18th International Conference on Renewable Energies and Power Quality (ICREPQ'20)
Granada (Spain), 1st to 2nd April 2020
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.18, June 2020

Energy Use and Recovery in Wastewater Treatment Facilities

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Abstract. Wastewater treatment facilities (WTFs) may require over 20% of the energy consumption of municipal utilities, and up to 3% of the total energy output of a country, also representing a significant source of GHGs emissions. On the other hand, wastewater contains different types of energy: chemical, thermal and kinetic. Until very recently, they went mostly untapped, the only form of recovery usually consisting of anaerobic digestion of process residuals (waste sludge), by which embedded wastewater chemical energy in extracted in form of methane. This could be sufficient to cover about half of total plant requirements, even though wastewater chemical energy alone may represent close to tenfold the energy requirements for its treatment. Implementation of new technologies is making more efficient strategies of energy recovery from sewage possible. Besides valorisation of its chemical and thermal energy contents, closure of the wastewater cycle by exploitation of the energy contents of process residuals could allow significant additional energy recovery and reduced GHG emissions. 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 by-products.

Key words. Wastewater treatment, energy demand, renewable energy sources, energy recovery technologies.

1. Introduction

Wastewater treatment facilities (WTFs), are ubiquitous, major energy consumers at municipal level worldwide. It was estimated that, on the average, these facilities alone may require up to 3% of the energy output of a country, representing over 20% of municipal energy bills [1]. The 'water-energy nexus' has become a high-priority issue in latter years, spurring new paradigms and solutions for water cycle management sustainability [2].

Energy consumption of state-of-the-art treatment facilities (including nutrient removal) should be between 20 and 26 kWh per population equivalent per year, even though older plants may have higher energy demands. On the other hand, wastewater contains energy in chemical, thermal and kinetic forms. Chemical energy embedded in wastewater organics was estimated at approximately 10 to 14 kJ/g COD, although these may be lower than actual numbers [2]. Extraction of thermal energy could yield about 21 kJ/L for a 5°C drop in wastewater temperature [3]. Kinetic energy is just 3 kJ/m^3-m drop. These numbers suggest the potential for energy recovery through innovative wastewater management.

The most common form of energy recovery from WTFs still consists of anaerobic digestion of process residuals (waste sludge), by which energy in the form of methane is produced, generally sufficient to cover about half of a facility's requirements. This established strategy, implemented in large part of existing WTFs makes it possible to recover just a fraction of wastewater embedded energy. Implementation of new process technologies could make more efficient strategies of energy recovery from sewage possible and achieve greater sustainability of the urban water cycle [4].

This paper summarizes the main energy-demanding components in WTFs, and discusses the most promising technologies currently available for energy recovery from both wastewater and its residual by-products.

2. Energy use in WTFs

Figure 1 shows typical energy consumption breakdowns in conventional WTFs. Values vary significantly, as facilities have many possible configurations and, furthermore, there is no standardized procedure for assessing energy breakdown. Some ranges shown strongly depend on the specific type of process and on its desired goal, varying within up to one order of magnitude: major variations can be observed in sludge dewatering, disinfection (e.g. chlorination vs. UV).

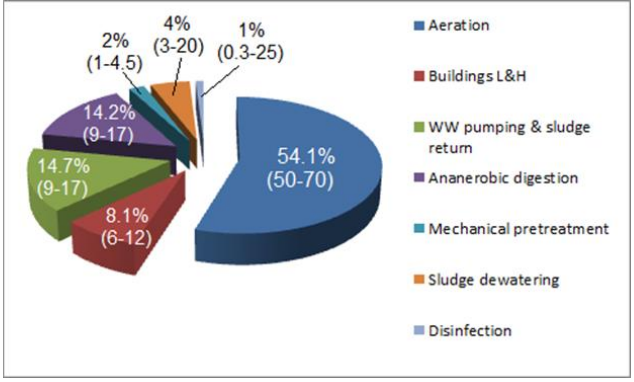

Figure 1. Energy demand breakdown in WTFs.

In-plant pumping requires significant energy amounts (some estimates rate them at up to 50% of total demand), as well as operation of other in-plant mechanical devices but both are often lumped in process units needs in many estimates. The theoretical (assuming 100% efficiency) pumping requirement is 2.725 kWh/$10^3 m^3$-m, hence optimization of a WTF hydraulic profile may lead to significant benefits, as well as the upgrade of electrically-driven units (e.g. mixing) and adoption of variable-speed drives to adjust output to actual needs.

One reason for high WTF energy demand is that most were designed to use some form of activated sludge process (ASP), which requires pumping of air into the biological reactor. This alone may require between 50 and 70%, of the whole WTF energy requirements. Although simple to operate, an ASP's operation is quite energy intensive. Energy efficiency may be improved by implementing more efficient aeration technology, i.e. high efficiency blowers, ultrafine bubbles diffusers. Older surface aerators had low specific oxygenation efficiency (0.4-0.8 kg O_2/kWh) while modern fine bubble aerators may reach 2.0-2.6 kg O_2/kWh [5]. The use of oxygen sensor devices and automated control can also be useful, as wastewater oxygen demand may vary by a factor of 5 to 7 in any day and unnecessary over-aeration not only wastes energy, but can also negatively affect process performance. Even aerating at 1 or 2 mg/L over the required DO setpoint is extremely wasteful. Intermittent aeration could save about 10% energy compared to continuous mode by reducing the time when an aeration system is turned on, based on measured DO concentration. Application of sensor-based DO control strategies for existing aeration systems could save from 25-40% of the energy used by manually controlled systems.

While some process improvements have increased WTFs' energy requirements, for example membrane bioreactors (MBRs) have several advantages over ASP but use more energy. On the other hand, recent developments in aerobic process technology significantly lowered energy requirements compared to ASPs and MBRs.

Ammonia oxidation is one of the energy demanding biological processes: aeration control strategies have been developed to use online ammonia-nitrate measurements as feedback to reduce inputs. Nitrogen removal requires approximately 4.6 kg O_2/kg of NH_4-N oxidized to nitrate, but an autotrophic de-ammonification process, Anammox, was discovered in the 1990's that provides up to 70–90% nitrogen removal with up to 65% reduction in aeration energy [6]. Another recent biological process development is represented by the proprietary NEREDA® process based on granular sludge growth (Figure 2), which flocs contain different types of bacteria and can achieve simultaneous carbon, N and P biological removal. NEREDA® facility claim energy requirements 60% lower than those of an equivalent ASP [7].

Small facilities may even stabilize excess biological solids by extended aeration, a modification of conventional ASP, providing organic matter stabilization without significant volume (water-content) reduction at great energy expense. By substituting aerobic processes with anaerobic ones, consistent energy savings could be obtained, at least equal to the energy otherwise spent for air insufflation, furthermore, energy could be recovered in form of biogas.

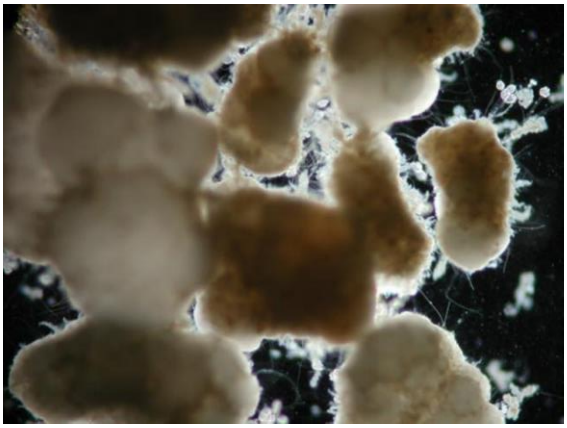

Figure 2. Granular Activated Sludge Flocs

3. New sewerage paradigms for energy efficiency

Stoichiometrically, methane production may be determined as 0.35 m^3 CH_4/kg COD, with heating value of approximately 10 kWh/m^3. By virtue of the significantly lower energy requirements and energy recovery, anaerobic processes could represent one of the principal core technologies in future urban sanitation [8]. An example of application to domestic sewage is represented by Upflow Anaerobic Sludge Blanket (UASB) reactors, used in many tropical countries, mostly due to favourable climatic conditions. The UASB process is based on granular sludge suspended in a blanket where organics uptake and degradation occurs. Biomass accumulation in the blanket enables the disconnection between sludge age and hydraulic retention time in the reactor.

The biggest issue hindering generalized adoption of anaerobic processes lies in their slower kinetics, which would require larger facilities and higher process temperatures than aerobic ones to remove equal COD amounts. Low temperatures are sometimes mentioned as a barrier, however, studies showed that these systems could perform well at process temperatures as low as 5^oC, with lower biogas production [9]. Evolution of UASBs include Expanded Granular Sludge Bed (EGSB), Anaerobic Baffled Reactor (ABR) and Anaerobic Membrane Bioreactor (AnMBR) designed to exploit more effectively the granular anaerobic biomass at low temperature and low organics concentration [10]. EGSBs have shown passive energy requirements 75% lower than ASPs, to which energy recovery as biogas must be added [11]. An additional advantage of anaerobic processes is that they produce smaller amounts (by 3-20 folds) of biomass compared to aerobic treatment, lowering energy demand for its final disposal.

Under current sewerage design paradigms, however, domestic wastewater is usually too diluted to render these processes economically convenient. A possible solution would consist of a generalized adoption of low-dilution systems, such as vacuum sewers. These could result in higher sewer COD concentration, from 8000, up to 20000 mg/L, in case of source-separated systems [2,12], making anaerobic process highly effective.

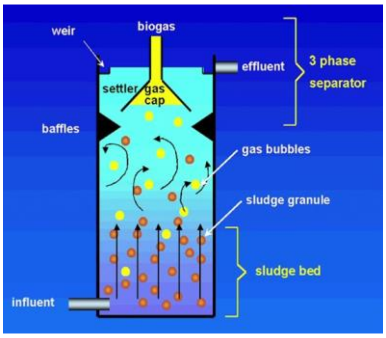

Figure 3. UASB reactor scheme

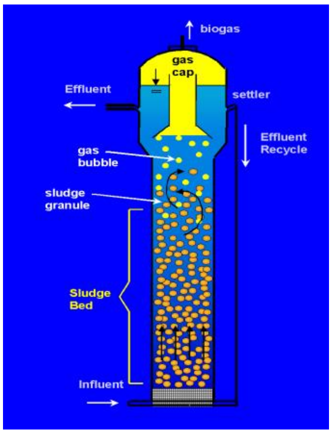

Figure 4. EGSB reactor scheme

Vacuum sewers rely on the differential pressure between atmospheric and vacuum mains negative pressure, to move the waste mass, rather than gravity flow, requiring less water for its conveyance. Vacuum sewers advantages over gravity systems include lower (by 30-35%) construction and O&M costs, including lower energy requirements (by about 1/3) for their operation [13]. Furthermore, from a sustainability viewpoint, these systems could make significant reduction of energy and GHGs emissions achievable [14].

Full scale experimental examples of such schemes in decentralized sanitation have already been reported, i.e. the pilot project servicing the Noorderhoek district of Sneek (The Netherlands) [15].

Other innovations in wastewater treatment have been proposed, including bioelectrochemical systems, i.e. microbial fuel cells (MFCs) (Figure 5), which can accomplish the direct conversion of the embedded chemical energy of wastewater into electricity [16]. Even though showing high efficiency in organics removal from both domestic and industrial wastewater [17] the actual energy recovery is still unsatisfactory so far, yielding in most cited studies power densities between 25-60 A/m^3, against expected theoretical yields in excess of 1000 A/m^3 [18,19], due to internal energy losses attributable to operational and materials factors [20].

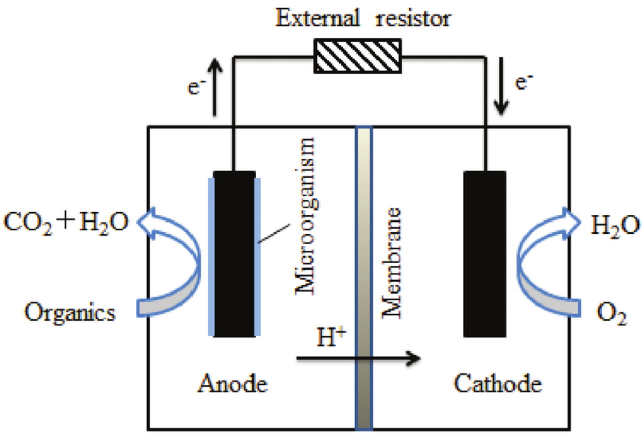

Figure 5. MFC scheme

4. Energy recovery from wastewater treatment residuals

Under conventional approaches (aerobic wastewater treatment and anaerobic sludge digestion) about 25-50% of a plants’ energy demand can be satisfied by auto-produced biogas. Due to the universal law of thermodynamics, some energy is always lost in any conversion process. Biological processes are no exception: combined losses in an anaerobic digestion processes sum up to about 19% of the initial sludge energy potential. This means that biogas produced would contain under the best scenario only about 81% of the initial estimated energy potential [21]. Biogas (≈70% methane) energy can be converted in combined heat and power (CHP) engines into electricity by about 40%, the remainder could be recovered as heat. Use of chemical fuel cells could increase electric conversion efficiency to 50% [22]. To allow more efficient offsite utilization, biogas may be converted into biomethane (>97% CH_4) [23].

Recovery of valuable energy-rich streams from raw wastewater should not be limited to sludge (where most organic solids are concentrated) but also from residuals from preliminary treatments (i.e. sewage scum, fat and grease) that are usually separated in conventional treatment trains and separately disposed. Sewage scum nowadays is mostly disposed of in landfills as wet material, at high (≈150-240 Euro/ton), however, it has been proven that this material could be fed to anaerobic digestion jointly with organic urban waste or sewage sludge, improving biogas productivity by its valuable composition (36-51% total lipids). Furthermore, it was shown that, as alternative, chemical extraction could yield valuable biodiesel and biolubricants from this residue [24].

Incineration is a widely used final disposal method for wastewater treatment residuals, however, it can recover energy only as heat, which may be used locally for centralized district heating or industrial purposes, but is not suitable for storage or transport. Other thermal processes (gasification, pyrolysis, hydrothermal carbonization) can extract sludge energy in gas, solid or liquid form, with allow more flexible use possibilities [25]. Pyrolysis may be driven by conventional thermal energy (e.g. electric or fossil) or by microwave devices, which more energetically efficient [26]. Pyrolysis can produce different types of storable energy (e.g. py-oil, biochar, py-gas) and recoverable residuals in various proportions, depending on process conditions, that may feed local Circular Economy circuits, with application beyond the wastewater treatment facility and it close surroundings [27,28]. Figure 6 shows a case of energy recovery balance from sludge pyrolysis. The balance of process products can be adjusted by adjusting process operational parameters to privilege the most desired component in each application.

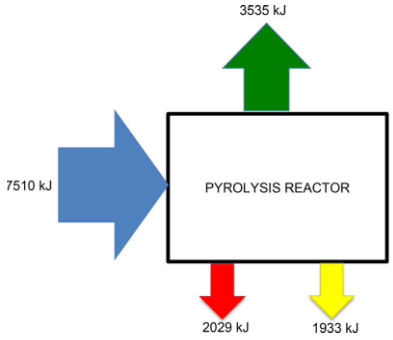

Figure 6. Example of sludge pyrolysis products energy balance

ASP/microalgae combined treatment facilities for domestic wastewaters designed to achieve sustainable combined removal of carbon and nutrients in a single unit were recently introduced [29]. Pyrolysis of excess biomass (combined sludge and microalgae) from these processes can efficiently extract the higher caloric value of these residuals [30]. A severe technological limitation lies in the fact that residuals' water content must be well below 30%, otherwise energy for water evaporation (2270 kJ/kg) will significantly affect process energy balance. Hydrothermal carbonization (HTC) is a residual thermal process operating pressure in liquid phase that can transform residuals' organics into various energy products such as hydrochar and bio-oil [31,32]. Although still requiring an external energy input (about 1330 kJ/kg), HTC does not require pre-drying of the waste stream. Aside from their possible value as secondary raw materials [27], at higher heating values of 22-28 MJ/kg for bio-oil (biodiesel), 15- 20 MJ/kg for biochar/hydrochar and 12-20 MJ/kg (depending on process conditions) [28], these recovered products could be significant, renewable second generation fossil fuels replacements in the future [33].

5. Discussion

At the moment, various options are available to reduce energy demands at existing wastewater treatment facilities. Standardized approaches to enhance in-plant energy efficiency are mainly impaired by the lack of standardized energy monitoring procedures and regular energy audits in these facilities, which are essential for identifying any potential for improvement [34]. Apart from the obvious solution of upgrading/substituting energy inefficient equipment, switching to a completely new process scheme may lead to better results than attempting to update an old layout. In the aerobic process domain, the most efficient and technologically robust solutions in term of energy demand nowadays seem to lie in granular sludge process.

In a DHV facility in Groningen (The Netherlands), expansion of a traditional nitrification/denitrification process was designed according to the proprietary Nereda® system, which uses about 14 kWh/PE-year for its operation, compared to the 25-28 kWh of the existing facility process. Granular sludge processes can be implemented in traditional facilities with relative ease, with only minor structural modifications.

Similarly, conventional nitrification-denitrification schemes require about 2.3 kWh/kg$_N$ removed [35]. The Anammox process, based on ammonium degradation under anaerobic conditions, demands just 0.9 kWh/kg$_N$ removed [36].

Either of these technologies could be introduced without major changes required of existing sewerage systems. As an alternative, UASB/EGSB anaerobic wastewater treatment could be considered. In addition to reducing net treatment energy demand, these processes have the best practical potential for capturing wastewater's embedded energy content. However, in order to be highly efficient, anaerobic treatment requires more concentrated wastewater. While literature has shown that anaerobic technology can be applied to diluted domestic sewage for organics removal, it showed low biogas recovery under prevailing standard conditions.

Considering that most of the developed world urban water infrastructure might be close or past its useful design life (50–75 years), therefore due to undergo substantial rehabilitation/refurbishment in the next future, lower running and investment costs for alternative collection technologies (i.e. vacuum systems) might finally override present objections to this technology fuelled by unfamiliarity and current technical paradigms. Gradual transitioning to decentralized facilities, served by low dilution collection system could not only save energy, but increase recovered resources [37]. UASBs operating at medium strength COD wastewater (up to 2600 mg/L) could generate 130–420 L $CH_4/m^3_{treated}$ (at 97% COD removal) with energy recovery of 4,7-15 $MJ/m^3_{treated}$ [38].

Bioelectrochemical systems have shown promising perspectives, but current technological status is not mature for full-scale applications with significant energy recovery.

6. Conclusions

Energy represents a significant part of wastewater treatment operations costs. Mixed liquor aeration is among the primary energy demands within the treatment cycle, and residual sludge disposal also requires significant energy expenditure. In addition to upgrading to more efficient equipment, technological switch to more efficient aerobic or anaerobic processes would drastically cut energy requirements and may even reduce the amounts of process residuals sent to disposal. Anaerobic technology would also allow the recovery of a considerable part of the chemical energy contained in wastewater organics.

Energy recovery from wastewater process residuals may significantly contribute to improve the energy balance of treatment facilities. In addition to traditional technologies (e.g.) incineration, gasification, pyrolysis and hydrothermal carbonization allow recovery of gas, liquid and solid products with high energy value, suitable for transportation and off-site use. These, and some traditionally wasted process by-products (i.e. pre-treatment scum) could be suitable for industrial valorisation by chemical synthesis for the extraction of valuable components, originating Circular Economy cycles at local level.

Improving energy efficiency by process modification and technological upgrade, and maximizing energy recovery could lead to "zero energy" wastewater treatment plant implementation.

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