh	Kilowatt-hour
LAERFTE	Law for the Use of Renewable Energies and the Financing of the Energy Transition
LGCC	General Law of Climate Change
LHV	Lower heating value
LPG	Liquefied petroleum gas
LTE	Law for the Energy Transition
LULUCF	Land Use, Land-Use Change and Forestry
MACCs	Marginal abatement cost curves
MBT	Mechanical-biological treatment
MSW	Municipal solid waste
Mt CO_{2-eq}	Million ton of carbon dioxide equivalent
MWe	Megawatt electric
NDC	Nationally Determined Contributions
NG	Natural gas
NOx	Nitrogen oxides

OFMSW	Organic fraction of municipal solid waste
PEAER	Special Program for the Use of Renewable Energy
PECC	Special Program of Climate Change
PETE	Special Program for the Energy Transition
PJ / EJ	Pentajoule / Exajoule
RES	Renewable energy source
rMSW	Residual municipal solid waste
RQ	Research question
RsQ	Research subquestion
SEMARNAT	Secretariat of Environment and Natural Resources of Mexico
SS-OFMSW	Source-separated organic fraction of the municipal solid waste
WWTP	Wastewater treatment plant
WtE	Waste-to-energy

GLOSSARY

ANAEROBIC DIGESTION Biochemical reaction of organic material that is converted into biogas as a result of microbiological activity in absence of oxygen.

BIOGAS Fuel gas derived from the anaerobic digestion of organic material that can be used for energetic purposes.

BIOMETHANE Fuel gas with a very high concentration of CH_4 derived from the upgrade of biogas, which can be used as a substitute of natural gas due to their similarities in chemical composition.

CLEAN ENERGY According to the Law of Energy Transition (Cámara de Diputados, 24 December 2015) are those energy sources and power generation processes whose gas or waste emissions do not surpass the regulatory thresholds. This concept includes renewable energy sources, nuclear power, large-scale hydropower plants, coal power plants and combined cycles with carbon capture and storage systems, whose GHG emissions are not greater that 100 kg/MWh.

COMPOST-LIKE OUTPUT Organic material resulting from the mechanical and biological treatment of rMSW. It is characterized by a lower quality and high level of impurities compared to compost.

DIGESTATE Solid and liquid fraction that is not converted into biogas during anaerobic digestion.

MECHANICAL BIOLOGICAL TREATMENT Waste processing facility that combines mechanical sorting and biological treatment units (e.g. compost or anaerobic digestion).

MUNICIPAL SOLID WASTE Wastes generated by households, institutions and public spaces (e.g. from street or park cleaning), as well as commercial and nonhazardous industrial waste, which are collected and treated by, or for municipalities.

OPEN DUMPING Disposal area of solid waste without planning and commiting of health and environmental standards.

ORGANIC FRACTION OF MUNICIPAL SOLID WASTE Biodegrable part of the municipal solid waste. It is also called biowaste.

RENEWABLE ENERGY SOURCES According to the Law of Energy Transition (Cámara de Diputados, 24 December 2015) are those energy sources naturally produced that are continuously or periodically available and do not release polluting emissions in its generation. This group includes the following energy sources: wind, solar radiation, hydro power from natural water streams and artificial reservoirs with a capacity lower than 30 MW, ocean power, geothermal power and the bioenergy sources determined by law.

RESIDUAL MUNICIPAL SOLID WASTE Material left over after the separation of recyclables and biowaste at source, which is composed of a mixed stream of organic and inorganic waste. It is also called grey waste and can be treated at MBT plants to reduce its volume before final disposal.

SANITARY LANDFILL Engineered disposal facility designed, contructed and operated under standards to minimize impacts on public health and environment. Some of the specifications are: site preparation, proper leachate and gas management and monitoring, compaction, daily and final cover (Hyman *et al.*, 2013).

SOURCE-SEPARATED ORGANIC FRACTION OF MUNICIPAL SOLID WASTE Organic material sorted from other waste fractions before collection, with a low rate of impurities that makes it a suitable resource to provide added-value outputs after a biological treatment.

TECHNICAL POTENTIAL Amount of energy that can be produced or GHG emission mitigated by implementing a technology or practice that has already been demonstrated, taking into account physical, structural, socio-geographical and technological performance barriers.

WASTE MANAGEMENT Activities related to waste handling like collection, transport, recovery of energy and materials, treatment and disposal.

WASTE-TO-ENERGY Process for the energy recovery from waste to supply human needs, such as incineration, captured landfill gas and biogas from the anaerobic digestion carried out in reactors.

1.1 Context of the waste management in Mexico

Mexico is the tenth most populated country in the world and the second in Latin America (UN, 2015). In this country, up to 42.9 million tons of municipal solid waste (MSW) are generated per year (INEGI, 2014), leading to a status of unsustainability in social, environmental and economic terms. The waste is constantly growing not only in its amount, but also in its complexity and hazardousness, mainly caused by four factors: increasing population, urbanization, industrialization and economic growth (Hyman *et al*., 2013).

The amount of MSW generated in Mexico is lower than countries with a larger population like the US (230 million tons) and even some with a smaller population like Germany (51 million tons) (Eurostat, 2014; Wilson *et al*., 2015). The relative amount of MSW generated by a Mexican per day is of about 1 kg, a quantity that has uninterruptedly grown from the 0.3 kg in 1950 and that accelerated in the last years (SEMARNAT, 2013b). According to the prospects, in the region of Latin America and the Caribbean, the average of generated waste will grow from the current 1.1 to 1.6 kg per capita and per day in 2025 compared to the base year 2012, and will grow two thirds in the total generation (Hoornweg & Bhada-Tata, 2012).

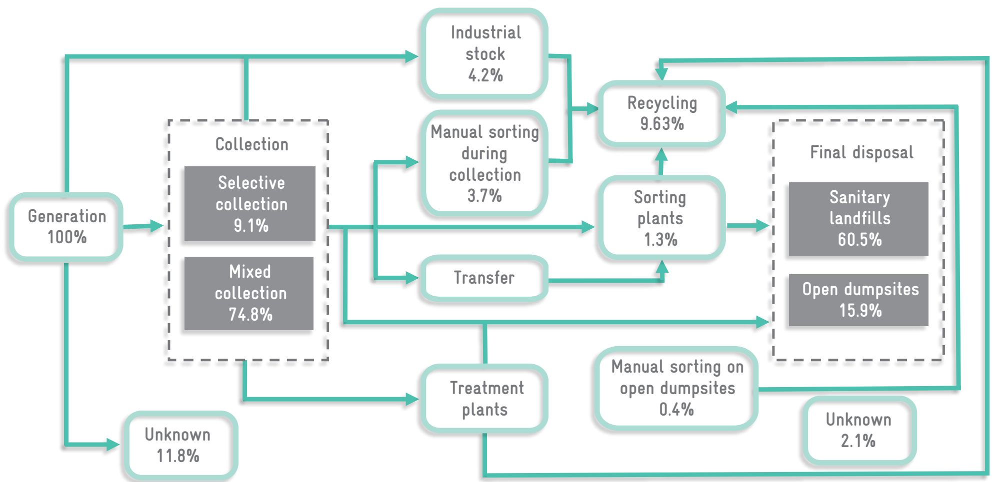
In Mexico, urbanization reached a rate of 78% in 2010 (IEA, 2013), which has a direct effect on the consumption patterns and consequently on waste generation: populations from the big urban areas double the generation rates of those living in municipalities with less than 10,000 inhabitants (Avedoy, 2012). Gross domestic product (GDP) in Mexico grew at a rate of 30.1%, (World Bank, 2017) meanwhile the MSW generation grew at a rate of 39.7% during the period 2000-2013 (INEGI, 2014). This positive correlation is not a coincidence according to the DG Environment News Alert Service (2010), that pointed out that the amount of solid waste has a positive and causal relationship with GDP.

Waste is derived from the discarded output that a society´s consumption system produces. MSW enters into a material flow and starts its own system: the waste management system, created by the interrelation of several elements that will be assessed in this report. It begins with waste generation at source and ends up with the final disposal. The first diversion of the mass flow occurs during the collection. The subsequent step is to treat the waste in order to reduce its impact and, in the midway, reincorporate some of this resource to the production system by recycling or other recovery methods, such as waste-to-energy (WtE). This flow has been illustrated for the case of Mexico and represented in **FIGURE 1**.

All in all, the amount of MSW generated has a very relevant impact on ecosystems and on climate. The final disposal of MSW is a clear example: a big share of the waste that ends up in open dumpsites contributes to produce heavy metals, leachate that pollutes groundwater, nitrogen oxides (NOx), furans and dioxins from multiple uncontrolled combustions that have very harmful effects on human health. Sanitary landfills are the main destination to dispose the waste. These sites are characterized by an insulation design to avoid pollution. They are such an overspread management solution mainly due to its apparent economic benefits in the short term. Nevertheless, the experience of industrialized countries showed that the operational costs in the long run make the sanitary landfills very expensive and unsustainable (Schnurer, 2015).

Furthermore, the degradation of the organic fraction of municipal solid waste (OFMSW) leads to the production of methane (CH_4) in a chemical process called anaerobic digestion (AD). CH_4 is considered a greenhouse gas (GHG) due to its global warming potential, which is 28 times higher than carbon dioxide (CO_2), according to the Intergovernmental Panel on Climate Change (IPCC) (Myhre *et al*., 2013). For that reason, many landfills have developed CH_4 collection systems to avoid this being released into the atmosphere. Nevertheless, these systems are not totally effective: even though a good operational design can reach a capture of 70% of the landfill gas, the majority of sanitary landfills in developing countries are within a range of 40-60% (World Bank, 2008).

FIGURE 1 Diagram of MSW management in Mexico



REFERENCE: INECC (2015) and based on the data provided by Avedoy (2012).

The waste sector contributes to 4.6% of the GHG emissions from Mexico according to the inventories: 30,903 kilotons of carbon dioxide equivalent (kt $CO_{2\text{-eq}}$) per year. Despite the sector is not so voluminous as others in terms of contribution to climate change, it grew 167% compared to the average rate of 33% in the historical series (1990-2010) (INECC, 2015). Within the sector, around two thirds of the emissions correspond to the methane from the final disposal of MSW (INECC, 2015). Landfilling of MSW in Mexico leads to the annual emission of 19,540 kt $CO_{2\text{-eq}}$ of GHG to the atmosphere every year (INECC, 2015). This emission intensity contrasts with other countries like Germany, where the MSW generated is slightly higher but the emissions from solid waste landfilling are about the half: 10,200 kt $CO_{2\text{-eq}}$ per year (EEA, 2014).

The social impact of the waste sector is equally important. Often street sweeping and solid waste management is the city's single largest source of employment (Hoornweg & Bhada-Tata, 2012), not only by registered workers, but also from the informal sector. They play a crucial role in developing countries during several steps of the process, especially in the collection of waste and the recovery of recyclables. In the context of Mexico, the situation of the informal sector often leads to a workers being marginalized and the emergence of complex systems ruled by chiefs ("caciques") as documented in literature, for instance in the book *The garbage society* (Castillo-Berthier, 1983).

To summarize, improvements in waste management deliver many benefits to society from the three approaches of sustainability: contributions to the economy by added values of waste outcomes like recycled materials and energy and less investments in landfill facilities; social improvements by protecting public health and increasing the job quality of waste management workers; reduction of environmental impact by reducing GHG emissions of leachate from landfills and improving soils with the use of composted organic waste (Hyman *et al.*, 2013).

1.2 Literature review

Methane, apart from being a gas with a global warming potential, also has a calorific value that can be used to supply energy. AD of waste can take place in reactors under controlled conditions, called digesters, leading to a win-win situation: waste is diverted from final disposal and methane is not released to the atmosphere; the gas can be applied to feed the energy demand of society. This is the approach sought in this thesis: to assess the potential that the AD of MSW has in terms of energy production and GHG mitigation. In order to achieve a successful analysis, it is important to do a revision of what has been already researched on the topic by other authors.

According to the official statistics, biogas contributed in 2005 to the primary energy mix with 0.69 PJ per year in Mexico. Ten years later, this number has increased to 1.87 PJ, which is consumed by power plants to generate electricity (SENER, 2016a). A large part of this biogas output comes from the AD reactors installed to treat manure from industrial farming: the installed capacity was 5.7 MWe (FIRCO, 2011). This has increased to a capacity of ca. 14.4 MWe at the end of 2015, produced by 360 biodigesters, from which 211 incorporated generators to recover the energy during the combustion of the biogas (FIRCO, 2016).

Municipal waste is composed both by solid waste and wastewater. The production of biogas from the sludge derived from wastewater treatment is still not very widespread, despite it being a good and homogeneous source of organic matter that can be anaerobically digested. Currently there are 25 wastewater treatment plants (WWTP) involved in the energy recovery of sludge (IMTA, 2017). For the solid waste, the recovery of biogas in landfills to generate power is implemented in few sites (Chavez, 2014; CMNUCC, 2008, 2009, 2010a, 2010b, 2011a, 2011b; CRE, 2012). The distribution of the projects is shown in the map below from **FIGURE 2**.

FIGURE 2 Biogas production projects from municipal waste in Mexico, on operation or in construction

REFERENCE: GIZ, 2017.

On the other hand, the treatment of MSW in AD reactors to produce biogas is limited to only pilot projects. The fact that these kinds of technologies started to be rolled out only 20 years ago creates a gap between the current installation and the potential that could be deployed. According to a study in 2010, the global potential of waste is 8-18 exajoules (EJ) (Scarlat *et al.*, 2015).

In Mexico, several studies about the biomass potential have been developed. This was estimated to be 3,569 PJ per year, which could feed 16% of the energy consumption of the country by 2030 (Masera *et al.*, 2011). Within the biomass, the technical energy and mitigation potential of waste has been recently assessed by Cruzado *et al.* (2017) for agricultural, agro-industrial and forest waste through its application in cement kilns and thermal power plants. Nonetheless, municipal waste was not included in the case study. In the report from Masera *et al.* (2006), the potential of biogas production from waste was fixed at 17.4 MW for 2010 and 668 MW for 2030, creating those scenarios based on several factors (e.g. economic growth, population growth or energy demand). Regarding biogas production from wastewater, the Mexican Institute of Water Technology (IMTA) did thorough research about the technical potential to produce biogas out of this sludge through an inventory of WWTPs all around the country (IMTA, 2017).

In the field of solid waste, the theoretical potential to produce biogas was analyzed together with other biomass sources, with the result of 39 PJ/year based on the amount of MSW collected in the country (Schulze, 2009). The potential of biogas capture in landfills was estimated to be 165 MWe, according to the inputs inside the disposal sites (Arvizu, 2010) and 652-912 MWe in other references (SENER, 2012). Furthermore, a large case study funded by the World Bank assessed the GHG mitigation potential with the approach of the whole Mexican energy system (Johnson *et al.*, 2009). One of these multiple factors was the biogas potential from MSW, which was referenced as 35 PJ/year (García *et al.*, 2013; Masera *et al.*, 2011; Rincon & Silva, 2014). Nevertheless, after a long search, the methods to reach that result could not be found by the author of this thesis. It was not specified whether that potential was based on the AD of MSW in digesters or only based on the potential to capture biogas from landfills. This potential was recently referred to in García & Masera (2016) as a range of 35-305 PJ per year, adding the statement that “there exists a great uncertainty” to estimate the potential of producing biogas out of MSW in Mexico.

Regarding GHG mitigation potential, the amount of 110 million tons of CO_2 equivalent (Mt $CO_{2\text{-eq}}$) could be reduced in 2030 if the potential of the energetic use biomass would be deployed (Masera *et al.*, 2011). In addition, the previously mentioned report, *Low-carbon development for Mexico* (Johnson *et al.*, 2009), the alternative scenario for 2030 implies a reduction of 477 Mt $CO_{2\text{-eq}}$ compared to the baseline. Out of this, 9.6% corresponds to the use of bioenergy. Nonetheless, it is explicitly stated that some interventions of high priority, such as biogas capture in sanitary landfills, were not taken into account for the assessment because it is assumed that in the baseline the landfill gas is burnt.

- Altogether, the author of this thesis considers the present research of high relevance, according to the existing information available in literature, for the following reasons:
- Previous reports tackle the potential for the AD of MSW in Mexico in a general way, missing the multiple barriers existing within the waste management system to deploy such potential, both general and country-specific;
- There is a gap in literature about the mitigation effects that the diversion of MSW to AD reactors could have, in terms of diverted MSW from landfilling;
- The utility to contrast these potential calculations with the commitments recently compromised by the Mexican government to increase the share of RES and fight against climate change;
- The encourage from the Mexican legislation to promote the research and design of alternatives to treat waste, as well as its valorization as a resource (Cámara de Diputados, 8 October 2003).

1.3 Research question

The situation described in the previous chapters about the benefits of treating MSW through AD systems provokes thought about the lost opportunities for Mexico to reduce the environmental impact of waste and produce a renewable energy source (RES).

The hypothesis of this master thesis is summed up in these two simple questions: firstly, how much biogas could be produced out of MSW? Secondly, how much can this support the fight against climate change?

The research question (RQ) is phrased in the following sentence:

> To what extent can the municipal solid waste from Mexico be treated by anaerobic digestion and how can this contribute to generate biogas and abate greenhouse gas emissions?

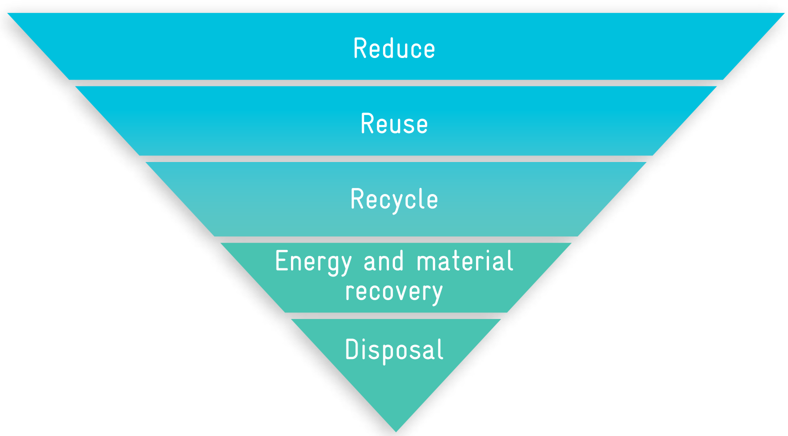
The research question is divided in three subquestions (RsQ):

- **RsQ1**: "What is the technical potential for biogas production?"
- **RsQ2**: "What is the potential for mitigation of greenhouse gas emissions of this scenario?"
- **RsQ3**: "Which benefits could this have for Mexico to reach its commitments to increase the use of renewable energy sources and the abatement of greenhouse gas emissions? Which policies could be applied to promote the deployment of this potential?"

2.1 Technical background

The installation of WtE facilities has proliferated in the last decades as a tool to handle MSW. The waste management hierarchy, which states its priority as maximizing the sustainability of the process, considers energy recovery from waste as a preferable method than final disposal (**FIGURE 3**). The hierarchy makes a distinction of the alternatives for waste management between waste disposal (incineration and landfill) and waste diversion (all the rest, including energy recovery through the production of biofuels).

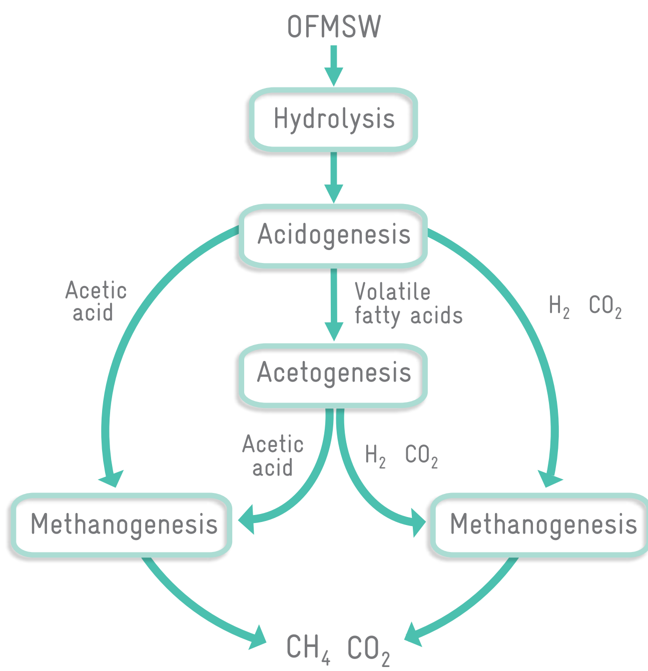
FIGURE 3 Stages of the waste management hierarchy in order of preference (top-down)



Currently, the most globally used WtE technologies are incineration and methane capture in landfills. Nevertheless, these technologies have some limitations to remark upon. On the one hand, incineration is not advisable for most part of the OFMSW (i.e. food and yard waste), whose average calorific value and high moisture content make them not a recommended feedstock (Georgieva & Varma, 1999). On the other hand, landfill gas recovery is a method applied to mitigate the emissions of methane produced through the decomposition of the OFMSW. It has been widely implemented in developing countries under the funding of Clean Development Mechanism from the Kyoto Protocol, which allowed for payment of the operating costs of landfills with the payments from carbon credits (Wilson *et al.*, 2015). Nonetheless, projects for landfill gas capture are still few in number in Latin America in comparison with implementation in the US and many European countries (World Bank, 2004).

AD in reactors is a third WtE process very attractive for use with biowaste. This is performed in mechanical-biological treatment (MBT) plants, where the waste is mechanically processed (pretreatment) before being fed to the reactors, with the aim of removing unwanted items from the incoming waste stream. Among the mechanical tools, there are grinders and shredders to reduce the particles size and separators to sort the waste according to its volume (e.g. screens, sieves) and composition (e.g. manual, magnetic and optical sorters). After the mechanical phase, there are two possibilities for the biological treatment: composting or AD. The first one consists of an oxidative stabilization of the biodegradable material, whose major advantages are the low requirements of infrastructure and the faster degradation. The main disadvantage is that it is a net energy consumer, in contrast with the added-value of the biogas produced in AD reactors (Mata-Álvarez *et al.*, 2000). The anaerobic digestion is based on the activity of microorganisms along 4 main steps (**FIGURE 4**) that decompose the large and complex biomolecules from the MSW to CH_4, CO_2 and other trace gases.

FIGURE 4 Anaerobic digestion process of the OFMSW



The procedure starts mixing and heating (if thermophilic AD) the mechanically sorted organic material and continues with the confinement of the feedstock inside the biodigester in the absence of oxygen. The outputs from the digestion process are biogas and digestate. The gas needs to be stored, cleaned to remove impurities and, additionally, can be upgraded to increase the methane share or be compressed. The digestate has to be split in two phases: liquid and solid. The liquid will follow several steps to remove its pollution charge and the solid digestate will be composted to reduce its volume and then be disposed, incinerated or used as an agricultural fertilizer. Furthermore, the odors generated in the process due to the decomposition of the waste need to be treated to avoid a local impact in the air quality.

This technique is rapidly growing in the last decades to treat all kinds of organic waste: animal manure, agricultural waste, sludge from wastewater and the OFMSW. Historically, it has been associated to the treatment of sludge and manure (Weiland, 2000) with a major aim to reduce the volume of pollutants despite using it as a source of energy, but it has evolved to the stage at which biogas as a product provides economic benefits. The application of AD on MSW implies not only a diversion of biowaste from landfilling to avoid leachate that pollutes the soil and groundwater, but is more productive than sanitary landfills with gas capture systems as the methane yield is 2-4 times more (Souza *et al.*, 2014).

The use of waste to produce biofuels has been broadly theorized. They are considered as second generation fuels, which all have common characteristics: there is no direct competition with food crops, have lower GHG emissions than first generation biofuels and use residues as feedstock (Luque *et al.*, 2008). All the benefits from AD technologies to treat MSW are minutely described in the following chapters in order to assess the positive impacts in terms of energy production and GHG mitigation for Mexico.

2.2 Conceptual framework

The concept of "potential" can be an object of discussion. As Verbruggen et al. (2010) explained, "potential" implies a gap between an actual situation and a scenario that can become actual, i.e. an equivalent concept of lost opportunities. These scenarios are closely related to a set of factors (barriers) that does not allow the potential to be deployed. However, the fact of analyzing this hypothetical and alternative situation provides a very useful tool to establish upper-boundaries to emergent RES and technologies.

Potential studies have different levels that vary depending on the assumed conditions. The first step is the "theoretical potential", considered as the highest level of potential, only constrained by natural and climatic factors (Hoogwijk & Graus, 2008). This concept can evolve to a more realistic scenario that can be implemented through demonstrated and likely to develop technologies or practices (Verbruggen *et al.*, 2010): the "technical potential". Among the barriers limiting these sorts of studies are socio-geographical constraints, technical losses in the conversion process (Hoogwijk & Graus, 2008) and other structural constraints (Krewitt *et al.*, 2008). In other words, they are assumptions of the elaborated calculations.

The biogas production is a chemical reaction promoted by bacteria feeding from the organic matter contained in the MSW. Therefore, the theoretical potential is based on the stoichiometry of that reaction, from heterogeneous organic molecules and their elements (C, H, O, N) to CH_4 (Davidsson, 2007). The theoretical potential is equivalent to the biochemical potential (Li *et al.*, 2011). This can be estimated by calculations or by practical measures in the laboratory (Christensen, 2010), providing conversion factors related to different sources of organic waste, which are given in the literature (Pacheco, 2016). Nevertheless, the practical yield biogas obtains in the reactor will always be lower than the theoretical calculations due to some factors:

- Not all organic components are degraded anaerobically;
- Bacterial activity: some of the substrate is used for bacterial mass growth, some organic molecules are not accessible;
- Management barriers: not all biowaste generated ends up in AD reactors.

This last factor is of extreme importance, due to the complexity of the waste management system and the multiple structural constraints linked to it. Technical potential is based partly on the technology performance, which may improve in time, and therefore the technical potential will probably increase in time. Meanwhile the theoretical potential remains constant (Blok, 2007).

The interpretation of the concept of potential for renewable energy supplies is open to criticism in the literature and varies according to the author's criteria. Moreover, the concept itself of MSW as a RES is debatable. Sims (2002) considers it renewable as they are produced continuously by industrial societies, but is not sustainable in the sense of the word because does not function as closed systems integrated in its environment. MSW is, in this way, only a transient resource, which is not an energy resource *per se*, but the end stage of many production and consumption processes. Even though the quickest way to reduce the volume of waste generated in most cities would be to reduce the economic activity, this seems an unattractive option in the current consumer-based lifestyle (Hoornweg & Bhada-Tata, 2012). Therefore, the energetic utilization of the OFMSW remains as the preferred option in the waste management hierarchy.

According to the International Energy Agency (IEA), the concept of RES includes combustible renewables and waste, including solid biomass, charcoal, renewable municipal waste, gas from biomass and liquid biomass, as well as other sources like hydro, solar, wind and tide energy (RETD, 2006). Biogas is therefore the product of a primary source of renewable energy (biomass) and this research case can be considered as a potential case study for renewable energy supply.

The deployment of RES potentials is crucial to foster a decarbonization of energy systems. "Decarbonization denotes the declining average carbon intensity of primary energy over time" (Kainuma *et al.*, 2007). In this sense, the inclusion of biogas as a primary energy source in the energy system helps to displace fossil fuels, which are nowadays the major contributors in Mexico. Biogas is a carbon-free energy source, as the emissions of CO_2 derived from its combustion are considered biogenic emissions, i.e. CO_2 emissions derived from plant or animal matter, excluding fossil carbon (Paustian *et al.*, 2006). This means that, after the emission, CO*2* is reintroduced into the natural cycle by photosynthetic organisms keeping a net carbon balance. That is the reason they are not taken into account in GHG inventories.

Nevertheless, if the carbon contained in the feedstock is released into the atmosphere as CH_4 without a combustion, despite its biogenic origin, it will be taken into account in the inventories because it has 28 times more global warming potential than CO_2 (Myhre *et al.*, 2013). This is the reason why the GHG emissions from landfills –very rich in methane– have that relevance in the Mexican inventory. Indeed, the contribution of treating the OFMSW in reactors contribute to divert that biomass from final disposal and the inherent methane emissions to the atmosphere will be avoided, contributing to increase the mitigation potential.

All in all, the AD of MSW has a double mitigation potential: the direct GHG savings through the production of biogas and the substitution of fossil fuels, plus the indirect savings through the avoidance of methane produced when the organic waste is disposed and released into the atmosphere without flaring. These indirect emissions are consequence of activities within well-defined boundaries, but which occur outside these specified boundaries (IPCC, 2014a). In this case, the boundaries are the production and utilization of biogas and the consequence of that activity is the diversion of organic waste from final disposal.

This situation fits to the concept proposed to the technical mitigation potential: "amount by which it is possible to reduce GHG emissions or improve energy efficiency by implementing a technology or practice that has already been demonstrated" (Verbruggen *et al*., 2010). This would support the idea that the Environmental Kuznets Curve (Kuznets, 1955) –which relates GDP growth with environmental impacts– follows an inverted U-shape, where it reaches the maximum disturbance at middle income rates and then decreases to a better environmental quality due to technological improvement (Panayotou, 2003). Therefore, as a developing country with a high economic growth, Mexico could implement technologies to abate the environmental impact from the rapidly growing MSW generation attached to its economic development. This has been proven for MSW management in other developing countries (Ghazi Alajmi, 2016) and could be applied to biodigestion technologies in Mexico.

2.3 Barriers

The set of factors that does not allow realizing a potential can be very diverse. An analysis of the context is necessary to define the existing barriers and the indicators that will be used to estimate their impact on the energy and mitigation potential. With this aim, an overview of the waste management status in Mexico has been carried out to assess the country's background and the limiting factors to treat MSW in AD reactors and generate biogas. This will have an effect on the potential to mitigate GHG emissions from the energy and waste sector, which at the same time is affected by extra limiting factors that will be explained below.

These factors are summarized in **TABLE 1**, which shows the barriers identified in the whole process to manage the MSW, to digest it to produce energy and to handle the secondary outputs that altogether influence the potential that theoretically could be produced but is technically constrained.

Collection of MSW is the first factor and its national rate surpasses 85% (Avedoy, 2012). The importance of collection and transportation of the waste on biogas projects has been highlighted in literature as the steps with the main uncertainties over techno-economic feasibility (Rajendran *et al.*, 2014). MSW is a highly dispersed resource territorially that requires transportation over large distances from the source to the energy production site, making this factor a challenge for the AD projects (Kothari *et al*., 2010).

TABLE 1 **List of barriers limiting the technical potential**

#	Barrier	Discards
1	Collection	Uncollected MSW
2	Municipality size	Waste from small municipalities
3	Sort of collection	Segregation of MSW at source or mechanically
4	Waste composition	Inorganic and organic material unsuitable for AD
5	Organic material recovery at MBT	Mechanically unrecovered organic material
6	Methanization	Digestate
7	Biogas composition	CO2 and other gases
8	Biogas upgrading	Energy consumption and biomethane losses
9	Gas compression	Energy consumption
10	Conversion to final energy	Efficiency losses
11	GHG emissions from digestate	Methane emissions

Despite the collection rate in Mexico being rather high, there is a large variance within this percentage. Per region, some federal States reach 100% coverage and other less than 50%. Per municipality size, it ranges from 86% in cities to 23.4% in towns with less than ten thousand inhabitants (Avedoy, 2012). This leads to the second barrier: municipality size. This socio-geographical barrier has been considered in other potential studies in countries like Brazil (Souza *et al.*, 2014), where only the 16 biggest cities were considered. Digesters become more common with the increase of the waste amount to treat as it is a capital intense technology often not economically favorable at a small scale (Trendewicz & Braun, 2013).

The state-of-the-art of the AD of solid waste in Europe and North America is to focus on those waste sources with a low share of impurities like plastics, metals or ashes. These sources of feedstock are manure, waste from food industries, etc. The main reasons are to avoid technical problems, increasing the biogas yield and, specially, providing an application to the digestate after the AD. Only digestate coming from the treatment of source-separated waste can be used as agricultural compost. Otherwise, this will be landfilled.

The sort of MSW collection is very determining in the process, splitting the stream in two categories: when the feedstock is mixed with other fractions, it is called residual municipal solid waste (rMSW) and when it is a source-separated organic fraction of the municipal solid waste (SS-OFMSW). The segregated collection of the OFMSW started in the 1990s in countries like Germany, Austria and Switzerland to use it for composting or fermentation (Deublein & Steinhauser, 2011). This system spread out to other regions and, despite it still being rare in low- and middle-income countries (Vögeli *et al.*, 2014), there are several successful cases in Mexico, as will be explained later on. For the case of rMSW, the direct effect is an increase in the additional costs to mechanically sort the biowaste at MBT plants (Vögeli *et al.*, 2014). The resulting material will generally have a lower quality: less organic charge (Bolzonella *et al.*, 2006), more contaminants that result in operational problems (De Baere & Mattheeuws, 2013) and, specially, an output of digestate after the methanization process with a low quality. This makes it unsuitable to be used as soil conditioner due to the contaminant (Wilson *et al.*, 2015). Despite all these disadvantages of using rMSW as feedstock to produce biogas, it still can be considered for the AD process (Bolzonella *et al.*, 2006). In Europe, even though biogas projects from SS-OFMSW were adopted earlier, those with rMSW also grew and even outstripped them (De Baere & Mattheeuws 2008).

The fourth barrier is waste composition. The characterization of MSW is a common assessment required to carry out waste management projects. This shows the share of every fraction according to its composition. For AD, only organic materials have the potential to produce biogas. Therefore, inorganic fractions like plastics, metals, glass and minerals are removed from the reactor input. Some fractions which are organics are not suitable for AD, however, due to their complexity to be degraded, like lignocellulosic material (e.g. wood and straw), leather, bones or textile. In general terms, food waste firstly, and yard waste (grass, leaves and brush trimmings) secondly, are the organic wastes which are most commonly used to produce biogas.

Following the split of MSW into the two streams previously mentioned, the rMSW is taken to MBT plants to sort it into several fractions prior the biological treatment. Nonetheless, this process is not 100% effective in recovering the complete organic fraction that will be used to feed the reactor. Therefore, a significant part of the potential is discarded.

Altogether, the stream of organic material that overpasses the collection and pretreatment phases constitutes the feedstock for the anaerobic digesters. The new limiting factor will be the biogas yield of the technology, which varies according to the project and the characteristics of the OFMSW input. After the AD, the output is divided into two phases: gas and solids. This last fraction is the digestate, a mixture of the compounds that did not degrade into biogas (e.g. lignin) and bacterial mass (5-10%) (Christensen, 2010), that constitutes normally about one third of the input mass. Moreover, not all biogas components have fuel properties: only CH4 has a calorific value and its share within the biogas is 48-65%. The second most important gas is CO_2 with 36-41% of the share, followed by water steam and other trace gases (e.g. H_2S and nitrogen) (Ward *et al.*, 2008).

Once the biogas is dewatered by a passive condensation and cleaned from corrosive gases (H_2S), it can be directly combusted to generate heat and/or power. Nevertheless, biogas is a precious energy carrier that can be used for other purposes, due to its similarity to natural gas (NG), which is composed by ca. 97-98% methane. The biogas can be upgraded in its CH_4 share to those numbers and become biomethane, which is chemically almost identical to NG. There are a number of upgrading processes commercialized: Pressure swing adsorption, water scrubbing, organic physical scrubbing and chemical scrubbing (Petersson & Wellinger, 2009). The main advantage of this process, on the one hand, is that the output has a more diverse utilization compared to biogas. On the other hand, the disadvantage is its high energy consumption and the gas losses that occur during the upgrading. Biomethane works as a substitute of NG to be injected in the network to be supplied to residences and industries or to feed vehicles as a fuel. In this last case, there is an additional loss of energy due to the biomethane volumetric reduction through a compression process.

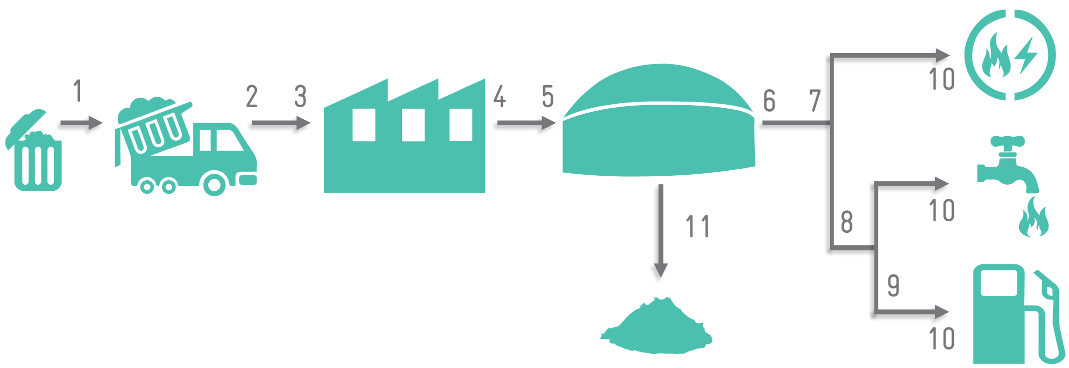
After all these steps, the result is a renewable fuel ready to be used. Nonetheless, this is a primary energy source that requires to be converted into final energy, with the aim to assess its capability to substitute fossil fuels and therefore the amount of GHG emissions mitigated. This is indicated by conversion efficiencies, which vary according to the kind of technology to which the biogas/biomethane will be applied.

The last barrier analyzed pertains only to the mitigation potential: the emissions of GHG from the digestate. This output produced during the AD still requires further treatment to reduce its volume, level of pathogens and carbon content. This is usually done in aerobic conditions to enhance composting. The final output is a nutrient-rich material that can be used on agricultural land, in case the digestate comes from the digestion of SS-OFMSW. For the case of rMSW, the digestate, after dewatering and composting, is considered as compost-like output (CLO), which due to the impurities and pollutants does not generally fulfill the quality standards to be applied on agricultural land. One of the alternatives for CLO is its incineration or its utilization as a soil amendment on land with no agricultural uses, such as energy crops or land regeneration (Kepp & McKendry, 2008). Nevertheless, the use of CLO on energy crops was identified to carry a risk for the environment from heavy metal leaching (Page *et al.*, 2014). Nowadays, the most common result is to dispose it in landfills after its stabilization (Donovan *et al.*, 2010).

Despite digestate showing a very low level of residual biogas yield (Kanning & Ketelsen, 2015), it still has a certain amount of methane formation potential that can contribute to climate change (Zeshan & Visvanathan, 2014). The indirect emissions from its application on land are on debate and hard to predict, as the net emissions depends on many factors like the climate conditions, crop rotation and the soil carbon cycles (Møller *et al.*, 2009). But in any case, the emissions of $CO_{2\text{-eq}}$ will be lower than in landfilling, as it will be shown in the following chapter.

To conclude, **FIGURE 5** represents the whole process of MSW management and AD, from the generation of MSW until the combustion of the biogas, together with the barriers located at the step where they occur. This approach to the potential for biogas, considering country-specific and general barriers, is expected to provide an innovative view to reach the most realistic result to enhance the investment in WtE projects.

FIGURE 5 Diagram of the system and the limiting factors to the deployment of the potential in numbers



3.1 Data collection

All factors applied in this research are based on literature sources, following the implementation of demonstrated best practices and their values in order to define a technical potential (Verbruggen *et al.*, 2010). For those factors expressed in ranges, the average values were applied to the calculations.

The first barrier for the technical potential corresponds to the collection rate of MSW. According to the law, Mexican municipalities need to undertake surveys about several topics that will be collected by Mexican National Institute of Statistics and Geography (INEGI). One of those topics is MSW management, where the authorities must fill a questionnaire with qualitative and quantitative data about recycling, characterization studies, waste treatment, final disposal, etc. (INEGI, 2013). The last version of daily MSW collected tons per municipality dates from 2014. This is available online (INEGI, 2015) and will be the basis for this research. Due to the fact that these numbers are directly reported by municipalities according to their waste weighting records, we can assert that the representativeness of this indicator is rather high. Despite the fact that application of a large data base can be very challenging, the results are expected to have a better quality than using average values for the whole country.

For barrier #2, the case study will only consider the amount of waste collected in municipalities and delegations with more than 50,000 inhabitants. This is the same constraint used for the mitigation targets from the waste sector, as will be explained in chapter 5.4. The total number of municipalities analyzed is 426. For barrier #3, despite there being an average value of 52.4% organics within MSW for the whole Republic of Mexico, this is not disaggregated into different subcategories. Nonetheless, there is available information about MSW characterization per federal State and divided into several subcategories: these were estimated for the The Mexican Model of Biogas 2.0 (EPA, 2009). The MSW fractions discarded from these study are the inorganics and the organic material that is not suitable for AD due to their low degradability rates, including fractions like wood, paper and cardboard. In short, there are three fractions considered to produce biogas in the case study: food waste, yard trimmings and other organics with the status of “very fast degradability”.

Barrier #4 represents the split of the waste stream into biowaste collected separately at source and the mix fraction of rMSW. As explained it chapter 2.3, MSW segregation before collection is globally still at a preliminary step. Nonetheless, this system has some successful examples in the country: e.g. Mexico City implemented it years ago and today 48% of the biowaste is collected separately (SEDEMA, 2014) to be biologically treated to produce compost. This value has been assumed for all municipalities assessed in this research (**TABLE 2**). Due to the size of the assumption, a sensitivity analysis will be carried out in chapter 5.6 to assess its impact on the final results. The remaining 52% is presumed to be collected mixed in the rMSW, which undergoes a mechanical sorting at the MBT plant. This is the basis of barrier #5: 90% of the collected rMSW is recovered and used for the AD process. This assumption is based on other research studies in literature about best practices in MBT plants (Bezama *et al.*, 2007; Montejo *et al.*, 2013).

TABLE 2 Applied values for barriers 4-7 for each waste stream

Sort of collection	SS-OFMSW	rMSW
Share of collected biowaste (%)	48	52
Recovered organics at MBT plant (%)	100	90
Biogas yield (m3/t)	91	117
Methane share within the biogas (%)	55	56
Digestate output (% of the reactor input)	33.2	31
Total solids of the digestate (%)	46	50–60%

Next step is to introduce the feedstock into the anaerobic digesters. Methanization (barrier #6) is the process in which the organic matter is converted to CH_4 through the activity of microorganisms. This is measured according to the reactor's biogas yield. For this case study, two European AD plants have been selected as references: Mons in Belgium for the stream of rMSW (Monson *et al.*, 2007) and Berlin for the stream of SS-OFMSW (Kanning & Ketelsen, 2015). Both experiences implemented dry AD systems to treat the waste. The application of numbers from real plants instead of laboratory experiences is considered relevant by the author due to the operational complexity and limitations that facilities face to treat the waste.

This case study uses as reference the following scenarios of energy use: (1) cogeneration of heat (a) and power (b); (2) injection of biomethane into the NG network; and (3) fuel feeding for vehicles adapted to compressed gas. After the collection and cleaning of biogas, this will face new losses depending on the use given to it. Barrier #8 applies only to scenarios (2) and (3), in which biogas needs to be upgraded to remove CO_2 traces. This process involves an energy consumption of 0.25 kWh[1] of electricity per m^3 of raw biogas treated and a loss of 0.1% of methane (Hoyer *et al.*, 2016; Kanning & Ketelsen, 2015; Petersson & Wellinger, 2009). These values correspond to the techniques of chemical scrubbing, which allow the resulting gas to reach 97% of methane concentration within the biogas. This number is a common standard in several countries using biomethane as a substitute of NG (Bruijstens *et al.*, 2008). Barrier #9 also involves an energy consumption[2] to compress the biomethane and use it to fuel vehicles: 0.011 kWh per MJ of compressed gas (López *et al.*, 2009). Both gas upgrading and gas compression technologies are adjusted to the scale of biogas production rates in all municipalities.

Barriers #10 and #11 pertain directly to the calculation of the mitigation potential. For the specific case of scenario (1), the net efficiency factors to heat and power are applied according to the size of the biogas plants (**TABLE 3**). All of them are among the most commonly employed in other biogas facilities like in wastewater treatment plants (Trendewicz & Braun, 2013). Further conversion factors used in this research can be found in **TABLE 4**: heating values, emission factors and characteristics of the reference fuel and technologies to estimate the GHG savings.

1 Energy consumption was discounted from the final energy output according to the average CHP electric efficiency.
2 Energy consumption was discounted from the final energy output according to the average CHP electric efficiency

TABLE 3 Conversion values of CHP technologies

	Microturbines	Fuel cells	Gas turbines
Size (kW)	< 250	250 – 2,800	> 2,800
ηe (%)	26 – 30	36 – 50	30
ηh (%)	30 – 37	30 – 40	40 – 52

TABLE 4 Conversion values applied to calculate the GHG mitigation potential

Parameter	Value	Literature source
Methane lower heating value (LHV) (MJ/m^3 CH_4)	35.88	Waldheim & Nilsson (2001)
Methane higher heating value (HHV) (MJ/m^3 CH_4)	39.82	
Emission factor of the Mexican electricity grid (t CO_{2-eq}/MWhe)	0.458	SEMARNAT (2015a)
LHV NG (MJ/kg)	46.74	INECC (2014)
Density NG (kg/m^3)	0.844	
Emission factor NG (over LHV) (kg CO_2/m^3)	2.27	
LHV diesel (MJ/kg)	43.18	
Density diesel (kg/L)	0.826	
Emission factor diesel (over LHV) (kg CO_2/L)	2.596	
Condensing boiler efficiency (over HHV) (%)	97	IEA (2013)
Emission factor from applying digestate on agricultural land (gr CO_{2-eq}/kg cured digestate)	13	Zeshan & Visvanathan (2014)
Emission factor from landfilling digestate (gr CO_{2-eq}/kg cured digestate)	129	
Total solids of cured digestate (%)	55	

3.2 Measurement

All factors described in chapter 3.1 will be applied to the main database of MSW per municipality. The first step to estimate the potential is modelling the mass balance for waste management before the biological treatment: collection and pretreatment (barriers #1-5). This leads to know how much feedstock is available for the next step: methanization. After the application of barriers #6 and #7 it is possible to know the amount of raw biogas and methane produced in the reactors. Biogas treatment (barriers #8 and #9) will provide the amount of final product ready to be used in each scenario.

The fuel output will be expressed in terms of gas volume, primary and final energy units (LHV) and fossil-fuel equivalents. This last conversion is of extreme relevance to estimate the emission savings from scenarios (1b), (2) and (3). The reference fuel to calculate the equivalence is NG for scenarios (1b) and (2), and diesel for (3). For the specific case of heat from cogeneration (1b), also required is the application of a reference energy converter to estimate the amount of NG equivalents: condensing boilers (**TABLE 4**).

All the energy produced from biogas will displace fossil fuels from the energy system, which will not be combusted and, therefore, will not emit GHG. This is the basis to estimate the direct mitigation from the use of biogas. The volume of fossil-fuel equivalents will be multiplied by the corresponding emission factors from **TABLE 4**, which are those applied by the federal Government in public policies (INECC, 2015). For scenario (1), the power output will be multiplied by the emission factor from the Mexican electricity grid (**TABLE 4**).

The indirect emissions avoided by diverting MSW from final disposal are calculated through the application of the Mexican Model of Biogas Version 2.0 (EPA, 2009). This tool is used by the Secretariat of Environment and Natural Resources of Mexico (SEMARNAT) to calculate the national GHG emissions from the waste sector. Indeed, this model was originally adapted from the Landfill Methane Outreach Program, designed by the US Environmental Protection Agency (EPA) to be used as a tool to calculate the potential of landfill gas recovery for landfill operators. The model incorporates the structure of the methodology recommended by the IPCC to create GHG inventories from waste management (Pipatti *et al.*, 2006). The methane emissions are calculated by the application of equation of first order decay for the organic matter when disposed in landfills (Aguilar-Virgen *et al.*, 2011):

$$Q_{LFG} = \sum_{t=1}^{n} \sum_{j=0.1}^{1} 2kL_0 \left[\frac{M_i}{10}\right] \left(e^{-kt_{ij}}\right)(MCF)(F)$$

Q_{LFG}	=	maximum expected landfill gas (LFG) generation flow rate (m^3/year).
i	=	1 year time increment.
n	=	(year of the calculation) – (initial year of waste acceptance).
j	=	0.1 year time increment.
k	=	methane generation rate (1/year).
L_0	=	potential methane generation capacity (m^3/Mg).
M_i	=	mass of solid waste disposed in the i^{th} year (Mg).
t_{ij}	=	age of the j^{th} section of waste mass M_i disposed in the i^{th} year (decimal years).
MCF	=	methane correction factor
F	=	fire adjustment factor.

This model requires several inputs to calculate methane emissions from each final disposal site of the country. These include the waste characterization per federal State and the historical database from the amounts of MSW disposed in every landfill since 1990. The specificity of each disposal site per municipality contributes to increase the reliability of the results compared to using average values for the whole country.

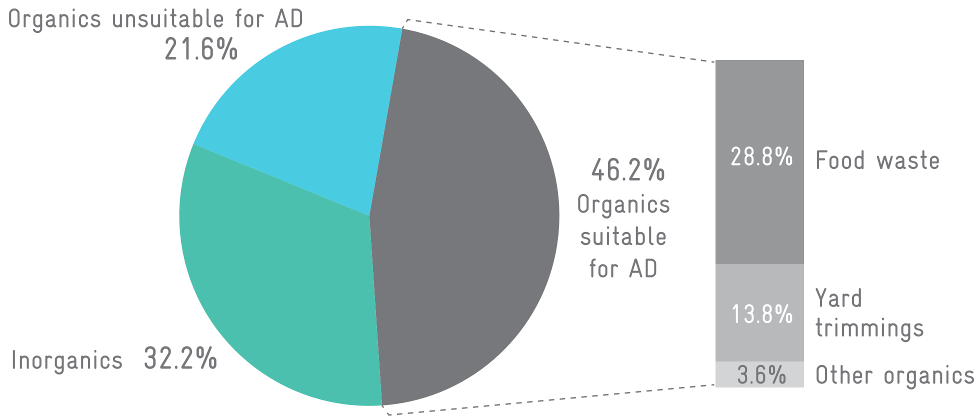
Furthermore, the results of annual emissions per final disposal site are aggregated and multiplied by the global potential warming of methane (Myhre *et al.*, 2013). Hence, to estimate the mitigation potential caused by the application of AD as an alternative treatment to final disposal, it is necessary to discount from the Model the tons per municipality calculated for the mass balance.

Finally, these indirect emission savings are partially offset with the extra emissions from handling the digestate after the AD. These are calculated through the values of digestate production for each waste stream (**TABLE 2**) multiplied by the emissions factors from cured digestate (**TABLE 4)** for each application: all digestate produced through the AD of SS-OFMSW will be applied on agricultural land as soil conditioner and all CLO derived from the AD of the OFrMSW will be landfilled. An adjustment of the total solids from both to multiply them by the emission factors is required.

To sum up, all direct and indirect emissions (+) and savings (-) will be aggregated to assess if the overall result contributes to mitigate the current situation through the deployment of the technical potential.

The MSW management system starts with the collection, where the rate for the country reaches 87.5% of the waste generated. The next barrier is the municipality size. Despite the amount of municipalities over 50,000 inhabitants represent only 17% of the total, they cover up to 85% of the collected MSW. This is caused by the large amount of small villages in the country that produce less waste in absolute and relative terms. From all collected waste in cities, 53.8% is not suitable for AD due to its composition, as can be seen in **FIGURE 6**. Those suitable reach the amount of 14.8 million tons, from which most belong to the fraction of food waste. This characterization of MSW fractions is consistent with the resulf ts of other reports published in the country (INECC, 2015).

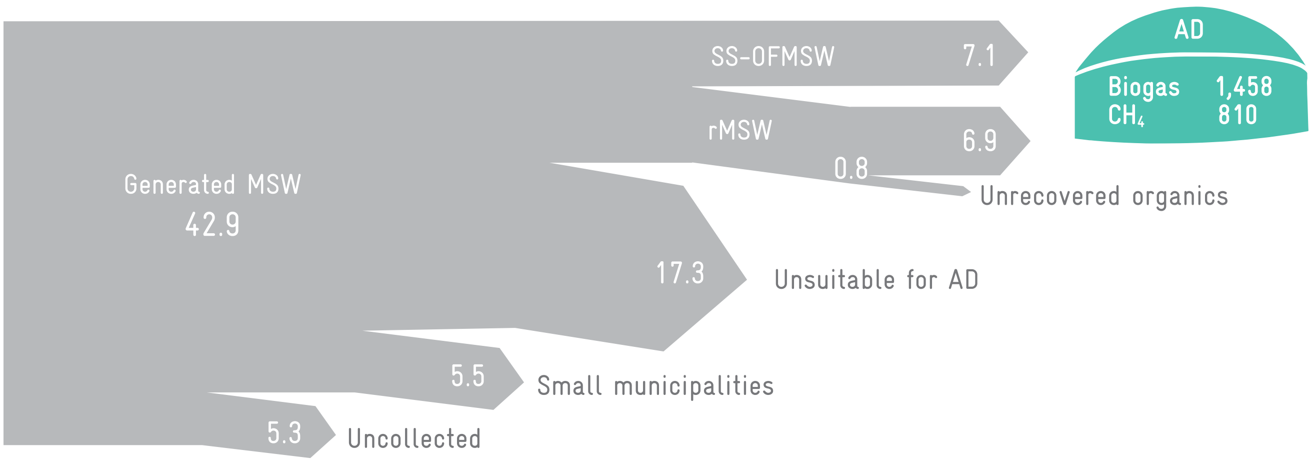
FIGURE 6 Characterization of the collected MSW in Mexican municipalities and delegations with more than 50,000 inhabitants



As referred in the previous chapter, in this study it is considered that 48% of the biowaste is potentially collected in separated fractions of organic and inorganic. The remaining 52% needs to be sorted at the MBT plant, where 770 thousand tons of organic waste cannot be recovered. Therefore, the rest will be anaerobically digested in its corresponding reactor, leading to a result of almost 1.5 billion cubic meters of biogas. From this, about 55.6% is methane in average. All these results are shown in the material flowchart from the waste generation until the biogas production (**FIGURE 7**).

For the biogas use, three alternatives are implemented. If this is combusted for cogeneration, it goes directly from the digester to the turbines. According to the amount of biogas output, the CHP technology varies in its efficiency. Microturbines are applied to the smaller towns, which add up to 9% of the municipalities analyzed but only reaches 0.4% of the total energy output due to the low efficiency of microturbines and the small amount of waste and gas generated. Fuel cells are applied in middle-size municipalities, which corresponds to 71% of the total, but the share in the energy output is only 29% overall. Finally, gas turbines are used in the big cities, which consists of 21% of the total municipalities analyzed and, due to the massive volume of MSW and biogas produced in these cities, the energy output is 70% of the total.

FIGURE 7 Mass balance of the MSW management (left) in million tons per year and biogas output (right) in million m^3 per year



For scenarios (2) and (3), the biogas still requires the removal of CO_2 prior its use. The upgrading process, though, results in a loss of biomethane, which is released to the atmosphere and, especially, in a relevant energy consumption. Both factors together are equivalent to 13.9% of the incoming gas to be upgraded. The resulting biomethane can be already injected in the NG grid, completing scenario (2). For the scenario (3), the biomethane needs to be compressed before its use to fuel vehicles. The compressor requires energy, which is discounted from the final output. This is not very relevant though, as it represents only 0.3% of the energy input from biomethane.

The final results are indicated in **TABLE 5**. All scenarios are expressed in primary energy units (LHV), which is the most common manner to refer to biofuels. Final energy and fuel equivalents are additionally given due to its crucial role to calculate the GHG emissions mitigated. They are needed to estimate the amount of fossil fuel displaced when biogas is introduced into the energy system. Scenario (1b) is only expressed in PJ of electricity. Scenario (3) is not expressed in final energy units, as this depends on the vehicle engine's efficiency, road status and other factors. These have a high variance and the final energy result is considered irrelevant for this case study and unnecessary in calculating the mitigation potential.

Furthermore, the total amount of biogas produced is not homogeneous across the whole country. **FIGURE 8** shows the geographical distribution of that output. The result is partially explained by the composition of MSW of each state, but especially by the population density and the urbanization level, those rural and/or less populated ones having a lower biogas generation potential. Annex A contains the complete results aggregated in federal states.

TABLE 5 Results of the potential for biogas in each scenario

Scenario		Primary energy (PJ/year)	Final energy (PJ/year)	Fuel equivalent
(1) CHP	a) Heat	29.06	12.47	294 million m^3 NG
	b) Power		9.79	–
(2) Injection to the NG network		25.03	27.78	635 million m^3 NG
(3) Vehicle feeding		24.95	–	700 million L diesel

FIGURE 8 Potential of biogas production per federal state

The results of the mitigation potential are expressed in **TABLE 6**. The results from the direct mitigation correspond to those savings from displacing fossil energy sources out of the system. The indirect effects from deploying the potential for biogas production are the avoidance of a great quantity of methane that is nowadays emitted by final disposal sites. The diversion of a great fraction of biowaste from landfilling to be treated in AD reactors implies a reduction of 64% of the emissions from disposal sites. Nonetheless, other factors linked to that treatment contribute to emissions of GHG in the atmosphere. The AD of SS-OFMSW results in an output of 2,360 kt of digestate that will be cured and applied to agricultural land, generating 26 kt $CO_{2\text{-eq}}$. The AD of rMSW produces 5,173 kilotons of CLO that will be equally cured to aerobically reduce its carbon content prior to its landfilling, which contributes to climate change with the emission of 667 kt of $CO_{2\text{-eq}}$ every year. Additionally, for scenarios (2) and (3), the mitigation effects are slightly reduced by the methane emissions from the gas losses during upgrading.

TABLE 6 Results of the mitigation potential of GHG emissions in kt $CO_{2\text{-eq}}$ per year

Negative values represent GHG emissions avoided and positive values represent additional GHG emissions caused by the production and use of biogas

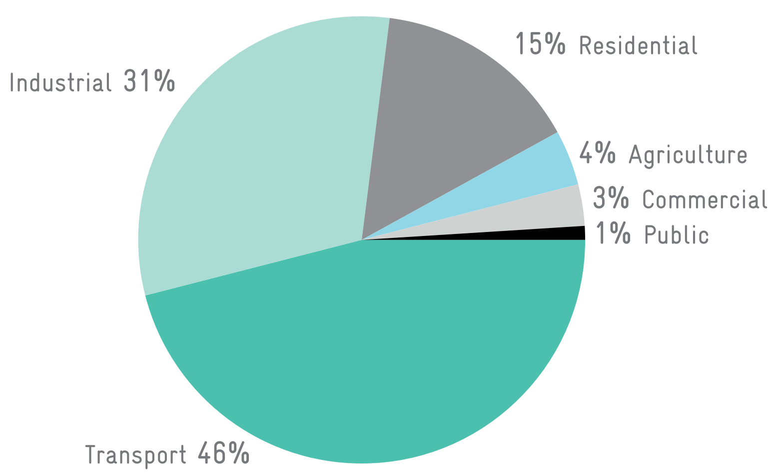
<table>
<tr><th rowspan="2">Scenario</th><th rowspan="2">Direct mitigation</th><th colspan="3">Indirect mitigation</th><th rowspan="2">Overall mitigation</th></tr>
<tr><th>Emissions during upgrading</th><th>Emissions from final disposal</th><th>Emissions from digestate</th></tr>
<tr><td>(1) CHP</td><td>– 1,912</td><td>–</td><td rowspan="3">-12,435</td><td rowspan="3">+693</td><td>-13,654</td></tr>
<tr><td>(2) Injection to the NG network</td><td>– 1,441</td><td rowspan="2">+15</td><td>-13,168</td></tr>
<tr><td>(3) Vehicle feeding</td><td>– 1,816</td><td>-13,543</td></tr>
</table>

The main purpose of this chapter is to discuss the results of the technical potential for biogas production and for GHG mitigation, completing the answers for RsQ1 and RsQ2, respectively. These numbers will be contrasted in the Mexican context to evaluate its impact on current sustainability problems that society faces (chapters 5.1 and 5.2). Then, the results will be framed in the future perspectives that the country has regarding increasing the share of renewable energy supply and reducing GHG emissions (5.3 and 5.4). The role that biogas from MSW plays in achieving the commitments of Mexico for these two topics will be assessed, answering in this way the first part of RsQ3. The second part will consist of providing an insight of the existing policies that can contribute to deploy the potential and enhance the management of MSW (5.5). To conclude, chapter 5.6 will be used to take a critical view of this research and to highlight its limitations and contributions to the field.

5.1 Potential for biogas production

The total energy consumption in Mexico reached 5,095 PJ in 2015 (SENER, 2016a) and the distribution among sectors is shown in **FIGURE 9**. The flexibility of biogas for its energetic use makes it a useful energy carrier for its consumption in every sector. This aligns with the alternative scenarios carried out in this thesis, allowing analysis of the sector where biogas has the higher impact. In the international context, the amount of biogas production has been estimated at 1025 PJ of energy, with an annual growth of 13.5% (SENER, 2012), which points to a promising future for waste AD systems.

FIGURE 9 Final energy consumption in Mexico



REFERENCE: SENER, 2016a.

Scenario (1), cogeneration of heat and power, results in the highest percentage between the three cases, with 16% more of primary energy than scenarios (2) and (3). This is mainly caused by the direct use of biogas after its extraction and cleaning from the AD reactor, avoiding in this way losses through further treatment before its combustion. This is required by other scenarios, especially during the upgrading process.

CHP technologies in Mexico started to spread after its regulation in 1992, which lead the sector to multiply by 6 the installed capacity in the following 17 years (Noriega & Rehovot, 2009). For bioenergy, cogeneration has a high potential with the use of bagasse from the sugar cane industry, which plays a relevant role in the Mexican economy. Indeed, the consumption of biomass by industry reached 37 PJ in 2015 (SENER, 2016a). In the regional context, bioenergy contributes to the renewable power supply with 10% of the installed capacity in Latin America and the Caribbean (SENER, 2016b).

After its conversion, the results of final energy for CHP remain high: up to 22.26 PJ per year due to the high efficiency values from cogeneration, in contrast with conventional power-only technologies. The electricity output is 9.8 PJ, a number that may not seem so relevant for the annually consumed 895 PJ of power that represents 17% of the energy consumption (SENER, 2016a). Nonetheless, the use of biogas to feed the electricity grid is of high relevance in order to diversify the supply together with other RES. This is a key element in fulfilling the commitments arranged by institutions, as will be explained in further chapters.

In comparison with other WtE technologies, biogas capture and combustion has a maximum yield of 65 kWhe per ton of MSW (SENER, 2016b). Meanwhile, according to the results of this study, the power output from the biogas produced in AD reactors has an average value of 86.6 kWhe per ton of MSW. Therefore, in line with theoretical studies, for the Mexican case it could be stated that AD treatment is more profitable in energy terms than landfilling. In addition, the externalities caused by the final disposal of biowaste implies that the benefits from AD are greater. Among them: an avoidance of soil, air and groundwater pollution from disposal, and fugitive GHG emissions from landfill gas collection.

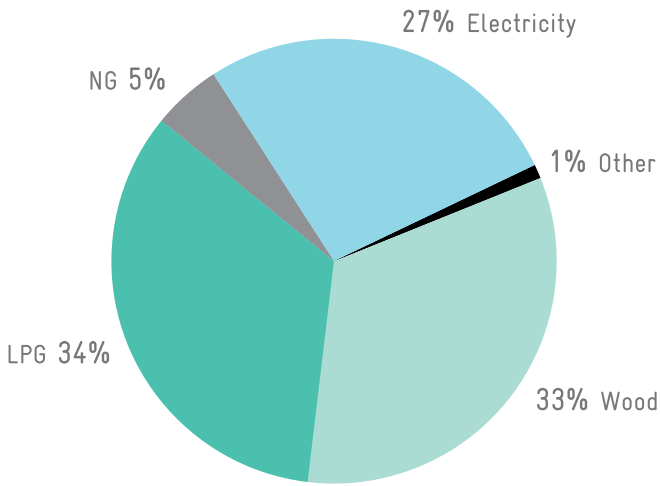
The second output from cogeneration, heat, has traditionally been discarded after the power generation but in the last decades has become a useful product due to the development of CHP. The most important market for heat is district heating, which consists of delivering low-temperature heat to consumers, mainly for space heating purposes (Blok, 2007). This can be explained because the implementation of CHP has occurred mainly in European and Northern American countries, where the space heating demand is rather high due to climatic conditions. Although space heating demand in Mexico is growing with increased wealth (IEA, 2013), the temperate and tropical climate of the country makes district heating of less demand than other countries. On the other hand, innovative solutions to use residual heat are evolving, for instance trigeneration, i.e. producing refrigerated air out of heat through an absorption chiller. This could highly contribute to reduce the impact of cooling systems, which are rapidly increasing in Mexico and in 2040, it is projected, up to 40% of households will own air conditioner devices (IEA, 2016b).

In any case, the main user of heat is the waste treatment plant itself. Thermophilic reactors require increasing the temperature of the feedstock to reach higher biogas yields. In addition, AD systems require dewatering the digestate, which in some cases is performed by the residual heat from the biogas combustions (Monson *et al.*, 2007). Altogether, a substantial part of the self-produced heat from the plants substitutes the purchase of energy from the grid leading to a displacement of conventional energy sources.

For scenario (2), injection to the NG network, biogas requires an upgrading to reach a very high content of methane. This is a destination for biogas in European countries and has grown in the last years. Due to the extreme similarity of biomethane and NG, this is a simple way to reduce the dependency of fossil gas without a high inversion in infrastructure changes as biomethane can be perfectly distributed through the NG pipelines. For many countries where there is an extensive gas grid, the injection of biomethane to the network has become the optimal solution for its distribution (Deublein & Steinhauser, 2011). The particular case of Mexico may nonetheless differ from this. In 2013, the amount of users connected to the NG distribution network was 2.5 million people (SENER, 2014).

Within the residential sector, one third of the energy consumption comes from wood (**FIGURE 10**), which is especially prevalent in rural areas. Another third corresponds to liquefied petroleum gas (LPG) (SENER, 2016a), a fuel that in the past replaced biomass in a very large portion of the country (IEA, 2016b) and plays the main role in residential energy supply in urban areas. Incrementally, the tendency is a substitution of LPG with NG, which nowadays accounts up to only 53 PJ, but the inclusion of new users of the NG network increases at an annual rate of 2.8% (SENER, 2014). Therefore, the deployment of the potential of biogas production from MSW into the NG grid can contribute to reach a decarbonization of residential energy consumption where other RES like wind, photovoltaic and solid biomass can not impact.

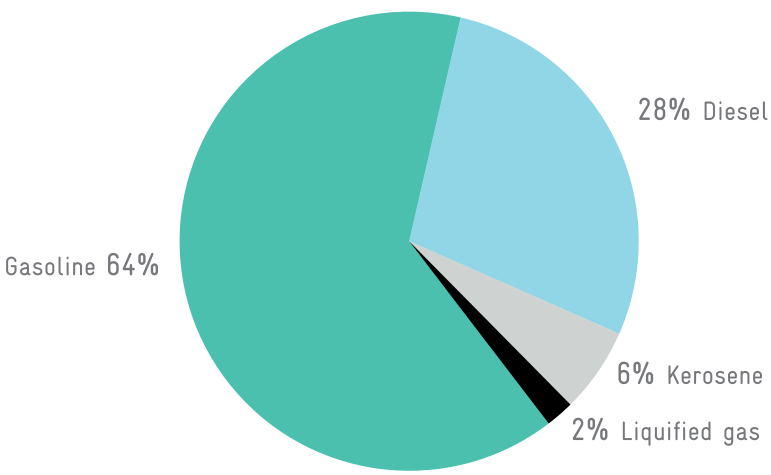
FIGURE 10 Residential energy consumption in Mexico



REFERENCE: SENER, 2016a.

The last scenario (3) corresponds to the application of biomethane for a vehicular use. In this context, transport is the sector with the highest energy consumption in Mexico: 2,362 PJ per annum and 46% of the total consumption. This sector is absolutely dominated by fossil energy sources in Mexico, specially with oil-derived fuels (**FIGURE 11**). This situation is similar in global terms, where transport makes up around 20% of the energy use and half of the mineral oil consumption, with the expectation that this will increase ca. 25% until 2050 (IEA, 2011).

FIGURE 11 Fuel consumption in the transport sector of Mexico



REFERENCE: SENER, 2016a.

Within the share of this energy use, more than 90% is consumed for road transportation. The use of gas is not very relevant, as its contribution accounts only to 55 PJ. Therefore, the penetration of compressed biomethane into this market is questionable, but the pressure to reduce the enormous amount of GHG emissions from the sector can make way to these technologies. Nowadays, the natural gas vehicles' market is fully matured in comparison with other potential sustainable solutions like electric vehicles (Wellinger *et al.*, 2013) and is therefore ready to compete with liquid fuels. Indeed, compressed natural gas for vehicles in Europe is typically 30-60 % cheaper than petrol or diesel (Callanan & Foley, 2011), which is a good incentive to expect a growth of this sort of technology, despite the infrastructural barriers needed, specially in fuel distribution.

Even though NG is also a fossil source, the carbon intensity per unit of energy in comparison with conventional fuels is lower and can contribute to mitigating the effects of the sector in the mid term. Furthermore, the easy substitution of NG with biomethane can lead to the inclusion of this biofuel in the market. Indeed, Deublein & Steinhauser (2011) stated than this use is generally less problematic and cheaper than feeding the biomethane into the NG network.

The use of biofuels is now experiencing an increase in the transport sector. It is expected that the total demand will be 27% of the fuels used in the sector in 2050 (Eisentraut *et al.*, 2011). Bioethanol and biodiesel are the most prominent among bioenergy fuels, but the controversy of its environmental impact caused by the use of land and the competition with food crops is one of the barriers that can inhibit its market growth in Mexico (Cruzado *et al.*, 2017). In that sense, second generation fuels like those derived from lignocellulosic biomass and biogas from municipal waste treatment are not constrained by this factor and this is, therefore, an advantage for their irruption in the market.

One of the main examples in the world about the use of biomethane in the transport sector is Sweden: its use has exceeded the use of NG and nowadays represents 65% of the gas used in transport (Börjesson & Mattiasson, 2007; Callanan & Foley, 2011). Moreover, the conversion of vehicles fueled by NG to biomethane has been proven to be cost-effective (Willis *et al.*, 2012). The incentive of reducing the costs from fuels, together with the aim of reducing the environmental impact, made several municipal administrations implement circular systems in the waste management. This means using the biowaste to generate biogas, upgrading this to biomethane and then using it to feed waste collection trucks. The advantage is not only the reduction of the GHG emissions, but the exponential reduction of expenditure in costs and the tax incentive of self-consumption for the company. One example is Berlin, where by treating the SS-OFMSW (ca. 6% of the total generated MSW), they are able to supply 150 trucks, half of the total fleet, and even produce heat and power for the demand of the waste treatment plant (EBA, 2016). This allows the company to displace the amount of 2.5 million litres of diesel every year (Renewable Energy Magazine, 2011).

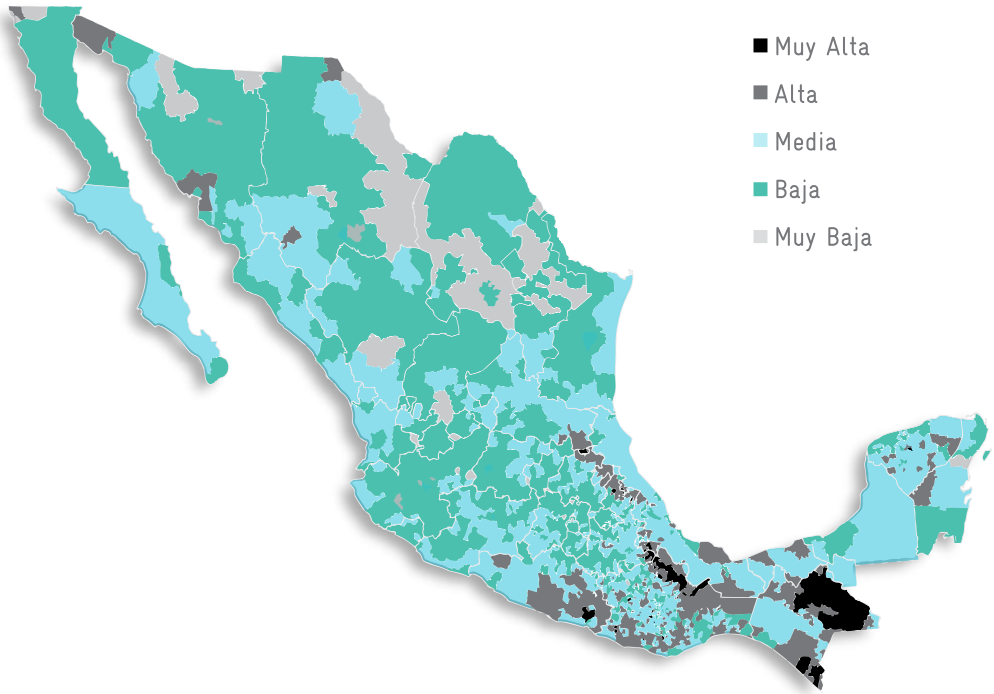
All in all, the energy output from anaerobically digesting the MSW can contribute to increasing the production of bioenergy for the country. Although the potential has been assessed separately, the combination of several uses for the biogas is also possible and even recommended. The cogeneration of heat and power from part of the biogas produced to fulfil the energy needs of the treatment plant can drive to a model of self-supply. Similarly, the retrofit of waste collection trucks to be fueled by compressed biomethane can greatly reduce the fuel costs of the waste management companies. Ultimately, the possibility to sell biomethane or power to the grid is very attractive in order to increase the revenues from waste management. The model implemented will depend on economic assessments of managers evaluating the pay-offs in order to have the highest impact on reducing tariffs.

5.2 Mitigation potential

Mexico is ranked 13th in the world in terms of highest emissions of anthropogenic GHG and second in Latin America after Brazil (CDIAC, 2014). The total emissions reached 665 Mt $CO_{2\text{-eq}}$ in 2013, according to the last national GHG emissions inventory published (INECC, 2015). In population terms, the annual emissions from Mexicans were 3.6 t $CO_{2\text{-eq}}$ per capita, which is lower than the average for OECD countries (9.4 t) and globally (4.5 t) (IEA, 2016b).

The emission of GHG to the atmosphere is directly linked with global warming and climate change. Mexico, due to its geographical and social conditions, is highly vulnerable to climate change, especially droughts, tropical storms and hurricanes. Losses derived from climate change have been estimated as 2.5 million people being affected and a cost of 16 billion euros in the period 2001 – 2013 (SEMARNAT, 2015b). The map from **FIGURE 12** shows the distribution of vulnerability across the country, where the southern region is the most affected. The northern part is on average less affected, but it is at high risk of specific problems like a strong decrease of net primary productivity, according to indicators (IPCC, 2007).

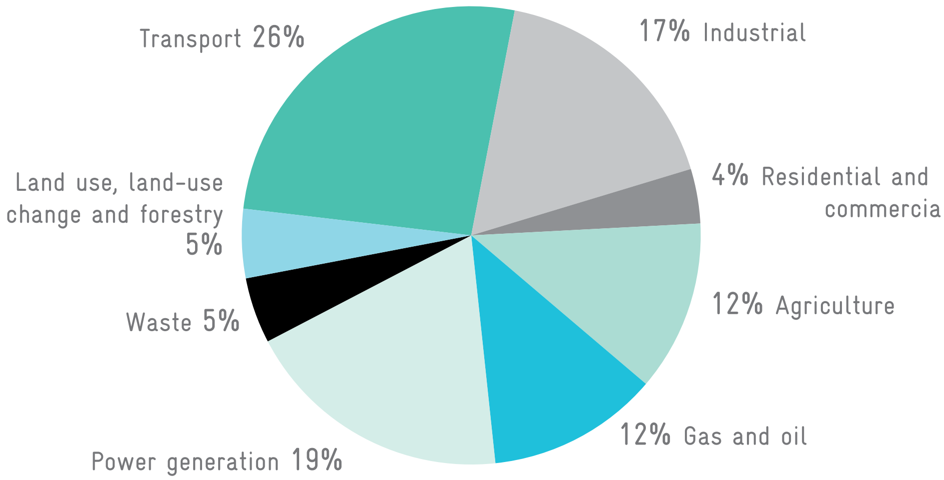
FIGURE 12 Vulnerability to climate change per municipality



REFERENCE: INECC, 2013.

The sources of GHG are multiple and includes several gases. Dioxide carbon is the main contributor with 75% of the total, but other gases with a higher global warming potential also play a role: CH^4 (19%) and N_2O (5%) (INECC, 2015). The distribution of the emissions among sectors is shown in **FIGURE 13**. As often in energy consumption, transport is the main sector. This is followed by electricity production and industries. Gas and oil production has a significant influence, due to the size of the petroleum industry in the country. Agriculture and farming contribute highly to the emissions as well, in particular because of the methane emissions from the enteric fermentation of livestock and manure management. The waste sector contributes 5% of the emissions and has 5 main sources: landfills, wastewater, biological treatment of organic waste (composting), incineration and open burning.

FIGURE 13 Distribution of the Mexican GHG emissions among sectors



REFERENCE: INECC, 2015.

The Fourth Assessment report of the IPCC (Bogner *et al.*, 2007) identifies the importance of the waste sector and its potential to reduce GHG emissions "through the conservation of raw materials, improved energy and resource efficiency and fossil fuel avoidance". Following this argument, the scenarios of direct mitigation from the production and use of biogas out MSW were calculated.

Among the three scenarios analyzed in this thesis, scenario (1) is the one with the highest impact on GHG mitigation: it has a potential of 1,912 kt $CO_{2\text{-eq}}$ per year. One factor influencing this result is the high efficiency of cogeneration systems, which allows the maximum benefit from combusting biogas. Other factors to explain this result are the avoidance of further energy losses and less technical difficulties in comparison with scenarios (2) and (3). In addition, the economic incentives of energy self-supply for waste treatments plants make CHP an attractive technology to consume the biogas. Furthermore, the high carbon intensity of the Mexican power grid is very influential on the mitigation potential. Currently, 79% of the primary energy to feed the electric system comes from fossil fuels: 57% natural gas, 11% oil and 11% coal (IEA, 2014). The use of biogas to produce electricity has a large niche for future implementation due to the importance of sustainable energy policies to increase the share of RES in the power system, as will be described in the following chapter.

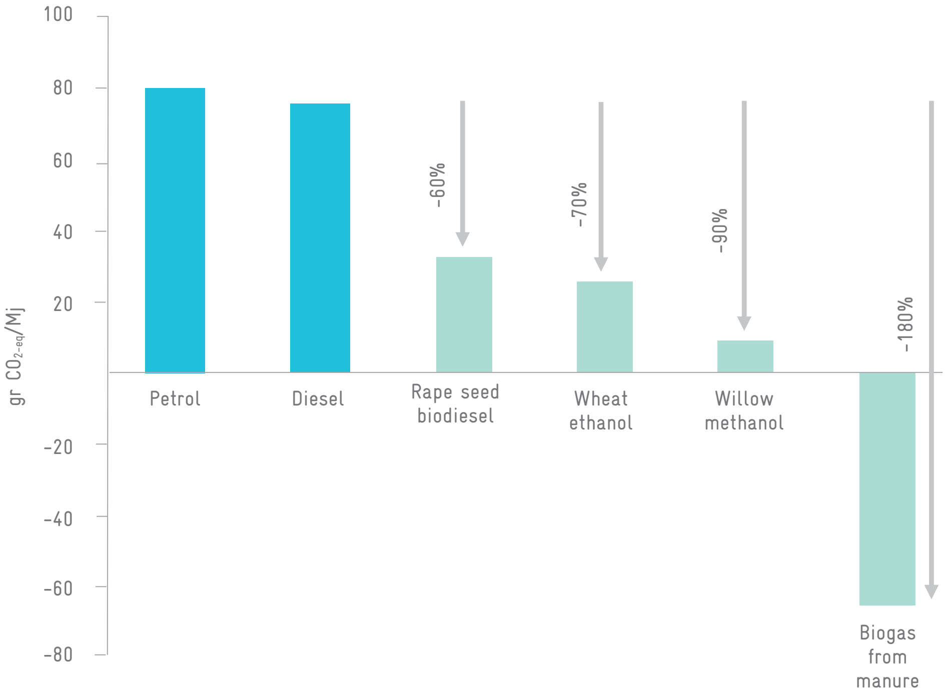
On the opposite side, scenario (2) has the lowest effect in mitigation terms: 1,441 kt $CO_{2\text{-eq}}$. Unlike scenario (1), the injection of the gas into the NG network requires a high consumption of energy during the upgrade of biogas to biomethane. Consequently, the resulting volume of NG displaced and the mitigation effect are lower. Moreover, the results are influenced by the efficiency values of the reference technology to assess the displacement of NG, which is the condensing boiler for this case study. The energy losses during conversion of chemical energy from CH_4 to thermal energy are extremely low. Of course these are good news in terms of energy savings, but it has a direct effect on the mitigation potential of alternatives to NG. Additionally, it must be mentioned that the carbon intensity of NG is lower than fossil fuels considered in the other scenarios. Altogether, these are the main explanatory factors of that result.

In any case, the relevance of substituting NG with RES in the residential sector must not be underestimated. The scenarios from IEA (2016b) about the energy consumption of Mexican buildings identify a growth of 80% for 2050 in comparison with 2010, meaning GHG emissions that will likely reach 124 Mt $CO_{2\text{-eq}}$. The alternative scenario, in which measures to not overpass the increase of 2°C in global temperature are considered, the emissions of buildings is expected to decrease to 31 Mt for 2050. To achieve that, water heating is crucial: it represented 45% of the residential energy consumption in 2010 and also represents 45% of total energy savings of the 2°C-scenario. Therefore, biomethane supply to buildings could contribute to decrease the residential carbon footprint.

The results from scenario (3) reveal a direct mitigation potential of 1,816 kt $CO_{2\text{-eq}}$ per year when using the upgraded and compressed biogas for supplying vehicles, which is energetically equivalent to 700 million litres of diesel. On the one hand, the mitigation potential is slightly lower than in the CHP scenario, but on the other, vehicle fuel does not face the disadvantage of a low demand of the heat output.

In recent years, the production of biofuels in energy crops has exponentially grown with the aim of substituting fossil fuels in transportation. The effect on GHG emissions reduction is clear, but life-cycle assessments have shown that these biofuels are not totally carbon-neutral. Two main reasons explain this: the demand of fossil fuels for cultivation and the production of chemical fertilizers. Additionally, the application of these fertilizers on land can lead to the emission of N_2O, a GHG with a global warming potential 265 times higher than CO_2. Often these emissions exceed those from the use of fossil fuels to cultivate the bioenergy crops, according to the report of Börjesson & Mattiasson (2007), who made a life-cycle assessment of the mitigation potential of several biofuels (**FIGURE 14**). The results concluded that the substitution of fossil fuels with second generation fuels in vehicles has a much stronger impact in reducing the emissions and even to achieve a net reduction of emissions by the use of biogas.

FIGURE 14 **Life-cycle GHG emissions from using vehicles powered by fossil fuels and biofuels. In percentage: average GHG mitigation by replacing biofuels with fossil fuels**



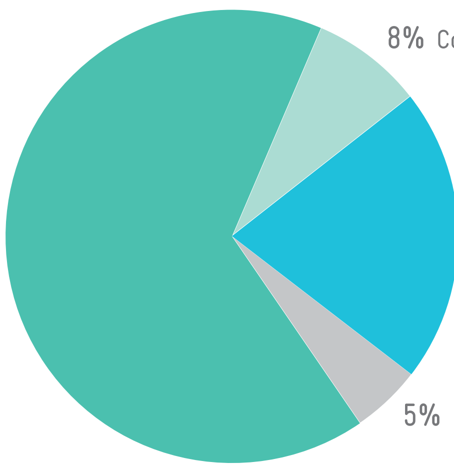
REFERENCE: Börjesson & Mattiasson, 2007.

In short, the production of biogas to substitute fossil fuels in transportation has a low impact on the sector due to the limited amount of fuel that can be obtained from digesting MSW, in contrast with the enormous energy demand from the sector. But in any case, the use of biomethane in vehicles can contribute to diversifying the energy consumption and ease the impact on climate of the transportation sector.

The global GHG emissions from the waste sector are estimated at ca. 1,500 Mt CO_{2-eq} per year and around 4% of the total anthropogenic GHG. Out of it, methane emissions from solid waste disposal sites are the main source within the sector, in a range of 700-800 Mt CO_{2-eq} every year (Bogner *et al.*, 2008; IPCC, 2006). Indeed, landfill emissions belong to the group of dominant anthropogenic CH_4 global sources with other relevant sectors as cattle, fossil fuels extraction and rice paddy agriculture (IPCC, 2013). Prospective scenarios indicate that the amount of CO_{2-eq} emitted by landfills can increase to 960 Mt in 2030 (EPA, 2012).

In Mexico, landfilling is the destination for almost all MSW. The available data about final disposal can slightly vary, but in any case the majority of waste will end up in sanitary landfills (**FIGURE 15**). Nonetheless, from the 196 sanitary landfills in the country, only 35% of them fulfil the environmental regulations (CFE, 2012). Furthermore, up to 29% of MSW is disposed in dumpsites. An assessment from the World Bank concluded that only 15% of the MSW generated in Mexico is adequately disposed (UNEP, 2005).

FIGURE 15 **Final disposal of MSW in Mexico**



* The percentage of recycling corresponds to the materials recovered at final disposal sites, excluding those separated at source in households and collection vehicles.
REFERENCE: SEMARNAT, 2013a.

The Mexican regulation does not require implementation of a biological treatment to reduce the volume of biowaste disposed, leading to its decomposition in anoxic conditions in disposal sites which generates methane. This could be partially solved by sealing the sites and collecting the biogas to be flared, but nowadays there are only a few projects with gas capture systems and therefore methane is released to the atmosphere.

Energy recovery can contribute to reduce the demand of fossil fuels, at the same time as a significant reduction in emissions from waste disposal occurs (IPCC, 2014b). This is what the results from this thesis highlight: the AD of the OFMSW leads to avoiding the emission of 12,435 kt CO_{2-eq} every year. This represents 64% of the emissions from landfilling. This high result can be explained by the fact that the waste fractions potentially treated in reactors (i.e. organics suitable for AD) are 46.2% of the total MSW. Meanwhile, those organics not considered for the biogas potential, and therefore assumed as being disposed and continuing to emit methane, represent 21.6% of the MSW. Furthermore, the fraction used for the case study includes those materials with the highest methane yield, both in reactors and landfills, generating in this way a multiplier effect.

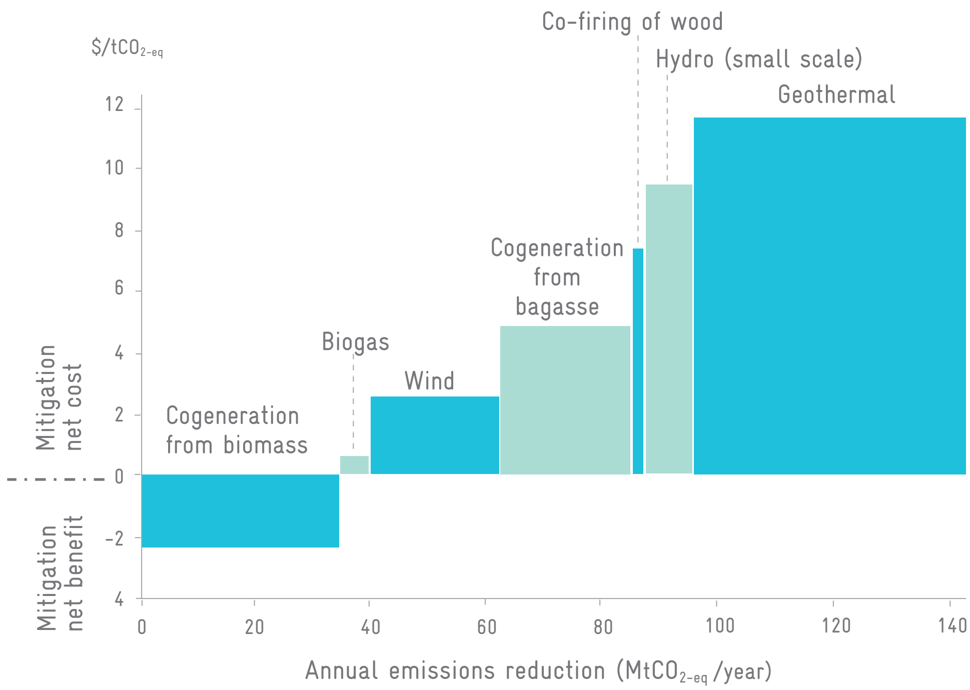
Nevertheless, the AD carried out in reactors does not mean that all organic material is transformed into biogas. A relevant amount of the biowaste input remains in a solid phase on the bottom of the reactors: the digestate. This material, after an additional aerobic treatment (composting), is fully stabilized and can be disposed. Therefore, in order to achieve an accurate result for the research about net mitigation effects, this fact is taken into account for the final potential. For the separately collected OFMSW, the resulting compost can be applied on land due to the low amount of impurities. This means that the emissions are much lower than disposing it in landfills. Unfortunately, the digestate from treating rMSW has too many impurities to be applied on land and therefore the CLO must be disposed underground. The total emissions from digestate management are 693 kt $CO_{2\text{-eq}}$. From this amount, 667 kt correspond to the emissions from the disposition of CLO and 26 kt from the land application of compost from SS-OFMSW digestion. This big difference shows the importance of biowaste segregation in households and commerce to reduce the impact on climate, plus the advantage of recovering nutrients from waste to grow new biomass.

Furthermore, the GHG emissions from digestate land use could even be lower. As this works as a soil conditioner and fertilizer, it is complicated to assess the indirect downstream emissions, which depend on the soil type, climatic conditions and crop rotation. This means that the emissions from this action ranges from low emission rates to even emission savings due to the substitution of fertilizers and the carbon sequestration in the soil (Møller *et al.*,2009).

To finish this chapter, it is considered pertinent to discuss the economic incentive to carry out successful mitigation projects. The global waste market size is estimated to be around 410 billion dollars per year, plus the hidden economy from the informal sector (Hyman *et al.*, 2013).

Marginal abatement cost curves (MACCs) assess several GHG mitigation measures with their costs. MACCs are a very helpful tool to achieve the higher impact with the lowest expenditure. The report from Johnson *et al.* (2009) assessed a large number of mitigation measures and the costs per unit of $CO_{2\text{-eq}}$ mitigated for the period 2009-2030. Some of them are shown in **FIGURE 16**. Among them, biogas production is slightly over the X axes: only +0.6 US-dollar ($) per ton of $CO_{2\text{-eq}}$. This is considered as a mitigation measure only by the displacement of fossil fuels and omitting the indirect mitigation. Notwithstanding, biogas projects are more profitable than other RES like wind, hydro and geothermal. This factor is of high relevance to promote AD projects, because it is stated in the Mexican law that the national mitigation policies must privilege those actions with the lowest cost, as it will be discussed in the next chapter.

FIGURE 16 MACCs of measures to reduce the carbon intensity of the electricity sector in Mexico



REFERENCE: Johnson et al., 2009.

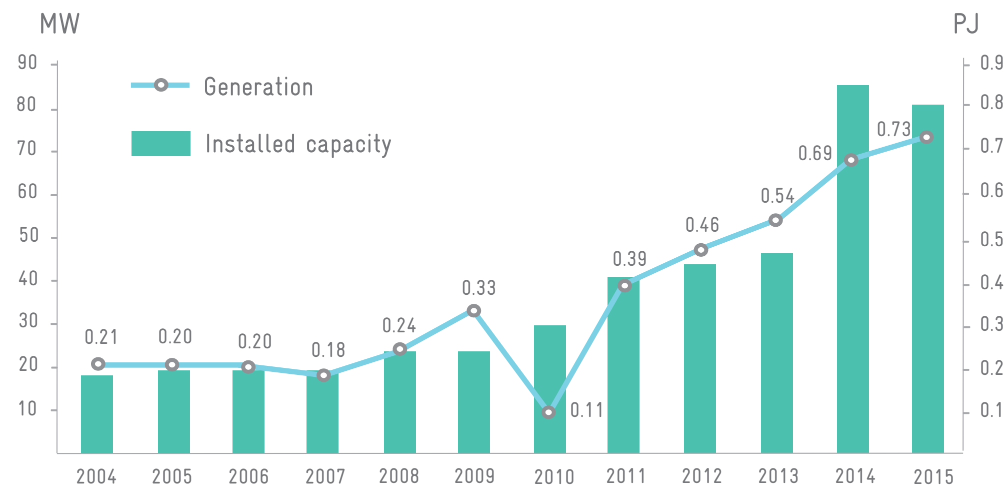
5.3 Energy commitments

The IEA, in its New Policies Scenario, forecasts an increase of the share of RES for the final energy consumption of Mexico. In that scenario, the consumption will increase to 5,360 PJ in 2020 and 6,530 PJ in 2040. The share of RES to the primary energy demand will increase to 19% and 31%, respectively. However, the contribution of bioenergy is expected to remain equal during the whole period in absolute terms and, therefore, decrease in the relative contribution to the energy system (IEA, 2016b).

To understand the targets of sustainable energy in Mexico, it is necessary to explain a few concepts. One of them is 'clean energy', a legally bound term that includes, not only RES, but also others like nuclear power, large hydropower plants, coal power plants and combined cycles with carbon capture and storage systems (Cámara de Diputados, 4 December 2015). The Electrical Industry Law considers the methane produced from waste treatment as a clean energy source (Cámara de Diputados, 11 August 2014) and the Secretariat of Energy assumes that the MSW can be used as an input to generate power as a RES (SENER, 2016b).

Historically, the production of biogas in Mexico has been directly connected with its combustion to generate power. During the last decade, it has grown in installed capacity and contribution to the electricity grid, generating a maximum of 0.73 PJ in 2015 (**FIGURE 17**). This has been enhanced by the Law for the Promotion and Development of Bioenergy, whose aim is to contribute to increase the production, commercialization and use of biofuels, including in that group to those derived from biomass coming from domestic activities, such as biowaste (Cámara de Diputados, 1 February 2008).

FIGURE 17 Installed capacity and generation of electricity from biogas in Mexico

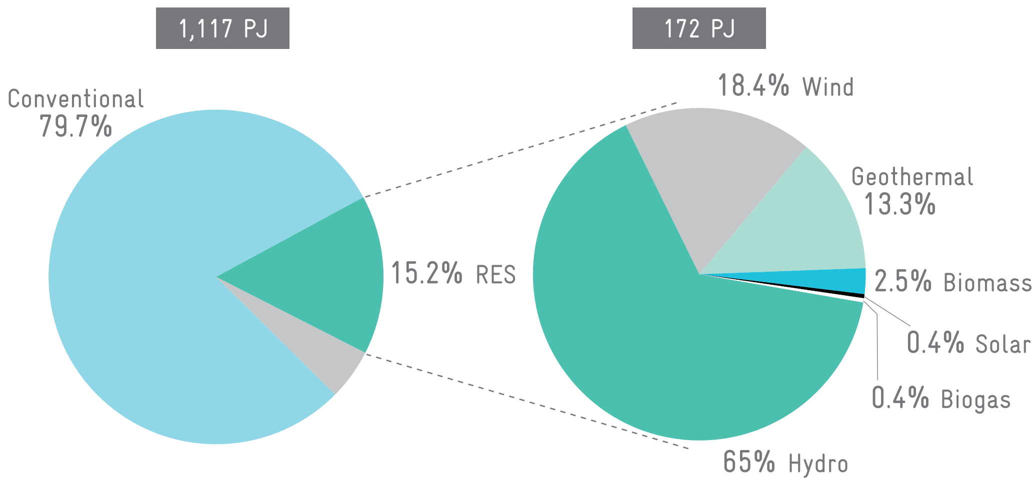


REFERENCE: SENER, 2016b.

Regarding the targets to develop sustainable energy sources, the main institutional instruments involved will be explained in the following lines. The Law for the Use of Renewable Energies and the Financing of the Energy Transition (LAERFTE) was approved to regulate the use of alternative energy sources for the power generation. This law stablished a target for 2024 to limit the maximum of 65% of fossil fuels in the generation of power, which must decrease to 60% in 2035 and 50% in 2050 (Cámara de Diputados, 12 January 2012). In order to develop this law, the Special Program for the Use of Renewable Energy (PEAER) was designed with the aim of introducing public policies to reach those targets (SENER, 2016b). This program analyses three possible scenarios to the penetration of RES into the power grid according to parameters like the economic growth. The intermediate scenario forecasts an increase of 20,545 MW of RES installed capacity added to the power supply in 2026. From this additional potential, bioenergy would contribute with 422 MW to the category of self-supply and 345 MW for the distributed generation.

Subsequently, the approval of the Law for the Energy Transition (LTE) took place (Cámara de Diputados, 24 December 2015). This implied that the LAERFTE was to be repealed in order to introduce a new program. The aim of the LTE is to promote clean energies, whose share in 2015 was slightly over 20% for power generation (**FIGURE 18**). Within this group, RES ranged three fourths of it, and bioenergy was a small contributor with the bagasse from the sugarcane industry and the biogas.

FIGURE 18 Share of power generation in Mexico in 2015

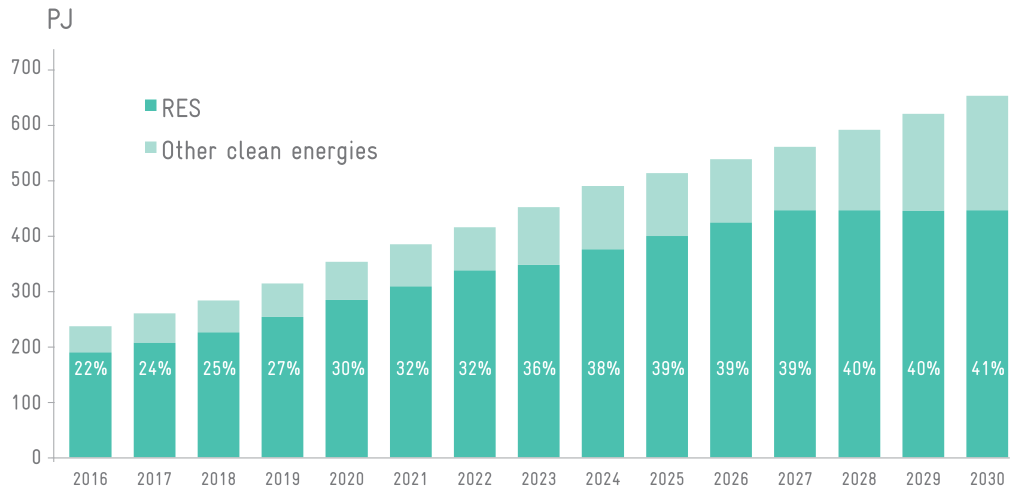


REFERENCE: SENER, 2016a.

The LTE states that the share of clean energies to power supply must reach the targets of 25% in 2018, 30% in 2021, 35% in 2024. With this aim, the law implies the development of three specific planning tools. One of them is the strategy, which adds to the middle-term targets mentioned before, of an increase in power supply from clean energies to 37.7% in 2030 and 50% in 2050. These long-run targets are to commit the targets to reduce GHG emissions stablished in the General Law of Climate Change (LGCC). The LTE assigned to the Secretariat of Energy to elaborate a new program to plan the national policies to implement the strategy actions and ensure their economic viability: The Special Program for the Energy Transition (PETE).

One of the most relevant tools to carry out this increase in the share of clean energies within the grid is the Transition Strategy to Promote the Use of Cleaner Technologies and Fuels (CONUEE, 2016). It includes the assessment of national energy policies to identify barriers and opportunities and to adopt correction means for the indicators, with the aim of reaching the targets and guaranteeing security in the power supply to satisfy its demand (SENER, 2016b). It also defines the pathway to achieve the goals in a scenario where all energy sources are disaggregated. The result is that the power generation will keep growing in the period 2016-2030, reaching almost 1600 PJ at the end of that lapse of time. The share of clean energies surpasses the agreed 37.7% (**FIGURE 19**) but bioenergy plays a minor role in this. It remains invariable across the whole period, despite the fact that bioenergy has been able to fulfil those goals set in previous renewable energy programs in contrast with other sources like geothermal and wind (SENER, 2012).

FIGURE 19 Contribution of clean energies to the gross electricity generation in PJ and percentage



REFERENCE: CONUEE, 2016.

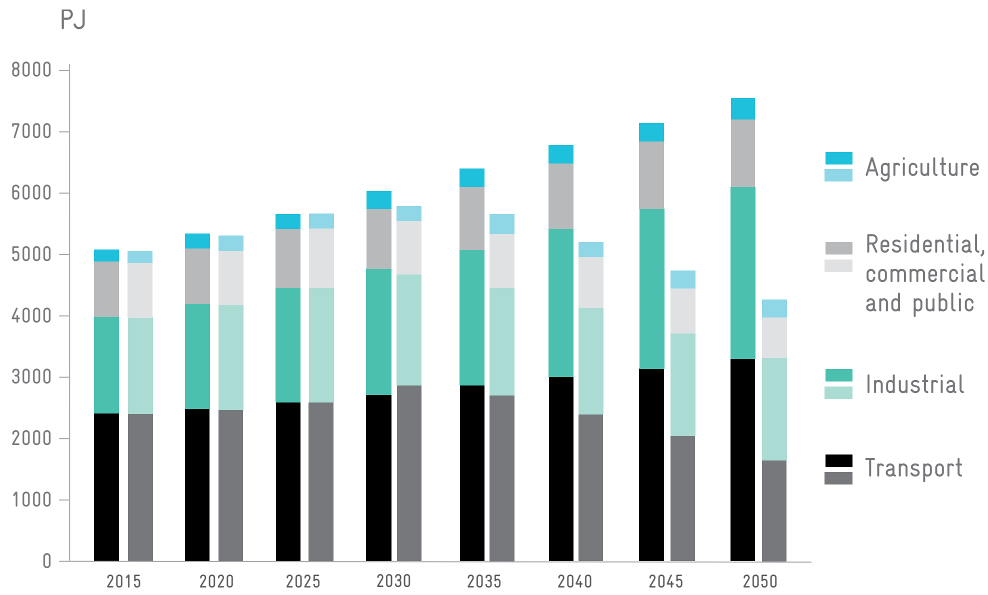
The scenario forecasts that the electricity generation will continue increasing to reach ca. 2,500 PJ in 2050, where 50% correspond to clean energies. If these growth patterns would be equivalent for biogas production, based on the current situation, the contribution of this energy source could reach 2 PJ in 2030 and 4 PJ in 2050. A comparison could be made to the power potential resulting from cogeneration from this case study: it is 13 times higher than the current biogas power output and a proper deployment of those 9.8 PJ could cover this hypothetical increase in biogas demand for 2050.

Clean power is one of the two parts of the LTE. The second corresponds to increasing the efficiency of the whole energy system. For this approach, the targets assumed by law seeks to decrease 40% of the final energy consumption of the country by the year 2050. The pathway is settled in an average consumption reduction of 1.9% per year until 2030 and 3.7% in the following years until 2050. This target implies the promotion of current initiatives to stabilize the consumption growth in the short term. For the long term, structural changes will be required in all sectors (CONUEE, 2016).

The means carried out to reach this goal are distributed among sectors in different proportions (**FIGURE 20**). Residential and commercial consumption is expected to decrease by long renovation cycles of buildings that will make them more efficient, focusing on energy savings from illumination, water heating and space conditioning. For these last factors, some of the proposals given in this report, like cogeneration, could contribute to increase the efficiency of heat generation. The transport sector is the key element for the strategy, not only because it is the main consumer, but also because it is the one experimenting the highest growth: 47% between 2000-2015. In terms of fuels, gasoline and diesel consumption has increased 50% and 51% in the same period, respectively. The strategy to decrease the consumption of this sector points out to promote public transportation and electric vehicles.

FIGURE 20 **Final energy consumption per sector in Mexico**

Baseline (blue) and energy-transition scenario (green)



REFERENCE: CONUEE, 2016.

5.4 Mitigation commitments

Scenarios analyzed by IPCC (2011) estimate that bioenergy must contribute to the global annual primary energy supply with 90-155 EJ in 2050 in order to keep global temperature increase below 2ºC. In Latin America this amount needs to be 10-12 EJ/year. For both cases, bioenergy will be the main RES.

The IPCC Working Group III in the Fourth Assessment Report in the review of GHG mitigation models for 2030 (Fisher *et al.*, 2007) and the results are shown in **TABLE 7**. The highest share of the sector for the global emissions reduction occurs in the model developed by Rao & Riahi (2006), where certain assumptions were made. For instance, an increase of recycling and incineration rates, which leads to a decrease of the waste landfilled, plus an increase in the effectiveness of composting in developing countries and the capture and energy utilization of landfill gas.

TABLE 7 **GHG mitigation models for waste management for 2030**

Model	Emissions reduction for 2030 (Mt $CO_{2\text{-eq}}$)	Share in global emissions reduction	Source
MiniCAM	340 – 768	2.9 – 3.2%	Smith & Wigley (2006)
SGM	837	6.0%	Fawcett & Sands (2006)
IMAGE 2.2	677	5.9%	Van Vuuren et al. (2006)
IMAGE 2.3	1,041 – 1,105	4.6 – 8%	Van Vuuren et al. (2007)
MESSAGE	896	6.0 – 20.2%	Rao & Riahi (2006)

From landfill gas, the methane emissions are modeled to reach 1,200-1,500 Mt in 2030 and 2,900 Mt in 2050 (UNEP, 2010; EPA, 2011). The projections from Monni *et al*. (2006) about the implementation of landfill gas capture shows that GHG global emissions would be 1,200 Mt $CO_{2\text{-eq}}$ in 2030 and 2,100 in 2050. Additionally, the use of this gas to generate power could displace fossil fuels from the grid and add a mitigation of 126 and 251 Mt $CO_{2\text{-eq}}$ in 2030 and 2050, respectively.

The LGCC came into force with the aim "to regulate, promote and make possible the instrumentation of national policies about climate change and to incorporate adaptation and mitigation actions with a long-term, systemic, decentralized, participative and integrated approach" (Cámara de Diputados, 6 June 2012). The targets assumed in the document are the following:

- 2020 → 30% reduction of GHG emissions compared to the baseline.
- 2024 → increase the contribution of clean energies for power generation to a 35% of the share.
- 2050 → 50% reduction of GHG emissions compared to the year 2000.

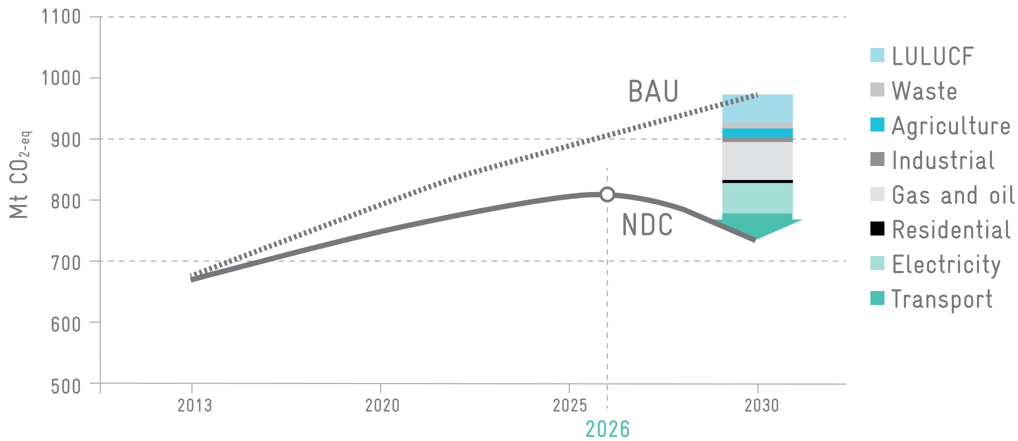
The LGCC notes that these targets are considered "aspirational". This means that the targets will be achieved if the international situation and the developed countries provide mechanisms of financial and technical support to Mexico. This is a similar concept to what will be called "conditional measures" in the next paragraphs. Within the law, it is specified that a strategy to fulfil the mitigation targets must be developed: The National Strategy on Climate Change (ENCC). This instrument carries out a diagnosis of the country regarding climate change that is used to define the long-term pathway and strategies for mitigation and adaptation. Consequently, the ENCC fixes the milestones for the following 10, 20 and 40 years ahead to guide the policies at all institutional levels. The criteria prioritizes those mitigation actions with the most effective marginal abatement cost, with the highest potential and environmental and social co-benefits. Among those actions, landfill emissions and biogas utilization are on the top of the priority list.

The measures to carry out in the period 2014-2018 were recorded in the Special Program of Climate Change (PECC) (SEMARNAT, 2014) as a result of a collaborative work among those Government Secretaries involved. This program consists on 5 targets and several strategies and lines of actions to achieve an annual reduction in the GHG emissions of 83.2 Mt $CO_{2\text{-eq}}$ in 2018. In the PECC, among others, there is a target for 2018 that municipalities will develop and construct infrastructures for the MSW management that do not emit methane in those with more than 50,000 inhabitants and, where economically feasible, they will implement technologies to generate power from that methane. In this way, the energetic utilization of waste is stated as one specific aim of the mitigation public policies.

In 2015, the Government presented the intended Nationally Determined Contributions (NDC), which were the basis for the international commitments from Mexico during the Climate Change Conference in Paris. It pursues to keep global temperature increase below 2°C (Mexican Government, 2016). The NDC of Mexico are composed of two types of measures: unconditional and conditional. The unconditional correspond to the set of actions and targets that the country will implement with its own resources, meanwhile the conditional measures could be implemented if a new multilateral climate regime is established for Mexico, where the country could obtain additional resources and mechanisms of technology transfer (SEMARNAT, 2015b).

The unconditional targets were based on those stablished by the LGCC, with the addition of a new horizon for 2030: a reduction of 22% in GHG emissions compared to the baseline (**FIGURE 21** & **ANNEX B**). The mitigation route implies a lower growth than the business as usual scenario (BAU) until 2026. This year is the inflection point when the net emissions start to decrease until the targets for 2030. The result from reaching this goal is a reduction of ca. 40% of the carbon intensity of the Mexican economy along that period of time.

FIGURE 21 **Mitigation targets from the unconditional NDC in comparison to the baseline, distributed among sectors**



REFERENCE: SEMARNAT, 2015b.

All GHG emissions from WtE, where the waste is used directly as fuel or converted into it like the biogas from this case study, need to be reported under the energy sector (IPCC, 2006). In that sense, the mitigation effects of each biogas use scenario must be framed for the commitment of different targets. For scenario (1), the energy output could contribute 1,245 kt CO_{2-eq} to the electricity generation targets, meanwhile the heat output could apply to the targets from the residential and commercial sector with 667 kt CO_{2-eq}. The goal for this sector was fixed in a reduction of 5,000 kt CO_{2-eq} and, therefore, the impact of heat from cogeneration could be significant. In case the biogas is used to feed the NG network, as stated in scenario (2), mitigation reaches 1,441 kt CO_{2-eq} that could cover 29% of this sector's targets if the potential is fully deployed. The implementation of scenario (3) leads to a direct mitigation of 1,816 kt CO_{2-eq} by the use of compressed biomethane into vehicles[3]. This should be applied to the transport sector, which it is expected to reduce its emissions by 18% for 2030, in contrast with the overall target of 22% for all the unconditional NDC. Biomethane use as transport fuel goes in line with the declared aim of increasing the Mexican vehicle fleet fueled by NG and clean fuels (SEMARNAT, 2015b).

The indirect mitigation potential from avoiding landfill gas emissions is without a doubt the most important of this project, being 6-8 times larger than the mitigation from the use of biogas. If the potential would be entirely deployed, 11,742 kt CO_{2-eq} could be mitigated. The targets from conditional contributions in the waste sector were determined as 14,000 kt CO_{2-eq}. The measures to achieve this target are reaching zero methane emissions from sanitary landfills and zero open burning, which represent 96% and 4% of the sector goal, respectively. Therefore, if the mitigation potential estimated here would be put into effect, 87% of the target for landfills would be covered by the AD of MSW.

Additionally, the conditional contributions from the NDC also tackle the emissions from landfills for 2030: it states the target of implementing methane capture systems and power generation from it in all municipalities with more than 50,000 inhabitants. Nonetheless, this target does not specify the quantity of emissions reduction from applying the measure. This conditional contribution, like the others, is dependent on global arrangements about the price of carbon credits, border taxes, technical cooperation, international funds for projects and technology transfers (SEMARNAT, 2015b). In case all conditional contributions would take place, the emissions reduction would be 36% compared to the BAU scenario.

[3] Mitigation effects from scenarios (2) and (3) need to discount the emission of 15 kt CO_{2-eq} during the biogas upgrading process.

5.5 Review of policies for the potential deployment

The failure of WtE projects in Mexico has been discussed in the literature (CFE, 2012). Some of the identified factors responsible for this situation are the lack of participation from the community, lack of planning and integration of stakeholders, as well as lack of experts and investment. With the aim of tackling these barriers, this chapter tries to summarize the existing policy mechanisms in Mexico and in other countries that can be the basis for promoting the WtE technologies and deploying the potential to produce biogas out of MSW.

To start with, the Transition Strategy to Promote the Use of Cleaner Technologies and Fuels mentioned in chapter 5.3 fixes lines of action to achieve the targets for clean energies. They are aggregated in five categories: regulation, institutions, capacity development, funding and research and innovation. For the specific case of WtE, it is specified that the legal frameworks must be harmonized to trigger the energetic use of MSW. Furthermore, for the category of funding, it is stated that there must be a facilitation for sustainable bioenergy producers to access funds. Specifically, it will be needed to assess the establishment of funding programs and incentives for the municipalities and the private sector to carry out projects for the energy recovery of MSW.

Similarly, the Law for the Promotion and Development of Bioenergy enhances the production of biofuels that do not put at risk the food security and sovereignty of the country. In that way, second generation fuels like biogas can expand in the market under the policies and programs boosted to commit the law (Cámara de los Diputados, 1 February 2008). In line with this, Masera *et al*. (2011) points out in the report *Bioenergy in Mexico* the need to carry out intersectoral programs among administrations to coordinate the development of those programs, as well as creating certification norms for biofuels.

Moreover, climate policies do not only fix mitigation targets, but also define pathways to meet them with concrete actions. Those relevant to deploy the technical potential for biogas production are summarized in **TABLE 8**, with the specific scenario affected by each measure. For instance, the ENCC clearly specifies the need to promote alternative technologies to avoid methane emissions from landfills in big municipalities. In connection with it, the PECC explicitly mentions second generation biofuels as a measure to reduce GHG emissions and the need to construct biodigesters to improve the MSW management. Furthermore, other actions are linked with the expansion of NG in buildings and transportation. Despite these contributing to the use of fossil gas, it influences the use of biomethane once the regulation and infrastructure allow its injection in the network and the gradual displacement of NG.

In the international context, many policies have enhanced the use of biogas as an energy source. One case is the Renewable Energy Directive from the European Union (EU), that sets quotas for the use of biofuels (EC, 2009). These have to fulfil certain parameters for sustainability during its production and with the GHG mitigation potential. The aim is to increase the share of bioenergy and especially boost second generation fuels whose impact in reducing GHG emissions is higher. Additionally, waste management policies are closely related to climate policies and integrated into them in places like Japan or the EU (Bogner *et al*., 2008). The implementation of the EU landfill directive 1999/31/EC (EU, 1999) imposed severe limitations to biodegradable waste landfilling, triggering the development of alternative technologies to reduce the organic load of MSW prior its final disposal. Among them anaerobic digestion, whose projects grew exponentially to treat all kind of organic wastes during the following years. For instance, in Germany about 1.2 million tons of biowaste are treated annually in digestion facilities (Daniel-Gromke *et al*., 2015).

The application of the directive was in order to reduce the landfill methane emissions from 69 to 32 Mt $CO_{2\text{-eq}}$ in the period 1990 – 2007 (ISWA, 2009). In other cases, like India, the law established the obligation of waste separation at source and the prohibition of disposing organic waste without a previous appropriate biological treatment (Vögeli & Zurbrügg, 2008).

The alternatives to reduce the emissions from final disposal sites can be grouped into two categories: methane capture and biowaste diversion from landfills. Both are positive to mitigate the emissions, but the impacts on sustainability are not equal: Bogner *et al*. (2007) assessed the impacts on the three approaches of sustainable development, highlighting the positive social and economic impacts of AD and landfill gas collection projects. However, the negative effects on the environment from landfills were also identified, even if the gas is collected: an improper management of sites leads to water and air pollution.

TABLE 8 Actions from climate policies to enhance biogas production from MSW

Policy instrument	Category	Action	Biogas use scenarios			Indirect mitigation from MSW disposal
			(1)	(2)	(3)	
ENCC	Milestones 10 years	Socio-economic schemes to incentive clean energies	X	X	X	
		Implementation of infrastructures for MSW management to avoid CH_4 emissions in municipalities bigger than 50,000 inhabitants				X
		Incentives and adoption of sustainable transportation systems in public and private sector			X	
	Milestones 20 years	Utilization of clean energies in the residential sector	X	X		
		Urban development plans include sustainable transportation systems with low emissions			X	
PECC	Goal #3	Promote diversification of the power grid with clean energies through public and private investment	X			
		Displace diesel and fuel oil with lower carbon intensity sources			X	
		Implementation of pilot projects to produce biofuels from waste	X	X	X	
		Development of programs to use biofuels in transport sector, thermal energy and power generation	X	X	X	
		Develop policies and measures to ensure the provision of natural gas		X		
	Goal #4	Sealing of disposal sites for MSW for methane capture				X
		Promote an appropriate MSW management, including the construction of biodigesters	X	X	X	X
		Promote and regulate the use of vehicular NG			X	

5.6 CONTRIBUTION AND LIMITATION OF RESULTS

The aim of this chapter is to provide a self-critical view of the research and to highlight the theoretical implications and contribution to literature.

The methodology of this research has focused on identifying the existing barriers for WtE projects. This step was the most time consuming due to the complexity of the waste management system in general, and the Mexican system in particular. Furthermore, the availability of technical data about biogas production was scarce for some issues. One of them was the biogas yield from the AD of rMSW: the fact that most part of the organic waste globally is not separated at source and so the amount of projects to produce biogas from this feedstock are not so abundant nor well documented. The given values about biogas yield from rMSW could seem slightly optimistic in contrast to those from applied to the SS-OFMSW. Nonetheless, after an exhaustive search, it can be stated that it could be the other way around: given values from the experience in Berlin (Kanning & Ketelsen, 2015) applied to the SS-OFMSW stream seem to be very conservative. Meanwhile, the data from many other AD projects to treat SS-OFMSW usually surpasses the 100 m^3 biogas/ton of waste: in Berlin this was only 91. The main reason to choose the report from Kanning & Ketelsen (2015) was the exhaustive analysis made for the whole AD process and the meticulous provision of information.

Moreover, the assumption of the amount of MSW that is segregated at source implied a deliberation about which should be the threshold applied to. Finally, the separation rate from Mexico City was used. This could be assumed to be lower, as other cities in the country do not pay so much attention to segregating biowaste. Alternatively, it could have been even higher, alluding to the fact that this is a technical potential and therefore the conditions do not necessarily apply to a current status.

With the aim of gaining insight into a critical assessment of this assumption, a sensitivity analysis was developed. This tool can be applied to the uncertainty of not improving the separation of MSW at source and checks how this impacts the final result. Therefore, the assumption in the sensitivity analysis shifts from a collection of 48% SS-OFMSW to 0% (i.e. all MSW is mixed). This has a direct impact on the emissions from the digestate handling, as all will be landfilled with no application on land: they would grow from the current 693 to 1,283 kt $CO_{2\text{-eq}}$. Nonetheless, the impact on the overall indirect GHG emissions is low: only 5% less GHG mitigated. The emissions reduction target for the waste sector in 2030 in case the potential would be deployed changes from 87% to 83% achievement. Therefore, regardless of the importance of waste segregation for a sustainable management, this is not a crucial issue for this research.

Regarding energy consumption of the process, some values were applied for the steps after the biogas generation (e.g. upgrading and gas compression). The energy consumption upstream (collection and pretreatment) was not taken into account. The underlying reason was the specificity of each locality to manage its waste: the availability of a MBT scheme in the municipality, the extension of the treatment provided and the energy demanded, the fuel consumption of collection vehicles, regarding the road status and distances done, etc. If all these factors were accounted, the time needed for this research would require an extension of time and resources. Finally, it was assumed that all that energy consumption during the pretreatment corresponds to a service provision for society that is/would be made also in the situation where biogas is not produced (e.g. by composting as a biological treatment instead of AD).

Capacity factors for the treatment and energy plants were also not taken into account. These factors are normally expressed in % or hours per year that the facilities can work at maximum. To give an example, if the MBT plant works at a capacity factor of 90%, the 10% remaining is dedicated to operation and maintenance. These values are used for the design of plants in order to be able to treat all waste input regardless of the amount of unproductive time. Therefore, it is not a barrier for this technical potential study as there is not a calculation about the amount of plants needed. Nonetheless, capacity factors are relevant to carry out techno-economical and market potential research, which include costs and consequently are affected by the time spent for operation and maintenance. This kind of potential study could be carried out in further research projects with the aim to deepen these barriers for the specific case of Mexican biogas plants.

More criticism could be made for the mitigation potential. A further limiting factor for the mitigation potential is the fugitive methane emissions from reactors. Nonetheless, life-cycle assessments point out its irrelevancy with about 1% methane losses (Börjesson & Berglund, 2006; Jungbluth *et al.*, 2007; Hamelin *et al.*, 2011). Furthermore, the base of the calculus was made with the amount of MSW collected in 2013, as well as the methane emissions from the Mexican model of biogas. In the discussion about the mitigation targets of the country, the comparison was made between future scenarios and current biogas production potential. Therefore, it is assumed that the biogas output does not increase in time. But the growth in waste generation in the last years points out to an increase of the amount of biogas that could potentially be produced. In a similar way, the implementation of waste mechanical sorting schemes could contribute to apply an alternative treatment unit to the organic matter unsuitable for AD, such as composting or incineration. This would lead to a decrease in the indirect emissions from landfills and enlarge the potential of the case study.

In literature, some authors have criticized the condition of carbon neutrality for biogas. Like other biofuels, emissions from land use and inputs of fossil fuels are required for the growth of biomass and will end up as waste. In general, it is accepted that this does not apply for second generation fuels because these emissions correspond to the use of biomass before it is discarded. Nevertheless, due to the added value of biogas, it would be reasonable to reconsider those discarded organics as a product. In any case, this is a discussion topic for conceptual research studies.

In addition to a self critical assessment of this thesis, it is also important to remark its contribution. As stated in the chapter 1.2 (literature review), there are few studies that have assessed the potential for bioenergy in Mexico. Within WtE potential, there is available information about biogas production from manure and wastewater. In the field of AD of MSW, there were only theoretical potentials and brief mentions referenced in the literature. In that sense, it was considered of relevance to carry out a more detailed analysis using a large database about the local waste management, with the ambition of estimating a more realistic potential for the appliance of WtE technologies to the biowaste generated in the country. In summary, it can be said that the goal of filling the literature gap was successfully achieved.

Moreover, the author considered that it was relevant not only to calculate the potential in numbers, but also to discuss what does it mean to the country and its purpose to promote RES and reduce the carbon intensity of its economy. This has been the most distinctive point compared to other potential studies due to the recent publication of the international commitments from the country for the following years. In consequence, the conclusions are of interest, not only from an academic view, but also as a practical tool for Mexican decision makers in the field.

6 CONCLUSION

The development of a technical potential case study has demonstrated to be a useful tool to answer the RQ proposed in this thesis: "To what extent can the MSW from Mexico be treated by AD and how can this contribute to generate biogas and abate GHG emissions?". Several barriers for biogas projects have been assessed in order to explore the boundaries of this potential: from waste generation to the use of biogas and the derived GHG emissions and savings.

According to the results of this case study, out of the 42.9 Mt of MSW generated each year in Mexico, up to 14 Mt can be used as feedstock for AD reactors. The annual outcome of primary energy is in the range of 25 – 29 PJ, depending on the scenario for the biogas use. This answers the RsQ1. Besides, the production of biogas from waste has a positive impact in abating the emission of gases that contribute to climate change. This mitigation effect is double: displacing fossil fuels from the energy system and diverting millions of tons of biowaste from releasing CH_4 to the atmosphere. Estimating the quantity of this effect leads to answer RsQ2. The direct mitigation potential from using biogas for energy purposes ranges from 1.4 to 1.9 Mt $CO_{2\text{-eq}}$/year and the indirect mitigation potential is of 11.7 Mt $CO_{2\text{-eq}}$/year.

These quantities are closely linked to answer RsQ3. The deployment of this potential can support the country in its aim to diversify the power grid together with other clean energies, as stated in the commitments from the LTE. If the technical potential could be realized, the power production from biogas in Mexico would be 13 times larger than today. Furthermore, the contribution is also applicable to reach those GHG mitigation internationally compromised targets listed in the NDC. The direct emission savings contribute to reducing the carbon intensity of several sectors like residential, transportation and electricity generation. Additionally, the MACCs developed for the country (Johnson *et al*., 2009) have shown the sustainability of this energy source is not only environmental but also economic. In any case, the highest contribution could be done in the waste sector, where the indirect mitigation effects from this potential could achieve 87% of the commitments for 2030 regarding landfill emissions.

The last goal of this research was to summarize the policies that can realise this potential. In this sense, current programs like PECC and ENCC can be the basis to promote AD technologies. They could be enriched with international experiences implemented in other countries, like the establishment of quotas for biofuels or introducing landfill directives. They have already been proven to enhance the spread of AD as a successful biological treatment for MSW to minimize its impact and produce an added value for society.

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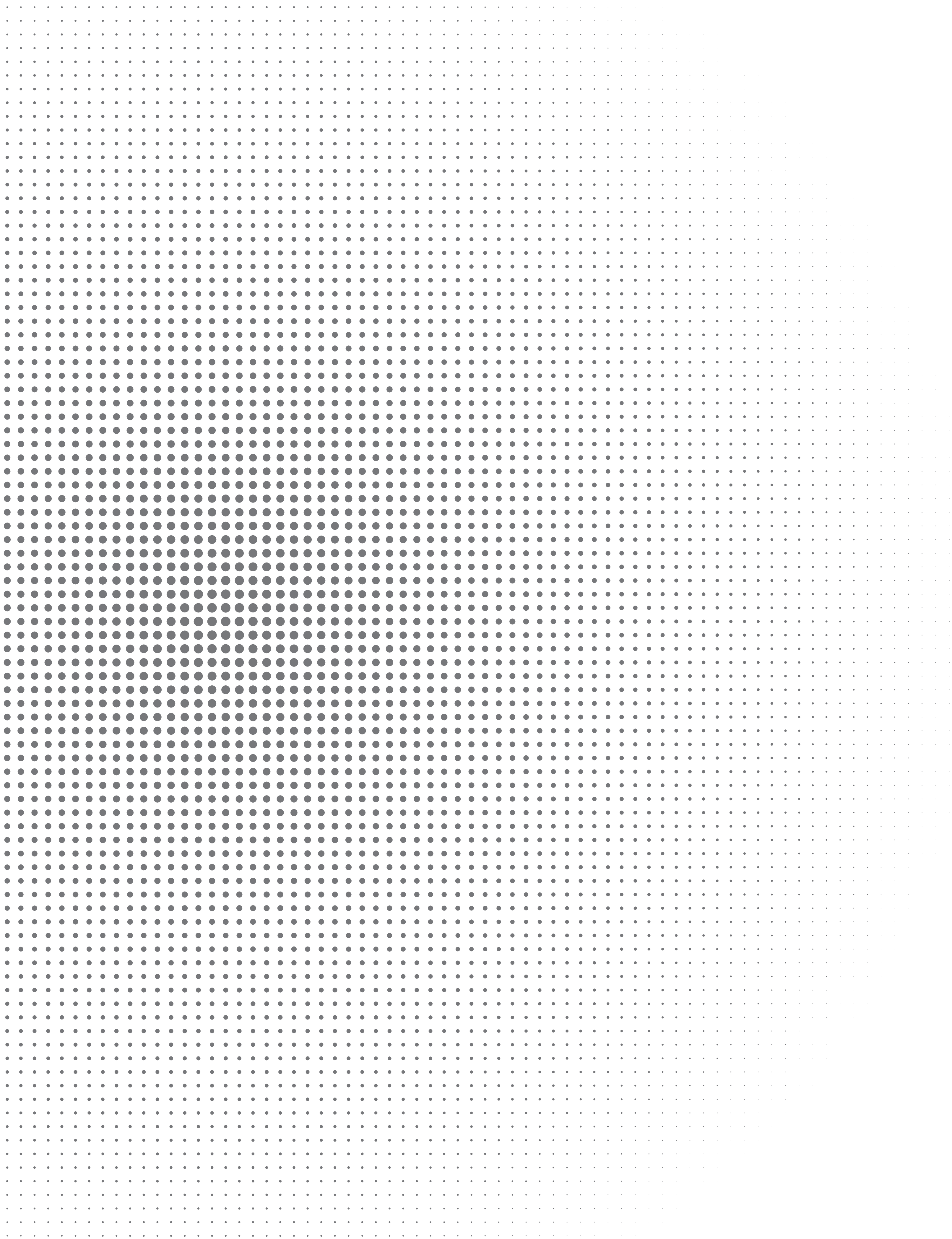
RESULTS OF THE POTENTIAL FOR BIOGAS PRODUCTION PER FEDERAL STATE

Federal state	# Municipalities and delegations assessed	Collected MSW (kt/year)	Feedstock for AD (kt/year)	Total biogas (million m^3 biogas/year)
Aguascalientes	4	254	136	14
Baja California	5	1,031	516	54
Baja California Sur	4	334	135	14
Campeche	6	226	115	12
Coahuila de Zaragoza	12	713	262	27
Colima	4	217	111	12
Chiapas	22	612	312	32
Chihuahua	9	1,094	362	38
Durango	4	309	125	13
Estado de México	56	4,412	2,319	241
Guanajuato	29	1,281	540	56
Guerrero	14	694	356	37
Hidalgo	12	408	204	21
Jalisco	23	1,991	1,081	112
Mexico City	16	6,018	1,226	127
Michoacán de Ocampo	17	1,095	577	60
Morelos	12	443	227	24
Nayarit	5	500	256	27
Nuevo León	13	1,302	527	55
Oaxaca	8	362	186	19
Puebla	23	1,198	709	74
Querétaro	9	602	220	23
Quintana Roo	5	689	369	38
San Luis Potosí	8	626	253	26
Sinaloa	10	1,002	449	47
Sonora	12	767	371	39
Tabasco	13	622	317	33
Tamaulipas	11	982	507	53
Tlaxcala	5	129	64	7
Veracruz	41	1,619	993	103
Yucatán	6	365	137	14
Zacatecas	8	196	79	8
Mexico	426	32,091	14,042	1,458



SCENARIOS OF GREENHOUSE GAS EMISSIONS

Scenarios of GHG emissions in Mexico: baseline and mitigation targets under the unconditional NDC measures

Sector	Baseline				Unconditional NDC target
	2013	2020	2025	2030	2030
Transport	174	214	237	266	218
Electricity	127	143	181	202	139
Residential and commercial	26	27	27	28	23
Oil and gas	80	123	132	137	118
Industrial	115	125	144	165	157
Agriculture	80	88	90	93	86
Waste	31	40	45	49	35
LULUCF	32	32	32	32	– 14
Total	665	792	888	973	762

REFERENCE: (SEMARNAT, 2015b).

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