From Waste to Resource

Shifting paradigms for smarter wastewater interventions in Latin America and the Caribbean

Background Paper I:

Efficient and Effective Management of Water Resource Recovery Facilities

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1818 H Street NW, Washington, DC 20433

Telephone: 202-473-1000; Internet: www.worldbank.org

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Background Paper I: Efficient and Effective Management of Water Resource Recovery Facilities

The World Bank is working with partners around the world to ensure that wastewater's inherent value is recognized. Energy, clean water, fertilizers, and nutrients can be extracted from wastewater and can contribute to the achievement of the Sustainable Development Goals. Wastewater can be treated up to different qualities to satisfy demand from different sectors, including industry and agriculture. It can be processed in ways that support the environment, and can even be reused as drinking water. Wastewater treatment for reuse is one solution to the world's water scarcity problem, freeing scarce freshwater resources for other uses, or for preservation. In addition, by-products of wastewater treatment can become valuable for agriculture and energy generation, making wastewater treatment plants more environmentally and financially sustainable. Therefore, improved wastewater management offers a double value proposition if, in addition to the environmental and health benefits of wastewater treatment, financial returns can cover operation and maintenance costs partially or fully. Resource recovery from wastewater facilities in the form of energy, reusable water, biosolids, and other resources, such as nutrients, represent an economic and financial benefit that contributes to the sustainability of water supply and sanitation systems and the water utilities operating them. One of the key advantages of adopting circular economy principles in the processing of wastewater is that resource recovery and reuse could transform sanitation from a costly service to one that is self-sustaining and adds value to the economy.

This background paper is part of the supporting material for the report "From Waste to Resource: Shifting Paradigms for Smarter Wastewater Interventions in Latin America and the Caribbean", a product of the "[Wastewater: from waste to resource](#)", an Initiative of the World Bank Water Global Practice.

There is extensive literature on the effective management of wastewater treatment plants (WWTPs) (WEF 2016). This paper seeks neither to replace nor to summarize the existing literature but rather to outline a list of aspects to consider when managing water resource recovery facilities (WRRFs),[1] from cradle to grave. In addition, examples of best practices are presented.

Clear policies, adequate intersectoral legislation, efficient regulation, and continuous training of human resources are required as a first step toward resource recovery. Assuming these aspects have been adequately covered, the following considerations will contribute to an effective management of WRRFs. This list is not exhaustive and is mostly geared toward avoiding common obstacles and challenges usually found in Latin America and the Caribbean (LAC).[2]

Effective management of WRRFs starts with adequate planning and design. Adequate process selection and design offer the most "bang for the buck." When treatment facilities are well planned, with resource recovery and sustainability in mind, the road to efficient management is paved. With this concept in mind, planners would do well to take several initial steps:

- Identify and forecast key wastewater influent characteristics.
- Set reasonable targets for effluent quality, based on the characteristics of the receiving water body and on water quality objectives.

1 WRRFs is the term currently used by the Water Environment Federation to refer to WWTPs that aim at recovering resources in some fashion.

2 The same may apply to low- and middle-income countries in other regions of the world.

When possible, plan for the gradual application of such targets.

- Select an adequate treatment process, using data from wastewater characterization and projections and effluent quality objectives, and considering resource recovery goals plus capital expenditure (CAPEX) and operating expenditure (OPEX) through a life-cycle analysis.
- Design a realistically sized process.
- Plan for reduce energy consumption (i.e., generating "negawatts") and set potential energy cogeneration strategies.
- Evaluate, optimize, and determine the actual treatment capacity of existing infrastructure, so as to maximize the use of it – existing infrastructure is also a resource!

Identifying the characteristics of wastewater influents

Every municipality is unique, resulting in different wastewater characteristics (e.g., flow rate, concentration of contaminants, temperature, seasonal variations). Most of these characteristics tend to differ considerably from city to city. In spite of these differences, it is very common to see treatment plant designs based on textbook influent parameters. Examples include the use of flow rate per capita values (e.g., 350 liters per capita per day) or biochemical oxygen demand loadings (e.g., 60 grams of a five-day biochemical oxygen demand [BOD5] per capita per day) in lieu of adequate wastewater characterization using sampling techniques and laboratory analysis. In Latin America and the Caribbean, textbook parameters are generally used with current population growth projections without considering the possibility that some neighborhoods may not be served by secondary collection systems (sewers). Even if all neighborhoods were served, not all households may be connected to the sewer lines running along their streets. In most cases, these textbook approaches result in wastewater flow rate projections and contaminant loadings that far exceed reality, thereby unnecessarily increasing the size of treatment facilities. The textbook approach, though quick and easy, generally results in treatment processes that are not adequately selected or sized, with CAPEX and OPEX values higher than necessary and resulting financial and environmental burdens.

In some cases, the textbook approach is used for lack of knowledge and understanding of the dynamics of municipal sewage systems. In other cases, the application of standard values is done to save time and costs in the initial stages of planning and design. Nothing could be more counterproductive. The total costs of adequate engineering and planning are minuscule (less than 0.10 percent) in comparison with the life-cycle costs (CAPEX and OPEX) of future facilities. Therefore, savings in the initial stages generate problems during the life of a utility, representing one of the main challenges to the sustainability of these facilities (particularly in Latin American and the Caribbean, but arguably in other parts of the world as well).

For greenfield projects (i.e., new treatment facilities), influent characterization must be planned in advance. This activity will involve the use of, for example (i) sampling techniques (which may require automatic samplers); (ii) multiple points of sampling (if the main sewer line to the future WWTP is nonexistent); (iii) experienced personnel to operate samplers and carry samples to the laboratories with appropriate techniques and a well-documented chain of custody documents; and (iv) certified laboratories. Depending on the importance of the future facility, the sampling work may last from a few days or weeks to a few months. In many cases, the goal is to not only determine the concentration of various contaminants but also to record flow rates.

When recording influent wastewater flow rates is not possible during the initial sampling process, flow rates must be projected based on realistic population growth rates, service areas (i.e., those areas covered with secondary sewer lines), connectivity to sewers, and future expansion work planned in sewer networks in the plant's area of influence. Simply multiplying future population projections by consumption per capita tends to yield unrealistically high flow projections. Unfortunately, this last approach is quite common, resulting in plants being larger than necessary. Remember: a larger-than-necessary facility is a waste of resources, i.e., exactly the opposite of what circular economy for sustainability stands for. When expanding existing facilities (brownfield projects), adequate records of influent wastewater characteristics should be available from the existing facility. If so, these records must be audited for accuracy and complemented, when needed, with additional sampling and monitoring efforts. Sampling and monitoring should take place at the existing plant, immediately downstream of preliminary treatment. These efforts can last one to four weeks, depending on the importance of the project. The existence of predetermined sampling points makes the process simpler than in the case of greenfield projects, which in most cases require multiple sampling points. If the plant to be expanded or retrofitted is medium to large (100 liters per second and above), effluent characterization can be used to calibrate a dynamic model of the plant for design purposes. Other aspects to consider when assessing future influent wastewater characteristics include (i) future industries operating in the area of service, and (ii) water consumption reduction measures (e.g., tariff structure changes, introduction of water saving devices, expansion of micrometering coverage).

Setting reasonable targets for effluent quality

Water quality objectives can be defined based on the receiving water body characteristics and desired uses (e.g., recreational, irrigation, etc.). Using river water quality modeling techniques, reasonable targets for effluent quality can be set and used to plan WRRFs. The gradual implementation of such targets in phases (when applicable) will likely enhance the sustainability of the treatment system by allowing planners to adjust targets based on knowledge they gather over time on influent wastewater characteristics and the effect of final effluent on the receiving water quality (river modeling calibration). In addition, the gradual application of effluent requirements will permit extending the coverage of treatment, as opposed to having high levels of treatment in a few plants, leaving larger areas without treatment.

There are no international effluent quality standards. The reason is that effluent standards must consider multiple factors influenced by local conditions, such as:

- The existing state of the receiving water body
- Desired uses and related quality requirements of the receiving water body
- State of wastewater treatment in the area (e.g., coverage)
- Financial implications of treatment levels (CAPEX and OPEX) and funding available (including existing tariff structures and willingness to pay)
- Climate conditions (e.g., ambient temperatures, seasonal precipitation patterns)
- Other physical conditions (e.g., altitude)

When possible, total maximum daily limits (TMDLs) for effluent should be defined and applied to facilities as part of the cleanup plan for the receiving water body. As opposed to blanket effluent concentrations (expressed in milligrams per liter, mg/L), TMDLs allocate maximum loadings of contaminants, expressed in a mass of a specific contaminant per day (e.g., 4 tons of total nitrogen per day), to each discharging facility. This approach is much more sensible since, with the exception of certain compounds that could be toxic to fish at high concentrations (e.g., ammonia), the contamination/cleanup of a receiving water body depends on the mass of contaminants discharged (e.g., tons nitrogen per day), and not their concentration (milligrams nitrogen per day). Copying standards from other countries (e.g., EU directives for effluent quality, EPA 503c[3] for biosolids management, etc.) may seem easy and cost-effective, but to ignore the specificities of the local context has negative environmental and financial implications.

Extremely stringent effluent quality standards imposed on areas with low levels of treatment coverage prevent, in many cases, the utility from reaching adequate treatment coverage. In this case, the cost of building a new plant or upgrading an existing plant may exceed existing funding. In these situations, the expansion, upgrade, and creation of greenfield WRRF projects elsewhere in the catchment are postponed since all funding goes to one or two plants, resulting in lower coverage, with detrimental implication for population health, receiving water body quality, and environmental conditions.

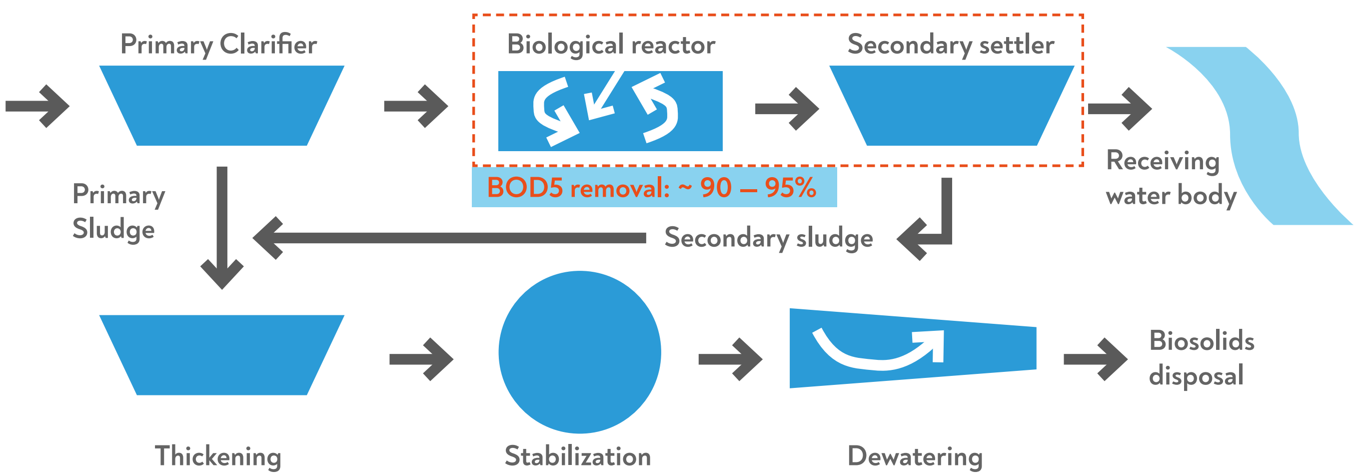
When developing effluent quality requirements based on concentrations of contaminants, it is of upmost importance to determine the period over which the requirements must be applied. For example, meeting 25 mg/L of BOD5 on a *monthly average of daily samples is reasonably achievable with secondary treatment. On the other hand, a requirement not to exceed 25 mg/L of* BOD_5 *on any daily sample is very stringent, given the natural variability in influent quality and operational modes. Such a daily limit is approximately equivalent to imposing a limit of 10 mg/L of* BOD_5 *based on* a *monthly average of daily samples*, which will require tertiary treatment (e.g., sand filtration), increasing in many cases the CAPEX and OPEX of the facility unnecessarily. Both numerical values of the limit may be the same (25 mg/L of BOD5), but the one applied as a threshold not be exceeded is much more stringent and expensive to attain.

Selecting an adequate treatment process

Appropriate treatment processes are key to recovering resources in a sustainable fashion. Selecting such processes depends on realistic wastewater characterization and projections and reasonable effluent quality objectives. In addition, the CAPEX and OPEX of treatment processes vary widely and must be considered.

In Latin America and the Caribbean, there is a strong tendency to prefer activated sludge systems to other type of treatment processes (World Bank 2016). Even though activated sludge is a well-proven technology that results in over 90 percent BOD removal (figures 1 and 2), the OPEX of this type of technology cannot always be supported by tariffs.

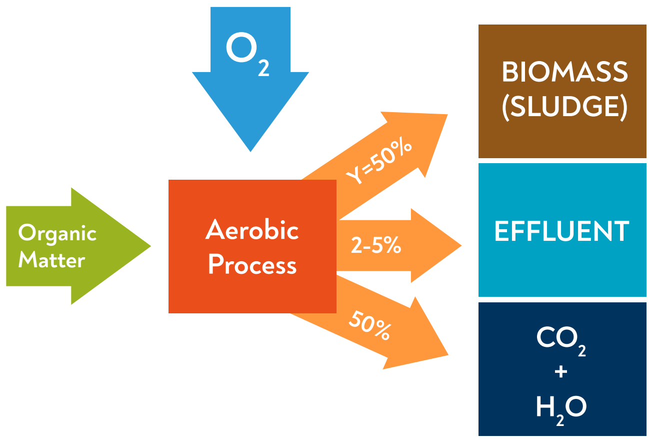
Figure 1 Treatment plant with activated sludge system



Source: Adapted from Pacheco Jordao (2013).
Note: BOD_5 = five-day biochemical oxygen demand.

3 U.S. Environmental Protection Agency's Part 503 Biosolids Rule.

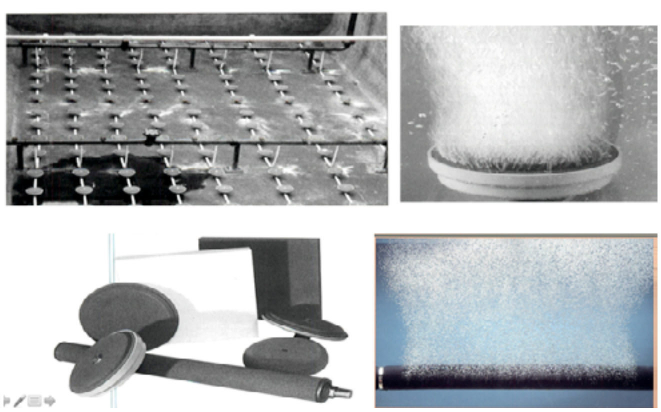
Figure 2 Removing organic matter in aerobic biological systems



Source: Adapted from Pacheco Jordao (2013).
Note: CO_2 = carbon dioxide; H_2O = water; O_2 = oxygen.

Activated sludge processes have aerobic reactors, which require air supplied by mechanical surface aerators or by submerged diffusers supplied by air blowers (see figure 3).

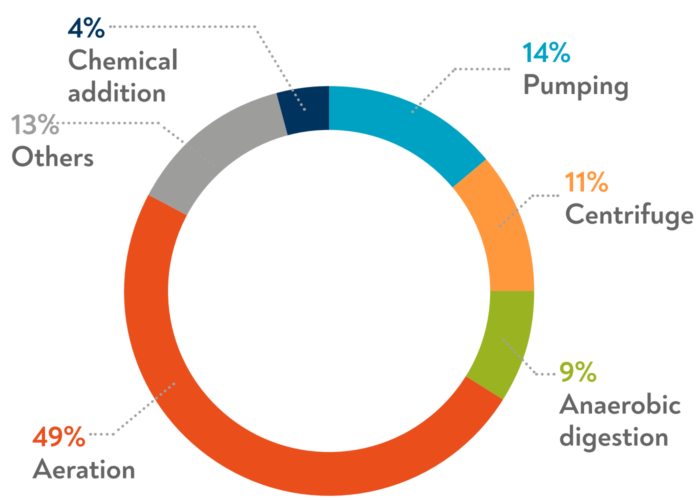
Figure 3 Ceramic and membrane fine pore diffusers



Source: Pacheco Jordao 2013.

Aeration represents the most significant use of energy in an activated sludge plant (WEF 2009; Reardon 1995; Rosso and Stenstrom 2005). If the activated sludge is "conventional" (i.e., primary clarification, followed by relatively small aeration tanks operating with short solids retention times, with anaerobic digestion of primary and secondary sludge), the energy consumption for aeration may vary from 45 to 65 percent (see figure 4). However, in extended aeration activated sludge systems (no primary clarifiers, longer retention times in the aerobic reactors, aerobic digesters), the energy devoted to aeration is on average 75 percent of a plant's total energy consumption (WEF 2010). This share increases if the plant operates at high altitude. For example, at 3,500 meters above sea level, a plant will consume approximately twice as much air (and energy to pump it) than the same plant operating at sea level. This is especially relevant for the Latin American and Caribbean region, since several cities are located at altitudes higher than 2,000 meters above sea level.

Figure 4 Energy consumption in a conventional activated sludge plant

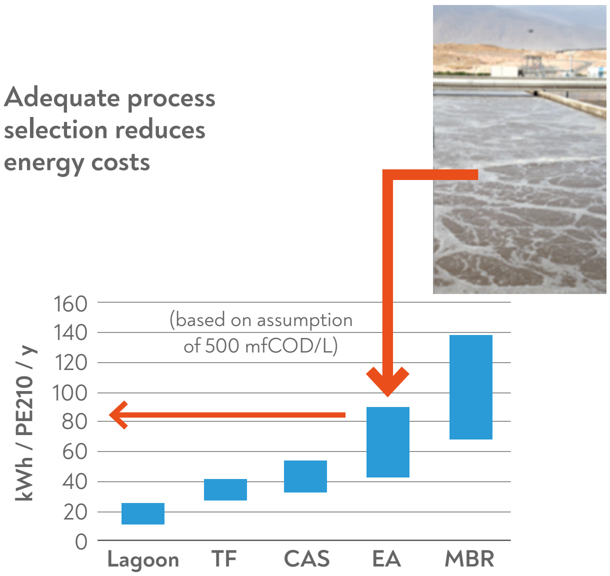


Aeration is the largest contribution to treatment processs energy (Reardon, 1995; Rosso and Stenstrom, 2005; MOP32, 2009)	Energy is the major operational component in the present value calculation of treatment costs (Reardon, 1995; Rosso et al., 2005; WEF, 2009)	Extended aeration (i.e., long SRT) is much worse: Aeration energy ~75%

Source: Adapted from WEF (2010), adopted drom MOP32, 2009.
Note: Process involves primary clarifiers and anaerobic digesters.

Selecting an adequate process while considering energy consumption is paramount in the design of sustainable WRRFs. Figure 5 shows the electricity consumed by different processes.

Figure 5 Electricity consumed (per population equivalent) by various treatment processes

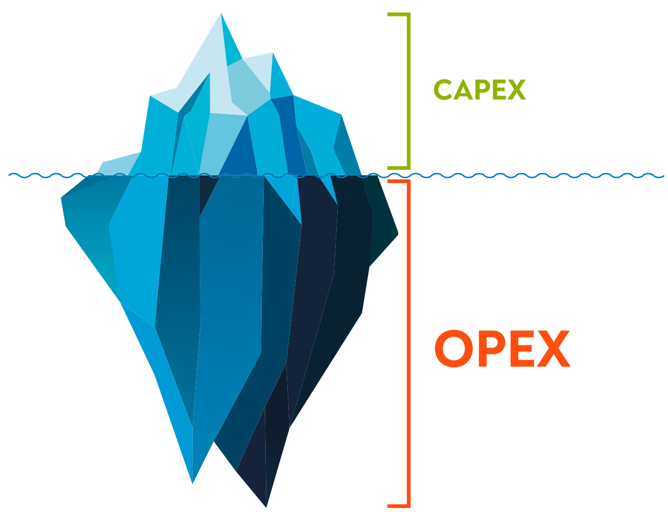


Source: Graph: WEF 2010; photograph: Nolasco 2017; overall figure: Nolasco 2019.
Note: CAS = conventional activated sludge; EA = extended aeration activated sludge; kWh = kilowatt-hour; MBR = membrane bioreactor; mg COD/L = milligrams of chemical oxygen demand per liter; PE120 = population equivalent discharging 120 grams of COD per day, i.e., per person discharging to the plant; TF = trickling filter.

In figure 4, a photo of an extended aeration activated sludge plant is shown. This plant is located in Peru, at 2,400 meters above sea level. This altitude increases the energy consumption from 75 kilowatt-hours/PE120[4]/year (shown in figure 4 and calculated at sea level) to more than 120 kilowatt-hours/PE120/year (i.e., three times the energy needed by a conventional activated sludge process, CAS, at sea level). Processes with such high electricity consumption are hard to sustain at normal tariff rates and should be avoided (at least for medium-sized and large plants) in areas located at 2,000 meters above sea level or higher. Other processes that produce a similar effluent quality but consume considerably less electricity are available and should be evaluated as options during the planning stage of these projects. Unfortunately, retrofitting extended aeration activated sludge plants, such as the one in figure 4, to other less energy consuming processes is expensive and not always easy to do once a plant is already operational.

The impact of OPEX on the sustainability of WWTPs must be considered when selecting the optimal treatment process. In general, for activated sludge systems (commonly used in Latin America and the Caribbean), the influence of CAPEX and OPEX can be graphically represented as an iceberg (figure 6), in which CAPEX is the tip of the iceberg, and OPEX extends along the life of the investment (brought to net present value), representing the bottom of the iceberg.

Figure 6 Capital and operating costs of activated sludge systems



Source: Adapted from Brischke (2017).
Note: The figure represents relative net present values along the life cycle of capital costs (CAPEX) and operation and maintenance costs (OPEX) for a conventional activated sludge system.

Realistic sizing of unit processes

Traditional WWTP design guidelines developed in the 1970s and based on experience from the 1960s are still cited in current literature (Metcalf

4 Population equivalent discharging 120 grams of COD per day, i.e., per person discharging to the plant.

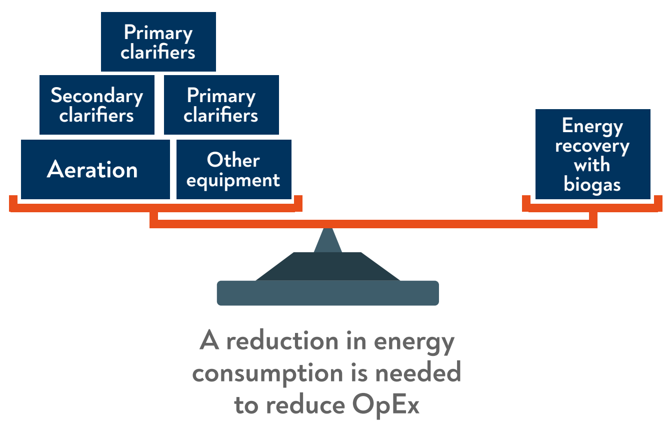
& Eddy Inc. et al. 2013; WEF 2016; WEF, ASCE, and EWRI 2018).[5] These guidelines are steady-state (i.e., assume all influent parameters and operational conditions to be constant, which is far from reality) and very conservative, resulting in the volumes of reactors being considerably larger than necessary. These guidelines are of little to no use when designing systems for biological nutrient removal or when trying to predict effluent quality. For these reasons, the use of steady-state design guidelines has been discontinued in most middle- and upper-middle-income countries. In countries with adequate wastewater treatment practice, process specialists use dynamic simulators with complex and realistic mathematical models for sizing reactors and other unit process treatment systems. The use of such simulators makes a design considerably more realistic, resulting in smaller and more efficient plants that can save and even produce energy.

Unfortunately, the use of steady-state design guidelines from the 1970s is still common in Latin America and the Caribbean. We could argue that these systems are still used for the sake of simplicity, and for the apparent savings in time and cost at the initial stages of planning (steady-state design guidelines can be easily implemented in an Excel spreadsheet, requiring little mathematical skill and data on influent data characteristics). However, such savings at the initial stages of planning and design result in the gross oversizing of utilities, which impacts the sustainability of systems and the capacity of WWTPs to become WRRFs.

Reducing energy consumption and setting energy cogeneration strategies

The first step toward achieving the sustainability of existing treatment plants (tied with the circular economy) is to reduce the consumption of electricity (i.e., to produce "negawatts"[6]). Illustrated in figure 7, a reduction of the relative weight of the energy consumed by a plant (the left side of the balance) is needed to permit the reasonable coverage of this consumption with the energy to be generated from biogas (the right side of the balance). A reduction in consumption can be planned at the design stages, when processes are selected and sized, or in existing facilities by implementing energy saving measures.

Figure 7 Energy balance in an activated sludge system



Source: Rosso et al. 2018.
Note: OPEX = operating expenditure.

5 In 1969, the Cuyanoga River (Cleveland, Ohio) caught fire and burned for several days due to the quantity of pollutants floating on its surface. Arguably, this event, combined with the polluted state of numerous water bodies in the United States, triggered the development and approval of the USA Federal Water Pollution Control Act (Clean Water Act 1972). Almost concurrently, in 1970, the Canada Water Act was approved. These laws started an unprecedented investment in the infrastructure of wastewater treatment facilities to control water pollution. To get financial support from the federal government for these new facilities, design guidelines were needed (at the time, municipal and state officials did not have the information available today on what constituted a well-designed WWTP). This led to the development of a series of guidelines, based mainly on the experience gained in the 1950s and 1960s. One of the most well-known guidelines is the "Recommended Standards for Wastewater Facilities," prepared by the Great Lakes–Upper Mississippi River Board of State and Provincial Health and Environmental Managers, generally referred to as the "10-States Design Guidelines," since it is undersigned by 10 American states and the Province of Ontario, Canada. These guidelines were based on experience from the 1950s and 1960s, when the knowledge of the biology involved in wastewater treatment was limited by the availability of instrumentation, adequate laboratory equipment, advances in biochemistry and genetics, etc. Therefore, the guidelines used for design were quite basic and meant to be on the "safe side" (i.e., conservative), which in turn resulted in oversized tanks, reactors, and treatment processes in general.

6 Taken from a conversation between Nolasco and José Luis Inglese, president of Aguas y Saneamientos Argentinos (AySA), a "negawatt" is a fictitious unit of power not spent, thanks to the adequate design of future facilities or by the savings realized in existing facilities.

In existing activated sludge plants, the aeration systems offer the most opportunity for energy savings, since they consume somewhere in the range of 50 to 75 percent of the total energy used by the facility. Potentially effective energy saving measures in these types of plants include the following (Baquero-Rodriguez et al. 2018; Rosso and Stenstrom 2005):

- Implementing automatic dissolved oxygen control systems, which prevent unnecessary over-aeration of the biomass in the reactors
- Cleaning fine pore diffusers
- Replacing broken/old fine pore diffusers
- Replacing inefficient air blowers
- Dosage of coagulants in primary clarifiers: to remove part of the organic loading going to the aeration tanks (which demands aeration) and redirect it to the anaerobic digesters, where it can generate more biogas, which in turn can be used to cogenerate energy
- Introducing unaerated zones in the front part of the aeration tanks of activated sludge plants that nitrify, so as to reduce oxygen demand by denitrification (i.e., the reduction of nitrate to nitrogen gas), while improving aeration efficiency by reducing fouling of diffusers and increasing the alpha factor – key to improve oxygen transfer efficiency)
- Reducing nitrogen loading to aeration basins by the nitrification and denitrification of recycle streams from the sludge treatment train (e.g., Sharon-Annamox processes)

The complexity and cost of application of these energy-saving strategies vary between plants, but in most cases, the first three measures are quite cost-effective energy management strategies.

The second step is to try to implement cogeneration of energy from biogas (the right-hand side of the balance shown in figure 6).[7]

Not all plants can generate biogas. Only those with anaerobic processes of adequate size and design can attain biogas generation and capture sufficient volume and quality to be used for energy cogeneration.

Obviously, those plants that treat wastewater in anaerobic systems (e.g., upflow anaerobic sludge blankets, covered anaerobic lagoons, etc.) are likely to have much less energy demand on the left-hand side of the balance and more potential for cogeneration with biogas on the right-hand side. Therefore, they have more potential to become energy-neutral plants (i.e., not requiring external sources of electricity to operate) or energy-positive plants (i.e., being able to produce surplus to sell to the network or for transport and use elsewhere).[8]

Plants with anaerobic digestion of sludge can also cogenerate energy. If these are activated sludge plants, in most cases, the energy produced will be able to cover the heat demand of the digester and about one-third of the electricity demanded by the plant (and thus the plants will not be energy neutral).[9] A quick rule-of-thumb applicable to most conventional activated sludge plants is that the energy cogenerated from biogas can be converted into heat (about one-third) and electricity (about one-third), and the remaining one-third will be lost in heat with the exhaust gases. Depending on the cost of electricity and equipment for cogeneration, systems for cogeneration with biogas may start becoming viable at 500 megawatts of installed generating capacity.

Tools to analyze the feasibility of converting wastewater to energy have been prepared by the World Bank and constitute a good starting point when deciding whether such a system is viable (World Bank 2015). Additional information can be extracted from the relevant literature (EPA 2011; EPA and WERF 2010; WEF 2010).

7 Cogeneration indicates generation of both heat and electricity.

8 See the case of SAGUAPAC in Santa Cruz de la Sierra, Bolivia.

9 There is a growing number of activated sludge plants in the European Union and North America that are becoming energy neutral. However, the investment in technology and infrastructure and the technological sophistication of such systems are considerable.

Evaluation, optimization, and adequate use of existing infrastructure

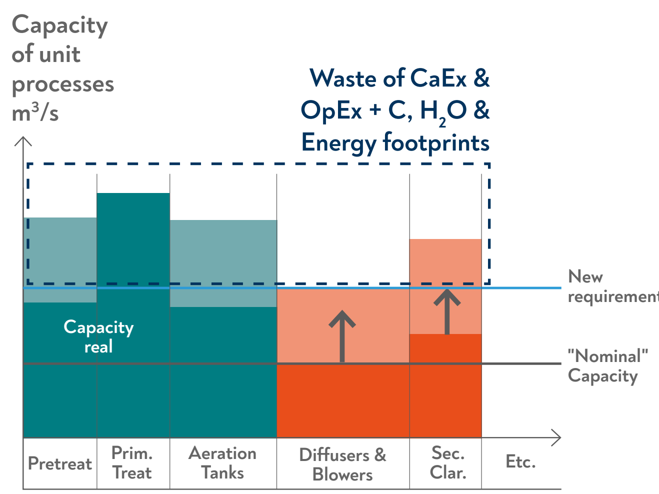
Any infrastructure already in place (i.e., existing WWTPs) constitutes a valuable resource whose actual treatment capacity may be evaluated early in the planning process. Specifically, what is the maximum flow rate the facility can treat while meeting effluent criteria? This step of the planning process is often overlooked or the existing capacity is miscalculated, leading to unnecessary expansions—and thus a waste of valuable resources and an increase in CAPEX, OPEX, and the system's carbon footprint, inter alia.

During the 1990s in the United States and Canada, plants built during the 1970s were starting to reach maturity and there was a need to expand their capacity or impose more stringent effluent limits. Instead of presuming that their "nominal" (design) treatment capacity was correct, Environment Canada and the U.S. Environmental Protection Agency decided to evaluate the actual capacity of these facilities using field testing. This led to the development of protocols and methodologies for plant evaluation (also referred to as process audits) (Environment Canada 2006).

The application of these capacity evaluation tools demonstrated that existing plants, designed using traditional guidelines, have considerable excess capacity in several of their unit treatment processes. Thereby, to expand the capacity of these plants to meet future higher flows, only those processes that present a bottleneck to meeting new demand need to be expanded, while the rest can be left untouched. This realization has led to considerable savings in CAPEX and OPEX.[10] The success of several applications of these methodologies led Environment Canada to impose their use in expansions that required federal funding.

Figure 7 shows the nominal (design) capacity of a typical plant, combined with the real capacity of several of its unit processes. In many cases (pretreatment, primary treatment, and aeration tank volume), the real capacity exceeds the nominal and meets or exceeds the new requirements, thereby not calling for any expansion. Other unit processes, while meeting the nominal capacity, do not have enough capacity to meet the new requirements. In the generic example of figure 7, these processes involve the diffusers and blowers (i.e., the aeration capacity) and the secondary clarifiers. These two units are the actual bottlenecks to meet the new requirements.

Figure 7 The circular economy approach: Wise use of existing infrastructure as a resource



Source: Nolasco 2014.
Note: C = carbon; CAPEX = capital expenditure; H_2O = water; m^3/s = cubic meters per second; OPEX = operating expenditure.

Field tests performed as part of a plant audit approach, combined with modern design methods (e.g., dynamic simulation), maximize the life of existing infrastructure, thereby enhancing the sustainability of overall systems. The evaluation techniques involved are not necessarily complex or expensive. In a recent project carried out by AySA, the water and wastewater utility in Buenos Aires, Argentina, the application of some of these process audit techniques resulted in savings of CAPEX valued at about $150 million.

10 In 1994, the Metro Toronto Ashbridges Bay Treatment Plant, using the Environment Canada process audit methodology, cancelled a plant expansion estimated at $200 million (approximately $400 million at current value).

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