

Article

# Energy Issues in Sustainable Urban Wastewater Management: Use, Demand Reduction and Recovery in the Urban Water Cycle

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**Abstract:** Urban water systems and, in particular, wastewater treatment facilities are among the major energy consumers at municipal level worldwide. Estimates indicate that on average these facilities alone may require about 1% to 3% of the total electric energy output of a country, representing a significant fraction of municipal energy bills. Specific power consumption of state-of-the-art facilities should range between 20 and 45 kWh per population-equivalent served, per year, even though older plants may have even higher demands. This figure does not include wastewater conveyance (pumping) and residues post-processing. On the other hand, wastewater and its byproducts contain energy in different forms: chemical, thermal and potential. Until very recently, the only form of energy recovery from most facilities consisted of anaerobic post-digestion of process residuals (waste sludge), by which chemical energy methane is obtained as biogas, in amounts generally sufficient to cover about half of plant requirements. Implementation of new technologies may allow more efficient strategies of energy savings and recovery from sewage treatment. Besides wastewater valorization by exploitation of its chemical and thermal energy contents, closure of the wastewater cycle by recovery of the energy content of process residuals could allow significant additional energy recovery and increased greenhouse emissions abatement.

**Keywords:** water–energy nexus; urban used water cycle; wastewater treatment plant; waste sludge; energy demand; energy recovery; GHGs reduction

## 1. Introduction

The water–energy nexus has been long neglected but became recently a high-priority issue from which better understanding and development of new paradigms of water cycle sustainability may arise [1,2]. After decades of unchanging practices, in fact, new strategic and technological approaches to urban water cycle management are being proposed [3]. Urban water systems and, in particular, wastewater treatment plants (WWTPs) are one of the major energy consumers at the municipal level worldwide. It has been estimated that on the average these facilities alone may require about 1% to 3% of the total electrical energy output of a country [4] and that over 20% of public utilities' electrical energy consumption by municipalities is required for their operation [5,6]. Furthermore, energy use by utilities is expected to grow significantly in the next decade in some areas. In Australia, for example, due to an expected population growth of 25% by 2030, and to the need to access new, more energy-intensive water sources mostly by reuse of treated wastewater, energy use by water utilities for enhanced effluent processing is estimated to grow between 130% and 200% above existing levels to fulfil a steady per-capita consumption [7].

According to current technology levels, specific power consumption of state-of-the-art WWTPs should range between 20 and 45 kWh per PE (population equivalent) per year, even though some older plants may double these energy demands [8]. Other data indicate power consumption of between 0.3–2.1 kWh/m<sup>3</sup> of treated wastewater in the EU, and between 0.41 to 0.87 kWh/m<sup>3</sup>, in the U.S., depending on type of treatment, plant size and topography, etc. [9]. Some assessments may include energy for pumping wastewater to the plant, while others do not, hence the wide range of reported values. According to the North Rhine Westphalia (Germany) Ministry of Environment's energy WWTP manual, the optimal target for overall electricity consumption at treatment plants is determined as 20 kWh/PE-year, with guide value at 26 kWh/PE-year [10]. Generally, the smaller the facility, the higher its specific power consumption. Power consumption depends not only on plant size but also on design and technology. The previous values pertain to modern facilities, which include nutrient (N and P) removal and anaerobic sludge digestion. Lack of nutrient removal processes implies lower energy requirements, lack of anaerobic digestion, on the other hand, will increase consumption (e.g., for aerobic sludge stabilization). The cited values do not include the upstream water supply cycle, wastewater conveyance (mostly energy for pumping) and residues post-processing and disposal (chemical and biological sludges). Consequently, these facilities may not only be considered as highly energy demanding, with high operational cost, but also significant sources of greenhouse gas (GHG) emissions, whose reduction has been recently mandated by European Union and other countries' policies.

On the other hand, wastewater contains energy in different forms: chemical, thermal and kinetic. The chemical energy contained in wastewater has been estimated by different studies as ranging from approximately 10 to 14 kJ/g COD (1.67–2.33 kWh/m<sup>3</sup> even assuming a diluted COD concentration of 600 mg/L), while thermal energy could yield about 21 MJ/m<sup>3</sup> (5.8 kWh/m<sup>3</sup>) for a drop of 5 °C in wastewater temperature, and potential energy would yield just 30 kJ/m<sup>3</sup> (0.008 kWh/m<sup>3</sup>) over a 10 m drop [11–13]. The first two numbers clearly illustrate the energy-saving potential of innovative wastewater management, highlighting the fact that the energy stored in wastewater is about six to nine times higher than the electric energy needed for treatment. Assuming this energy could be practically exploited, WWTPs could be transformed into energy-neutral or even in net energy producers [14,15].

Until very recently, the almost unique form of energy recovery from these facilities consisted of the anaerobic post-digestion of process residuals (waste activated sludge, WAS) by which chemical energy in the form of biogas (mostly methane) is obtained. This is still one of the main energy recovery options applied, generally sufficient to cover about half of total plants requirements, but with low (30% to 60%) conversion efficiency of the organically embedded chemical energy into a readily usable source [16]. However, implementation of new process technologies is nowadays making possible more efficient strategies of energy recovery from sewage [17]. Besides wastewater valorization by exploitation of its chemical and thermal energy contents, closure of the wastewater cycle by taking advantage of the energy contents of process residuals could provide significant additional energy recovery and increased GHGs abatement.

Wastewater and its residual products can therefore be considered renewable energy sources if addressed by proper technological solutions.

This paper summarizes the main items of energy consumption in the wastewater treatment cycle and discusses the most promising state-of-the-art technologies currently available for energy recovery from both wastewater and its residual byproducts.

## 2. Wastewater Embedded Energy

According to current paradigms, wastewater is still typically viewed as an energy-demanding problem requiring expensive solutions, rather than a resource. Despite the fact that most countries spend substantial amounts of energy treating sewage to release it as harmlessly as possible into receiving waters, wastewater represents a mostly-untapped, potentially huge source of energy, including intrinsic energy embedded within wastewater organics; thermal energy (5.8 kWh/m<sup>3</sup> per 5 °C) recoverable

through heat extraction, e.g., by a heat pump; and an external fossil-fuel energy equivalent required for the production of the same amounts of fertilizing elements N and P contained in wastewater (19.3 kWh/kg N and 2.11 kWh/kg P) [18].

Owen [19] theoretically calculated the chemical energy of wastewater as 3.86 kWh/kg COD oxidized to CO<sub>2</sub> and H<sub>2</sub>O. Several other studies attempted to determine experimentally the energy content of raw municipal wastewater by bomb calorimeter tests, finding energy values ranging around 3.2 kJ/g dry sample, which translates into organic-content-based value of 14.7 kJ/g COD (4.1 kWh/kg COD) [11]. Subsequent studies postulated that this value would in fact be a substantial underestimation of real wastewater internal energy content, given that the methodology previously used had some faulty premises and that the true value may in fact be significantly greater. By comparison, freeze-drying based wastewater energy estimation enabled a greater fraction of that energy to be measured, up to almost 30 kJ/g COD (8.3 kWh/kg COD), matching more closely with internal chemical energy calculations based on thermodynamic calculations from First Principles (reaction enthalpy) [20].

Shizas and Bagley [11] determined for the North Toronto WWTP a wastewater total energy content of 62.8 MWh/d, according to their embedded energy estimates, compared to a measured electrical consumption to run the entire treatment plant of 6.8 MWh/day, with ratio between embedded and required energy greater than 9.2. If by conservative calculations, a median energy content of 12 kJ/g COD (3.3 kWh/kg COD) (according to the earlier estimates) with a world population of 7.7 billion people (as of 2019), with each one producing at least 60 g COD/day, is assumed, wastewater-embedded energy would thus correspond to over 562 TWh/year. If all the energy contained in wastewater could be harnessed, water industries could become energy self-sufficient or even net producers, and wastewater could become also a needed source of energy in developing countries, which often lack an affordable local energy supply, through decentralized, local wastewater treatment systems [21]. To generate this large amount of energy, furthermore, almost 50 MTOEs (millions of tons of oil equivalent) would be required, whose combustion would produce GHG emissions of approximately  $100 \times 10^6$  t CO<sub>2</sub> (about 1% of current worldwide CO<sub>2</sub>-equivalent emission estimate).

#### *WAS Embedded Energy*

A residual of wastewater treatment, biological waste sludge is a concentrate (literally) of chemical energy. Due to higher organic solids concentration (raw wastewater has a Volatile to Total solids ratio of around 0.10, about 5 times lower than the one observed in primary sludge), sludge contains a higher embedded chemical energy than wastewater (in fact, about 5 times as much). It was estimated that the energy content of primary domestic sludge is between 15 and 16 kJ/g (d.w.) (4.2–4.4 kWh/kg COD) while mixed (primary plus secondary) sludge sent to digestion may contain between 11.5 and 13 kJ/g (3.2–3.6 kWh/g COD) [11,22]. According to the determination methodology of Heidrich et al. [20], these values may actually be substantially higher.

### **3. Wastewater Treatment Energy Demand**

Energy demand (mostly electric) of wastewater treatment to required standards is a significant component of the urban water cycle overall costs. It was estimated that 30% to 35% of total cost of wastewater treatment facilities in the U.S.A. is due to electric energy supply [23]. More stringent limits for nutrient removal or mandatory removal of presently-unregulated contaminants, such as contaminants of emerging concern (CEC) and pharmaceuticals and personal care products (PPCP), with introduction of additional process steps, might imply a significant increase in energy demand of treatment facilities, therefore energy reduction and recovery represent an important sustainability issue for maintaining required standards.

To date, numerous efforts to adapt mainstream processes to make them less energy intensive have resulted in alternative outcomes, mainly due to the lack of standardized energy monitoring procedures and regular energy audits in these facilities, essential for identifying any potential for improvement [24,25]. A common practice is to compare energy demand in terms of kWh/m<sup>3</sup> treated

or kWh/PE; however, this can be highly misleading as it is assumed that pollutant concentration in the influent (BOD or COD, TSS, N and P) would not differ significantly between facilities. A more sensible approach would be to compare energy consumption in terms of units of pollutant removed, for example, kWh/kg removed [26], or in terms of “electrical energy per order” (EEO), which is defined as the amount of kWh’s required to reduce a pollutants’ concentration by one order of magnitude (i.e. one log or 90%) in 1 m<sup>3</sup> of solution [27]. EEO values (expressed as kWh/m<sup>3</sup>-log) therefore measure actual process efficiency and not absolute pollutant removal. They are normally used for advanced oxidation processes (AOPs) and other processes working on direct electric energy input to compare technology efficiency for a given reaction [28] but could easily be adopted for any process driven directly or indirectly (in this case also accounting for energy conversion efficiency) by an electric power supply.

One frequent reason for high energy demand in WWTPs is that, conventionally, they were designed to process wastewater using aerobic activated sludge processes (ASP), requiring pumping of large flows of compressed air or, less often, oxygen into the biological tank. This component may represent more than 50%, and up to 70%, of the entire energy demand of a conventional facility [29,30]. Although ASP is quite simple to handle, its operation is rather energy intensive.

Figure 1 shows typical figures [29] and ranges of energy consumption breakdowns in ASP WWTPs found in the literature. These values may vary significantly as WWTPs may have many possible configuration options, and no standardized method for energy breakdown among process units is established. Figures on aeration energy demand largely agree, although in a fairly wide range, but some of the ranges indicated will strongly depend on the specific type of technology adopted and on the desired end product of the process, varying within up to one order of magnitude: sludge dewatering with belt press may require less than 4% of the total plant energy, while achievement of lower final humidity could significantly boost this consumption. Disinfection requirements will also vary significantly depending on technology: Simple chlorination may require no more than 0.3% of total plant energy, while UV disinfection may account for up to 25% of total electrical energy use at a municipal WWTPs [31].

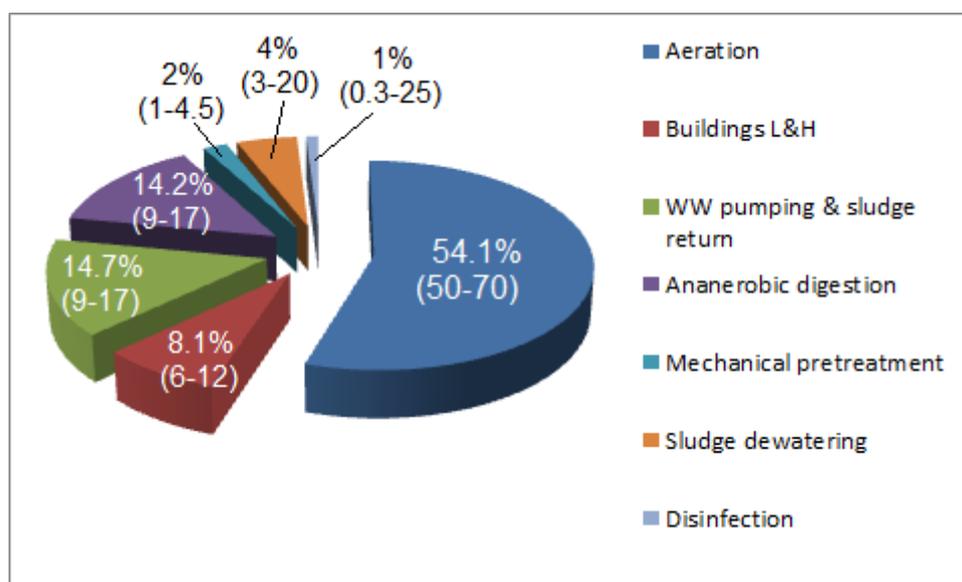


Figure 1. Wastewater treatment plant energy consumption breakdown.

Often, in-plant energy estimates neglect external energy embedded in chemicals contributing to the processes. The chemicals consumed at the plant result in both upstream and on-site energy use and emissions; their energy impact on treatment facilities has been estimated as 7% of total demand [32]. However, chemicals’ costs are usually assessed as financial rather than energy costs (these also depend

on indirect factors, such as their transport) and as such may be greater than pure energy costs at some facilities [33].

### 3.1. WAS Treatment Energy Demand

Finally, pre-disposal excess waste activated sludge (WAS) treatment (or post-treatment as it is usually called in the WWTP process chain) is costly both in financial and energy terms: The former component was estimated in up to 50% to 60% of the total operational costs of WWTPs [34]. These processes are needed to reduce excess sludge volume and stabilize organics and pathogenic bacterial contents that were generated during the treatment process. WAS in fact still contains large quantities of water (primary sludge usually has about 93% to 97% residual humidity, secondary sludge around 98% to 99%), and a significant organic load, making its disposal unsanitary and overly expensive. Various approaches, relying on a combination of physical, chemical and biological methods are employed to WAS post-processing [35]. These processes are usually quite energy demanding as, due to sludge particles properties, only some of the water present within may be removed mechanically, in proportion depending on actual sludge composition and characteristics [36].

Small or older facilities may stabilize WAS by extended aeration or aerobic digestion. This process is a modification of conventional ASP, providing organic matter stabilization without significant volume (water-content) reduction. Aerobically stabilized sludge usually has humidity content of 98% to 99% and thus requires subsequent drying. Extended aeration is typically designed for small WWTPs, where wastewater is aerated for longer than in conventional ASP. As a consequence, extended aeration WWTPs use more energy than other common small plant configurations at an average energy intensity of between 0.21–5.5 kWh/m<sup>3</sup> [37,38]. Aerobic sludge digestion is quite similar to ASP: As organic matter supply depletes; bacterial cells undergo an endogenous phase. Spent cell tissue is hence oxidized into carbon dioxide, water, and ammonia. Aerobic digestion is less capital and operationally demanding than other WAS post-processing technologies; however, it is more energy intensive, as oxygen supply must be continuously poured into the process. Aerobic digestion has been rated as the greatest consumer of energy out of all sludge stabilization methods, with median energy intensity of 0.52 kWh/m<sup>3</sup> in small plants [38]. While usually adopted in small WWTPs for its simplicity, aerobic stabilization has sometimes been adopted also in large facilities [39].

Energy demand for WAS post-processing can be benchmarked by thermal technologies, which may be considered a standardized baseline. Minimum thermodynamic requirement for sludge drying can in fact be calculated based on sensible and latent heat that is necessary to evaporate water, which is approximately 0.63 kWh/kg. In practice, such requirements (depending on technology) range from 0.82 to 1.1 kWh/kg evaporated water, and total sludge drying energy demand can be calculated at approximately 2500 kWh/ton dry sludge, on average [40]. Table 1 shows rated energy requirements of some commercially available waste activated sludge drying technologies.

**Table 1.** Rated energy requirements of commercially available WAS drying technologies.

Technology	Total Energy * [kWh/kg]
Band dryer <sup>TM</sup>	0.82
Paddle dryer <sup>TM</sup>	0.95
Flash dryers	1.05
Rotary dryers	1.05
Drum	1.07
Fluid bed	1.10
Greenhouse	1.53

\* Sum of thermal (between 95% to 99%) and electric (1% to 5%).

WAS however, has a residual chemical energy content that is attractive for energy recovery purposes. In current practice, therefore, it is common to include in post-treatment WAS anaerobic digestion (a more appealing alternative to aerobic stabilization), with the purpose of recovering a fraction of the chemical energy still contained in the sludge as methane-containing biogas. This will be addressed in Section 5.

### 3.2. Treatment Residuals Disposal Energy Demand

Disposal of wastewater processes residuals (processed waste biological sludge) generally makes up a relevant share of the financial and energy costs of a wastewater treatment facility. Wastewater residues disposal may occur according to alternative technologies and disposal routes, with variable environmental impacts. Estimating the true “cost” of each is quite difficult due to the number and variety of the parameters involved. With equal adopted technology capital, operating and energy cost will vary not just from country to country, but even between different sites in the same country. Table 2 shows the range of observed direct financial costs for common final sludge disposal alternatives [41]. Transportation of sludge to its destination may have significant impact also on energy requirements for its disposal.

**Table 2.** Range of sludge treatment and disposal cost in EU countries.

Disposal Type	Cost Range (Euro)	
	Minimum	Maximum
Land application	25	210
Landfilling (where allowed)	125	255
Composting	150	310
Thermal drying	80	210
Incineration	80	438

As seen in Table 2, even actual observed costs for the most common disposal practices are distributed in a wide range of values. The lack of uniform analytical indicators implies that direct comparisons between the sparsely available data is practically meaningless for making reliable estimates, making general energy requirements assessments unfeasible. It should be noted however that, among the disposal options listed in Table 2, some could allow recovery of materials (e.g., nutrients and carbon) or energy (e.g., incineration), or both, as discussed later, with some cost recovery.

## 4. Towards More Energy-Efficient WWTPs

As mentioned, WWTPs energy audits can be a very effective tool to identify process units that are inefficient and overly energy hungry. In addition to equipment energy efficiency check-up and replacement, design verification of existing facilities should also be performed: One of the most overlooked issues in plants’ energy requirements is pumping. Without considering losses due to pumps efficiency (typically between 65% and 80%), theoretical pumping energy requirements are  $9.81 \text{ kJ/m}^3\text{-m}$ , or  $2.725 \text{ kWh}/10^3\text{m}^3\text{-m}$ . Typical sewage systems pumping energy requirements have been estimated to  $69 \text{ kWh/PE-year}$  [42], or over twice the average amount of energy used for treatment of the wastewater to high standards. In-plant pumping requirements may also be significant (some estimates rate them at up to 50% of total energy) but they are often lumped together with treatment process needs in many surveys and are thus difficult to properly estimate. As most plants are constructed on flat terrain, pumping cannot be avoided, but the internal hydraulic profile should be designed to minimize head loss. Double pumping should be avoided: It is not uncommon to observe that flow is often pumped multiple times, e.g., from inlet sewer to headworks, then from headworks to primary sedimentation, and then from final clarifiers to disinfection and discharge. Every time flow drops into

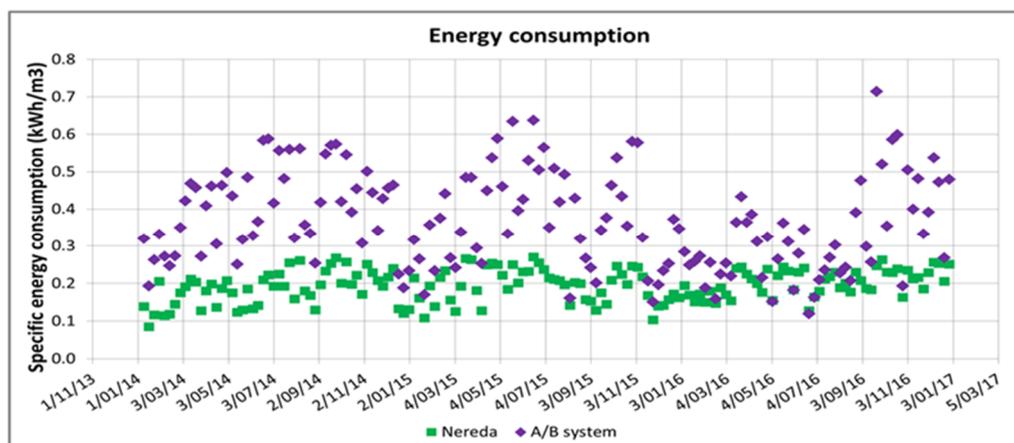
a sump well, total pumping head lost at each site could be as high as 5 m, requiring additional lifting energy of at least 0.014 kWh/m<sup>3</sup>. Discharge pumping should be needed only when water level in the receiving stream is high, which may be only for short high flow periods. Minimization of in-plant static head losses may lead to significant reduction of energy consumption.

Implementation of low energy equipment and processes could result in significant energy savings [14]. Energy efficiency improvements may be obtained by implementing high efficiency aeration technology, including high efficiency blowers, fine or ultrafine bubble diffusers, oxygen sensor devices [43]. Oxygen requirements typically vary during the day by a factor of 5 to 7, depending on incoming loads. Online sensors and model-based control systems may enable operators to enact energy and performance efficient process control strategies [44]. Other measures to improve both energy use and process performance may consist in specific interventions such as use of low energy mixers in anaerobic process phases (e.g., biological denitrification and phosphorous removal). Many design manuals indicate energy requirements for mixing at around 8–16 W/m<sup>3</sup>. Mixing energy can be reduced to 2 W/m<sup>3</sup>, which by causing minimal surface turbulence reduce oxygen transfer into solution but still prevent solids stratification [45]. Therefore, in addition to direct power savings, such modifications may even improve process performance.

In order to identify appropriate process modifications in terms of energy and treatment efficiency, process simulation studies may also be conducted to test modified process schemes [46,47]. Sometimes, switching to a completely new process may prove more successful than attempting to update an old layout.

Some technological improvements in process treatment effectiveness may imply drawbacks of increased energy requirements. One example is given by membrane bioreactors (MBRs), a common upgrade of ASPs, which use more energy than the latter [48]. Significant potential reduction in MBRs energy use may derive from process modification, such as the use of anaerobic fluidized membrane bioreactor (AFMBR), combining an MBR with an anaerobic fluidized bed reactor (AFBR) [49], or other similar anaerobic schemes being developed.

Additional recent developments in process technology have perfected biological processes that have significantly lower energy requirements than traditional ASPs. For example, the NEREDA<sup>®</sup> Process [50], a patented process based on the aerobic granular sludge (AGS) formation phenomenon [51,52] and operated according to an optimized sequencing batch reactor (SBR) cycle, in addition to sporting a much reduced footprint, has demonstrated energy requirements of less than 60% of those of an equivalent ASP, resulting from lack of moving parts, mixers, or recycle pumps inside process units (Figure 2).



**Figure 2.** Energy consumption patterns for the Garmerwolde plant in Groningen, The Netherlands. Nereda<sup>®</sup> vs. traditional A/B process. (DHV Royal Haskoning).

The AGS process selectively develops biomass that forms granules, rather than flocs, which include phosphate-accumulating nitrifiers, denitrifiers and glycogen-accumulating organisms, allowing simultaneous anaerobic, aerobic and anoxic conditions to coexist, thus reducing the need for multiple tanks and recirculation and allowing simultaneous biological removal of organic, nitrogen and phosphorus components. Granular biomass also shows faster settling compared to flocs, disposing of the need for large clarifiers. In DHV's Garmerwolde facility in Groningen, The Netherlands, a Nereda<sup>®</sup> and an A/B (adsorption/bio-oxidation) process (two-stage N-removing modification of conventional ASP) are operated side-by-side, the former treating 40% of the total incoming wastewater flow, with an energy usage of 13.9 kWh/PE-year as opposed to the 25 to 28 kWh of the ASP process. Depending on wastewater flow and characteristics, a Nereda<sup>®</sup> plant could include multiple modular reactors (often 3) or a combination of buffer tank and one/two reactors. An advantage of AGS processes is that they can be implemented in traditional WWTPs relatively easily with minor modifications. Process configuration is flexible; therefore, Nereda<sup>®</sup> technology can be used to upgrade existing ASP or SBR plants, achieving approximately twice the active biomass concentration, with outstanding settling characteristics. As a result of retrofit to this technology, both biological and hydraulic capacity of existing plants would be significantly increased, with considerable improvement of effluent quality.

Disposing of aeration altogether, immediate consistent energy savings could be obtained, at least equal to the energy otherwise spent for air insufflation. This could be achieved by substituting ASPs (or other aerobic processes) with anaerobic biodegradation (anaerobic digestion, AD), that could in fact represent one of the principal core technologies in future urban sanitation realizations [53]. AD has existed as a technology for over 100 years and sports several advantages in addition to low energy requirements including low facilities' construction costs, low excess sludge production, plain operation and maintenance, energy generation in the form of biogas, robustness in terms of COD removal efficiency, pH stability and process recovery time.

The main problem preventing its generalized adoption is that domestic wastewater in developed countries is usually too diluted to render this process economically convenient as, being characterized by lower reaction rates, it would require much larger facilities than those needed by aerobic processes to reach the same COD removal objectives. Low temperatures are also mentioned as barriers to the feasibility of AD of domestic wastewaters; however, studies have shown that good performance of these systems could be attained even at temperatures as low as 5 °C [54]. Several researchers have remarked that if a technological shift in urban sewerage could be completed through the adoption of low-dilution collection systems, anaerobic processes could become the mainstream process for domestic wastewater treatment [55]. An ideal process technology in this sense could be represented by Upflow Anaerobic Sludge Blanket (UASB) reactors, already used to treat urban sewage in several large cities of tropical countries (e.g., Cali (Colombia), Belo Horizonte (Brazil), due to low energy requirements, higher organic concentration in wastewater and extremely favorable climatic conditions [56]. UASB operation is based on the formation of a granular sludge (0.5 to 1 m in diameter) suspended in the tank by the effect of the upward influent current. Solids accumulation in the blanket enables disconnection between solid and liquid retention time in the reactor, increasing applicable organic loads. Wastewater organics are degraded by anaerobic microorganisms while flowing through the blanket; at the same time, methane-containing biogas is produced and may be collected as energy source. UASB operation is controlled by hydraulic loading rates. Upflow velocity of 0.7–1 m/h must be maintained to keep the sludge blanket in suspension and ensure that biomass is not washed out.

Enhancements of the UASB process include Expanded Granular Sludge Bed (EGSB) [57] and Anaerobic Baffled reactors (ABR), both designed to exploit more effectively the granular nature of UASB biomass under low temperature and low organics concentration conditions. The latter employ plug-flow staging of the various anaerobic treatment phases, this being a more efficient configuration than the complete mix scheme used by EGSBs [58]. In pilot scale applications, EGSB systems have shown energy consumption savings of up to 75%, compared to a conventional activated sludge

process [59]. While EGSB applications are nowadays common, ABR use, showing promising results at pilot-scale, is still limited in full-scale installations.

If implemented under proper conditions, anaerobic wastewater treatment could become a net energy producer. Another non-negligible advantage of AD is that the amounts of digested sludge from this process are much lower (by 3–20-fold) than those produced by aerobic treatment, constituting another highly valuable energy (and economic) benefit in terms of reduced residue disposal demand.

Both direct and indirect energy recovery could derive from the optimization of nutrients removal and recovery strategies from wastewater. Currently, nutrients (N and P) removal before discharge is often required, in compliance to environmental protection regulations. In conventional ASP nitrification–denitrification, process energy consumption is 2.3 kWh/kg N removed [60]. A new, casually discovered, mechanism of autotrophic N-removal (Anammox) in which ammonium is oxidised under anaerobic conditions has recently been introduced in wastewater treatment practice, with energy requirements of just 0.9 kWh/kg N removed [61–63]. It was also shown that autotrophic N-removal determines lower sludge production by up to one order of magnitude [64], reducing disposal costs for residues. The Anammox process, however, has shown so far better results in the presence of high N concentrations and relatively high temperatures. Although recent studies have shown that Anammox may perform well even at low temperature (13 °C), such applications rely on the successful selection of the only “cold-tolerant” anammox bacterial species so far identified (*Ca. Kuenenia*) in the system’s microbiome [65]. It remains to be demonstrated that Anammox could be widely used in mainstream applications. If successful, conversion from conventional nitrification–denitrification to Anammox process in a WWTP could imply over 60% energy savings for nitrogen control. It should also be considered that recovery of fertilizing elements N and P in usable form would imply indirect energy savings equivalent to those required for their production less those required by the recovery process [66].

Liquid-phase P recovery technologies could reduce, in general, the cumulative energy demand of WWTPs, by reducing energy requirements for sludge handling [67]. On average, the application of P-recovery technologies could reduce cumulative WWTP energy demand by 17.7%, and it was suggested that up to 27% overall energy advantage could exist between a biological P-recovery facility and a conventional chemical P-removing facility [68]. Implementing P recovery technologies as struvite or other P-containing fertilizer materials could reduce a facility’s energy requirements compared to conventional P removal by ferric chloride or ferric sulfate salts [66,69].

Finally, in a larger frame of reference, treatment facilities decentralization may be a long-term winning strategy for improving the energy efficiency of the Urban Water Cycle. Decentralized wastewater treatment will require less pumping and shorter pipes, implying less energy than centralized ones, therefore decreasing infrastructural energy requirements and cost. About 80% to 90% of capital costs in such systems are related to the collection system itself, and pumping energy is typically much larger than energy for actual treatment [42]. Almost all current wastewater treatment technologies could, in principle, be applied to such systems including “natural” solutions that are notoriously low-energy demanding, although they are area-extensive. Decentralized (cluster) wastewater treatment operating at local scale not only can have beneficial effects on wastewater disposal in environmental and public health terms but could reduce energy demand and increase reuse of wastewater [17]. Recent developments in renewable energy, in particular solar PV and wind, will make decentralized wastewater treatment even more attractive from an energy point of view, thus meeting the challenges related to the climate variability issue [70].

Less diluted sewage could be achieved by generalized adoption of vacuum, rather than gravity sewers. In these systems, the energy that moves waste along pipes is the difference between atmospheric pressure and vacuum mains negative pressure, therefore requiring less water for transport of waste through the system. Vacuum sewer systems have some notable advantages over gravity ones, including lower (by 30% to 35%) construction costs, lower O&M costs, including lower overall energy (by a similar percentage) for their operation [71]. Hence, from the viewpoint of sustainability, significant reduction

of energy and GHGs emissions could be achieved within their life cycle [72]. Similar considerations extend to wastewater treatment, since the more energy-efficient anaerobic technology is ideally suited to these conditions. This technological paradigm switch could significantly improve the overall economics and sustainability of an urban water system, not just of the wastewater treatment processes.

With respect to the removal of emerging contaminants (CECs—contaminants of emerging concern) including pharmaceuticals, while current regulations worldwide do not generally foresee their mandatory removal from wastewater (with some notable exceptions such as Switzerland), stricter effluent standards are under discussion [73]. This would almost certainly increase energy requirements for wastewater treatment significantly, as their removal is currently based mostly on the combination of MBRs and AOPs [74], both highly energy intensive in absolute and specific, i.e., per unit of pollutant removed (EEO), terms [75]. A new class of processes indicated as AO(R)Ps (Advanced Oxidation and Reduction Processes) based on water radiolysis has been proposed for such purpose for its high removal efficiency yield and low EEO indexes [76]. These new technologies have been used for some time in different production sectors, but their adoption in water treatment is still poorly diffused, although showing very promising experimental results in a few existing applications. It has been shown that, in combination to conventional processes, they can achieve significant overall efficiency improvement not just towards removal of CECs but also of conventional contaminants [77]. Hence, Electron Beam and Plasma technologies could have a primary role in future strategies addressing emerging contaminants, contributing to optimized process energy demand [78].

## 5. Technological Energy Recovery Opportunities

Once established that wastewater and WAS contain considerable energy in the organic material, the major challenge consists in capturing that potential and doing so with minimal losses and costs. Unfortunately, under conventional approaches (anaerobic treatment of WAS) only about  $\frac{1}{4}$ – $\frac{1}{2}$  of a plants' energy needs can be satisfied by using biogas produced by digestion of organics. These limits are due to several factors, including partial degradability of some organics originally present in wastewater, biological process efficiency and thermodynamic efficiency of recovery processes technology. Thermal, chemical, radiolytic or electrical processes may be used to condition refractory organics to increase biodegradability (and biogas production), but the related direct or indirect energy cost may often offset gains.

Due to universal thermodynamic laws, some energy is always lost in any conversion processes and biological processes are no exception. In anaerobic processes, about 8% of the potential embedded energy is lost in the conversion of higher carbohydrates into lower ones (methane). Additionally, about 7% is lost due to metabolic requirements to form new microorganism cells that carry out the process. Further energy losses of about 5% can be attributed to wastewater process inefficiency, with combined losses totaling about 19% of the initial content. This means that biogas produced would contain under the best scenario only about 81% of the initial estimated energy potential [79].

Under the AD approach, biogas produced (about 70% methane) is generally used in combined heat and power (CHP) engines capable of converting only about up to 40% of the methane energy into electricity, while the remainder may be in part recovered as heat, which may or may not be useful, depending on local conditions. A significant drawback of biogas is that it contains trace components of corrosive agents (e.g.,  $H_2S$ ) that make it unsuitable for general uses other than CHP feeding. In order to allow its wider utilization, biogas should be converted into biomethane (a fuel containing >97%  $CH_4$ ) with higher heat value, lower corrosion potential and therefore more valuable. This requires further, expensive, processing [80]. A different approach to produce electricity from biogas may be realized using chemical fuel cells application, which may increase electric conversion efficiency to 50% [81].

Advantages of the substitution of aerobic processes with anaerobic ones for wastewater treatment were illustrated in the previous section. However, this would require a major paradigmatic shift in urban sewerage planning and design to achieve maximum efficiency and sustainability, as the effectiveness of these processes is enhanced by concentrated substrates ( $COD > 4000$  mg/L) and high

process temperatures. A possible strategy to achieve this condition is through adoption of low-dilution sewerage, for example, vacuum sewers. If combined with source separation, these systems could result in much higher in-sewer COD concentration. Based on per capita organic matter contribution and modified wastewater discharge flows, COD values of approximately 8000 mg/L, with possible range extending up to 20,000 mg/L, depending on local conditions, could be achieved. Objections to this approach are mostly based on practitioners' and public agencies' unfamiliarity with this technology and on the cost for existing systems replacement. It should be considered, however, that in most of the developed world, urban water infrastructure is nowadays close or past its useful design lifespan (usually, 50–75 years) and thus due to undergo substantial rehabilitation/refurbishment in the near future. Gradually switching to decentralized facilities served by source-separated low dilution system could not only save energy but increase its recovered amount. It has in fact been reported that UASBs operated for low-strength (COD = 100–2600 mg/L) domestic wastewater treatment could generate 130–420 L CH<sub>4</sub>/m<sup>3</sup> (at 97% COD removal) [82].

Other novel methods have been proposed, among them wastewater processing with bioelectrochemical methods, i.e., microbial fuel cells (MFCs), which could accomplish the direct conversion of the embedded chemical (organics) energy into electricity [83]. The theoretical electrochemical potential (voltage) can be estimated at about 1.1 V for wastewater organics [84]. Even though MFCs have shown considerable efficiency in organics removal from domestic and industrial wastewaters [85], their performance in terms of actual energy recovery is still quite unsatisfactory, achieving in optimal conditions power densities of 25–60 A/m<sup>3</sup> against expected values exceeding 1000 A/m<sup>3</sup> indicated by other researchers [86,87]. This is due to high internal losses that can be attributed to operational factors, construction materials and process scale, with current values that at this stage of technological development may be much greater than 50% [88].

#### *Energy Recovery From Process Residuals*

Final wastewater processes residuals require safe and appropriate disposal that may require significant energy input and costs, as seen in Section 3.2. In addition to disposal through incineration, other technologies exist for useful recovery of energy and materials from these residuals. A severe technological limitation of these options is given by the water content of sludges, which unless it is well below 30%, will require more energy evaporation than that produced by the residual's combustion [41].

While incineration can recover energy only as heat (it may be used for centralized district heating of private and public buildings), other thermal processes (e.g., pyrolysis, hydrothermal carbonization) can extract energy from sludge in solid or liquid form, with more ample application possibilities [89]. Pyrolysis may be driven by conventional thermal energy (e.g., electric or from primary fuels), by convection or by microwave-assisted devices, which are more energetically efficient [90]. Still, effective sludge pyrolysis requires sludge humidity not exceeding 10%. WAS pyrolysis may produce different types of storable energy (e.g., py-oil, biochar, py-gas) and recoverable residuals that may feed local Circular Economy circuits [91]. Recovered products characteristics depend strongly on sludge properties [92]. Lately, combined ASP/microalgae wastewater treatment facilities were designed, built and operated to achieve more sustainable combined removal of carbon and nutrients in a single unit [93]. It was shown that pyrolysis of combined WAS and microalgae may improve the caloric value of these residuals [94].

The hydrothermal carbonization (HTC) process is a thermal conversion process that converts high-moisture biomass into hydrochar [95]. Unlike pyrolysis, HTC generates a process liquid residual that may be further processed for nutrients recovery and biogas production. This technology, operating at relatively low temperature (180–250 °C), short process times (1–12 h) and pressure up to 30 bar, generates a product (hydrochar) used not only as solid fuel and energy storage but also, similarly to biochar, as soil amendment, absorbent and CO<sub>2</sub> sequestrator [96]. Both biochar and hydrochar could be significant fossil fuel replacements in combustion processes.

## 6. Discussion

At the moment, the most efficient and technologically robust solutions in term of energy demand reduction in WWTPs seem to lie in AGS processes, as far as aerobic technologies are concerned, or, as an alternative, UASB/EGSB anaerobic treatment of domestic wastewater. In addition to reducing net treatment energy demand, AD at the moment has the best practical potential for capturing wastewater's embedded energy content and should be considered a preferred option in future design of domestic WWTPs [53]. However, retrofitting conventional aerobic plants to anaerobic processes could be costly and would require more concentrated sewage to achieve optimal efficiency. As an alternative, in addition to upgrading aerobic facilities to more energy-efficient equipment, introducing automatic system control for performance optimization and reducing solids retention in aeration tanks could result in lower energy expenditure and in higher fractions of organics in the biosolids sent to WAS digestion, with increased biogas production.

While literature has shown that anaerobic technology could be applied to diluted domestic sewage with low biogas recovery, AD is better suited to systems based on source separation and vacuum collection, as shown by the practical showcase application of Noorderhoek, Sneek (The Netherlands). In this experimental district system, counting 232 homes, organic waste and toilet water (blackwater) are collected by a vacuum system with low dilution ratio of 1:7 compared to conventional systems. Wastewater, treated by a UASB process, produces biogas which satisfies 12% of the heating demand in the district [97].

Pyrolysis or HTC processes, in addition to providing a safe and sustainable final disposal option for wastewater process residuals, could significantly improve the overall energy footprint of a WWTP, as WAS constitutes an ideal feedstock for the production of certain renewable biofuels [98].

Bioelectrochemical systems show promising perspectives, but the current technological progress involves high construction costs and is not yet mature for full-scale, significant energy recovery.

## 7. Conclusions

Energy represents a significant part of wastewater treatment operational requirements and costs worldwide, with pumping and aeration among the primary energy consumers within the treatment cycle. Residual sludge disposal also requires significant amounts of energy. Consequently, efficient pumping and aeration are crucial for high total energy efficiency. The switch to anaerobic treatment technology, which has increasingly been shown as a possible solution, would drastically cut process energy requirements and the amounts of process residual to be disposed of, while recovering part of the chemical energy embedded in wastewater organics. New technologies are being proposed to improve the efficiency and energy footprint of specific pollutant removal, such as pharmaceuticals and other contaminants of emerging concern.

Considering the costs of sewer construction and operation, decentralized systems, and particularly those based on low sewage dilution, such as vacuum sewers that favor the adoption of energy-recovery technologies like anaerobic digestion, will be increasingly interesting from an energy point of view. Other different forms of wastewater-contained energy include thermal and kinetic energy. Either, although less relevant than the chemical form, could be locally recovered with existing technologies. Bioelectrochemical processes show interesting potential, even though they still need to prove their applicability and energy recovery potential at large scale.

Energy recovery from wastewater process residuals may significantly contribute to improving the energy balance of WWTPs. In addition to traditional systems such as incineration, technologies such as pyrolysis and hydrothermal carbonization allow recovery of liquid and solid phases with energy values that may be transported more easily than biogas for off-site use. These may also find applications in the chemical synthesis industry for extraction of other valuable components and originate Circular Economy cycles at the local level.

Urban water systems need the supply of relevant amounts of energy for their operation. Future, more stringent emissions regulations on nutrients or emerging compounds may further increase these

requirements. Improving internal energy efficiency by process modification and technological upgrade and exploiting available incoming energy wisely could lead in the next future to the “zero energy” wastewater treatment plant concept implementation, which not only reduces facilities’ energy footprint but allows recovery of wastewater-embedded resources for reuse.

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