

Energy recovery from methane in wastewater treatment

Case studies in El Salvador,
Mexico and Panama

Silvia Saravia Matus
Diego Fernández
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Natalia Sarmanto



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This document was prepared by Silvia Saravia Matus, Economic Affairs Officer with the National Resources Division of the Economic Commission for Latin America and the Caribbean (ECLAC), and Diego Fernández, Pedro Chavarro, Alfredo Montañez and Natalia Sarmanto, all of whom are consultants for the same division.

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Abstract

There is abundant evidence of the benefits—which include the ability to make use of by-products such as water, nutrients, biosolids and energy—of integrating circular economy principles into drinking water supply and wastewater treatment systems. However, despite the environmental and social returns that it affords, this approach is not recognized as a profitable option for sanitation utilities.

While numerous studies in the region have demonstrated the financial viability of capturing methane for energy generation in wastewater treatment plants (WWTPs) with installed capacities exceeding 500 litres per second (l/s) (Saravia Matus and others, 2022a), little attention has been given to smaller WWTPs. Since wastewater treatment systems in the region typically operate on a smaller scale, this study analyses the financial viability and social, economic and environmental benefits of using methane for cogeneration in 10 WWTPs having installed capacities of under 500 l/s in selected municipalities of El Salvador, Mexico and Panama.

The combined results for the three countries indicate that the efficient utilization of methane in the plants in El Salvador, Mexico and Panama that were studied would require an investment of US\$ 6.82 million. Such an investment would make it possible to generate 8,846 MWh/year of electricity, which would translate into annual savings amounting to US\$ 1.52 million. This means that the investment could be recovered within 6.5 years, on average, while reducing CO₂-equivalent emissions by 5,425 tons per year (equal to the emissions associated with the consumption of 2,000 cubic metres of diesel fuel each year, or the per capita emissions of 3,390 persons in Latin America and the Caribbean).¹

The findings of this study therefore point to the advisability of conducting projects in the region that focus on utilizing the methane emissions of WWTPs as an energy source. The study therefore offers recommendations concerning the replication and expansion of the analysis of the potential for harnessing the methane produced in small and medium-scale WWTPs. It also proposes strategies for

¹ Estimated on the basis of per capita emissions documented by the World Bank for Colombia in 2020 of 1.6 tons/year.

promoting different options for financing climate action. This underscores the importance of placing priority on high-impact projects aimed at reducing emissions and deriving the associated economic, social and health benefits from those efforts.

The study also highlights the importance of building water and sanitation utilities' technical, operational, policy-based and forward-planning capacities. The present challenge is therefore to devise ways of enhancing the sector's institutional capacities, not only for the application of circular economy principles in water management in the region but also for meeting the challenges associated with the current innovations being driven by artificial intelligence and big data solutions. Doing so will make it possible to leverage activities and projects that will make a direct contribution to the achievement of Sustainable Development Goal 6.

Introduction

The application of circular economy principles in the field of water resource management is of key importance in ensuring access to quality water and sanitation services. Recovering methane as an energy source both reduces the negative environmental impacts of plant operations and boosts their technical and financial efficiency. This approach addresses a range of different issues and, in so doing, helps to set up a virtuous economic, environmental and social circle.

According to the World Bank (2023), methane abatement or “bending the methane curve” is the fastest and most profitable strategy for ensuring that the goal of holding the rise in global temperatures to 1.5°C remains within reach while, at the same time, supporting the livelihoods of billions of people. It is estimated that 20% of global methane emissions come from the anaerobic decomposition of food and other organic matter present in landfills, open dumps and wastewater processing plants (UNEP/Climate and Clean Air Coalition, 2021). In discussing how to overcome the climate and development challenges posed by methane emissions, the World Bank has drawn attention to the pivotal role to be played by the waste treatment sector, which has set itself the goal of reducing methane emissions by at least 35% by 2030 and by nearly 55% by 2050 relative to 2020 levels, in line with the goals of the Paris Agreement (2016). The measures recommended by the United Nations Environment Programme (UNEP) for reducing methane emissions in the water and sanitation sector include the modernization or upgrading of municipal wastewater treatment systems, including secondary and tertiary anaerobic treatment for the recovery and use of biogas (UNEP/Climate and Clean Air Coalition, 2021).

The use of methane as an energy source has become a valuable option in various countries of the region. According to a study conducted by Saravia Matus and others (2022a), it is estimated that 75 WWTPs located in Colombia, Costa Rica, Mexico, Peru and the Plurinational State of Bolivia having capacities ranging between 500 and 4,000 l/s could capture 103 million cubic metres of methane per year. With that amount of methane, they could generate 360,725 MWh/year, which is equivalent to the amount of energy consumed annually by over 200,000 people (approximately 412,000 MWh/year of energy).

This study endeavours to identify and analyse similar opportunities in small-scale municipal wastewater treatment systems in El Salvador, Mexico and Panama by taking a closer look at WWTPs with treatment capacities between 50 l/s and 500 l/s. The sample used for the purposes of this analysis is composed of 10 WWTPs: the San Juan Opico, Ciudad Futura and Metapán plants in El Salvador; the San Martín de las Pirámides, Centenario, Bicentenario and San Miguelito plants in Mexico; and the Montijo, Puerto Armuelles and Soná plants in Panama. These facilities were selected on the basis of criteria of opportunity, replicability and local interest in the study.

The first step was to explore the many benefits to be derived from a circular form of wastewater management. The next step was to estimate the energy potential of methane emissions, bearing in mind the different technologies, organic loads and levels of utilization of installed capacity of each WWTP as measured using the methodology proposed by Saravia Matus and others (2022a) based on the work of the Intergovernmental Panel on Climate Change (IPCC) (2006 and 2019). The next step was to calculate the estimated investment needed to generate electricity from that methane and the economic benefits that such a project would yield. These data then served as the basis for an evaluation of the financial viability of tapping the methane in each of these WWTPs over a time horizon of 20 years. The effect of the reduction in CO₂-equivalent emissions for each WWTP was also calculated. Lastly, conclusions were drawn based on these findings, and recommendations were developed for replicating and scaling up these processes in the countries of the region.

The estimates of the cost of using methane as an energy source and the size of the associated investments cited in this study were initially prepared by ECLAC based on information supplied by the National Water and Sewer System Administration of El Salvador (ANDA), the Salvadoran Water Authority (ASA), the National Water Commission of Mexico (CONAGUA), the Water Commission of the State of Mexico (CAEM), the Quintana Roo Drinking Water and Sewerage Commission (CAPA), the National Water and Sewer System Institute of Panama (IDAAN) and the National Water Council of Panama (CONAGUA). These estimates were then validated at training workshops organized by ECLAC in July 2023 in Quintana Roo, in September 2023 in San Salvador and in March 2024 in Panama City in coordination with the above-mentioned agencies. These workshops were attended by nearly 100 participants, including representatives of local and national water and sanitation agencies in each of the countries covered by this study, along with technical personnel in charge of operations in these WWTPs. The participants' assessments of these workshops reflected a high level of satisfaction and interest in promoting investments in this area within the water and sanitation sector.

The analysis presented in this study was subject to some limitations in relation to the estimation of these plants' current levels of methane emissions. As a result, certain assumptions had to be made in estimating how much the use of methane as an energy source would reduce the emissions of each WWTP. These assumptions were developed and checked with the national counterpart agencies.

I. Harnessing methane emissions and electricity cogeneration: taking a circular economy approach to wastewater treatment

ECLAC sees the circular economy as a model for changing production patterns in ways that will optimize the use of available resources and spur the development of innovative processes and new business models that will yield environmental benefits (by easing the pressure on natural resources while reducing emissions and pollution), economic benefits (by spurring new activities and increasing the efficiency of production chains) and social benefits (by creating green jobs that provide people with a better quality of life). Main objectives are to reduce the extraction of finite natural resources and lessen countries' import dependency by creating and leveraging a cycle in which materials and products are kept in use for as long as possible, thereby minimizing the generation of waste (de Miguel and others, 2021).

In this conceptual construct, water is recognized as being a finite resource and, as such, one whose use should be limited and regulated whenever possible. Its reuse should also be maximized in order to avoid the negative externalities associated with water shortages or a deterioration in water quality. The circular economy is therefore a very important management model for the operationalization of wastewater treatment, since this innovative approach affords a whole host of benefits, especially in terms of the recovery of water, biosolids, nutrients and, of course, energy.

These countries' municipal wastewater is 99.8% water, which means that, once treated, it can be used for a variety of purposes, including crop irrigation, tourism and landscaping, industrial processes and the replenishment of aquifers, among others. A number of technologies and systems are now available for treating wastewater to make it suitable for household use, particularly for flushing toilets (López and others, 2017).

In addition, nutrients can be extracted from the sludge left over from earlier stages in wastewater treatment processes. This can be done by using as simple a method as dumping raw sludge from WWTPs on farmland, by using non-traditional toilet designs that can separate out bodily fluids for use

in soil enrichment or by employing more sophisticated wastewater treatment technologies to recover phosphates through struvite crystallization (Mo and Zhang, 2013). Lastly, with regard to the upcycling of the energy deriving from wastewater treatment processes, which is the main focus of this study, the findings indicate that it is indeed possible to make use of WWTP by-products to generate energy in a gaseous state.

This can be done by means of anaerobic (without the use of oxygen) digestion—as opposed to an aerobic form of processing—of municipal wastewater. Methane gas can also be generated through sludge digestion in both anaerobic and aerobic treatment plants. The anaerobic digestion of wastewater and sludge generates methane gas (CH₄) as a by-product. This gas can be employed in various on-site processes, such as to heat up the sludge digester in order to increase the efficiency of the anaerobic digestion process or to dry out the sludge in order to reduce its volume prior to its final disposition (López and others, 2017). This biogas can also be used to generate energy that can then be fed into the public distribution systems, or it can even be further purified for direct use as a fuel for motor vehicles or for industrial and/or residential use.

A municipal wastewater treatment plant's total methane production, measured in terms of a unit of time (m³/day or a similar metric), is mainly determined by the treatment technology being used, along with the concentration and composition of the organic matter in the wastewater, which will vary depending on: the supply of drinking water, the socioeconomic level of the population group in question, the infiltration of rainwater into the sewerage system, the type of sanitation facilities involved and the types of activities conducted in the catchment area (Von Sperling, 2005). The temperature at which it is processed and the characteristics and efficiency of the technology used for that purpose are also factors (López and others, 2017).

For example, an anaerobic WWTP using a methane generator that takes in material containing 100 tons of chemical oxygen demand (COD) over the span of a year can produce nearly 285 MWh/year (Hernández, 2021).² This is equivalent to the amount of energy used in a year by 158 households. This technology also has the advantage of delivering a six- to eightfold reduction in the volume of sludge to be handled by the treatment facility, which will provide additional benefits in terms of the reduction of the cost of biosolid treatment and final disposition.

Energy recovery through the anaerobic digestion of the sludge resulting from aerobic wastewater treatment processes is also feasible, allowing methane to be captured and then used in energy generation and cogeneration. This environmentally beneficial technique can reduce treatment plants' greenhouse gas (GHG) emissions by 21% and can supply as much as 14% of the energy needed to run the plant (Aguilar and Blanco, 2018). In fact, in large WWTPs such as the El Trebal Mapocho treatment plant in Santiago, Chile, 86% of the energy used by the plant is renewable energy generated from recovered methane (Aguas Andinas, 2020).

There is also documentary evidence that, using an aerobic wastewater treatment technology, the Zona Noreste WWTP in Villa Hermosa, Mexico, could produce biogas with an energy potential equal to 128% of the plant's energy demand (Ramírez, Medrano and Escobedo, 2020). Aguilar and Blanco (2018) have reported that the Ahogado WWTP, which uses an activated sludge process, and the San Pedro Mártir WWTP, which uses dual sludge processing, generate up to 78% and 68%, respectively, of the electricity needed to run the plants.

According to UNEP/Climate and Clean Air Coalition (2021), 20% of the methane emissions associated with human activity are accounted for by the waste sector. This includes the final disposition of solid waste and wastewater treatment. Methane is a powerful local air pollutant that contributes to

² This example is cited simply in order to provide a frame of reference, since the efficiency of a generator and its level of output will depend on the size/capacity of the plant, its location and other factors mentioned above.

the formation of ozone and is the GHG that makes the second-largest contribution, after carbon dioxide, to climate change. Moreover, it is 28 times more powerful than CO₂ in trapping heat over a 100-year timespan and 84 times more powerful over a 20-year time horizon, and it accounts for approximately 30% of the global warming experienced to date (UNEP/Climate and Clean Air Coalition, 2021; European Commission, 2023). A 45% cut in methane emissions would avert 260,000 premature deaths, 775,000 hospital visits for the treatment of asthma, 73 billion hours of work lost owing to extreme heat and 25 million tons of crop losses per year (UNEP/Climate and Air Coalition, 2021).

Thus, the adoption of a circular economy approach to wastewater treatment would provide valuable environmental, economic and financial returns in terms of the sustainability of water supply and sanitation systems and for the companies that run them (Rodríguez and others, 2020). The application of circular economy principles in wastewater management and in resource recovery and reuse can transform sanitation from a costly service to a self-sustaining one that clearly adds value to the economy (Rodríguez and others, 2020).

II. Economic, environmental and social viability of harnessing the energy potential of methane in WWTPs having a capacity under 500 l/s: case studies in El Salvador, Mexico and Panama

Since the viability of utilizing methane as an energy source in WWTPs having a capacity of over 500 l/s has been well documented (Nolasco, 2010; Silva, Mambeli and Tiago, 2016; Saravia Matus and others, 2022a) and, in view of the proliferation of WWTPs with a capacity of less than 500 l/s in Latin America and the Caribbean—in Mexico, Colombia and Peru alone there are more than 3,161 WWTPs operating at that smaller scale (Saravia Matus and others, 2022a)—this study has focused on the financial viability of methane recovery in WWTPs with capacities below that threshold in selected municipalities in El Salvador, Mexico and Panama.

As a basis for this analysis, an initial estimate was prepared of the emissions associated with each treatment process in each WWTP, along with the amounts of recoverable methane and of the electrical energy that could be generated from it. A detailed financial viability study was also conducted that covers the environmental, social and economic benefits that could be derived from harnessing methane for the cogeneration of energy in 10 WWTPs (four in Mexico, three in El Salvador and three in Panama).

These 10 WWTPs were selected on the basis of a joint study carried out with the National Water and Sewer System Administration of El Salvador (ANDA), the Salvadoran Water Authority (ASA), the National Water Commission of Mexico (CONAGUA), the Water Commission of the State of Mexico (CAEM), the Quintana Roo Drinking Water and Sewerage Commission (CAPA) and the National Water and Sewer System Institute of Panama (IDAAN). The selection criteria are described below:³

³ In the case of Mexico, although this was not an explicit selection criterion, three of the plants are located in the State of Quintana Roo, a strategic zone for the country because of its importance as a regional and international tourist destination. The fourth WWTP in Mexico is located in San Martín de las Pirámides, a municipality of the State of Mexico that is of great importance because it encompasses a significant portion of the Teotihuacán archaeological zone containing the awe-inspiring Pyramid of the Sun.

- (i) **Opportunity:** Priority was assigned to WWTPs that would be able to capture and utilize methane as an energy source for use in generating electricity or heat or in other applications with a view to maximizing economic and environmental benefits.
- (ii) **Replicability:** Plants were selected on the basis of their potential to serve as replicable models for projects in different regions of El Salvador, Mexico, Panama and other Latin American and Caribbean countries. WWTPs were therefore selected that have the capacity to serve more than 30,000 people (50 l/s) but fewer than 200,000 (300 l/s). This range was sufficient to evaluate the viability of the implementation of such systems in diverse geographical, climatic and demographic contexts.
- (iii) **Local interest:** Priority was also given to WWTPs whose operators and local governments displayed a willingness to develop and maintain a short- and medium-term project of this sort and a commitment to that undertaking. The participation of local actors is crucial to ensure the successful operation of methane recovery facilities over the long term, engage the community in this effort and promote a sense of ownership of the associated technology.

An additional consideration was location. Plants were selected, in part, on the basis of their strategic location for the promotion of a sustainable approach to wastewater treatment that will both help to protect the environment and give the surrounding area an economic boost while bringing in more tourism. Synergies between tourism and the utilization of methane in these WWTPs have made it possible to open up opportunities for promoting the adoption of sustainable practices at the international level and creating local jobs while also working to protect human health and the health of the environment.

A. Methodology used for estimating methane emissions from wastewater treatment processes

The procedure for estimating methane emissions from wastewater treatment processes proposed by IPCC (2006 and 2019) was used for this analysis. This methodology uses the specific organic load of the wastewater received by each plant to estimate the amount of methane that will be generated (see annexes A1, A2 and A3).⁴

This methodological approach makes it possible to estimate the methane emissions generated at each stage in the biological treatment of wastewater. The main such stages or phases are: (i) the secondary treatment stage, which may be either anaerobic or aerobic; and (ii) the subsequent phases involving the digestion of the sludge generated during the primary and secondary wastewater treatment stages. During the secondary stage, the volume of a plant's methane emissions will depend on two main factors: the technology being used, which will determine whether the organic material degrades into biogas or sludge; and the plant's operational performance.

WWTPs that use anaerobic technologies employing either compact reactors or pool systems degrade the organic material, converting most of it into biogas with a high methane content (Saravia Matus and others, 2022a and 2023b).

⁴ For a more detailed discussion of the methodology, see: Saravia Matus and others (2024).

Aerobic wastewater treatment systems, meanwhile, generate very little methane if they are operating efficiently, as their organic material degradation processes convert that material into sludge. In these systems, methane emissions are not generated during the treatment of the wastewater but rather during the anaerobic digestion process in the sludge train.⁵ What is more, if the sludge is aerobically stabilized, no significant volume of methane emissions is produced.

In the case of WWTPs that use dual (anaerobic and aerobic) technologies, potential methane emissions have to be estimated separately based on the principal flows or processes, as recommended by IPCC (2019). This means that, for the first treatment run (the anaerobic process), the COD to be used for the estimate is the COD of the load being fed into the system, whereas, for the second treatment run (the aerobic process), the organic load to be used for the estimate corresponds to the difference between the initial organic load and the load removed during the anaerobic treatment stage (the first run).⁶

For systems involving a secondary aerobic process followed by a stage of anaerobic sludge digestion, the emissions of the first run (aerobic treatment) have to be calculated on the basis of the load (in biochemical oxygen demand (BOD)/year) entering the system, whereas, for the second run (anaerobic sludge digestion), emissions should be estimated using the amount of sludge generated during the prior biological treatment process (the first run).

B. Potential for using methane as an energy source for selected WWTPs in El Salvador, Mexico and Panama

1. Overview of the selected WWTPs

A total of 10 WWTPs were used in this study: three plants in El Salvador (Ciudad Futura, Department of San Salvador; San Juan Opico, Department of La Libertad; and Metapán, Department of Santa Ana), four plants in Mexico (Centenario, Bicentenario and San Miguelito, in the State of Quintana Roo, and San Martín de las Pirámides in the State of Mexico) and three plants in Panama (Montijo and Soná, in the Province of Veraguas, and Puerto Armuelles, in the Province of Chiriquí) (see map 1). Table 1 gives the location of each of the 10 WWTPs, the type of technology they use, their installed capacity, the volume of the flow that they treat and parametric indications of the concentration of their influent pollution load.

Description of the WWTPs analysed in this study: The location and administrative unit are given for each WWTP in each country (province, department and/or State, along with the corresponding municipalities), as are the treatment processes used and the basic institutional and operational data.

⁵ Process used at wastewater cleaning and filtering stations.

⁶ In this case, it is not necessary to calculate the emissions from the recycling of sludge generated during the aerobic phase in the upflow anaerobic sludge blanket (UASB) reactor for the following reasons: (i) the greater proportion of aerobic sludge generated in the course of the previous conventional activated sludge (CAS) process is recirculated during the same process, passing through the clarifier or secondary sedimenter to the biological CAS reactor. This is a common practice in aerobic processing that is necessary in order to keep, with the help of aeration, the sludge in an activated state so that the organic load can be removed more efficiently; (ii) the excess sludge from the CAS reactor resulting from the purification process could be fed back into the UASB reactor, but this material is essentially aerobic sludge that could affect the methanogenic activity of the sludge in the anaerobic reactor.

Map 1
Location of WWTPs covered in the study



Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico) and National Water and Sewer System Institute (IDAAN) (Panama).

Table 1
General profile of WWTPs used in the study

Name	Location	Treatment technology	Installed capacity (l/s)	Flow treated (l/s)	Population served	Influent concentrations		
						COD (Mg/l)	BOD (Mg/l)	TSS (Mg/l)
El Salvador								
San Juan Opico	(La Libertad Dept.)	Anaerobic (UASB) + aerobic (TF)	30	25.34	10 040	496.0	198.0	265
Ciudad Futura	(San Salvador Dept.)	Anaerobic (UASB) + aerobic (TF)	30	26.04	21 250	780.0	375.0	1 411
Metapán	(Santa Ana Dept.)	Anaerobic (UASB) + aerobic (TF)	60	50.00	19 830	700.0	312.5	530
Mexico								
San Martín de las Pirámides	Teotihuacan - Mexico State	Anaerobic/aerobic (UASB + CAS)	70.0	45.0	30 240	609	251	245
Centenario	Othon P. Blanco- Quintana Roo State	Aerobic (CAS)	180.0	120.0	29 623	539	259	
Bicentenario	Solidaridad - Quintana Roo State	Aerobic (CAS + TF)	120.0	60.0	14 811	944	454	
San Miguelito	Cozumel - (Quintana Roo State)	Aerobic (CAS + TF)	220.0	160.0	39 497	832	400	

Name	Location	Treatment technology	Installed capacity (l/s)	Flow treated (l/s)	Population served	Influent concentrations		
						COD (Mg/l)	BOD (Mg/l)	TSS (Mg/l)
Panama								
Montijo	Montijo District (Veraguas Province)	Anaerobic (UASB) + aerobic (CAS)	8.4	8.4	2 178	262.2	126.0	
Puerto Armuelles	Barú District (Chiriquí Province)	Aerobic (CAS)	64.0	42.5	20 000	475.9	228.8	
Soná	Montijo District (Veraguas Province)	Aerobic (CAS)	25.0	25.0	12 786	517.1	248.6	

Source: El Salvador: Information from the National Water and Sewer System Administration (ANDA) and the Salvadoran Water Authority (ASA); Mexico: Drinking Water and Sewerage Commission (CAPA), National Water Commission (CONAGUA) and Water Commission of the State of Mexico (CAEM); Panama: National Water and Sewer System Institute (IDAAN).

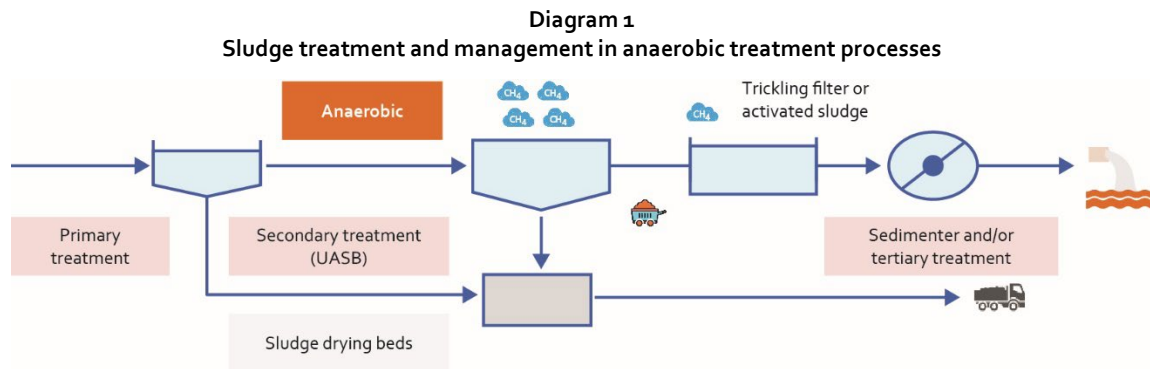
Note: TSS – total suspended solids, TF – trickling filter, UASB – upflow anaerobic sludge blanket, CAS – conventional activated sludge.

The technology used in the secondary phase of wastewater treatment in the WWTPs covered in this study is as follows: (i) in five of the WWTPs, secondary biological treatment is performed using an upflow anaerobic reactor⁷ (three WWTPs in El Salvador, one in Mexico and one in Panama), supplemented by aerobic treatment using a trickling filter (TF) in the case of the WWTPs in El Salvador (San Juan Opico, Ciudad Futura and Metapán) and by a different aerobic process using conventional activated sludge (CAS) in the San Martín de las Pirámides plant in Mexico and the Montijo plant in Panama; (ii) in the other five WWTPs, secondary biological treatment is aerobic (the three WWTPs in the State of Quintana Roo, Mexico, and the two in Panama (Puerto Armuelles and Soná), all of which use a CAS process.

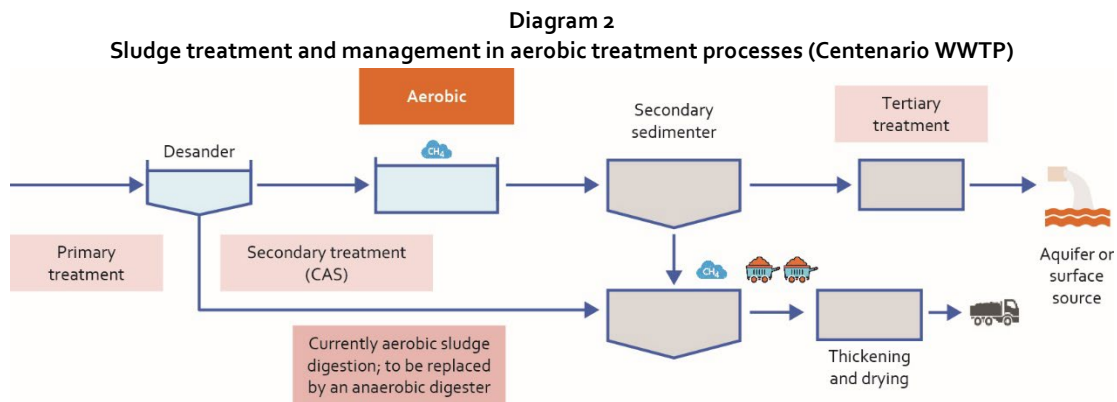
UASB reactors, which generate methane directly, generally involve three stages (see diagram 1): (i) a preliminary or primary treatment stage, which uses screens and a desander to remove solids, along with a flow meter; (ii) a two-phase secondary treatment process in which, during the first phase, the wastewater passes through the UASB reactor, where the organic matter is degraded through a methane-producing process (in the El Salvador WWTPs, the UASB reactors are open, whereas the reactor in the WWTP in San Martín de las Pirámides is not; the Metapán WWTP uses three biogas burners during this phase of the water train in the anaerobic treatment process) and, during the second phase of the secondary treatment process, the wastewater flowing out of the UASB reactor is channelled⁸ into an aerobic treatment process using either TF or CAS technology; and (iii) in a third phase, the treated water is fed through a decanter, where the sludge formed during its passage through the biological filter or the CAS reactor is separated out and then purged and poured into drying yards, while the treated water is then discharged.

⁷ Also known as an upflow anaerobic sludge blanket (UASB) reactor.

⁸ The San Juan Opico WWTP uses three pumping systems. One of them uses two 2-horsepower (hp) motors to pump the water from the UASB reactor into the biological filter. Each of the other two uses a 0.5-hp motor to pump sludge from the UASB reactor and from the secondary sedimenter into the sludge drying yard.



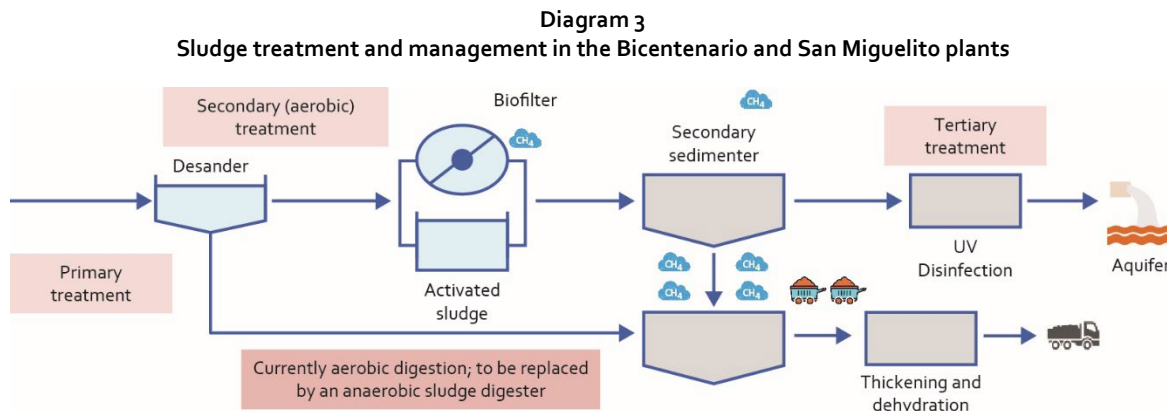
Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA), Salvadoran Water Authority (ASA), Water Commission of the State of Mexico (CAEM) and National Water and Sewer System Institute (IDAAN).



Source: Prepared by the authors, on the basis of Secretariat of Environment and Natural Resources (SEMARNAT), *Informe de la situación del medio ambiente en México: compendio de estadísticas ambientales, indicadores clave y de desempeño ambiental. Edición 2012*, Mexico City, 2013.

The WWTPs with the greatest installed capacity (120 l/s and 220 l/s) are the plants in the State of Quintana Roo in Mexico that use aerobic technologies, followed by the WWTPs in San Martín de las Pirámides in Mexico and in Metapán in El Salvador, which use anaerobic technology and have capacities of 70 l/s and 60 l/s, respectively, along with the WWTP in Puerto Armuelles in Panama, with an installed capacity of 64 l/s. Lastly, there are the WWTPs with a capacity of 30 l/s or less: the WWTPs in San Juan Opico and Ciudad Futura in El Salvador (both with a capacity of 30 l/s), and the WWTPs in Soná and Montijo in Panama, with installed capacities of 25 l/s and 8 l/s, respectively.

The plants in Quintana Roo, Mexico, are the ones that are using the least of their installed capacity. Information on the flows treated by these WWTPs, updated in 2023 by authorities and technical personnel in charge of these plants' operation who attended the ECLAC-CONAGUA (National Water Commission of Mexico) workshop held in 2023, indicates that, on average, these WWTPs are running at 63% of their capacity, as the Bicentenario plant is only using 50% of its capacity while the San Miguelito is running at 73% of capacity. The data on the concentrations of organic load (COD and BOD, as appropriate) were updated at that workshop thanks to the input supplied by the operators of these WWTPs.



Source: Prepared by the authors, on the basis of Secretariat of Environment and Natural Resources (SEMARNAT), *Informe de la situación del medio ambiente en México: compendio de estadísticas ambientales, indicadores clave y de desempeño ambiental. Edición 2012*, Mexico City, 2013.

These plants' energy operating costs are an essential consideration when analysing the options for harnessing methane as an energy source in order to reduce those costs. Information compiled by hydraulic engineering and project evaluation consultants (Consultores en Ingeniería Hidráulica y Evaluación de Proyectos, n.d.) indicate that, in 2022, the San Martín de las Pirámides WWTP was using an estimated 844,165 kWh/year, which represented 62% of its total annual operating costs of 3,324,700 Mexican pesos (approximately US\$ 170,000). The aeration equipment (blowers) were the units using the most power. According to information supplied by representatives of the Water Commission of the State of Mexico at the 2023 ECLAC–CONAGUA workshop, energy was costing US\$ 0.19/kWh.

Operating problems in the WWTPs covered in this study include inefficiencies in the San Juan Opico and Ciudad Futura WWTPs in El Salvador associated with electromechanical issues caused by power cuts, the deterioration or damage of pumping equipment and an uneven distribution of flows in the biological or trickling filters (ANDA, 2022). In the case of the San Martín de las Pirámides WWTP in Mexico, diagnostic studies conducted by hydraulic engineering and project evaluation consultants (Consultores en Ingeniería Hidráulica y Evaluación de Proyectos, n.d.) show that the influent pumping automation system is in need of repair, the blowers and their instrument panels require general maintenance, the pumping sump or pit needs desilting and the CAS reactors need to be purged. In addition, an expert opinion needs to be secured regarding the structural integrity of the anaerobic reactor. The reconditioning of this equipment will require an investment of some 1.8 million Mexican pesos (between US\$ 88,000 and US\$ 95,000). Generally speaking, detailed information on the characteristics of these WWTPs and the volumes of sludge produced in the course of treatment was not available; information on routine monitoring was also incomplete, especially in the case of the WWTPs in Panama.

Box 1
Operating characteristics of the WWTPs covered in this study

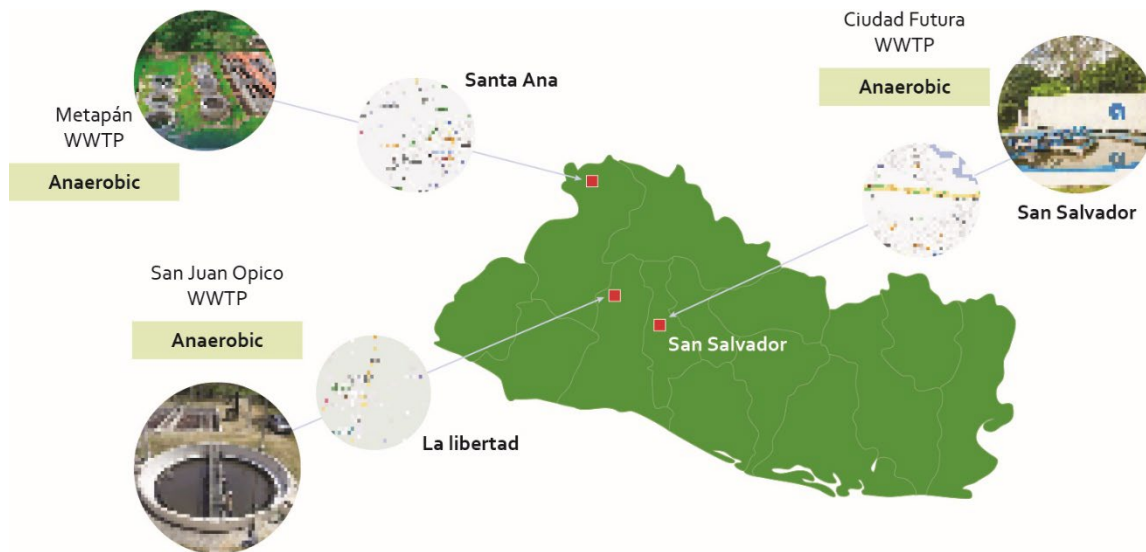
Institutional and operational aspects

Location of the WWTPs in El Salvador

The San Juan Opico WWTP is operated by the National Water and Sewer System Administration (ANDA) and is located in the Las Playitas sector of the municipality of San Juan Opico (Department of La Libertad). It has an installed capacity of 30 l/s, processes a flow of 25.34 l/s and serves an estimated population of 10,040 people (ANDA, 2022). The Ciudad Futura WWTP, which is also run by ANDA, is in the municipality of Cuscatancingo, Department of San Salvador. It has an installed capacity of 30 l/s, processes a treatment flow of 26.04 l/s and serves an estimated 21,250 persons. The Metapán WWTP, which is operated by the municipality, is the newest of these plants. It has the largest installed capacity (60 l/s) and an average treatment flow of 50 l/s. It serves a population of nearly 19,830 (see table 1 and map 1).

In all three of these WWTPs, secondary treatment is conducted using an upflow anaerobic sludge blanket (UASB) reactor together with a trickling filter and involves three stages. In the primary treatment stage, screens and a desander are used to remove solids; a flow meter is also used. The secondary treatment stage involves two phases: in the first, the wastewater is fed through a UASB reactor, where the organic matter is degraded (methane is generated as part of this process); in the second, the wastewater flowing out of the UASB reactor is pumped into the trickling filter, where it is treated in an aerobic environment (ANDA, 2022). Then, in the third stage, the treated water is passed through a decanter, where the sludge formed in the biofilter is separated out and then flushed out into drying yards while the treated water is then ready for discharge (ANDA, 2022).

Map 1
Location of WWTPs in El Salvador



Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico) and National Water and Sewer System Institute (IDAAN) (Panama).

Location of WWTPs in Mexico

Three of these WWTPs are located in the State of Quintana Roo, and all of these plants use aerobic treatment systems (see map 2). The fourth WWTP is located in the State of Mexico and uses anaerobic treatment processes. Together, these plants have an installed capacity of 590 l/s and treat nearly 385 l/s, providing service to approximately 115,000 people.

The San Martín de las Pirámides WWTP was built in 2015 and came on stream in 2016. The start-up investment of 44,419,220 Mexican pesos (US\$ 2,380,451) was funded by the federal (60%) and State (40%) governments. It is operated by the Water Commission of the State of Mexico (CAEM) in coordination with the Teotihuacan Decentralized Public Drinking Water, Sewerage and Sanitation Agency (ODEAPAST) and is located in the Municipality of Teotihuacan, State of Mexico. It has an installed capacity of 70 l/s, a treatment flow of 45 l/s and an average influent COD concentration of 580 mg/l (equivalent to a load of nearly 823 tons of COD/year). The plant uses dual anaerobic/aerobic technology with a UASB + CAS system in an aerobic environment.

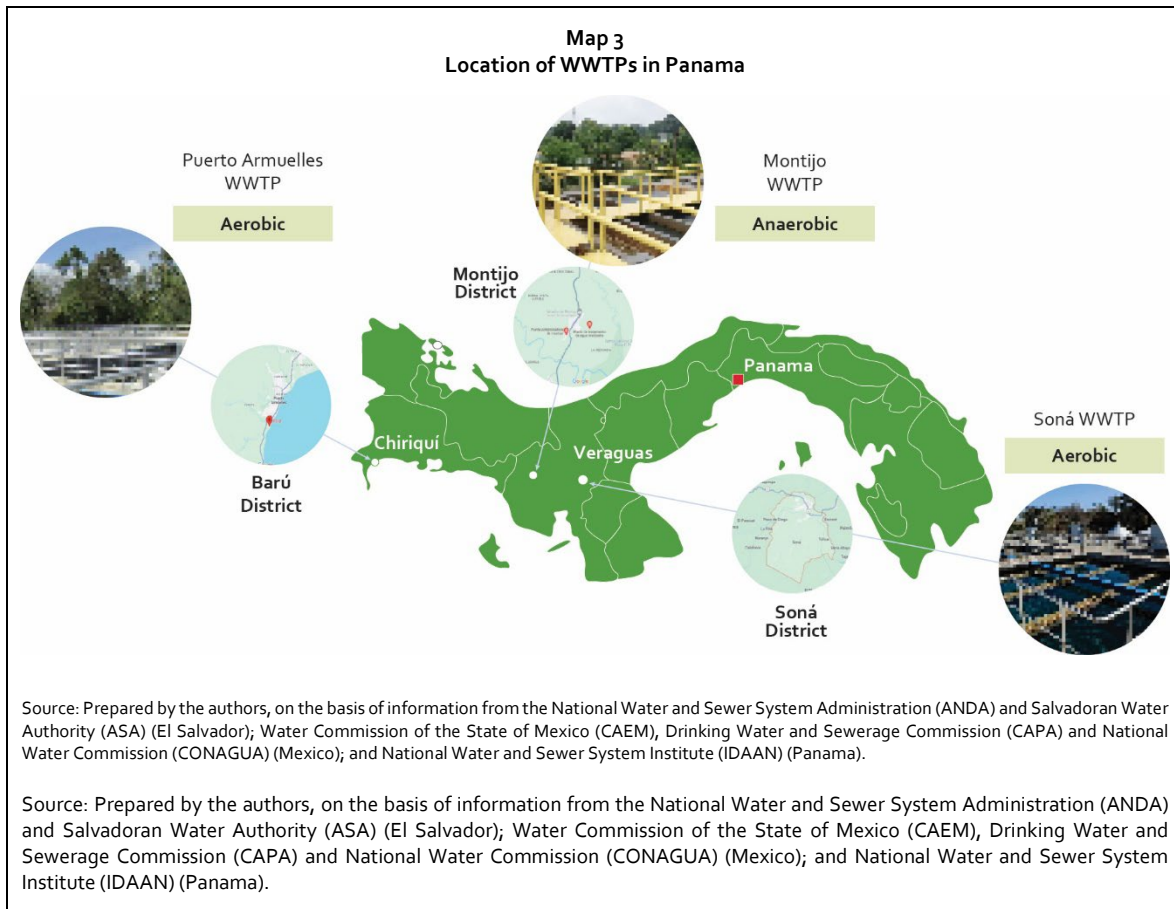
The Centenario WWTP is run by the Drinking Water and Sewerage Commission (CAPA) and is located in Chetumal, Municipality of Othón P. Blanco, State of Quintana Roo. It came on stream in 1999 and has an installed capacity of 180 l/s, a treatment flow averaging 120 l/s and a mean influent BOD concentration of 259 mg/l (nearly 980 tons of BOD/year). The Bicentenario WWTP is also run by CAPA and started up operations in 2011 in Tulum, Municipality of Solidaridad, State of Quintana Roo. With an installed capacity of 120 l/s, it is being expanded and refurbished to handle biological nutrient (nitrogen) removal processes. Its treatment flow averages 60 l/s, and its reported average influent BOD concentration of 454 mg/l is equivalent to approximately 859 tons per year. The plant uses a dual aerobic secondary treatment process involving the use of a trickling filter and a CAS reactor. Lastly, the San Miguelito WWTP started up operations in 1980. It was expanded in April 2012 and now has an installed capacity of 220 l/s. It is located on the island of Cozumel, State of Quintana Roo, and, like the Centenario and Bicentenario plants, is operated by CAPA. Its current treatment flow averages 160 l/s, and it has an average influent concentration of 400 milligrams of BOD per litre of wastewater (nearly 2,018 tons per year). It uses a treatment process similar to the one employed in the Bicentenario WWTP.



Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico); and National Water and Sewer System Institute (IDAAN) (Panama).

In the case of Panama, two of the WWTPs selected for this study use an aerobic secondary treatment process (Puerto Armuelles and Soná), while the other uses an anaerobic process (the WWTP in Montijo).

The Montijo plant has an installed capacity of 8.4 l/s and serves an estimated population of 2,178 persons. Its dual (anaerobic/aerobic) treatment technology consists of a UASB reactor and a CAS system for the aerobic phase (see map 3). The WWTP in Puerto Armuelles has an installed capacity of 64 l/s, which enables it to serve approximately 20,000 people with its average discharge of 150 litres per person per day. It uses a CAS system and, although it has the infrastructure for anaerobic sludge digestion, IDAAN reports that this is not in operation. In 2021, the plant used 92,100 kWh. Lastly, the WWTP in Soná-Paraiso has an installed capacity of 25 l/s and serves a population estimated at 12,786 people. It also uses CAS technology. In 2021, its energy use amounted to 204,720 kWh.



2. Methane emissions as an energy source

Estimates are given below of the methane emissions that could be captured and converted into energy in the 10 WWTPs covered in this study. The calculations of the potential methane capture and the associated investments (summarized in tables 2 and 3 below) were performed and validated at training workshops and during technical tours conducted in the State of Quintana Roo, Mexico, in July 2023 (in coordination with CONAGUA, CAPA and CAEM), in San Salvador in the first week of September 2023 (in coordination with ASA and ANDA) and in Panama in March 2024 (in coordination with IDAAN).

**Table 2
Potential methane emissions and methane capture in each treatment phase**

WWTP	Methane emissions (m3/year)				Methane capture (m3/year)			
	Anaerobic (UASB)	Aerobic	Anaerobic (UASB)	Aerobic	Anaerobic (UASB)	Aerobic	Anaerobic (UASB)	Aerobic
El Salvador								
San Juan Opico	110 982	486	-	111 468	99 884	-	-	99 884
Ciudad Futura	179 350	563	-	179 898	161 415	-	-	161 415
Metapán	309 053	2 794	-	311 847	278 148	-	-	278 148
Total	599 384	3 842	-	603 227	539 446	-	-	539 446

WWTP	Methane emissions (m ³ /year)				Methane capture (m ³ /year)			
	Anaerobic (UASB)	Aerobic	Anaerobic (UASB)	Aerobic	Anaerobic (UASB)	Aerobic	Anaerobic (UASB)	Aerobic
Mexico								
San Martín de las Pirámides	230 465	629	-	231 094	207 419	-	-	207 419
Centenario	-	5 266	439 102	444 368	-	-	395 192	395 192
Bicentenario	-	3 920	398 930	402 850	-	-	359 037	359 037
San Miguelito	-	10 845	904 200	915 045	-	-	813 780	813 780
Total	230 465	20 660	1 742 233	1 993 358	217 790	-	1 568 009	1 775 428
Panama								
Montijo	19 446	132	-	19 577	17 501	-	-	17 501
Puerto Armuelles	-	1 647	137 357	139 004	-	-	123 621	123 621
Soná	-	1 053	87 812	88 865	-	-	79 031	79 031
Total	19 446	2 832	225 169	247 447	17 501	-	202 652	220 153

Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico); and National Water and Sewer System Institute (IDAAN) (Panama).

Table 3
Energy potential of the 10 WWTPs

WWTP	Installed capacity (l/s)	Treatment flow (l/s)	Population served	Methane		Energy content (MWh/year)	Cogeneration	
				Emissions (m ³ /year)	Recoverable (m ³ /year)		Electricity (MWh/year)	Heat (MWh/year)
El Salvador								
Ciudad de San Juan Opico	30	25.34	10 040	111 468	99 884	996	349	398
Ciudad Futura	30	26.04	21 250	179 912	161 415	1 609	563	644
Metapán	60	50.00	19 830	311 847	278 148	2 773	971	1 109
Total	120	101.58	51 120	603 227	539 446	5 378	1 882	2 151
Mexico								
San Martín de las Pirámides	70.0	45.0	30 240	231 094	207 419	2 068	724	827
Centenario	180.0	120.0	29 623	444 368	395 192	3 940	1 379	1 576
Bicentenario	120.0	60.0	14 811	402 850	359 037	3 580	1 253	1 432
San Miguelito	220.0	160.0	39 497	915 045	813 780	8 113	2 840	3 245
Total	590.0	385.0	114 171	1 993 358	17 775 428	17 701	6 195	7 080
Panama								
Montijo	8.4	8.4	2 178	19 577	17 501	174	61	70
Puerto Armuelles	64.0	42.5	20 000	139 004	123 621	1 233	431	493
Soná-Paraiso	25.0	25.0	12 786	88 865	79 031	788	276	315
Total	97.4	75.9	34 964	247 447	220 153	2 195	768	878

Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico); and National Water and Sewer System Institute (IDAAN) (Panama).

These workshops were attended by representatives of the relevant agencies, including technical personnel responsible for the operation of each WWTP in question. Their presence made it possible to obtain valuable feedback and to fully validate the calculations and estimates, as well as creating an opportunity for a rewarding exchange of information on projects and other activities being conducted under the leadership of water and sanitation authorities in El Salvador, Mexico and Panama.⁹

The assumption that not all the methane is recoverable is embedded in the methodology used to arrive at these estimates. For instance, in the WWTPs that use dual aerobic technologies (for example, the three WWTPs in the State of Quintana Roo, Mexico), the small amount of methane emitted during the aerobic treatment phase is not recoverable, and, because of inefficiencies in the systems used for routing and capturing methane, only 90% or less of the methane generated during the anaerobic treatment of wastewater can be harnessed.

The results indicate that the WWTPs in Mexico have the greatest potential for converting methane into energy. Those four WWTPs generate nearly 2 million m³ of methane per year, which is more than three times as much methane as the estimated volume generated by the three WWTPs in El Salvador and eight times as much as the three plants in Panama. This finding is directly related to the fact that these systems, and especially the three in the State of Quintana Roo, have a larger installed capacity and greater treatment flows than the others. Of the WWTPs that use anaerobic technologies, the Metapán plant in El Salvador, with an average treated flow of 50 l/s, generates more methane than the plants in San Martín de las Pirámides and Montijo in Panama because of its greater influent contaminant concentration and flow. In absolute terms, the WWTPs with the greatest methane generation potential are the San Miguelito, Centenario and Bicentenario plants in Quintana Roo, followed by the Metapán plant in El Salvador. The specific results for each country will be analysed below.

Methane generation and capture – WWTPs in El Salvador. According to the reported results of tests run by ANDA and information confirmed at the workshop organized by ECLAC with ANDA and ASA in September 2023, the three WWTPs in El Salvador had COD concentrations averaging between 496 and 780 milligrams per litre of wastewater. The influent organic loads of these plants amount to approximately 2,141 tons per year (COD concentrations of 396 tons in San Juan Opico, 641 tons in Ciudad Futura and 1,104 tons in Metapán). These plants produce an estimated 603,227 m³ of methane per year, of which 51.7% is accounted for by the Metapán plant (the equivalent of nearly 8,487 tons of CO₂ emissions per year)¹⁰ (see table 2). Of this amount, only some 539,446 m³ of methane, with an energy content of 5,375 MWh/year, is recoverable. However, given the efficiency levels of the cogeneration systems, only an estimated 1,841 MWh of electricity and 2,151 MWh of heat per year can be generated.

The specific case of the Ciudad Futura plant can be used to illustrate the extent of this potential energy source. ANDA reports that the energy consumption of the drinking water pumping stations at that location totals approximately 1,164 MWh per year. Thus, the electricity that could be generated from that plant's methane emissions could supply 48% of the energy needed to supply drinking water to the population in that area.

Methane generation and recovery – WWTPs in Mexico. On the basis of the characteristics given in table 1, it was estimated that the San Martín de las Pirámides, Centenario, Bicentenario and San Miguelito WWTPs take in an annual organic load, measured in BOD₅, of 823 tons, 980 tons, 859 tons and 2,018 tons, respectively. This organic load, after passing through the different WWTP treatment

⁹ For further information about these workshops, see: (i) El Salvador: [online] <https://www.cepal.org/en/events/eclac-promoting-circular-economy-potable-water-and-sanitation-sector-salvador>; (ii) Mexico: <https://www.cepal.org/en/events/eclac-promoting-circular-economy-potable-water-and-sanitation-sector-mexico>; and (iii) Panama: <https://www.cepal.org/en/notes/technical-assistance-methane-utilization-and-nutrient-recovery-selected-municipalities-panama>.

¹⁰ In comparative terms, this is equivalent to the amount of carbon dioxide emissions produced each day by 2.5 million Salvadorans.

phases and including the anaerobic digester for further treatment of aerobic sludge at the Centenario, Bicentenario and San Miguelito plants, generates methane emissions estimated at 1,993,358 m³ per year, in other words, more than 28,047 tons of CO₂ equivalent per year (see table 2). As noted earlier, it is not possible to recover all the methane generated in the process. For example, in WWTPs that use aerobic technologies (activated sludge, percolating filters or combined systems), the emissions generated at the treatment phase are too small to capture. In these cases, only the methane generated from anaerobic sludge digestion can be captured. The same principle applies in the case of WWTPs that employ combined anaerobic/aerobic technologies.

Similarly, inefficiencies in methane routing and capture systems mean that only up to 90% of the methane that is generated can be captured. Accordingly, the total that could be harnessed from all the WWTPs in Mexico would be 1,775,428 m³, with an energy content of 17,804 MWh/year, which is equivalent to the consumption of 8,680 inhabitants (at an average consumption rate of 2,051 KWh/year) (see table 3).

In the specific case of San Martín de las Pirámides, greater potential was identified to use methane for energy, given the combined anaerobic/aerobic technology used for wastewater treatment. In this case, the plant's energy consumption was estimated at 844,165 KWh/year, which represented 62% of its annual operating costs (Consultores en Ingeniería Hidráulica y Evaluación de Proyectos, n.d.). Furthermore, if the necessary changes were made to harness the energy from the methane generated, it could provide as much as 86% of the electricity the plant needs to operate. This does not include the option of recovering caloric energy to heat the anaerobic reactor, which would further increase the plant's operating efficiency.

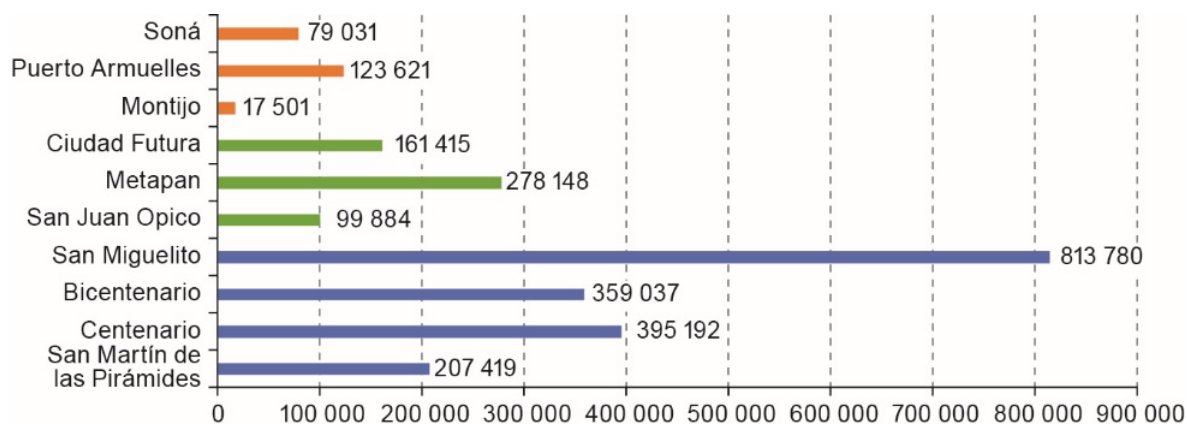
Given the low level of utilization observed in some of these WWTPs, it is worth asking what future emissions levels would look like if the infrastructure were to be used at 80% of its capacity. The calculations indicate that, at that utilization level and taking the BOD concentration levels shown in table 1, annual methane emissions could be expected to be 2,472,321 m³, of which 2,201,969 m³ could be recovered to generate 7,684 MWh of electrical energy and 8,781 MWh of heat energy (see table 3).

Methane generation and recovery – WWTPs in Panama. According to the values reported in table 1, the annual organic loads received by the Montijo, Puerto Armuelles and Soná-Paraíso WWTPs, measured in BOD₅, total 572 tons per year. After passing through the plant's different treatment phases, these loads combined generate estimated methane emissions of 247,447 m³ per year, that is, over 3,481.6 tons of CO₂ equivalent¹¹ (see table 3).

On the basis of the methane estimation methodology proposed herein, it may be concluded that a total of 220,153 m³ of methane could be recovered from the three plants analysed, with an energy content equivalent to 2,195 MWh/year. This would be enough to supply the yearly energy consumption of about 2,200 of the country's inhabitants. However, the efficiencies inherent to cogeneration systems only allow 768 MWh of electrical energy and 878 MWh of heat energy to be used per year. The potential of this energy source is better illustrated by the specific cases of the Puerto Armuelles and Soná-Paraíso plants. In 2021, energy consumption was 92 MWh/year at Puerto Armuelles, and 205 MWh/year at Soná-Paraíso. In terms of potential electricity generation, Puerto Armuelles and Soná-Paraíso could produce up to 431 MWh/year and 276 MWh/year, respectively; this means that they could cover their own energy demand entirely and even generate surpluses.

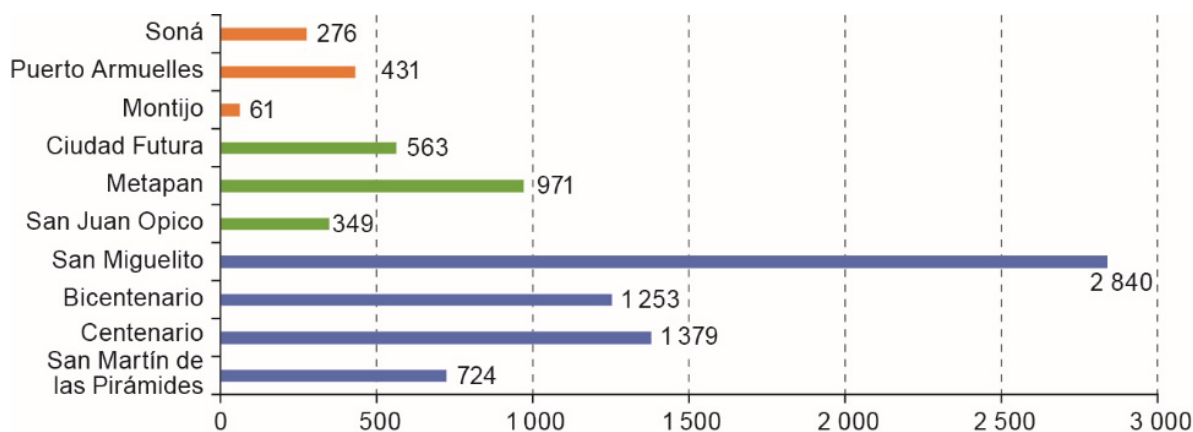
¹¹ This is equivalent to the daily CO₂ emissions of approximately 396 thousand Panamanians.

Figure 1
Results of the estimation of recoverable methane in the 10 WWTPs analysed
(M³/year)



Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico); and National Water and Sewer System Institute (IDAAN) (Panama).

Figure 2
Results of the estimation of electric power in the 10 WWTPs analysed
(Mwh/year)



Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico); and National Water and Sewer System Institute (IDAAN) (Panama).

3. Estimating the investment costs

In order to calculate the benefits that using the methane generated by wastewater treatment in the 10 WWTPs analysed would bring—to ANDA in El Salvador, to CAEM and CAPA in Mexico and to IDAAN in Panama—it is necessary to determine what investment costs would have to be incurred to harness the methane generated at the plants and transform it into energy (see table 4).

Table 4
Estimated investment costs to capture methane for energy in selected WWTPs in El Salvador
(Current dollars)

Item	San Juan Opico	Ciudad Futura	Metapána	Total
Centrifugal fan	N/A	N/A	N/A	N/A
Biogas pipe (assuming maximum flow rate of 50 m)	7 500	7 500	1 500	22 500
Flare	28 400	28 400	N/A	85 200
Biogas meter	68 100	68 100	68 100	204 300
Desulfurizer	17 400	17 400	17 400	52 200
Biogas purification system (demister, dehumidifier)	41 700	41 700	41 700	125 100
Biogas combined heat and power (CHP) generator	121 121	190 472	266 764	578 357
High-density polyethylene (HDPE) anaerobic digester covers		7 200		7 200
Total	284 221	360 772	395 464	1 040 457

Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA).

^a Investment information was validated by ASA. The Metapán WWTP has three flares for biogas burning.

Table 5
Estimated investment costs to capture methane for energy in selected WWTPs in Mexico
(Current dollars)

Item	San Martín de las Pirámides	Centenario	Bicentenario	San Miguelito	Total
Aerobic sludge thickener	N/A	122 600	137 800	180 800	441 200
Sludge pumping system (piping, sludge pump)	N/A	6 100	6 900	9 000	22 000
Sludge digester	N/A	0	0	0	0
Adaptation of aerobic sludge digester to anaerobic digester	N/A	342 920	392 320	518 760	1 254 000
Centrifugal fan	N/A	1 600	1 600	1 600	4 800
Biogas pipe ^b	9 000	7 500	7 500	7 500	30 000
Flare	34 080	28 400	28 400	28 400	113 600
Biogas meter	81 720	68 100	68 100	68 100	272 400
Desulfurizer	20 880	17 400	17 400	17 400	69 600
Biogas purification system (demister, dehumidifier)	51 040	41 700	41 700	41 700	166 800
Biogas combined heat and power generator	309 447	459 974	455 883	699 861	1 925 165
Total	505 167	1 096 294	1 157 603	1 573 121	4 332 185

Source: Prepared by the authors, on the basis of information from Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA).

^a Costs supplied by the Water Commission of the State of Mexico (CAEM).

^b Assuming maximum flow rate of 50 m.

Table 6
Estimated investment costs to capture methane for energy in selected WWTPs in Panama
(Current dollars)

Item	Montijo	Puerto Armuelles	Soná-Paráiso	Total
Aerobic sludge thickener	N/A	60 200	35 700	95 900
Sludge pumping system (piping, sludge pump)	N/A	3 000	1 800	4 800
Sludge digester	N/A	362 400	207 600	570 000
Centrifugal fan	N/A	1 600	1600	3 200
Biogas pipe (assuming maximum flow rate of 50 m)	7 500	7 500	7 500	22 500
Flare	28 400	28 400	28 400	85 200
Biogas meter	68 100	68 100	68 100	204 300
Desulfurizer	17 400	17 400	17 400	52 200
Biogas purification system (demister, dehumidifier)	41 700	41 700	41 700	125 100
Biogas combined heat and power generator	17 926	189 929	80 948	288 803
Transformer station, grid connection point	-	-	-	-
Heat recovery circuit (e.g. upflow anaerobic sludge blanket (UASB) reactor or sludge drying)	-	-	-	-
Total	181 026	780 229	490 748	1 452 003

Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Institute (IDAAN).

The work involved consists of installing a biogas routing, storage and purification system (the first few rows of table 5), as well as power generators, and a hot water circuit (to harness the heat energy). Lastly, if the plant generates surplus energy, it is worth installing a power transformer station to connect to the grid and market these surpluses.¹²

In the case of El Salvador, the required investment is relatively similar for the three plants analysed, because their systems use the same treatment technology. The difference is that Metapán receives a greater organic load (51.7% of the total entering all three plants) owing to the combined effect of a greater flow rate and concentration of COD (chemical oxygen demand), which requires a more powerful —and consequently more expensive— generator. In summary, the required investment is close to US\$ 1.04 million, which represents an average of US\$ 20.4 per person served by the three plants, and US\$ 193.5 per MWh of electricity generated per year by the plants. Naturally, differences in the size of the population served and the organic load in the wastewater influence the investment cost per person served.

In the case of Mexico, aerobic WWTPs without sludge pumping and thickening systems will require larger investments for these purposes.¹³ Given that the three WWTPs in Quintana Roo have aerobic sludge digesters, these could be adapted to convert them into anaerobic digesters, which essentially involves enclosing the tanks to make them operate under anaerobic conditions and several other adjustments.¹⁴ This would be in addition to installing a biogas routing, storage and purification

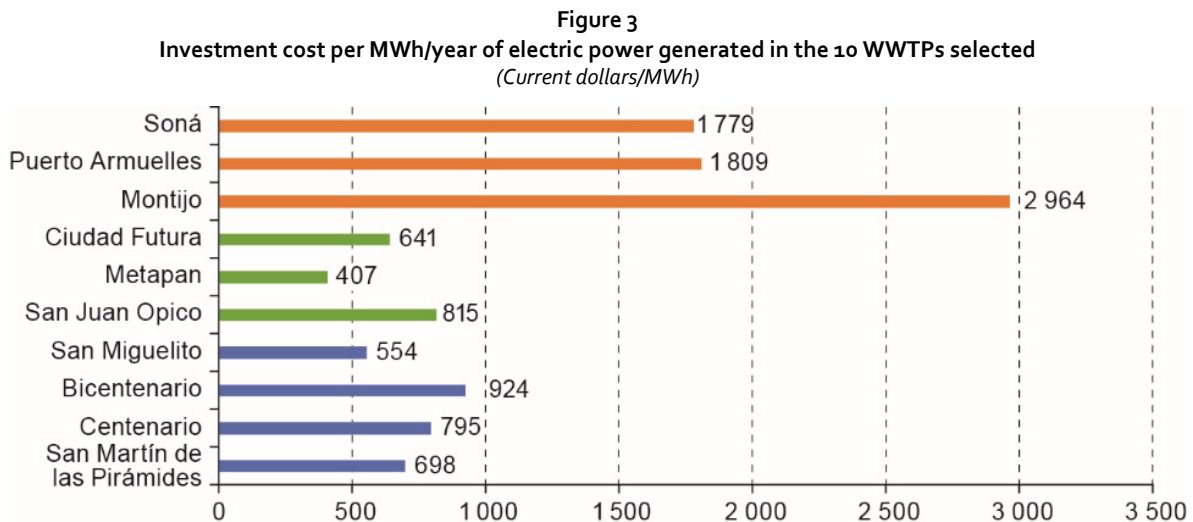
¹² The procedure here does not estimate the investment cost associated with installing a hot water circuit (to capture heat energy) nor the transformer station to connect to the grid and market any surpluses.

¹³ Given that the Centenario, Bicentenario and San Miguelito plants —according to information reported by CAPA and CAEM— operate sludge recirculation lifts and sludge thickeners, this investment would not be needed.

¹⁴ This cost would represent at least 40% of the total investment that would be needed to build a new anaerobic reactor.

system and a power generator.¹⁵ The San Martín de las Pirámides plant would require the same investments, except for adaption to an anaerobic sludge digester, which would not be needed. In sum, the investment needed is estimated at US\$ 4.33 million, which is US\$ 569 per MWh¹⁶ of electric power generated per year by the Mexican plants. If the systems are assumed to have a useful life of 20 years, the investment cost per MWh generated over their lifespan would be US\$ 28.20. The technology used in wastewater treatment, as well as differences in the way installed capacity is used and the organic load entering the system, mean that the investment cost is higher for the Bicentenario, Centenario and San Miguelito plants (see figures 3 and 4).

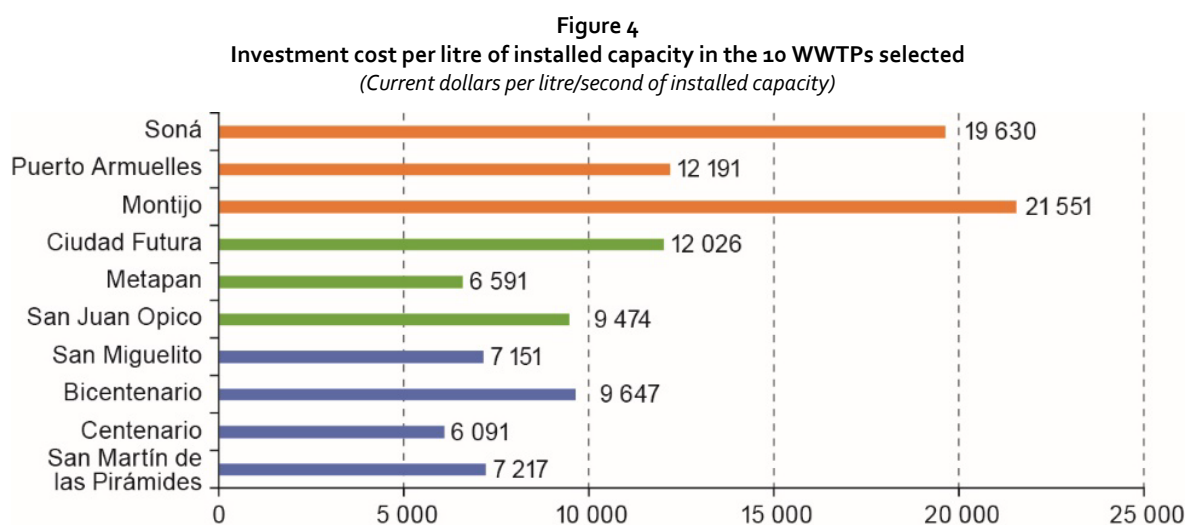
Lastly, in the case of Panama, the plants that use aerobic treatment technologies (Soná and Puerto Armuelles) will need investments in sludge pumping and thickening systems, and to build anaerobic sludge digesters. As in the Mexican and Salvadoran plants, it will also be necessary to install biogas routing, storage and purification systems and to procure and install power generators. Of course, if the plant already has a sludge pumping and thickening system, this investment can be omitted. In the case of the Montijo plant, which uses anaerobic treatment technology, the same investments will be required, except for the pumping, thickening and anaerobic sludge digestion system. In sum, an investment of close to US\$ 1.45 million is required, representing an average of US\$ 160 per person served by the plants, and US\$ 1,890 per MWh of the electric power they generate annually. It is important to note that differences in terms of population served and organic load in wastewater influence the investment cost (see figures 3 and 4).



Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico); and National Water and Sewer System Institute (IDAAN) (Panama).

¹⁵ A circuit could also be installed to capture the heat energy produced by the generator, which can be used for the aeration equipment needed for the activated sludge process and/or for sludge drying. Furthermore, if the plant generates surplus energy, it is worth installing a power transformer station to connect to the grid and market these surpluses.

¹⁶ According to IRENA (2022), in 2020 average per kWh generation costs by source were as follows: photovoltaic energy, US\$ 0.057; onshore wind, US\$ 0.039; offshore wind, US\$ 0.084; and geothermal power, from US\$ 0.071 to US\$ 0.075.



Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico); and National Water and Sewer System Institute (IDAAN) (Panama).

4. Economic benefits of methane capture

The financial evaluation of the project involves a simple assumption: that the energy generated in each plant will be used to operate that plant and will replace externally sourced energy.

Replacing external energy sources will generate savings in the running of the plants, as far fewer resources will have to be reserved for paying electric power bills. Specifically, in the case of El Salvador, data validated by ANDA and ASA experts show that the saving would be US\$ 0.17/KWh (based on the price of energy for the industrial sector). This represents annual savings of over US\$ 300,000 (see table 7). In the case of Mexico (the Centenario, Bicentenario and San Miguelito plants), the saving would be US\$ 0.167/KWh (based on the price of energy for the non-residential sector), according to data documented by Global Petrol Prices (2022). For the San Martín de las Pirámides plant, information reported by the Water Commission of the State of Mexico (CAEM) indicates that the saving would be US\$ 0.19/KWh. On the basis of these energy costs, the total annual saving for Mexico is estimated at US\$ 1,049,172 (see table 7).

Financial evaluation for El Salvador. Taking a discount rate of 10% and a time horizon of 20 years, the proposed investments bring revenues estimated at US\$ 2.5 million, representing a return of almost 2.5 times the amount invested and an internal rate of return (IRR) of 29%.

Specifically, harnessing methane and generating electrical power at the Metapán plant would yield a return of 3.1 times the investment and an IRR of 37%. This means that the initial investment would be recouped in 3.4 years. In the Ciudad de San Juan Opico plant, the investment would be recovered around year 7, and at Ciudad Futura in year 5, with an IRR of 26%.

Financial valuation for Mexico. Using the same parameters as for El Salvador, it was found that the investments proposed in the four plants in Mexico would bring estimated revenues of US\$ 8.39 million over 20 years, representing an average return of 2.06 times the amount invested and an IRR of 24%.

Table 7
Financial evaluation of methane harnessing in electric power generation in the 10 WWTPs selected
(Current dollars)

Country/plant	Flow treated (l/s)	Inhabitants served	Initial investment	Initial investment (p.e.) ^a	Annual saving	NPV savings (20 years)	IRR (Percentages)	B/C	Years to recoup investment
El Salvador									
San Juan Opico	25.34	10 040	284 121	28.3	59 253	504 451	20	1.77	6.90
Ciudad Futura	26.04	21 250	360 772	17.0	95 754	815 204	26	2.26	4.97
Metapán	50.00	19 830	395 464	19.9	145 228	1 236 408	37	3.13	3.44
Total	101.58	51 120	1 040 357	20.4	300 234	2 556 063	29	2.46	4.57
Mexico									
San Martín de las Pirámides	45	30 240	505 167	16.7	135 420	1 152 903	27	2.28	4.92
Centenario	120	29 623	1 096 294	37.0	230 297	1 960 646	21	1.79	6.84
Bicentenario	60	14 811	1 157 603	78.2	209 228	1 781 273	17	1.54	8.65
San Miguelito	160	39 497	1 573 121	39.8	474 228	4 037 366	30	2.57	4.38
Total	385	114 171	4 332 185	37.9	1 049 172	8 392 189	24	2.06	5.69
Panama									
Montijo	8.4	2 178	181 026	83.1	13 345	114 186	4	0.63	>20
Puerto Armuelles	42.5	20 000	780 229	39.0	94 903	807 960	11	1.04	18.7
Soná-Paraíso	25.0	12 786	490 748	38.4	60 671	516 529	11	1.05	17.8
Total	75.9	34 964	1 452 003	41.5	169 009	1 438 872	7	0.99	>20

Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico); and National Water and Sewer System Institute (IDAAN) (Panama).

^a p.e. refers to per capita investment equivalent (per inhabitant served).

By individual plant, at San Martín de las Pirámides methane harnessing and electric power generation would yield a return of 2.28 times the initial investment, equivalent to an IRR of 27%, which would enable the investment to be recouped in about six years. At the San Miguelito plant—which has the largest capacity of the four analysed—the estimated return is 2.56 times the initial investment, with an IRR of 30% and 4.4 years to recover the investment. At the Bicentenario plant, the investment would not be recouped until around year 9, while in the San Miguelito plant this would occur midway through year 4.

This financial valuation does not include any increased operating costs arising from methane capture for energy, because these could be offset in view of the following: (i) the use of heat energy from the methane capture process for heating both the bioreactors in the water train and the anaerobic digesters in the sludge train, which may help to reduce the energy supply costs for these stages, and (ii) the anaerobic process produces six to eight times less sludge than the aerobic process, which significantly reduces the costs of treatment and final disposal of the sludge train (Pavlostathis, 2011). This cost can represent up to 50% of the operating costs of a WWTP that uses aerobic technology (Chao and Tianfeng, 2013). It should be noted, however, that the flow taken for the financial evaluation was assumed not to vary over time. This is a great assumption to make, considering that urban growth and increasing connections to sewerage networks necessarily entail larger flows entering wastewater treatment plants. Alternative results are shown below, keeping all variables constant and assuming 80% utilization level of each plant's installed capacity (see table 8).

Table 8
Mexico: energy potential of the WWTPs analysed using 80% of their installed capacity

Plant	Installed capacity (l/s)	Flow treated (l/s)	Methane		Energy content (MWh/year)	Energy cogeneration	
			Generated (m ³ /year)	Recoverable (m ³ /year)		Electricity (MWh/year)	Heat (MWh/year)
San Martín de las Pirámides	70.0	56.0	287 969	258 121	2 573	901	1 029
Centenario	180.0	144.0	533 242	474 230	4 728	1 655	1 891
Bicentenario	120.0	96.0	644 560	574 460	5 727	2 005	2 291
San Miguelito	220.0	176.0	1 006 549	895 158	8 925	3 124	3 570
Total	590.0	472.0	2 472 321	2 201 969	21 954	7 684	8 781

Source: Prepared by the authors, on the basis of information from the Drinking Water and Sewerage Commission (CAPA) and Water Commission of the State of Mexico (CAEM).

In this scenario, this group of WWTPs could produce an estimated 7,684 MWh/year of electrical energy, from the capture and use of 2,201,969 m³ of methane per year. Generating power in this way could generate overall yearly savings estimated at US\$ 1,301,806, with total income of US\$ 11.083 billion discounted at a rate of 10% for 20 years. This would yield a cost-benefit ratio of 2.56 times the amount initially invested.

Table 9
Mexico: financial valuation of methane capture to generate electrical energy in WWTPs analysed assuming 80% installed capacity use
(Current dollars)

Plant	Flow treated (l/s)	Inhabitants served	Initial investment	Initial investment (p.e.) ^a	Annual saving	NPV savings (20 years)	IRR (Percentages)	Cost-benefit ratio	Years to recoup investment
San Martín de las Pirámides	56.0	37 632	505 167	13.4	169 035	1 439 094	33	2.85	3.77
Centenario	144.0	35 547	1 096 294	30.8	276 356	2 352 275	25	2.15	5.47
Bicentenario	96.0	23 698	1 157 603	48.8	334 764	2 850 038	29	2.46	4.56
San Miguelito	176.0	43 447	1 573 121	36.2	521 650	4 441 103	33	2.82	3.81
Total	472.0	140 324	4 332 185	30.9	1 301 806	11 083 010	30	2.56	4.40

Source: Commission (CAPA) and Water Commission of the State of Mexico (CAEM).

^a p.e. refers to per capita investment equivalent (per inhabitant served).

The San Martín de las Pirámides plant has a notably greater potential to harness methane, owing largely to the wastewater treatment technology it already uses, as does the San Miguelito plant, thanks to its greater size and treatment capacity. At the same time, methane capture and use is financially viable at all the Quinta Roo plants, as they would be able to recover the investment costs of incorporating anaerobic digesters for aerobic sludge within 3 to 6 years, using 80% of their installed capacity. Lastly, if the plant operators arranged to aggregate the projects, both CAPA and CAEM would reap overall returns in excess of the investment costs incurred.

Financial valuation for Panama. Harnessing methane would generate a cost saving of US\$ 0.22/KWh (based on the energy rate paid by IDAAN) at the wastewater treatment facilities. Overall, the annual savings are estimated at US\$ 169,009 (see table 7). The financial valuation (using a 10% discount rate²⁷ over a 20-year horizon) shows that investments in adapting the Puerto Armuelles and Soná-Paraíso plants could be recouped in approximately 19 and 18 years respectively, reflecting an IRR close to 11%. By contrast, the Montijo plant shows an IRR of 4% and a cost-benefit ratio of 0.63, meaning that the return on investment would not occur as quickly. Although the Montijo plant generates methane directly using an upflow anaerobic sludge blanket (UASB) reactor and requires less investment than aerobic plants, such as those in Puerto Armuelles and Soná-Paraíso, it is too small (less than 10 l/s) to generate stronger investment returns.

As with the plants in Mexico, the financial valuation does not include the increase in operating costs arising from using methane for energy, given that these could be offset by using heat energy generated and by the smaller volume of sludge. Consequently, alternative results are given, keeping all variables constant and assuming a utilization level of 80% of the installed capacity for the Puerto Armuelles plant, which is the highest-capacity plant of the group analysed in Panama (see table 10). In this scenario, the Puerto Armuelles plant could produce an estimated 518 MWh/year of electric power (20% more than the generation estimated with the current operating flow), from the capture and use of 148,345 m³ of methane per year. This could generate overall yearly savings estimated at US\$ 133,883, with total revenue of US\$ 969,552, discounted at a rate of 10% over 20 years. In relation to the cost of the initial investment, this would yield a cost-benefit ratio of 1.24 times the amount invested, while also improving the IRR (13%) and recovering the investment in a shorter time (12.5 years).

Table 10
Financial valuation of methane capture to generate electrical energy at Puerto Armuelles WWTP
assuming 80% installed capacity use
(Current dollars)

Plant	Flow treated (l/s)	Inhabitants served	Initial investment	Initial investment (p.e.) ^a	Annual revenues	NPV savings (20 years)	IRR (percentages)	Cost-benefit ratio	Years to recoup investment
Puerto Armuelles	51.2	24 000	780 229	32.5	113 883	969 552	13	1.24	12.5

Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Institute (IDAAN).

^a p.e. refers to per capita investment equivalent (per inhabitant served).

5. Environmental benefits of harnessing methane

Wastewater treatment is an effective way to mitigate pollution caused by the discharge of wastewater into unpolluted sources. It must be recalled, however, that the treatment process itself contributes to greenhouse gas (GHG) emissions: on the one hand, methane is generated by the decomposition of organic matter under anaerobic conditions, and, on the other, pollution is generated indirectly by the consumption of energy to run aerobic reactors (Noyola, Morgan-Sagastume and Güereca, 2013). There are thus multiple benefits to harnessing the methane generated in WWTPs, including GHG emissions reductions with the limitation of methane emissions and the replacement of conventionally sourced energy with renewable energy from non-conventional sources, such as biogas (Nolasco, 2010).

²⁷ The rate used by the World Bank, the Inter-American Development Bank, the Asian Development Bank, and by countries such as Canada and Mexico, for project valuation (Castillo and Zhangallimbay, 2021).

The estimation of the environmental impact of the projects proposed here, for the 10 WWTPs, used an electric power consumption parameter of 32 KWh/inhabitant/year (Nolasco, 2010), along with each country's national power system emission factor. It should also be recalled that WWTPs currently generate biogas emissions at the anaerobic treatment phase (three plants in El Salvador, the San Martín de las Pirámides plant and the Montijo plant). The Metapán and San Martín de las Pirámides plants burn the methane they generate, but the Ciudad Futura and San Juan Opico plants release it into the atmosphere.

Reducing WWTP emissions in El Salvador. The calculations used El Salvador's 2022 national power system emission factor, which was 0.68 tCO₂e/MWh. Two effects were taken into account for estimating emissions under the project implementation scenario. The first effect is the emissions reduction resulting from the capture and use of the methane volumes that were being emitted previously, through an alternative energy technology (AET) at the Metapán WWTP and into the atmosphere at the San Juan de Opico, Ciudad Futura, San Martín de las Pirámides and Montijo plants. The second effect is the reduction in electric power demand thanks to internal generation from methane capture.

The results shown in table 12 indicate that the projects could potentially reduce emissions by some 4,810 tons of CO₂ equivalent per year in the case of El Salvador. These results are constrained by data availability issues, however. In fact, given the benefits of harnessing heat energy, the emissions reduction is likely to be larger.

Reducing WWTP emissions in Mexico. Despite the limitations on the information available to estimate the environmental impact of the projects proposed here, in the case of San Martín de las Pirámides, the power consumption recorded by hydraulic engineering and project evaluation consultants (Consultores en Ingeniería Hidráulica y Evaluación de Proyectos, n.d.)—844,165 kWh/year— may be used as a starting point. Accordingly, the emissions associated with the plant's energy consumption can be obtained using this figure and taking the 2022 national power system emission factor of 0.435 tCO₂e/MWh.¹⁸ Furthermore, considering that the methane emitted by this WWTP (see table 3) is not currently being harnessed and is burned before being emitted, these two components may be added to obtain the total emissions in the base scenario (CO₂ emissions from the burning of biogas are determined based on a factor of 2.75 Kg CO₂eq/Kg CH₄ burned).

For the other plants, the power consumption parameter of 32 kWh/inhabitant/year mentioned earlier is used, given that no information is available on their current energy consumption level and that they use aerobic systems with CAS technologies. Thus, because these WWTPs currently use aerobic sludge digesters, estimation of emissions in the base scenario should include only the emissions from wastewater treatment under aerobic conditions. In addition, the same two effects considered in the case of El Salvador are included in the estimation of emissions under the scenario of project implementation.

A particularity arises regarding the reduction of methane emissions and the implementation of an anaerobic sludge digestion system in the case of plants whose base scenario involves aerobic technologies with aerobic sludge digesters. In this case, although installing an anaerobic sludge digester will increase methane emissions, it is possible to harness approximately 90% of these emissions for electric power by means of a system for capturing and using them. However, a small amount of methane will be emitted into the atmosphere owing to possible inefficiencies in the gas collection and routing systems. Added to the emissions generated during the wastewater treatment phase, which are considered to be marginal, this methane will increase total emissions.

¹⁸ Published by the Energy Regulatory Commission of Mexico [online]: https://www.gob.mx/cms/uploads/attachment/file/806468/4_-_Aviso_FE_2022_1_.pdf.

Table 11
Emissions reduction in the 10 WWTPs studied
(Tons of CO₂ equivalent per year)

Name	Base scenario (1)			Project scenario (2)			Emissions reduction (2 - 1)
	Energy consumption	Methane emissions	Total emissions	Generated energy consumption	Methane emissions	Total emissions	
El Salvador							
Ciudad de San Juan Opico	218	1 568	1 787	0	163	163	-1 623.8
Ciudad Futura	462	2 531	2 994	79	260	340	-2 654.1
Metapán	432	575	1 006	0	474	474	-531.9
Total	1 112	8 457	5 787	79	897	977	-4 809.9
Mexico							
San Martín de las Pirámides	367	426	793	52	333	385	-407.6
Centenario	412	74	486	0	692	692	205.5
Bicentenario	206	55	261	0	616	616	355.1
San Miguelito	550	153	702	0	1 425	1 425	722.4
Total	1 536	3 533	2 243	52	3 066	3 119	875.4
Panama							
Montijo	23	275	299	3	29	32	-267
Puerto Armuelles	31	23	54	0	216	216	162
Soná-Paraíso	69	15	84	0	138	138	55
Total	123	313	437	3	384	387	-50

Source: Prepared by the authors, on the basis of information from the National Water and Sewer System Administration (ANDA) and Salvadoran Water Authority (ASA) (El Salvador); Water Commission of the State of Mexico (CAEM), Drinking Water and Sewerage Commission (CAPA) and National Water Commission (CONAGUA) (Mexico); and National Water and Sewer System Institute (IDAAN) (Panama).

In the case of anaerobic wastewater treatment technologies that already use the biogas they generate, the balance is positive owing to the significant reduction of methane emissions from the anaerobic reactors (approximately 51%; see San Martín de las Pirámides WWTP, table 11). Thus, the final outcome will depend on the degree to which the energy from the national power system is replaced by the power generated internally by the plant and the difference in methane emissions between the base scenario and the project implementation scenario.

The results presented indicate that going ahead with the projects could potentially reduce emissions by some 407.6 tons of CO₂ equivalent per year. However, in the Centenario, Bicentenario and San Miguelito plants, emissions rise because the energy harnessed does not fully offset the effect of the increase in emissions caused by possible inefficiencies in methane capture, routing and storage systems. These results are limited by data availability, however. In fact, the emissions reduction is likely to be larger, given the benefits of harnessing heat energy, as well as the additional emission factors associated with the transportation and final disposal of large volumes of sludge from aerobic digestion at the Centenario, Bicentenario and San Miguelito plants.

Reducing WWTP emissions in Panama. Despite the limitations in the data for estimating the environmental impact of the projects proposed here, in the case of the Puerto Armuelles and Soná-Paraíso plants, the energy consumption recorded by IDAAN for 2021 may be used as a starting point. The emissions associated with these plants' energy consumption may be calculated based on this

consumption and a national power system emission factor of 0.3363 tCO₂e/MWh.¹⁹ Furthermore, given that these plants use aerobic treatment processes, only the emissions associated with wastewater treatment under aerobic conditions should be included in the estimation of emissions in the base scenario. In the case of anaerobic wastewater treatment technologies (Montijo WWTP), which use the biogas that they generate, a positive balance occurs owing to the significant reduction of methane emissions from the anaerobic reactors or units (approximately 89%).

The results given in table 11 show that the methane recovery projects envisaged could reduce emissions by approximately 50 tons of CO₂ equivalent per year. However, in the Puerto Armuelles and Soná-Paráiso plants, emissions would rise because the energy harnessed does not fully compensate for the increase in emissions arising from possible inefficiencies in methane capture, routing and storage systems. The outcomes in terms of emissions reduction will likely be positive given the benefits of using heat energy, as well as the additional emission factors associated, for example, with the transportation and final disposal of the sludge volumes derived from aerobic sludge digestion at the Puerto Armuelles and Soná-Paráiso plants.

¹⁹ Power grid emission factor for Panama [online]: https://www.ensa.com.pa/sites/default/files/fieldable-panels-panes/ensa_simple_info/files/inventario_de_emisiones_de_gases_2017.pdf.

III. Conclusions

At the international level, the reduction of CH₄ (a greenhouse gas with global warming potential between 28 and 84 times greater than CO₂) has been considered to be the fastest and most cost-effective strategy to keep within the target of limiting global warming to 1.5°C, while supporting the livelihoods of billions of people (UNEP/Climate and Clean Air Coalition, 2021). In turn, the application of circular economy principles in various productive activities has been shown to be a highly beneficial approach environmentally, socially and economically. The circular economy is valuable as a conceptual framework insofar as it leverages resources that were previously considered waste, which often impose additional costs on society for their proper disposal.

In the water and sanitation sector, this approach to wastewater treatment has been shown to be profitable in plants with capacities greater than 500 l/s. However, the possibilities for lower capacity plants have been little explored. This document provides evidence in this regard, by testing the financial viability of methane energy use in 10 WWTPs in El Salvador (3), Mexico (4) and Panama (3), all with capacities of under 500 l/s. The results indicate that investing US\$ 6.82 million would help to generate 8,846 MWh/year of electric power, with annual savings of US\$ 1.52 million. These savings would enable the investment to be recouped within 4.49 years, without factoring in a discount rate; and in 6.5 years, discounting savings at a rate of 10%.

This type of solution has considerable development potential in plants such as Metapán in El Salvador, with cost recovery in less than 4 years. Ciudad Futura in El Salvador, San Martín de las Pirámides in Mexico and San Miguelito in Panama also show notable investment recovery periods, of less than 5 years. These initiatives could become more viable with the increase in the flow of wastewater treated as a result of urban development, population growth and efficiency gains in biological treatment processes.

From an environmental perspective, CO₂ equivalent emissions would be reduced considerably: by 4,810 tons in El Salvador, 4,07.6 tons in Mexico and 207 tons in Panama. However, some projects, such as Centenario and San Miguelito, show an increase in net emissions. This reflects the lack of accurate data on real energy consumption, suboptimal operation levels, and unaccounted emissions

associated with aerobic sludge digestion. WWTPs that use aerobic digestion generate 6 to 8 times more sludge than those that use anaerobic digestion; this implies additional transportation and final disposal processes. The absence of data on these additional emissions in the base scenario contributes to the negative balance seen for these plants.

Lastly, although this document does not include income derived from the sale of carbon credits in the valuation of the projects' financial viability, it is important to note that the emissions reduction mentioned could generate annual revenues ranging between US\$ 10,849 and US\$ 54,246, at a per-ton carbon price of between US\$ 2 and US\$ 10. This would represent between 0.71% and 3.57% of the savings generated annually by the production of electrical power in the WWTPs analysed.

The conclusiveness of these figures adds to the debate today on the global carbon price and other related topics. For example, it is essential to establish an adequate carbon price to encourage the gradual reduction of emissions. Conversely, underestimating the carbon price would generate confusing signals that would complicate the achievement of global emissions reduction goals. This is worrisome considering that 75% of global emissions currently carry a price of under US\$ 10 per ton (World Bank, 2017). This figure contrasts starkly with the social cost of carbon, which is estimated at US\$ 25.83 per ton for Latin America and the Caribbean (Alatorre and others, 2019) and US\$ 77 dollars and US\$ 124 per ton by 2030 and 2050, respectively (Stern and others, 2022).

Recommendations

These initiatives cannot be adopted without increasing both public and private investment in the sector. Furthermore, following the recommendations of Salazar-Xirinachs and Llinás (2023), productive transformation in Latin America and the Caribbean must focus on activities and processes that promote learning and innovation, which requires strengthening the human capital managing the sector.

Consequently, although the sector faces significant restrictions in terms of accessing financing, procedures exist to obtain resources from multilateral climate finance funds. These funds, such as the Green Climate Fund (GCF) and the Global Environment Facility (GEF), prioritize initiatives that have a strong impact on emissions reduction and economic, social and health benefits. Therefore, one recommendation is to devise projects spanning several WWTPs (rather than individual plants), whether at the national, subnational or even regional level in Central America and the Caribbean, with a view to enhancing eligibility.

At the same time, there have been successful experiences with revolving funds at the national level, where governments and multilateral banks finance projects through an autonomous entity that manages the fund and provides financing adapted to the needs of the sector and prioritizes project financing, based on impact. These funds have the advantage of being sustainable over time and generating a multiplier effect that provides the sector with more resources for future investments.

In order to access financing, countries must therefore follow four key stages in developing their methane recovery projects: (i) identify the potential for WWTPs to harness methane to meet global and national mitigation targets; (ii) align with national priorities and policies to reduce GHG emissions; (iii) analyse the economic and financial footing of projects; and (iv) develop financing plans and economic feasibility studies to evaluate returns and possibilities of leveraging with local co-financing, seeking access to international funds.

In addition, to strengthen not only investment, but also the capacities of sector agents to pursue initiatives such as those proposed in this document, it is crucial to develop what Salazar-Xirinachs (2023) calls technical, operational, political and prospective (TOPP) capabilities. These are essential for public policies to be effective in transforming the realities of the sector.

While technical and operational capabilities cover the planning, formulation and evaluation of medium- and long-term policies, as well as effective coordination between public and private institutions; political capabilities focus on the management of social dialogue, public leadership and coordination between different levels of government, and prospective capabilities refer to the anticipation of megatrends, the construction of future scenarios and rapid response to crises (Salazar-Xirinachs, 2023).

Enhancing the sector's institutional, technical and operational capacities will not only enable circular water management in Latin America and the Caribbean, but will also overcome barriers to projects that can contribute to the fulfilment of SDG 6 on clean water and sanitation. To strengthen these capacities, ECLAC has developed training for WWTP authorities and operators in El Salvador, Mexico and Panama. These sessions include tools to evaluate the methane generation potential and financial viability of the projects. In addition, a methodological model has been developed to identify methane potential depending on the operating conditions and treatment system technologies. This model is freely available for authorities to use in order to improve the assessment of environmental and economic benefits, and to reduce the costs associated with the management and final disposal of biosolids.

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Annexes

Annex A1

Estimation of methane emissions in the secondary phase of wastewater treatment

This section explains the method used to estimate the volume of emissive (and capturable) methane in the secondary treatment of wastewater, based on the methodology proposed by IPCC (2019):

$$CH_4 = (TOW - S) * EF \quad (1)$$

$$S = S_{mass} * K_{rem} \quad (2)$$

$$EF = Bo * MCF \quad (3)$$

$$GA = CH_4 (1 - L) \quad (4)$$

Where:

- CH_4 :** Amount of methane generated by aerobic or anaerobic treatment (kg/year).²⁰
- TOW :** Specific organic load of COD entering the anaerobic system (kg/year) or BOD (Kg/year) entering the aerobic system.
- S :** Organic component removed from wastewater in the form of sludge (kg COD/year, or Kg BOD/year).
- EF :** Methane emission factor (kg CH_4 /kg COD, or kg CH_4 /kg BOD).
- S_{mass} :** Amount of sludge removed in the secondary treatment process, whether aerobic or anaerobic (Kg/year). To estimate this value, first, the organic load entering the system is multiplied by a sludge generation factor. According to Cleveson, von Sperling and Fernandes (2007) for anaerobic systems, this factor varies between 0.12 and 0.18 Kg total suspended solids (TSS)/Kg COD applied (a factor of 0.15 is recommended). In aerobic systems, the factor will depend on the technology being used, for example, in conventional activated sludge (CAS) systems and in plants using submerged aerated biofilters, the solids production value used is 0.6–0.8 Kg TSS/Kg COD applied; while in trickle filters, sludge production is considered to average 0.55–0.75 kg TSS/kg COD.
- K_{rem} :** Sludge factor²¹ (kg BOD/kg dry sludge mass).²² According to the reference values given in table 6.6A of the IPCC methodologies (2019), the default value of 0.8 kg BOD/Kg of dry sludge mass should be adopted in the case of sludge from anaerobic treatment; in the case of sludge from aerobic treatment with an added anaerobic sludge digestion process, 1 kg BOD/kg of dry sludge mass should be taken as the default value.
- Bo :** Maximum CH_4 producing capacity. According to IPCC (2019), this parameter is equivalent to 0.6 (kg CH_4 /kg BOD), or 0.25 (kg CH_4 /kg COD).
- MCF :** Methane correction factor (fraction or percentage). This is an indication of the extent or degree to which each system is anaerobic and, therefore, varies depending on the treatment system. For example, in a perfectly anaerobic closed unit, such as a UASB reactor, the value is 1. In anaerobic lagoons, a value of 0.8 is

²⁰ To express this in volume terms (m^3), the weight is divided by the gas density (a standard value of 0.67 kg/ m^3 is recommended).

²¹ Amount of organic matter contained in the sludge.

²² This may be multiplied by a factor of 2.08 if the estimate is to be performed using COD.

recommended (IPCC, 2019). For aerobic systems, although IPCC (2006) established a factor of zero for compact aerobic systems, it corrected this in its updated methodologies (2019), determining that CH₄ emissions may occur at some treatment phases of aerobic systems (for example, in sedimentation tanks). Accordingly, IPCC identified a range between 0.003 to 0.09.²³

GA: Amount of usable methane (CH₄) (m³).

L: The fraction of biogas that is lost during capture, routing and reuse (i.e. methane that is not captured). 0.1 is a standard value for UASB reactors and anaerobic sludge digesters. During methane capture, either for flaring or for energy use, a fraction of the biogas is lost in the capture, routing and reuse system. Thus, the difference between the methane generated and the methane captured will be the amount of methane emitted into the atmosphere.

²³ For aerobic processes, the value adopted is 0.03.

Annex A2

Estimating methane emissions from anaerobic digestion of aerobic sludge

According to the formula recommended by the IPCC (2019) for calculating emissions in anaerobic sludge digestion processes, the methane generated during the stabilization of aerobic sludge in an anaerobic biodigester is expressed as follows:

$$CH_4 = M * EF \quad (5)$$

Where:

- CH₄*: Amount of methane generated by anaerobic treatment (kg/year).²⁴
- M*: Mass of organic waste treated by biological treatment. This is assumed to be the amount of sludge generated by the previous biological treatment process, expressed in Kg, and corresponds to the *S_{mass}* parameter given by the equation.
- EF*: Methane emission factor (g CH₄/kg of sludge treated). The values used are those applied by López and others (2017), i.e. theoretical biogas production of 0.8 m³/Kg volatile solids (VS), equivalent to 0.56 m³/kg substrate (ST) (375 g of CH₄/kg of sludge).

Equation 4 is also to be applied in this case to estimate the usable methane.

²⁴ To express this in volume terms (m³), the weight is divided by the gas density (a standard value of 0.67 kg/m³ is recommended).

Annex A3

Estimating methane energy potential and the electric power that can be generated

Once the volumes of emitted and usable methane have been determined, its energy content can be estimated at each stage (secondary treatment and sludge digestion).

The electrical energy that can be generated and the heat energy that can be captured from power generation (cogeneration) (both in kWh/year) are estimated on the basis of these equations:

$$CEM = GA * PCI \quad (6)$$

$$GE_e = CEM * ESG_e \quad (7)$$

$$GE_c = CEM * ESG_c \quad (8)$$

Where:

CEM: Energy content of the captured methane (kWh/year).

GA: Amount of usable methane (CH₄) (m³).

PCI: Calorific value of methane. Typical value: 9.97 (kWh/year).

GE_e: Electrical energy that can be generated (kWh/year).

GE_c: Heat energy that can be generated (kWh/year).

ESG_e: Efficiency of the electrical power generating system. An average efficiency rate of 35% of electricity generation is assumed.²⁵

ESG_c: Efficiency of the heat recovery system. An average efficiency rate of 40% (engine and exhaust gas cooling) is assumed.²⁶

²⁵ This may vary between 20% and 45%, depending on the technology and size of the generator.

²⁶ This may vary between 30% and 50%, depending on the technology and size of the generator.



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