

# **The circular economy opportunities for wastewater treatment systems in Latin America and the Caribbean**

Silvia Saravia Matus  
Marina Gil Sevilla  
Diego Fernández  
Alfredo Montañez  
Elisa Blanco  
Lisbeth Naranjo  
Alba Llavona  
Natalia Sarmanto



UNITED NATIONS

**ECLAC**

# Thank you for your interest in this ECLAC publication



UNITED NATIONS



Please register if you would like to receive information on our editorial products and activities. When you register, you may specify your particular areas of interest and you will gain access to our products in other formats.

[Register](#)

---

Click on the link below for our social networks and other channels for accessing our publications:

 <https://bit.ly/m/CEPAL>



SERIES

NATURAL RESOURCES AND DEVELOPMENT 213

# The circular economy opportunities for wastewater treatment systems in Latin America and the Caribbean

Silvia Saravia Matus  
Marina Gil Sevilla  
Diego Fernández  
Alfredo Montañez  
Elisa Blanco  
Lisbeth Naranjo  
Alba Llavona  
Natalia Sarmanto



UNITED NATIONS

ECLAC

This document was prepared by Silvia Saravia Matus, Economic Affairs Officer, and Marina Gil Sevilla, Senior Research Assistant, both of whom are with the Water and Energy Unit of the Natural Resources Division of the Economic Commission for Latin America and the Caribbean (ECLAC); and Diego Fernández, Alfredo Montañez, Elisa Blanco, Lisbeth Naranjo, Alba Llavona and Natalia Sarmanto, Consultants with that Unit. The authors are grateful for the comments made by Laura Martínez Botia.

Funding for the preparation of this material was provided by the 2030 Agenda for Sustainable Development Sub-Fund of the United Nations peace and development trust fund under the project entitled "Potable water, sanitation and renewable energies to improve the health conditions of the population and promote productive uses in the most lagging behind municipalities of the countries of the northern subregion of Latin America and the Caribbean" (PDF-SDG-2021-07), for which ECLAC is the lead agency.

The United Nations and the countries it represents assume no responsibility for the content of links to external sites in this publication.

Mention of any firm names and commercial products or services does not imply endorsement by the United Nations or the countries it represents.

The views expressed in this document, a translation of a Spanish original which did not undergo formal editing, are those of the authors and do not necessarily reflect the views of the Organization or the countries it represents.

United Nations publication  
ISSN: 2664-4541 (electronic version)  
ISSN: 2664-4525 (print version)  
LC/TS.2022/193  
Distribution: L  
Copyright © United Nations, 2025  
All rights reserved  
Printed at United Nations, Santiago  
S.2500001[E]

This publication should be cited as: S. Saravia Matus et al. (2025). The circular economy opportunities for wastewater treatment systems in Latin America and the Caribbean, *Natural Resources and Development Series* (213) (LC/TS.2022/193), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC).

Applications for authorization to reproduce this work in whole or in part should be sent to the Economic Commission for Latin America and the Caribbean (ECLAC), Documents and Publications Division, publicaciones.cepal@un.org. Member States of the United Nations and their governmental institutions may reproduce this work without prior authorization but are requested to mention the source and to inform ECLAC of such reproduction.

## Contents

<b>Abstract</b> .....	7
<b>Introduction</b> .....	9
<b>I. Wastewater-related issues in Latin America and the Caribbean</b> .....	11
A. Wastewater treatment in Latin America and the Caribbean: the present situation.....	11
B. Targets and agreements for increasing wastewater treatment in Latin America and the Caribbean .....	14
<b>II. From waste to resources: circular economic opportunities for wastewater treatment systems in Latin America and the Caribbean</b> .....	17
A. The scope of the circular economy .....	18
1. The circular economy and sustainable development.....	19
2. The circular economy and water.....	20
B. The technological potential of the circular economy approach to wastewater treatment .....	21
1. Water reuse.....	22
2. Energy generation.....	23
3. Nutrient extraction.....	26
C. Expected benefits.....	27
1. Direct economic benefits.....	27
2. Environmental benefits .....	28
3. Social benefits.....	29
D. Main findings.....	29
<b>III. The potential for harnessing methane to generate energy in wastewater treatment plants in Latin America and the Caribbean</b> .....	31
A. Description of WWTPs in selected countries of the region .....	32
B. Selection of WWTPs for analysis.....	38
C. Methodology and parameters used in estimating methane emissions by type of technology .....	40

D.	Estimation of methane emissions in the target-group WWTPs of the selected countries (baseline scenario).....	43
E.	Estimation of methane emissions in the target-group WWTPs of the selected countries (modified scenario).....	45
<b>IV.</b>	<b>Estimated costs and benefits of harnessing methane emissions for cogeneration in the target-group WWTPs.....</b>	<b>49</b>
A.	Cost of the investments required to capture methane emissions for generating energy in the target-group WWTPs .....	49
B.	Economic benefits.....	52
C.	Environmental benefits .....	56
D.	Macroeconomic and social benefits.....	58
<b>V.</b>	<b>Conclusions and recommendations .....</b>	<b>61</b>
A.	Findings and recommendations concerning the adoption of a policy and plan for harnessing methane in WWTPs of Latin American and Caribbean countries .....	61
B.	Contributions to a transformative economic recovery for the region .....	63
	<b>Bibliography.....</b>	<b>65</b>
	<b>Annexes .....</b>	<b>71</b>
	Annex A1 .....	72
	Annex A2 .....	81
	Annex A3 .....	84
	<b>Natural Resources and Development Series: Issues published.....</b>	<b>92</b>
<b>Tables</b>		
Table 1	Summary of NDC proposals concerning wastewater treatment in Latin America and the Caribbean, by country .....	14
Table 2	Description of the selected countries .....	32
Table 3	Basic statistics on WWTPs in place in the five selected countries.....	34
Table 4	Number of WWTPs with capacities of 500 l/s–4,000 l/s in the selected countries .....	38
Table 6	General parameters for estimating the amount of methane emitted during the treatment of wastewater .....	42
Table 7	Parameters for estimating methane generated by anaerobic and anaerobic-aerobic wastewater treatment technologies.....	42
Table 8	Estimated methane emissions from the treatment of household wastewater in the target-group WWTPs .....	44
Table 9	Estimated methane emissions produced by the treatment of household wastewater by the target-group WWTPs in each country.....	45
Table 10	Estimated methane emissions and potential energy content obtainable from.....	46
Table 11	Estimated methane emissions and potential energy content in each country obtainable from household wastewater treatment in the target-group WWTPs.....	47
Table 12	Investments needed to harness the generable methane in target-group WWTPs .....	50
Table 13	Estimated cost of investments needed to make use of generable methane in the target-group WWTPs, by type of technology.....	50

Table 14	Estimated cost of investments needed to make use of generable methane in the target-group WWTPs, by country .....	51
Table 15	Industrial-sector electricity prices in the second quarter of 2019 .....	53
Table 16	Financial evaluation of projects for harnessing methane in the target-group WWTPs .....	53
Table 17	Reduction in emissions following investments for capturing and utilizing methane in the target-group WWTPs.....	57
Table 18	Impact of the proposed investments on GDP, value added and employment, by country .....	59
Table A1.1	Overview of the wastewater treatment technologies used in Latin America and the Caribbean .....	77
Table A1.2	Classification of WWTPs listed in the database, by type of technology employed .....	78
Table A3.1	Investments required to harness generable methane in WWTPs using (compact) aerobic and advanced primary wastewater treatment processes .....	84
Table A3.2	Estimated cost of investments required to harness generable methane in WWTPs that use (compact) aerobic wastewater treatment technologies .....	85
Table A3.3	Investments required to harness generable methane in WWTP lagoon systems.....	86
Table A3.4	Estimated cost of the investment required to harness generable methane in WWTP lagoon systems.....	87
Table A3.5	Investments required to harness generable methane in WWTPs that use anaerobic and (compact) anaerobic/aerobic wastewater treatment systems .....	87
Table A3.6	Estimated cost of the investments required to harness generable methane in WWTPs using anaerobic and anaerobic/(compact) aerobic technologies.....	88
Table A3.7	Investments required in WWTPs that use compact anaerobic technologies .....	89
Table A3.8	Investments required in WWTPs that use anaerobic technologies.....	91

## Figures

Figure 1	Access to sanitation and wastewater treatment services in selected Latin American and Caribbean countries, 2020 .....	12
Figure 2	Safely treated domestic wastewater in Latin America and the Caribbean, 2020.....	13
Figure 3	Distribution of the 3,336 WWTPs, by treatment capacity (l/s).....	35
Figure 4	Lorenz curve: installed capacity in relation to the number of WWTPs in the selected countries .....	36
Figure 5	Number of plants and total treatment capacity, by treatment capacity category.....	37
Figure 6	Shares of aerobic and anaerobic technologies used to treat wastewater flows in the target group of WWTPs.....	40
Figure 7	Estimated methane emissions, by type of wastewater treatment process .....	44
Figure 8	Cost of investments per MWh/year of generable electricity .....	52
Figure 9	Cost of investments p.e. versus projected returns p.e. over a 20-year period from using methane to generate electricity .....	54
Figure 10	Use of installed capacity in the target-group WWTPs, by type of wastewater treatment technology .....	55
Figure 11	Use of installed capacity in the target-group WWTPs, by country .....	55
Figure 12	Cost of investments p.e. versus projected returns p.e. over a 20-year period from using methane for the cogeneration of energy, based on an installed capacity use rate of 85%.....	56

Figure 13	Emissions reductions in the target-group WWTPs, by country .....	58
Figure 14	Impact of the proposed investments on GDP and value added, by country .....	59
Figure 15	Impact of the proposed investments in terms of green job creation, by country.....	60
Figure A1.1	Distribution of WWTPs providing sufficient information, by type of treatment process employed and treatment capacity .....	79

## Diagrams

Diagram 1	Difference between the linear and circular economies .....	18
Diagram 2	The circular economy and the Sustainable Development Goals.....	20
Diagram A1.1	Conventional activated sludge treatment system .....	72
Diagram A1.2	Extended aeration treatment system.....	73
Diagram A1.3	Conventional activated sludge system with denitrification .....	73
Diagram A1.4	Oxidation ditch treatment system .....	74
Diagram A1.5	Treatment system using a biological filter.....	74
Diagram A1.6	Upflow anaerobic sludge blanket (UASB) system.....	75
Diagram A1.7	Treatment system using an upflow anaerobic sludge blanked or another type of anaerobic reactor + activated sludge .....	76
Diagram A1.8	Treatment systems using an upflow anaerobic sludge blanket or another type of anaerobic reactor + a biological filter or trickling filter .....	77

## Abstract

The application of circular economic principles for the recovery of methane in wastewater treatment plants (WWTPs) has become widespread in most of the megacities of Latin America and the Caribbean. Many people live in smaller cities in which WWTPs have not yet put these principles into practice, however.

To promote the adoption of these technologies in the region's medium-sized WWTPs, the present study estimates the investments that would be needed and the economic, social and environmental benefits to be derived from recovering methane and using it to generate electricity in 75 plants having capacities of between 500 l/s and 4,000 l/s that serve some 33 million people in the Plurinational State of Bolivia, Colombia, Costa Rica, Mexico and Peru.

The study's findings indicate that an estimated investment of US\$ 251 million, or US\$ 7.6 per population equivalent (p.e.), would be needed. This would generate income over a 20-year period of US\$ 10.3 p.e., thus yielding a benefit-cost ratio of 1.36. These investments would also create an estimated 11,383 new green jobs and reduce the volume of the methane emissions that these plants release into the atmosphere by 88%.

This study therefore provides evidence of the feasibility of making these types of investments in mid-capacity WWTPs. These kinds of investments are needed to speed up progress towards achieving Sustainable Development Goals 6 and 7 but making them work requires innovative governance and access to the necessary funding and technological support. One of the main conclusions of this study is that efforts such as these will help to bring about a transformative recovery for the region and are of pivotal importance for the establishment of standards that will allow the world's societies to live within planetary boundaries.



## Introduction

In 2020, approximately 582 million people in Latin America and the Caribbean (roughly 89% of the region's population) had access to some form of sanitation (55% had access to basic sanitation and 34.1% to safely managed sanitation services); 67% of the population had hook-ups to a sewerage system (19% in rural areas and 78% in urban areas) but only 34% had connections to a sewerage network that used safely managed wastewater treatment systems (JMP, 2021). These figures attest to the fact that the countries of the region are lagging far behind in this respect, since, in that same year, just 41% of wastewater was being treated, whereas the world average is 55.5% and the average for the countries of the Organisation for Economic Co-operation and Development (OECD) is over 80% (United Nations, 2021). The low coverage rates for wastewater treatment in the region have major environmental implications, especially in terms of water pollution, which has serious consequences for people's health as result of the faecal-oral transmission of pathogens and for the health of the ecosystems inhabited by fish and birds. Increasing treatment levels will help put a stop to these problems, but the corresponding technologies use more energy and are a source of methane emissions whose harmful impacts in terms of climate change must be averted. The objective of this report is therefore to explore what opportunities a circular economy can open up for treating wastewater in a more sustainable way. The report will focus on medium-sized cities (with populations of between 300,000 and 2.3 million), where waste can be converted into resources on a technically efficient scale.



## I. Wastewater-related issues in Latin America and the Caribbean

This chapter<sup>1</sup> will outline the wastewater-related issues that have arisen in Latin America and the Caribbean (section A) and the targets agreed upon and set by the different countries of the region for urban wastewater treatment efforts in their nationally determined contributions (section B).

### A. Wastewater treatment in Latin America and the Caribbean: the present situation

One of the main sources of water pollution in Latin America and the Caribbean is the improper and/or insufficient treatment of household wastewater. Small and medium-sized population centres do not typically have any specific regulations on wastewater treatment in place, and wastewater treatment plants (WWTPs) are often in poor condition or have fallen into disuse because of a lack of financial resources or operating capacity. Very few rural settlements have wastewater collection systems, and fewer still have WWTPs (Peña, 2016).

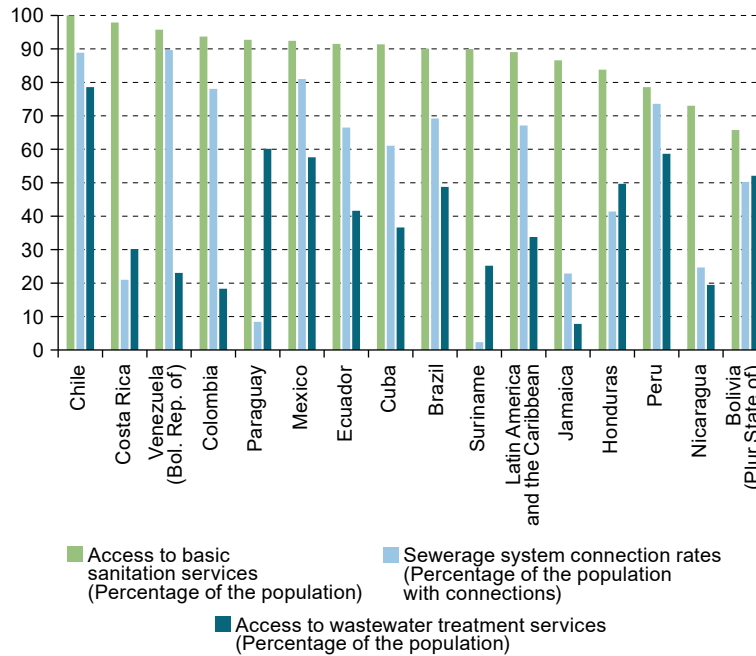
In 2020, around 7 out of 10 people in the region did not have access to safely managed sanitation systems, and up to one fourth of all river segments were subject to a severe degree of pathogenic contamination, with monthly concentrations of faecal coliform bacteria of more than 1,000 colony-forming units (cfu)/100 ml. What is more, the level of these concentrations rose by almost two thirds between 1990 and 2010. These pathogens mainly originate in domestic wastewater sewer outflows (UNEP, 2016).

---

<sup>1</sup> This chapter is based on "Conclusions report on investment in circular water treatment and renewable energy systems for Latin America and the Caribbean with the Nexus approach". That report was prepared as part of the GIZ Nexus programme in 2022 for use at the first focus session held in the Americas for World Water Week, in which ECLAC took part.

As shown in figure 1, wastewater treatment and management levels vary a great deal from one country in the region to the next. Regional averages fail to reflect that variability.

**Figure 1**  
Access to sanitation and wastewater treatment services in selected Latin American and Caribbean countries, 2020  
(Percentages)



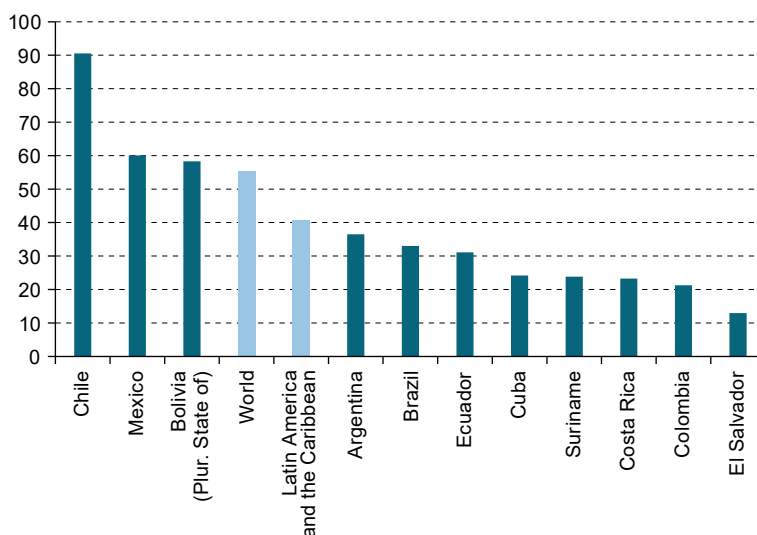
Source: Prepared by the authors, on the basis of WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP), "Rural and urban service levels, 2015 and 2022", 2022 [online] <https://washdata.org/data/household#!/>.

With regard to target 6.3 of the Sustainable Development Goals, which deals with water quality, most of the Latin American and Caribbean countries have not provided monitoring data, and only 11 of the 33 member countries of ECLAC have provided information on the proportion of wastewater flows safely treated (indicator 6.3.1).

The fact that so little information is available is in itself a clear indication of how far behind the region is in this respect, but a look at the statistics of the countries that have been reporting such information also attests to how far they are lagging behind. In 8 of the 11 reporting countries, no more than 40% of household wastewater is being treated adequately or safely (see figure 2). El Salvador reports the lowest rate of safe treatment coverage (12.95%), while Colombia, Costa Rica, Suriname and Cuba all report coverage rates of under 25%.

The situation is similar with respect to indicator 6.3.2 (the proportion of bodies of water with good ambient water quality that therefore do not pose a threat to the environment or human health). The lack of data and the absence of close monitoring give rise to an additional concern in this connection, since the pollution of bodies of water is one of the main environmental externalities capable of destroying entire ecosystems and therefore eliminating the benefits they provide (freshwater and food, regulation of the climate and cultural services) and undermining their sustainability (Saravia Matus and others, 2020).

**Figure 2**  
**Safely treated domestic wastewater in Latin America and the Caribbean, 2020**  
 (Percentages)



Source: Prepared by the authors, on the basis of United Nations, "Safely treated domestic wastewater", 2021 [online] <http://data.un.org/>.

In most Latin American and Caribbean countries, it is common practice to dump untreated or inadequately treated wastewater into lakes, rivers and ravines, posing serious problems for households located along these watercourses that rely on them for their drinking water (Schady, 2015). This is why many river systems are so severely polluted, including the Medellín River in Colombia and the Matanza River in Argentina, waterways that provide drinking water to the surrounding populations and water for irrigating human and animal food crops, in addition to serving as the habitat for many different animal and plant species.

The discharge of nutrient loads containing nitrogenous and phosphorous compounds is a precursor to harmful algal blooms (HABs), which proliferate in the presence of high levels of solar radiation and high temperatures. These blooms unfortunately have toxic effects on organisms such as fish and birds and, consequently, on the people who eat them. Their consequences may range from allergies to death, if the toxin is lethal for these organisms (for example, red tides) or for humans (cyanotoxins produced by microalgae, which are microscopic organisms found in water). These HABs are on the rise in coastal areas with growing populations, since this coincides with the discharge of more water from urban areas into the sea (Guzmán, 2019).

The failure to treat wastewater also correlates with outbreaks of serious diseases such as hepatitis A (González-Saldía and others, 2019). The hepatitis A virus is a dangerous pathogen that is transmitted via the faecal-oral route, and the epidemiology of the infection is directly related to the population's access to drinking water and to the sewerage infrastructure that is in place (Báez and others, 2016). A study conducted at the University of Concepción in Chile of a sea floodplain that is heavily polluted with human faecal matter detected a space-time correlation with an outbreak of hepatitis A in the coastal population (Báez and others, 2016). In other Latin American countries, the hepatitis A virus had previously been found to be circulating in environmental samples taken in cities such as Córdoba, Argentina; Caracas, Bolivarian Republic of Venezuela; and Rio de Janeiro, Brazil (Báez and others, 2016). Human faecal contamination is potentially more dangerous than animal faecal contamination because it is associated with the proliferation of all human-specific pathogens, including the hepatitis A virus (González-Saldía and others, 2019).

The foregoing is all the more worrisome when viewed within the context of climate change. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2021), Latin America and the Caribbean are one of the world regions most subject to climate-related disasters. Hydrometeorological phenomena such as floods, storms, droughts and heatwaves account for 93% of all disasters in the last 20 years and are on the rise. In a scenario of water scarcity in which waterway flow volumes are diminishing, river systems' dilution capacity wanes, reducing ecosystems' ability to withstand changes. Their ability to preserve their biodiversity is therefore reduced, and concentrations of contaminants increase. On the other hand, torrential rainfall can cause septic tanks to overflow, thereby posing a serious public health hazard.

Glacial retreat and saltwater intrusion, together with the uneven distribution of precipitation, is reducing the available water supply. Droughts can have severely adverse impacts on the quality of the water used to irrigate crops (Peña-Guerrero and others, 2020). During droughts, more untreated wastewater is used for irrigation, and this practice is quite widespread in some Latin American and Caribbean countries. This puts child and adult farmworkers—as well as the people who consume the food they produce—at risk of contracting various kinds of infections and diseases of the digestive tract as a result of the ingestion of bacteria and contact with viruses and protozoa. Livestock can also fall victim to diseases such as brucellosis owing to the intake of wastewater and feed irrigated with untreated water. This will also, of course, harm people who consume the meat of infected animals (Cisneros, Sanz and Teran, 2015).

## B. Targets and agreements for increasing wastewater treatment in Latin America and the Caribbean

In order to determine what headway has been made in the treatment of wastewater in Latin America and the Caribbean, the nationally determined contributions (NDCs) of the countries of the region were analysed. NDCs set out the agreements entered into by countries and the targets that they have set for improving wastewater treatment, among other things. This information was obtained from the provisional registry of nationally determined contributions (UNFCCC, 2025).

While all the Latin American and Caribbean countries have presented their initial NDCs, only three (Argentina, Grenada and Suriname) of the 33 States have submitted their second NDCs. Under the Paris Agreement, they are required to have done so by 2025.

This desk review showed that the NDCs of 12 of the 33 countries of the region (36%) include contributions relating to the treatment of domestic and industrial wastewater, while those of 8 countries (24%) include provisions specifically on the treatment of household wastewater.

Table 1 provides an overview of selected countries' NDC proposals. Wastewater treatment focusing on the reduction of methane emissions and the reinforcement of the sector's resilience figure prominently in the commitments they have assumed.

**Table 1**  
Summary of NDC proposals concerning wastewater treatment in Latin America and the Caribbean, by country

Country/year <sup>a</sup>	Proposals
South America	
Bolivia (Plurinational State of) (2016)	Water-related measures: household and industrial wastewater treatment plants (WWTPs) are to reduce the amount of methane that they emit into the atmosphere.
Chile (2020)	Measures provided for in the projected scenarios for 2030 and 2050: use of sludge from WWTPs as a forest biostabilizer. In a neutral carbon scenario: new treatment plants in Greater Concepción and Greater Valparaíso by 2035 equipped with methane management and sludge utilization systems.

Country/year <sup>a</sup>	Proposals
Colombia (2020)	Objective: achieve a 68% coverage rate for domestic urban wastewater treatment by 2030. Objective: increase the coverage and quality of the treatment of wastewater flows in order to protect the most polluted basins and water supply sources and to strengthen the climate adaptation aspects of the processes involved in executing the Saneamiento de Vertimientos (SAVER) programme. Projected use and estimated impact and outcomes: based on the prioritization scheme applied by the SAVER programme, the optimization or construction of sustainable infrastructure capable of dealing with the challenges posed by climate change; technological information management to facilitate adaptation.
Central America and Mexico	
Costa Rica (2020)	The country's contribution in this area is focused on comprehensive waste management, particularly with regard to organic waste, and on the modernization of the sewerage and wastewater treatment system, especially in urban areas. Contribution for target 8.4: by 2030, at least 50% of wastewater in densely populated areas will be treated based on an approach focused on resilience to climate change. Contribution for target 8.2: by 2026, the base fee for water use, wastewater discharge and environmental services will have been updated on the basis of climate change and use efficiency criteria.
Guatemala (2017)	Mitigation: implementation of the Wastewater Discharge and Re-use and Sludge Disposal Regulations (Government Agreement 236-2006) as a tool for reducing the sector's emissions.
Mexico (2020)	Action line D3: increased treatment of industrial and urban wastewater to ensure the quantity and quality of the water supply for human settlements with more than 500,000 inhabitants.
Nicaragua (2020)	Medium-term measures to be considered in future NDCs (2025–2030): biodigesters in municipal and industrial WWTPs. Wastewater treatment systems have expanded substantially since 2007; in 2010, 13 departmental capitals were running WWTPs. Since the Managua wastewater treatment plant entered into operation, the percentage of wastewater being treated in the city soared from 35.22% in 2007 to 98.19% in 2011, and the treatment index for the country as a whole climbed from 19.66% to 57.63%.
The Caribbean	
Saint Lucia (2021)	Objective: reduce emissions throughout the energy sector using 2010 as the base year. Co-benefits: reduction of wastewater emissions and introduction of renewable energy technologies in the water sector.

Source: Prepared by the authors, on the basis of the countries' nationally determined contributions (NDCs).

<sup>a</sup> The latest available update was used in each case.

The review of these NDCs indicates that many of these countries are planning to incorporate circular economic principles into their efforts to improve wastewater treatment. This study is therefore attaching economic, social and environmental value to the scenarios being developed by countries of the region in order to help fulfil the Paris Agreement.



## **II. From waste to resources: circular economic opportunities for wastewater treatment systems in Latin America and the Caribbean**

The circular economy represents a way of thinking about production processes as a system that is in sync with the available supply of resources. In order to ensure that the system is sustainable, it is designed to make the most of those resources and to reduce waste by reusing, repairing and recycling. Circularity allows resources to be managed more efficiently and reduces the economy's reliance on the use of finite resources while actually boosting productivity and bolstering long-term resilience.

The implementation of circular economic processes in municipal wastewater systems can make it feasible to reuse treated wastewater and feed it back into the cycle. Instead of using energy from conventional sources for wastewater treatment processes, biogas emission and capture systems and thermal and electrical energy cogeneration systems can be put in place. These systems will recover energy and thus provide a direct way of reducing the use of combustible fuels, and they are thus aligned with the call made by the participants in the twenty-sixth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change for the phasedown of coal power and phase-out of fossil fuel subsidies. By recovering nutrients from wastewater, both greenhouse gas emissions and waste can be limited and profits can instead be realized from their sale.

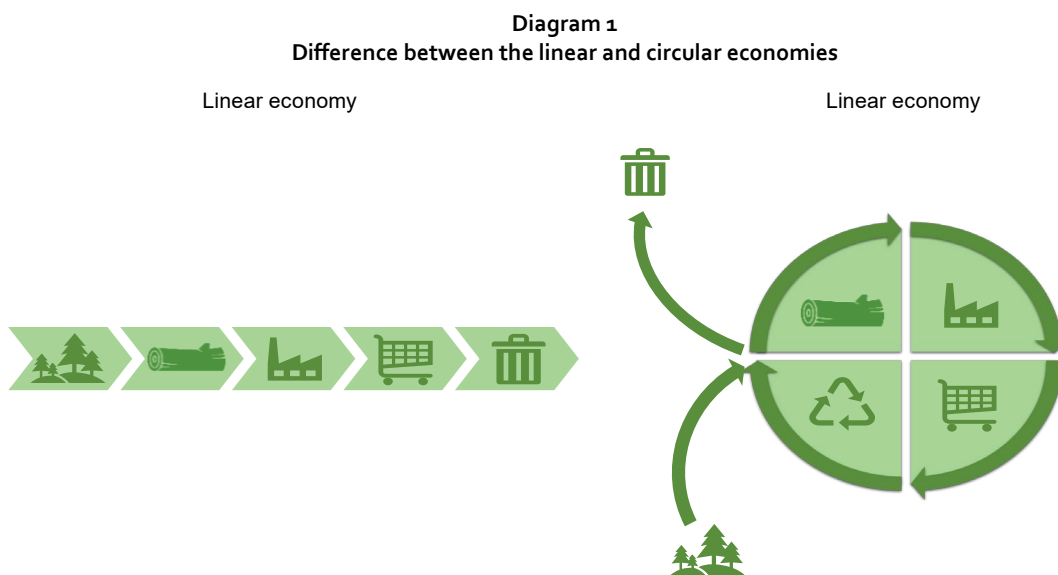
The following discussion will review the concept of a circular economy, how it ties in with the Sustainable Development Goals and its relevance for the water sector (section A). It will then move on to a detailed look at the technological potential for implementing circular economic schemes for the treatment of wastewater (section B), including the opportunities offered by: (i) the reuse of wastewater; (ii) the use of biogas to generate energy, among other options; and (iii) nutrient extraction. The main strengths of each of these elements will be examined, along with the challenges involved in their adoption. Finally, the economic, social and environmental benefits to be derived from the Latin American and Caribbean countries' adoption of these circular economic techniques in the treatment of municipal wastewater (section C) will be explored.

## A. The scope of the circular economy

The circular economy is a new paradigm that is intended to decouple economic growth from the extraction of finite natural resources and energy consumption by regenerating resources and using them more efficiently (Ellen MacArthur Foundation, 2012; Mulder y Albaladejo, 2021).

Its orientation is entirely different from that of the linear economy, which, as its name suggests, defines the traditional production stream as a linear process of “extraction-production-disposal” (see diagram 1). The linear economy is the outgrowth of production and commercial practices and consumption patterns that require a constant supply of products made using natural resources, which endangers the availability and sustainability of essential ecosystem services. The harvesting of raw materials entailed by this approach uses up large amounts of energy and water, results in emissions of toxic substances and has a disruptive effect on natural capital. In terms of volume, it is estimated that nearly 82 billion tons of raw materials were fed into the economic system in 2020, and this figure is expected to continue climbing in the future (Ellen MacArthur Foundation, 2012). Although efforts are being made to improve it, the linear economy is, in and of itself, unsustainable.

The circular economy is a way of seeking to minimize impacts along the entire service or production value chain in order to make it environmentally, socially and economically sustainable. Circular production and consumption systems promote the efficient use of materials, water and energy (Quirós, 2021). They also take into account ecosystems’ recovery capacity and the circular use of material flows (Quirós, 2021).



Source: EcoGreen Mundo, “Diferencias entre the circular economy y la economía lineal”, 2015 [online] <https://ecogreenmundo.com/diferencias-entre-la-economia-circular-y-la-economia-lineal/>.

The six pillars of the circular economic system, known as the 6 Rs<sup>2</sup> (Quirós, 2021), are set out below.

- **Rethink and reduce:** using resources more efficiently
- **Redesign:** putting options for reusing, repairing and recycling ahead of production

<sup>2</sup> The number of principles cited in the literature varies. The initial so-called 3 Rs of the circular economy were “reduce, reuse and recycle” (King and others, 2006; Brennan, Tennant and Blomsma, 2015; Ghisellini Cialani and Ulgiati, 2016). The Waste Framework Directive of the European Union introduced “recover” as the fourth “R”. Since then, academics have proposed going further than the 4R framework and applying the 6 Rs expressed here (Sihvonen and Ritola, 2015), while others have proposed 9 Rs (Van Buren and others, 2016; Potting and others, 2017) and even 38 Rs (Srinivas, 2021).

- **Reuse:** reusing products all along the production chain
- **Repair and remanufacture:** considering options for product maintenance and refurbishment
- **Recycle:** processing waste so the materials it contains can be reused
- **Recover:** extracting energy from materials

This model also avoids removing or incinerating waste before the maximum possible use has been made of those materials. This also involves taking a new approach to product design that takes their durability and refurbishment into consideration, along with the reuse of products and their components, recycling and the implementation of regenerative farming systems.

Circularity entails a more effective form of resource management that offers multiple benefits, including the gradual, systemic decoupling of economic activity from the consumption of a finite supply of resources while increasing productivity, thereby enhancing the long-term resilience of cities and countries.

In more specific terms, the circular economy will contribute to the health of the environment by doing away with energy- or water-hungry production systems and by using less toxic materials (Ellen MacArthur Foundation, 2013; UNEP, 2012). Both of these factors will be reflected in a reduction in greenhouse gas emissions, along with appropriate water use and the protection of biodiversity. This new economic approach will also have social benefits, as it will create jobs and lower the cost of food and services, reduce social externalities and promote innovation (Ellen MacArthur Foundation, 2015; Gower and Schröder, 2016; Schroeder, Anggraeni and Weber, 2019).

Embracing the principles of the circular economy is seen as a way of shielding the economy from natural resource price shocks and mitigating the need to absorb waste disposal costs (Ellen MacArthur Foundation, 2012). It is estimated that changing over to a circular economy would save the European Union as much as US\$ 700 billion per year in net material costs and generate a net profit of US\$ 2.1 trillion per year (Ellen MacArthur Foundation, 2015).

The practices associated with a circular economy are thus seen as being of significant importance in transitioning from the traditional economic model to sustainable consumption and production systems.

## 1. The circular economy and sustainable development

There is a close link between the circular economy and the Sustainable Development Goals of the 2030 Agenda. Such practices as recycling household waste, electronic waste and wastewater, using renewable energy and making more efficient use of resources are more than enough to support a number of the Goals.

Circular economic practices are most closely related to some of the targets for Sustainable Development Goal 6 (clean water and sanitation), Goal 7 (affordable and clean energy), Goal 8 (decent work and economic growth), Goal 12 (responsible production and consumption) and Goal 15 (life on land) (Schroeder, Anggraeni and Weber, 2019). Water recycling and water reuse make a direct contribution to the achievement of targets 6.1, 6.2, 6.3, 6.4 and 14.1; waste reduction directly supports efforts to achieve targets 12.3 and 12.5; and the industrial symbiosis secured by clustering activities around the efficient use of energy and of materials discarded by others makes a direct contribution to the attainment of targets 3.9, 6.3, 7.3, 8.2, 12.4, 9.4 and 17.7 (Montesinos and Martín, 2020).

There are also a number of indirect synergies that can be generated through the adoption of a circular economy that would promote economic growth and employment (Goal 8), help to do away with poverty (Goal 1), help to eradicate hunger and promote sustainable food production (Goal 2) and protect the biodiversity of the planet's oceans (Goal 14) (Schroeder, Anggraeni and Weber, 2019; Velenturf and Purnell, 2021). These synergies could further progress, to a greater or lesser degree, towards virtually all of the Sustainable Development Goals (see diagram 2).

Diagram 2  
The circular economy and the Sustainable Development Goals



Source: A. Velenturf and P. Purnell, "Principles for a sustainable circular economy", *Sustainable Production and Consumption*, vol. 27, Amsterdam, Elsevier, 2021.

Note: The coloured portions of each pie chart indicate the percentage of each Goal on which the introduction of the circular economy would have a strong (red) or partial (orange) impact.

Thus, circular economic practices would not only help to put sustainable systems in place but would also help to achieve many of the Sustainable Development Goals. This approach is therefore seen as both a solution and as a useful tool for governments that are working to fulfil their development target commitments.

## 2. The circular economy and water

Since climate change is having a direct impact on water resources, circular practices are of crucial importance in the water sector. For example, to help deal with water shortages, climate action should include lowering the demand for water, reducing water wastage and reusing treated wastewater, to name only a few of the possible measures that could be pursued. Increasing the sector's climate resilience often goes hand in hand with collateral benefits in terms of the mitigation of greenhouse gases, sustainable development and the protection of the world's ecosystems and their biodiversity (Denton and others, 2014). Water-related climate impacts also affect other sectors, such as agriculture and energy (by, for example, reducing the available supply of water for irrigation and for use in cooling power systems). The ways in which water, energy and food are interlinked therefore require analysis (Kerres and others, 2020). All these objectives can be achieved by adopting circular economic practices.

The principles of the circular economy reflect an awareness that water is a finite resource. That awareness necessarily leads to a search for ways to reduce the use of finite resources as raw materials and, as part of that effort, to avoid using water whenever possible and maximizing the reuse of water in order to avert the negative externalities associated with water shortages and poor water quality. In an economy based on this approach, production systems' impact on natural resources is minimized, thereby paving the way for the restoration of river basins and ecosystems.

The circular economy supports water security and resilience (Quirós, 2021) because it:

- Increases water storage capacity and its conservation.
- Holds out a strong potential for nature-based solutions through the promotion of integrated, flexible approaches.

- Encourages the exploration of alternative ways of using water, such as the reuse of treated wastewater.

The benefits of circular economic principles as applied to wastewater are especially clear. The recovery of resources from wastewater facilities can be a source of reusable water, energy, biosolids and nutrients. These economic and financial benefits contribute to the sustainability of water supply and sanitation systems and to the companies that run them (Rodríguez and others, 2020). The application of circular economic principles to wastewater management and to the recovery and reuse of resources transforms sanitation from a costly service into a self-sustaining one that adds value to the economy (Rodríguez and others, 2020).

The following section will review the different resource recovery technologies and opportunities associated with municipal wastewater treatment, including water reuse, harnessing wastewater as an energy source and nutrient extraction.

## **B. The technological potential of the circular economy approach to wastewater treatment**

The application of the circular economy approach to water treatment redefines wastewater, which then ceases to be regarded as waste and is instead seen as a reusable resource. In addition to reducing wastewater disposal in urban areas, this generates new sources of water and thus increases the water supply. In addition, the use of wastewater to generate energy (in the form of heat, biogas or electricity) replaces other energy sources, improves the output and economic sustainability of wastewater treatment systems and reduces their methane emissions—a major source of greenhouse gases—in line with the proposals made at the twenty-sixth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change.

Supplying, transporting and treating water are energy-intensive processes that produce carbon emissions when they are powered by fossil fuels. Energy use in water- and wastewater-related activities represents approximately 4% of world electricity consumption and could be double that by 2040 (Kerres and others, 2020). Wastewater treatment processes can also produce emissions of methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O), which have a global warming potential that is 80 and 300 times greater than CO<sub>2</sub>, respectively (EPA, 2021; Kerres and others, 2020). Thus, instead of generating waste in the form of dirty water, energy derivatives and greenhouse gas emissions, it is possible to recover good-quality water, produce energy and obtain nutrients.

It is estimated that, globally, over 80% of wastewater is not treated in any way (Kerres and others, 2020). This is mainly because huge investments need to be made in the water and sanitation sector and, in most cases, investment levels are lagging far behind. As cities continue to grow, it is imperative for investments in the sector to be made in the most sustainable and efficient way possible by incorporating circular economic technologies into wastewater management systems. In this context, wastewater is and must be considered a valuable source of energy and nutrients, as well as constituting an additional source of water (Rodríguez and others, 2020).

Circular economic processes can be introduced at different stages and points of interaction in wastewater systems. As mentioned earlier, these types of processes can make it possible to reuse wastewater, generate energy in the form of heat, biogas or electricity and recover nutrients. Each of these processes will be explored in greater detail in the following sections, along with the benefits and opportunities associated with the application of these circular economic techniques in municipal wastewater treatment.

## 1. Water reuse

Municipal wastewater is 99.8% water (López and others, 2017). Once treated, this water can be used for various purposes, with the most common ones being irrigation, industrial processes and the replenishment of groundwater. Various technologies and systems that allow its household use, especially for flushing toilets, are already available (López and others, 2017).

In urban settings, treated wastewater is mainly used for watering people's yards and gardens. Since this involves human exposure to the water, care has to be taken to avert possible health problems. Countries are therefore drawing up and implementing specific regulations governing its use (Mo and Zhang, 2013). In accordance with these protocols, treated wastewater may be used for watering gardens, flushing toilets, washing motor vehicles or, in some cases, even for direct consumption. In the United States, an estimated 64 billion litres of wastewater are used every day, and that figure is rising by 15% each year (Mo and Zhang, 2013).

The reuse of treated wastewater has many advantages. The installation of wastewater treatment systems can reduce the uncertainty around the availability of water associated with climate change by increasing the available water supply. It can also save energy by reducing the amount of energy used to obtain and distribute water. The amount of water that can be reused is proportional to the initial or primary demand, and the system is therefore sustainable over time. Finally, it can also lessen the need to explore other more energy-intensive ways of sourcing water, such as desalination.

The main constraints on the widespread adoption of systems for reusing wastewater are the size of the initial investment in treatment infrastructure that is required and the variability of effluent quality. Concerns about health and environmental security also continue to be factors that hinder the more widespread use of water treatment technologies.

When reclaimed water is intended for household use, it can be routed directly through the potable water distribution system (Leverenz, Tchobanoglous and Asano, 2011). Urbanization, and climate change, public water supplies are becoming stressed, and the chances of tapping new water supplies for metropolitan areas are getting more difficult, if not impossible. As a consequence, existing water supplies must go further. One way to achieve this objective is by increased water reuse, particularly in supplementing municipal water supplies. Although water reuse offers many opportunities it also involves a number of problems. A significant cost for nonpotable water reuse in urban areas is associated with the need to provide separate piping and storage systems for reclaimed water. In most situations, the cost of a dual distribution system has been prohibitive and thus, has limited implementation for water reuse programs. The solution to the problem of distribution is to implement direct potable reuse (DPR). A positive aspect of that approach is that it can improve the overall reliability of the water supply, since a dual distribution system (which would also need to be connected up to the network) is then not required, nor are the injection or dispersion systems employed in indirect distribution networks (Leverenz, Tchobanoglous and Asano, 2011). The stringent requirements that must be met by water being treated for reuse as potable water may increase operating costs, however. The low degree of public acceptance of the idea of direct potable reuse remains a major barrier as well (Mo and Zhang, 2013).

A final application for the reuse of treated wastewater is aquifer recharge, which has many different benefits. Recharge makes it possible to diminish land subsidence and reduce saltwater intrusion in coastal areas. It is also a way of using aquifers' natural storage capacity rather than having to build more storage infrastructure. This storage option avoids losses through evaporation, as well as serving as a natural filter that provides an additional form of water treatment that facilitates the subsequent recovery and reuse of the resource (Mo and Zhang, 2013). There are certain challenges associated with this approach, however, including the attendant requirements in terms of monitoring water quality and the operation of the ancillary facilities. In addition, aquifer recharge with water that has not been fully treated can increase the risk of aquifer contamination. Finally, there is the fact that not all recharged water can be recovered, since groundwater may flow away from the extraction site or be contaminated by other flows of poor-quality groundwater.

## 2. Energy generation

Energy is another component of wastewater that may be recovered or regenerated, as WWTP waste can be harnessed in the form of heat, biogas or electricity. Each of these technologies, along with its benefits and the challenges faced in expanding its application, will be discussed below.

### (a) Heat (and cold) generation

The extraction of thermal energy from WWTP wastewater is usually performed using a heat pump: a mechanical device that transfers water from one place to another. The water is then used to heat up or cool down an environment (GIZ, 2020). The system recovers the hot/cold wastewater and runs it through pipes so that it can be used to heat or cool the treatment process or to heat or cool nearby industrial plants, apartments or private homes. Heat pumps are an efficient technology for own-consumption of renewable energy and are in line with the principles of the circular economy.

These systems have an especially strong potential for domestic use, and various versions are widely available. They harness the temperature of wastewater, which remains constant throughout the year at around 20 degrees (Pistonesi, Haure and D'Elmar, 2010). This technology can be used both in residential buildings that require between 5 kW and 30 kW of energy and in large buildings and urban heating systems that consume 100 kW to 1,000 kW or more (GIZ, 2020). The outlook for their demand is enormous, since it is estimated that energy demand will more than double by 2030 (IEA/OECD, 2016). These systems are already highly versatile in terms of their application in the municipal sector but will be even more so in the future.

One of the main benefits of running heat pumps on treated wastewater is that they are highly energy-efficient systems, as they deliver between two and four units of heat energy for each unit of electrical energy consumed (GIZ, 2020). Indeed, the International Energy Agency (IEA) considers them to be the best air conditioning technology available and estimates the reduction of CO<sub>2</sub> emissions attributable to the use of heat pumps at 6%, with the potential to reach 16% in the future (IEA/OECD, 2016). In addition, they are durable devices that require little maintenance. The use of heat pumps to supply hot water and heating to a block of residential buildings rather than a gas-fired boiler is estimated to provide a savings of US\$ 990 per year (Arnabat, 2017). Consequently, they offer many different advantages, including significant monetary savings.

The main disadvantage of this option is that the initial investment it requires is still larger than the initial investment for conventional heating and air conditioning equipment, but this is counterbalanced by the fact that its operating costs are considerably lower. On the other hand, the pumps are usually somewhat loud and, in some cases, noise levels may be bothersome.<sup>3</sup> In addition, in very cold or very hot climates, the pumps' performance may decrease considerably because the temperature of the wastewater may dissipate before it enters the system; it is also true that, if the spaces to be heated or cooled are not well insulated, the systems will use more energy than otherwise expected (GIZ, 2020). Thus, in addition to the initial investment, the cost of fitting out the areas to be covered and the system as a whole must be taken into consideration.

### (b) Harnessing methane emissions and electricity cogeneration

WWTP waste can be harnessed and used to generate energy in the form of biogas by using anaerobic (without the use of oxygen) digesters rather than aerobic digestion equipment. The gases generated during the digestion of sludge in both anaerobic and aerobic treatment plants can also be utilized. The anaerobic processing of wastewater and sludge generates methane gas (CH<sub>4</sub>) as a by-product that can be used *in situ* to run other processes within WWTP itself, such as heating the sludge digester, boosting the efficiency of the anaerobic digestion process and drying and compacting the sludge before its final disposition (López and others, 2017). Furthermore, this biogas, once purified, can then be used directly as a fuel for vehicles or for industrial or residential purposes.

<sup>3</sup> There are systems that use radiant floor heating or radiators that are very quiet, but this is not the case of those that use fans (GIZ, 2020).

The total volume of methane production per unit of time ( $\text{m}^3/\text{day}$  or some similar metric) in a municipal WWTP mainly depends on the type of treatment technology being used, in addition to the concentration and composition of organic matter present in the wastewater, which are influenced by the size of the drinking water supply, the socioeconomic level of the population, rainwater infiltrations in the sewerage network, the type of sanitation facility involved and the activities performed in the area where the wastewater is collected (Von Sperling, 2005). The temperature at which the process is operating and the characteristics and efficiency of the technology employed also have an influence (López and others, 2017).

Obtaining energy in the form of biogas has a series of advantages. The main one is the reduction of local energy requirements. For example, an anaerobic WWTP that has a chemical oxygen demand (COD) of 100 kW/h over the year may produce close to 285 kW/h if it is equipped with a system that harnesses methane.<sup>4</sup> These processes also significantly reduce the amount of waste in the form of sludge that is produced. Whereas the customary aerobic processes generate between 30 kg and 60 kg of sludge per 100 kg of corrodible material, this could be reduced to just 5 kg of sludge with the use of anaerobic processes (Hernández, 2021). These technologies are thus particularly attuned to circular economic concepts, since they reduce and repurpose production process waste and convert it into resources for use in other processes.

The fact that energy can be recovered from the sludge generated by the aerobic treatment of wastewater through the anaerobic digestion of the sludge means that methane emissions can be captured and the methane can then be used for energy generation or cogeneration. It has been demonstrated that this technique can reduce WWTP greenhouse gas emissions by 21% and provide up to 14% of a plant's energy requirements, along with the attendant environmental benefits (Aguilar-Benítez and Blanco, 2018).

The main challenge for implementation on a mass scale is the higher start-up cost compared to the initial investment required for the aerobic processes currently in use. Using this technology on an industrial scale requires the system to be fitted out for processing the gas, in addition to the purchase of a reactor or anaerobic digesters, which calls for gasholders, compressors, desulfators and engine generators,<sup>5</sup> among other equipment (Linares, 2020). In short, while this kind of system clearly has benefits in terms of energy supply and can be profitable, it requires a large start-up investment unless suitable, or at least the minimum, infrastructure is not already in place.

Combined heat and power (CHP) systems use the methane recovered from wastewater and sludge to generate thermal energy and electricity. Biogas can power turbines and generate approximately 1,300 kW/h of electrical energy per 1 million litres of treated wastewater (Mo and Zhang, 2013). One study conducted on this subject indicates that, if all WWTPs in the State of Texas were to use these systems, a 26% reduction in the state's total electricity use could be achieved (Stillwell, Hoppock and Webber, 2010). The supply of electrical power generated by such systems is reliable and consistent, but the capital start-up costs are relatively high (some US\$ 4,500/kW (Mo and Zhang, 2013). In addition, these systems require large volumes of biogas and thus are viable only for WWTPs with a flow above 231 litres per second (l/s), or, in other words, 20 million litres per day (Mo and Zhang, 2013). This is the amount generated by a population of around 135,000 persons.<sup>6</sup> Some more recent studies using information on the countries of the region indicate that these schemes could be financially viable in plants that serve populations of above 300,000 inhabitants (Silva, Mambeli and Tiago, 2016; Nolasco, 2010). The technical and professional skills needed to operate these systems is another consideration. Therefore, although these systems are highly efficient, their high initial investment requirements, the fact that they need large volumes of wastewater in order to operate and the skilled personnel needed to run them are all factors that are limiting their use.

<sup>4</sup> This figure is provided only as a way of providing a frame of reference, since efficiency and production levels vary depending on the size/capacity of the plant, its geographical location and other characteristics mentioned earlier.

<sup>5</sup> Engine generators are 1.5 times more efficient than turbines (Felca and others, 2018).

<sup>6</sup> For an average discharge of 150 l/h/d.

### (c) Other systems for generating electricity

There are various processes for generating electricity and thermal energy as by-products of the anaerobic treatment of wastewater and anaerobic digestion of sludge. The most common one uses methane emissions as a biogas. Other methods include bioelectrochemical systems, microalgae, hydroelectricity and incineration. The following discussion will provide an overview of each method and an evaluation of the potential for its adoption within a circular economy.

**Bioelectrochemical systems.** These systems use biological catalysts to spur chemical reactions enabled by enzymes or microorganisms present in wastewater. They can store energy in microbial fuel cells or microbial electrolysis cells. In the first case, the enzymatic or microbial energy is converted directly into electricity (McCarty, Bae and Kim, 2011; Mo and Zhang, 2013). The amount of energy obtained ranges between 10 and 100 MW/m<sup>2</sup> (Liu, Ramnarayanan and Logan, 2004). In addition to producing energy even more efficiently than anaerobic processes can, this method can reduce the excess sludge by around 20% compared to conventional treatments (Foley, 2010; McCarty, Bae and Kim, 2011). Its most notable disadvantages are energy loss during the electricity generation process, low rates of organic use and its capital costs, which are some 800 times higher than those of an anaerobic system (Liu, Ramnarayanan and Logan 2004; McCarty, Bae and Kim, 2011). In microbial electrolysis treatments, energy is recovered in the form of biochemicals, particularly hydrogen and methane. This kind of system is quite new, however, and few studies on its efficiency levels are as yet available (Mo and Zhang, 2013).

**Microalgae.** This technology recovers energy by growing the microalgae in wastewater and then converting them into energy and has the potential to generate 2,600 kWh per ton of dry algae (Aresta, Dibenedetto and Barberio, 2005). During their cultivation, microalgae absorb carbon and nutrients from the wastewater, thereby reducing the waste load to be treated. The microalgae also use carbon dioxide more quickly than conventional organic crops, resulting in negative greenhouse gas emissions amounting to 51 kg of CO<sub>2</sub> equivalent per kWh generated, and are therefore a means of reducing and mitigating carbon dioxide emissions (Groom, Gray and Townsend, 2008; Kumar and others, 2010). Challenges hindering this method's integration into the matrix include the cost of growing the algae, the large amounts of energy required to collect, dehydrate and extract lipids, and the need to identify the highest-yield species of microalgae (Kumar and others, 2010; Mo and Zhang, 2013).

**Effluent-powered hydroelectricity.** Hydroelectricity can be produced using turbines or other devices installed in pipes, channels and ducts to generate electricity from moving water. In the case of WWTPs, these technologies can use conduit systems and the effluent itself to generate energy. In addition to generating power, this type of hydroelectric system can increase the concentration of oxygen dissolved in the wastewater, thereby leveraging aerobic treatment processes (Gaius-Obaseki, 2010). The main constraint is that, in these systems, the effluent must have sufficient kinetic energy, which requires a significant flow or infrastructure of a substantial height (Gaius-Obaseki, 2010).

**Incineration.** A plant that uses combustion can generate energy while limiting atmospheric waste. The process consists of transporting the sludge to an oven and burning it to generate electrical energy. This also reduces the volume of waste to a minimum (Mo and Zhang, 2013). Before that, however, the sludge is dried so that it will be easier to store and use as fuel (Linares, 2020; Mo and Zhang, 2013). Advantages of this technique include the fact that it does not require a large initial investment and that it recovers energy rather than consuming it. What is more, minerals (approximately 90% of the phosphates and other metals) can be reclaimed from the ashes (Hao and others, 2020). It has been calculated that, by incinerating the biosolids in all wastewater treatment plants in Texas, electricity consumption in the state's entire wastewater sector could be reduced by around 57% (Stillwell, Hoppock and Webber, 2010). This technique has serious negative impacts, however, because it produces emissions of volatile organic compounds, such as sulfur dioxide (SO<sub>2</sub>) and carbon dioxide (CO<sub>2</sub>), derivative compounds of nitrogen dioxide (NO<sub>2</sub>) and heavy metals (Linares, 2020). Therefore, although it is certainly a way of reusing waste, these environmental drawbacks will have to be overcome before it can be compatible with the principles of the circular economy.

### 3. Nutrient extraction

One process that is in line with the circular economic focus on harnessing the resources in wastewater which has recently been gaining momentum is the effort to make use of the nutrients contained in wastewater. This can be done in a quite straightforward manner by simply spreading the sludge from WWTPs on the ground. Alternatively, use can be made of new types of toilets that have been developed that can separate out the urine so that it can then be applied to soil. Another option is to use struvite crystallization or other more sophisticated wastewater treatment technologies to extract the valuable phosphorus contained in WWTP sludge. The following paragraphs will provide an overview of each method and will assess the potential for their widespread use.

The first way of extracting nutrients from wastewater consists of spreading biosolids on the soil, following their treatment through digestion, alkaline treatment, composting or drying. Biosolids in this form are mainly used as fertilizers that can take the place of fossil-based fertilizers. These nutrients can also be used to prepare the soil, however, and as a landfill cover (Mo and Zhang, 2013). This way of applying biosolids is a simple and quick way of making use of the nutrients they contain, but it raises some major social and environmental concerns related to health hazards and the pungent smell that the biosolids give off (Mo and Zhang, 2013).

A second way of recovering nutrients from wastewater is to separate out the urine. This is already being done in some rural areas on a small scale. This procedure reduces the waste load of WWTP flow, since urine contains around 75% of the nitrogen and 50% of the phosphorus found in domestic wastewater. It is estimated that around 70% of these nutrients could be recovered through the use of collector toilets (Mo and Zhang, 2013). Urine separation is a more efficient way of extracting energy than other nutrient-recycling technologies. It also offers the possibility of recovering the cost through direct sales (Benetto and others, 2009; Flores, Buckley and Fenner, 2008; Larsen and others, 2009). These systems are installed in people's homes, since that is where the separation process usually needs to take place, and the support and participation of local communities is therefore a prerequisite for their use. The avoidance of cross-contamination with faeces is also a challenge (Mo and Zhang, 2013; Verstraete and others, 2009). Recovering the nitrogen and phosphorus from urine would reduce the labour and resource requirements of WWTPs, but it calls for close coordination and a solid local community system.

A third way to recover nutrients from wastewater is through controlled struvite crystallization, which can be used to recycle nutrients from sludge digester liquor. This technique yields high nutrient recovery rates, especially for phosphate (Mo and Zhang, 2013), since its concentration in sludge digestion liquids is usually quite high —so much so that the theoretical crystallization potential may be as high as 67,000 tons of fertilizer per year in the United Kingdom alone (Gaterell and others, 2011). Because phosphate sources are limited and many of them are located in countries experiencing ongoing political and social strife,<sup>7</sup> the price of this mineral has soared by over 30% since 2011 (and the rise has been particularly sharp in 2022 as a consequence of the war in Ukraine). Consequently, the outlook for the economically attractive and cost-effective recovery of this nutrient from wastewater is quite bright (Ellen MacArthur Foundation, 2013; Kerres and others, 2020; Rodríguez and others, 2020), since, even though obtaining phosphate from wastewater is between two and eight times more costly than extracting it from rocks, and despite the large investment that using this technology calls for, the profits from selling this material can balance out those costs, even without taking into consideration the added social and environmental benefits of reducing this form of waste.

<sup>7</sup> Morocco, Western Sahara, China, Egypt, Algeria, the Syrian Arab Republic, Brazil, South Africa and Saudi Arabia account for 91% of world reserves (USGS, 2011).

## C. Expected benefits

The above descriptions of the relevant technologies make it quite clear that wastewater should be regarded as a resource rather than as waste as such. Seen in this light, it is evident that applying the principles of the circular economy to municipal wastewater treatment offers multiple benefits. Those benefits are classified according to their economic, environmental or social nature in the following discussion.

### 1. Direct economic benefits

The economic benefits are set out below.

- **Sale of treated water.** Partially treated wastewater can be sold directly to users at a lower price than fully treated wastewater. While the low price of freshwater makes it difficult to charge an adequate price for reclaimed water, at least one success story in this regard has been reported in Honolulu, Hawaii (Lazarova and others, 2013). In Honolulu, two types of water are sold depending on the intended user. The first type is sold to the industrial sector on the island, which includes refineries, factories and energy companies, all located near the facilities where the water is treated. These users receive water that has been treated and then processed by reverse osmosis, which produces very pure, high-quality water. A second type is sold to golf courses and for watering gardens and for use in other types of irrigation. This water is sold at a lower price because it has not been subjected to reverse osmosis. The amount of water produced and sold under this system since its creation in 2000 has been rising steadily, and in 2012 totalled 11.5 million cubic metres, of which 17% was purified water for industrial uses and 83% was for irrigation. In view of increasing water shortages and uncertainty about the availability of water supplies, the demand for this water and its value are expected to continue to climb.
- **Intersectoral water swaps or transfers.** These transactions are not sales but instead commercial exchanges of water sources that provide a direct savings or profit. Agreements may be entered into by producers of treated irrigation water and producers of freshwater for household or industrial use (Winpenny and others, 2010). This model may be used for water exchanges between users that do not require high-quality water and larger water consumers having specific requirements, which will pay a higher price (WWAP, 2017). Although these swaps do not increase the total water supply, they do provide a savings relative to the cost of resorting to other sources such as the treatment and filtration of scarce surface water or the deepening of wells, with all the energy costs involved in the use of groundwater.
- **Sale of biogas.** Biofuels produced by microalgae and biochemical processes can be sold in that form or as biogas. Biofuels can be used for transportation, the development of bioplastics and biochemicals, as nutritional supplements for humans and animals, and as antioxidants and cosmetic ingredients (WWAP, 2017). The La Farfana WWTP in Santiago has realized US\$ 1 million per year in profits from direct sales (Rodríguez and others, 2020). That plant treats between 222 million and 289 million cubic metres of wastewater each year and produces, on average, 25 million cubic metres of biogas (World Bank, 2019b). It is estimated that, in less than three years, these sales alone will enable the firm to recoup its US\$ 2.7 million investment in modernizing the plant and bringing in this technology (Rodríguez and others, 2020). The reduction of greenhouse gases is an added benefit. It is estimated that this system will reduce emissions of CO<sub>2</sub> equivalent by 19,788 tons per year, which could potentially constitute another income stream if the firm is able to sell the corresponding carbon credits (World Bank, 2019b). Furthermore the gas company that signed the sales contracts saved an estimated US\$ 1.6 million by purchasing this biogas instead of relying on conventional sources (World Bank, 2019b).
- **Sale of fertilizers and savings on waste disposal.** The sale of by-products, including fertilizers such as phosphorus, nitrogen and biosolids, is the way that WWTPs usually cover their costs. The water utility of New Cairo, Egypt, obtains an additional income stream by selling its

sludge to companies in the cement industry and the agricultural sector (World Bank, 2019a). The La Farfana plant in Chile, which produces 800 tons/day of sludge, provides these biosolids to farmers free of charge, thereby saving itself the expense of dumping those biosolids in landfills, which costs US\$ 40/ton, or US\$ 11.6 million per year (World Bank, 2019b).

- **Sale of phosphates.** The economic potential of phosphate extraction and sales is on the rise, as the sources of this mineral will be dwindling or will actually be depleted within the next 50 to 100 years (Van Vuuren, Bouwman and Beusen, 2010). The Ostara company of Canada recovers phosphates as granules, called Crystal Green, and shares the proceeds of the sales of these fertilizers with the city in order to offset the cost of the necessary facilities.
- **Cost reductions.** First of all, and as mentioned earlier, promoting the circular economy within the context of WWTPs lowers the associated costs by reducing waste and thus the cost of its disposal. In addition, anaerobic treatment processes both use less energy and actually generate energy as well, which also provides energy savings. This approach also lowers the cost of water obtained from natural sources. In a rural sanitation system in San Pedro de Potosí, in Mexico, an estimated 33% reduction in costs was achieved thanks to the reuse of water. This represented energy savings of US\$ 3 million per year, which helped to cover the water company's operating and maintenance costs (Rodríguez and others, 2020).
- **GDP and trade.** Contaminated water can have a direct adverse effect on economic activities that use water, such as industrial production, fisheries, aquaculture and tourism (UNEP, 2016). Furthermore, it may indirectly limit the exportation of certain goods owing to restrictions or outright bans on selling contaminated products (WWAP, 2017). It is estimated that, for every US\$ 1 spent on sanitation services, the return amounts to US\$ 5.50 (WWAP, 2017). Accordingly, in addition to promoting trade, investing in water treatment systems based on circular economic principles can generate GDP gains and further a country's development.

## 2. Environmental benefits

In addition to the economic benefits discussed above, promoting a circular economy approach in wastewater treatment affords a number of environmental benefits. Some of the most significant ones are set out below.

- **Climate change mitigation.** When wastewater is discharged into bodies of surface water, it increases the amount of nutrients and organic matter in the water, which leads to the emission of even more greenhouse gases (Kerres and others, 2020). The application of circular economic principles in its treatment reduces these emissions. Replacing liquefied gas with methane and reducing the use of wood as a fuel results in a substantial decrease in those emissions (Cornejo and Wilkie, 2010). In other words, the expansion of water treatment capacity via the circular economy approach has a positive effect in terms of greenhouse gas emissions, particularly of methane, because the inputs of organic matter and nutrients into surface water bodies and greenhouse gas emissions into the atmosphere are both reduced. This can make an effective contribution to national efforts to mitigate climate change.
- **Protection of water quality.** The discharge of untreated wastewater into the environment has a negative impact on water quality and this, in turn, reduces the supply of quality water resources available for direct use.
- **Safeguarding aquatic systems.** Basing wastewater treatment on the circular economy paradigm minimizes the amount of waste discharged into bodies of water. Eutrophication,<sup>8</sup> which is driven by the presence of excess nitrogen and phosphorus, can give rise to blooms of potentially toxic algae, as well as decreasing biodiversity (WWAP, 2017). When the discharge of these nutrients into natural water sources is reduced and they are instead incorporated into

<sup>8</sup> There are 31 areas subject to eutrophication and 19 areas suffering from hypoxia (known as "dead zones" because the deficit of oxygen has wiped out the areas' local biodiversity) in the region. More of these areas are found in the Atlantic Ocean than in the Pacific Ocean (ECLAC, 2022).

agricultural processes, the risk of the formation of these algae blooms decreases. Discharges into seas and oceans are estimated to have impacted 245,000 km<sup>2</sup> of marine ecosystems, with repercussions for the fishing industry, a range of different livelihoods and food chains (WWAP, 2017). By extracting these nutrients from treated water, the immediate effects of this contamination are reduced along with the resulting deterioration of aquatic ecosystems.

- **Increased energy sustainability.** By increasing the use of methane derived from wastewater and given that its availability is proportional to population growth, the sustainability of the system is reinforced. This approach also results in a more diversified energy matrix and the use of a smaller share of environmentally harmful forms of energy, such as energy generated from coal and wood.

### 3. Social benefits

The positive effects of adopting a circular economy approach in the treatment of wastewater can also be seen in society at large. The main benefits are set out below.

- **Improvements in public health.** The efficient management of human waste provides unquestionable benefits to society, particularly in terms of public health. Reducing the waste discharged into bodies of water is reflected in a decrease in the incidence of diseases transmitted via contaminated fresh water (WWAP, 2017), such as cholera, various types of diarrhoea, dysentery, hepatitis A, typhoid fever and poliomyelitis. It is estimated that around 842,000 people die each year from diarrhoea caused by contaminated water (Mills and Cumming, 2016).

In 2014 it was estimated that 5.7 million disability-adjusted life years (DALYs) had been lost in the region owing to these diseases, for an economic loss of US\$ 1.8 billion (Dalal and Svanström, 2015). This clearly has long-term repercussions on the well-being of the communities in question and their members' livelihoods.

- **Creation of green jobs.** There is an initial beneficial effect on job creation when the first steps involved in implementing the circular economy approach in wastewater treatment begin to be taken. In countries with different levels of development, there is invariably a relationship between water management, in general, and employment opportunities. In other words, water plays a key role in direct job creation and maintenance in a wide range of sectors, and its influence extends to all the jobs indirectly created as a result of its multiplier effect (WWAP, 2017).

## D. Main findings

This review of the literature and of the documentation concerning the many different options for introducing circularity into wastewater treatment processes attests to the great potential that exists in this respect, particularly in Latin America and the Caribbean, given the current situation in the wastewater treatment sector in the region.

Of all the different opportunities that have been examined here, the one that holds out the greatest promise for Latin America and the Caribbean is the generation of energy from methane. First of all, this technology can be less costly than bioelectrochemical systems and less complicated than generating energy from microalgae. While options such as incineration as a source of electricity may be economically and technically viable, their serious environmental impacts in terms of emissions of volatile organic compounds run counter to circular economic principles. With regard to nutrient extraction, the available urine separation systems are subject to significant constraints that would make it difficult to achieve economies of scale. Finally, controlled struvite crystallization systems are so costly that their implementation in the region would be financially unsustainable.

In contrast, the literature contains documentation of the financial viability of introducing systems for utilizing methane for energy generation and cogeneration in WWTPs serving populations of over 300,000 inhabitants. This points to the existence of a vast potential for implementing this type of technology in medium-sized cities.

Circular economic systems for harnessing methane offer substantial social, environmental and economic benefits, especially since such a system is not exclusive but can instead be used alongside other schemes in other areas of the wastewater treatment process, such as the use of waste sludge as a source of nutrients in agriculture (as in the case of WWTPs in La Farfana in Chile and in New Cairo in Egypt) and the sale of treated wastewater for use in irrigation or in heating and cooling systems. In addition, a crucial consideration is that it will result in a decrease in greenhouse gas emissions by reducing the methane emissions of WWTPs and through the cogeneration of energy that WWTPs can use as part of their internal operations. Surpluses of renewable energy may even be generated that can be used instead of drawing energy from the national energy grid, which generally relies on non-renewable sources. In view of this potential, opportunities for implementing this technology in the region need to be identified, along with the associated benefits. A review of those opportunities and benefits is undertaken in the following chapters.

### III. The potential for harnessing methane to generate energy in wastewater treatment plants in Latin America and the Caribbean

The International Energy Agency (IEA/OECD, 2016) estimates that the energy used worldwide by potable water and sanitation sectors in 2014 amounted to 120 million tons of petroleum equivalent, which is equal to the total energy demand of Australia. At the global level, the largest share of this energy is used to extract groundwater and surface water (40%), while the second-largest share is used for the treatment of wastewater (25%). The proportions in developed countries differ from the global average, however, with 42% of electricity consumption being accounted for by wastewater treatment, 20% by the distribution of water to consumers and the rest by large-scale transfers from one watershed to another, the treatment of fresh water and water reuse. The distribution in developing countries, including those of Latin America and the Caribbean, is very different; wastewater is not, on the whole, properly treated, and, in most cases, the extraction and distribution of water in middle-income countries are powered by fossil fuels. While further analysis of the sector's energy matrix and the impact of greenhouse gas emissions is needed, the carbon footprint of energy use—whose cost represents around 40% of total operating costs in the region—and the methane emissions of wastewater management operations are crucial considerations.

With regard to this last point, the significant opportunities that exist to use the waste sludge generated by the water treatment process as a renewable energy source are of critical significance. It is estimated that this source could provide as much as 87% of the energy needed to power the world's wastewater treatment plants (WWTPs) (Gasson, 2021).

In order to determine what opportunities exist for incorporating a circular economy approach into wastewater treatment in Latin America and the Caribbean that would include the use of methane to generate energy for own-consumption and/or for sale to third parties, this study will estimate the volume of methane emissions from a selected group of WWTPs in the region and the size of the investments needed for the associated technological conversions. These estimates will then be used to assess the economic and environmental benefits of doing so.

This chapter will begin with a description of the most commonly used technologies and scales of operation in the region. As a basis for preparing that overview, a database on over 3,000 WWTPs in selected countries was constructed (section A). The next step was to select those WWTPs having treatment capacities

of between 500 litres per second (l/s) and 4,000 l/s and to analyse them in order to gauge the technical and financial potential for recovering methane in cities or municipalities having populations of between 300,000 and 2.3 million people in which circular economic principles have not yet been applied (section B). The discussion of this selection process will be followed by a presentation on the methodology, equations and parameters employed in estimating the methane emissions (and energy potential) of the selected WWTPs (section C). Finally, estimates are provided of the methane emissions of the selected WWTPs in a baseline scenario (section D) and in a scenario in which WWTPs have been re-engineered thanks to a series of investments that will be examined in detail in chapter IV (section E).

## A. Description of WWTPs in selected countries of the region

Five countries in Central and South America were selected based on the availability of the information needed to determine the relevant characteristics of their WWTPs, such as: (i) installed capacity; (ii) their treated wastewater flows; and (iii) the technologies they use.

The countries that were selected are Mexico and Costa Rica, in the northern and central parts of the region, and, in its southern portion, Colombia, Peru and the Plurinational State of Bolivia. These countries account for 35% of the region's population of 229.5 million people. Table 2 provides a brief socioeconomic description of the drinking water and sanitation sectors in the selected countries.

**Table 2**  
Description of the selected countries

Country	GDP (2019)	Population	Description of the sector
Bolivia (Plurinational State of)	US\$ 29.7 billion and US\$ 2,579.9 per capita (ECLAC, 2019)	11.46 million, of whom 28.7% live in rural areas (Dirven, 2019)	Average per capita water consumption in 2017 was 97 litres per day. The country treats approximately 61% of the wastewater discharged into the sewer system (Mejía, Uzcátegui and Valverde, 2017). However, no information is available on the effective removal of the pollutant load of wastewater or on compliance with the Bolivian regulation on wastewater discharges. This wastewater treatment coverage rate should be viewed in the context of the country's 59% sewerage service coverage rate (Mejía, Uzcátegui and Valverde, 2017).
Colombia	US\$ 394.8 billion and US\$ 7,843 per capita (ECLAC, 2019)	50.2 million, of whom 19% live in rural areas (Dirven, 2019)	Activities registered as "Water distribution; wastewater disposal and treatment; waste management and environmental sanitation activities" accounted for 0.91% of GDP (DANE, 2020). The average amount of water consumed per inhabitant is 112.27 litres per person per day according to Briseño and Rubiano (2018), and the country treated 48.56% of the total volume of water discharged by sewerage systems into water bodies (equivalent to 31.50 m <sup>3</sup> /s) (Superintendency of Residential Public Services, 2020).

Country	GDP (2019)	Population	Description of the sector
Costa Rica	US\$ 51.6 billion and US\$ 10,234 per capita (ECLAC, 2019)	5.05 million, of whom 19.2% live in rural areas (Dirven, 2019)	According to BCCR (2021), per capita water consumption in 2017 was 157 litres per day. The wastewater disposal rate in 2019 was: 75% of the population used septic tanks; 7% were served by the public sanitation utility; and the remaining 18% did not have access to any wastewater disposal system (CTIE-Agua, 2021).
Mexico	US\$ 1.308 trillion and US\$ 10,255 per capita (ECLAC, 2019)	132.7 million, of whom 21.8% live in rural areas (Dirven, 2019)	Mexico has the highest per capita water consumption rate in the region: 366 litres per day (Fortuño, 2017). Its wastewater treatment coverage rate of 65.7% (equivalent to 141.5 m <sup>3</sup> /s) represents an increase of 42.7 percentage points since 2001. This improvement reflects the major effort deployed by the country in this connection over the past two decades (CONAGUA, 2020).
Peru	US\$ 210.9 billion y US\$ 6,489 per capita (ECLAC, 2019)	33.3 million, of whom 19.7% live in rural areas (Dirven, 2019)	According to INEI (2020), household water use in 2019 in Metropolitan Lima totalled 415,773,000 m <sup>3</sup> , or 106.2 litres per person per day, on average. The household wastewater coverage rate for the country as a whole is 72%. This rate reflects the extensive treatment capacity in place in Lima and the Province of Callao; the figure for the rest of the country, without including those two regions, is 48% (Moscoso, 2016).

Source: Prepared by the authors, on the basis of M. Dirven, "Nueva definición de lo rural en América Latina y el Caribe en el marco de FAO para una reflexión colectiva para definir líneas de acción para llegar al 2030 con un ámbito rural distinto", 2030: *Alimentación, agricultura y desarrollo rural en América Latina y el Caribe*, No. 2, Santiago, Food and Agriculture Organization of the United Nations (FAO), 2019; Economic Commission for Latin America and the Caribbean (ECLAC), "Total annual gross domestic product (GDP) at current prices in dollars", Santiago, 2019 [online] <https://statistics.cepal.org/portal/cepalstat/dashboard.html?theme=2&lang=en>; Mejía, A., G. Uzcátegui and O. Valverde, *Agua y saneamiento en el Estado Plurinacional de Bolivia*, Buenos Aires, Development Bank of Latin America and the Caribbean (CAF), 2017; National Administrative Department of Statistics (DANE), "Producto interno bruto desde el enfoque de la producción a precios constantes", 2020 [online] <https://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-trimestrales/historicos-producto-interno-bruto-pib>; H. Briseño and J. Rubiano, "El servicio de agua potable para uso residencial en Colombia", *Revista U.D.C.A Actualidad & Divulgación Científica*, vol. 21, No. 1, Bogotá, University of Applied and Environmental Sciences, 2018; Superintendency of Residential Public Services, Estudio sectorial de los servicios públicos de acueducto y alcantarillado 2019, Bogotá, 2020; Central Bank of Costa Rica (BCCR), "Cuenta de Agua 2021", San José, 2021 [online] <https://www.bccr.fi.cr/indicadores-economicos/DocCuentaAgua/Cuenta-agua-2021.xlsx>; Interinstitutional Technical Committee on Water Statistics (CTIE-Agua), "Boletín agua/2021", San José, 2021 [online] [http://www.da.go.cr/wp-content/uploads/2019/01/Boletin\\_Agua\\_2021\\_CTIEEstadisticas.pdf](http://www.da.go.cr/wp-content/uploads/2019/01/Boletin_Agua_2021_CTIEEstadisticas.pdf); M. Fortuño, "La economía del agua: el futuro se avecina complicado", Cologny, World Economic Forum (WEF), 31 March 2017 [online] <https://es.weforum.org/agenda/2017/03/la-economia-del-agua-cada-vez-sera-mas-importante>; National Water Commission (CONAGUA), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City, 2020; National Institute of Statistics and Informatics (INEI), *Anuario de estadísticas ambientales 2020*, Lima, 2020; J. Moscoso, *Manual de buenas prácticas para el uso seguro y productivo de las aguas residuales domésticas*, Lima, Ministry of Agriculture and Irrigation/National Water Authority (MINAGRI/ANA), 2016.

The 3,336 WWTPs located in these countries use a wide range of technologies. In fact, almost all the types of wastewater treatment processes in use anywhere in Latin America and the Caribbean are, at different operating scales, represented in this group of countries. For a detailed description of the technologies that are in use, see annex A1; for an overview of the basic statistics compiled on these WWTPs, by country, see table 3.

**Table 3**  
Basic statistics on WWTPs in place in the five selected countries

Country	No. of WWTPs	Percentage of WWTPs (Percentages)	Installed capacity (l/s)	Total population 2020	Amount of wastewater produced by the population (l/s)	Coverage of installed capacity (Percentages) <sup>a</sup>
Bolivia (Plurinational State of) <sup>b</sup>	50	1	6 220	11 673 021	20 266	31
Colombia <sup>c</sup>	430	13	51 843	50 882 891	88 338	59
Costa Rica <sup>d</sup>	30	1	3 614	5 094 118	8 844	41
Mexico <sup>e</sup>	2 639	79	194 699	128 932 753	223 842	87
Peru <sup>f</sup>	187	6	42 533	32 971 854	57 243	74
Total	3 336	100	298 909	229 554 637	398 532	75

Source: Prepared by the authors, on the basis of Potable Water and Basic Sanitation Supervisory and Social Oversight Authority/ Ministry of Environment and Water (AAPS/MMAYA), *Indicadores de desempeño de las EPSA reguladas categorías A, B, C, D 2019*, La Paz, 2019; Superintendency of Residential Public Services, "Sistemas de tratamiento de aguas residuales", Bogotá, 2021; F. Ruiz, "Gestión de las excretas y aguas residuales en Costa Rica: situación actual y perspectiva", San José, Costa Rican Water Supply and Sanitation Institute, 2012; National Water Commission (CONAGUA), "Catálogo de plantas de tratamiento de aguas residuales en operación de CONAGUA", Mexico City, 2021 [online] <https://datos.gob.mx/busca/dataset/catalogo-de-plantas-de-tratamiento-de-aguas-residuales-en-operacion-de-conagua>; J. Méndez and J. Marchán, *Diagnóstico situacional de los sistemas de tratamiento de aguas residuales en las EPS del Perú y propuestas de solución*, Lima, National Superintendence of Sanitation Services (SUNASS), 2008; Chillón Rímac Lurín Water Observatory, *Análisis geoespacial de canales de riego en relación a las plantas de tratamiento de aguas residuales (PTAR) y áreas verdes en el ámbito de Lima metropolitana*, Lima, 2017.

<sup>a</sup> Installed capacity/amount of wastewater per person.

<sup>b</sup> For the Plurinational State of Bolivia, the information was obtained from the report on performance indicators for the country's regulated potable water and sanitation utilities prepared by the Potable Water and Basic Sanitation Supervisory and Social Oversight Authority (AAPS/MMAYA, 2019). This report provided comprehensive, up-to-date information on WWTPs in the country.

<sup>c</sup> The information was obtained from the Superintendency of Residential Public Services (2021), which did not provide full information on WWTPs in the country but did supply relevant data on their installed capacity and the wastewater treatment technologies they employ.

<sup>d</sup> The information on WWTPs in Costa Rica was obtained from "Gestión de las excretas y aguas residuales en Costa Rica: situación actual y perspectiva" (Ruiz, 2012) rather than from a database or updated information system providing documentation on installed capacity, volume of treated flows or the technology used for that purpose. That document provides information on WWTPs run by the Communal Water and Sanitation System Administrative Associations (ASADAS), the public utilities company of Heredia, the Costa Rican Water Supply and Sanitation Institute and the Municipality of Alajuela. It should be noted, however, that, according to the records of the Ministry of Health (which are not comprehensive), there are 912 WWTPs serving condominiums and residential complexes, and it was not possible to obtain enough information on those WWTPs to include them in this inventory. Nonetheless, because of their scale of operation, they would not be included in the target group for this study in any case.

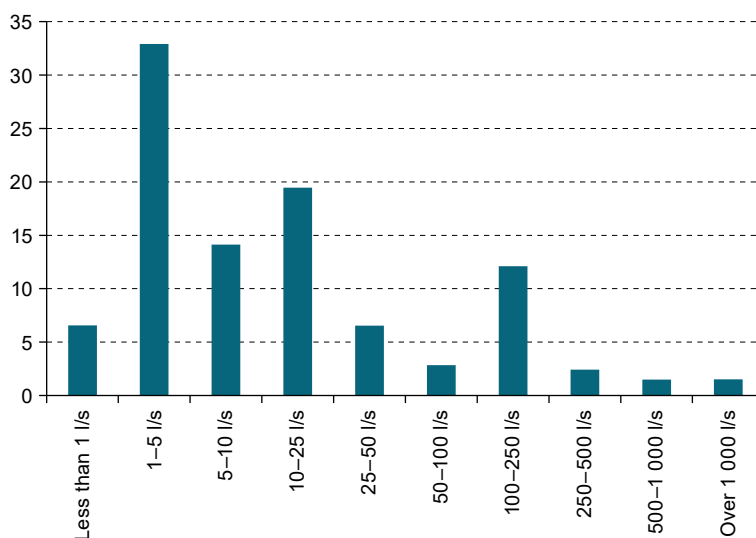
<sup>e</sup> The information for Mexico was obtained from CONAGUA (2021), which ensures its reliability and accessibility.

<sup>f</sup> Information for Peru is subject to certain limitations, as it was obtained from a document prepared by Méndez and Marchán (2008). This information was supplemented with information obtained from a study conducted by the Chillón Rímac Lurín Water Observatory (2017) in Metropolitana Lima. This made it possible to update the available information and, in particular, to document a large proportion of the new wastewater treatment projects undertaken in 2008–2017.

These plants have a total capacity of 298,909 (l/s), which is enough to serve 172 million people. The plants' distribution and treatment capacities appear to be aligned with the distribution of the population in each of the countries. However, an evaluation of the capacity of these WWTPs based on a figure of 150 litres per person per day (l/p/d) indicates that there is ample treatment capacity in Mexico and Peru (with capacities to treat 87% and 74% of the total wastewater flow, respectively) and limited capacity in the Plurinational State of Bolivia (with capacity to treat 31% of the total wastewater flow).

An analysis of the 3,336 documented WWTPs<sup>9</sup> indicates that, because municipal treatment plants are widely dispersed in a number of the countries covered by this study, there is a marked preponderance of small systems (see figure 3). In fact, 1,788 of WWTPs (54% of the total) have a capacity of less than 10 l/s, and 867 of them (26% of the total) have a capacity of between 10 l/s and 50 l/s. In addition, with wastewater discharge volumes of 150 l/p/d, the first group (capacity of less than 10 l/s) serves populations of fewer than 5,760 people, while the second group (between 10 l/s and 50 l/s) can serve populations of up to nearly 29,000 persons.

**Figure 3**  
Distribution of the 3,336 WWTPs, by treatment capacity (l/s)<sup>a</sup>  
(Percentages)



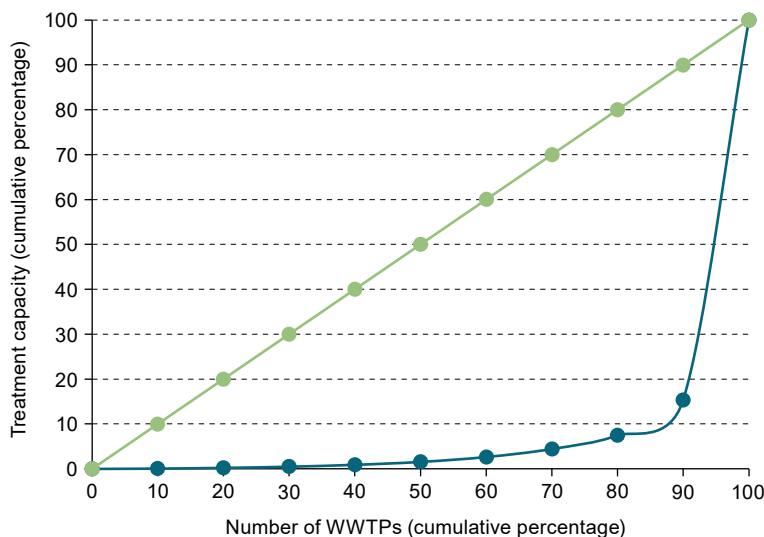
Source: Prepared by the authors, on the basis of Authority for Supervision and Social Control of Drinking Water and Basic Sanitation/ Ministry of Environment and Water (AAPS/MMAYA), *Indicadores de desempeño de las EPSA reguladas categorías A, B, C, D 2019*, La Paz, 2019; Superintendency of Residential Public Services, "Sistemas de tratamiento de aguas residuales", Bogotá, 2021; F. Ruiz, "Gestión de las excretas y aguas residuales en Costa Rica: situación actual y perspectiva", San José, Costa Rican Water Supply and Sanitation Institute, 2012; National Water Commission (CONAGUA), "Catálogo de plantas de tratamiento de aguas residuales en operación de CONAGUA", Mexico City, 2021 [online] <https://datos.gob.mx/busca/dataset/catalogo-de-plantas-de-tratamiento-de-aguas-residuales-en-operacion-de-conagua>; J. Méndez and J. Marchán, *Diagnóstico situacional de los sistemas de tratamiento de aguas residuales en las EPS del Perú y propuestas de solución*, Lima, National Superintendence of Sanitation Services (SUNASS), 2008; Chillón Rímac Lurín Water Observatory, *Análisis geoespacial de canales de riego en relación a las plantas de tratamiento de aguas residuales (PTAR) y áreas verdes en el ámbito de Lima metropolitana*, Lima, 2017.

<sup>a</sup> For ease of comparison, the treatment capacities can be converted into the size of the populations for which they can provide coverage based on a per capita discharge volume of 150 litres per day: WWTPs with a capacity of 1 l/s or less can serve a population of 576 persons; 5 l/s = 2,880 persons; 10 l/s = 5,760 persons; 25 l/s = 14,400 persons; 50 l/s = 28,800 persons; 100 l/s = 57,600 persons; 250 l/s = 144,000 persons; 500 l/s = 288,000 persons; and 1,000 l/s = 576,000 persons.

However, when the entire treatment capacity distribution is analysed (see figure 4), the predominance of small WWTPs turns out to be much less marked. A Lorenz curve of total plant capacity versus the number of plants shows that 80% of WWTPs have an aggregate treatment capacity below 8% and the next 10% of WWTPs have a treatment capacity of 7%, while 90% of WWTPs have a cumulative capacity of 15% and the remaining 10% account for 90% of the total treatment capacity of the 3,336 WWTPs.

<sup>9</sup> See ECLAC (2021b). The compilation of this database in 2021 was made possible by funding from the French Development Agency.

**Figure 4**  
**Lorenz curve: installed capacity in relation to the number of WWTPs in the selected countries**  
 (Percentages)

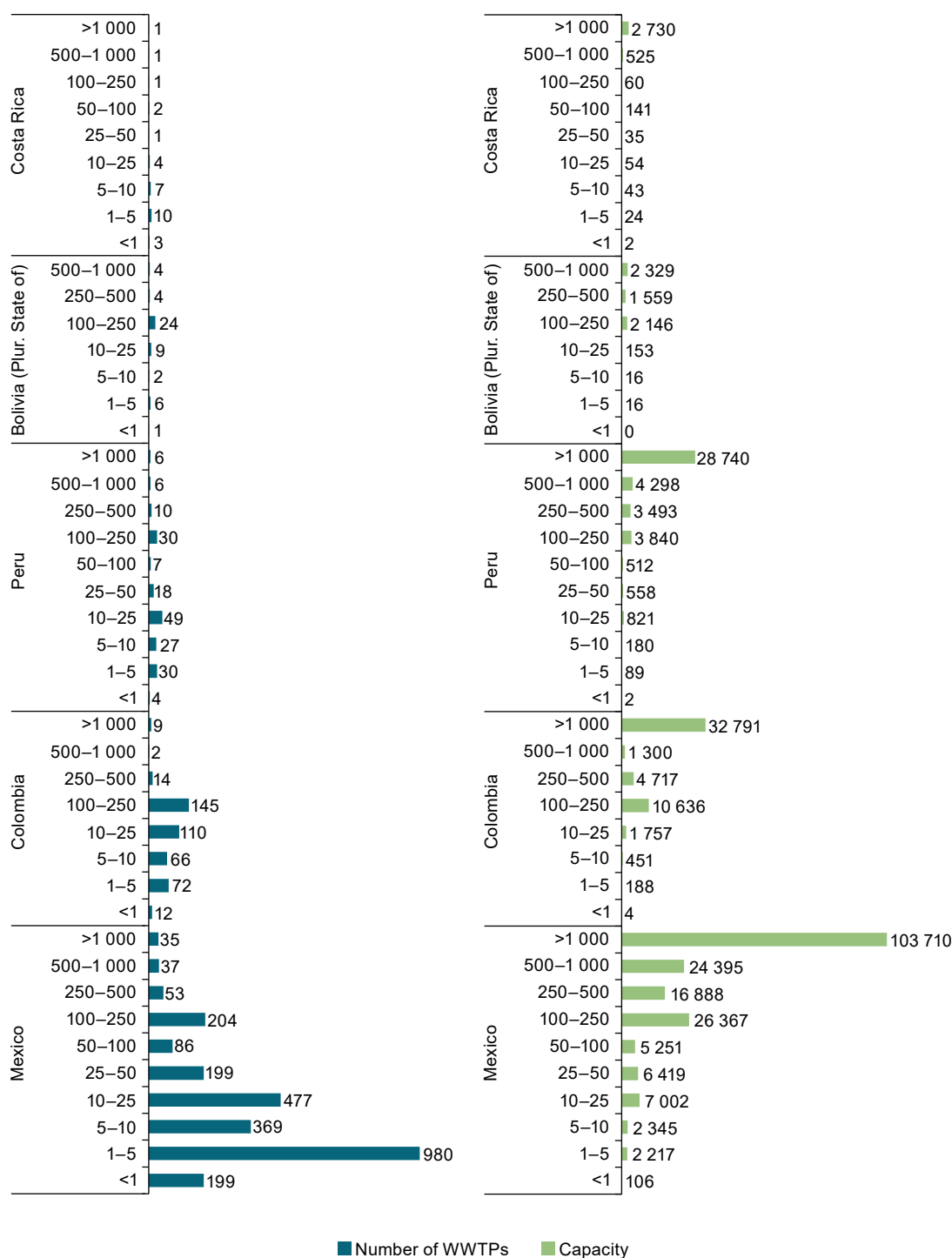


Source: Prepared by the authors, on the basis of Authority for Supervision and Social Control of Drinking Water and Basic Sanitation/ Ministry of Environment and Water (AAPS/MMAYA), *Indicadores de desempeño de las EPSA reguladas categorías A, B, C, D 2019, La Paz, 2019*; Superintendency of Residential Public Services, "Sistemas de tratamiento de aguas residuales", Bogotá, 2021; F. Ruiz, "Gestión de las excretas y aguas residuales en Costa Rica: situación actual y perspectiva", San José, Costa Rican Water Supply and Sanitation Institute, 2012; National Water Commission (CONAGUA), "Catálogo de plantas de tratamiento de aguas residuales en operación de CONAGUA", Mexico City, 2021 [online] <https://datos.gob.mx/busca/dataset/catalogo-de-plantas-de-tratamiento-de-aguas-residuales-en-operacion-de-conagua>; J. Méndez and J. Marchán, *Diagnóstico situacional de los sistemas de tratamiento de aguas residuales en las EPS del Perú y propuestas de solución*, Lima, National Superintendence of Sanitation Services (SUNASS), 2008; Chillón Rímac Lurín Water Observatory, *Análisis geoespacial de canales de riego en relación a las plantas de tratamiento de aguas residuales (PTAR) y áreas verdes en el ámbito de Lima metropolitana*, Lima, 2017.

The distribution of WWTP size is strongly influenced by the figures for Mexico, where 84% of the plants have a capacity of less than 50 l/s. The situation is similar for Costa Rica, with 83% of its WWTPs having a capacity in that same range. It is followed by Peru, with 68% of its plants in that category. Colombia has more plants with a capacity of between 100 l/s and 500 l/s, which represent 37% of its WWTPs. The case of the Plurinational State of Bolivia is striking, not only because of the large number of municipalities with WWTPs but also because of the fragmentation of treatment service suppliers. This is mainly accounted for by the fact that there are so many service providers within the same municipality's urban area in many instances; WWTPs with capacities of between 100 l/s and 500 l/s represent 56% of the total number of treatment plants in the country.

WWTPs with treatment capacities over 1,000 l/s in Colombia, Costa Rica, Mexico and Peru account for over 50% of the total treatment capacity of each country (see figure 5). In the Plurinational State of Bolivia, which has no WWTP in that capacity range, systems with capacities between 500 l/s and 1,000 l/s represent 37% of the country's total treatment capacity. In fact, WWTPs with capacities of between 50 l/s and 500 l/s are the backbone of that country's wastewater treatment system, as they account for 59.6% of the country's total installed capacity. In Peru, Mexico and Colombia, these systems account for between 18% and 25% of total installed capacity, while, in Costa Rica, only three WWTPs are within that capacity range and together account for 5.5% of that country's documented installed capacity.

**Figure 5**  
**Number of plants and total treatment capacity, by treatment capacity category**  
*(Number of plants and cubic metres per second)*



Source: Prepared by the authors, on the basis of Authority for Supervision and Social Control of Drinking Water and Basic Sanitation/Ministry of Environment and Water (AAPS/MMAYA), *Indicadores de desempeño de las EPSA reguladas categorías A, B, C, D 2019*, La Paz, 2019; Superintendency of Residential Public Services, "Sistemas de tratamiento de aguas residuales", Bogotá, 2021; F. Ruiz, "Gestión de las excretas y aguas residuales en Costa Rica: situación actual y perspectiva", San José, Costa Rican Water Supply and Sanitation Institute, 2012; National Water Commission (CONAGUA), "Catálogo de plantas de tratamiento de aguas residuales en operación de CONAGUA", Mexico City, 2021 [online] <https://datos.gob.mx/busca/dataset/catalogo-de-plantas-de-tratamiento-de-aguas-residuales-en-operacion-de-conagua>; J. Méndez and J. Marchán, *Diagnóstico situacional de los sistemas de tratamiento de aguas residuales en las EPS del Perú y propuestas de solución*, Lima, National Superintendence of Sanitation Services (SUNASS), 2008; Chillón Rimac Lurín Water Observatory, *Análisis geoespacial de canales de riego en relación a las plantas de tratamiento de aguas residuales (PTAR) y áreas verdes en el ámbito de Lima metropolitana*, Lima, 2017.

## B. Selection of WWTPs for analysis

A number of studies have established that projects in the region focusing on harnessing methane to generate energy in WWTPs working with flows of less than 500 l/s (serving populations of under 300,000) are not financially viable. This is because the economic benefits—whether in terms of cost savings or sales—derived from generating energy from methane and reducing greenhouse gas emissions are not offset by the size of the required investment and the associated operating costs (Silva, Mambeli and Tiago, 2016; Nolasco, 2010).

However, a review of WWTPs in the region with capacities of over 4,000 l/s (345.6 million litres per day, sufficient to serve a population of 2.3 million people<sup>10</sup>), shows that they already have technological solutions in place for capturing biogas to generate energy or to use for heating. For example, in Mexico, the Norte, Dulces Nombres, Agua Prieta and Atotonilco de Tula WWTPs, which serve the metropolitan areas of Monterrey (the first two), Guadalajara and el Valle de Mexico, respectively, have equipment in place to tap into this resource. In Colombia, the El Salitre, Aguas Claras and Cañaveralejo WWTPs, which serve Bogotá, the metropolitan area of Valle de Aburrá and Cali, respectively, use biogas to dry the sludge, and the latter two also use it to generate energy. In Peru, the Taboada WWTP, which serves Lima and the Province of Callao, has obtained authorization from the Callao regional government to generate 2.2 MW. In Chile, the La Farfana plant, which treats 50% of the wastewater generated by the population of Greater Santiago, uses biogas to dry its sludge and feeds any excess biogas into the city's natural gas distribution system.

The 75 WWTPs with capacities between 500 l/s and 4,000 l/s listed in table 4<sup>11</sup> serve as a sample for assessing the feasibility of harnessing methane emissions in these plants.

**Table 4**  
Number of WWTPs with capacities of 500 l/s–4,000 l/s in the selected countries

Country	Total WWTPs	Installed capacity	Treated flow	Persons served
Bolivia (Plurinational State of)	4	2 329	1 556	896 117
Colombia	3	3 100	2 071	1 192 833
Costa Rica	1	2 730	2 730	1 572 705
Mexico	59	61 555	46 271	26 652 286
Peru	8	9 238	4 744	2 732 556
Total	75	78 952	57 372	33 046 496

Source: Prepared by the authors, on the basis of Authority for Supervision and Social Control of Drinking Water and Basic Sanitation/Ministry of Environment and Water (AAPS/MMAYA), *Indicadores de desempeño de las EPSA reguladas categorías A, B, C, D 2019*, La Paz, 2019; Superintendency of Residential Public Services, “Sistemas de tratamiento de aguas residuales”, Bogotá, 2021; F. Ruiz, “Gestión de las excretas y aguas residuales en Costa Rica: situación actual y perspectiva”, San José, Costa Rican Water Supply and Sanitation Institute, 2012; National Water Commission (CONAGUA), “Catálogo de plantas de tratamiento de aguas residuales en operación de CONAGUA”, Mexico City, 2021 [online] <https://datos.gob.mx/busca/dataset/catalogo-de-plantas-de-tratamiento-de-aguas-residuales-en-operacion-de-conagua>; J. Méndez and J. Marchán, *Diagnóstico situacional de los sistemas de tratamiento de aguas residuales en las EPS del Perú y propuestas de solución*, Lima, National Superintendence of Sanitation Services (SUNASS), 2008; Chillón Rímac Lurín Water Observatory, *Análisis geoespacial de canales de riego en relación a las plantas de tratamiento de aguas residuales (PTAR) y áreas verdes en el ámbito de Lima metropolitana*, Lima, 2017.

<sup>10</sup> An average discharge of 150 litres per person per day was used.

<sup>11</sup> There are actually 91 WWTPs in this capacity range in the target group, but 16 of them are not suitable for the subsequent methane emissions estimation exercise and the assessment of the benefits of the utilization of those emissions owing to characteristics of their installed capacity and/or the type of treatment processes used, since three of them use submarine emissaries, four of them use an advanced primary treatment (APT) process and nine are lagoon systems.

Therefore, of all the plants listed in table 3, this analysis will cover only 0.7%, 3.3%, 2.2%, 5.1% and 8% of the documented WWTPs in, Colombia, Costa Rica, Mexico, Peru and the Plurinational State of Bolivia, respectively. However, these WWTPs represent 6%, 75%, 32%, 21% and 37% of the total documented installed capacity in Colombia, Costa Rica, Mexico, Peru and the Plurinational State of Bolivia, respectively, and serve a total population of 33 million people.

The fact that the number of WWTPs in this sample is so small but represents a considerable portion of the total installed capacity<sup>12</sup> is attributable to the fragmentation of the 3,336 WWTPs in these five countries. As discussed earlier, 80% of WWTPs have a treatment capacity of under 50 l/s.

Of the 75 plants in the target group, 83% use aerobic (including aerobic/anoxic) technologies and treat 89% of the wastewater processed by the target group (51.1 mil l/s). In all, 60% of the target-group WWTPs use a conventional activated sludge (CAS) process to treat 64% of the wastewater handled by this group (see table 5).

**Table 5**  
Classification of WWTPs with capacities of 500 l/s–4,000 l/s, by type of technology used

Type of treatment	Technology	Technology ID	Total WWTP	Treated flow (l/s)	Equivalent population served
Aerobic	Conventional activated sludge	CAS	45	36 799	21 216 960
	Extended aeration	EA	5	5 835	3 360 960
	Aerated aerobic lagoons	AL	4	2 363	1 361 088
Aerobic/ anoxic	Oxidation ditches	OD	1	492	283 392
	Extended aeration with denitrification	EA-Dn	1	625	360 000
	Trickling filters/percolating beds/biofilters	TF/PB/B	5	4 611	2 655 936
	Other combinations of lagoon series	L + L	1	345	204 480
Anaerobic	Upflow anaerobic sludge blanket	UASB	1	750	432 000
	Anaerobic lagoons	An L	1	269	154 944
Anaerobic/ aerobic	Upflow anaerobic sludge blanket and conventional activated sludge	UASB + CAS	1	428	253 440
	Anaerobic lagoons + other types of lagoons	An L + L	10	4 856	2 825 856
<b>Total</b>			<b>75</b>	<b>57 372</b>	<b>33 046 272</b>

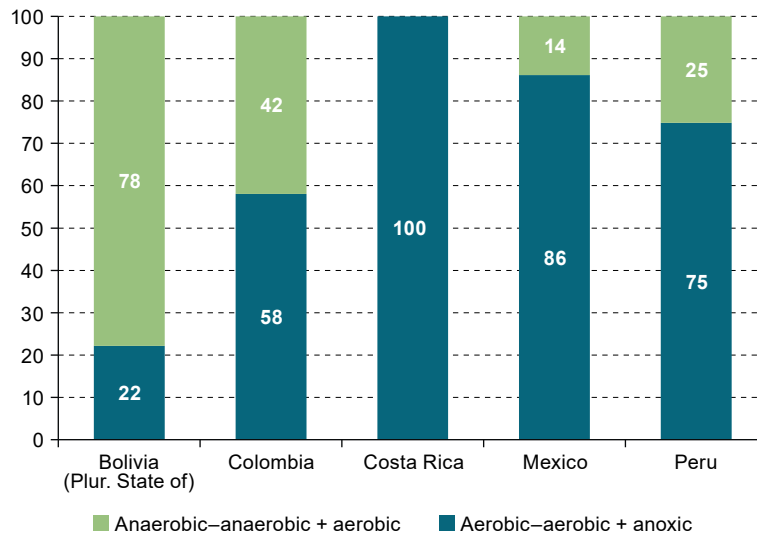
Source: Prepared by the authors, on the basis of Authority for Supervision and Social Control of Drinking Water and Basic Sanitation/ Ministry of Environment and Water (AAPS/MMAYA), *Indicadores de desempeño de las EPSA reguladas categorías A, B, C, D 2019*, La Paz, 2019; Superintendency of Residential Public Services, "Sistemas de tratamiento de aguas residuales", Bogotá, 2021; F. Ruiz, "Gestión de las excretas y aguas residuales en Costa Rica: situación actual y perspectiva", San José, Costa Rican Water Supply and Sanitation Institute, 2012; National Water Commission (CONAGUA), "Catálogo de plantas de tratamiento de aguas residuales en operación de CONAGUA", Mexico City, 2021 [online] <https://datos.gob.mx/busca/dataset/catalogo-de-plantas-de-tratamiento-de-aguas-residuales-en-operacion-de-conagua>; J. Méndez and J. Marchán, *Diagnóstico situacional de los sistemas de tratamiento de aguas residuales en las EPS del Perú y propuestas de solución*, Lima, National Superintendence of Sanitation Services (SUNASS), 2008; Chillón Rímac Lurín Water Observatory, *Análisis geoespacial de canales de riego en relación a las plantas de tratamiento de aguas residuales (PTAR) y áreas verdes en el ámbito de Lima metropolitana*, Lima, 2017.

The systems that use anaerobic and dual (anaerobic/aerobic) systems represent 17% of the systems employed by this group of 75 WWTPs and process 11% of the wastewater treated by this group.

<sup>12</sup> The case of Colombia is somewhat different. It has seven WWTPs (with a total installed capacity of 11,691 l/s) with treatment capacities of between 500 l/s and 4,000 l/s, but four of these could not be taken into account because of the types of processing that they perform (two use submarine emissaries and the other two are lagoon systems with capacities of over 1,000 l/s).

Figure 6 depicts the composition of the treated flows in terms of the technology used in each country. This determines the estimated volume of methane emissions per member of the served population, since properly run aerobic systems do not generate methane emissions unless they employ anaerobic (rather than aerobic) sludge digestion processes. Anaerobic technologies, on the other hand, produce high levels of methane emissions.

**Figure 6**  
Shares of aerobic and anaerobic technologies used to treat wastewater flows in the target group of WWTPs  
(Percentages)



Source: Prepared by the authors.

Since such a large percentage of flows are treated using anaerobic and dual systems in the Plurinational State of Bolivia and in Colombia, the selected WWTPs in these countries will have higher levels of methane emissions and therefore hold out a greater potential for the introduction of circular systems for capturing and utilizing methane than is the case in Mexico, Costa Rica and Peru, as will be discussed in the following chapters.

### C. Methodology and parameters used in estimating methane emissions by type of technology

In order to estimate the level of methane emissions associated with wastewater treatment processes, the approach proposed by Nolasco (2010), which is in turn based on the methodology published by Doorn and others (2006), was used. That methodology employs the specific organic load ( $BOD_5$ ) and total suspended solids (TSS) that a plant takes in (kg/year) to estimate the amount of methane per population equivalent (p.e.) generated in the target-group WWTPs<sup>33</sup> (see annex A2).

<sup>33</sup> Since the analysis focuses on municipal WWTPs, it can be assumed that the wastewater is chiefly of household origin and that this wastewater exhibits the average levels of  $BOD_5$  (biological oxygen demand of microorganisms over a five-day period) and total suspended solids (TSS) per capita.

This methodology permits the use of three different equations for estimating methane emissions, taking into account the particular types (anaerobic, aerobic and dual (anaerobic-aerobic) of technologies used.

Some of the considerations relating to the estimation of methane emissions based on the type of technology employed are as follows:

- First of all, WWTPs that use anaerobic technologies—whether they are compact reactors or lagoon systems—are employing a process that degrades organic matter mainly into biogas with a high methane content (see equation 1 in annex A2).
- Meanwhile, systems that use aerobic processes generate very little or no methane, as long as they are operated correctly. However, the processes that these WWTPs use produce large volumes of aerobic sludge that then has to be stabilized before it is used as a soil enhancer or for some other purpose.

Aerobic sludge can be stabilized through aerobic or anaerobic digestion. The former uses a large amount of energy per unit of volume (is more energy inefficient) and therefore involves higher operating costs. A potentially attractive alternative is therefore anaerobic stabilization using digesters that emit biogas that can then be captured and used in various processes within WWTP (see equation 4 in annex A2). In this study, methane and electricity generation will be quantified based on the assumption that anaerobic sludge stabilization is taking place in all cases.

Finally, some WWTPs use dual wastewater treatment technologies. In these plants, an anaerobic reactor is used for the first treatment stage and an aerobic treatment process is employed in the second stage; this second stage usually involves the use of conventional activated sludge or trickling filters. In these systems, methane is emitted during the first stage as the organic matter in the wastewater degrades and in the second stage during the digestion (using an anaerobic reactor) of the sludge produced during the aerobic treatment process (see annex A2, equation 7).

Equations 10 and 11 (see annex A2) were used to estimate the electricity and thermal energy that can be generated from the methane emissions captured in WWTPs. In these equations, it is assumed that compact systems for capturing, routing and reusing methane have a 90% efficiency rate and that lagoon systems have an 85% efficiency rate. The calculation then uses the **calorific value of the captured methane** (9.97 kWh/year), along with the **average efficiencies of electricity generation systems (35%)<sup>14</sup> and heat recovery systems (40%)<sup>15</sup>** to estimate the electrical and thermal energy that can be generated by the **75 WWTPs** that were evaluated.

In the light of the above considerations, there are a series of general, invariable parameters that can be applied in estimating the methane emissions of all the technologies considered in this study: the organic load taken in by the treatment system per person per year;<sup>16</sup> the maximum capacity of methane production based on the system's incoming organic load; and, lastly, the density of the methane under normal temperature and pressure conditions, as illustrated in table 6.

In the case of compact aerobic and dual technologies, factors such as the percentage of organic matter contained in the sludge (dry weight) and the portion of the sludge that is converted into biogas do not vary as a function of the technology that is used (see annex A2, equation 4).

<sup>14</sup> May range from 20% to 45% depending on the technology and the size of the engine generator.

<sup>15</sup> May range from 30% to 50% depending on the technology and the size of the engine generator.

<sup>16</sup> The value recommended by CIGEA (1998)—42g of BOD p.e./day— was used. It should be noted, however, that, in the cited document, a range of from 30 g p.e./day to 45 g p.e./day is proposed.

**Table 6**  
General parameters for estimating the amount of methane emitted during the treatment of wastewater

Type of treatment	Parametre	Standard value	Unit of measurement
All systems	Bo: maximum methane (CH <sub>4</sub> ) production capacity	0.6	kg of CH <sub>4</sub> generated/kg of degraded BOD
	DM: density of methane under normal temperature and pressure conditions	0.67	kg/m <sup>3</sup>
	QBOD: specific organic load (BOD p.e.) taken in by the system	15.33	kg/year
Aerobic and anaerobic-aerobic (other than extensive or lagoon systems)	DOC: proportion of organic matter contained in the sludge (dry weight)	0.5	kg VS/kg TS
	DOCf: fraction of DOC converted into biogas in the anaerobic digester	0.5	Proportion

Source: Prepared by the authors.

This methodology does involve a number of factors that vary depending on the wastewater treatment technologies used, however. The methane emissions of a WWTP using anaerobic technologies will, for instance, be influenced by how efficient the system is in removing BOD<sub>5</sub> (BOD<sub>d</sub>) and by the correction factor set by Doorn and others (2006) for each type of anaerobic technology (see table 7).

**Table 7**  
Parameters for estimating methane generated by anaerobic and anaerobic-aerobic wastewater treatment technologies

Type of treatment	Technology ID	MCFi <sup>a</sup> (Percentages)	BODd <sup>b</sup> (Percentages)	MCFj <sup>c</sup> (Percentages)	Ss <sup>d</sup> (kg TS/kg BOD)	L <sup>e</sup>	CH <sub>4</sub> p,e. <sup>f</sup> generated (m <sup>3</sup> /year)
Anaerobic treatment	UASB	1.0	0.7	-	-	0.10	9.6
	An L	0.8	0.6	-	-	0.15	6.7
Anaerobic-aerobic treatment	UASB + CAS	1.0	0.7	1	0.90	0.10	10.5
	An L + L	0.8	0.6	-	-	0.15	6.7
Aerobic treatment	CAS	-	-	1	0.90	0.10	3.1
	EA	-	-	1	0.60	0.10	2.1
	AL	0.1	0.1	-	-	-	1.1
Aerobic/anoxic treatment	OD	-	-	1	0.75	0.10	2.6
	EA-Dn	-	-	1	0.60	0.10	2.1
	TF	-	-	1	0.65	0.10	2.2
	L + L	0.2	0.2	-	-	-	1.1

Source: Prepared by the authors, on the basis of M. Doorn and others, "Tratamiento y eliminación de aguas residuales", *Directrices del IPCC de 2006 para los inventarios nacionales de gases de efecto invernadero*, S. Eggleston and others (eds.), Hayama, Institute for Global Environmental Strategies (IGES), 2006.

<sup>a</sup> MCFi: This IPCC methane correction factor indicates the extent to which each system operates under anaerobic conditions. It varies depending on the treatment system. For example, in fully enclosed anaerobic reactors, its value is 1. In the case of fully aerobic systems, its value is zero. For overloaded aerobic systems or lagoons that are not completely aerobic, it reaches values in the range of from 0.1 to 0.3 (Doorn and others, 2006)<sup>a</sup>.

<sup>b</sup> BODd: The fraction of BOD degraded by the system. This signals the efficiency of COD removal in the anaerobic treatment of wastewater. Its value will vary depending on the anaerobic technology being used.

<sup>c</sup> MCFj: This IPCC methane correction factor is used for anaerobic sludge digestion systems.

<sup>d</sup> Ss: The organic matter to sludge conversion factor (kg TS/kg BOD).

<sup>e</sup> L: The fraction of biogas lost during methane capture, routing and reuse (i.e. uncaptured methane).

<sup>f</sup> Methane emitted per person served per year (m<sup>3</sup>).

The methane emissions of dual (anaerobic-aerobic) technologies, on the other hand, depend not only on how efficiently the system operates and the extent to which each system is anaerobic, but also on the volume of sludge generated during the aerobic treatment stage that is then digested anaerobically.

Emissions in systems that use (non-lagoon) aerobic and aerobic/anoxic technologies will vary depending on the volume of sludge produced during the degradation of the organic matter in the water and how that sludge is then treated. For the purposes of this exercise, it is assumed that the aerobic technologies use anaerobic sludge digesters, which are the option that has the highest levels of emissions and of subsequent biogas capture.

Table 7 shows that aerobic lagoon and series lagoon systems do not emit methane as a by-product of the anaerobic sludge digestion process; instead, methane is emitted directly by the lagoon system treatment processes, which do not produce any substantial volume of sludge that then has to be treated.

Thus, a WWTP using an upflow anaerobic sludge blanket (UASB) with a 70% BOD removal efficiency level will emit an estimated 9.6 m<sup>3</sup> of methane p.e. per year, which would come to 2.8 million m<sup>3</sup> of methane for a WWTP that processes the wastewater produced by 288,000 people. If the assumed inefficiencies of the methane capture and routing systems are taken into account, along with those of the energy generation and heat recovery systems, then an estimated 8,691 MWh/year of electricity (equivalent to the electricity used by 58,000 persons in a day) and 9,933 MWh/year of thermal energy could be generated.

By contrast, an aerobic WWTP that serves 288,000 people and uses an optimally performing conventional activated sludge (CAS) treatment process could generate an estimated 3,973 tons of sludge, whose anaerobic digestion will emit 3.1 m<sup>3</sup> of methane p.e. (892,000 m<sup>3</sup> of methane). This would generate 2,793 MWh/year of electricity (equivalent to the amount used by 19,000 people in a day) and 3,192 MWh/year of thermal energy.

#### **D. Estimation of methane emissions in the target-group WWTPs of the selected countries (baseline scenario)**

Using the parameters outlined above, the potential emissions of the 75 WWTPs<sup>17</sup> has been estimated at 107.9 million m<sup>3</sup> of methane, with an energy content of 1,076 GWh/year, which is equivalent to the amount of electricity used by 594,857 people in a year (based on an average per capita consumption level of 1,809 kWh/year) (see table 8). It must be borne in mind, however, that the implementation of methane recovery and utilization systems has not been taken into account, so these 107.9 million m<sup>3</sup> of CH<sub>4</sub> are the potential methane emissions of these WWTPs, not the amount of recoverable methane.

Since the emissions from the aerobic treatment of wastewater and anaerobic sludge digestion total some 2.8 m<sup>3</sup> of methane per member of the served population per year, total emissions come to 81.5 million cubic metres of methane per year (enough to fill 24,000 Olympic-sized swimming pools).

At this point it is important to point out that this level of methane production is attributable to the predominance of systems that use CAS technologies. While these systems treat 72% of the wastewater processed by aerobic WWTP, they have the potential to generate 65.5 million cubic metres of methane emissions, which is the equivalent of 80% of the methane generated by the anaerobic digestion of the sludge produced by aerobic wastewater processes and 60% of the methane generated by WWTPs being analysed here.

Table 8 shows how little methane is generated by the treatment of wastewater in aerobic lagoon systems (1.1 m<sup>3</sup> of methane p.e.).

<sup>17</sup> Or average methane emissions of 3.3 m<sup>3</sup> per member of the served population.

**Table 8**  
**Estimated methane emissions from the treatment of household wastewater in the target-group WWTPs**

Type of treatment	Technology ID	Total WWTP	Treated flow (l/s)	Percentage of water treated (Percentages)	Equivalent population served	Methane p.e. generated (m <sup>3</sup> /year)	Methane generated CH <sub>4</sub> (m <sup>3</sup> /year)
Anaerobic treatment	UASB	1	750	1.3	432 000	9.61	4 151 456
	An L	1	269	0.5	155 174	6.59	1 022 539
Aerobic/anaerobic treatment	UASB + CAS	1	428	0.7	246 262	10.54	2 594 746
	An L + L	10	4 856	8.5	2 797 256	6.67	18 663 243
Aerobic treatment	CAS	45	36 799	64.1	21 196 007	3.09	65 471 933
	EA	5	5 835	10.2	3 360 851	2.06	6 920 844
	A L	4	2 363	4.1	1 360 950	1.10	1 494 688
Aerobic/anoxic treatment	OD	1	492	0.9	283 473	2.57	729 678
	EA-Dn	1	625	1.1	360 000	2.06	741 331
	TF	5	4 611	8.0	2 655 936	2.23	5 925 017
	L + L	1	345	0.6	198 587	1.10	218 102
<b>Total</b>		<b>75</b>	<b>57 372</b>	<b>100.0</b>	<b>33 046 496</b>	<b>3.27</b>	<b>107 933 577</b>

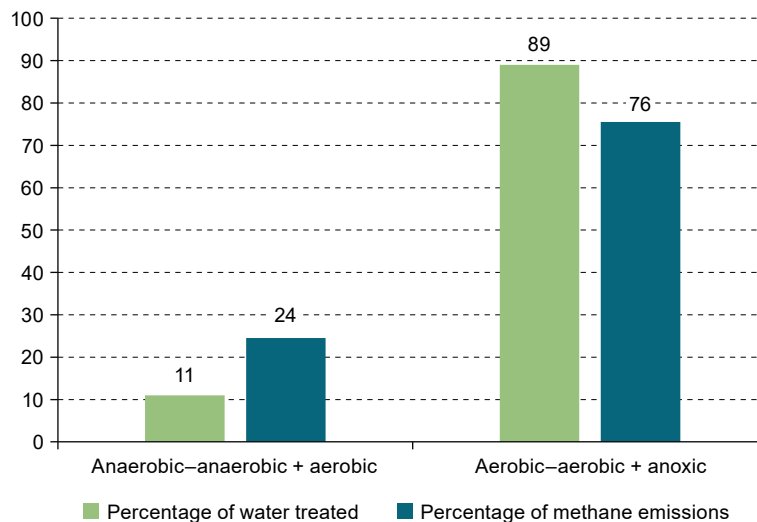
Source: Prepared by the authors.

The plants using anaerobic and dual technologies have average methane emissions p.e. of 7.3 m<sup>3</sup>, which is equivalent to 26.4 million cubic metres of methane emissions.

This indicates that, in principle, WWTPs that use these technologies have a greater potential to emit pollutants, which, from the standpoint of the circular economy, constitutes a valuable opportunity for harnessing the substantial energy potential of this level of emissions.

A comparison that provides a way of providing context for a consideration of the differences in emissions from the different types of technologies is depicted in figure 7. The reader will see that plants using aerobic technologies treat 89% of the wastewater processed by the target-group WWTPs and produce 76% of the group's methane emissions. In contrast, while anaerobic technologies are used to treat only 11% of that wastewater, they generate 24% of the methane emissions of the target-group WWTPs.

**Figure 7**  
**Estimated methane emissions, by type of wastewater treatment process**  
 (Percentages)



Source: Prepared by the authors.

The methane emissions of the target-group WWTPs in each country thus reflect the distribution of the technologies used in WWTPs that process each country's wastewater. It should be noted here that, even though the Plurinational State of Bolivia does not have a large amount of installed capacity for treating wastewater, the technologies that it uses are of the types that produce large volumes of methane emissions.<sup>18</sup> Consequently, it, like Colombia, has a strong potential for implementing circular economic processes for harnessing those emissions, as may be seen from table 9.

In the cases of Costa Rica, Mexico and Peru, emissions p.e. are at much the same level in relative terms owing to the predominance of aerobic wastewater treatment technologies, as was illustrated in figure 6.

**Table 9**  
**Estimated methane emissions produced by the treatment of household wastewater by the target-group WWTPs in each country**

Country	Methane emissions ( <i>m<sup>3</sup>/year</i> )	Persons served	Methane emissions p.e. ( <i>m<sup>3</sup>/year</i> )
Bolivia (Plurinational State of)	4 872 005	896 117	5.4
Colombia	6 428 546	1 192 833	5.4
Costa Rica	4 857 897	1 572 705	3.1
Mexico	82 377 024	26 652 286	3.1
Peru	9 398 105	2 732 556	3.4
Total	107 933 577	33 046 496	3.3

Source: Prepared by the authors.

Finally, it should be pointed out that, although the 107.9 million m<sup>3</sup> of methane that can be emitted by these 75 WWTPs potentially represents a total amount of energy of 1,079 GWh/year, not all of that methane can be captured, nor does that figure represent its total energy content. These figures therefore need to be viewed with caution until the efficiency rates of the methane capture and routing systems and of the electricity and thermal energy cogeneration systems are taken into account.

## **E. Estimation of methane emissions in the target-group WWTPs of the selected countries (modified scenario)**

In the preceding section, initial estimates were provided of the methane emissions of the selected 75 WWTPs in Colombia, Costa Rica, Mexico, Peru and the Plurinational State of Bolivia. The relationship between the wastewater treatment technologies employed and the methane emissions produced during those processes was also analysed. It was noted that methane emissions are an inherent component of anaerobic processes because those technologies convert organic matter into biogas. It was also explained that aerobic processes require the implementation of an anaerobic sludge digestion system during whose operation methane is emitted and can be captured and used to power processing operations within the corresponding WWTP.

However, unlike the systems using other aerobic technologies, the aerobic lagoon systems do not have the necessary set-ups for anaerobic sludge digestion and therefore do not generate significant amounts of methane. Consequently, one very promising option for the incorporation of circular economy approaches is the conversion of these aerobic lagoons into anaerobic lagoons, which would make it possible to produce, capture and utilize a greater volume of biogas for the cogeneration of electricity and thermal energy.

<sup>18</sup> The four WWTPs in the Plurinational State of Bolivia that were analysed use lagoon systems that handle no more than 1,000 l/s of wastewater. Of those four, three use systems involving the use of anaerobic and other types of lagoons, while the other uses a combination of series lagoons that do not include any anaerobic lagoons but do include lagoons that are large enough to be converted into anaerobic ponds.

This is not a viable solution for all lagoon systems, however, as its applicability depends on a number of different features. Consequently, only 16 of the 25 lagoon systems with a treatment capacity of between 500 l/s and 4,000 l/s could be included in the target group. The other nine cover such large areas that it would not be viable to convert these aerobic lagoons into anaerobic ones, and it would therefore be impossible to estimate the benefits derived from harnessing methane emissions in the converted WWTPs.

If the proposed modifications are made, then WWTPs that are using lagoon systems will potentially be generating between 21.4 million m<sup>3</sup> and 29.9 million m<sup>3</sup> of methane emissions (see table 7 for differing emissions levels of the various types of systems). The target-group WWTPs together will thus potentially be producing from 107.9 million m<sup>3</sup> to 116.5 million m<sup>3</sup> of methane emissions (see table 10).

Given the efficiency levels of the systems for capturing, routing and storing the methane<sup>19</sup> (see equation 3 in annex A2), however, only 103.4 million cubic metres could be captured or recovered (89% of the generable methane produced by these 75 WWTPs).

**Table 10**  
Estimated methane emissions and potential energy content obtainable  
from household wastewater treatment in the target-group WWTPs

Technology ID (original)	Technology ID (modified)	Treated flow (l/s)	Equivalent population served	Methane generated p.e. (m <sup>3</sup> /year)	Methane generated CH <sub>4</sub> (hm <sup>3</sup> /year)	Recoverable methane CH <sub>4</sub> (hm <sup>3</sup> /year)	Energy content of recoverable methane (MWh/year)	Generable electricity (MWh/year)	Recoverable thermal energy (co-generation) (MWh/year)
CAS	CAS	36 799	21 196 007	3.09	65 472	58 925	587 480	205 618	234 992
OD	OD	492	283 473	2.57	730	657	6 547	2 292	2 619
EA	EA	5 835	3 360 851	2.06	6 921	6 229	62 101	21 735	24 840
EA-Dn	EA-Dn	625	360 000	2.06	741	667	6 652	2 328	2 661
TF	TF	4 611	2 655 936	2.23	5 925	5 333	53 165	18 608	21 266
A L	An L	2 363	1 360 950	6.59	8 968	7 623	76 000	26 600	30 400
L + L	An L + L	345	198 587	6.67	1 325	1 126	11 228	3 930	4 491
UASB	UASB	750	432 000	9.61	4 151	3 736	37 251	13 038	14 900
An L	An L	269	155 174	6.67	1 035	880	8 774	3 071	3 510
UASB + CAS	UASB + CAS	428	246 262	10.54	2 595	2 335	23 283	8 149	9 313
An L + L	An L + L	4 856	2 797 256	6.67	18 663	15 864	158 162	55 357	63 265
Total		57 372	33 046 496	3.53	116 527	103 374	1 030 643	360 725	412 257

Source: Prepared by the authors, on the basis of M. Doorn and others, "Tratamiento y eliminación de aguas residuales", *Directrices del IPCC de 2006 para los inventarios nacionales de gases de efecto invernadero*, S. Eggleston and others (eds.), Hayama, Institute for Global Environmental Strategies (IGES), 2006.

The methane that can be captured has a potential energy content of 1,030 GWh/year. However, since the efficiency of the electricity generation system<sup>20</sup> has to be factored in, the amounts that can actually be generated come to 360,725 MWh/year of electricity—equivalent to the amount used by 202,000 people in a year—and 412,257 MWh/year of thermal energy. This potentially totals 772,982 MWh/year, if a cogeneration system for recovering the thermal energy produced by the generation of electricity is brought online.

Table 11 illustrates the potential composition of the emissions and their potential energy content for each of the countries in the target group. As may be seen from the table, in contrast to the documented levels of emissions p.e. shown in table 9, the levels given in table 11 are considerably higher for Mexico,

<sup>19</sup> These levels are 90% for anaerobic reactors and sludge digesters and 85% for anaerobic lagoon systems.

<sup>20</sup> These efficiency levels are assumed to be 35% for the generation of electricity and 40% for thermal energy cogeneration.

Peru and the Plurinational State of Bolivia, with increases of 0.2 m<sup>3</sup>, 0.5 m<sup>3</sup> and 1.3 m<sup>3</sup>, respectively, which also then entail increases in the amount of recoverable methane and the energy potential of this approach for those countries. These values will serve as the basis for the assessment presented in the next chapter of the economic and environmental benefits of applying circular economic principles to wastewater treatment processes.

**Table 11**  
Estimated methane emissions and potential energy content in each country obtainable from household wastewater treatment in the target-group WWTPs

Country	Number of WWTPs	Treated flow (l/s)	Equivalent population served	Methane generated CH <sub>4</sub> (hm <sup>3</sup> /year)	Methane generated p.e. (m <sup>3</sup> /year)	Recoverable methane CH <sub>4</sub> (hm <sup>3</sup> /year)	Energy content of recoverable methane (MWh/year)	Generable electricity (MWh/year)	Recoverable thermal energy (cogeneration) (MWh/year)
Bolivia (Plurinational State of)	4	1 556	896 117	5 979	6.67	5 082	50 668	17 734	20 267
Colombia	3	2 071	1 192 833	6 429	5.39	5 701	56 839	19 894	22 735
Costa Rica	1	2 730	1 572 705	4 858	3.09	4 372	43 590	15 256	17 436
Mexico	59	46 271	26 652 286	88 703	3.33	79 026	787 886	275 760	315 154
Peru	8	4 744	2 732 556	10 558	3.86	9 194	91 661	32 081	36 664
Total	75	57 372	33 046 496	116 527	3.53	103 374	1 030 643	360 725	412 257

Source: Prepared by the authors.



## **IV. Estimated costs and benefits of harnessing methane emissions for cogeneration in the target-group WWTPs**

This chapter will focus on estimating the economic, environmental and social benefits associated with harnessing the methane emissions from wastewater treatment processes in the plants selected for this analysis. As a first step, the cost of the investments that each of WWTPs will need to make are examined, and detailed estimates are developed for the three major types of WWTPs (see section A).

In section B, the economic benefits of these investments will be examined. The potentially usable amounts of biogas will be estimated, along with the corresponding energy content. A number of assumptions will then be made as a basis for evaluating the returns from energy generation as an input for a cost-benefit analysis.

The environmental benefits of this approach will be explored in section C, while an effort will be made to gauge the macroeconomic and social benefits to be gained from the proposed investments in section D. This will include estimates of the number of jobs that would be created and the projected increases in gross domestic product (GDP) and in the value added to the national economies of the countries included in the sample.

### **A. Cost of the investments required to capture methane emissions for generating energy in the target-group WWTPs**

The amount of methane that could potentially be produced in a WWTP has been estimated using a baseline scenario and a modified one. In order to calculate the benefits of making use of that methane, however, it is first necessary to determine the cost of the investments that would have to be made in order to leverage the emissions generated by the wastewater treatment processes used in lagoon systems and in compact aerobic systems and then to capture that methane and convert it into energy and, ultimately, income. Each of these investments basically falls into one of three categories, depending on the technology used in the baseline scenario for each WWTP. In principle, in WWTPs that use (compact) aerobic treatment processes, anaerobic sludge digesters would be needed, since, without them, there would be no appreciable amounts of methane to capture.

Methane routing, storage and purification systems would also have to be put in place in these WWTPs, together with engine generators and thermal energy cogeneration systems.

One of the limitations of this study is that the cost of the investments needed to introduce thermal energy cogeneration systems (see the last column in table 12) have not been estimated. Consequently, the benefits of such an investment have not been included in the overall cost-benefit analysis either.

**Table 12**  
Investments needed to harness the generable methane in target-group WWTPs

Technology ID	Sludge digestion system	Infrastructure works to deepen existing lagoon ponds	HDPE covers for new anaerobic lagoon ponds	Methane routing, storage and purification systems	Electricity generation systems	Thermal energy cogeneration systems
CAS	x			x	x	x
OD	x			x	x	x
EA	x			x	x	x
EA-Dn	x			x	x	x
TF	x			x	x	x
A L		x	x	x	x	x
L + L		x	x	x	x	x
An L		x	x	x	x	x
An L + L		x	x	x	x	x
UASB				x	x	x
UASB + CAS				x	x	x

Source: Prepared by the authors.

In the case of lagoon systems, a number of infrastructure works are needed to alter the lagoon ponds and blanket them with high-density polyethylene (HDPE) covers. For these types of plants, the additional investments indicated in columns 4, 5 and 6 of table 12 will also be required in order to configure a system for capturing methane for use in cogeneration.

For compact anaerobic technologies, there is another type of investment that is needed. In these plants, since an anaerobic reactor is already in place that will perform the function of capturing the biogas, the only added cost is the cost of its use for that purpose. These investments<sup>21</sup> are detailed in annex A3.

The total cost of the proposed investments for capturing methane emissions for use in generating energy in 75 plants serving a total of 33 million people is estimated at US\$ 251 million (see tables 13 and 14).

**Table 13**  
Estimated cost of investments needed to make use of generable methane in the target-group WWTPs, by type of technology  
(Dollars at 2021 prices)

Technology ID	Total number of WWTPs	Treated flow (l/s)	Equivalent population served	Recoverable methane CH <sub>4</sub> (hm <sup>3</sup> /year)	Generable electricity (MWh/year)	Initial investment	Initial investment p.e.
CAS	45	36 799	21 196 007	58 925	205 618	188 391 300	8.89
OD	1	492	283 473	657	2 292	2 420 500	8.54
EA	5	5 835	3 360 851	6 229	21 735	17 202 600	5.12

<sup>21</sup> The specific factors that could come into play with regard to these investments in individual WWTPs are not taken into account in this exercise.

Technology ID	Total number of WWTPs	Treated flow (l/s)	Equivalent population served	Recoverable methane CH <sub>4</sub> (hm <sup>3</sup> /year)	Generable electricity (MWh/year)	Initial investment	Initial investment p.e.
EA-Dn	1	625	360 000	667	2 328	2 627 300	7.30
TF	5	4 611	2 655 936	5 333	18 608	20 441 300	7.70
A L	4	2 363	1 360 950	7 623	26 600	5 442 480	4.00
L + L	1	345	198 587	1 126	3 930	1 360 620	6.85
UASB	1	750	432 000	3 736	13 038	1 030 200	2.38
An L	1	269	155 174	880	3 071	1 020 420	6.58
UASB + CAS	1	428	246 262	2 335	8 149	1 000 300	4.06
An L + L	10	4 856	2 797 256	15 864	55 357	10 204 200	3.65
Total	75	57 372	33 046 496	103 374	360 725	251 141 220	7.60

Source: Prepared by the authors.

**Table 14**  
**Estimated cost of investments needed to make use of generable methane**  
**in the target-group WWTPs, by country**  
*(Dollars at 2021 prices)*

Country	Total number of WWTPs	Treated flow (l/s)	Equivalent population served	Recoverable methane CH <sub>4</sub> (hm <sup>3</sup> /year)	Generable electricity (MWh/year)	Investment	Investment p.e.
Bolivia (Plurinational State of)	4	1 556	896 117	5 082 043	17 733 791	4 421 880	4.93
Colombia	3	2 071	1 192 833	5 700 972	19 893 540	8 471 020	7.10
Costa Rica	1	2 730	1 572 705	4 372 107	15 256 468	8 875 900	5.64
Mexico	59	46 271	26 652 286	79 025 643	275 759 982	208 124 440	7.81
Peru	8	4 744	2 732 556	9 193 655	32 081 260	21 247 980	7.78
Total	75	57 372	33 046 496	103 374 420	360 725 040	251 141 220	7.69

Source: Prepared by the authors.

Plants that use (compact) aerobic technologies account for by far the largest share (95%) of these investments because they treat 84% of the total volume of household wastewater processed by the target-group WWTPs. This is mainly a reflection of the size of the investments involved in implementing sludge thickening, pumping and anaerobic digestion systems, which amount to 85% (US\$ 196.7 million) of the total investments required in this type of plant.

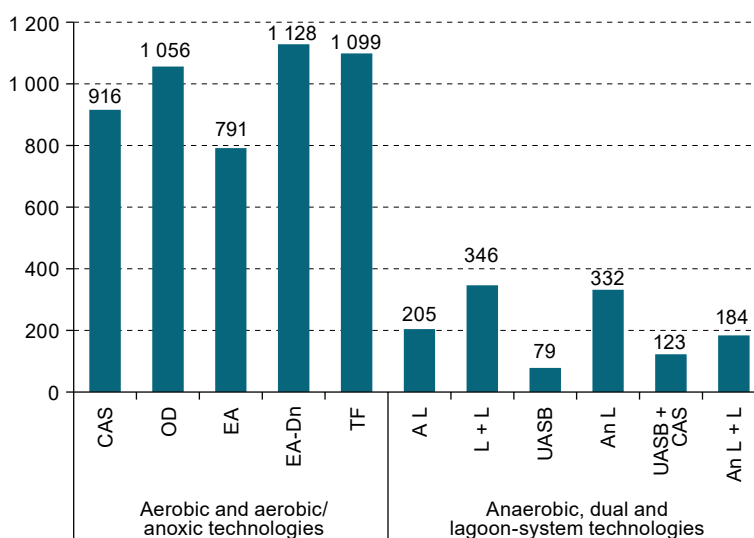
By contrast, plants that use compact anaerobic technologies (UASB and UASB + CAS) process just 2.05% of the total volume of wastewater and account for only 0.81% of the total investment in the target-group WWTPs. Finally, lagoon systems treat 13.7% of the wastewater and account for 7% of the required investment.

These differences can also be seen in terms of investment p.e., with the estimated cost required for the necessary conversions being twice as high in compact aerobic systems as it would be for anaerobic systems (see the final column of table 13).

These investments would make it possible to generate a total of 360,725 MWh/year of electrical energy—the equivalent of the amount of electricity used in a year by 200,000 people.

The investments plotted in figure 8 average out to US\$ 696 per MWh/year of generable electricity in these 75 WWTPs. The average investment per MWh/year of generable electricity for the plants using (compact) aerobic technology is US\$ 922, while the corresponding average for plants using anaerobic, dual or lagoon-system technologies is US\$ 182.

**Figure 8**  
**Cost of investments per MWh/year of generable electricity**  
*(Dollars at 2021 prices)*



Source: Prepared by the authors.

The investments required per MWh/year of generable electricity differ so sharply because the plants using anaerobic technologies would require much smaller investments than aerobic systems would and have the potential to generate a much greater volume of methane and then capture that methane for use in generating more energy p.e.<sup>22</sup>

## B. Economic benefits

Once the costs of the investment required to produce and harness methane and the amount of energy that could be generated by each of the types of systems used in WWTPs in this sample have been calculated, it then becomes possible to undertake a financial assessment in order to determine which projects should be implemented.<sup>23</sup>

In order to simplify the analysis, it can be assumed that all of the energy generated by each of these WWTPs will be used within the plant itself as a substitute for externally sourced energy.

The value of the energy generated by WWTPs can then be ascertained by looking at the prices per kWh paid in each country's industrial sector (see table 15). This pricing information has been provided by the Mining and Energy Planning Unit (UPME, 2021), which published that information for the countries in the sample covering the first and second quarters of 2019. These figures provide a valuable frame of reference since they do not reflect the economic shocks created by the corona virus (COVID-19) pandemic in 2020 and 2021 or by the war in Ukraine since 2022.

<sup>22</sup> Using cogeneration technology, aerobic systems have the potential to generate a total of 19.3 kWh/year p.e. and 9 kWh/year p.e. of electricity, on average, whereas anaerobic systems could generate a total of 37.2 kWh/year p.e. and 17 kWh/year p.e. of electricity, on average.

<sup>23</sup> The financial analysis presented in this section considers only the benefits of using methane to generate electricity. It does not take into account a number of other types of benefits, such as the savings in terms of sludge disposal expenses made possible by the installation of anaerobic sludge digesters in the WWTPs that use aerobic treatment technologies.

**Table 15**  
**Industrial-sector electricity prices in the second quarter of 2019**  
*(Dollars per kWh)*

Country	Price
Bolivia (Plurinational State of)	0.22
Colombia	0.12
Costa Rica	0.13
Mexico	0.13
Peru	0.09

Source: Prepared by the authors, on the basis of Mining and Energy Planning Unit (UPME), "Precios de energía eléctrica, comparación por países", Bogotá, 2021.

As may be seen from table 16, the implementation of these investments could provide income (savings) of US\$ 46.6 million per year just from the production of electricity. Over a 10-year period with a discount rate of 12.28%,<sup>24</sup> this is equivalent to a net present return of US\$ 260.4 million. If the investment is valued over a 20-year period, then the net present return would be US\$ 342.2 million, which is considerably higher than the present value of the investment itself.

**Table 16**  
**Financial evaluation of projects for harnessing methane in the target-group WWTPs**  
*(Dollars at 2021 prices)*

Technology ID	Total number of WWTPs	Treated flow (l/s)	Equivalent population served	Initial investment	Investment p.e.	NVP income (20 years)	NVP income (10 years)	Benefit-cost ratio (20 years)	Benefit-cost ratio (10 years)
CAS	45	36 799	21 196 007	188 391 300	8.89	192 541 240	146 526 890	1.02	0.78
OD	1	492	283 473	2 420 500	8.54	2 164 842	1 647 479	0.89	0.68
EA	5	5 835	3 360 851	17 202 600	5.12	20 533 090	15 626 002	1.19	0.91
EA-Dn	1	625	360 000	2 627 300	7.30	1 548 308	1 178 286	0.59	0.45
TF	5	4 611	2 655 936	20 441 300	7.70	15 707 420	11 953 592	0.77	0.58
A L	4	2 363	1 360 950	5 442 480	4.00	23 986 891	18 254 399	4.41	3.35
L + L	1	345	198 587	1 360 620	6.85	6 277 094	4 776 966	4.61	4.68
UASB	1	750	432 000	1 030 200	2.38	12 316 736	9 373 228	11.96	9.10
An L	1	269	155 174	1 020 420	6.58	2 042 191	1 554 139	2.00	1.52
UASB+CAS	1	428	246 262	1 000 300	4.06	7 201 750	5 480 644	7.20	5.48
An L + L	10	4 856	2 797 256	10 204 200	3.65	57 875 740	44 044 342	5.67	4.32
Total	75	57 372	33 046 496	251 141 220	7.59	342 195 299	260 415 966	1.36	1.04

Source: Prepared by the authors.

Thus, the implementation of circular economy schemes in WWTPs included in the sample for this study would call for investments totalling US\$ 7.6 p.e. Those investments would then provide returns over a 20-year period on the order of US\$ 10.3 p.e., yielding a benefit-cost ratio of 1.36.

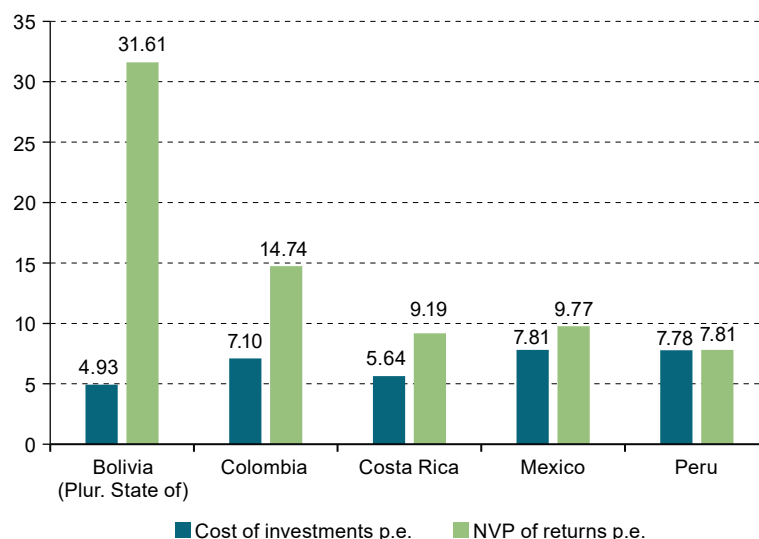
As has been emphasized throughout this document, the benefit-cost ratio is far higher for plants using anaerobic technologies than for those that use aerobic technologies. In the former, US\$ 3.8 in investments p.e. yield returns of US\$ 21.14 p.e. over a 20-year period, whereas, in the latter, US\$ 8.30 in investments p.e. would yield returns over a 20-year period of US\$ 8.35.

<sup>24</sup> This is the discount rate used by the Potable Water and Basic Sanitation Regulation Commission of Colombia for water and sewerage utilities having more than 100,000 subscribers in urban areas.

Consequently, aerobic technologies such as extended aeration with denitrification, oxidation ditches and trickling filters would not allow WWTPs using them to recoup their investment over a 20-year period. However, these differentials should be analysed thoroughly because there are a variety of factors that can alter this ratio. Those factors will be touched upon later in this section.

Figure 9 depicts the gap existing between the investments needed in each country to implement the proposed technologies and the net present value (NVP) of the income they would generate over a 20-year period. (Both values are shown in terms of the equivalent population served). This illustrates the Plurinational State of Bolivia's strong potential for developing projects of this type. This potential is primarily a consequence of the predominance of lagoon systems in that country, which, as shown by this study, lend themselves to conversion into anaerobic lagoons for capturing and making use of their methane emissions. The exercise presented here shows that, as a result of the implementation of these projects in the Bolivian WWTPs, all the wastewater that they process would be treated anaerobically, which could potentially generate a large volume of methane that could then be harnessed for energy generation.

**Figure 9**  
**Cost of investments p.e. versus projected returns p.e. over a 20-year period**  
**from using methane to generate electricity**  
*(Dollars at 2021 prices)*



Source: Prepared by the authors.

A favourable differential (US\$ 7.6 p.e.) exists in Colombia as well. As in the Plurinational State of Bolivia, this is a consequence of the use of anaerobic technologies to treat 42% of the wastewater processed by the Colombian WWTPs in the group covered by this analysis.

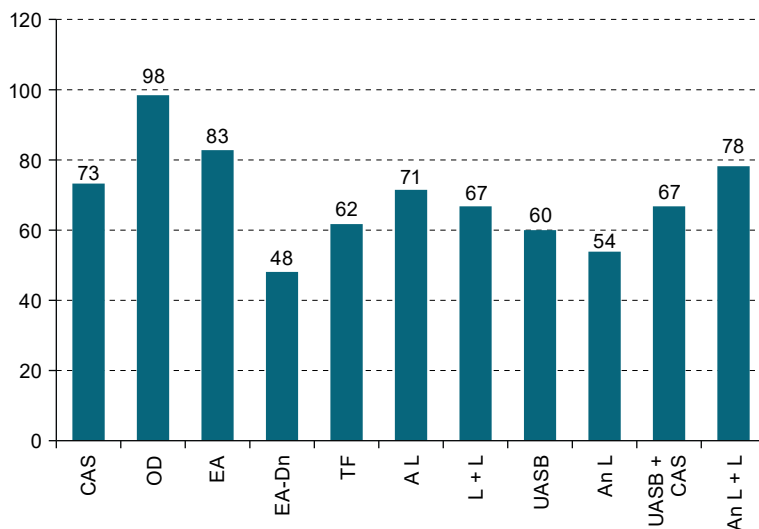
In the case of Peru, the cost of the investments and the returns on those investments over a 20-year period are virtually the same. One of the reasons for this is the significant underutilization of the Peruvian WWTPs in the sample, since only 51% of their installed capacity is being used (see figure 11). As a result, the figures, in p.e. terms, balance one another out.

At this point, a clarification concerning the assessment of the financial viability of such projects is called for. Although the scenario being used for this purpose is based on a 20-year period, the exercise assumes that methane production and trends in energy prices will remain constant.

However, it should be remembered that installed capacity and the utilization rate are key factors in determining the financial viability of these investments. This is because the level of methane emissions

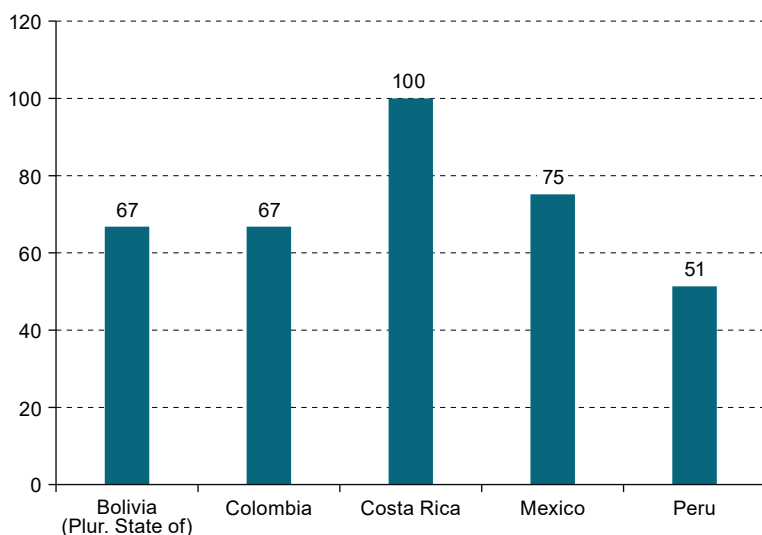
has a great deal to do with the organic load of the wastewater entering a WWTP, and this, in turn, depends on the size of the population being served by that plant. Figures 10 and 11 illustrate how much of the installed capacity of these WWTPs is actually being utilized.

**Figure 10**  
Use of installed capacity in the target-group WWTPs, by type of wastewater treatment technology  
(Percentages)



Source: Prepared by the authors.

**Figure 11**  
Use of installed capacity in the target-group WWTPs, by country  
(Percentages)

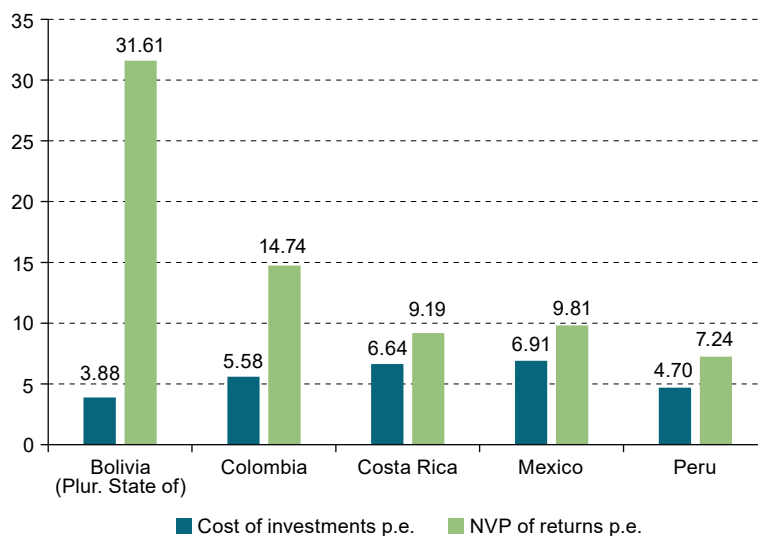


Source: Prepared by the authors.

Thus, the viability of these investments will increase in line with increases in the utilization of these plants' installed capacity. These utilities should therefore expand their networks and sewerage service areas.

If the figures depicted in figure 9 are recalculated on the assumption of an overall installed capacity use rate of 85%, then the resulting investment levels and returns p.e. are as shown in figure 12. When a higher installed capacity use rate is incorporated into the equations, then the benefit-cost ratio changes substantially. The change is the most striking in the case of Peru, where these types of investments did not appear to be financially viable in the original scenario.

**Figure 12**  
**Cost of investments p.e. versus projected returns p.e. over a 20-year period from using methane for the cogeneration of energy, based on an installed capacity use rate of 85%**  
*(Dollars at 2021 prices)*



Source: Prepared by the authors.

In summary, the type of technology used for wastewater treatment, the installed capacity use rate and the size of the organic load of the wastewater to be treated in each plant<sup>25</sup> are all important factors when it comes to determining the financial sustainability of a project for implementing a circular economy technique involving the reuse of the methane generated by the treatment of wastewater.

Given the favourable benefit-cost ratio of projects using anaerobic technologies and particularly lagoon systems, there is a promising opportunity for converting aerobic lagoon systems into anaerobic ones that can capture methane and use it to generate energy. In addition, the results of this exercise suggest that it would be viable even for lagoon systems with treatment capacities of less than 500 l/s to use methane to generate energy.

There are currently some WWTPs that treat wastewater with aerobic technologies but that also use anaerobic sludge digesters. However, they are not utilizing the methane emissions from that process. These plants could undertake investments at no more than a marginal cost that would augment their incomes or savings.

### C. Environmental benefits

As mentioned earlier, wastewater treatment processes have major impacts in terms of water quality, the protection of aquatic ecosystems and climate change mitigation.

<sup>25</sup> Because of the limitations of the available sources of information, differences in the characteristics of the wastewater being treated by the different WWTPs in the target group could not be taken into consideration. Doing so would undoubtedly have enhanced the findings being presented here.

In addition, the introduction of a circular economy approach would heighten the environmental benefits of wastewater treatment, since it could help provide energy that could take the place of electricity generated by technologies powered by fossil fuels and could reduce greenhouse gas—and particularly methane—emissions.

In this section, therefore, an effort will be made to document the environmental benefits of reducing emissions by having the 75 WWTPs in the target group use those emissions to generate electricity. First, however, a few caveats are called for.

The usual procedure for estimating reductions in emissions in the case at hand would be start off with an evaluation of WWTP emissions under a baseline scenario and a second scenario based on the investments outlined in section A of this chapter. The analysis being presented here is limited by the fact that accurate information on the baseline situation in each of these WWTPs is not available. More specifically, information is unavailable on the amount of energy used by each of these WWTPs and, in the case of the plants that use aerobic technologies, no information is available on the type of sludge digestion process that they use either.

Here, however, the intention is not to estimate the profits to be derived from selling carbon credits but rather to estimate the potential reductions in greenhouse gases that would be brought about by the proposed investments. Accordingly, a few simple assumptions have been made:

- First, as in the case of the estimation of the methane emissions of these 75 WWTPs, it is assumed that the plants using (compact) aerobic technologies are using anaerobic sludge digesters.
- Second, any possible indirect emissions caused by pollution from the energy source used by WWTP for its operations, or any other type of indirect emissions associated with individual features of any of these WWTPs, are excluded from the analysis.
- Third, the total methane emissions generated by the wastewater treatment processes used by these 75 WWTPs are the figures employed in the analysis, even though such plants often burn off methane in order to reduce their greenhouse gas emissions.

Table 17 shows the reductions in methane emissions of WWTPs in the target group using a baseline scenario that incorporates the considerations discussed above.<sup>26</sup>

**Table 17**  
Reduction in emissions following investments for capturing and utilizing methane in the target-group WWTPs

Technology ID (original)	Technology ID (modified)	CH <sub>4</sub> emissions (baseline scenario) (m <sup>3</sup> )	CH <sub>4</sub> emissions (modified scenario) (m <sup>3</sup> )	Emissions reductions (Percentages)
CAS	CAS	65 471 933	6 547 193	90
OD	OD	729 678	72 968	90
EA	EA	6 920 844	692 084	90
EA-Dn	EA-Dn	741 331	74 133	90
TF	TF	5 925 017	592 502	90
A L	An L	1 494 688	1 345 220	10
L + L	An L + L	218 102	198 746	9
UASB	UASB	4 151 456	415 146	90
An L	An L	1 022 539	155 298	85
UASB + CAS	UASB + CAS	2 594 746	259 475	90
An L + L	An L + L	18 663 243	2 799 486	85
Total		107 933 577	13 152 250	88

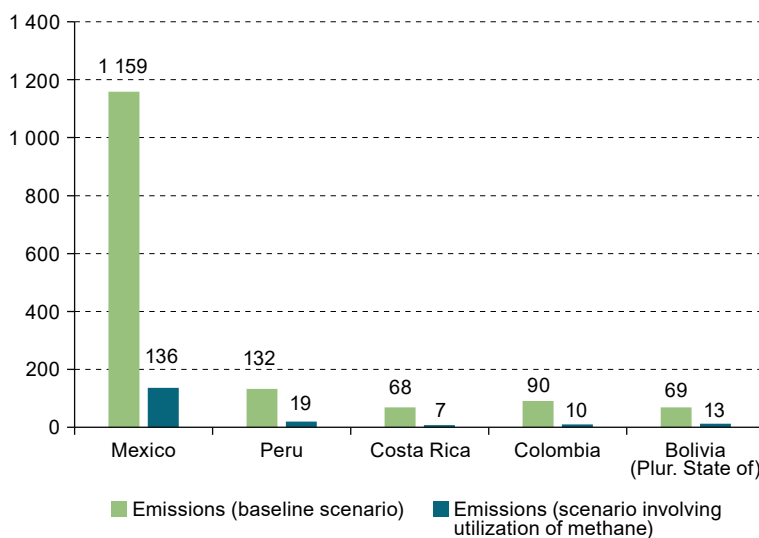
Source: Prepared by the authors.

<sup>26</sup> The baseline scenario corresponds to the estimated and documented emissions shown in table 8.

As can be seen from the table, an 88% reduction in emissions is achieved, with methane emissions decreasing from 107 million m<sup>3</sup> (equivalent to 1.5 million tons of CO<sub>2</sub>, which is, in turn, the equivalent of the emissions of 320,000 people in a year<sup>27</sup>) to 13.1 million m<sup>3</sup> (equivalent to 0.2 million tons of CO<sub>2</sub>).

The reduction in emissions for each country is shown in figure 13, with reductions ranging from 82% to 90%. Thus, the aggregate reduction for the 75 target-group WWTPs (figures for 2018) comes to 26% for Nicaragua, 22% for Costa Rica and 1.7% for Colombia.

**Figure 13**  
Emissions reductions in the target-group WWTPs, by country  
(Thousands of tons of CO<sub>2</sub>)



Source: Prepared by the authors.

## D. Macroeconomic and social benefits

These calculations take into consideration the economic and environmental benefits of introducing circular economic principles into wastewater management processes, along with the social benefits associated with improvements in public health. In addition, the proposed investments for using methane to generate electricity give rise to social benefits in the aggregate in the form of green job creation, increases in value added in the countries and increased GDP growth.

A simulator based on input-output matrices for 2011 developed by the ECLAC International Trade and Integration Division was used to estimate the direct and indirect impacts of investment in the sanitation sector in 10 Latin American and Caribbean economies on employment, value added, production and intermediate consumption.

When undertaking this simulation of the impact of such investments on GDP, value added and employment, the fact that disaggregated input-output matrices for the potable water and sanitation sectors are not available for the Plurinational State of Bolivia, and that country could therefore not be included in this part of the analysis.

The results shown in table 18 indicate that investments totalling US\$ 247 million in order to utilize methane emissions to generate electricity would have a total impact amounting to US\$ 320 million on GDP in the four other countries in the target group and would generate US\$ 228 million in value added.

<sup>27</sup> See World Bank, "Emisiones de CO<sub>2</sub>" [online] <https://data.worldbank.org/indicator/EN.GHG.ALL.MT.CE.AR5>.

**Table 18**  
Impact of the proposed investments on GDP, value added and employment, by country

Country	Number of WWTPs	Initial investment (Millions of dollars)	Increase in GDP (Millions of dollars)	Increase in gross value added (Millions of dollars)	Direct creation of new jobs	Indirect creation of new jobs
Colombia	3	8.47	12.74	7.91	176	245
Costa Rica	1	8.88	11.77	8.08	423	99
Mexico	59	208.12	263.27	193.42	7 230	959
Peru	8	21.25	32.33	19.03	1 699	552
Total	71	246.72	320.11	228.44	9 528	1 855

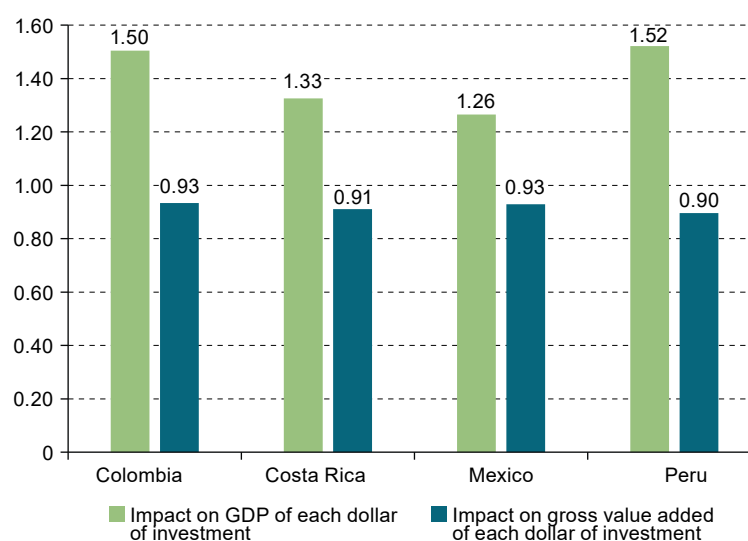
Source: Prepared by the authors.

Thus, the results indicate that the proposed investments would give rise to the creation of 11,383 new green jobs. In all, 9,528 of those jobs would be in the sanitation sector (direct job creation) while the other 1,855 would be created indirectly.

The social benefits stemming from the proposed investments are not evenly distributed among the countries in question. This is because the effect of such investments is determined by the complex web of production linkages existing in each country. Consequently, for each dollar of investment, the impact on GDP would be on the order of US\$ 1.5 in Colombia and Peru but less in the cases of Mexico and Costa Rica (see figure 14).

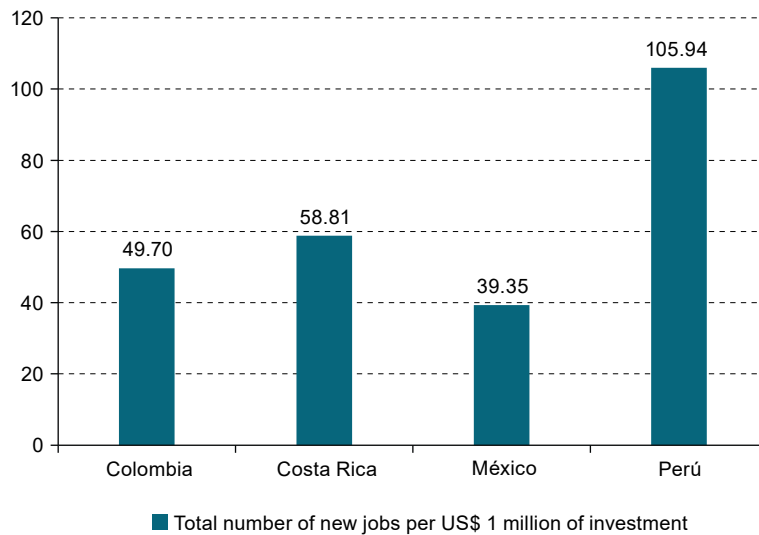
For much the same reason, every US\$ 1 million of investment in harnessing methane to generate electrical energy would create approximately 106 jobs in Peru, 59 jobs in Costa Rica, 50 jobs in Colombia and 39 jobs in Mexico (see figure 15).

**Figure 14**  
Impact of the proposed investments on GDP and value added, by country  
(Dollars at 2021 prices)



Source: Prepared by the authors.

**Figure 15**  
Impact of the proposed investments in terms of green job creation, by country  
(Number of jobs)



Source: Prepared by the authors.

Thus, the above impacts correspond to increases (for the four countries) of 0.011%, 0.014% and 0.013% in GDP, value added and job creation, respectively. While these figures may not seem large, it must be remembered that they would be the outcome of investment in just 71 of the 3,286 WWTPs listed in the database for these four countries.

## V. Conclusions and recommendations

### A. Findings and recommendations concerning the adoption of a policy and plan for harnessing methane in WWTPs of Latin American and Caribbean countries

This study provides evidence on the costs and benefits of incorporating circular economic principles into wastewater treatment systems. More specifically, it furnishes estimates of the investments needed in 75 WWTPs having capacities of between 500 l/s and 4,000 l/s that serve 33 million people in five Latin American and Caribbean in order to enable them to harness methane for use in generating electricity. Proof of the feasibility of this type of conversion is especially important for areas where this option is not currently being considered but nonetheless offers a way of improving the quality, efficiency and financial viability of these utilities. The calculations used in the study indicate that, on average, investments amounting to US\$ 7.6 p.e. would yield US\$ 10.3 p.e. in returns over a 20-year period, for a benefit-cost ratio of 1.36. This would also reduce these plants' methane emissions by 88%, which is the equivalent of one-fourth of the total emissions of Nicaragua in 2018.

The benefit-cost ratio for aerobic and anaerobic lagoon systems having a capacity of between 500 l/s and 4,000 l/s is particularly striking: 3.81 over a 10-year period and 5.0 over 20 years. The fact that this profit ratio is so high suggests that converting lagoon system with capacities under 500 l/s may also be viable. This is a possibility that warrants further exploration in future studies.

At that benefit-cost ratio, given that the cost of the investments required for the conversion of lagoon systems in Bolivian municipalities are substantially lower (US\$ 4.93p.e), there appears to be a business opportunity for re-engineering WWTPs in that country, as they could secure operating profits of up to US\$ 31.6 p.e., which is over twice as high as the ratio for the other four countries covered in this part of the analysis.

Accordingly, this study suggests that one of the avenues that remains to be explored would be the economic, social and environmental benefits that could be derived from the implementation of circular economic schemes in lagoon systems with installed capacities of less than 500 l/s. In essence, what needs

to be determined is the range of operating scales at which this type of technology and compact anaerobic technologies would attain a positive benefit-cost ratio. This would provide a basis for promoting the conversion of those systems in WWTPs that are seeking to adopt circular economic principles.

The reduction of methane emissions in all of the types of systems covered in the study affords significant environmental benefits. An evaluation using a baseline scenario that shows the direct and indirect emissions of each WWTP makes it clear that more robust and specific reductions in CO<sub>2</sub> equivalent emissions are attainable in every one of the plants covered by the study.

Yet the environmental benefits of using circular economic systems for the treatment of wastewater are not limited to the reduction of methane emissions. The reduction in the pollution of bodies of water made possible by this approach, since it enhances the financial viability of wastewater treatment systems, has positive implications for public health. For example, the literature points to the presence of a positive correlation between a reduction in deaths related to waterborne diseases and the presence of suitable drinking water and sanitation infrastructure and service coverage. What is more, gender parity in school attendance improves when safely managed drinking water and sanitation infrastructure is in place (Saravia Matus and others, 2022). Lowering air and water pollution also has a positive impact on housing prices, promotes tourism and help to ensure a healthy environment. The social benefits are also noteworthy: the investment required in the selected WWTPs in Colombia, Costa Rica, Mexico and Peru would (directly and indirectly) create an estimated 11,383 green jobs.

The need to achieve greater economies of scale in wastewater treatment should be underscored, however, since 34% of the installed capacity of the countries covered by this study is spread out among 3,243 different systems with capacities of between 0.03 l/s and 500 l/s. Reducing the extremely high degree of fragmentation characterizing WWTPs of these countries would boost the efficiency of WWTPs, lower their operating costs and have less of a negative impact on the environment by lowering emissions of CO<sub>2</sub> equivalent.

For example, 50 WWTPs with capacities of 10 l/s, or 25 WWTPs with capacities of 20 l/s, that cannot afford to implement circular economic schemes may produce more pollution than a single WWTP with an equivalent capacity that introduces circular economic systems that enable it to make use of treatment processes' various by-products.

The main barriers to the adoption of these systems tend to be the absence of personnel with the requisite skills, the lack of long-term financing and the need to make additional investments in order to have sewerage networks that will allow an increase in WWTP capacity utilization rates. In fact, this study shows that a higher installed capacity utilization rate would strengthen the economic viability of these types of projects.

Thus, the challenge facing the region involves expanding its sewerage systems and substantially raising the installed capacity utilization rates of its wastewater treatment systems—given that the current rates are considerably lower than the existing design parameters in many countries<sup>28</sup>—by incorporating circular economic principles and prioritizing financing for projects that will achieve an economically and environmentally efficient operating scale.

Progress needs to be made in assessing the economic viability of implementing technologies for maximizing the utilization of the various by-products of wastewater treatment processes and in determining what the requisite conditions for their introduction are. This is important because there are also other options that have not been evaluated in this study that may generate income streams for WWTPs, such as the sale of green bonds and of treated water, the recovery of nutrients for use in agriculture or improvements in the utilization of sludge as a soil amendment.

In order to help take advantage of these opportunities, regulatory standards will need to be updated and policies and incentives will have to be designed for attracting demand for the various goods and

<sup>28</sup> Mexico, Peru and, recently, Costa Rica are good examples.

services produced by circular wastewater treatment systems. Investment incentives in the sector will also need to be reviewed to ensure that investments meet safe management requirements. This is the way forward towards greater WWTP financial viability and the conversion of these systems into sustainable businesses that are aligned with the Goals set forth in the 2030 Agenda for Sustainable Development. Only by doing so can the region ensure that it is not left behind and that it keeps pace with the major technological changes taking place in this sector in more developed countries.

## **B. Contributions to a transformative economic recovery for the region**

The findings of this study show that these types of innovative solutions will help to drive progress towards a sustainable development process in keeping with the 2030 Agenda. They also offer a viable avenue for helping to bring about a transformative economic reactivation in Latin America and the Caribbean in the wake of the COVID-19 pandemic and against the backdrop of the war in Ukraine. Two pillars will underpin this reactivation: (a) technological innovations that help to give rise to structural change; and (b) the promotion of a major investment push in line with the tenets of sustainability (ECLAC, 2021a).

The proposal made here for converting WWTPs into circular economic systems focuses on concrete, innovative action aimed at taking up the challenge of transforming wastewater treatment systems and their accompanying economic structure in the region. This course of action would avoid major negative impacts on the environment and people's health while opening the way for converting waste into such products as biogas for use in generating electricity, treated water that can be sold and sludge that can be used to restore depleted soil or as a source of nutrients for use in agriculture. As early as 2012, ECLAC was drawing attention to the need to close infrastructure gaps through the use of inputs and sustainable products—especially in the areas of transport, water and sanitation, housing and energy—as a necessary component of a structural change for equality. At that time, however, the countries of the region still had to overcome a number of obstacles and institutional shortcomings in order to be able to implement those changes.

A number of authors (Moglia and others, 2021) contend that cities and other areas with high population densities and insufficient water and sanitation infrastructure (Leach and others, 2021) are the starting point for a transformative recovery that will increase resilience to climate change. Circular-economy wastewater treatment systems will help to promote energy self-sufficiency, lower the risk of interruptions in water distribution and reduce water pollution, among other benefits (Moglia and others, 2021). New types of policies can serve as the foundation for a reconfiguration of the relationship between the State and its citizens that will enable the countries to cope with another pandemic or with climate- or war-generated external shocks. It has been shown that getting ahead of major crises and developing greater resilience to them should be seen as an issue of central importance, especially in the case of drinking water and sanitation utilities, since these services constitute human rights and play a crucial role in the areas of environmental and public health.

A big investment push will be required in order to bring about these major changes—changes whose economic profitability has been demonstrated. Developed countries have worked to drive some of these green transitions by making structural changes in drinking water and wastewater treatment sectors, but, as a result of their subsequent failure to ensure the continuity of those investments, those facilities have become vulnerable and their continued functionality is at risk (Barbier, 2020). This illustrates the fact that it is important not only to maintain fiscal support over time but also to open up such projects to the private sector. This is why ECLAC has recommended that, as part of the effort to speed up the recovery from the pandemic, expansionary fiscal policies should be maintained and opportunities identified for innovation and responsible private management of sustainable natural resource use, particularly in relation to the crucially important role that water plays in ensuring the well-being of the region's societies (ECLAC, 2021a).



## Bibliography

- AAPS/MMAYA (Authority for Supervision and Social Control of Drinking Water and Basic Sanitation/Ministry of Environment and Water) (2019), *Indicadores de desempeño de las EPSA reguladas categorías A, B, C, D 2019*, La Paz.
- Aguilar-Benítez, I. and P. Blanco (2018), "Recuperación de metano y reducción de emisiones en PTAR Nuevo Laredo, Tamaulipas, México", *Tecnología y ciencias del agua*, vol. 9, No. 2, Jiutepec, Mexican Institute of Water Technology.
- Aresta, M., A. Dibenedetto and G. Barberio (2005), "Utilization of macro-algae for enhanced CO<sub>2</sub> fixation and biofuels production: development of a computing software for an LCA study", *Fuel Processing Technology*, vol. 86, No. 14-15, Amsterdam, Elsevier.
- Arnabat, I. (2017), "Bomba de calor para ACS a partir de fuentes de calor residual", Derio, Caloryfrio, 21 November [online] <https://www.caloryfrio.com/calefaccion/bomba-de-calor/bomba-de-calor-para-ac-s-fuentes-calor-residual.html>.
- Báez, P. and others (2016), "Evidencia de circulación del virus de la hepatitis A, subgenotipo IA, en muestras ambientales en Antioquia, Colombia", *Biomédica*, vol. 36, No. 2, Bogotá, National Health Institute.
- Barbier, E. (2020), "Greening the post-pandemic recovery in the G20", *Environmental and Resource Economics*, vol. 76, Berlin, Springer.
- BCCR (Central Bank of Costa Rica) (2021), "Cuenta de Agua 2021", San José [online] <https://www.bccr.fi.cr/indicadores-economicos/DocCuentaAgua/Cuenta-agua-2021.xlsx>.
- Benetto, E. and others (2009), "Life cycle assessment of ecological sanitation system for small-scale wastewater treatment", *Science of The Total Environment*, vol. 407, No. 5, Amsterdam, Elsevier.
- Brennan, G., M. Tennant and F. Blomsma (2015), "Business and production solutions: closing loops and the circular economy", *Sustainability*, H. Kopnina and E. Shoreman-Ouimet (eds.), London, Routledge.
- Briseño, H. and J. Rubiano (2018), "El servicio de agua potable para uso residencial en Colombia", *Revista U.D.C.A Actualidad & Divulgación Científica*, vol. 21, No. 1, Bogotá, University of Applied and Environmental Sciences.
- Chillón Rímac Lurín Water Observatory (2017), *Análisis geoespacial de canales de riego en relación a las plantas de tratamiento de aguas residuales (PTAR) y áreas verdes en el ámbito de Lima metropolitana*, Lima.
- CIGEA (Centre for Environmental Information, Management and Education) (1998), "Metodología para la evaluación aproximada de la carga contaminante", Havana.
- Cisneros, R., Z. Sanz and J. Teran (2015), "Wastewater reuse for irrigation in Bolivia: production, commercialization and consumption of wastewater irrigated crops in the Altiplano region", *Water and Sanitation Program: Field Note*, Washington, D.C., World Bank.

- CONAGUA (National Water Commission) (2022), *Inventario Nacional de Plantas Municipales de Potabilización y de Tratamiento de Aguas Residuales en Operación: diciembre 2022*, Mexico City.
- \_\_\_\_\_. (2021), "Catálogo de plantas de tratamiento de aguas residuales en operación de CONAGUA", Mexico City [online] <https://datos.gob.mx/busca/dataset/catalogo-de-plantas-de-tratamiento-de-aguas-residuales-en-operacion-de-conagua>.
- \_\_\_\_\_. (2020), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City.
- Cornejo, C. and A. Wilkie (2010), "De estiércol a energía: captura de metano en Ecuador", *Revista Tecnológica ESPOL - RTE*, vol. 23, No. 1, Guayaquil, Escuela Superior Politécnica del Litoral (ESPOL).
- CTIE-Agua (Interinstitutional Technical Committee on Water Statistics) (2021), "Boletín agua/2021", San José [online] [http://www.da.go.cr/wp-content/uploads/2019/01/Boletin\\_Agua\\_2021\\_CTIEestadisticas.pdf](http://www.da.go.cr/wp-content/uploads/2019/01/Boletin_Agua_2021_CTIEestadisticas.pdf).
- Dalal, K. and L. Svanström (2015), "Economic burden of disability adjusted life years (DALYs) of injuries", *Health*, vol. 7, No. 4, Glendale, Scientific Research Publishing (SCIRP).
- DANE (National Administrative Department of Statistics) (2020), "Producto interno bruto desde el enfoque de la producción a precios constantes" [online] <https://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-trimestrales/historicos-producto-interno-bruto-pib>.
- Denton, F. and others (2014), "Climate-resilient pathways: adaptation, mitigation, and sustainable development", *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. Field and others (eds.), Cambridge, Cambridge University Press.
- Dirven, M. (2019), "Nueva definición de lo rural en América Latina y el Caribe en el marco de FAO para una reflexión colectiva para definir líneas de acción para llegar al 2030 con un ámbito rural distinto", *2030: Alimentación, agricultura y desarrollo rural en América Latina y el Caribe*, No. 2, Santiago, Food and Agriculture Organization of the United Nations (FAO).
- Doorn, M. and others (2006), "Tratamiento y eliminación de aguas residuales", *Directrices del IPCC de 2006 para los inventarios nacionales de gases de efecto invernadero*, S. Eggleston and others (eds.), Hayama, Institute for Global Environmental Strategies (IGES).
- ECLAC (Economic Commission for Latin America and the Caribbean) (2022), *A decade of action for a change of era (LC/FDS.5/3)*, Santiago.
- \_\_\_\_\_. (2021a), "The recovery paradox in Latin America and the Caribbean: growth amid persisting structural problems: inequality, poverty and low investment and productivity", *Special Report COVID-19*, No. 11, Santiago.
- \_\_\_\_\_. (2021b), "Base de datos PTAR", Santiago, unpublished.
- \_\_\_\_\_. (2019), "Total annual gross domestic product (GDP) at current prices in dollars", Santiago [online] <https://statistics.cepal.org/portal/cepalstat/dashboard.html?theme=2&lang=en>.
- \_\_\_\_\_. (2012), *Cambio estructural para la igualdad: una visión integrada del desarrollo (LC/G.2524(SES.34/3))*, Santiago.
- EcoGreen Mundo (2015), "Diferencias entre la economía circular y la economía lineal" [online] <https://ecogreenmundo.com/diferencias-entre-la-economia-circular-y-la-economia-lineal/>.
- Ellen MacArthur Foundation (2015), "Delivering the circular economy: a toolkit for policymakers. Executive summary", Cowes.
- \_\_\_\_\_. (2012), "Towards the circular economy. Vol. 1: an economic and business rationale for an accelerated transition", Cowes, 31 December [online] <https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an>.
- EPA (United States Environmental Protection Agency) (2021), "Overview of greenhouse gases" [online] <https://www.epa.gov/ghgemissions/overview-greenhouse-gases#CH4-reference>.
- \_\_\_\_\_. (1985), *Estimating Sludge Management Costs*, Cincinnati.
- Felca, A. and others (2018), "Analysis of biogas produced by the anaerobic digestion of sludge generated at wastewater treatment plants in the South of Minas Gerais, Brazil as a potential energy source", *Sustainable Cities and Society*, vol. 41, Amsterdam, Elsevier.
- Flores, A., C. Buckley and R. Fenner (2008), "Selecting wastewater systems for sustainability in developing countries", document presented at the 11th International Conference on Urban Drainage, Edinburgh, International Association for Hydro-Environment Engineering and Research/International Water Association (IAHR/IWA).

- Foley, K. (2010), "Wastewater treatment and energy: an analysis on the feasibility of using renewable energy to power wastewater treatment plants in Singapore", Cambridge, Massachusetts Institute of Technology (MIT).
- Fortuño, M. (2017), "La economía del agua: el futuro se avecina complicado", Cologny, World Economic Forum (WEF), 31 March [online] <https://es.weforum.org/agenda/2017/03/la-economia-del-agua-cada-vez-sera-mas-importante>.
- Gaius-Obaseki, T. (2010), "Hydropower opportunities in the water industry", *International Journal of Environmental Sciences*, vol. 1, No. 3, Berlin, Springer.
- Gasson, C. (2021), "Is net zero now water's biggest priority?", Oxford, Global Water Intelligence (GWI), 12 August [online] <https://www.globalwaterintel.com/news/2021/32/is-net-zero-now-water-s-biggest-priority>.
- Gaterell, M. and others (2011), "An economic and environmental evaluation of the opportunities for substituting phosphorus recovered from wastewater treatment works in existing UK fertiliser markets", *Environmental Technology*, vol. 21, No. 9, Hoboken, Taylor & Francis.
- Ghisellini, P., C. Cialani and S. Ulgiati (2016), "A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems", *Journal of Cleaner Production*, vol. 114, Amsterdam, Elsevier.
- GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) (2020), *Bombas de calor: una guía para el usuario*, Bonn.
- González-Saldía, R. and others (2019), "Fecal pollution source tracking and thalassogenic diseases: The temporal-spatial concordance between maximum concentrations of human mitochondrial DNA in seawater and Hepatitis A outbreaks among a coastal population", *The Science of the Total Environment*, vol. 686, Amsterdam, Elsevier.
- Gower, R. and P. Schröder (2016), *Virtuous Circle: How the Circular Economy Can Create Jobs and Save Lives in Low and Middle-income Countries*, London, Tearfund/Institute of Development Studies (IDS).
- Groom, M., E. Gray and P. Townsend (2008), "Biofuels and biodiversity: principles for creating better policies for biofuel production", *Conservation Biology*, vol. 22, No. 3, Washington, D.C., Society for Conservation Biology.
- Guzmán, F. (2019), "Cada vez son más frecuentes los florecimientos de algas nocivos", *Gaceta UNAM*, Mexico City, National Autonomous University of Mexico (UNAM), 27 May [online] <https://www.gaceta.unam.mx/cada-vez-son-mas-frecuentes-los-florecimientos-de-algas-nocivos/>.
- Hao, X. and others (2020), "Sustainable disposal of excess sludge: incineration without anaerobic digestion", *Water Research*, vol. 170, Amsterdam, Elsevier.
- Hernández, A. (2021), "Recuperación de metano en plantas de tratamiento de aguas residuales municipales" document presented at technical meeting on the circular economy, Santiago, Economic Commission for Latin America and the Caribbean (ECLAC).
- IEA/OECD (International Energy Agency/Organisation for Economic Co-operation and Development) (2016), *Energy Efficiency in China 2016: Special Report*, Paris.
- INEI (National Institute of Statistics and Informatics) (2020), *Anuario de estadísticas ambientales 2020*, Lima.
- IPCC (Intergovernmental Panel on Climate Change) (2021), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte and others (eds.), Cambridge, Cambridge University Press.
- JMP (WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene) (2022), "Rural and urban service levels, 2015 and 2022" [online] <https://washdata.org/data/household#!/>.
- Kerres, M. and others (2020), *Stop Floating, Start Swimming. Water and Climate Change – Interlinkages and Prospects for Future Action*, Bonn, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).
- King, A. and others (2006), "Reducing waste: repair, recondition, remanufacture or recycle?", *Sustainable Development*, vol. 14, No. 4, Hoboken, Wiley.
- Kumar, A. and others (2010), "Enhanced CO<sub>2</sub> fixation and biofuel production via microalgae: recent developments and future directions", *Trends in Biotechnology*, vol. 28, No. 7, Cambridge, Cell Press.
- Larsen, T. and others (2009), "Source separation: will we see a paradigm shift in wastewater handling?", *Environmental Science & Technology*, vol. 43, No. 16, Washington, D.C., American Chemical Society (ACS).
- Lazarova, V. and others (2013), *Milestones in Water Reuse: The Best Success Stories*, London, Knowledge Unlatched/IWA Publishing.

- Leach, M. and others (2021), "Post-pandemic transformations: how and why COVID-19 requires us to rethink development", *World Development*, vol. 138, Amsterdam, Elsevier.
- Leverenz, H., G. Tchobanoglous and T. Asano (2011), "Direct potable reuse: a future imperative", *Journal of Water Reuse and Desalination*, vol. 1, No. 1, London, IWA Publishing.
- Linares, D. (2020), "Aprovechamiento de lodos residuales de una planta de tratamiento de aguas residuales (PTAR) para la generación de energía eléctrica", Bogotá, Santo Tomás University.
- Liu, H., R. Ramnarayanan and B. Logan (2004), "Production of electricity during wastewater treatment using a single chamber microbial fuel cell", *Environmental Science & Technology*, vol. 38, No. 7, Washington, D.C., American Chemical Society (ACS).
- López, J. and others (2017), *Guía técnica para el manejo y aprovechamiento de biogás en plantas de tratamiento de aguas residuales*, Mexico City, Energy Secretariat (SENER) and others.
- McCarty, P., J. Bae and J. Kim (2011), "Domestic wastewater treatment as a net energy producer – can this be achieved?", *Environmental Science & Technology*, vol. 45, No. 17, Washington, D.C., American Chemical Society (ACS).
- Mejía, A., G. Uzcátegui and O. Valverde (2017), *Agua y saneamiento en el Estado Plurinacional de Bolivia*, Buenos Aires, Development Bank of Latin America and the Caribbean (CAF).
- Méndez, J. and J. Marchán (2008), *Diagnóstico situacional de los sistemas de tratamiento de aguas residuales en las EPS del Perú y propuestas de solución*, Lima, National Superintendence of Sanitation Services (SUNASS).
- Mills, J. and O. Cumming (2016), *The Impact of Water, Sanitation and Hygiene on Key Health and Social Outcomes: Review of Evidence*, London, Sanitation and Hygiene Applied Research for Equity/ United Nations Children's Fund (SHARE/UNICEF).
- Mo, W. and Q. Zhang (2013), "Energy–nutrients–water nexus: integrated resource recovery in municipal wastewater treatment plants", *Journal of Environmental Management*, vol. 127, Amsterdam, Elsevier.
- Moglia, M. and others (2021), "Accelerating a green recovery of cities: lessons from a scoping review and a proposal for mission-oriented recovery towards post-pandemic urban resilience", *Developments in the Built Environment*, vol. 7, Amsterdam, Elsevier.
- Montañez, A. (2022), "Conclusions report on investment in circular water treatment and renewable energy systems for Latin America and the Caribbean with the Nexus approach", Bogotá, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).
- Montesinos, R. and V. Martín (2020), "Economía circular y Objetivos de Desarrollo Sostenible", *Distribución y Consumo*, vol. 1, Madrid, Mercasa.
- Moscoso, J. (2016), *Manual de buenas prácticas para el uso seguro y productivo de las aguas residuales domésticas*, Lima, Ministry of Agriculture and Irrigation/National Water Authority (MINAGRI/ANA).
- Mulder, N. and M. Albaladejo (coords.) (2021), "El comercio internacional y la economía circular en América Latina y el Caribe", *International Trade series*, No. 159 (LC/TS.2020/174), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC).
- Nolasco, D. (2010), "Desarrollo de proyectos MDL en plantas de tratamiento de aguas residuales", *Technical Note*, No. 116, Washington, D.C., Inter-American Development Bank (IDB).
- Peña, H. (2016), "Desafíos de la seguridad hídrica en América Latina y el Caribe", *Natural Resources and Infrastructure series*, No. 178 (LC/L.4169/Rev.1), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC).
- Peña-Guerrero, M. and others (2020), "Drought impacts on water quality and potential implications for agricultural production in the Maipo River Basin, Central Chile" *Hydrological Sciences Journal*, vol. 65, No. 6, Milton Park, Taylor & Francis.
- Pistonesi, C., J. Haure and R. D'Elmar (2010), "Energía a partir de las aguas residuales", Buenos Aires, Editorial de la Universidad Tecnológica Nacional (edUTecNe).
- Potting, J. and others (2017), "Circular economy: measuring innovation in the product chain", *Policy Report*, No. 2544, The Hague, Netherlands Environmental Assessment Agency (PBL).
- Quirós, A. (2021), "Introducción a la economía circular y el desarrollo sostenible", Santa Tecla, Central American Commission on Environment and Development (CCAD).
- Rodriguez, D. and others (2020), *From Waste to Resource: Shifting Paradigms for Smarter Wastewater Interventions in Latin America and the Caribbean*, Washington, D.C., World Bank.

- Ruiz, F. (2012), "Gestión de las excretas y aguas residuales en Costa Rica: situación actual y perspectiva", San José, Costa Rican Water Supply and Sanitation Institute.
- Saravia Matus, S. and others (2022), "Brechas, desafíos y oportunidades en materia de agua y género en América Latina y el Caribe", *Natural Resources and Development series*, No. 211 (LC/TS.2022/170), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC).
- \_\_\_\_\_(2020), "Desafíos hídricos en Chile y recomendaciones para el cumplimiento del ODS 6 en América Latina y el Caribe", *Natural Resources and Development series*, No. 198 (LC/TS.2020/134), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC).
- Schady, N. (2015), "Does access to better water and sanitation infrastructure improve child outcomes? Evidence from Latin America and the Caribbean", *IDB Working Paper Series*, No. 603, Washington, D.C., Inter-American Development Bank (IDB).
- Schroeder, P., K. Anggraeni and U. Weber (2019), "The relevance of circular economy practices to the Sustainable Development Goals", *Journal of Industrial Ecology*, vol. 23, No. 1, Hoboken, Wiley.
- Sihvonen, S. and T. Ritola (2015), "Conceptualizing ReX for aggregating end-of-life strategies in product development", *Procedia CIRP*, vol. 29, Amsterdam, Elsevier.
- Silva, I., R. Mambeli and G. Tiago (2016), "Electricity generation from biogas of anaerobic wastewater treatment Plants in Brazil: an assessment of feasibility and potential", *Journal of Cleaner Production*, vol. 126, Amsterdam, Elsevier.
- Srinivas, H. (2021), "Moving towards a circular economy: more than just 3Rs!", Concept Note Series, No. E-097, Kobe, Global Development Research Center (GDRC) [online] <https://www.gdrc.org/uem/waste/more-3r.html>.
- Stillwell, A., D. Hoppock and M. Webber (2010), "Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus", *Sustainability*, vol. 2, No. 4, Basel, Multidisciplinary Digital Publishing Institute (MDPI).
- Superintendency of Residential Public Services (2021), "Sistemas de tratamiento de aguas residuales", Bogotá.
- \_\_\_\_\_(2020), *Estudio sectorial de los servicios públicos de acueducto y alcantarillado 2019*, Bogotá.
- UNEP (United Nations Environment Programme) (2016), *A Snapshot of the World's Water Quality: Towards a Global Assessment*, Nairobi.
- \_\_\_\_\_(2012), *Global Outlook on Sustainable Consumption and Production Policies: Taking Action Together*, Nairobi.
- UNFCCC (United Nations Framework Convention on Climate Change) (2025), "NDC registry", Bonn [online] <https://unfccc.int/NDCREG>.
- United Nations (2021), "Safely treated domestic wastewater" [online] <http://data.un.org/>.
- UPME (Mining and Energy Planning Unit) (2021), "Precios de energía eléctrica, comparación por países", Bogotá.
- USGS (United States Geological Survey) (2021), *Mineral Commodity Summaries 2021*, Reston.
- Van Buren, N. and others (2016), "Towards a circular economy: the role of Dutch logistics industries and governments", *Sustainability*, vol. 8, No. 7, Basel, Multidisciplinary Digital Publishing Institute (MDPI).
- VanVuuren, D., A. Bouwman and A. Beusen (2010), "Phosphorus demand for the 1970–2100 period: a scenario analysis of resource depletion", *Global Environmental Change*, vol. 20, No. 3, Amsterdam, Elsevier.
- Velenturf, A. and P. Purnell (2021), "Principles for a sustainable circular economy", *Sustainable Production and Consumption*, vol. 27, Amsterdam, Elsevier.
- Verstraete, W., P. Van de Caveye and V. Diamantis (2009), "Maximum use of resources present in domestic 'used water'", *Bioresource Technology*, vol. 100, No. 23, Amsterdam, Elsevier.
- Von Sperling, M. (2005), "Princípios do tratamento biológico de águas residuárias", Belo Horizonte, Federal University of Minas Gerais (UFMG).
- Winpenny, J. and others (2010), *The Wealth of Waste: The Economics of Wastewater Use in Agriculture*, Rome, Food and Agriculture Organization of the United Nations (FAO).
- World Bank (2019a), "Wastewater: from waste to resource. The case of New Cairo, Egypt", *Water Global Practice*, Washington, D.C.
- \_\_\_\_\_(2019b) "Wastewater: from waste to resource. The case of Santiago, Chile", *Water Global Practice*, Washington, D.C.
- WWAP (World Water Assessment Programme) (2017), *UN World Water Development Report 2017. Wastewater: The Untapped Resource*, Paris.



## **Annexes**

## Annex A1

### Classification of wastewater treatment technologies

A detailed description is provided below of the most commonly used wastewater treatment technologies in the region.

#### 1. Intensive or compact systems

##### (a) Aerobic treatment technologies

This category includes the technologies that use oxygen in the secondary biological treatment of wastewater. These systems generate primary and secondary (biological) sludge that then needs to be stabilized. The amount of sludge produced depends on the type of technology, and it is therefore helpful to classify them as precisely as possible.

Aerobic treatment systems do not generate greenhouse gases as long as they are scaled and operated correctly. If these plants are overloaded, they will not function completely aerobically and therefore may produce methane emissions (Doorn and others, 2006).

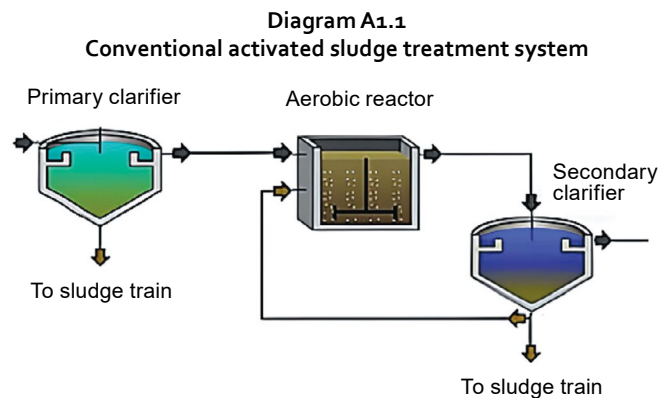
Either aerobic or anaerobic technologies can be used to stabilize the primary and secondary sludge. For the purpose of quantifying the amounts of methane and electrical energy generated by treatment, in this study it has been assumed that anaerobic sludge stabilization processes are being used in all cases.

The most common types of intensive aerobic WWTPs are outlined below. This is not an exhaustive list, and there may be cases that have been omitted, although, if so, they would be similar to the ones that are outlined.

##### (i) Aerobic treatment with suspended biomass

###### Conventional activated sludge (CAS)

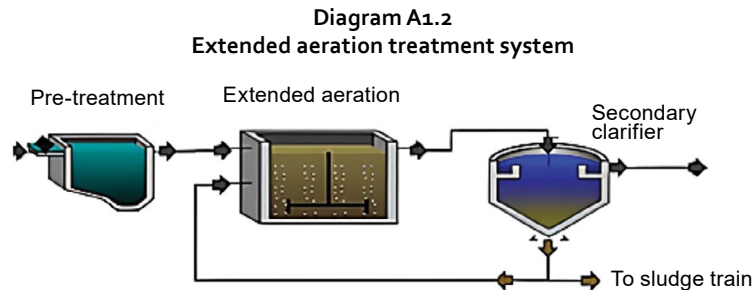
These systems are composed of a primary clarifier, an aerobic reactor and a secondary settling tank, also known as a sedimentation clarifier, with the sludge being partially recirculated. The objective is to oxidize the organic matter in the wastewater, expressed as BOD<sub>5</sub>. This is, therefore, a secondary treatment. In the aerobic reactor, aerobic biomass develops while suspended in the liquid, which is then allowed to settle to obtain the treated wastewater. A portion of the settled sludge is recirculated to the aeration tank (activated sludge). The remaining sludge, which results from the growth of the biomass as it consumes organic matter, is purged from the system and sent to a sludge treatment train for stabilization.



Source: National Water Commission (CONAGUA), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City, 2020.

### Extended aeration (EA)

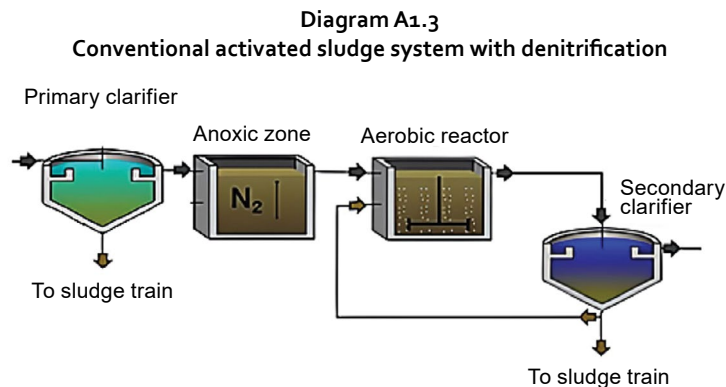
This system is similar to the preceding one but the sludge remains in the system for a longer time and is partially stabilized aerobically in the aerobic reactor. It uses more electricity but generates less sludge than CAS systems.



Source: National Water Commission (CONAGUA), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City, 2020.

### Conventional activated sludge with denitrification (CAS-Dn)

This is similar to the main type of CAS system but incorporates units that eliminate the nitrogen present in the wastewater using a nitrification-denitrification (tertiary treatment) process. The units and internal flows can be configured and arranged in different ways. In some cases the phosphorus is eliminated as well using either biological or physiochemical methods. Given the objective of this study, the systems using these different methods can all be grouped in the same category.



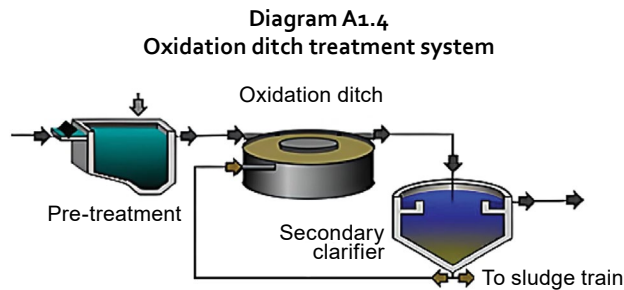
Source: National Water Commission (CONAGUA), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City, 2020.

### Extended aeration with denitrification (EA-Dn)

The same methods as used in CAS-Dn systems are used in extended aeration (EA) systems.

### Oxidation ditch (OD)

This is a variant of EA systems. It is designed in such a way that it generates a larger volume of sludge than the usual type of EA system and therefore belongs in a separate category. It may employ a biological method for eliminating nitrogen (nitrification-denitrification).



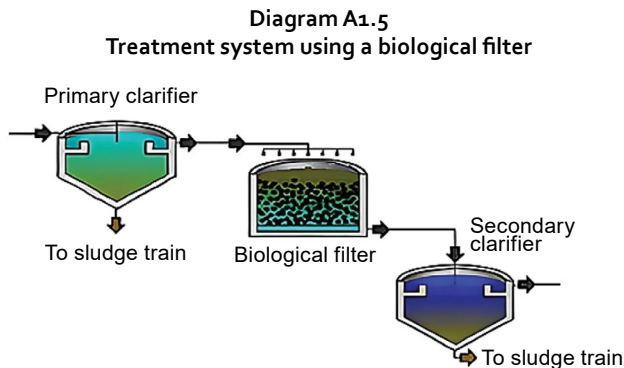
Source: National Water Commission (CONAGUA), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City, 2020.

**(ii) Aerobic treatment systems with fixed biomass**

Unlike the processes outlined above, in these systems aerobic biomass is affixed to some kind of supporting structure as it grows (stone beds or, now, plastic materials).

**Trickling filters/percolating beds/biological filters (TF) and rotating biological contactors or biodiscs (BD)**

With trickling filters (TF), the wastewater pours into a percolating bed made of stone or plastic and is naturally aerated as it flows along the bed. The biomass adheres to these structures and begins to grow. The amount of sludge that this system produces that must then be stabilized is smaller than in CAS systems.



Source: National Water Commission (CONAGUA), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City, 2020.

Biodiscs (BD) are an aerobic treatment system composed of a set of plastic discs that are partially submerged in the effluent. The biomass grows while adhering to the discs. The discs rotate at a slow speed (low revolutions per minute (rpm)) so that the biomass on the discs alternates between being exposed to the air and being submerged in the wastewater.

Biodiscs (BD) can be grouped together with trickling filters (TF). Any other type of fixed-biomass technology can also be placed in the same category.

**(b) Anaerobic treatment technologies**

Some WWTPs use anaerobic (absence of oxygen) technologies for the secondary biological treatment of wastewater. Since they use no air, they consume much less electricity than aerobic WWTPs do. The amount of sludge to be purged is also smaller than the amount produced in aerobic processes (assuming the installed capacity of the two WWTPs is comparable). In addition, this is stabilized sludge that can be fed directly into dewatering or similar systems. The anaerobic processing of wastewater does generate greenhouse gases (methane). The methane can be:

- Released into the atmosphere (an option that is to be avoided)
- Flared off
- Used as a biofuel to generate electricity and thermal energy in combined heat and power (CHP) cogeneration units that use Otto cycle or Stirling engines or biogas-fuelled microturbines.

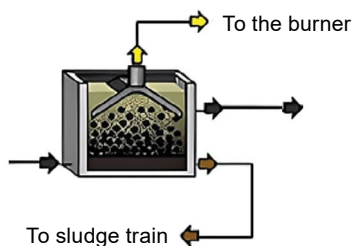
The most common types of intensive anaerobic WWTPs can be grouped into one of two categories.

**(i) Upflow anaerobic sludge blanket (UASB) reactors**

In this system, the wastewater is made to flow upward through a blanket of anaerobic sludge. A three-phase separator located in the upper part of the reactor separates the treated wastewater, the anaerobic sludge (which remains in the reactor) and the biogas, which is extracted.

In many cases, the UASB process needs to be supplemented with an aerobic post-treatment in order to meet regulatory standards for treated wastewater. In those cases, the UASB process may be regarded as a pre-treatment (see the section on dual plants below).

**Diagram A1.6**  
**Upflow anaerobic sludge blanket (UASB) system**



Source: National Water Commission (CONAGUA), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City, 2020.

**(ii) Other types of anaerobic reactors (An R)**

Older WWTPs and those serving very small populations use various types of anaerobic treatment technologies, such as, for example, Imhoff tanks, septic tanks and anaerobic contact reactors. These systems will be grouped together in a separate category.

## 2. Extensive systems (lagoons and other similar systems)

Some WWTP lagoon systems are spread out over very large areas of land. These lagoon technologies can be classified according to the type of biological process that they use. There are anaerobic lagoons, aerated lagoons (with mechanical aerators or air injection systems), aerobic lagoons (this term is usually applied to lagoon systems that do not employ aerators but that have a low enough organic load that they can rely on natural aeration), facultative lagoon systems (utilizing an aerobic process for the upper layer and an anaerobic process for the lower layer) and maturation lagoons (systems using very large, shallow lagoons that use sunlight to eliminate pathogens).

These systems can be classified as follows:

**(a) Anaerobic lagoons (An L)**

As their name indicates, these lagoon systems use anaerobic biological processes to degrade the organic matter in wastewater, which releases methane (a greenhouse gas). These lagoons may be covered with membranes of appropriate materials (HDPE, PVC, EPDM) to capture the gases that the lagoons emit in order to reduce the dispersal of noxious odours and to permit the biogas to be used to generate energy (as in the case of compact anaerobic reactors).

### (b) Facultative lagoons (Fc L) and constructed wetlands (W)

As noted earlier, facultative lagoons have a lower anaerobic layer that releases greenhouse gases (methane). Unlike what happens with fully anaerobic lagoons, these emissions cannot be captured (if the lagoon were covered, it would no longer be a facultative lagoon), but if their greenhouse gas emissions are to be quantified, then they need to be placed in a separate category.

Constructed wetlands are treatment systems that combine microbial biological processes, the growth of emergent macrophytes and physical processes (filtration, precipitation) to recreate the processes that occur in natural wetlands, swamps and floodplains. Wetlands may encompass aerobic, anoxic and anaerobic areas. For the purposes of this study, they will be classified together with facultative lagoons.

### (c) Aerated, aerobic and maturation lagoons (A L, M L)

Although these systems are different in physical terms, they can be placed in the same category because they emit either no or only negligible amounts of greenhouse gases.

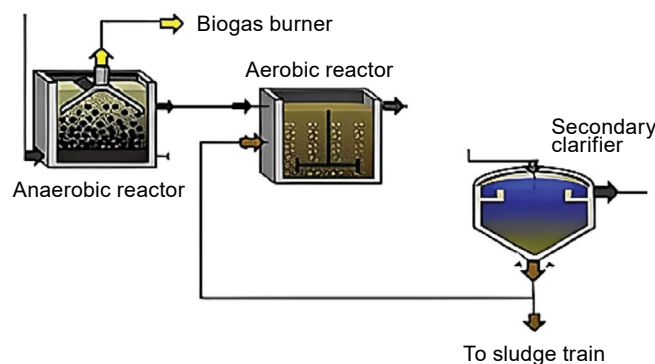
## 3. Dual or combined systems

WWTPs that combine two or more of the types of technologies described above can be classified under this heading. A number of very different lines of reasoning could be employed regarding their classification, but for the purposes of this study, the following categories, which are in use in some countries, appear to be applicable:

### (a) UASB + CAS and An R + CAS

This category includes all of the anaerobic pre-treatments that are followed up with an activated sludge stage.

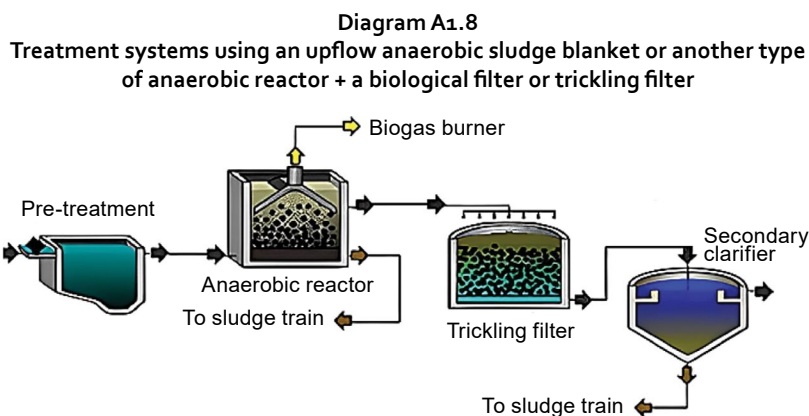
**Diagram A1.7**  
Treatment system using an upflow anaerobic sludge blanketed or another type of anaerobic reactor + activated sludge



Source: National Water Commission (CONAGUA), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City, 2020.

### (b) UASB + TF and An R + TF

All the anaerobic pre-treatments followed by the use of a trickling filter are included here.



Source: National Water Commission (CONAGUA), *Situación del subsector agua potable, alcantarillado y saneamiento: edición 2020*, Mexico City, 2020.

**(c) Anaerobic lagoons + other types of lagoons (An L + L)**

For the purposes of this study, it is appropriate to specifically identify WWTPs that have one or more anaerobic lagoons as part of a series of lagoons, since that configuration provides an opportunity for capturing methane.

**(d) Other combinations of series lagoons (L + L)**

By default, this category is composed of lagoon systems that do not include anaerobic lagoons. These systems do not provide an opportunity for capturing methane even though they release greenhouse gases. In this case, mitigation would involve the substitution of facultative systems, for example.

#### 4. Summary of the proposed classification

Table A1.1 provides an overview of the proposed classification and includes an identifier for each of the technologies outlined in this annex, the name of the technology and the designation of each type of biological system as belonging to one of four different categories: aerobic, anoxic/aerobic (which, for the purposes of this analysis are classed as aerobic technologies), anaerobic and anaerobic/aerobic (dual).

**Table A1.1**  
Overview of the wastewater treatment technologies used in Latin America and the Caribbean

Identifier	Name of the technology	Type of biological system
CAS	Conventional activated sludge	Aerobic
EA	Extended aeration	Aerobic
CAS-Dn	Conventional activated sludge with denitrification	Aerobic/anoxic
EA-Dn	Extended aeration with	Aerobic/anoxic
OD	Oxidation ditch	Aerobic/anoxic
TF	Trickling filter/percolating bed/biological filter	Aerobic/anoxic
BD	Biodiscs	
UASB	Upflow anaerobic sludge blanket reactor	Anaerobic
An R	Other anaerobic reactors/ Imhoff tanks/septic tanks	Anaerobic
An L	Anaerobic lagoons	Anaerobic
Fc L	Facultative lagoons	Aerobic/anaerobic
W	Constructed wetlands	

Identifier	Name of the technology	Type of biological system
A L	Aerated lagoons/aerobic lagoons	Aerobic
M L	Maturation lagoons	
UASB + CAS	Upflow anaerobic sludge blanket reactor and activated sludge	Anaerobic/aerobic
An R + CAS	Other anaerobic reactors and activated sludge	
UASB + TF	Upflow anaerobic sludge blanket reactor and trickling filter	Anaerobic/aerobic
An R + TF	Other anaerobic reactors and trickling filter	
An L + L	Anaerobic lagoon(s) and other lagoons	Anaerobic/aerobic
L + L	Combinations of other non-anaerobic lagoon(s)	Aerobic/anoxic

Source: Prepared by the authors.

## 5. Technological composition of WWTPs listed in the database: summary of the proposed classification

Table A1.2 reflects the constraints created by the shortcomings of the available information sources, as the information reported by nearly 50% of WWTPs is insufficient to permit the classification of their technologies into the categories proposed in the preceding section. It has been possible, nevertheless, to classify some of these plants based on the types of treatment processes they use: 20 are aerobic systems, 172 are anaerobic systems, 3 are dual (anaerobic/aerobic) systems and 134 use other types of treatment processes (such as preliminary or primary processing or involving the use of submarine emissaries).

Aerobic technologies are the most commonly used systems for wastewater treatment in the region according to the data compiled for this study, accounting for 29% of all the systems and for 44% of the installed capacity of the countries whose WWTPs were evaluated.

**Table A1.2**  
Classification of WWTPs listed in the database, by type of technology employed

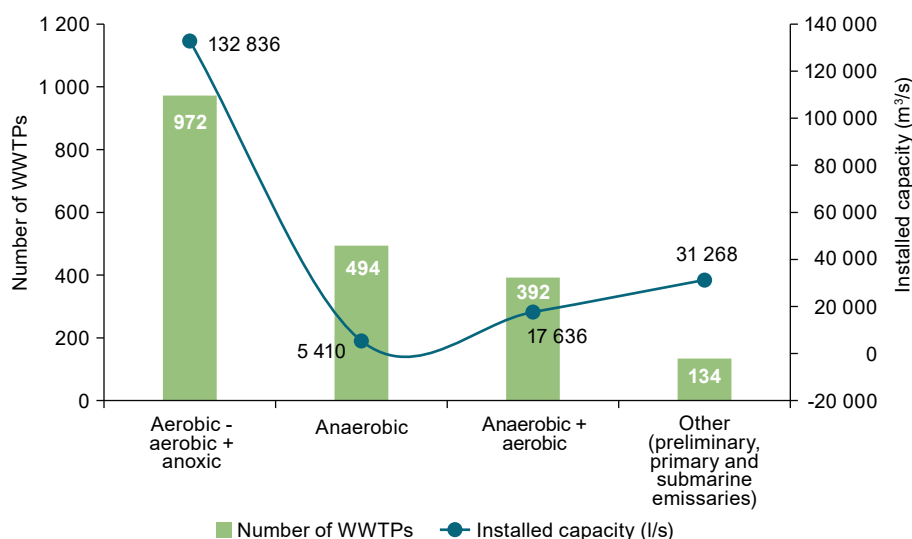
Type of treatment	Technology	Technology ID	Number of WWTPs	Installed capacity (l/s)
Aerobic	Conventional activated sludge	CAS	792	104 832
	Extended aeration	EA	12	919
	Aerated aerobic lagoons	A L	41	13 999
	Maturation lagoons	M L	2	131
	Aerobic (without detailed information)	-	20	655
Anoxic/aerobic	Other combinations of series lagoons	L + L	2	1 572
	Oxidation ditches	OD	22	1 596
	Conventional activated sludge with denitrification	CAS-Dn	7	303
	Extended aeration with denitrification	EA-Dn	2	1 323
	Biodiscs	BD	24	1 255
	Trickling filters/percolating beds/biological filters	TF	48	6 250
Anaerobic	Upflow anaerobic sludge blanket reactor	UASB	161	2 410
	Other anaerobic reactors/Imhoff tanks/septic tanks	Ran	158	702
	Anaerobic lagoons	An L	3	620
	Anaerobic (without detailed information)	-	172	1 678

Type of treatment	Technology	Technology ID	Number of WWTPs	Installed capacity (l/s)
Anaerobic/aerobic	Anaerobic upflow reactors and activated sludge	UASB + CAS	1	12
	Anaerobic upflow reactors and trickling filters	UASB + TF	67	815
	Other anaerobic reactors and trickling filters	An R + TF	177	4 536
	Other anaerobic reactors and activated sludge	An R + CAS	10	53
	Anaerobic lagoons + other type of lagoon systems	An L + L	17	8 531
	Constructed wetlands	W	79	1 375
	Facultative lagoons	Fc L	38	1 659
	Anaerobic/aerobic (without detailed information)	-	3	654
Other	Preliminary	-	27	8 804
	Primary	P	104	19 089
	Submarine emissaries	-	3	3 375
No or incomplete information		-	1 344	111 758
Total			3 336	298 908

Source: Prepared by the authors.

CAS systems are by far the most common type of aerobic treatment used (81% de WWTPs) and account for 79% of these systems' treatment capacity.

**Figure A1.1**  
Distribution of WWTPs providing sufficient information, by type of treatment process employed and treatment capacity



Source: Prepared by the authors, on the basis of Authority for Supervision and Social Control of Drinking Water and Basic Sanitation/ Ministry of Environment and Water (AAPS/MMAYA), *Indicadores de desempeño de las EPSA reguladas categorías A, B, C, D 2019*, La Paz, 2019; Superintendency of Residential Public Services, "Sistemas de tratamiento de aguas residuales", Bogotá, 2021; F. Ruiz, "Gestión de las excretas y aguas residuales en Costa Rica: situación actual y perspectiva", San José, Costa Rican Water Supply and Sanitation Institute, 2012; National Water Commission (CONAGUA), "Catálogo de plantas de tratamiento de aguas residuales en operación de CONAGUA", Mexico City, 2021 [online] <https://datos.gob.mx/busca/dataset/catalogo-de-plantas-de-tratamiento-de-aguas-residuales-en-operacion-de-conagua>; J. Méndez and J. Marchán, *Diagnóstico situacional de los sistemas de tratamiento de aguas residuales en las EPS del Perú y propuestas de solución*, Lima, National Superintendence of Sanitation Services (SUNASS), 2008; Chillón Rímac Lurín Water Observatory, *Análisis geoespacial de canales de riego en relación a las plantas de tratamiento de aguas residuales (PTAR) y áreas verdes en el ámbito de Lima metropolitana*, Lima, 2017.

Most of the anaerobic and dual systems are in use by low-capacity WWTPs, while plants with higher treatment capacities tend not to use these technologies. Consequently, WWTPs using these systems account for only 7.7% of the total treatment capacity of the 3,336 WWTPs in the countries that were evaluated.

Another indication of the degree of fragmentation of these WWTPs is the fact that 44% of their treatment capacity is accounted for by just 16 of the 880 WWTPs that use anaerobic or dual technologies. By the same token, most UASB and other types of anaerobic reactors are being used by plants with limited treatment capacities; in fact, 99.5% of the plants employing these technologies have a treatment capacity of under 500 l/s.

## Annex A2

### The proposed methodology

The methane emissions of WWTPs covered in this study can be estimated by grouping the relevant technologies into three different categories based on the classification outlined in annex A1: WWTPs that use anaerobic wastewater treatment technologies; WWTPs that use aerobic technologies that generate substantial volumes of sludge; and WWTPs whose systems use both anaerobic and aerobic wastewater treatment processes.

#### 1. Estimation of methane emissions from WWTP anaerobic wastewater treatment processes

This section will explain the method used to estimate the volume of methane emissions produced when municipal wastewater is treated anaerobically, whether using anaerobic reactors (UASB or other similar equipment) or anaerobic lagoon systems. This method employs the calculation procedure proposed by Nolasco (2010), which is, in turn, based on the methodology advanced by Doorn and others (2006):

$$MG = (EF * QBOD * BODd) / DM \quad (1)$$

$$EFi = Bo * MCFi \quad (2)$$

Where:

- MG: quantity of methane (CH<sub>4</sub> p.e.) generated (m<sup>3</sup>/year).
- EFi = emission factor according to IPCC (kg of CH<sub>4</sub> generated/kg of degraded BOD).
- QBOD: specific organic load (BOD p.e.) received by the system (kg/year).
- BODd: Fraction of BOD degraded by the system. Denotes how efficient the anaerobic treatment is in removing COD from the wastewater, which varies depending on the type of anaerobic technology used.
- Bo: maximum CH<sub>4</sub> production capacity (kg of CH<sub>4</sub> generated/kg of degraded BOD).
- MCFi: methane correction factor according to IPCC. This is an indication of the extent or degree to which each system is anaerobic. This varies depending on the treatment system being employed. For example, in fully enclosed anaerobic reactors, its value is 1. In the case of fully aerobic systems, its value is zero. For overloaded aerobic systems or lagoons that are not completely aerobic, it reaches values in the range of from 0.1 to 0.3 (Doorn and others, 2006).
- DM: density of methane under normal temperatures and pressure (kg/m<sup>3</sup>).
- When methane is captured, whether in order to flare it off or to make use of its energy content, a fraction of the biogas is lost in the course of its capture, routing and reuse. The usable amount of methane captured will therefore be:

$$GU = MG(1 - L) \quad (3)$$

Where:

- GU: amount of methane (CH<sub>4</sub>) that is usable (m<sup>3</sup>).
- MG: amount of methane (CH<sub>4</sub>) generated (m<sup>3</sup>).
- L: fraction of the biogas lost during its capture, routing and reuse (i.e. methane not captured).

The difference between the methane generated and the methane captured equals the amount of methane emitted into the atmosphere in the relevant scenario.

## 2. Estimation of methane emissions from the anaerobic digestion of aerobic sludge

Unlike anaerobic WWTPs, systems that use aerobic processes generate little or no methane (as long as they are properly run); however, these WWTPs do produce a large volume of aerobic sludge during the degradation of organic matter, and that sludge has to be stabilized before its final disposition (whether it is utilized as a soil amendment or for another purpose).

Aerobic sludge can be stabilized by means of either aerobic or anaerobic digestion. The former uses large amounts of energy per unit of volume (is more energy-inefficient) and its operating costs are therefore higher. A potentially attractive alternative is therefore anaerobic sludge stabilization using digesters that emit biogas that can then be captured and used to power various processes conducted in WWTP.

The methane generated during the stabilization of aerobic sludge in an anaerobic biodigester can be calculated as follows:

$$MG = (EF_j * S * DOC * DOC_f) / DM \quad (4)$$

$$EF_j = B_o * MCF_j \quad (5)$$

$$S = ss * QBOD \quad (6)$$

Where:

- MG: quantity of methane (CH<sub>4</sub> p.e.) generated (m<sup>3</sup>/year)
- S: quantity of sludge generated (TS p.e.) during aerobic treatment (dry weight) (kg/year). This will depend on the type of aerobic treatment technology used.
- Ss: organic matter to sludge conversion factor (kg TS/kg BOD).
- QBOD: specific organic load (BOD p.e.) received by the system (kg/year).
- DOC: proportion of organic matter contained in the sludge that is generated (dry weight) (kg VS/kg TS). Generally assumed to be 0.5.
- DOC<sub>f</sub>: Fraction of the DOC converted into biogas during the anaerobic digestion process. Typically its value is 0.5.
- E<sub>fj</sub> = Emission factor according to IPCC (kg of CH<sub>4</sub> generated/kg of degraded DBO).
- B<sub>o</sub>: maximum CH<sub>4</sub> production capacity (kg of CH<sub>4</sub> generated/kg of degraded BOD).
- MCF<sub>j</sub>: correction factor according to IPCC for anaerobic sludge digestion systems.
- DM: density of methane under normal temperature and pressure (kg/m<sup>3</sup>).

If the biogas is captured and its energy content is utilized, then equation 3 should also be applied here.

## 3. Estimation of methane emissions from anaerobic/aerobic wastewater treatment in a WWTP

In some WWTPs, wastewater is first treated anaerobically and then aerobically. In these systems, the aerobic sludge from the second stage can be anaerobically stabilized in a sludge biodigester. In this case, there are two different sources of methane, and the equation for calculating MG is a combination of equations (1) and (4).

$$MG = [(EF_i * QBOD * BOD_d) + (EF_j * S * DOC * DOC_f)] / DM \quad (7)$$

$$S = ss * QBOD_r \quad (8)$$

Where:

- MG: quantity of methane (CH<sub>4</sub> p.e.) generated (m<sup>3</sup>/year).
- Efi: emission factor of the anaerobic wastewater reactor according to IPCC (kg of CH<sub>4</sub> generated/kg of degraded BOD). In this case, equation 2 is applicable.
- QBOD: specific organic load (BOD p.e.) received by the system's anaerobic reactor (kg/year), which is used during the first stage of wastewater treatment.
- BODd: Fraction of BOD degraded by the system. Denotes how efficient the anaerobic treatment is in removing COD from the wastewater, which varies depending on the type of anaerobic technology used.
- S: quantity of sludge generated (total solids (TS) p.e.) during the aerobic wastewater treatment process (dry weight) (kg/year). This depends on the type of aerobic treatment technology being used. This quantity is generated by the remaining BOD in the wastewater after it has been treated anaerobically.
- Ss: organic matter to sludge conversion factor (kg TS/kg BOD).
- QBODr: remaining organic load (BOD p.e.) received by the system in the aerobic stage, following aerobic treatment (kg/year).
- DOC: proportion of organic matter contained in the aerobic sludge that has been generated (dry weight) (kg VS/kg TS). Generally assumed to be 0.5.
- DOCf: Fraction of the DOC converted into biogas during the anaerobic digestion process. Typically, its value is 0.5.
- E<sub>fj</sub> = emission factor of the anaerobic sludge digester (kg of CH<sub>4</sub> generated/kg of degraded BOD). In this case, equation 5 is applicable.

#### 4. Estimation of potential energy content of methane and of generable electricity

The analysis of these wastewater plants' methane generation potential indicates that they could generate energy that could then take the place of external energy sources for powering treatment processes that they conduct and, in some cases, could even generate surplus energy.

Once the volume of methane generated per year and the volume of usable methane (equation 3) have been determined, it is then possible to estimate the energy content of that methane, the amount of generable electricity (kWh/year) and the recoverable thermal energy associated with the generation of electricity (cogeneration) (kWh/year) based on the following equations:

$$ECM = GU * PIV \quad (9)$$

$$GE_e = ECM * ESG_e \quad (10)$$

$$GE_t = ECM * ESG_t \quad (11)$$

Where:

- ECM: energy content of the methane captured (kWh/year).
- GU: quantity (m<sup>3</sup>) of usable methane (CH<sub>4</sub>).
- PIV: calorific value of the methane. Typically: 9.97 kWh/year.
- GE<sub>e</sub>: generable electrical energy (kWh/year).
- GE<sub>t</sub>: generable thermal energy (kWh/year).
- ESG<sub>e</sub>: efficiency of the system used to generate electrical energy. Average efficiency of electricity generation is assumed to be 35%.<sup>29</sup>
- ESG<sub>t</sub>: efficiency of the system for recovering thermal energy. Average efficiency of thermal energy recovery (cooling of the engine and exhaust) is assumed to be 40%.<sup>30</sup>

<sup>29</sup> May range from 20% to 45% depending on the technology used and the size of the engine generator.

<sup>30</sup> May range from 30% to 50% depending on the technology used and the size of the engine generator.

## Annex A3

### Investments to be undertaken in each type of system

Based on the technologies reported to be in use by the 75 WWTPs covered by this analysis and the estimation methodology proposed in annex A2, the relevant investments that would need to be made in the compact aerobic WWTPs, in lagoon systems and in anaerobic or dual WWTPs are outlined below.

#### 1. Anaerobic digestion of the sludge generated in WWTPs that employ (compact) aerobic and advanced primary treatment processes: use of biogas to generate energy

In plants that treat wastewater aerobically, a series of investments can be made to introduce anaerobic sludge digestion processes that will generate methane. These investments involve the construction of a sludge thickener, a sludge conveyor system and a sludge digester (see table A3.1, columns 1–3). This equipment would represent between 80% and 89% of the total investment required in this kind of system in order to harness methane for use in generating energy.

**Table A3.1**  
Investments required to harness generable methane in WWTPs using (compact) aerobic and advanced primary wastewater treatment processes

Baseline scenario	Post-investment scenario	1	2	3	4	5
Conventional activated sludge	Original technology + anaerobic sludge digestion and utilization of methane	Aerobic sludge thickener	Sludge pumping equipment (pipes, sludge pump)	Sludge digester	Biogas pipeline + centrifugal blower	Flare
Oxidation ditches						
Extended aeration						
Extended aeration with denitrification						
Trickling filters/percolating beds/biological filters						
Advanced primary treatment						
Baseline scenario	Post-investment scenario	6	7	8	9	10
Conventional activated sludge	Original technology + anaerobic sludge digestion and utilization of methane	Biogas metre	Biogas purification system (mist eliminator, desulfurizer, dehumidifier)	Biogas engine generator (CHP)	Electrical substation, grid interconnection point	Hot water recovery circuit (for example, for heating the sludge digester or sludge dewatering unit)
Oxidation ditches						
Extended aeration						
Extended aeration with denitrification						
Trickling filters/percolating beds/biological filters						
Advanced primary treatment						

Source: Prepared by the authors.

The electricity generation and routing systems (columns 5–8) represent between 11% and 20% of the total cost of the investments required for aerobic systems.

Finally, the investments listed in columns 9 and 10 are not included in these estimates and would therefore have to be looked at separately at a later stage.<sup>31</sup> The calculation of the investments in infrastructure works (the sludge thickener and anaerobic sludge digester) is based on the information provided in *Estimating Sludge Management Costs* (EPA, 1985).

Table A3.2 shows the estimated cost of the investments required by the (compact) aerobic WWTPs based on the technologies they use and scale of operations. It should be noted that the required investments for (compact) aerobic technologies are the costliest in p.e. terms (US\$ 8.29).

**Table A3.2**  
**Estimated cost of investments required to harness generable methane in WWTPs that use (compact) aerobic wastewater treatment technologies**  
*(Dollars at 2021 prices)*

Baseline scenario		Installed capacity	Total WWTPs	Investment per system	Total investment
Conventional activated sludge	CAS	From 500 to 1 000 l/s	24	2 665 000	63 960 000
		From 1 000 to 1 500 l/s	11	4 489 800	49 387 800
		From 1 500 to 2 000 l/s	4	6 450 300	25 801 200
		From 2 000 to 2 500 l/s	2	6 752 500	13 505 000
		From 2 500 to 3 000 l/s	3	8 875 900	26 627 700
		From 3 000 to 3 500 l/s	1	9 109 600	9 109 600
Oxidation ditches	OD	From 500 to 1 000 l/s	1	2 420 500	2 420 500
Extended aeration	EA	From 500 to 1 000 l/s	2	2 369 700	4 739 400
		From 1 000 to 1 500 l/s	1	2 728 700	2 728 700
		From 2 000 to 2 500 l/s	1	4 794 400	4 794 400
		From 2 500 to 3 000 l/s	1	4 940 100	4 940 100
Extended aeration with denitrification	EA-Dn	From 1 000 to 1 500 l/s	1	2 627 300	2 627 300
Trickling filters/percolating beds/biological filters	TF	From 500 to 1 000 l/s	3	2 350 500	7 051 500
		From 1 500 to 2 000 l/s	1	4 521 000	4 521 000
		From 3 500 to 4 000 l/s	1	8 868 800	8 868 800
<b>Total</b>			<b>57</b>		<b>231 083 000</b>

Source: Prepared by the authors.

## 2. Adaptation of anaerobic lagoons and conversion of aerobic lagoons into anaerobic lagoons to permit biogas to be harnessed for generating energy

As discussed earlier, lagoon systems (both existing anaerobic lagoon systems that do not yet generate energy from their methane emissions and aerobic lagoons that could be converted into anaerobic ones) offer a great deal of potential for the implementation of circular economy schemes for methane emission, capture and utilization.

For these lagoon systems, the investments listed in columns 1–3 of table A3.3 are substantially different from the investments required for the technologies dealt with above because methane is directly generated by the wastewater treatment process and there is thus no need to invest in sludge digestion equipment.

<sup>31</sup> The investments listed in column 9 correspond to the specific situation that would arise if more electricity is generated than is needed by the WWTP in question, in which case the excess energy could be supplied to the relevant electricity utilities. The investment listed in column 10 concerns the recovery of the thermal energy associated with the generation of electricity using the methane captured in the plant (cogeneration), which could be used to heat the sludge digester, for drying the sludge or for other purposes.

Assuming optimum operations and the absence of any infiltration problems in anaerobic lagoon systems, the required investment would consist of covering the lagoons with materials that would permit methane capture, such as high-density polyethylene (HDPE) covers, together with the investments detailed in the preceding section concerning the biogas routing, storage and cleaning system (see table A3.3, columns 4–7) and the installation of electricity and thermal energy cogeneration systems (see table A3.3, columns 8–10).<sup>32</sup>

**Table A3.3**  
Investments required to harness generable methane in WWTP lagoon systems

Baseline scenario	Post-investment scenario	1	2	3	4	5
Aerated aerobic lagoons	Combination of anaerobic lagoons + methane recovery and utilization	Note: It is assumed that aerobic or other types of lagoons can be modified for conversion into anaerobic lagoons capable of capturing biogas. <sup>a</sup>	Infrastructure works to deepen existing lagoon ponds	HDPE cover on new anaerobic lagoons	Biogas pipeline + centrifugal blower	Flare
Other combinations of series lagoons						
Anaerobic lagoons						
Anaerobic lagoons + other types of lagoons		Note: It is assumed that the existing lagoons do not suffer from problems of infiltration. <sup>b</sup>				
Baseline scenario	Post-investment scenario	6	7	8	9	10
Aerated aerobic lagoons	Combination of aerobic lagoons + recovery and utilization of methane	Biogas metre	Biogas purification system (mist eliminator, desulfurizer, dehumidifier)	Biogas engine generator (CHP)	Electrical substation, grid interconnection point	Hot water recovery circuit (for example, for heating the sludge digester or sludge dewatering unit)
Other combinations of series lagoons						
Anaerobic lagoons						
Anaerobic lagoons + other types of lagoons						

Source: Prepared by the authors.

<sup>a</sup> For major works, impermeable bottom and surface covers are recommended.

<sup>b</sup> If that is not the case, a new lagoon may have to be built.

With aerobic lagoons, an additional investment may be called for in order to deepen them. Otherwise, the cost of covering the lagoon (biogas capture system) and of biogas routing, storage and utilization are similar to the cost of the required investments for anaerobic lagoons (see table A3.4).

<sup>32</sup> The investment in a biogas metre (column 6) could be unnecessary if an inflated cover is used. These kinds of cover may be damaged by wind and by the accumulation of rainwater when they are disinflated, however. Floating covers are generally preferred because they are designed to allow rainwater to drain off. They do require an external biogas accumulator, however.

**Table A3.4**  
**Estimated cost of the investment required to harness generable methane in WWTP lagoon systems**  
*(Dollars at 2021 prices)*

Baseline scenario		Installed capacity	Total number of WWTPs	Investment per system	Total investment
Aerated aerobic lagoons	A L	From 500 to 1 000 l/s	4	1 360 620	5 442 480
Other combinations of series lagoons	L + L	From 500 to 1 000 l/s	1	1 360 620	1 360 620
Anaerobic lagoons	An L	From 500 to 1 000 l/s	1	1 020 420	1 020 420
Anaerobic lagoons + other types of lagoons	An L + L	From 500 to 1 000 l/s	10	1 020 420	10 204 200
Total			16		18 027 720

Source: Prepared by the authors.

The huge advantages of converting aerobic lagoon systems into anaerobic ones are that the required investment is much smaller and the methane generation factor—once the investment has been made—is considerably higher than it is for compact aerobic systems.

As an example of the difference this makes, the investment needed to make use of biogas in a CAS system would cost a WWTP with a capacity of between approximately 500 l/s and 1,000 l/s approximately US\$ 2.7 million, and the output would come to 3.1 m<sup>3</sup> of methane per person served. By contrast, the required investment to convert an aerobic lagoon system with the same capacity into an anaerobic lagoon system capable of making use of methane emissions would cost approximately US\$ 1.4 million and would generate some 6.6 m<sup>3</sup> p.e. of methane.

Lagoon systems with treatment capacities of over 1,000 l/s cover such large areas that investing in the necessary infrastructure to capture generable biogas is not feasible for these systems. Their conversion has therefore not been taken into consideration in this study. Constructed wetlands have not been included either because it would not be feasible to try to harness their methane emissions.

### 3. Harnessing biogas and generating energy in WWTPs using anaerobic or (compact) dual systems

The investments required in WWTPs that treat wastewater anaerobically represent a quite different case than the ones considered above because the only investments that are called for are in the routing, storage and purification and the energy cogeneration systems (see table A3.5).

**Table A3.5**  
**Investments required to harness generable methane in WWTPs that use anaerobic and (compact) anaerobic/aerobic wastewater treatment systems**

Baseline scenario	Post-investment scenario	1	2	3	4
Upflow anaerobic sludge blanket reactor	Original technology + utilization of methane	It is assumed that the UASB reactor is already in place	Biogas pipeline + centrifugal blower	Flare	Biogas metre
Upflow anaerobic sludge blanket reactor and activated sludge		It is assumed that the UASB reactor is already in place and is receiving the aerobic sludge from the CAS system			

Baseline scenario	Post-investment scenario	5	6	7	8
Upflow anaerobic sludge blanket reactor	Original technology + utilization of methane	Biogas purification system (mist eliminator, desulfurizer, dehumidifier)	Biogas engine generator (CHP)	Electrical substation, grid interconnection point	Circuit for utilizing heated water (to heat sludge digester or to dry out the sludge, for example)
Upflow anaerobic sludge blanket reactor and activated sludge					

Source: Prepared by the authors.

In this case, no investment in the system for methane capture is required, since the anaerobic reactor captures the biogas emissions from the degradation of organic matter. Consequently for dual systems, the sludge produced during the aerobic wastewater treatment stage can be fed into the anaerobic reactor. No additional investment in the sludge thickener or digester is therefore needed.

Nevertheless, as noted earlier, large-capacity anaerobic technologies are not commonly used to treat wastewater in the region. In fact, of all WWTPs evaluated for this study, only two of the ones with treatment capacities of over 500 l/s used UASB technologies (see table A3.6).

**Table A3.6**  
**Estimated cost of the investments required to harness generable methane in WWTPs**  
**using anaerobic and anaerobic/(compact) aerobic technologies**  
*(Dollars at 2021 prices)*

Baseline scenario		Installed capacity	Total number of WWTPs	Total investment
Upflow anaerobic sludge blanket reactor and conventional activated sludge	UASB + CAS	From 500 to 1 000 l/s	1	1 000 300
Upflow anaerobic sludge blanket reactor	UASB	From 1 000 to 1 500 l/s	1	1 030 200
Total			2	2 030 500

Source: Prepared by the authors.

**Table A3.7**  
**Investments required in WWTPs that use compact anaerobic technologies**  
*(Dollars at 2021 prices)*

Baseline scenario	Post-investment scenario	Installed capacity	Aerobic sludge thickener	Sludge pumping equipment (pipes, sludge pump)	Sludge digester	Centrifugal blower	Biogas pipes <sup>9</sup>	Flare	Biogas metre	Desulfurizer	Biogas purification system (mist eliminator, dehumidifier)	Biogas engine generator	Total Investment	
Conventional activated sludge	CAS	Conventional activated sludge+ anaerobic sludge digestion, harnessing methane for energy generation	From 500 to 1 000 l/s	330 800	16 500	1 773 600	2 200	17 700	31 300	75 100	19 700	49 300	348 800	2 665 000
			From 1 000 to 1 500 l/s	452 000	22 600	3 424 400	3 300	34 200	36 700	85 900	31 200	50 700	348 800	4 489 800
			From 1 500 to 2 000 l/s	555 300	27 800	5 136 600	6 700	51 400	44 100	89 800	31 200	57 400	450 000	6 450 300
			From 2 000 to 2 500 l/s	647 600	32 400	5 330 100	6 700	53 300	46 700	97 100	31 200	57 400	450 000	6 752 500
			From 2 500 to 3 000 l/s	732 200	36 600	7 106 800	8 300	71 100	52 400	105 700	31 200	66 600	665 000	8 875 900
			From 3 000 to 3 500 l/s	810 900	40 500	7 228 000	10 300	72 300	62 600	106 700	31 200	82 100	665 000	9 109 600
Oxidation ditches	OD	Oxidation ditches+ anaerobic sludge digestion, harnessing methane for energy generation	From 500 to 1 000 l/s	295 900	14 800	1 737 200	1 600	17 400	28 400	68 100	17 400	41 700	198 000	2 420 500
Extended aeration	EA	Extended aeration+ anaerobic sludge digestion, harnessing methane for energy generation	From 500 to 1 000 l/s	258 100	12 900	1 661 400	2 200	16 600	31 300	70 600	17 400	41 700	257 500	2 369 700
			From 1 000 to 1 500 l/s	352 800	17 600	1 807 000	2 800	18 100	31 300	81 300	19 700	49 300	348 800	2 728 700
			From 2 000 to 2 500 l/s	505 400	25 300	3 553 400	3 300	35 500	44 100	87 300	39 400	50 700	450 000	4 794 400
			From 2 500 to 3 000 l/s	571 400	28 600	3 614 000	6 700	36 100	44 100	92 400	39 400	57 400	450 000	4 940 100

Baseline scenario	Post-project scenario	Installed capacity	Aerobic sludge thickener	Sludge pumping equipment (pipes, sludge pump)	Sludge digester	Centrifugal blower	Biogas pipes <sup>a</sup>	Flare	Biogas metre	Desulfurizer	Biogas purification system (mist eliminator, dehumidifier)	Biogas engine generator	Total Investment	
Extended aeration with denitrification	EA-Dn	Extended aeration with denitrification+ anaerobic sludge digestion, harnessing methane for energy generation	From 1 000 to 1 500 l/s	352 800	17 600	1 807 000	2 200	18 100	31 300	71 800	19 700	49 300	257 500	2 627 300
Trickling filters/ percolating beds/ biological filters	TF	Trickling filters/ percolating beds/ biological filters+ anaerobic sludge digestion, harnessing methane for energy generation	From 500 to 1 000 l/s	271 100	13 600	1 693 700	1 600	16 900	28 400	68 100	17 400	41 700	198 000	2 350 500
			From 1 500 to 2 000 l/s	455 100	22 800	3 469 800	2 800	34 700	36 700	81 300	19 700	49 300	348 800	4 521 000
			From 3 500 to 4 000 l/s	725 400	36 300	7 106 800	8 300	71 100	52 400	105 700	31 200	66 600	665 000	8 868 800

Source: Prepared by the authors.

<sup>a</sup> A maximum run of 50 metres is assumed.

**Table A3.8**  
**Investments required in WWTPs that use anaerobic technologies**  
*(Dollars at 2021 prices)*

Baseline scenario		Post-investment scenario	Installed capacity	Infrastructure works to deepen existing lagoons	HDPE cover on anaerobic lagoons	Centrifugal blower	Biogas pipes <sup>a</sup>	Flare	Biogas metre	Desulfurizer	Biogas purification system (mist eliminator, dehumidifier)	Biogas engine generator	Total investment
Aerated aerobic lagoons	A L	Anaerobic lagoons + recovery and utilization of methane	From 500 to 1 000 l/s	340 200	447 120	2 800	34 700	36 700	81 300	19 700	49 300	348 800	1 360 620
Other combinations of series lagoons	L + L	Combination of anaerobic series lagoons + recovery and utilization of methane	From 500 to 1 000 l/s	340 200	447 120	2 800	34 700	36 700	81 300	19 700	49 300	348 800	1 360 620
Anaerobic lagoons	An L	Anaerobic lagoons + recovery and utilization of methane	From 500 to 1 000 l/s	Not applicable	447 120	2 800	34 700	36 700	81 300	19 700	49 300	348 800	1 020 420
Anaerobic lagoons + other types of lagoons	An L + L	Anaerobic lagoons + other types of lagoons + recovery and utilization of methane	From 500 to 1 000 l/s	Not applicable	447 120	2 800	34 700	36 700	81 300	19 700	49 300	348 800	1 020 420
Upflow anaerobic sludge blanket reactor and conventional activated sludge	UASB + CAS	Upflow anaerobic sludge blanket reactor + utilization of methane	From 500 to 1 000 l/s	Not applicable	Not applicable	8 300	71 100	52 400	105 700	31 200	66 600	665 000	1 000 300
Upflow anaerobic sludge blanket	UASB	Upflow anaerobic sludge blanket reactor + utilization of methane	From 1 000 to 1 500 l/s	Not applicable	Not applicable	10 300	72 300	62 600	106 700	31 200	82 100	665 000	1 030 200

Source: Prepared by the authors.

<sup>a</sup> A maximum run of 50 metres is assumed.



UNITED NATIONS

Series

ECLAC

Natural Resources and Development

## Issues published

A complete list as well as pdf files are available at  
[www.cepal.org/en/publications](http://www.cepal.org/en/publications)

- 213. The circular economy opportunities for wastewater treatment systems in Latin America and the Caribbean, Silvia Saravia Matus, Marina Gil Sevilla, Diego Fernández, Alfredo Montañez, Elisa Blanco, Lisbeth Naranjo, Alba Llavona and Natalia Sarmanto (LC/TS.2022/193), 2025.
- 212. La institucionalidad y la regulación minera en los países andinos: Bolivia (Estado Plurinacional de), Chile, Colombia, Ecuador y Perú, Rafael Poveda Bonilla (LC/TS.2022/190), 2022.
- 211. Brechas, desafíos y oportunidades de agua y género en América Latina y el Caribe, Silvia Saravia Matus, Marina Gil Sevilla, Natalia Sarmanto, Elisa Blanco, Alba Llavona y Lisbeth Naranjo (LC/TS. 2022/170), 2022.
- 210. Soluciones basadas en la naturaleza y la bioeconomía: contribución a una transformación sostenible e inclusiva de la agricultura y a la recuperación pos-COVID-19, Laura Meza y Adrián Rodríguez (LC/TS. 2022/43), 2022.
- 209. Hacia una planificación sostenible para una transición energética justa en América Latina y el Caribe: análisis de mejores prácticas en países seleccionados, Antonio Levy, Diego Messina y Rubén Contreras Lisperguer (LC/TS.2021/130), 2021.
- 208. Contribución de la bioeconomía a la recuperación pospandemia de COVID-19 en el Uruguay: biotecnología y valorización de subproductos agropecuarios y agroindustriales, Magdalena Borges, Atilio Deana, Lucía Pittaluga, Carolina Balian y Adrián Rodríguez (LC/TS.2021/112), 2021.
- 207. Desarrollo de indicadores de pobreza energética en América Latina y el Caribe, Rubén Calvo, Nicolás Álamos, Marco Billi, Anahí Urquiza y Rubén Contreras Lisperguer (LC/TS.2021/104), 2021.
- 206. Oportunidades de la bioeconomía para la recuperación pospandemia de COVID-19: un análisis basado en las recomendaciones de la Misión Internacional de Sabios Colombia 2019, Rafael H. Aramendis y Adrián G. Rodríguez (LC/TS.2021/103), 2021.
- 205. Políticas regulatorias y tarifarias en el sector de agua potable y saneamiento en América Latina y el Caribe, Diego Fernández, Silvia Saravia Matus y Marina Gil (LC/TS. 2021/81), 2021.
- 204. Análisis comparativo de acciones con enfoque del Nexo Agua-Energía-Alimentación: lecciones aprendidas para los países de América Latina y el Caribe, Bárbara A. Willaarts, Elisa Blanco, Alba Llavona y Diego Martínez (LC/TS.2021/18), 2021.

## NATURAL RESOURCES AND DEVELOPMENT

### Issues published:

- 213 The circular economy opportunities for wastewater treatment systems in Latin America and the Caribbean

*Silvia Saravia Matus, Marina Gil Sevilla, Diego Fernández, Alfredo Montañez, Elisa Blanco, Lisbeth Naranjo, Alba Llavona and Natalia Sarmanto*

- 212 La institucionalidad y la regulación minera en los países andinos

Bolivia (Estado Plurinacional de), Chile, Colombia, Ecuador y Perú

*Rafael Poveda Bonilla*

- 211 Brechas, desafíos y oportunidades de agua y género en América Latina y el Caribe

*Silvia Saravia Matus, Marina Gil Sevilla, Natalia Sarmanto, Elisa Blanco, Alba Llavona y Lisbeth Naranjo*



Economic Commission for Latin America and the Caribbean (ECLAC)  
Comisión Económica para América Latina y el Caribe (CEPAL)  
[www.cepal.org/en](http://www.cepal.org/en)



LC/TS.2022/193