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Biogas in Mexico

lessons learned from partnership projects in 2018-2019

Danish Climate and Energy Partnership Programme in Mexico 2017-2020

Bioenergy

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Preface

This report is made as a part of the Energy Partnership program between Denmark and Mexico 2017 – 2020.

The general objective of the partnership program is to support Mexico in achieving an increased share of Renewable Energy in its energy mix in line with the goals in its Energy Transition Law.

One element of the program focuses on bioenergy and on identifying and assessing relevant biomass resources for energy utilization in Mexico. For the period 2017 – 2019, it was decided to work with resources for biogas production based on organic residues and waste, and five projects were initiated:

1. Feedstock database for biogas production in Mexico.
   This project identified and described the 20 most promising wet feedstocks for biogas production. The description includes the information necessary for a first evaluation of a biogas project for each feedstock: available amounts, current use, biogas potential etc.
2. Biogas presentation sheets: plants in Denmark and Mexico.
   This project presents 6 Danish and 5 Mexican biogas plants and provides an overview of the state of art of different typical biogas technologies and plant in the two countries. Each plant is described in a fact sheet with key information on input feedstocks, biogas production and costs.
3. Biogas Tool: calculation costs and benefits of biogas production in Mexico.
   The Biogas Tool is a spreadsheet-based calculation tool that can be used to obtain a preliminary technical and economic evaluation of biogas projects based on user input.
4. Pre-feasibility studies for biogas production in Sonora.
   In collaboration with "The Ecology and Sustainable Development Commission of the State of Sonora" (CEDES), three possible projects for biogas production were evaluated.
5. Pre-feasibility study for biogas production in Guanajuato.
   In collaboration with the "Institute of Ecology" (from 2018 the "Ministry of Environment and Territorial Planning") of Guanajuato, a site for biogas production in the state was chosen and evaluated.

The overall purpose of the biogas projects has been to gain knowledge on the possibilities and challenges related to the utilization of available resources for biogas in Mexico. The projects have focused solely on bioenergy from residues and waste, so the main question has been whether such resources can be used for biogas production in an economically, technically and environmentally sustainable way. Detailed results from all five projects are documented in separate reports.

This report presents the general findings and learnings from the projects in Mexico in light of international experiences with biogas. Furthermore, incentives and actions that might be relevant to consider in a possible future biogas strategy or road map for Mexico are described.

The findings from the projects have been summarized in this report by Adalberto Noyola and Juan Morgan Sagastume (UNAM); Bodil Harder (Danish Energy Agency); Benly Liliana Ramírez Higareda, Jorge López, and

Miriam Castro (IBTech®); and Hans Henrik Lindboe (Ea Energy Analyses). The report is based on findings, observations and conclusions obtained by the team of Mexican consultants from IBTech, Mexican biogas experts, and the partners and contributors involved in the projects described above. The future of biogas in Mexico and the recommendations for next steps have further been discussed with central stakeholders at two workshops in Mexico City.

We would like to thank all contributors for their essential and valuable input without which it would not have been possible to write this report. All contributors are listed below.

Consultants and partners

Mexican Consultants (IBTech®)

Benly Liliana Ramírez Higareda, *MSc*
Jorge Edgardo López Hernández, *Eng.*
Miriam Castro Martínez, *Eng.*
Ana María Pérez Villeda, *Eng.*
Rafael Leyva Huitrón, *Eng.*

International Consultant

Hans Henrik Lindboe, Ea Energy Analyses a/s

Experts involved in the Feedstock Database

Engineering Institute of the National Autonomous University of Mexico (II-UNAM)
Adalberto Noyola, *PhD*
Ulises Durán Hinojosa, *PhD*
Iván Moreno Andrade, *PhD*
Juan Manuel Morgan Sagastume, *PhD*

Potosinan Institute of Research on Science and Technology (IPICYT)
Felipe Alatriste Mondragón, *PhD*

Partners in Sonora

CEDES
Leonardo Corrales Vargas, General Director of Conservation
Claudia María Martínez Peralta, Researcher on Sustainability issues
Lucía del Carmen Hoyos Salazar

NORSON
Francisco Halim Olivarría Mosri, Corporate Project Manager

PEGSON
Javier Valenzuela Rogel, General Director

ILIS

AGUA DE HERMOSILLO
Nery Vargas Valdez, Supervision Department
Narda Amoya, WWTP Hermosillo Supervisor

HERMOSILLO WWTP
Víctor Aguilar Urcid, Director

TECMED LANDFILL
Hugo A. Valencia Santacruz

Partners in Guanajuato

IEE
Alberto Carmona Velázquez, Director of Planning and Environmental Policy
Alberto García Tenorio, Biomass Energy Specialist

San Jerónimo WWTP, SITRATA
Diego Isaac Dávila Cano, WWTP General Director

MARKETS AND SLAUGHTERHOUSES
Rastro Municipal de San Francisco del Rincón
Alberto Cano Estrada
Rastro Municipal de Purísima del Rincón
José Antonio Flores Romero
Mercado municipal de San Francisco del Rincón
Miguel Ángel Parada Frausto
Mercado municipal de Purísima del Rincón

LÁCTEOS JALPA
José Juventino López, owner
José Guadalupe López

AGRICULTURAL LANDS
Lorenzo Valadez García, President of the Local Farmers Association

Danish Energy Agency (DEA)

Bodil Harder

Part 1. Biogas in an international perspective

International overview

Global development and dissemination of biogas digesters took off in the 1970s, and today there are probably more than 30 million biogas plants globally, most of them small systems in rural areas in Asia.

Biogas is a gaseous fuel produced from wet biomasses using anaerobic digestion. The gas basically consists of 55-70 % methane and 30-45 % carbon dioxide. Typical feedstock includes manure, sewage sludge, industrial organic waste, agricultural residues and the organic fraction of household waste.

Global biogas generation has increased rapidly since 2000. During 2000 – 2014, the average annual growth of production was 11.2 %. In 2016, the production of biogas exceeded 60 billion Nm^3. Using an average energy density factor of 21.6 MJ/Nm^3 (60% methane), the total biogas production was 1.3 EJ.

In the period 2000 – 2016, Europe was the largest producer of biogas followed by Asia and the Americas as shown in Figure 1. However, the growth in Europe and Asia seems to have slowed down in recent years. In the Americas, biogas production has not increased significantly over the last 20 years. Africa produces only 0.03 % of global production and is not included in the figure.

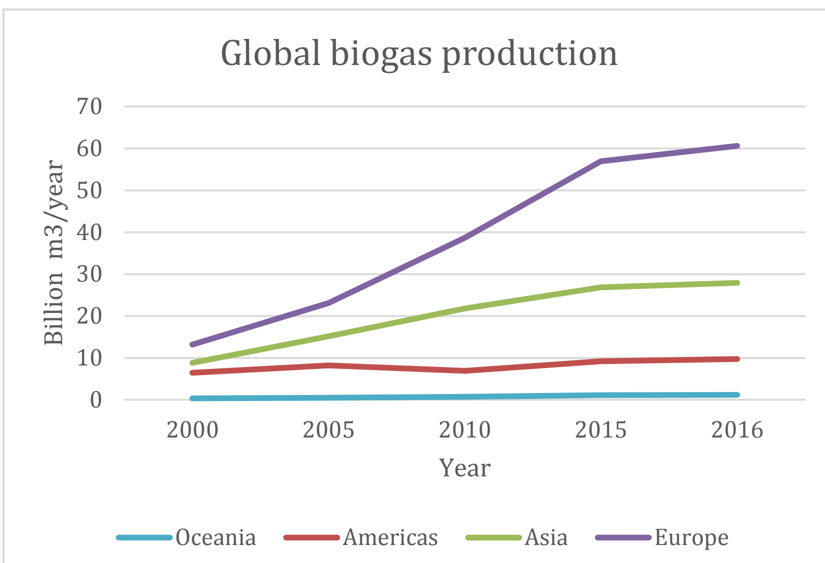

Figure 1. Global biogas production. Source: Own calculation based on Global Bioenergy Statistics 2017 & 2018, WBA.

Biogas offers the opportunity to extract clean energy from agricultural residues and other wastes and thereby increase employment and income in rural areas. In some countries, this has historically been the main driving force for developments in the biogas sector.

The value of the biogas industry can be attributed mainly to three characteristics of biogas:

- **Waste treatment and recycling of nutrients.** The biogas process offers an environmentally friendly treatment of a wide range of organic wastes and residues and also makes recycling of nutrients easier. Biogas production is an energy efficient and thus attractive option for treatment of wastewater and wastewater sludge.
- **Greenhouse gas abatement.** The biogas process offers a climate friendly solution, as biogas production often leads to reduced methane emissions from manure and waste. This has been a main driving force for developments in recent years in Europe as well as in some Asian countries.
- **Renewable energy production.** Biogas is a versatile fuel. It can be used directly for heat and electricity production or it can be upgraded to 100 % methane and used as a transport fuel and/or to help meet peak-load demand in flexible electricity systems dominated by wind and solar power. The versatility of biogas as a flexible energy carrier in a green economy is expected to become a major driving force in future developments for biogas.

In some countries, a key advantage of biogas is attributed to its potential as a vehicle fuel, possibly in combination with new electrofuel technologies. The transport sector currently accounts for one-third of total global emissions of greenhouse gases, and biogas offers one of the cheapest second-generation biofuel alternatives.

The future global energy mix

The International Energy Agency's (IEA) World Energy Outlook (WEO) is a comprehensive analysis of the challenges facing the global and regional energy sectors and possible available solutions. Previously, the WEO focused on meeting security of supply challenges for oil. However, for the last decade the focus has been on regulation issues, and on the supply of clean and affordable energy in light of increasing concerns about climate change.

The 2018 edition presents three scenarios: Current policies, New Policies and Sustainable Development. Only the Sustainable Development scenario is in alignment with the UNFCCC Paris Agreement. The New Policies scenario provides a measured assessment of where today's policy frameworks and ambitions, together with the continued evolution of known technologies, might take the energy sector in the coming decades. The policy ambitions include those announced as of August 2018 and incorporate the commitments made in the Nationally Determined Contributions under the Paris Agreement. However, these policies are not sufficient to reach the 2 degree target.

Figure 2 shows the development in electricity production in the three scenarios. In the Sustainable Development scenario, the contribution from wind and solar will be almost ten times as high in 2040 as in 2017. In the New Policies scenario, growth in the wind and solar contribution is "only" five-fold. In the Sustainable Development scenario, natural gas is projected to be the only fossil fuel that does not experience a substantial decline before 2040.

			New Policies		Current Policies		Sustainable Development	
	2000	2017	2025	2040	2025	2040	2025	2040
Coal	6 001	9 858	9 896	10 335	10 694	13 910	7 193	1 982
Oil	1 212	940	763	527	779	610	605	197
Gas	2 747	5 855	6 829	9 071	7 072	10 295	6 810	5 358
Nuclear	2 591	2 637	3 089	3 726	3 079	3 648	3 303	4 960
Hydro	2 618	4 109	4 821	6 179	4 801	5 973	5 012	6 990
Wind and solar PV	32	1 519	3 766	8 529	3 485	6 635	4 647	14 139
Other renewables	217	722	1 057	2 044	1 031	1 653	1 259	3 456
Total generation	**15 441**	**25 679**	**30 253**	**40 443**	**30 971**	**42 755**	**28 859**	**37 114**
Electricity demand	*13 156*	*22 209*	*26 417*	*35 526*	*26 950*	*37 258*	*25 336*	*33 176*

Figure 2. Projections of world electricity production by fuel and technology in three scenarios. Source: World Energy Outlook 2018, IEA

In all scenarios, wind and solar plays a significant role in the electricity sector. Wind and solar are fluctuating electricity producers, and the electricity sector will increasingly need flexible production and consumption technologies to serve as reserve and balancing resources. Gas technologies are well suited to deliver flexibility due to their good ramping properties and reasonably low investment costs.

The figure shows that the New Policies are not strong enough to reach a Sustainable Development. By 2040, the “other renewables” - which include biogas - should produce 109 % more energy than is foreseen with the Current Policies and 70 % more energy than is foreseen with the New Policies in order to reach a Sustainable Development.

The value of biogas towards 2040

As mentioned in the overview above, production and utilization of biogas can serve multiple purposes: 1) Waste treatment and recycling of nutrients, 2) Greenhouse gas abatement, and 3) Renewable energy production.

<u>1. Waste treatment and recycling of nutrients</u>

The value of biogas treatment of animal manure and organic wastes is difficult to assess in general. The value should be calculated as the cost of alternative treatments. Alternative treatments can be landfilling, or aerobic biological mechanical treatment to reduce nutrient discharge. In such alternatives, part of the avoided cost is the cost of having to procure commercial fertilizers for agriculture instead of using biogas-treated organic wastes and animal manure.

If the alternative treatment is landfilling, the avoided cost is the landfill cost. For animal manure, the alternative to biogas treatment can be subject to different types of restrictions on utilizing the manure as a fertilizer depending on veterinarian considerations and local waste disposal regulations. For some biomasses, the avoided cost is related to the cost of the disposal of the biomass to the local wastewater treatment plant.

A comprehensive analysis on biogas in Denmark found that the avoided cost of commercial fertilizers alone represents a value of app. 1 USD/ton manure that is biogas treated (*Biogas i Danmark*, Danish Energy Agency, 2014). The value was calculated as the added value compared to the fertilizer value of untreated manure, and calculates as 0.05 – 0.1 USD/m^3 CH_4.

In regions with strict environmental and agricultural regulation, the value of biogas from treatment of manure and organic wastes can be quite high. In addition, some consumer segments are now demanding documentation for organic and environmental benign production of foodstuffs, including Best Available Technology for waste recycling and disposal. In many cases, such documentation– including documentation for biogas production – represents a substantial value for the producer.

The considerations above show that the environmental and recycling value of biogas treatment is difficult to assess in general and must be calculated case by case.

2. Greenhouse gas abatement

Abatement of greenhouse gas emissions has a cost. If the major abatement mechanism is a carbon trading system (like the emission trading system of the European Union, EU-ETS), the cost is publicly available in the form of **a carbon price**. The current carbon price in the EU-ETS is 26 USD/ton of CO_2. Other types of regulation such as taxes, standards, premiums etc. can be applied, but these different types of abatement tool only affect efficiency and cost distribution. However, if the Paris Agreement is to be fulfilled, the real cost of CO_2 abatement to society has to be paid one way or the other.

According to the UNFCCC Paris Agreement from December 2015, the parties must pursue efforts to limit the atmospheric temperature increase to 1.5 degrees Celsius. Several global development scenarios show that dramatic changes in the energy, industry, transport and agricultural sectors are necessary in order to achieve this goal. It will likely not be enough to undertake a complete change from fossil to renewable fuels. Furthermore, it may be necessary to develop *carbon sink* technologies with the ability to capture carbon from the atmosphere and store it for hundreds or thousands of years. The UNFCCC, the IEA, and several other parties are in the process of performing analyses to estimate the costs of such technologies. Carbon sinks are considered to represent the long-term marginal cost[1] of CO_2 abatement.

Examples of carbon sinks are: increased and permanent forestation, carbon capture, and storage of CO_2 from biomass combustion, or direct carbon extraction and storage from the atmosphere. The point is that if the predicted rise in temperature is to be limited to 1.5 degrees, or even if it is to be limited to 2 degrees, at some point in time, the increasing marginal cost of CO_2 abatement must be added to the cost of fossil fuels in order to express the real and total cost of burning fossil fuel.

Natural gas emits approx. 3 kg CO_2 per m^3 gas, depending on the source and specific content of hydrocarbons. The current price in the EU-ETS, (USD 28 per ton CO_2) corresponds to an abatement value of 7 US¢/m^3 biogas methane. This is the current CO_2 value of biogas in the EU. Some analysts state that the long-term CO_2 abatement cost is probably higher than 100 USD/ton of CO_2 if the temperature rise is to be limited to 2 degrees. Figure 3 shows the CO_2 value of biogas as a function of the marginal CO_2 abatement cost.

[1] Marginal cost is the additional cost incurred in the production of one more unit of a good or service.

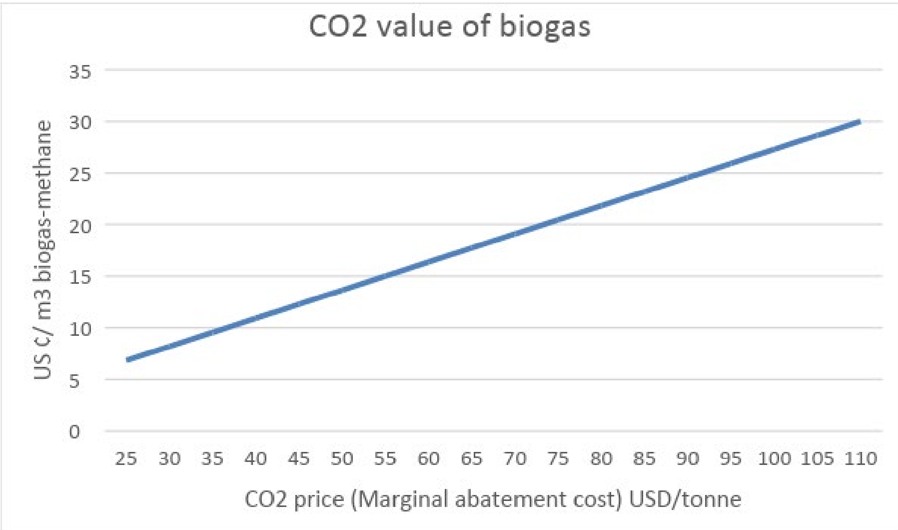

Figure 3. CO_2 value of biogas when displacing natural gas as function of marginal CO_2 abatement cost

3. Energy value

Biogas can be used directly to produce electricity and heat. For renewable electricity production alone, wind power and solar PV are often cheaper options. The price of these options is decreasing and today wind and solar PV are even cheaper options than fossil fuels in electricity production[2]. In places with low wind resources, or when heat is needed, the value of biogas-based electricity and heat will be higher.

Biogas can also be upgraded and fed into the natural gas network or it can be further pressurized and used directly as a transport fuel. The CO_2 content in biogas can be synthesized with hydrogen, thereby removing CO_2 and increasing the methane content by up to 50 %[3]. Alternatively, the biogas can be chemically changed to a liquid fuel, e.g. methanol, which can be used as a transport fuel.

Historically, the energy value of biogas has been measured based on the most competitive local alternative. In most countries today, the energy value will be directly compared to local oil or gas prices. In the World Energy Outlook report, the historical natural gas prices and price projections are shown for key regions of the world. In all regions, gas prices are currently historically low, and projected to increase slowly towards 2040. 1 MBtu equals approx. 30 m^3 methane, and the current price in the USA of 3 USD/MBtu equals a price of 0.1 USD/m^3 CH_4.

The prices in Figure 4 resemble gas hub prices, and costs of transport to point of consumption must be added to represent the local value of gas. Transport costs differ depending on location and consumption pattern. However, for large consumers the average transport cost (Europe) can be estimated at approx. 1 USD/MBtu

[2] https://www.xataka.com.mx/energia/en-mexico-producir-energia-limpia-ya-cuesta-menos-que-el-costo-promedio-de-generar-energia-por-gas-y-carbon

[3] $2H_2 + CO_2 \rightarrow CH_4 + O_2$

(0.03 USD/m^3 CH_4). Thus, the total long-term gas price can be estimated at approx. 0.4 USD/m^3 CH_4 in Europe and Asia, and at approx. 0.2 USD/m^3 CH_4 in the USA.

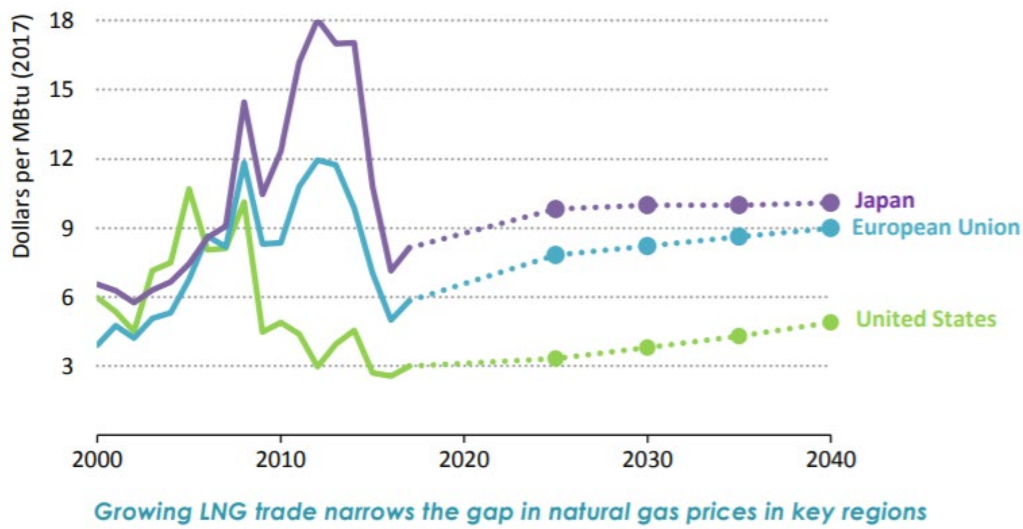

Figure 4. Projection of natural gas prices in key regions. Source: World Energy Outlook 2018, New Policies Scenario.

The role of biogas in the future energy system

In a North American context, the main role of biogas is likely to replace natural gas whenever possible and feasible. Projections show that natural gas prices for the coming decade will be below 20 US¢/m^3 CH_4. In addition to this raw energy value, two additional value components are essential: 1) The value of waste treatment and nutrient recycling and 2) The CO_2 value of displacing natural gas with biogas.

The value of waste & recycling is only partly internalized in the markets worldwide, and regulation and/or support schemes are needed for the value to be factored in efficiently by investors. As shown in Figure 3 above, the CO_2 value of biogas can potentially reach 15 – 30 US¢/ m^3 CH_4 but is currently absent as a price signal to investors in many countries, including Mexico.

In conclusion, according to the calculations above, the socioeconomic value of biogas in North America will probably approximate $20_{Energy} + 5\text{-}10_{Waste\&recycle} + 15\text{-}30_{CO2} = 40\text{-}60$ US¢/m^3 CH_4, depending on the national strategy for greenhouse gas emissions abatement and on the valuation of efficient waste handling and recycling. In order to further develop this gas resource, it is necessary to internalize not only the energy value, but also the waste & recycle value and the CO_2 value in the market. New policies that reward biogas production US¢ 40-60 per m^3 CH_4 in total could be considered.

Biogas in Denmark

Production of biogas in Denmark started in the 1980s, motivated partly by new environmental regulation. After some years with failures, farmers and industry found a durable concept in which manure (slurry) and organic industrial waste were digested together at biogas plants located near larger livestock farms.

The Danish biogas concept solved a problem for the industry: How to get rid of organic waste at a reasonable cost and without violating environmental rules? For livestock farmers, biogas plants represented a way forward in a situation in which farmers had to limit fertilizer consumption for the sake of the aquatic environment while all manure had to be applied as a fertilizer on mandatory "harmony land areas". The farmers wanted to maximize their harvest yield and increase their number of animals and therefore welcomed the service provided by the biogas plants: increasing the fertilizer value of the manure through the digestion process and distributing excess digestate to non-livestock farmers.

In parallel with the development of agricultural biogas plants, wastewater treatment plants established digesters for wastewater sludge, partly in order to reduce the amount of sludge, which also had to be disposed of in an environmentally friendly way.

Over the past 20 years, biogas has become increasingly more important as a renewable energy source and as a way of reducing greenhouse gas emissions from agriculture. This development has been promoted through government support schemes. A subsidy scheme introduced in 2012 contributed in particular to a rapid biogas expansion: Biogas production increased more than fourfold from 2012 to 2020, reaching a total annual production of around 20 PJ. see Figure 5.

Until recently, most of the biogas produced was used in electricity production. However, the subsidy scheme from 2012 made it viable to upgrade the biogas and inject it into the natural gas grid, where it replaces fossil natural gas and is used for industry processes, transport, heat and power. In 2018, approx. 8 % of Danish gas consumption comprised upgraded biogas – an EU record.

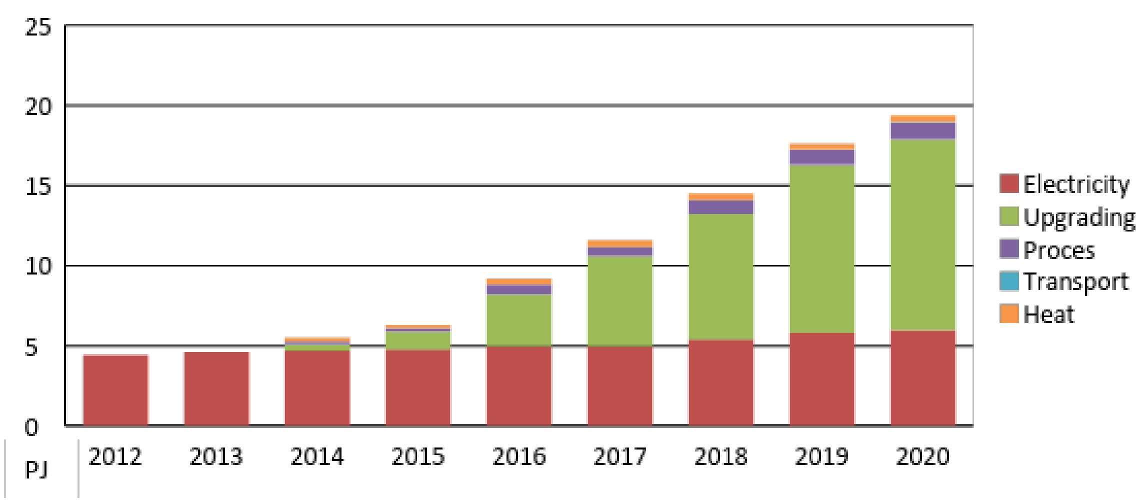

Figure 5. Recent and expected biogas production and use in Denmark 2012-2020 (PJ).

Currently, 32 biogas plants produce biomethane in Denmark, and in 2018 7.2 PJ (or 1993 GWh biomethane) was produced.

In Denmark, all livestock manure (both liquid and solid fractions) is used as fertilizer on cropland and, in 2019, about 25 % is being used in biogas production before being applied on fields. The limited growing season in Denmark requires the manure to be stored for up to 8 months and brought to the fields in the spring, securing that the nutrients are available when the crops need them. Anaerobic digestion of the manure before storage reduces the methane emissions from the storage. Co-digestion of slurry with organic waste from industry, the service sector and households makes it possible to increase the gas production in the plants as well as to recycle nutrients from organic waste.

The increased biogas production has been achieved through various regulatory incentives in the areas of the environment, agriculture and energy, including:

- Dedicated governmental support schemes
- Taxes on consumption of fossil fuels
- Restricted use of fertilizer/manure on fields
- A ban on organic waste in landfills since 1997
- Fees for waste treatment
- Dialogue and joint efforts with key stakeholders through follow-up programs
- Support for research, development and demonstration of new technologies
- Limit on the use of energy crops in biogas production

The main factor behind the increase in biogas production is a subsidy scheme with high feed-in tariffs for biogas used for energy purposes, see Figure 6. The energy subsidy, so to speak, has to pay for the Danish biogas expansion, even though biogas is being promoted also for agricultural and environmental reasons.

Biogas for energy purposes eligible for subsidies from 2012	**Total subsidy DKK**	**Total subsidy MXN**
	DKK/GJ	MXN/GJ
Upgrading	115	404
Industrial processes	75	263
Transport	75	263
Heat	36	126
	DKK/kWh	MXN/kWh
Electricity		
Fixed price incl. electricity price	1.15	4.0
Fixed premium on top of electricity price	0.79	2.8

Figure 6. Subsidies in Denmark for biogas utilization, 2012 - 2020.

The growing production of biogas increased the costs of the subsidy scheme. The total costs are expected to exceed DKK 1.7 billion (USD 230 million, MXN 4.65 billion) in 2019. The increasing support expenditures have motivated a political decision to discontinue the current subsidy scheme for new plants from 2020. It is likely that a new scheme for Renewable Natural Gas, including biomethane and other green gasses such as hydrogen and methanized gas, will be implemented instead.

The focus on Renewable Natural Gas, instead of the direct production of electricity from biogas, is due to the fact that Denmark has a high share of renewable electricity in its energy system and is closer to a situation in which backup renewable electricity is needed from other sources than wind and solar power.

The Danish case shows that biogas plants *can* work. They can efficiently use organic waste and residues for biogas production, while at the same time recycling the nutrients in the feedstocks and disposing of the wastes in an environmentally friendly way. Many Danish plants have been in operation for more than 20 years and continue to deliver renewable gas to the Danish energy system. However, the Danish case also shows that a high level of support can lead to costs that are politically unacceptable and this, in turn, can lead to go–stop policies. Studies also indicate that a high level of support can lead to increased production costs - either because plants are built on less favorable sites or because every actor in the value chain wants a slice of the cake. For these reasons, among others, a subsidy scheme at the level of the current Danish scheme cannot be recommended for Mexico.

Biogas in California

Like Denmark, California experiences increased biogas production from livestock manure due to substantial incentive schemes designed to reduce methane emissions. The goal is a 40 % reduction of methane emissions statewide by 2030[4]. Emissions from manure represent approximately 26 % of California's methane emissions[5].

The incentives in California are a mixture of blending obligations for transport fuels, investment support schemes for biogas in the dairy production, and feed-in tariff programs, see Figure 7.

At the moment the two blending obligation programs *Renewable Fuel Standard* (RFS) at the federal level and the Californian *Low Carbon Fuel Standard* (LCFS) seem to be the most important drivers.

The Renewable Fuel Standard adopted in 2005 requires a certain *volume* of renewable transport fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel. Obligated parties under the RFS program are refiners or importers of gasoline or diesel fuel. Compliance is achieved by blending renewable fuels into transportation fuel, or by obtaining credits (called "Renewable Identification Numbers", or RINs) to meet a specified Renewable Volume Obligation (RVO).

The Low Carbon Fuel Standard adopted in 2009 aims at encouraging the production and use of cleaner low-carbon fuels in California and thereby reducing greenhouse gas emissions. The LCFS standards are expressed in terms of the "carbon intensity" (CI) of gasoline and diesel fuel and their respective substitutes (gCO_2e/MJ). The LCFS allows the market to determine how the carbon intensity of the transportation fuels is reduced. The regulated parties are providers of petroleum and biofuels primarily for road transport. They must comply with the following limits for CI of their fuels sold in each year.

The Carbon Intensity of a fuel is determined using a life cycle analysis (LCA) methodology that examines the GHG emissions associated with the production, transportation, and use of the fuel, as well as indirect effects such as changes in land use. Because of avoided methane emissions from the storage of manure in open lagoons, which is a common practice in California as well as in Mexico, the Carbon Intensity of biogas produced from manure in covered lagoon digesters is very low and the biogas is therefore very valuable.

Together with investment support schemes, this has led to an increasing number of lagoon digesters in California's huge dairy production, as well as to increased focus on upgrade and injection of biogas into the natural gas grid. The first projects transport the raw biogas in low-pressure pipelines from several dairy farms to a single, common upgrading facility.

Unlike in Denmark, in Mexico and California co-digestion of manure with other feedstocks is not common.

[4] The goal is established by law in S.B.1383
[5] https://ngtnews.com/cpuc-approves-dairy-biomethane-pilot-program

Biogas incentives in California	
Low Carbon Fuel Standard (LCFS)	The LCFS scheme mandates sellers of gasoline and diesel to lower the carbon intensity (CI) of their fuels. Biogas from manure that is upgraded to Renewable Natural Gas (RNG) and used as a transportation fuel has very low carbon intensity and therefore a high value in the LCFS scheme. The RNG can be injected into the natural gas grid or used at a local gas station.
Renewable Fuel Standard (RFS)	RFS is a federal program that mandates refiners or importers to replace a certain volume of petroleum-based transportation fuel, heating oil or jet fuel by renewable fuels. Compliance is achieved by blending renewable fuels into the transportation fuel, or by obtaining credits called "Renewable Identification Numbers", or RINs.
CDFA Dairy Digester Research & Development Program (DDRDP)	California Department of Food and Agriculture's Dairy Digester support program gives up to 50 % funding and a maximum of USD3 million to digester projects in which biogas is used for electricity production or as a transportation fuel.
CPUC BioMat	The Bioenergy Market Adjusting Tariff (BioMAT) is a feed-in tariff program for small bioenergy renewable generators. The BioMAT program offers a fixed-price standard contract to export electricity to three Californian utilities.
CPUC Interconnection Pilot Program	The California Public Utilities Commission (CPUC) funds six pilot projects demonstrating the collection of biomethane from dairy digesters and its injection into natural gas pipelines. Forty-five dairies will participate in the pilot projects. The six projects will receive approximately USD 319 million in infrastructure investments and operation expenses over the next 20 years[6].
Compliance Offset Program – Livestock Projects	California has a Cap & Trade program designed to reduce greenhouse gases (GHGs) from multiple sources. The cap declines approximately 3 percent each year beginning in 2013. A portion of the Cap & Trade compliance can be met through credits generated by livestock biogas projects that demonstrate GHG reductions.

Figure 7. Biogas incentive schemes in California, USA.

Biogas in Mexico

The energy mix in Mexico is dominated by oil and gas, which together with coal cover around 89 % of the primary energy demand, see Figure 8. The transport sector is heavily dependent on oil. For power generation, oil is rapidly losing ground to natural gas, the cost advantage of which has been reinforced by the shale gas boom in the United States. Mexico is a net importer of oil and meets almost 50 % of its gas demand through imports. Of the non-fossil energy sources, bioenergy - with 5 % - constitutes the major part and the remaining 6 % is covered by nuclear, hydro, wind power, and solar PV.

[6] http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M246/K748/246748640.PDF

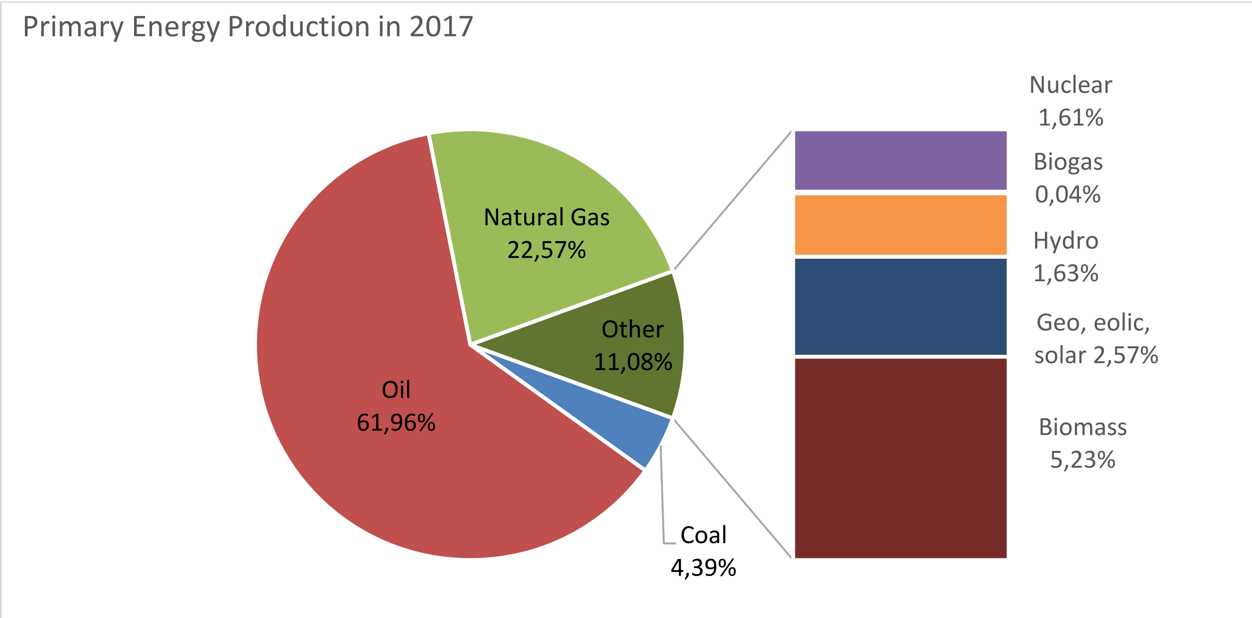

Figure 8. Primary energy demand by fuel in Mexico 2017.[7]

The main use of bioenergy is still in residential cooking and water heating. According to the IEA an increased use of bioenergy in power generation and industry is foreseen and a reduced use of solid biomass in households, where it is replaced by LPG and piped natural gas for cooking and heating.

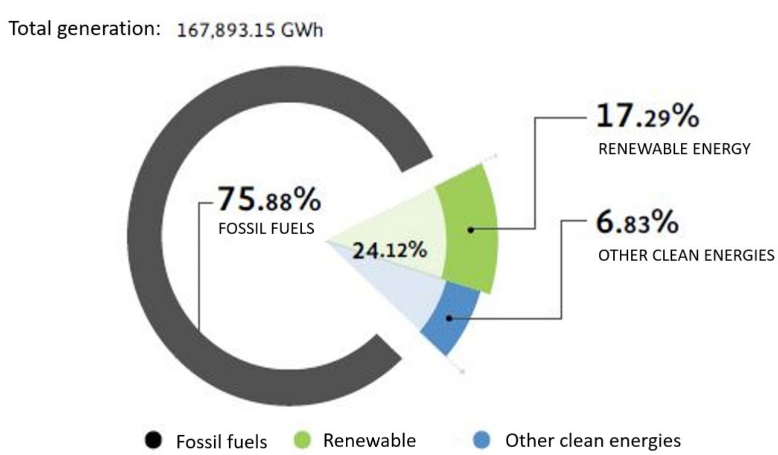

Figure 9. Sources of electricity production in Mexico. Black is fossil fuels, green is renewable energy, and blue is other clean energy sources as nuclear and efficient co-generation.[8].

At the end of 2014, there were 2,167 biogas digesters in the agricultural sector in Mexico[9], varying in size from small household plants of less than 25m³ to larger plants with a reactor capacity of more than 1000m³.

[7] Secretaría de Energía. (2019). Sistema de Información Energética. Consulted on May 4th, 2019 from: https://sie.energia.gob.mx/bdiController.do?action=cuadro&subAction=applyOptions
[8] https://www.gob.mx/cms/uploads/attachment/file/418391/RAEL_Primer_Semestre_2018.pdf

The most important financing mechanisms for biogas plants in the agricultural sector have been the Shared Risk Trust (FIRCO) from the Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Feeding (SAGARPA), the Clean Development Mechanism (CDM), and the Methane Market Initiative (M2M). Up to 2017, FIRCO has provided funds for 380 biogas digesters, 187 motor generators, and 24 turbines.[10]

However, relatively few agricultural biodigesters utilize the biogas for energy purposes replacing fossil fuels. In 2013, a study focusing on pig farms and dairy stables in 11 states confirmed the existence of 345 biodigesters, of which only 20 % used the biogas for energy purposes[11]. Other studies have also found disappointing experiences with biogas production, especially in the agricultural sector[12]. Biodigesters were not well managed, investment costs could not be recovered, the workforce was not appropriately trained, and the systems were not monitored by the competent authorities.

Recently, new wastewater treatment plants have been built in many cities in Mexico. Often, the plants are built by private companies contracted by the city's water authorities. The plants typically include biodigesters for the digestion of primary and secondary sludge, and the biogas is used for electricity and heat by the plant itself (self-consumption).

In 2017, there were 9 sludge anaerobic digestion systems producing electricity at municipal wastewater treatments plants (WWTPs) in Mexico[13] and 8 active landfill stations with gas collection and electricity production[14]. Recently, projects with biogas production from solid urban waste have been established.

This has led to an increase in the installed capacity and the amount of electricity generated from biogas (Figure 10). Landfill gas constitutes an important share, but the recent growth is also due to the installation of biodigester projects at wastewater treatment plants in the agri-food sector and projects on biogas generation from urban waste[15].

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[9] IRRI Mexico & Tetra Tech ES, 2015.

[10] DEA 2017. Biomass roadmap for Mexico: Assessment of potentials. Background report.

[11] UNAM 2013. Evaluación de opciones tecnológicas para el tratamiento integral de aguas residuales para el sector pecuniario en Mexico.

[12] Estrategias de Mitigación. El programa de Biodigestores en Yucatán, México. Península, 2018

[13] IMTA, 2017.

[14] Zurita, Álvaro, 2016.

[15] SENER 2018, Reporte de Avance de Energías Limpias Primer Semestre 2018 México.

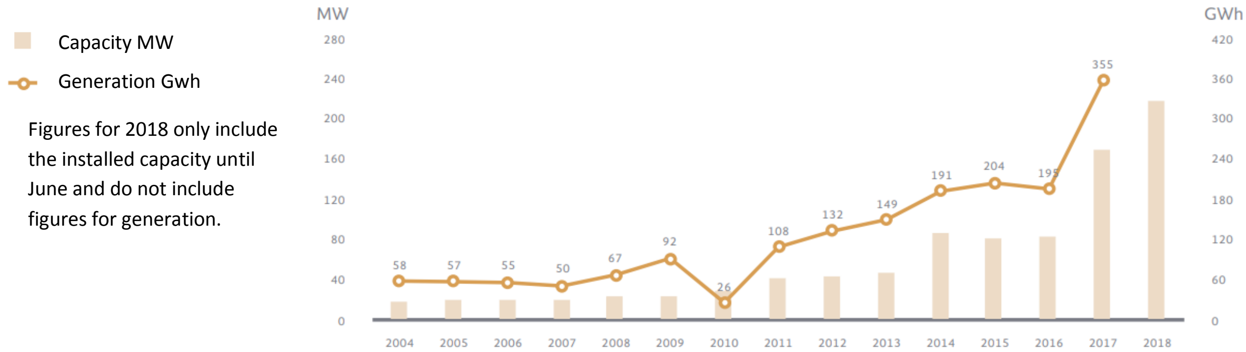

Figure 10. Development of the electricity production (generation and installed capacity) from biogas in Mexico.[6]

There is huge potential for a further increase in biogas production from waste in Mexico. Around 53 million tons of urban solid waste (MSW) are generated every year. More than half of this, 52 %, is organic waste. Nevertheless, just 9.1 % of the MSW is collected separately, the rest is mixed. From the total MSW generated, just 9.6 % is recycled, the final disposal of 14 % is unknown, and the major part (76.4 %) is transported to a final disposal site[16]. Almost all the MSW that is transported to disposal sites is deposited in either open dumps (79 %), controlled sites (13 %) or landfills (8 %)[17], as shown in Figure 11 below.

Also wastes from the service sector and from food industry, for example slaughterhouses and cheese factories, are deposited in landfills/dumps, where they cause methane emissions.

The National Water Commission (CONAGUA, 2018) reported that 235 m^3/s of municipal wastewater were produced in 2017, 91 % being collected in sewer systems (215m^3/s). However, only 63 % of the collected sewage entered a treatment system (136 m^3/s)[18], and only 28-30 % of wastewater generated in Mexico is treated properly[19]. The new treatment systems that should be constructed in the future for achieving near 100 % treatment are an opportunity for the biogas market in Mexico, as biogas-producing technologies may take some of the share.

In the agricultural sector, liquid manure from pig production and dairy farms is usually led to open lagoons, where it also generates methane, or it can be led directly to rivers or other natural recipients. In some areas this can represent a major environmental problem.

Biogas production can play a role in better treatment systems for the mentioned wastes and residues, especially if the produced digestate can be reused as fertilizer in a safe and environmentally sound way. Biogas production is not in itself a wastewater treatment system, as the digestate contains nutrients. Recycling of nutrients could, however, also be improved in Mexico. While solid manure from cattle and chicken in general is reused on cropland as fertilizer or soil improver after a composting process, recycling of nutrients from pig manure is in-efficient or non-existing.

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[16] INECC, 2012. Diagnóstico Básico para la Gestión Integral de Residuos 2012-Versión extensa. México.
[17] Ricardo Ortiz Conde, Director de Gestión Integral de Residuos, Semarnat, 2018.
[18] CONAGUA, 2018. Estadísticas del agua en México, edición 2018. http://sina.conagua.gob.mx/publicaciones/EAM_2018.pdf
[19] Morgan-Sagastume, 2016. Aprovechamiento energético de biogás en PTAR. Convención Anual ANEAS.

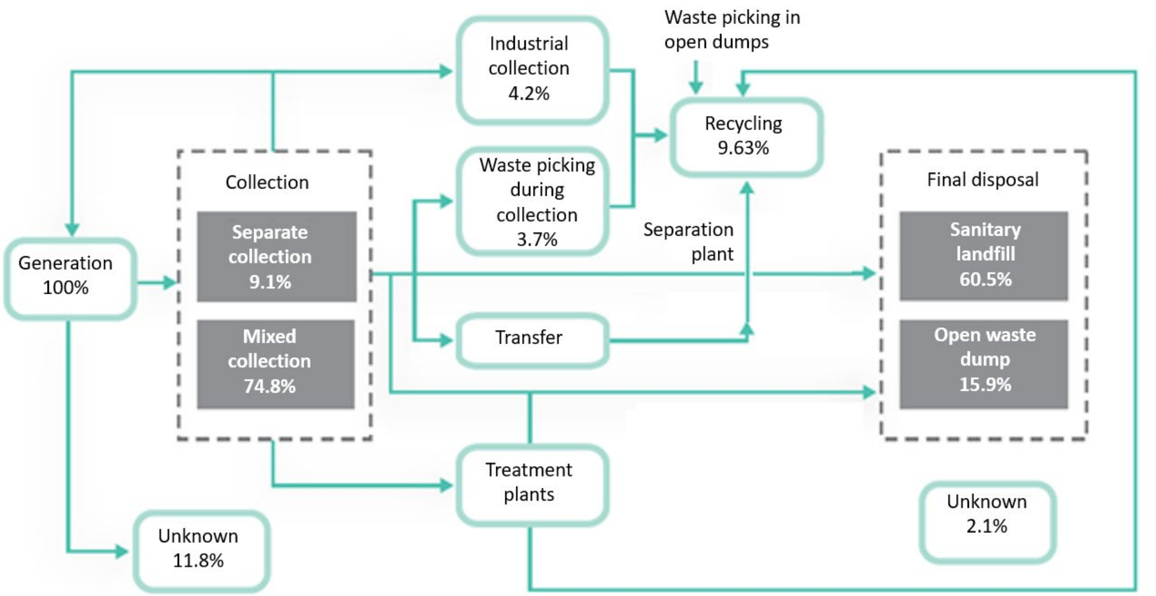

Figure 11. Flow and final disposal of residues in Mexico in 2012[20].

Conclusion

In future energy systems, we will still need hydrocarbons in the form of gas or liquids. Biogas provides this as renewable energy. In future energy systems, in line with the UNFCCC Paris Agreement, biogas could replace fossil fuels in the industry and transport sector and deliver flexible electricity production complementing wind power and solar PV. As described in this part of this report, the total value of biogas per m^3 CH_4 (not including job creation) will probably approximate US¢ 40 towards 2030 and increase to US¢ 50 towards 2040.

Biogas production must be seen not only as an energy resource, but as an element in a sustainable treatment system for organic waste, which can recycle nutrients and reduce methane emissions. Successful utilization of these opportunities can contribute to income and job creation in rural areas.

Based on different subsets of these advantages, biogas production has increased globally by a factor of 6 since 2000, most noticeable in Europe and Asia. In Denmark and California, the increased biogas production has been driven by different kinds of incentive schemes with which experiences are still being gained.

For Mexico, biogas production is highly relevant as a part of waste treatment systems. Methane emissions still derive from organic waste deposited in landfills/dumps without gas collection. Technically, a large part of the organic wastes and residues currently managed unsustainably could be used as feedstock for anaerobic digestion.

[20] INECC, 2012. Diagnóstico Básico para la Gestión Integral de Residuos 2012-Versión extensa. México.

Mexico has an emerging biogas industry, and many biogas projects have been established. Experiences with biogas have thus been gained, but unsolved problems and barriers have lowered the benefits and energy utilization of biogas plants.

Biogas could be a valuable resource in Mexico, replacing imported gas, reducing the need for mineral fertilizers reducing CO_2 emissions, and providing jobs in rural regions. By employing mechanisms that partly or fully reward the waste & recycle value and the CO_2 value of biogas, Mexico has the possibility to develop this national resource efficiently. Such a strategy could take learning from other countries with well-developed biogas sectors.

Part 2: Partnership projects on biogas 2018 - 2019

As an element in the bioenergy part of the Energy Partnership program between Denmark and Mexico 2017 – 2020, the following five biogas projects were carried out in the period April 2018 to May 2019.

1. Feedstock database for biogas production in Mexico.
   This project identified and described the 20 most promising wet feedstocks for biogas production. The description includes the information necessary for a first evaluation of a biogas project for each feedstock: available amounts, current use, biogas potential etc.
2. Biogas presentation sheets: plants in Denmark and Mexico.
   This project presents 6 Danish and 5 Mexican biogas plants and provides an overview of the state of art of different typical biogas technologies and plant in the two countries. Each plant is described in a fact sheet with key information on input feedstocks, biogas production and costs.
3. Biogas Tool: calculation costs and benefits of biogas production in Mexico.
   The Biogas Tool is a spreadsheet-based calculation tool that can be used to obtain a preliminary technical and economic evaluation of biogas projects based on user input.
4. Pre-feasibility studies for biogas production in Sonora.
   In collaboration with "The Ecology and Sustainable Development Commission of the State of Sonora" (CEDES), three possible projects for biogas production were evaluated.
5. Pre-feasibility study for biogas production in Guanajuato.
   In collaboration with "The Institute of Ecology" (from 2018 the "Ministry of Environment and Planning") of Guanajuato, a site for biogas production in Guanajuato was chosen and evaluated.

Below is a presentation of the main conclusions and learnings from these projects.

Feedstock Database for biogas in Mexico.

In the project "Feedstock database for biogas in Mexico", the 20 most important types of wastes and residues for biogas production in Mexico were selected and described. The theoretical biogas potential from these feedstocks, of which none have higher usage, represents more than 500 PJ, see Figure 12.

Wastewater sludge, organic wastes from households and markets, manure from livestock, and waste from slaughterhouses are among the feedstocks with the largest potential. Previous studies have shown biogas potentials of up to 633 PJ from different selections of feedstocks[21].

In order to estimate the realizable production, logistics as well as technical, economic, and environmental issues must be taken into account. This will lower the potential. However, although the technically and economically realizable biogas production in Mexico is much smaller than the theoretical potential, the

[21] Rios, M., & Kaltschmitt, M., 2013.

Feedstock Database shows that Mexico has a huge biogas potential from wastes and residues which have no other uses and which often represent a potential environmental or climate problem if not treated in a proper way.

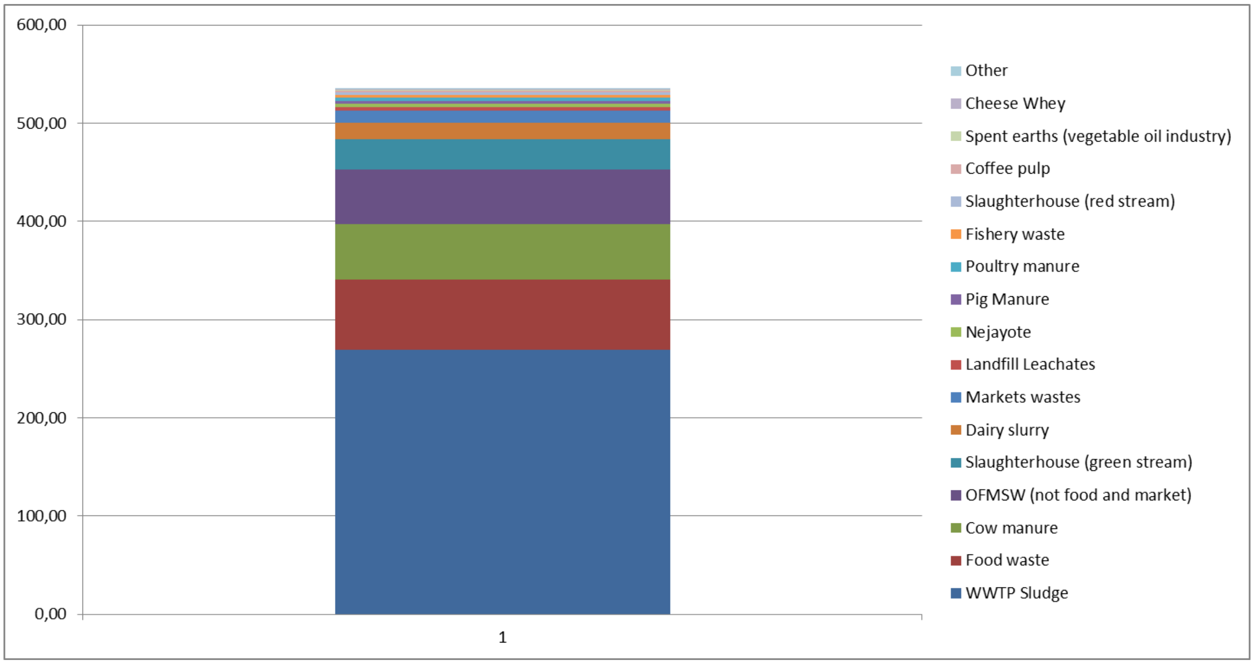

Figure 12. Theoretical biogas potential based on the "Feedstock database for biogas in Mexico".

Biogas Technology presentation sheets

In the project "Biogas presentation sheets", eleven biogas plants, 5 Mexican and 6 Danish, have been described. Included in the description are key figures on capacity, feedstocks, and gas production, as well as investment and operational costs.

All figures have been approved by the plant owners. However, they have not been verified by a third party, and it has not been possible to make a detailed documentation and harmonization of all costs. However, the figures and descriptions show some typical differences between biogas technology in Denmark and Mexico.

The five Mexican plants cover three different reactor types: two covered lagoons, two Continuously Stirred Tank Reactors at wastewater treatment plants, and one "Internal Circulation"-reactor (IC), which is an evolution of an UASB-reactor. The plants use only one type of feedstock, they have typically only one digestion step, and not all the digestate is used on cropland. Three of the Mexican plants use the biogas for combined heat and power production, and two plants use the biogas in boilers for industrial purposes.

The Danish plants are all Continuously Stirred Tank Reactors (CSTR) digesting manure together with organic waste from food industry and agricultural residues. All the Danish plants have heated reactors and at least two digestion steps. All the digestate from the Danish plants is reused as fertilizer on cropland. Half of the Danish plants produce electricity and heat from the gas and half of them upgrade the biogas and inject it into the natural gas grid.

The Danish plants treat feedstocks with a 3-4 times higher dry matter content: 12 % in average in contrast to 3-4 % in the Mexican plants. Consequently, the Danish plants also have gas production that is 3-4 times higher per ton of feedstock. Compared to the Mexican plants, the Danish plants have lower investment costs per ton of feedstock treated yearly, but much higher operational costs; although the Danish operational costs showed here do not include the purchase of biomass feedstocks, see Figure 12.

In Denmark the price of biomass feedstocks with a high gas potential has increased from negative prices in the 1990s, when biogas plants were paid a fee for treating the “waste”, to today when the biogas plants have to compete and the waste has become a valuable “biogas resource”. The higher operational costs of the Danish plants are related to higher transport costs, higher energy consumption for heating and stirring, and higher personnel costs. Mexico has a more advantageous climate, so not all the anaerobic reactors and digesters need to be heated. This gives better opportunities for technologies like UASB, IC, and similar, which use less dry matter content. In Denmark, it would not be feasible to heat these large volumes of water.

Key figures for Mexican and Danish biogas plants		MX Plants	DK Plants
DM content in rector	%	2.90	11.75
Gas production/ton feedstock	m^3 CH_4/ton	8.28	31.07
Production costs/m^3 gas	USD/m^3	0.87	0.64
CAPEX /ton treated/year	USD/ton/year	91.45	66.11
OPEX/ton treated/year	USD/ton/year	1.61	13.29
Personnel	Jobs/1,000 tons treated	0.08	0.25

Figure 13. Key figures for 5 Mexican and 6 Danish biogas plants evaluated in this Program.

For the described plants, the resulting average production cost for one cubic meter of biogas produced on the Danish plants is a little lower than the average cost for the Mexican plants. However, this result is mainly due to the fact that the Mexican plants are underutilized. They are, in fact, treating only between one-fifth and four-fifths of the feedstock for which the plants were originally designed. If the Mexican plants were using their design capacity, they would probably have productions costs at the same level as the Danish plants.

The Biogas Tool

An Excel calculation tool for making preliminary technical and economic evaluations of biogas projects in a Mexican context has been developed and made available. The tool features a feedstock database with data on the 20 most relevant biogas substrates in Mexico.

In addition, the tool includes technical and economic data on 3 types of biogas plant: Lagoon (pond), Continuous Stirred Tank Reactor (CSTR) and the Upflow Anaerobic Sludge Blanket (UASB) reactor. Finally, the tool includes the typical energy value of biogas, depending on how the gas is utilized.

When using the tool, the user is guided through a series of input cells. The user can include an optional number of the 20 substrates as well as introduce an additional feedstock. The tool suggests an appropriate anaerobic digestion technology; however, the user is free to select the recommended option or another option. The tool requires the user to select between biogas uses: cogeneration of heat and energy, heat production, electricity generation, only biogas burning, or sale of biogas.

Based on user input and choices, the Tool calculates the annual biogas yield, the design and sizing of the main unit operations, the basic investment costs, operational costs, income streams, as well as collateral benefits of the project (mitigation of GHGs and production of biofertilizers).

It is worth stressing the flexibility of the biogas tool, since it is possible to enter specific information on a project from the characterization of the feedstock to the costs of input, energy, and economic information in general. However, it is also possible to use the information provided by the tool. In addition, the simulator offers advice on the best substrate or mixture of substrates according to the characterization.

The Biogas Tool has been tested to observe the differences in the type and quantity of feedstock and anaerobic digestion technology.

Figure 14 shows plant sizes according to technology and feedstock (dairy slurry, WWTP sludge, and red slaughterhouse). For all feedstock, the anaerobic lagoon (AL) is larger than the CSTR or the UASB reactor. However, CAPEX (Figure 15) is generally larger for the CSTR technology than for the anaerobic lagoon, whereas the UASB reactor has a lower CAPEX than the AL. However, it should be noted that the area and the cost of the land must be defined by the user, and for cases in which the required area is very large, the AL can be more expensive than the CSTR.

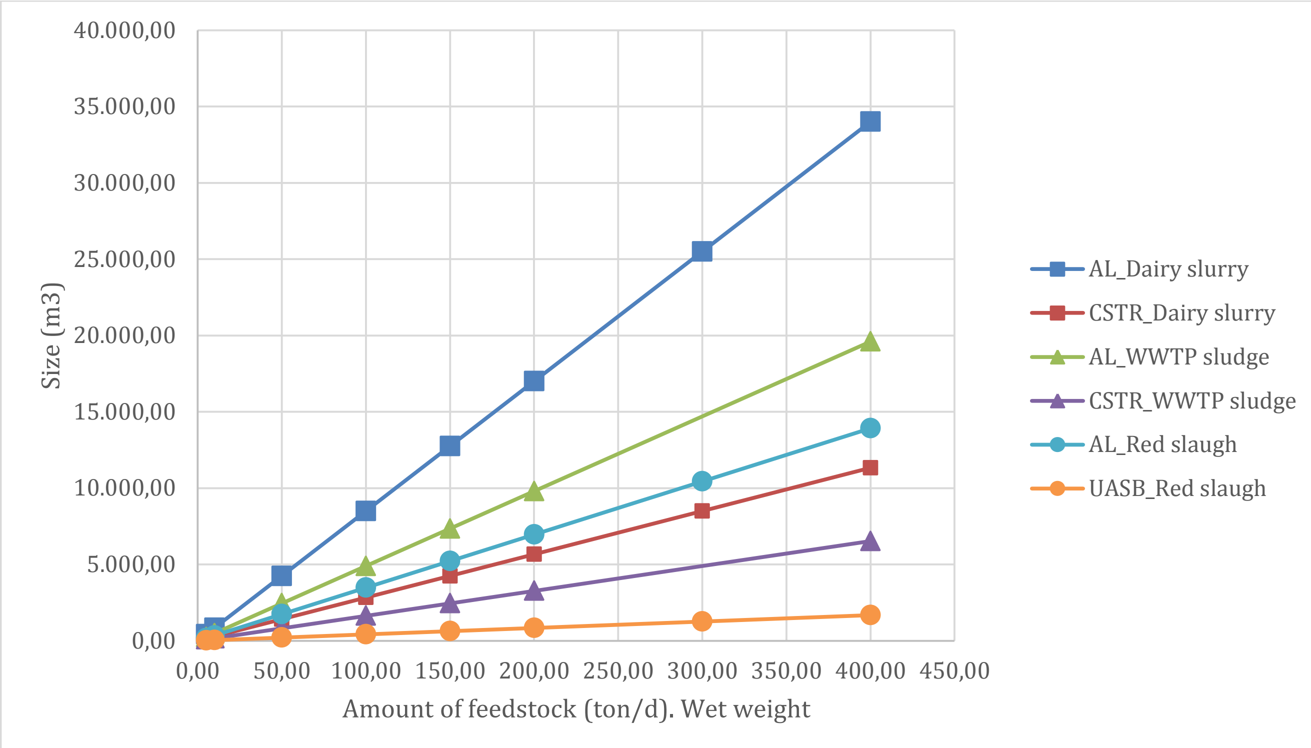

Figure 14. Comparison of plant sizes (technology and feedstock).

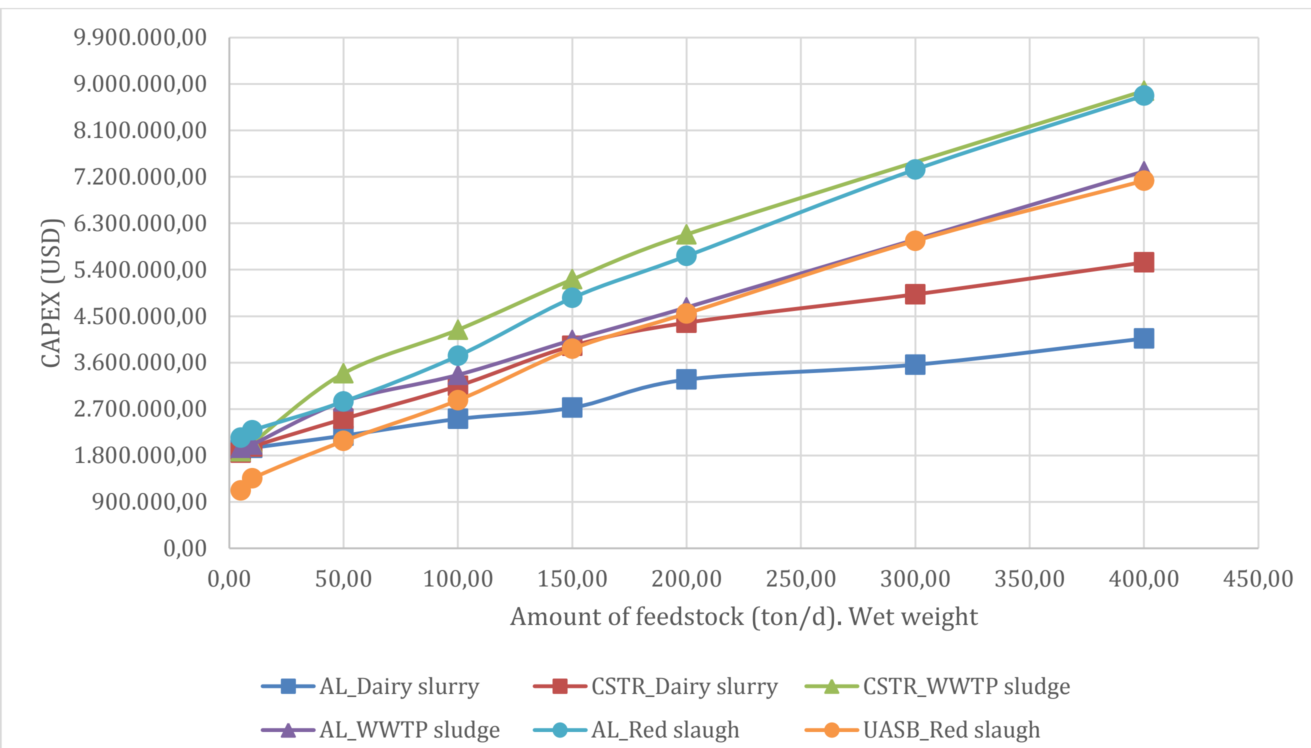

Figure 15. Comparison of CAPEX (sizes and feedstock).

On the other hand, for small amounts of feedstock, the payback time is greater for the CSTR technology for any type of feedstock (see Figure 16) due to the high degree of automation and thus higher CAPEX related to this technology. However, as the feedstock quantity increases, the payback time is reduced and becomes comparable with the payback time for AL. For larger feedstock quantities than those shown in the figure, the payback time may be even smaller for a CSTR than for the AL.

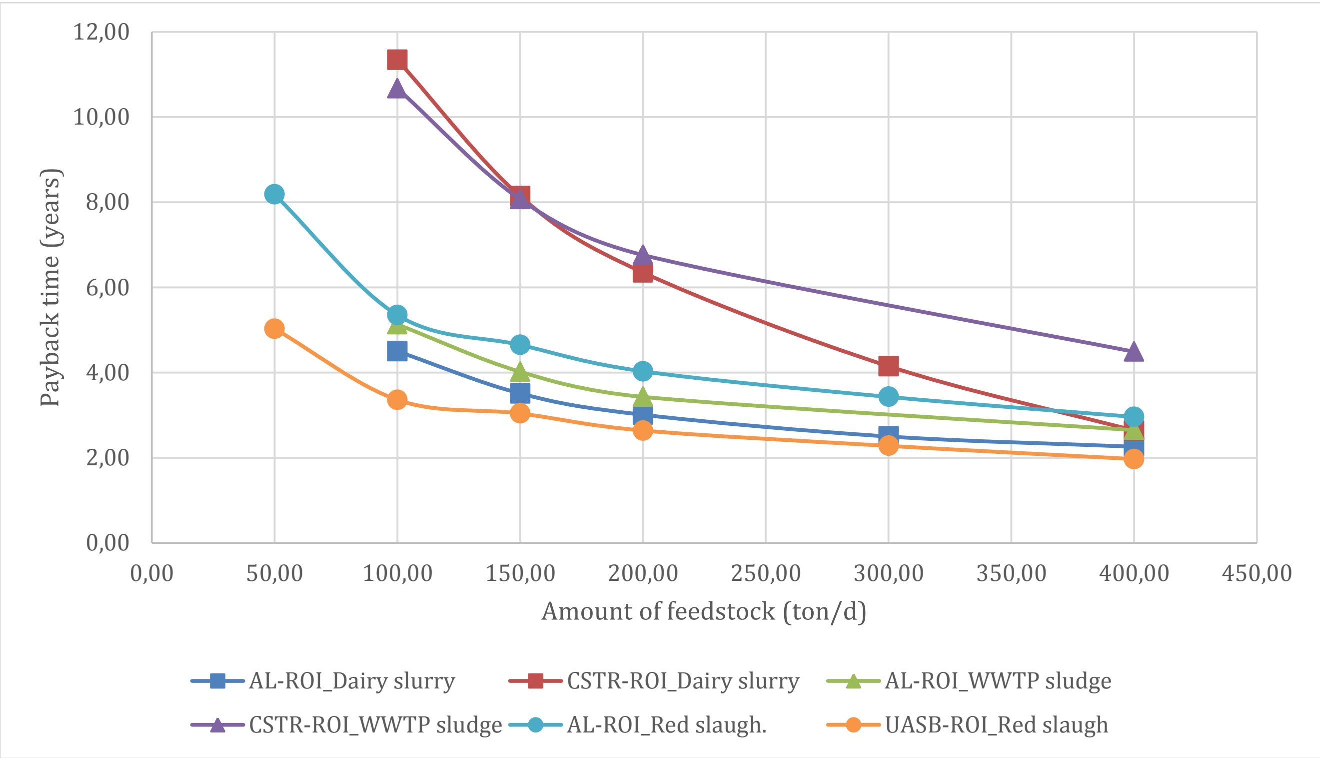

Figure 16. Comparison of the payback time (technology and feedstock).

In general, a greater viability of UASB and CSTR could be observed for large amounts of feedstock, and for small substrate flows AL seems to be more convenient. However, the function of the tool is precisely to evaluate each case with its particularities.

Pre-feasibility studies for biogas production in Sonora

In Sonora, three pre-feasibility studies were carried out:

1. Anaerobic digester at pig farms in Sonora
2. UASB at NORSON slaughterhouse, Hermosillo
3. Co-digestion of industrial residues at Hermosillo wastewater treatment plant

Anaerobic lagoon at pig farms in Sonora

In 2017, Sonora produced 206,012 pigs, or 18 % of national production. This study investigated the feasibility of installing a lagoon-type biodigester at pig farms located around 80 km west of Hermosillo.

The study was performed in collaboration with Norson S.A. de C.V - a Sonora-based company that produces, processes and sells pork meat. Norson has 89 pig farms and expects to build five new farms for around 70,000 additional pigs in 2019.

The manure from the pigs is usually collected in open ponds together with wastewater from the stables. Usually, the ponds are not covered and the methane produced in the ponds is not collected. The water evaporates and is not reused, and the nutrients are not recycled.

The proposed solution is a system for anaerobic treatment (lagoon type) of manure from 12,800 pigs.

UASB at NORSON slaughterhouse, Hermosillo

This study investigated the feasibility of an anaerobic reactor (UASB type) at the industrial site for treatment of industrial wastewater from the Norson slaughterhouse.

Norson has already installed a wastewater treatment system in order to reduce the concentration of pollutants in the wastewater before discharging it into the sewerage. The proposal is to install an Upflow Anaerobic Sludge Blanket (UASB) reactor downstream of the existing facility.

The biogas produced could replace the share of the energy consumed for electricity and heating at the Norson slaughterhouse which is today produced from fossil fuels, including natural gas. Biogas could also replace the fossil fuels used by Norson's vehicles, but this possibility was not evaluated in the study. The study assumes that the biogas will be used in a combined heat and power (CHP) unit, i.e. with cogeneration of electricity and heat.

Norson currently pays a fee for discharging wastewater into the sewerage, and an additional "pollution" fee when the wastewater does not comply with the NOM-002-SEMARNAT-1997 standard. The pollution fee is very low compared to the discharge fee. If the pollution fee were relatively higher compared to the discharge fee, it would improve the business case of this project.

Co-digestion of industrial residues at Hermosillo wastewater treatment plant

This pre-feasibility study evaluated whether organic waste from industries in the Hermosillo Industrial Park could be used as feedstocks in existing biodigesters at the Hermosillo Wastewater Treatment Plant (WWTP). This would mean that more renewable energy could be produced and it would reduce the need to deposit solid organic waste in landfills.

The study found that 8,229 tons of residues from slaughterhouses, cheese factories and other food industries could be redirected to the Hermosillo WWTP and contribute to the production of almost 450,000 m^3 methane per year.

The proposed solution includes

- re-negotiation of the contract between the owner and the operator of the Hermosillo WWTP;
- investments in a receiving tank and conditioning technology at the WWTP;
- a new “disposal fee” of MXN 100/ton to be paid by the industries to the WWTP.

The Hermosillo wastewater treatment plant in Sonora has advanced technology and highly qualified staff. At the moment the digesters are underutilized, and the biogas produced is flared. Some of the problems at the plant are the high content of sand in the primary sludge and the high sulfide content in the biogas produced, which is detrimental to the combustion engine generators. This biogas-cleaning challenge has to be addressed in order to be able to utilize the biogas for electricity production in the existing motor generators.

Pre-feasibility study of biogas production in Guanajuato

The aim of this study was to evaluate whether the Metropolitan Wastewater Treatment Plant (WWTP) “San Jerónimo” could receive wastes from slaughterhouses, as well as biodegradable wastes from municipal markets, and consider these as additional feedstocks for the sludge digester currently used at the facility. Two slaughterhouses, two markets and a cheese factory were visited, as well as agricultural areas where the digestate might be reused as fertilizer.

Unfortunately, no suitable available organic waste streams were found that it was logistically possible to use for biodigestion under the current framework conditions. Most of the organic residues at the markets were used for animal feeding, which is already an excellent and sustainable solution. A big part of the residues from the slaughterhouses were also used for animal feeding, or as raw material for candles and cosmetics, and most of the remaining residues were composted and reused as fertilizer.

The remaining residues, both at the markets and at the slaughterhouse, were dumped and mixed with inorganic residues before being disposed of at landfills or dump sites. No incentives promoted the separation and reuse of the residues, as they could freely be disposed of in open dumps. However, it was assessed that, even if relevant incentives were put in place, the amount of waste would be too small to result in an economically feasible project, the logistics taken into account.

However, some opportunities were found during the analysis at the San Jerónimo WWTP. The electricity production could be increased by changing the current means of biogas use, without using additional feedstock:

- The working load of the CHP unit could be increased from 65 % to 90 %. This would increase the efficiency of the CHP unit and the amount of electricity produced.
- Then, the thermal energy from the CHP unit could be used to heat the digester. This would reduce the biogas used directly in a boiler to heat the anaerobic digester, and it would mean that no biogas was flared.
- Potentially, this could generate savings of approx. USD 14,000/year.

If the recommendations described above were implemented, the kWh/h produced would exceed the electricity demand in the WWTP. So, the scenario is only reasonable if the surplus energy can be sold to the grid. This, however, poses a barrier, as grid connection is considered an expensive and complicated legal procedure. Alternatively, the recommendations could be a good option for a future scenario, in which the capacity of the WWTP is increased up to the design flow and the plant as a result has a higher electricity demand.

Learnings from the partnership projects

Some biogas projects can be economically viable in Mexico

The pre-feasibility studies show that even when the full waste & recycle value and the full CO_2 value of biogas are not included, biogas projects can potentially be economically feasible in Mexico in situations in which the full energy value is obtainable and large amounts of organic waste have to be disposed of in an environmentally sound way.

The pre-feasibility studies in Sonora showed a simple payback period of between 3.6 and 8 years, which is promising for entering into more detailed feasibility studies if the will and local financial support are available. The main results of the projects are summarized in Figure 17.

	Investment cost	Payback time	GHG reductions	N recycling
	USD	year	Ton CO_2/year	Ton N/year
Lagoon at pig farm (only anaerobic lagoon and biogas)	637,381	6.7	8,870	158
UASB at Norson	882,391	8	703	4
Co-digestion with recycling of N	588,176	3.6-4.8	6,751	37

Figure 17. Costs and benefits of the three pre-feasibility studies in Sonora.

Two of the projects (Lagoon at pig farm and Co-digestion of industrial waste at WWTP) would lead to significantly reduced methane emissions: 8,870 and 6,751 tons CO2e/year. The cost per m^3 of GHG emissions avoided depends on the stage of the project, as investment costs, operational costs and revenues have to be taken into account. After the payback period, the costs of the projects will have been recovered and, consequently, there will be no costs related to avoiding GHG emissions; on the contrary, there will be revenues.

The yearly amount of nitrogen in the slurry used in the lagoon system amounts to 158 tons N/year, which could potentially be recycled if the digestate could be used as fertilizer on cropland. If the same amount of fertilizer were to be bought as urea, it would require buying 768 tons of urea, amounting to an annual cost of USD 282,980, in order to get the same amount of fertilizer (158 tons N). However, as sanitary barriers currently prevent the use of pig slurry digestate as fertilizer, this is not included in the business case.

For the Co-digestion system, the payback period of 3.6 to 4.8 years depends on whether the sludge can be used as fertilizer or not. The content of nitrogen in the residues is 37.2 tons, which can be recycled on cropland or otherwise have to be deposited in a landfill for a fee.

The Guanajuato case clearly showed that for a biogas project to be feasible, it is very important to secure access to sufficient and permanent waste streams consisting of organic waste with no competitive usage. If the waste can be used for a more valuable purpose, it will – and should – sooner or later be re-directed to this purpose. Many biogas plants are running below their designed capacity because the expected amounts of feedstock fail to show up in practice. It is also an important factor that the feedstocks are collected, or are required to be collected, because the transport costs burden the business case. Transport distances are often long, reducing the feasibility of co-digestion of feedstocks from more than one producer.

Legal barriers prevent recycling of nutrients

The Sonora and the Guanajuato cases show that legal barriers still prevent efficient reuse of nutrients from biogas digestate. The study in Sonora showed that current Mexican legislation does not facilitate recycling of anaerobically treated sludge from industries or from pig farms for agricultural purposes. It is common practice in Denmark to use liquid digestate from biogas plants directly as fertilizer on agricultural land. In Denmark, the input streams are usually manure and "clean" waste streams from food production, and thermophilic processes or pasteurization of certain wastes are used to kill pathogens. See the appendix for a closer description of Danish regulations.

Mexico has no legislative framework that allows this practice. Current standards (NOMs) in Mexico allow for the reuse of treated wastewater for irrigation only if it the wastewater complies with a strict quality standard. Furthermore, a planned new standard is even stricter[22]. The existing legislative framework requires sludge-water separation[23], further treatment of the wastewater and further dewatering of the sludge, even though both the sludge and the water in some cases may be used on the same agricultural lands[24].

Adjustments are needed in order to avoid unnecessary removal of nutrients from liquids used for irrigation, but at the same time it is important to ensure that the digestate has the right quality and is safe to use before it is used for irrigation or as a fertilizer. Special treatments of certain feedstocks, such as pig manure and slaughterhouse waste, may be required in order to kill pathogens and helminth eggs.

When organic waste is used for enhanced biogas production at WWTPs, the level of treatment and final use/disposal of the wastewater is important to consider. If the treated water is discharged to natural waterways, and therefore has to comply with NOM 001, nitrogen has to be removed in the treatment process, which increases energy consumption. This should be considered before feedstocks with a high content of N are added to a biodigester at a Wastewater Treatment Plant.

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[22] <120 ppm TSS, PROY-NOM-001-SEMARNAT-2017, soon to be implemented in Mexico. This standard establishes the maximum permissible limits for pollutants in wastewater discharges into national waters bodies.

[23] The moisture content of biosolids used for soil improvement may be no higher than 85 %, see NOM-004-SEMARNAT-2002, the standard that specifies the maximum permissible limits for pollutants in sludge and biosolids intended for use in soil improvement.

[24] This was the case for the San Jerónimo WWTP and the Hermosillo WWTP.

Apart from the legislative aspect, public acceptance of the use of sludge from pig farms is an important factor to consider. It was remarkable that, in Guanajuato, farmers were accustomed to using untreated, raw wastewater to irrigate their crops. Although treated wastewater and stabilized sludge from the WWTP are a better and safer option, this option was not yet broadly accepted. If more of the locally produced nutrients were recycled, there would be less need for imported mineral fertilizers. Pig livestock in Mexico produces about 28.5 million tons of manure per year, of which only 10 % is utilized[25]. In 2017, Mexico imported nitrogenous fertilizers for USD 691 million, an increase of 11.9 % since 2016, and mixed fertilizers for USD 511.2 million[26].

Grid connection and sale of electricity are a barrier

Grid connection and sale of electricity on the market seem to be difficult and costly for small producers. It is viewed as a costly, complicated and unclear process, also for projects below 500 kW. Grid connection and the necessary administration and costs therefore represent a barrier for the supply of produced biogas electricity to the electricity grid. However, experiences from Solar PV systems show that this need not be the case in general for capacities below 500 kW[27]. However, in the Solar PV area, developer companies handle the grid connection issue for their customers and built expertise in this area. This is currently not the case in the biogas area.

Existing clean energy incentives (CELs) do not promote the biogas sector

In 2014, the Energy Industry Law introduced the Clean Energy Certificates (CELs), which are issued by the Energy Regulatory Commission (CRE). This economic instrument provides an extra premium for clean energy generation. The premium is paid for each megawatt-hour (MWh) produced and sold to the grid system. The CELs are intended to encourage the generation of clean energy to help Mexico meet its commitments under the Paris agreement[28]. As CELs are a market instrument, the price is not fixed but depends on supply and demand. Market participants may submit offers to sell CELs at any price, as well as submit bids to buy CELs at any price. The purchase/sale can be made through the CEL Market organized by CENACE at least once a year, and they can also be freely marketed through Bilateral Agreements or Long Term Auctions[29].

In the three auctions that have been carried out in Mexico, the sale price of 1 MWh plus one CEL went from USD 47.78 in the auction in 2015 to USD 33.4 in the second auction in 2016 and USD 20.57 in 2017[30]. This is positive for the solar PV and wind energy sectors, which have been obtaining the CELs, with a participation of 54 % and 46 %, respectively[31].

However, the problem is that CELs are not promoting the biogas sector due to the following reasons:

[25] DEA, IBTech, II-UNAM, 2019. Feedstock database for biogas in Mexico.
[26] http://www.worldstopexports.com/mexicos-top-10-imports/
[27] DEA, 2019. Status Assessment of Distributed Renewable Energy Generation in Mexico.
[28] KPGM, (2016). Oportunidades en el sector eléctrico en México. Global Strategy Group Energía y Recursos Naturales. México.
[29] Gobierno de México. Preguntas frecuentes sobre Certificados de Energía Limpia. Available at: https://www.gob.mx/cre/articulos/preguntas-frecuentes-sobre-los-certificados-de-energias-limpias
[30] Currently, the auctions for 2019 have been momentarily frozen by the new administration. http://www.zocalo.com.mx/new_site/articulo/no-interesa-a-cfe-energias-limpias
[31] El Economista. Subastas tira precios de energía renovable. Available at: https://www.eleconomista.com.mx/empresas/Subastas-tiran-precios-de-energia-renovable-20171123-0032.html

- Electricity produced from biogas is more expensive than electricity produced form solar PV and wind, so energy from biogas is not competitive under the current, free energy market.
- Important collateral benefits from biogas projects (discussed above) are not considered in CEL incentives or in other incentives.
- CELs only promote electricity production, whereas biogas can be used not only for electricity production but also for thermal energy and vehicle fuel production. No incentives promote these latter biogas uses.
- Many biogas projects use the energy for own consumption, which is not covered by CEL.

Technological challenges need to be addressed

Biogas production has many technological challenges. Lack of gas cleaning (removal of H_2S) is a common problem at Mexican biogas plants. However, the choice and design of biogas plant also represents a challenge, as the plant has to be adapted to the feedstocks, the site characteristics, as well as to the goals that the system is to achieve. Often, there will be a trade-off between costs and biogas production efficiency. In addition, the final disposal or use of the digestate also has to be considered.

In the agricultural sector and in some industries, the typical biodigester is usually a “covered lagoon” or “biobolsa”. This type of biodigester represents a completely different and cheaper concept than at a typical Danish biogas plant, which uses Continuously Stirred Tank Reactors (CSTRs).

A covered lagoon is made of high-density polyethylene or polypropylene. It is not heated and often also not stirred. The result is a lower and varying biogas production, as most systems rely on ambient temperature. Furthermore, in colder months less methane is produced. With no stirring, solids will settle, leading to a gradually reduced digester volume. As it is difficult to empty a digester made of polypropylene, digesters filled with sediments are often just abandoned and new ones are built as needed, which in turn will be abandoned when completely filled with sediments. Naturally, this is not the most efficient way to treat manure.

However, there are more advanced types of lagoon digester systems, with pretreatment of feedstocks, external pump stirring systems, serial digestion, and post treatment of digestate. Such features can improve biogas production, reduce the required area, and improve the recycling of nutrients, but they also increase the investment and operating costs. Another option could be to develop lagoon types with fixed concrete bottoms that only need to be emptied every 3-5 years. Whether this is feasible has not yet been evaluated. In lagoon systems, the solids are often separated from the liquid before the liquid enters the anaerobic lagoon in order to reduce the organic load of solids, reduce the volume of the lagoon, and /or reduce sedimentation. In this practice, a part of the methane potential is lost.

Danish biogas digesters are made of steel or concrete and they are fully stirred and heated. They can co-digest different feedstocks and are a more costly investment. They are adapted to a colder climate and to Danish manure management systems, in which all manure is handled and stored as slurry. The solids are not separated from the liquid before the liquid enters the digester. Nor is the digestate separated into solids and liquids before it is applied to cropland in the spring.

However, attempts to directly transfer technology from one country to another often fail. Designing a biodigestion system which is adapted to the feedstocks and the local conditions in Mexico, and which aims to meet specific objectives and efficiencies at the lowest degree of complexity and costs and with maximum benefits, remains a complex challenge.

Waste management is the responsibility of the municipalities

The service of environmentally sound waste treatment is often not priced in Mexico. Moreover, application of environmental law is subject to lack of surveillance, enforcement and real penalties due to the political cost of its application. This is a challenge for the promotion of biogas, because biogas offers a cheaper solution for the treatment of organic waste than other technologies (e.g. incineration). If consumers and companies had to pay the real costs of waste treatment, including mandatory separation of organic and in-organic waste, this would substantially improve the biogas business case.

The municipalities are usually responsible for the collection of wastewater and for the transportation and handling of wastes from households, food markets and the service sector. Currently, these waste producers do not pay the real costs of waste management[32]. For poor municipalities, waste handling consumes a large share of the municipal budget, and the municipalities cannot afford to operate their wastewater treatment plants properly, nor can they afford to establish controlled landfill sites, which results in uncontrolled dump sites.

Companies have to handle their own waste, and they typically pay a fee for depositing waste at landfills. In these cases, the waste treatment service has a price, and without this, the Sonora-cases would not have been feasible. However, the fee for disposing of waste at landfills is very low, which poses a barrier to treating the organic wastes in an anaerobic digester instead of directly disposing of it at landfills, or even worse, at dump sites.

Companies also pay fees if they discharge their wastewater into the sewage system leading to a municipal wastewater treatment plant. However, there are no strong incentives against disposing of organic waste at landfills or against discharging liquid organic matter to the sewage system. A higher penalty for doing this might encourage more to choose the treatment solution instead of the “easy” solution that involves dumping or discharging without treatment.

Co-digestion projects would be easier and more feasible if the legislative requirements for source-separation of organic waste from households and companies and for appropriate separation and disposal of oil and grease from restaurants were enforced in practice.

Market development could lower costs

An immature biogas-sector and market lead to higher costs. During the projects, it was discovered that the costs for motor generators and other equipment in Mexico were surprisingly high compared to Denmark and Europe. This must be due to the fact that the market is immature and the fact that there are only very few providers of such equipment. If the biogas sector develops in Mexico, the prices can be expected to fall. This will improve the business case for biogas in Mexico.

[32] http://www.foroenres2018.mx/presentaciones/8_10%20de%20oct%20Magda%20Correal.pdf

Educational and organizational issues

There is limited knowledge about robust low-cost solutions, gas cleaning, and maintenance in Mexico. At biogas plants, all aspects of the operation have to be taken care of. Several times during the projects, situations were observed in which a problem, e.g. removal of sulfur from the biogas, was not solved and the gas was flared, severely diminishing the business case. Many of such problems could relatively easy be solved through different kinds of practical, educational activities and experience sharing.

Biogas is an organizational challenge. All stakeholders and authorities must react to ”the whole picture” at the same time in order to realize the benefits of biogas. In Sonora, the industries, the wastewater company, the farmers, and the authorities had to work together in order to realize one of the biogas cases. This demands a high degree of confidence, collaboration, and clear agreements.

Part 3. Possible steps forward

As we have seen, biogas production represents a way to treat organic waste, produce renewable energy, reduce methane emissions and facilitate recycling of nutrients. We have also seen that a number of barriers prevent wider utilization of this technology.

In Part 1, we estimated that the total value of biogas could exceed 40 US¢/m^3 methane within a decade in Mexico, and that the value could become even higher in the long term. Often, however, only the "energy value" is obtainable for the investor, which is often not enough to develop viable projects, because biogas as a renewable energy source is more expensive than wind and solar PV. In order for biogas to be viable in general, the waste & recycle value and the fossil CO_2emissions avoided must also be monetized.

We know from Mexican and Danish experiences that biogas technology can actually work, but also that projects have to be very carefully designed and that a number of conditions must be fulfilled in order to actually achieve a durable and sustainable project and harvest the anticipated benefits. A single unfulfilled condition can be enough to influence the business case negatively and make the project unfeasible. We also learned from Danish experiences that government support schemes that are too generous can lead to unnecessarily high socioeconomic expenses and inappropriate stop-go policies.

An investment and follow-up program

To support the biogas development in Mexico, a new investment and follow-up program should be considered. A lot of knowledge and experience on biogas already exists in Mexico, and it is important to build on and strengthen this asset. An investment and follow-up program could be based on previous experiences (e.g. FIRCO). However, it should be reshaped and strengthened with regard to the following important aspects:

- Improving the quality of plant/digester designs by developing and ensuring compliance with national recommendations and standards.
- Ensuring gas cleaning, especially for removal of H_2S from biogas.
- Developing grid connection guidelines for electricity generation. The guidelines should be accessible to end users and there should be a telephone number and an e-mail address for queries.
- Exploring and analyzing different utilizations of biogas or how to replace fossil fuels in the most valuable way.
- Training plant owners, producers and operators in operation, monitoring and control of the digesters.
- Remote follow-up in order to assess operational performances and provide timely alerts and corrective measures.
- Organizing meetings and workshops that strengthen collaboration and sharing of experiences and knowledge on plant operation and performance.
- Developing a Data Base with information on residues (quantity, quality, availability, contacts) available from main producers.

- Integrating information on successful cases of recycling of nutrients for crop production and the use of digestate (biosolids) as safe organic fertilizers and soil amendment.
- Capacity building on partnership agreements and stakeholder participation in biogas projects.
- A thorough assessment of feedstock availability and proper management at site, transportation conditions and logistics.
- Legal advice to investors regarding contracts guaranteeing feedstock availability, proper functioning of equipment, and delivery of the promised biogas quality.
- Enforcement of a culture of payment for the service of re-collection and treatment of residues.

An important requirement for a successful and stable biogas production in Mexico is the development of *Mexican biogas technology and know-how.* Many of the digesters currently marketed (primarily covered lagoons) have not found the right balance between low investment and operation costs, easy operation, efficient energy production, and appropriate nutrient and water recovery.

The investment and follow-up program could facilitate such a development if investment support is granted on the condition that the biogas is utilized for energy, and if enough resources are devoted to activities helping stakeholders to overcome common challenges like the ones listed above.

Such a program could both support new projects and the recovering of existing systems under poor performance, aiming at improving biogas production and utilization.

One beneficial result could be the development of biogas technologies adapted to Mexican livestock units, food industries, organic household waste and wastewater treatment facilities. The program could prepare "success stories" presenting well-managed biogas projects or new projects which may be identified as demonstration facilities. This would be crucial in order to increase the knowledge level and public acceptance, and it would result in a stronger market for biogas solutions in Mexico.

The newly established Biogas National Council (CNBiogás) could be a relevant partner for such a program. Private companies, universities, research centers, non-governmental organizations and consultants could participate, presenting their solutions and sharing results and experiences with other participants in the program and to other stakeholders.

The program could be targeted at specific sectors or divided into sub-programs, such as:

a. Biogas in agriculture and in the food industry, in collaboration with SAGARPA[33],
b. Biogas from wastewater treatment plants, in collaboration with CONAGUA[34]
c. Biogas treatment of urban bio-waste, in collaboration with SEMARNAT[35]
d. Small scale biogas in rural areas, in collaboration with Secretaría del Bienestar

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[33] Ministry of Agriculture, Livestock and Fishery
[34] National Commission of Water
[35] Ministry of Environment and Natural Resources

Other ministries involved in this programs should be SENER[36], SSA[37], SEP[38], and SECTUR[39]. The Mexican government should be included, not only at federal level, but also at state and municipal levels.

a. Biogas in agriculture and in the food industry

Focus: To improve the handling of manure, biogas production and recycling of nutrients in the livestock industry in Mexico, as well as to promote the proper treatment of residues in the food industry in Mexico. The starting point could be an assessment of current methane emissions and opportunities for recycling of nutrients in the sector. The program could include a *voluntary agreement* with relevant industry organizations on an action plan aimed at reduced emissions and increased recycling of nutrients.

b. Biogas from wastewater treatment plants

Focus: To increase and optimize biogas production and utilization at wastewater treatment plants. The goal would be to reduce energy consumption from the grid through biogas utilization and to promote the usage of treated sludge on cropland by establishing pilot agricultural plots.

c. Biogas of urban bio-waste

Focus: To improve the urban waste handling systems in Mexico. A national waste initiative could seek to motivate states and municipalities to work closer together on this challenge. For example, financial resources could be made available for front-runner states or municipalities with successful experiences resulting in improved waste management practices. A small number of states could be selected for a next step involving the successful replication of experiences to municipalities.

d. Small-scale biogas in rural areas

Many existing biodigesters in Mexico are small-scale household digesters producing biogas for cooking stoves or heating purposes, and replacing firewood. Many of these digesters are well run and both the biogas and the digestate are used. This point to the fact that biogas can play a role in mitigating social inequality and poverty, mostly in rural areas. On this basis, the development of small-scale biogas production could result in an important positive social, economic and environmental impact.

Incentives and framework conditions

As we have seen, biogas production has to be regarded as an element in an integrated treatment system for organic waste in connection with the production of renewable energy. The following conditions must be in place to make biogas production viable:

1. A suitable waste stream with no more valuable use must be available which requires appropriate treatment in order to comply with discharge regulations or in order to improve the local environment and/or in order to recycle nutrients.

[36] Ministry of Energy
[37] Ministry of Public Health
[38] Ministry of Public Education
[39] Ministry of Tourism

2. The biogas project must provide a lower carbon footprint compared with the current waste handling practice due to reduced methane emissions from the waste.

3. The biogas project must allow for the replacement of fossil fuel.

The general framework conditions could be adjusted in order to allow biogas to be produced in situations in which all three criteria are fulfilled.

This would allow for a new paradigm in Mexican society (and ideally within the Mexican legal framework) with the notion that anaerobic digestion is a suitable way to dispose of liquid or solid wastes with high organic content, because the energy (biogas) and resources (nutrients) may be recovered.

It is complicated to establish balanced and supportive framework conditions for biogas production, as several sectors and aspects are involved: energy, environment, agriculture, society and waste. Similarly, several governmental levels are involved: the federal, state and municipal levels. However, important elements to consider when creating supportive framework conditions for biogas are:

- Grid connection and distributed generation models. Existing models could be communicated or improved.
- A guaranteed value of biogas for energy purposes. This could be for electricity, industry purposes or transport. Clean Energy Certificates could be a part of this, but it is recommended that the number of CELs for each type of clean energy is defined beforehand and that auctions are carried out separately.
- Easier access to financing, e.g. through bank loans.
- Possibilities and conditions for power purchase agreements between companies, and between authorities and companies.
- The future regulation of large livestock producers:
    - Appropriate treatment of manure, including biogas production and recycling of nutrients, could be a condition for new/increased livestock production.
    - Bigger companies could be required to calculate and publish their GHG emissions together with their mitigation commitments.
- A ban on, or increased fees or penalties for, the disposal of organic waste at landfills, along with the enforcement of regulation that prevents the use of open dump sites or even landfills.
- Mandatory gas collection from all new sanitary landfills and from existing landfills above a certain capacity.
- Requirements on future WWTPs concerning biogas production and use. WWTPs with higher flows than 250 lps could be required to have anaerobic digester and biogas use.
- Recycling of nutrients: a technology catalogue of treatment methods that produce "safe" biofertilizers from organic waste could be developed.
- Biogas as a biofuel in the transport sector. Biogas could be recognized as a biofuel in relation to blending obligations for transport fuels.

If Mexico continues to pursue a development towards a fossil-free energy system, wind and solar PV will likely become more dominant in the electricity production at some point in time. In such an energy system, the value of biogas as a replacement for fossil natural gas, as a transport fuel, or as an integrator of wind and solar power will increase because wind and solar are fluctuating energy sources that need back-up renewable fuels.

Until the value of biogas as a renewable fuel increases, the challenge is to develop the biogas sector in Mexico by joining efforts to handle the waste challenges and take care of the environment and GHG emission mitigation. Picking the low-hanging fruit first and maximizing benefits would be a sound policy for supporting the development of the biogas industry in Mexico.

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Abbreviations:

DEA: Danish Energy Agency
II-UNAM: Engineering Institute of National Autonomous University of Mexico
IPICYT: Potosinan Institute of Research on Science and Technology.

Appendix: **Nutrient recycling and regulation in Denmark**

Recycling nutrients, substituting industrially produced mineral fertilizer, becomes increasingly important because of the depletion of the global natural reserves of phospherous. Digestate from biogas plants is an excellent plant fertilizer, rich in nutrients and organic matter, and with more accessible nutrients than raw manure. In Denmark and Europe both raw manure/slurry and digestate from biogas plants is used directly as fertilizer for crops without any further processing.

In Denmark the Ministry of Environment and Food are responsible for the regulation of the use of manure as fertilizer and for implementing relevant EU legislation[40]. The most important regulation is:

- A statutory order regulating manure management from livestock production[41]
- A statutory order regulating the use of fertilizers by agriculture and on plant cover[42]
- A statutory order regulating the use of organic waste as fertilizer on farmland[43]
- The use of residues from animals e.g. slaughterhouses is regulated by Danish Veterinary and Food administration[44]

Important elements in this regulation are:

- Livestock manure is allowed to be used untreated on agricultural land. The same holds for content of the digestive tract, milk and milk-based products.
- Manure and slurry must be stored in tight and covered storage tanks. Permits are needed and documentation for compliance with requirements for strength, density and durability has to be provided. The requirements are stricter near water extraction plants, streams, lakes and coastal waters.
- Nutrients in manure and slurry must be used as fertilizers on crop land. The only alternative is incineration on approved incineration plants.
- Ceilings limit the quantities of N and P per hectare that can legally be applied to agricultural land.
- If a farm has more manure than can be legally applied on the farms own land, there must be a written agreement that the excess manure is allocated to another farm, a biogas plant or an incineration plant.
- Application of liquid fertilizer or degassed biomass must take place with certain technologies in order to avoid odor and emissions
- Application of liquid fertilizer or degassed biomass must take place just before and in the growing season in order to use the nutrients efficiently and avoid leakages
- Certain types of organic waste can be applied to farm land without permission, other types need permission. Both have to apply limits for heavy metals, environmentally harmful substances and physical impurities.

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[40] https://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:32018L0851&from=DA

[41] https://www.retsinformation.dk/Forms/R0710.aspx?id=202840

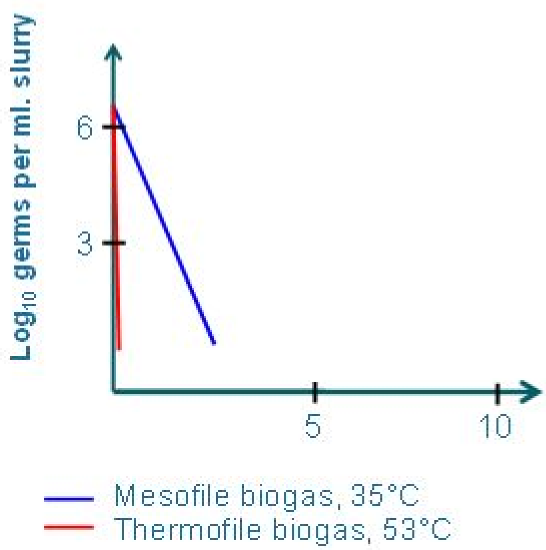
[42] https://www.retsinformation.dk/Forms/r0710.aspx?id=202172

[43] https://www.retsinformation.dk/Forms/R0710.aspx?id=202047

[44] https://www.foedevarestyrelsen.dk/Leksikon/Sider/Biogasanl%C3%A6g.aspx

- Organic waste must undergo specified hygienically justified treatments before land application: stabilization, controlled composting or controlled sterilization (70 degrees C in 1 hour)[45] depending on type.
- Animal by-products have to apply with https://eur-lex.europa.eu/legal-content/DA/TXT/?uri=celex%3A32009R1069. This regulation bans the use of risky animal by-products for feed. High risk material, such as animals died from certain diseases, must be burned. Lower risk materials can be used for biogas, but sometimes only after pressure sterilization. In order to handle such materials the biogas plant has to have an approved sterilization unit.

The Danish regulation builds on the experience that anaerobic digestion efficiently eliminates relevant pathogens in Denmark. The figure below is based on experiments done by a veterinary follow-up program for biogas production in Denmark in 1998.



Date	Before	After
Mar. 18	1,300,000	<5
May 13	140,000	<5
July 15	690,000	<5
Sept. 9	9,000,000	<5
Nov. 11	62,000	<5

Test results from Ribe Biogas, bacteria per ml. slurry

[45] Animal by products have to apply with https://eur-lex.europa.eu/legal-content/DA/TXT/?uri=celex%3A32009R1069. This regulation aims at avoiding health risks by banning the use of animal by-products giving rise to a risk of transmissible spongiform encephalopathy (TSE) for feed. It states that high risk material (category 1) must be burned. Lower risk materials (category 2 and 3) can be used for biogas but sometimes only after pressure sterilization.