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Energy consumption reduction in a waste water treatment plant

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Abstract

Against the background of energy transition, the operators of large municipal WWTPs have come to understand the importance of issues related to energy use. Since about 2000, one such operator in the Paris conurbation, Syndicat Interdépartemental pour l'Assainissement de l'Agglomération Parisienne, has set up actions enabling energy consumption optimization, to reduce both its costs and the associated environmental impacts. Using energy (electricity, gas, fuel, and biogas) meters for sectorial recording, consumption has been mapped at various scales (macroscopic, plant, process). Electric power has emerged as the leading energy source in WWTPs and biological treatment processes (aeration) as the main consumers. On this basis, energy use optimization paths have been described, needing action at three levels. First, operating cost optimization should involve the full treatment chain, including all costs (reagents, etc.), to make the best operating choices. Two further levels, comprising process and equipment, should then be considered to determine suitable action sets.

Key words: electricity consumption, energy efficiency, methodological framework, wastewater treatment plant

INTRODUCTION

The regulations governing wastewater treatment have evolved substantially since the mid-1990s. Enforcement of the legislation incorporating the requirements of the EU Urban Waste Water Treatment Directive (UWWTD 1991) and Water Framework Directives (WFD 2000), and, more recently, the French 2012-2018 Sewerage-Directed National Action Plan, have led to ever-stricter demands on the quality of water discharges to the environment. As such, the largest French conurbations have pursued a policy of wastewater treatment plant (WWTP) building and upgrading. Efficient technologies for physicochemical and biological treatment of wastewater and by-products have been integrated into the plants in the main conurbations – e.g., physicochemical lamellar settling, biofilters, membrane bioreactors (MBRs), thermal dryers, etc. While these technologies enable high-quality treatment, their operation involves high power consumption.

The Energy Transition Act for Green Growth (validated by the Constitutional Council on August 12, 2015) outlines the mid-century headline goals of the new French energy model. The more thrifty and sustainable step includes a 40% abatement of greenhouse gas emissions and a 20% reduction in energy consumption, both by 2030; a 30% reduction in fossil fuel use by 2050; and the promotion of renewable energy to reach 32% of energy consumption and 40% of electricity generation.

In this context of high performance with low energy costs, the major industrial actors, especially WWTP operators, are tackling the issues stemming from energy expenditure (Müller *et al.* 2006; Friedrich *et al.* 2008; Chudoba *et al.* 2011). Around Paris, the Syndicat Interdépartemental pour l'Assainissement de l'Agglomération Parisienne (SIAAP), which is responsible for the transport and treatment of wastewater produced by 8.5 million people in the Ile de France region (2.5 million cubic meters per day), has worked since about 2005 to measure and optimize energy consumption.

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The aims are abatement of the consumption and costs involved in energy purchase, and consequent mitigation of the associated environmental impacts. The approach is based on the requirements of the ISO 50 0001 energy management standard. To that end, energy use must be mapped to identify the largest consumers. Subsequently, individual actions plans are developed and followed up (benchmarks) to mitigate power consumption.

The purpose of this paper is to describe the approach implemented by SIAAP in connection with energy efficiency. As a first step, the main consumers were identified through various scales of observation. The macroscopic scale enabled determination of the most widely used energy source. The main consumers were thus identified at plant and workshop levels. Subsequently, using implementation examples at SIAAP, an optimization methodology taking the treatment chain, process and equipment levels into account was determined. Relevant monitoring benchmarks were also defined.

OBSERVATION SCALES

Three observation scales can be distinguished with respect to energy consumption: macroscopic, plant and process. The approach has the twin goals of (1) mapping consumption at various scales, and (2) identifying the main consumers, so that priorities can be assigned to optimization actions.

To make the observation step efficient, all energy sources must be considered. Consideration in this paper covers both imported energy (electricity, natural gas and fuel oil) and the biogas produced at the plant.

Macroscopic scale

The SIAAP plants

The 2.5 Mm^3 of wastewater disposed of daily in the SIAAP drainage basin is transported to plants featuring full treatment process trains (Figure 1).

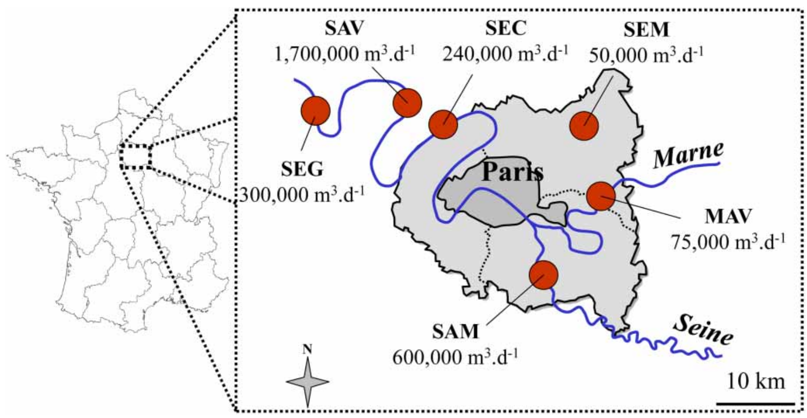

Figure 1 | SIAAP's wastewater treatment plants.

The plants, which are upstream and downstream of Paris, handle dry weather flows of between 50,000 and 1,700,000 m^3/d. Several technologies are applied to treat the wastewater and sludge. The Seine Aval (SAV) plant combines conventional biological treatment and biofiltration to treat the wastewater, and the sludge process includes high pressure heat treatment. The Seine Grésillons (SEG), Seine Centre (SEC) and Marne Aval (MAV) plants use biofiltration for wastewater treatment.

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The sludges from both SEC and MAV are incinerated after dewatering, and SEG uses thermal drying. The Seine Amont (SAM) plant uses activated sludge to treat wastewater, and several processes (drying, incineration, and pyrolysis) for its sludge. Lastly, the Seine Morée (SEM) plant, commissioned in late 2013, uses membrane filtration for wastewater treatment.

Imported energy

The macroscopic approach involves assessing the total consumption of each energy type (electricity, natural gas, and fuel oil) imported by the plants. That work was done between 2010 and 2014, along with determination of the costs incurred (Figure 2). These energy inputs do not account for total plant consumption, which also includes the energy produced internally – e.g., biogas, and from turbines, photovoltaic panels, etc.

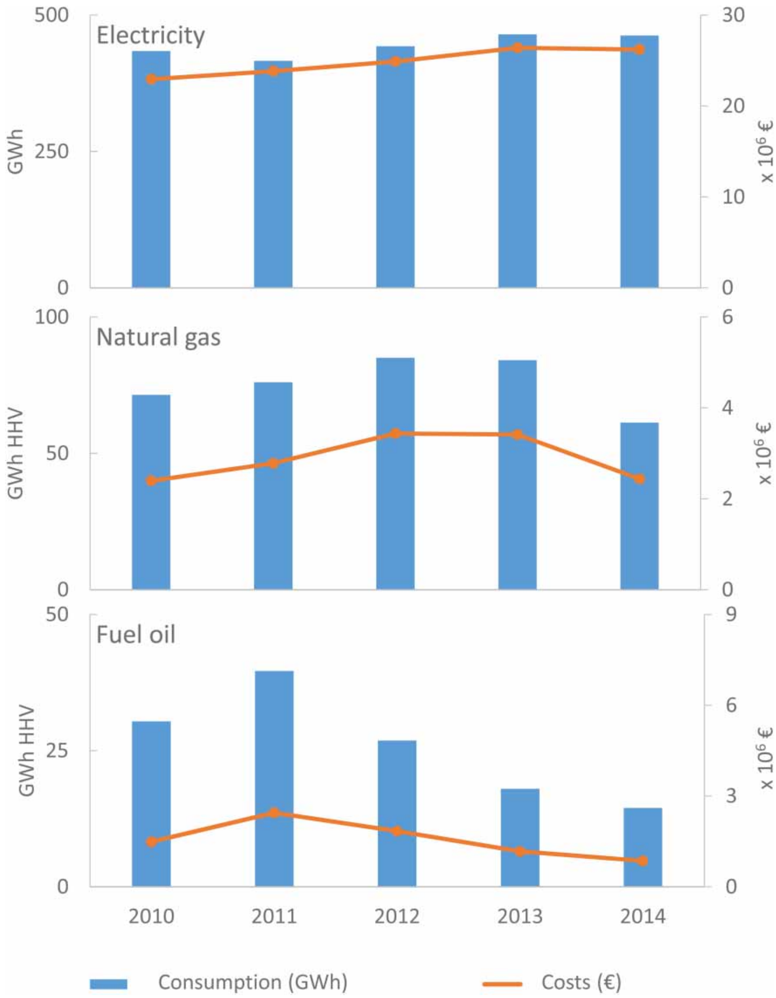

Figure 2 | Consumption of imported energy (electricity, natural gas and fuel oil) at the SIAAP plants between 2010 and 2014. For natural gas and fuel oil, consumptions are expressed as the HHV.

To enable comparisons, the energy consumption, excluding that of electricity, has been converted to Watt-hours (Wh) taking the higher heating value (Wh HHV) into account. For natural gas, the conversion factor is 11.4543 kWh HHV/Nm^3. The fuel oil lower heating value (LHV) is based on 9.92 kWh LHV/l to which the conversion factor kWh HHV = 1.1 kWh LHV has been applied.

Electricity consumption ranged from 416 to 465 GWh over the period. Optimization carried out over several years produced results in 2011 but these were concealed subsequently when new

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processes were commissioned. For instance, the additional treatment of nitrogen SAV in 2012, enlargement of SEG in 2013 and the new membrane treatment plant SEM in 2013, which are critical to meeting the regulatory objectives, imply an electrical input of 465 GWh/year for SIAAP as a whole; a level that remained unchanged in the last two years. The costs incurred for that level of consumption follow the same trend and remain flat at 26 M€/a.

During the 2010–2014 period, total natural gas consumption by the plants ranged from 61 to 85 GWh HHV/year, the lowest consumption occurring in 2014. The sharp increases experienced in 2012 (sludge treatment, SAM) and 2013 (sludge treatment, SEG) were offset by significant decreases at SAV and SEG in 2014, because of reduced operating times. The costs incurred by buying natural gas, between 2.4 and 3.4 M€/a over the period, were affected by a marked price rise. In 2014, with the same total gas cost – 2.4 M€ – as in 2010, the imported quantity of natural gas was 15% less.

The consumption of fuel oil, which is primarily used for running the diesel generators and incinerators at SAV, SEC and SAM, fell between 2011 and 2014. Some 40 GWh HHV were used in 2011 but usage was down to 14 GWh HHV in 2014. On the whole, the lower consumption is due to steps taken at the plants, especially SAV and SAM where consumption dropped by over 90%.

It is thus clear that, among the imported energies, electric power predominates. Natural gas and fuel oil purchases are between 5 and 8, and 10 and 30 times less costly, respectively, than those of electricity. Accordingly, if priorities are to be given when investigating consumption optimization and reduction, one should focus on electric power and its principal consumers.

Energy consumed

In order to complete energy mapping for 2014, the amount of electricity imported by each plant was compared with the total energy requirement (Figure 3). The latter was established by adding up all the energy used by the plants (electricity, natural gas, fuel oil, and biogas) to treat their influents and the resulting sludge. The amount of biogas consumed, but not flared, was calculated using the conversion factor 6.42647 kWh LHV/m^3 (kWh HHV = 1.1 kWh LHH).

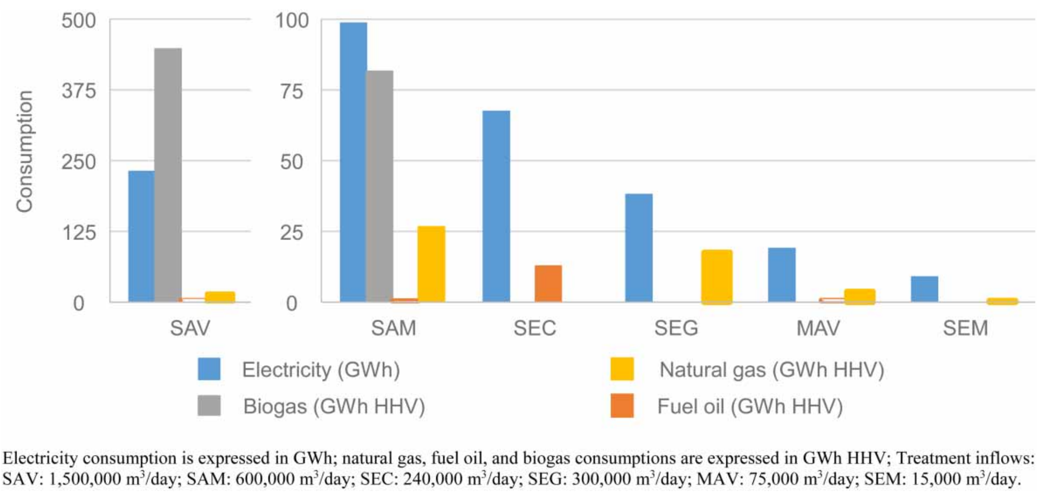

Figure 3 | Consumptions of energy from various sources (electricity, natural gas, fuel oil, and biogas) per treatment plant in 2014.

The largest electricity import was at SAV, with nearly 230 GWh in 2014. The quantities imported by SAM, SEC, SEG, MAV and SEM were 98, 67, 38, 19 and 8.9 GWh, respectively. That distribution is

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linked, primarily, to the flows treated by the plants. SAV treated the majority of the wastewater handled by SIAAP (65%), SAM treated almost 20%, SEC some 9%; and SEG, MAV and SEM, 4, 2 and 0.3% of the influent wastewater, respectively.

The other energy types were used mainly in sludge treatment. For instance, biogas – from digestion – is used at SAV and SAM, and accounts for 447 GWh HHV and 81 GWh HHV at them, respectively. Most of the fuel oil is used at SEC (12 GWh HHV), for incineration. Natural gas is used mainly at SAM (26.6 GWh HHV) and SEG (17.6 GWh HHV) in the sludge heat treatment facilities.

As a proportion of the total energy usage for wastewater and sludge treatment, electricity comprises 33%, 48%, 84%, 68%, 82% and 94% for SAV, SAM, SEC, SEG, MAV and SEM, respectively. The small (less than 50%) proportional use of electricity at SAV and SAM arises primarily from the use of biogas from the digesters in the treatment processes. This is true for the majority of plants using locally produced biogas (Wett *et al.* 2007). That source makes it possible to generate 65% of the energy needed at SAV, and highlights the efforts made over several years to optimize energy consumption and minimize the purchase of non-renewable energy.

In WWTPs where electricity comprises more than 60% of the energy input (SEC, SEG, MAV, SEM), the use of renewable energy and heat needs optimization. SEC and MAV have fluidized bed furnaces, and SEG has dryers as sludge treatment, but only a small proportion of the heat available is used in processes in any of them. While SEM manages its whole sludge disposal on trucks (after dewatering), imported energy is its primary source for wastewater treatment.

Plant scale

When macroscopic mapping is complete, the observation scale must be changed to establish guidelines for the optimization actions. Hence, plant-level is the next level of observation. This part of the paper is focused on the SAV site, as its energy consumption is the highest among those discussed because of the huge flows handled (578 Mm^3 in 2014). In addition, the presence of meters in the various workshops provides useful insights.

Treatment process trains

Under normal conditions, the SAV process train is suitable for complete treatment of carbon, nitrogen and phosphorus. The emission thresholds are set out in a prefectural decree incorporating, inter alia, the UWWTD limits (annual abatement efficiencies of 70% for total nitrogen and 80% for total phosphorus). The conventional process trains are illustrated in Figure 4.

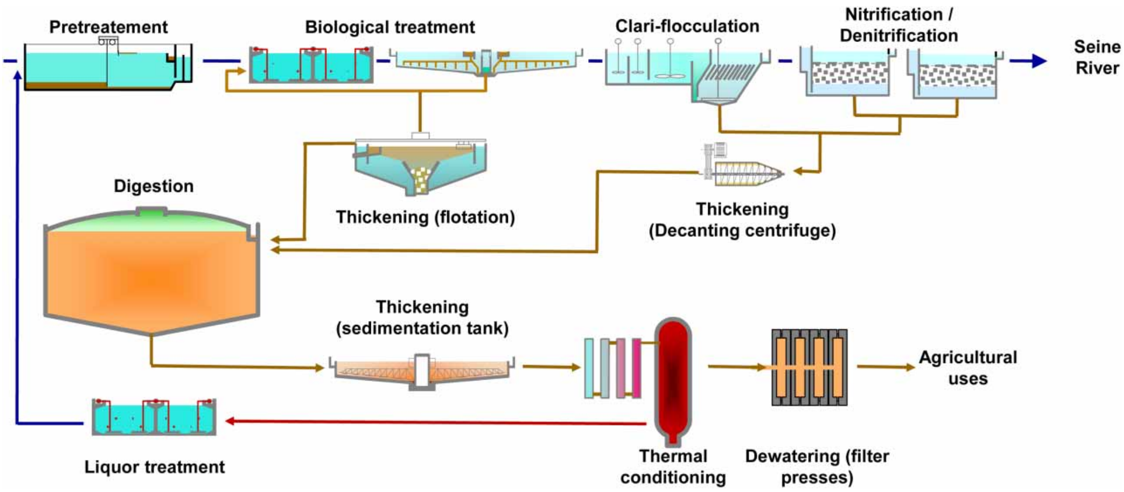

Figure 4 | Schematic diagram of the wastewater and sludge process trains at SAV.

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The wastewater treatment process train comprises four main units. After *pretreatment*, (screening, grit removal and oil separation), the effluent is treated *biologically* (primary settling tank, aeration tanks and secondary clarifiers). Organic content and some of the suspended solids are abated in that step. Subsequent *physicochemical* phosphate removal occurs in the clarifier. Lastly, comprehensive treatment of nitrogen is carried out by *nitrification–denitrification*, before discharge to the river Seine.

After the biological and nitrification–denitrification processes, sludge treatment comprises several thickening steps using various technologies (flotation, decanting centrifuge, etc.). The thickened sludge is fed to digesters suitable for producing biogas. On completion of digestion, further thickening is conducted by sedimentation before thermal conditioning (20 bars, 200 °C), after which the sludge is dewatered using filter presses before disposal. The thermal treatment liquors are treated in MBRs, which combine biological treatment with membrane separation, and then returned to the plant inlet. The final step comprises incinerating the fats and foul smelling gases (not shown on the figure).

All thickening steps (before and after digestion) have been grouped to make a simple, clear energy benchmark. The current arrangement does not enable individualization of all consumers. Thus, odor treatment-related electricity consumption is included in the total consumptions of the associated processes.

Electricity consumption per process

Gas turbines (TAGs) generate electric power from biogas, which comes in addition to the 230 GWh/a of electricity purchased at SAV. The additional 38.5 GWh/a has been taken into account in the treatment process consumption breakdown (Figure 5).

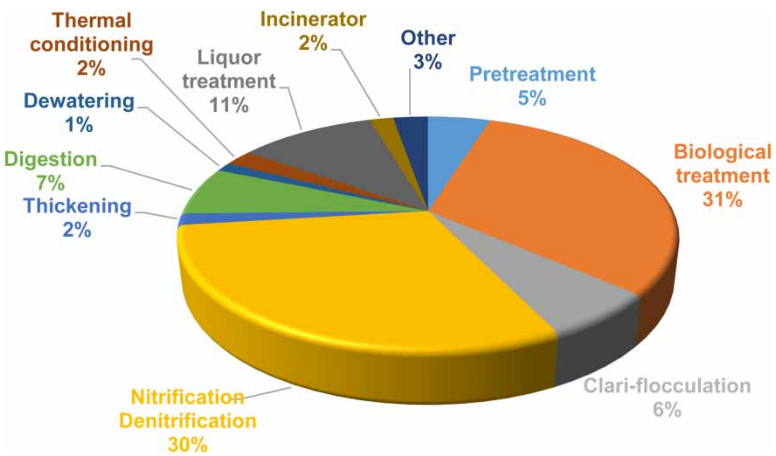

Figure 5 | Distribution of electricity consumption per production unit at SAV in 2014.

Over 70% of the electricity is consumed by the wastewater treatment process train at SAV (pretreatment, biological treatment, clari-flocculation, and nitrification/denitrification), while the treatment of process liquors reaches 11%. If the latter is included in the wastewater train, more than 80% of electricity consumption arises in the wastewater chain. The sludge treatment chain consumes 14% of the plant's electricity, of which about half (7%) is due to digester operation (stirring compressors).

Generally speaking, the three processes that are most energy hungry are biological (activated sludge, nitrification/denitrification and liquor treatment with membrane bioreactors). Between them, these consume 72% of the electricity at the site.

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Other energy consumption

More than half (66%) of the SAV site's energy input is derived from non-electricity sources (biogas, natural gas, fuel oil). Figure 6 shows the various uses to which this energy is put.

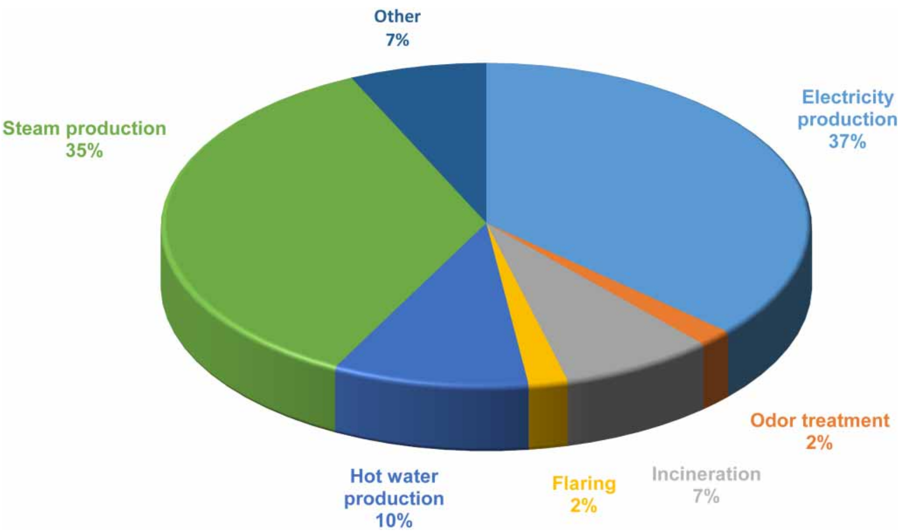

Figure 6 | Distribution of energy consumption (biogas, natural gas and fuel oil) at SAV by type of use in 2014.

In total, 471 GWh HHV/a are generated at SAV, with biogas accounting for 456 GWh HHV. More than a third is used for generating electricity through TAGs – i.e., 173 GWh HHV of biogas is used to produce 38.5 GWh of electricity. The conversion efficiency of the turbines is about 22%, slightly above the normal range of 10 to 16% (Mckendry 2002). Another 35% enables steam production for sludge thermal conditioning, while the hot water used for heating the premises consumes some 10%. Incinerating the baking gases and fats requires nearly 7% of the plant's energy. Odor treatment – 2% of site energy – is linked to the thermal treatment of odors of only the liquor treatment facilities. Lastly, it is emphasized that only 2% of the biogas produced is flared.

Process scale

Once plant-wide mapping is complete, the mesh-size should be reduced to identify energy-intensive equipment and develop suitable action sets for relevant and efficient optimization. Processes are the third observation level, at which it appears that aeration is significant in the two most energy-intensive units – nitrification/denitrification and biological processing. Aeration accounts for ca. 56% of total consumption in biological processing and 45% for nitrification/denitrification. Similarly large shares of energy consumption arising from aeration have also been reported from other SIAAP plants (Rocher *et al.* 2012) and elsewhere (Ingildsen 2002; Krzeminski *et al.* 2012; Rieger *et al.* 2012).

METHODOLOGICAL APPROACH FOR ENERGY CONSUMPTION OPTIMIZATION

The goal now is to provide a methodological approach that can be applied to WWTP to determine suitable optimization guidelines. Such determination can be made jointly at several levels of action. First, the whole treatment chain should be considered to gain a broader vision than that from a purely energy-directed approach. Two further levels, comprising processes and equipment, should

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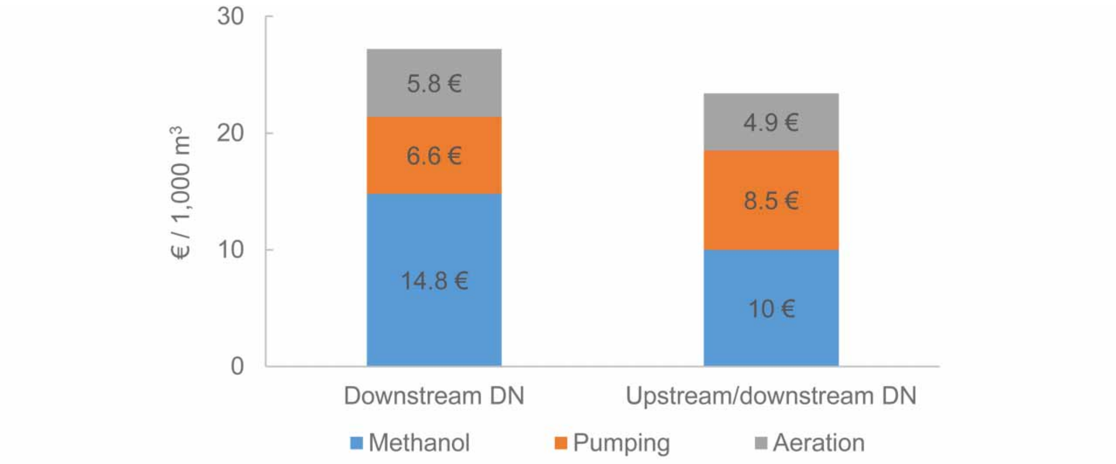
then be considered to determine suitable action sets. An example from SIAAP is used for each of these levels to illustrate the application of the optimization methodology.

Please note, for clarity, that a treatment chain may comprise from one to several processes, and that each process may involve one or more items of equipment.

Scope of action

Treatment chain level

Rocher *et al.* (2012) compare the costs relating to use of various treatment chains. The purpose of their work was to investigate cost, and therefore consumption, variations under two different operating modes at SEC (Figure 7).



Downstream DN: denitrification is carried out after nitrification step and the addition of a carbon substrate (methanol). Upstream/downstream DN: a portion of the nitrified effluent is returned to the start of the organic matter removal step, so that only polishing is required in downstream denitrification, using the methanol carbon substrate.

Figure 7 | Comparison of the operating costs (electricity + reagent) of two different process chains: downstream denitrification and upstream/downstream denitrification, respectively, at SEC (Rocher *et al.* 2012).

In downstream denitrification (downstream DN), after thorough removal of organic matter (needs aeration), the effluent is nitrified (aeration) and then denitrified (needs exogenous carbon substrate, methanol). In this case, only three pumping steps are used to deliver effluent in each treatment step (organic matter removal, nitrification, denitrification). The pumping costs are 6.6 €/1,000 m^3 of treated water with costs for aeration and methanol of 5.8 and 14.8 €/1,000 m^3, respectively. In upstream/downstream denitrification (upstream/downstream DN), a portion of the nitrified effluent is recirculated to the start of the organic matter removal step. In this operating mode, aeration costs are lower at 4.9 €/1,000 m^3, since the organic matter removal requires no additional oxygen. On the other hand, pumping costs amount to 8.5 €/1,000 m^3 because an additional (recirculation) pumping step is required to move the necessary volumes of water (60 to 80% hydraulic recirculation). In this mode, the cost of methanol is 10 €/1,000 m^3, since it is used only for polishing and not for full nitrate treatment.

Thus, with respect only to energy consumption, the downstream DN mode seems the more advantageous. Pumping and aeration costs amount to 12.4 €/1,000 m^3, compared to €13.4 €/1,000 in upstream/downstream DN. Considering the whole treatment chain, however, it is clear that the latter mode is better, with total operating costs that are 14% lower.

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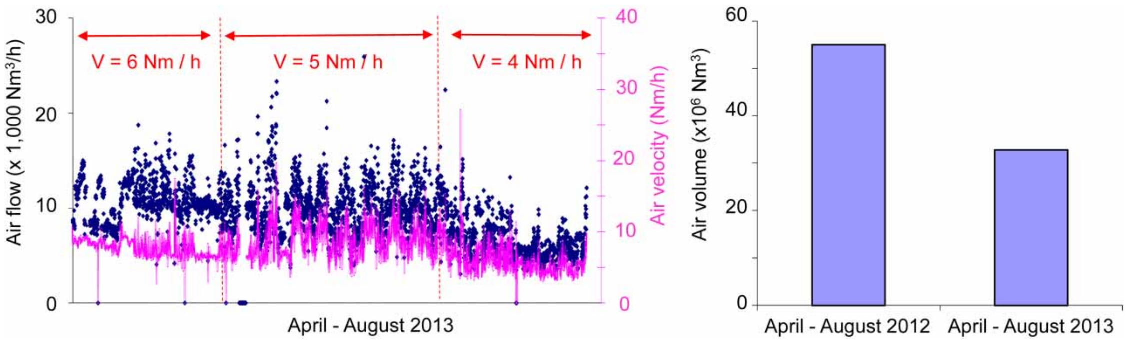

Figure 8 | Temporal variation in aeration flows (plot), air flow velocities (line) and minimum rated velocity ($V_{m/h}$) in the nitrification stage at SEG in 2013 (left), and comparison of the total air volumes injected over the same time periods before and after process adjustment (right).

Operating cost optimization is, then, an integrated approach necessarily involving the whole treatment chain, including all inputs, i.e. all reagents, gas and electricity. The method-based approach should then make it possible to optimize the energy consumption of the various steps making up a chain.

Process level

Returning to energy mapping, the nitrification that comprises part of the nitrogen process train is energy-intensive, because of aeration. Aeration minimization has been attempted in nitrification at SEG and this is taken as a model illustrating the method-based approach. Following observation of injected air flows into the biofilters (Biolest®, Stereau), changes have been made to the air blowing control system (Figure 8).

The regulation parameter taken into account at SEG was the minimum air velocity in the filtering medium. Initially at 8 Nm/h, it was reduced to 6, 5 then 4 Nm/h (dashed markers). While the injected air flows decreased substantially there was no detrimental effect on effluent quality on completion of nitrification. There was no effect on biofilter functioning (anaerobic zone, quality of washing, etc.). The total volume of air injected in 2013 was 40% lower than that injected in the same period in 2012. Based on a rate of 0.033 kWh/Nm^3 of produced air, the energy consumption reduction in 2013 has been estimated at around 0.7 MWh per ton of removed nitrogen.

Aeration regulation formulae include many parameters that can be refined during operation. The changes should take into account the constraints resulting from biological activity, as well as any specific to the site concerned.

Equipment level

It appears that aeration processes are the principal process train energy consumers. Hence, the option of fitting meters on air compressors is relevant. For instance, the two aerators at SAM were fitted with electricity meters and the recorded values have been compared with the air flows produced by each system (Figure 9).

The two aerators consume electric power for air production for the same process. Aerator 2 needs 9 to 18 MWh less to produce the same air flow. That difference, which is linked to the network layout and machinery operation, could have induced excess consumption of between 3 and 6 GWh at SAM in a full year. Thanks to the metering and these findings, actions could be taken so that energy expenditure matches needs more closely.

Thus, equipment level is the third relevant intervention level against a background of optimized energy consumption. To determine the action set(s) required, the energy-extensive systems should

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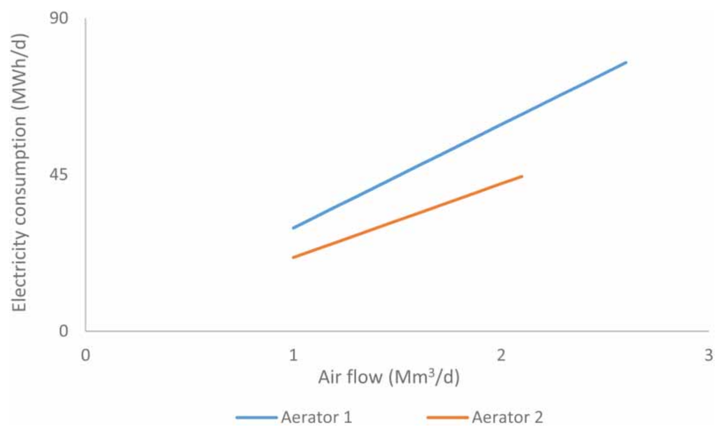

Figure 9 | Relationship between energy consumption (MWh) and the air flow produced by the aerators at SAM.

be identified and fitted with electricity meters. Subsequently, the set(s) can be defined on the basis of the findings, taking each system's specific constraints into account.

Methodology for monitoring optimization actions

Whatever the intervention level, consumption metering is required to optimize energy use. Once a metering plan is developed and implemented, relevant benchmarks can be selected to enable monitoring and comparison of consumptions. Benchmarks with precisely defined scopes should be devised to minimize errors, particularly in comparisons. Apart from performance monitoring, optimization actions should be subject to an integrated follow-up of key parameters, particularly with respect to nitrogen.

Selection of benchmarks

At plant scale. It is helpful for treatment plant operators to know the energy consumption of the entire process train. Most treatment plant energy consumption surveys focus on electricity (Devi *et al.* 2007; Merlin and Lissolo 2010). It can be shown, however, that using the benchmark of electrical power consumed per cubic meter of treated water is not advisable, if the wastewater treatment process train (including sludge) needs other energy sources. For SIAAP, for example, different plants use different energy sources for treating wastewater and the associated sludge. A follow-up benchmark for SIAAP plant functioning can take the form of the energy – i.e., total energy – used to produce 1 m^3 of treated wastewater (Table 1).

Table 1 | Energy consumption ratio (electricity, natural gas, fuel oil) needed to treat 1 m^3 of wastewater in the various SIAAP plants in 2014

2014	SAV	SAM	SEC	SEG	MAV	SEM
Energy ratio (kWh HHV/m^3)	1.20	1.14	1.00	1.51	1.30	3.64

Apart from SEM, which was commissioned in 2014, the energy ratio has substantially the same order of magnitude in all SIAAP plants. It ranges from 1.00 to 1.51 kWh HHV/m^3 of treated wastewater. These values are lower than the 1.69 kWh/m^3 energy ratio determined in a Californian WWTP (Stokes & Horvath 2010) but exceed the 1.07 kWh/m^3 determined for a small treatment plant in an institutional area at New Delhi, India (Singh *et al.* 2012).

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The electricity consumption of MBRs, as at SEM treatment system, is higher than most of treatment processes. Due to the high membrane aeration rates required to manage fouling and clogging, MBR energy consumption was three times higher even than that of conventional activated sludge (CAS) systems combined with advanced treatment techniques (Gnirss & Dittrich 2000). However, the gap has been reduced significantly in recent years. Pellegrin & Kinnear (2011) reported MBR electrical consumption in the range 1.43 to 4.23 kWh/m^3, while Judd (2011) reported 1.3 to 3 kWh/m^3. Mizuta & Shimada (2010) analyzed electricity consumption at 985 Japanese municipal WWTPs and reported that CAS systems consumed between 0.3 and 1.9 kWh/m^3. A balanced comparison of MBR and CAS (or other) systems is only possible, however, when similar effluent quality is produced.

Process scale. Determining characteristic ratios to monitor the functioning of the main wastewater treatment process train is also advantageous for following-up optimization actions. In the light of the above, a relevant benchmark at process level is electricity consumption per unit quantity of nitrogen removed during nitrification. It is important that the electricity consumption takes into account the same equipment, to enable comparison without generating bias in interpretation. That will therefore involve the establishment of specific metering of the relevant systems. In this context, at SAV, careful monitoring of nitrification energy consumption enabled it to be kept within the range 2.2 to 2.4 MWh/t-N-NH_4^+ removed. At SEG, power consumption was simultaneously abated from 4.4 to 3.7 MWh/t-N-NH_4^+ removed. This shows that improving the control loop is an effective tool in reducing energy consumption in nitrification.

Integrated approach

Energy optimization requires an integrated approach. When referring to standards using other factors than electricity consumption – e.g., greenhouse gas effect (GGE) emissions – the application of optimization tools may result in shifted balances. For instance, with regard to nitrogen removal, the conversion of ammonia to nitrate is not a simple process, there are many intermediate nitrogenous species. Among these is nitrous oxide (N_2O) which has a global warming potential in the range 265 to 295 (that of CO_2 is 1) (Solomon *et al.* 2007; USEPA 2016). Under the Mocopée research program (Mocopée 2015), the Antony (Haut-de Seine dept., 92) and Lyon-Villeurbanne (Rhône dept., 69) research centers of IRSTEA (the Research Institute on Science and Technology for Environment and Agriculture), have measured the emissions of that species from the nitrifying biofilters at SAV (Bollon *et al.* 2016).

On the one hand, the measurements revealed significant nitrous oxide emissions during nitrification. On the other, a close relationship was found between the injected air flows and N_2O emissions, the emission rate being inversely proportional to air flow (Bollon *et al.* 2016).

Thus, in this case, the methodology for optimizing electricity consumption applied should take all constraints into account, in order to reduce energy consumption and costs without increasing GGE emissions.

CONCLUSIONS

In order to optimize energy consumption, SIAAP has set up a two-stage approach. First, energy consumption was mapped, enabling identification of consumers and definition of priority actions. Electricity was found to be the main form of energy purchased by SIAAP (465 GWh/a; 26 M€/a), SAV being the largest consumer. It has been shown for this site that the biological treatment processes are the principal consumers, accounting for 11 to 31% of electricity consumption. Subsequently, more detailed observation of processes made it possible to pinpoint aeration as the main consumer of electricity.

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Second, in line with the findings from mapping, examples of optimization action sets have been described at various scales, in relation to both running costs and energy consumption. Thus, it appears that taking the whole process into account is essential to get a comprehensive picture of running costs and help make reasonable choices with respect to operating modes. The action sets should focus on the energy-intensive processes initially, moving on to others later. Lastly, the sources of over-consumption can be identified and remedied suitably, through close monitoring of the major systems. Action follow-up requires the development of relevant benchmarks with precisely controlled content, to prevent misinterpretation. In addition, in the case of nitrogen treatment, emissions of nitrogen oxide and other species must be taken into account in order to reduce energy consumption and costs without increasing GGE emissions.

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