Energy Balance in the Water Cycle in Italy: State of the Art and Perspectives

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Abstract

Energy consumption for water withdrawal is the main contribution to energy consumption in drinking water supply systems. Energy consumption in large Italian WWTPs should be lower than about 25 kWh PE^{-1} y^{-1}. Energy recovery in Italian WWTPs takes place mostly by the exploitation of biogas from anaerobic digestion of sewage sludge.

Keywords

Benchmark • Drinking water • Electricity • Techno-economic-environmental assessment • Wastewater treatment

1 Introduction

There is an increasing interest towards energy efficiency in the water cycle due to the increasing cost for energy supply and the consequent emission of greenhouse gases and air pollution. In drinking water supply systems (DWSSs), the predominant electrical energy consumption (EEC) is due to pumping: in groundwater-based DWSSs, raw water extraction accounts for about 30% of the overall EE consumption, 69% being the contribution of water distribution. As regards surface water-based DWSSs, raw water extraction accounts for 10%, clean water distribution for 80% and treatment for 10% of the total EEC.

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Energy consumption in a wastewater treatment plant (WWTP) is affected by several factors, such as design capacity, population served, plant configuration, type of sewer system, inlet and outlet wastewater quality, electrical efficiency of electro-mechanical devices and age of the plant; as a consequence, the EEC of a WWTP can vary from 1.5 to 40 kWh kg $BOD^{-1}_{removed}$. Wastewater pumping and bioreactor aeration are responsible for the major contribution to the overall EEC; sludge recirculation and aerobic stabilisation can be comparably relevant in small WWTPs (Foladori et al. 2015).

The energy potential of wastewater is quite interesting (about 500 kWh PE^{-1} y^{-1} of thermal energy and about 150 kWh PE^{-1} y^{-1} of chemical energy). Actually, renewable energy recovery (through biogas production and utilisation, hydropower or heat from wastewater) is quite practicable. Consolidated sludge pre-treatment options (e.g. hydrolysis) are available for boosting the anaerobic stage. Another interesting solution is the sludge co-digestion with other organic substrates with high methane yield. Moreover, biogas cleaning for producing bio-methane to be used in higher efficiency machineries is being practised in large plants. In addition, research is focusing on Microbial Fuel Cells (MFCs), hydrogen and methanol production. In the field of sludge combustion, pyrolysis-gasification is being proposed, together with Organic Rankine Cycle (ORC) systems for recovering energy from low-temperature streams. Finally, wind and solar energy exploitation is another practicable option.

The workgroup "Water treatment plant management" (WG), which has been active at the University of Brescia since 1998, has focused on the water-energy nexus for about 10 years. As regards the DWSSs, the WG conducted a research aimed at analysing EEC in seven full-scale Italian DWSSs. Italian companies usually have data concerning a global EEC in DWSSs, resulting from the electricity bill, and they do not carry on any analytical monitoring of EEC. This prevents them from having any control of EEC in each single stage of the DWSS and from identifying opportunities

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for reducing energy consumption in DWSS. The first aim of the research was to divide this all-inclusive EEC data into three main parts, respectively, related to water withdrawal, treatment and distribution. Moreover, the objective was to focus on the drinking water treatment plant (DWTP) to detect EEC related to each drinking water treatment process, in order to quantify the incidence of each treatment phase in the whole DWTP.

The WG carried out also one of the largest surveys in Europe about energy consumption of WWTPs, based on a total population equivalent of more than 9,000,000 PE, with the aim of adding a new benchmark to the international framework of energy consumption in WWTPs. Moreover, a survey on about 600 Italian WWTPs (corresponding to approximately a quarter of the national load of treated sewage) was carried out to understand the current status of implementation of energy recovery options (Papa et al. 2017).

In case a new (water or wastewater) treatment plant has to be built, the entire design-to-construction process can focus on optimising the interactions among the different treatment units. Thus, original solutions including energy saving and recovery can be properly addressed. On the contrary, retrofitting existing plants is indeed a challenge. The choice either or not to implement new solutions is quite a difficult task: consequences at various levels (environmental, economic, social, technical and administrative) must be carefully evaluated. An example of such a kind of analysis is shortly reported here for the case of wastewater treatment.

2 Materials and Methods

The investigation on the EEC in DWSSs was carried out on seven different DWSSs, managed by two drinking water companies. The DWSS water flow ranges from 78,000 to 634,682 $m^3\ y^{-1}$, supplying between 1000 and 6223 inhabitants. Raw water is taken from groundwater in all the plants and the main contaminants are iron, manganese, ammonia and arsenic. Only two DWTPs apply non-conventional treatments (ozone oxidation and reverse osmosis filtration, respectively), whereas the remaining plants adopt conventional schemes (such as air oxidation, sand filtration, disinfection by sodium hypochlorite or chlorine dioxide). The monitoring activity was carried out using two different methodologies depending on factors as the availability of remote data, the type of data recording, of installed equipment, the availability of skilled personnel, etc. A detailed description of the methods applied is reported in Collivignarelli and Sorlini (2014).

A number of 289 plants located in Italy were included in the WWTP survey. Data were obtained from a questionnaire compiled by the treatment plant managers of 19 large multi-utility bodies. In total, 45 variables were considered in the survey. Three energy consumption indicators (ECIs) were calculated for each WWTP: ECI_{m3} (=daily energy consumption/daily treated volume); ECI_{COD} (=daily energy consumption/daily COD load removed); ECI_{PE} (annual energy consumption/PE served). Details are in Vaccari et al. (2018).

As for the investigation on the extent of implementation of resource recovery options in Italian WWTPs, an easy-to-fill-out questionnaire was elaborated and sent out to several water management companies. The survey outcomes were parameterised according to WWTP size. For details, the reader may refer to Papa et al. (2017).

Finally, for discussing the implications of improving the energy production in existing WWTPs, commercially available systems were supposed to be used for retrofitting two plants of different size (50,000 and 500,000 PE): a detailed evaluation of technical, social, economic, administrative and environmental aspects was carried out, following the procedure described in Bertanza et al. (2018).

3 Results and Discussion

The survey on DWSS showed that the EEC for water withdrawal and distribution represented from 76 to 96% of the total: the specific consumption for water withdrawal increased from 0.184 to 0.433 kWh m^{-3} with increasing the aquifer depth, while the specific consumption related to the distribution system was a little lower (from 0.146 to 0.325 kWh m^{-3}). On average, as regards the conventional DWTPs monitored, treatments accounted for 8% of the total DWSS energy consumption. In both DWTPs using more energy-consuming unconventional technologies, the impact on total DWSS energy consumption was greater, ranging from 18% in case of ozone oxidation to 24% in case of reverse osmosis. When ozone was used as oxidant, the oxidation phase covered about 92% of the DWTP energy consumption, due to EEC of the ozone generator (responsible for 47% of the ozone oxidation consumption), the booster pump (24%) and the air compressor (18%). When oxygen was used instead of ozone, the specific EEC was reduced to 0.019 kWh m^{-3}. Among the conventional treatments, sand filtration had a specific consumption of 0.007 kWh m^{-3}, due to sludge extraction pumps, backwashing pumps and blowers. Finally, EEC of disinfection was negligible when sodium hypochlorite was used while it increased with chlorine dioxide due to in situ generation.

As concerns EEC in WWTPs, the median value of ECI_{m3} for all the plants was 0.45 kWh m^{-3}. Observing the single classes, the higher median (0.60 kWh m^{-3}) was for small plants in the class <2000 PE. The classes from 2000 to over 100,000 PE had medians in the range 0.28–0.42 kWh m^{-3}, not significantly different among the classes. The median of ECI_{PE} was 70 kWh PE^{-1} y^{-1} for the entire data sample, but it decreased significantly for increasing capacity of the plants, passing from 120 kWh PE^{-1} y^{-1} for plants <2000 PE, to 68.3 for plants with 2000–10,000 PE, to 53.3 for plants with 10,000–100,000 PE and to 35 for plants >100,000 PE. The indicator ECI_{COD} had the same trend, passing from 3.2 kWh kg_{COD}^{-1} for plants <2000 PE, to 1.76 for plants with 2000–10,000 PE, to 1.45 for plants with 10,000–100,000 PE and to 0.85 for plants >100,000 PE. The statistical analysis confirmed that ECI_{COD} and ECI_{PE} had a high positive correlation, which means that the two indicators provided the same information.

Energy recovery in the Italian WWTPs takes place mostly by the exploitation of biogas from anaerobic digestion of sewage sludge. This option is common only in large WWTPs (almost half). Heat is the main product, but there is also room for electricity production through co-generation systems. Interestingly, 80% of WWTPs exploiting biogas also implement some actions for increasing its production (mechanical or chemical sludge pre-treatment, co-digestion with other organic substrates and enhanced primary sedimentation). On the other hand, hydropower and heat recovery from wastewater streams were indicated in 3 and 1 WWTPs, respectively. Finally, 17 WWTPs produce energy by means of photovoltaic systems.

By simulating the effect of WWTPs retrofitting scenarios, it was shown that, actually, both small (50kPE) and large plants (500kPE) may substantially achieve the power self-sufficiency. Nevertheless, for small plants, potential criticalities should be accounted for, such as the increased complexity of the upgraded plant, the lower reliability of the whole system, the requirement of skilled personnel, new permissions, licences and administrative constraints, a greater use of reagents and a considerably higher overall cost (personnel and depreciation of new equipment being the most relevant items). On the contrary, the large plant case study received a positive overall score: the impact of potential critical aspects, in fact, is less relevant if compared to the small plant, because the large plant was supposed to be already equipped with anaerobic digestion and primary sedimentation.

4 Conclusion

In DWTPs using unconventional technologies, the impact of treatment on the total DWSS energy consumption is greater compared to conventional plants, ranging from 18% in case of ozonation to 24% in case of membrane filtration by reverse osmosis. On average, for the monitored conventional DWTPs, treatments account for 8% of the total DWSS energy consumption. Although the main EEC in the DWSSs is for water pumping, the EEC in the treatment plant should not be neglected, especially if advanced technologies (e.g. membrane systems) or in situ generated oxidants (e.g. ozone or chlorine dioxide) are required. Therefore, it is important to adopt high energy demanding technologies only in case of highly contaminated water and to use appropriate pre-treatments to improve water quality before energy-consuming treatments (such as membrane filtration).

About EEC in WWTPs, the survey allowed to identify the following benchmark values: 23 kWh PE^{-1} y^{-1} for large plants (more than 100,000 PE served), 42–48 kWh PE^{-1} y^{-1} for intermediate size plants (2000–100,000 PE) and 76 kWh PE^{-1} y^{-1} for small plants. Those targets can be reached by changing old electrical devices with high efficiency ones, installing inverters and adequate automation in the pumping stations, adopting controls based on DO in aeration tanks, optimising the air distribution in aerobic stabilisation basins (Campanelli et al. 2013).

In addition, the Italian survey revealed that there is room for improving energy production, the exploitation of biogas being the most common action, but diffused only in large WWTPs. Nevertheless, moving in this direction means that the plant configuration must be modified and the operation strategies adjusted consequently, so that retrofitting existing plants may pose a challenge. Hence, since energy saving and recovery represent surely a task to be encouraged, a very detailed (holistic) investigation has to be performed, case by case, in order to highlight all those aspects that can result in critical situations, so as to guide, eventually, to the definition of the best upgrading option.

References

Bertanza, G., Canato, M., & Laera, G. (2018). Towards energy self-sufficiency and integral material recovery in waste water treatment plants: assessment of upgrading options. *Journal of Cleaner Production, 170,* 1206–1218.

Campanelli, M., Foladori, P., & Vaccari, M. (2013). *Consumi elettrici ed efficienza energetica nel trattamento delle acque reflue*. Bologna, Italy: Maggioli Editore. ISBN 978-88-387-8368-5.

Collivignarelli, C., & Sorlini, S. (2014). *Il consumo energetico nei sistemi di approvvigionamento* (idropotabile ed.). Bologna, Italy: Maggioli Editore. ISBN 978-88-916-0586-3.

Foladori, P., Vaccari, M., & Vitali, F. (2015). Energy audit in small wastewater treatment plants—Methodology, energy consumption indicators and lessons learned. *Water Science and Technology, 72,* 1007–1015.

Papa, M., Foladori, P., Guglielmi, L., & Bertanza, G. (2017). How far are we from closing the loop of sewage resource recovery? A real picture of municipal wastewater treatment plants in Italy. *Journal of Environmental Management, 198,* 9–15.

Vaccari, M., Foladori, P., Nembrini, S., & Vitali, F. (2018). Benchmarking of energy consumption in municipal wastewater treatment plants—a survey of over 200 plants in Italy. *Water Science and Technology, 77,* 2242–2252.