

ENERGY RECOVERY IN WASTEWATER TREATMENT SYSTEMS THROUGH HYDRAULIC MICRO-MACHINERY. CASE STUDY

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Abstract:

The wastewater treatment plants (WWTP) treat the water from domestic and industrial use so that its discharge, once it passes through them, is harmless to the environment. However, large amounts of energy are necessary to carry out this process. Therefore, energy and process optimization are a key issue within these types of plant. One of the possibilities within the WWTPs is the recovery of hydraulic energy. This paper presents alternatives for the recovery of hydraulic energy, through the use of hydraulic micro-machinery such as PATs or hydrostatic pressure wheels. This type of machinery is capable of recovering a part of that energy that until now it was not possible to recover, in a more economical way and assuming an improvement for plants that have the possibility of installing it. In the here described case study, savings of over 4% were achieved with periods of return on investment of less than 5 years.

Keywords: efficiency; sustainability; recovery systems; Pump working as turbines (PATs)

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1. Introduction

Achieving the highest quality of water in the effluent in the shortest possible time is essential for a wastewater treatment plant (WWTP) (Torregrosa et al., 2016). However, to achieve the desired quality, WWTPs spend a big amount of energy on hydraulic machines, making it faster and more effective. Currently, one of the great challenges facing these plants is reducing this amount of energy without compromising the final quality of the water, improving sustainability (Mo et al., 2013; Longo et al., 2018).

WWTPs are essential for developed countries, without them, human-made environmental disasters would be immensely greater. However, the existence of these facilities causes an increase in the amount of very abundant energy to purify the water, which refers to another problem in the near future, the shortage of fossil fuels (Stillwell et al., 2010; Belloir et al., 2015).

The European Union with directive 91/271 / EEC and objective 20/20/20 establishes guidelines for the implementation and regulation of a WWTP and sets an objective to achieve energy improvement respectively. Directive 91/271 / EEC was conceived on May 21, 1991 in order to protect the environment from urban and industrial discharges and is based on 4 principles:

- Planning: to identify the sensitive areas that must be protected and which are also the focus of discharge of treatment plants with more than 10 000 equivalent inhabitants.

- Regulation: to establish control parameters and ensures that the necessary purification measures are carried out for a minimum number of equivalent inhabitants and that there is an adequate water collection system.
- Monitoring: to continuously check that the parameters are under the established limits, giving values of the monitored parameters, the analytical method and the sampling frequency.
- Reporting: to verify that all the measures are carried out and that the quality of the water, the state of the facilities and the efficiency of the treatments is adequate, reviewed every two years.

For the year 2020, the EU set itself a challenge, the 20/20/20 objective. Taking the year 1990 as a reference, this objective aims to:

- A reduction in atmospheric emissions of greenhouse gases by 20%.
- Save 20% of energy consumption through better performance of the equipment that consumes it, also covering transportation needs with 10% biofuels.
- Promote the use of renewable energy up to 20%.

Water purifiers have very high energy consumption, but at the same time they have many possibilities to recover energy and nutrients (Yang et al., 2010). The idealistic goal for this type of facility in the future is to be able to become self-sustaining, generating as much or more energy than they consume helping to achieve the objectives of the European Union (Gu et al., 2017). Within a WWTP, the

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recoverable hydraulic potential depends almost unilaterally on the treated flow, which means that the larger the plant, the greater the benefits obtained in global terms. Within a WWTP, the consumed energy ratio is shown in Table 1.

Table 1. General energy ratio (Cajigas, 2011).

| Treatment | Capacity (Equivalent-resident.) | Energy ratio | |
|--|------------------------------------|--------------------|---------------------------|
| | | kWh/m ³ | kWh/kgDBO ₅ el |
| Soft technologies | <2 000 | 0.32 | 0.23 |
| Prolonged aeration | <2 000-100 000 | 0.73 | 0.70 |
| Active sludge with aerobic digestion | 15 000-100 000 | 0.72 | 0.84 |
| Active sludge with anaerobic digestion | 15 000-100 000 | 0.32 | 0.6 |

The approximate energy consumption in a plant can also be broken down for each one of the phases that the discharge has until it is purified. Table 2 shows the typical consumptions by phases divided into prolonged aeration plants (AP), plants with active sludge treatments with aerobic digestion (AS + AD) and active sludge with anaerobic digestion (AS + AnD).

Table 2. Energy consumption in each stage. (Cajigas, 2011).

| | AP | | AS+AD | | AS + AnD | |
|--------------------------|--------------------|------|--------------------|------|--------------------|------|
| | kWh/m ³ | % | kWh/m ³ | % | kWh/m ³ | % |
| Water Line | 0.79 | 84.5 | 0.65 | 69.0 | 0.61 | 65.2 |
| Pretreatment | 0.04 | 4.3 | 0.04 | 4.3 | 0.04 | 3.7 |
| Homogenization tank | 0.10 | 10.7 | 0.10 | 10.7 | 0.10 | 10.7 |
| Primary settling | - | 0.0 | 0.005 | 0.5 | 0.005 | 0.5 |
| Biological treatment | 0.40 | 42.8 | 0.25 | 26.7 | 0.22 | 23.5 |
| Secondary settling | 0.08 | 8.6 | 0.08 | 8.6 | 0.08 | 8.6 |
| Tertiary treatment | 0.12 | 12.8 | 0.12 | 12.8 | 0.12 | 12.8 |
| Disinfection | 0.05 | 5.3 | 0.05 | 5.3 | 0.05 | 5.3 |
| Sludge Line | 0.10 | 10.7 | 0.31 | 33.2 | 0.20 | 21.4 |
| Aerobic Digestion | - | 0.0 | 0.21 | 22.5 | - | 0.0 |
| Anaerobic Digestion | - | 0.0 | - | 0.0 | 0.08 | 8.6 |
| Thickening and flotation | 0.01 | 1.1 | 0.01 | 1.1 | 0.04 | 4.3 |
| Dehydration | 0.09 | 9.6 | 0.09 | 9.6 | 0.08 | 8.6 |
| Auxiliars | 0.05 | 4.8 | 0.05 | 4.8 | 0.05 | 4.8 |
| Deodorization | 0.03 | 3.2 | 0.03 | 3.2 | 0.03 | 3.2 |
| Others | 0.015 | 1.6 | 0.015 | 1.6 | 0.015 | 1.6 |

The amount of energy invested in this process is such that the energy optimization of the processes and the recovery of energy is a prevailing theme within this type of plant. One of the possibilities within the WWTPs is the recovery of hydraulic energy, which has been seldom exploited due to the high costs of installing a classic turbine station (Berger *et al.*, 2013).

Hydropower has recently started to be applied for energy recovery in existing water systems such as WWTPs. Most studies are solely focussed on economic feasibility, considering potential energy production and viable payback periods under 5-10 years (Power *et al.*, 2017; Munaaim *et al.*, 2018). Sustainability is of paramount importance in these cases.

Furthermore, other renewable energy technologies (solar, wind, biogas) must be considered, as they usually present higher potential, but sometimes not applicable (Ali *et al.*, 2020; Kollmann *et al.*, 2017; Tang *et al.*, 2019). As a general rule there is not a standalone technology that can lead to 100% energy self-sufficiency. In order to manage this typically, a suitable combination of renewable technologies will be needed (Maktabifard *et al.*, 2018). Biogas is the main contributor to energy neutrality (Díaz-Elsayed *et al.*, 2019). recent studies present that less of 20% of the WWTPs are large enough to include anaerobic processes (Gandiglio *et al.*, 2017) and therefore, to present biogas generation potential. Wind, solar or hydropower energy potentials depend on the particular geographical site (Ghoneim *et al.*, 2016). Furthermore, economic aspects of energy recovery must also be considered (Simon-Várhelyi *et al.*, 2020; Padilla-Rovera & Güereca, 2019).

The objective of this research is to propose a work methodology, which on the one hand allows developing an energy study of a WWTP. This study allows knowing where the energy consumption is located as well as the making decision can reduce the energy consumption as far as possible. On the other hand, considering possible points of energy recovery and establishing its installation could install recovery systems, which help to increase the sustainability indicators of the WWTP.

This research presents alternatives for the recovery of hydraulic energy through the use of hydraulic micro-machinery (e.g., PATs). This analysis was carried out in a case study located in a WWTP in the province of Alicante.

2. Materials and Methods

Figure 1 shows the proposal of the methodology carried out in the development of energy efficiency improvement in treatment systems. The objective is to carry out an energy recovery in the water line, taking into account the existing recovery possibilities, thus achieving an algorithm that can be extrapolated to other WWTPs. The proposed steps are:

- (i) Identification of consumption points; previous step that will depend on the type of plant analyzed. Energy consumption in pre-treatment, primary, secondary, tertiary treatment, pumping, among others, must be considered.
- (ii) Energy balance of the plant: once the consumption points within the water line have been identified, the consumption must be quantified. It will be separated by the areas that have been seen in the previous section, and the data of each of the machines will be quantified based on previous data d or by means of an estimate based on the hours of consumption that it has annually and the power consumed.

Obviously, if exact data are available, consumption will prevail, which can be estimated through equations, since they will give a more realistic value. However, if it is necessary to estimate, Equation 1 will be the one used.

$$E(kWh) = P(kW) \cdot t(h) \tag{1}$$

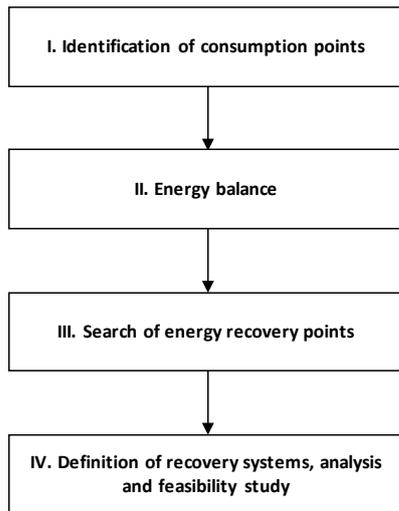


Figure 1. Proposed methodology.

where: E is the energy consumed annually in kWh, P is the power consumed by the machine in kW and t is the time the machine works throughout the year in h.

- (iii) Location of areas of recovery energy: A task is to know where the areas are with recovery potential that requires a personal assessment by the manager. The study should focus on those points where the flow has extra energy that is not used, either in the form of kinetic energy (speed), potential (height) or flow (pressure).
- (iv) Energy recovery: Any type of hydraulic machinery can be used but especially turbines. However, the economic investment as well as the low powers at some points are key and the use of pumps working as turbines is an alternative solution. Therefore, the use of hydraulic machines operating in its reverse mode is proposed, as well as hydraulic wheels in open channels. Both types of machines were proposed by other authors (Pérez-Sánchez et al., 2013).
- (v) Economic feasibility analysis: In this section, an estimate of the investment must be made, including the machinery and civil works necessary to carry out the project. The feasibility is defined by the determination of the return period (RP) and the net present value (NPV). The RP is defined by Equation 2:

$$RP(\text{years}) = \frac{\text{Cost } (\text{€})}{\text{Annual savings } \left(\frac{\text{€}}{\text{year}}\right)} < 10 \text{ years} \quad (2)$$

- Another way to calculate the feasibility would be through the Net Present Value (NPV). It is more accurate, but at the same time a little more complex to study. This method of calculating the profitability of the project considers the cash flows during the period to be profitable (again 10 years) and the interest rate (Equation 3).

$$VAN = \sum_{t=1}^n \frac{V_t}{(1+k)^t} - I_0 \quad (3)$$

- where: V_t the cash flows in periods t, k the interest rate, I_0 the value of the initial investment and t the number of periods considered. If the NPV is positive, the investment produces profits, and if it is negative, it produces losses.

3. Results

3.1. Case study

The case study wastewater treatment plant is located on township of province of Alicante (Spain) (Fig. 2a). This WWTP is small and treats the generated water by 2500 inhabitants as well as the water generated by the industrial companies that are installed in this village.

3.2. Results

3.2.1. Identification of the points

In a water treatment plant, the water goes through different stages (Figure 2b): pretreatment, primary treatment, secondary treatment, intensive secondary treatment and tertiary treatment. Not all exist in all plants since the decontamination requirement depends fundamentally on the type of contaminant that exists. However, what would follow is the order in which it has been specified in each of the stages.

3.2.1.1. Pretreatment

This stage is the first to proceed to the entry of water into the plant. Raw water contains all kinds of substances from both domestic and industrial use such as bulky objects to substances diluted in organic and inorganic water. For this reason, the water receives a decontamination process that tries to progressively eliminate all intrusive

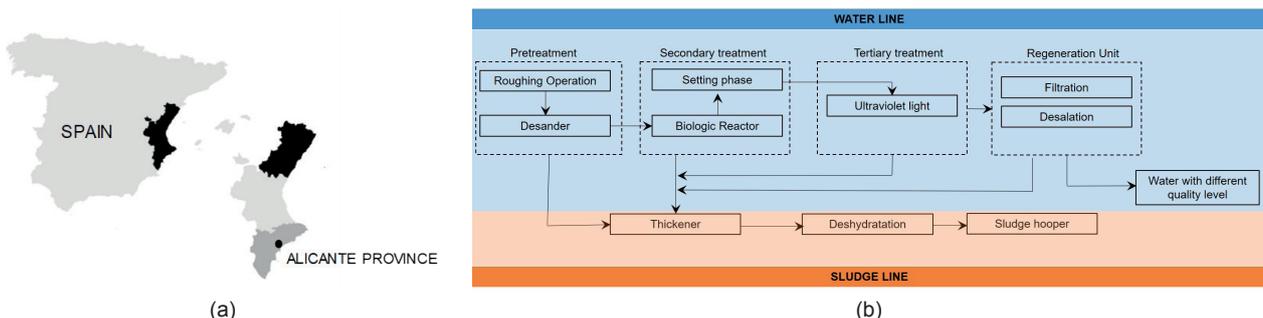


Figure 2 a) Case study; b) Water and Sludge line in WWTP.

and unwanted elements, going from the largest to the smallest. In this case study, there are two thick grating, one thick screw, one sieve, one strainer and a fine screw.

Three parallel blowers are in charge of giving the necessary air flow so that the fats separate from the water and come out afloat. These blowers are connected by pipes that carry the air to the air diffusers placed on the grill at the bottom of the channel.

3.2.1.2. Primary Treatment

The primary treatment consists of the removal of the settleable solid matter that is in the water and has not been deposited in the sand trap. The method is assisted by gravity, although flocculants can be used to obtain better results, which obtain a more efficient thickening. At this stage, the use of scrapers to remove the sludge from the bottom of the tank may be the only expense you have, however, depending on the use you have (if you have it), the expense of the thickener dispenser must be taken into account, and the possible presence of pumps when leaving or entering the tank if they are necessary.

In treatment plants that receive a small flow, this phase can be dispensed with if the process carried out in the secondary is prolonged aeration, which case must be treated as a consumption belonging to the secondary treatment. In this case study, there is no primary treatment.

3.2.1.3. Secondary Treatment

Secondary treatment is biological. The organic matter present in the fluid is degraded through the use of microorganisms, thus ensuring that the water is free from the vast majority of contaminants it contains. The existing processes to remove organic matter are very varied and depend fundamentally on the characteristics of the incoming flow, the available space and the criteria of the planner of the plant.

The existing consumption in this area of the plant depends fundamentally on the method used, since it can be from practically nil to being the highest of the entire plant.

The activated sludge process consists of two clearly differentiated phases in which first it would correspond to the purification with the help of microorganisms (biological) and a second one that would be very similar to that of the primary treatment (physical-chemical). The energy consumption in the biological will be of the same nature that was produced in the degreaser and desander, since in the reactor, when adding the activated sludge to the flow, the bacteria present will begin to consume the organic contaminants existing in the flow (mainly P and N). If the reactor is aerobic, it is necessary to add oxygen, since the dissolved in the water is insufficient. To add it, use will be made of air turbochargers that are in charge of giving sufficient air flow so that the digestion of microorganisms is optimal.

3.2.1.4. Tertiary Treatment

Tertiary treatment is purely optional in a WWTP and will often only be done when required, since the purpose of this part of the treatment is to make the water drinkable.

The treatments are very diverse and have different consumption levels, however the most common in their use are: ion exchange, adsorption, UV rays, microfiltration and ultrafiltration, reverse osmosis, electro-disinfection, ceramic membranes and advanced oxidation. These normal processes usually have a very high energy expenditure for the achieved purification, which is why they are not usually included.

3.2.2. Energy balance

As a consequence of the application of the methodology described with data from a real plant located in the province of Alicante (Spain). The identification of the consumption points, discretized, show an annual consumption of 64790 kWh/year. Grouped by phases can be seen in Table 3.

Table 3. Identified points in the case study.

| Treatment | Stage | Annual energy (kWh/year) | % |
|---------------------|---------------------------|--------------------------|---------|
| Pretreatment | Cleaning | 112,76 | 0,17% |
| | De-sanding and degreasing | 1582,35 | 2,44% |
| Secondary treatment | Reactor | 59355,13 | 91,61% |
| | Decanters | 3739,95 | 5,77% |
| TOTAL | | 64790,18 | 100,00% |

If the energy analysis is characterized in the pretreatment, the highest consumptions of the plant in this area correspond to the grease pumps and the drain pumps (Figure 3). Grease pumps have such a high consumption, as a consequence, they operate with a fluid with a specific weight different from water. Therefore, as these machines are specific for water, the efficiency decreases and energy consumption increases. As for the emptying machines, it represents 60,66% of the energy consumption given to the transferred flow and the performance of the machines for operating with fluids with a density far from that of water.

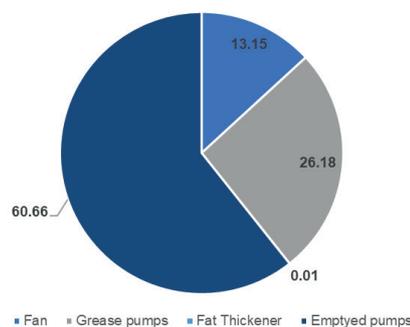


Figure 3 Example of consumed energy distribution in case study.

When the energy analysis is focused on secondary treatment, the highest consumption is located on the fans. These pumps represent above 75% of consumed energy in this stage (Table 4). This highlights the importance of installing a fan that has a good efficiency and high reliability since working above 1000 h each year. Table 4 shows

the identified points in which the energy consumption and operation time is shown.

Table 4. Identification of consumed energy points in secondary treatment.

| Location | Annual energy (kWh/year) | Time (h) |
|---------------------|--------------------------|----------|
| Reactor | 13956.13 | 1049.33 |
| Anoxic Stirrer 1 | 5155.97 | 387.67 |
| Anoxic Stirrer 2 | 4921.00 | 370.00 |
| Oxic Stirrer 1 | 1940.69 | 145.92 |
| Oxic Stirrer 2 | 1938.48 | 145.75 |
| Fan | 45399.00 | 321.67 |
| Magnetic levitation | 45167.00 | 320.33 |
| Variable Geometry 1 | 130.50 | 0.75 |
| Variable Geometry 2 | 101.50 | 0.58 |

3.2.3. Possibilities to recover energy and feasibility

Related to the location of possible energy recovery points, two locations are clearly favourable. The first point is the installation of a PAT in the discharge from the plant to the channel, taking advantage of 7 m w.c. (meter water column) The second point is the installation of hydraulic wheels in the pretreatment channels.

The flow of the plant was studied over time in which the flow in the effluent is analysed every 20 min (area where the PAT would be installed). Figure 4 shows the frequency histogram of flows when the rain flows are deleted in order to consider the minimum operated flow.

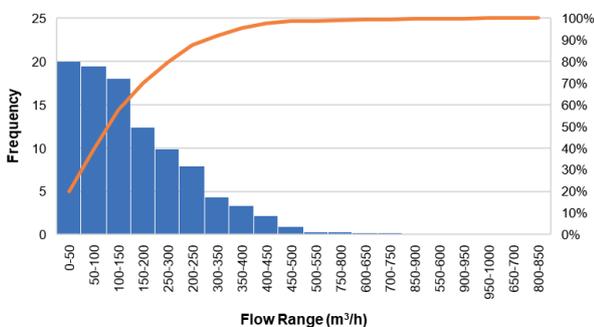


Figure 4 Example of consumed energy distribution in case study.

All the days belonging to the flow study have an absence of precipitations. If it should happen that on any of those days it has rained, it must be considered to omit this data since the real flow that usually enters the plant in one day would be falsified.

The flow-patterns variability is highly variable, changing from 0 to 3 compared to the mean value. However, there was a deposit in order to guarantee the flows were uniform and therefore, the recovery system operated under fixed point of flow and head.

Regarding the proposed PAT, machinery selection was carried out considering a radial machine with a specific number of revolutions equal to 79 rpm (m, kW). The selection was developed according to proposed methodology

by Romero et al., in 2018. The average flow was 270 m³/h (oscillating between the minimum and maximum flow of 30 and 1018 m³/h respectively) depending on the day. As a consequence of the lamination established in the outlet tank, an available head of 7 m w.c. is considered. The hourly recovery power is shown in Figure 5, estimating a total of 26200 kWh/year, representing an energy savings around € 3200 each year approximately.

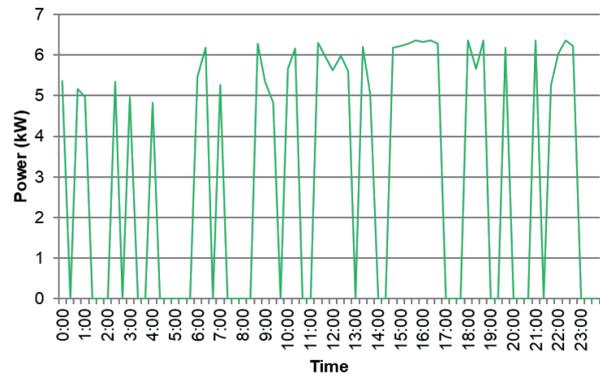


Figure 5. Hourly recovered energy using selected PAT

The hourly recovered energy is shown in Figure 6. As the figure shows, the potential energy recoverable by the proposed wheel is equal to 7,3 kWh/day, which is equivalent to 2666 kWh/year, assuming a saving in the energy consumption of €320/year approximately.

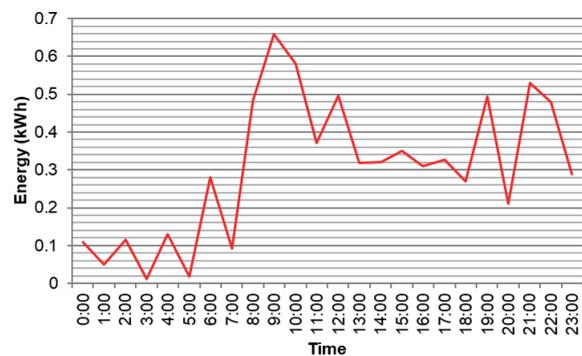


Figure 6. Hourly recovered energy using hydraulic wheel

4. Conclusions

This research presents a real application of energy recovery in WWTPs. Unlike the classic methods of energy recovery in the water line, which were usually discarded due to lack of viability, the hydraulic micro-machinery manages to recover part of this energy in a profitable way, as has been shown throughout this document. The low performance it shows compared to conventional turbines, is offset by very low costs that manage to pay off the investment, as can be seen in the case study, in less than 5 years.

The proposed methodology can be extrapolated to any type of wastewater treatment plant, following the 4 steps described: identification of consumption points, energy balance, location of potential improvement areas, energy recovery and feasibility analysis. The use of this

methodology in others WWTPs can help to identify the energy hotspot of the process allowing water managers to take decision in order to reduce the energy consumption as well as considering other alternatives, which improve the sustainability.

In this way, applying both methods, with PAT a 4% improvement in plant consumption would be achieved. These recovery values would help the continuous energy improvement of WWTPs, in which it is desired that in the future, through these and other recovery methods, a sufficient amount of energy is recovered so that it is

completely self-sustainable and even capable of certain cases of injecting energy into the grid, if combined with hybrid systems (photovoltaic panels and wind turbines).

Future lines of research must continue to establish criteria in the processes to search of increasing sustainability and reducing the operating costs of treatment plants. Apart from this, other optimization strategies must be considered, to improve the treatment processes. This improvement will affect a lower cost of irrigated water and therefore, an increase in the benefits of agricultural structures.

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