Balancing effluent quality, economical cost and greenhouse gas emissions during the evaluation of plant-wide wastewater treatment control strategies

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Abstract: The objective of this paper is to complement the effluent quality (EQI) and operational cost (OCI) indices used to evaluate (plant-wide) control strategies in wastewater treatment systems with a new dimension dealing with greenhouse gas (GHG) emissions. The GHG evaluation is based on a set of comprehensive dynamic models that estimate the most significant potential on-site (secondary and sludge treatment, sludge disposal) and off-site (net energy use, embedded chemicals) sources of GHG emissions. The study presented here calculates and discusses the changes in the EQI, OCI and the formation of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) as a consequence of varying four process variables: i) system aeration in the activated sludge section; ii) capture efficiency of particulates in the primary clarifier; iii) the temperature (T) regime in the anaerobic digester; and iv) the control of nitrogen rich returns coming from the sludge treatment. Simulation results show the undesirable effects that energy optimization might have on GHG production: Although off-site CO_2 emissions may decrease, primarily as a result of: i) reduced aeration energy requirements; and/or ii) increased energy recovery from the sludge treatment, such effects might be counterbalanced by increased N_2O emissions in the activated sludge plant due to the 300-fold stronger greenhouse effect of N_2O than CO_2. The reported results emphasize the importance of a plant-wide approach and the need to consider the interactions between the different treatment units when evaluating the global warming potential (GWP) of a wastewater treatment plant.

Keywords: Activated sludge modelling, Benchmarking, Global warming, Model-based evaluation, Multi-criteria decision making, Process control, Sustainability

1. INTRODUCTION

The constantly changing nature of wastewater (quantity/quality), uncertainties surrounding its source of origin and the great variety of ambient conditions make wastewater treatment plants (WWTPs) truly dynamic systems. Comprehensive studies and full-scale applications have shown the feasibility of using automatic control to optimize the operation under these conditions. WWTP models and simulation studies have been used to evaluate performance and compare control strategies in general (**Gernaey *et al.*, 2012**) or before full-scale implementation (**Olsson, 2012**). The complexity of modern WWTPs with different sub-processes, interconnections and recycles makes it necessary to consider a plant-wide perspective in order to avoid sub-optimal performance (**Olsson and Newell, 1999; Jeppsson *et al.*, 2007; Nopens *et al.*, 2010, Gernaey *et al.*, 2012**).

The main focus for a WWTP has historically been the effluent water quality under constraints of technical feasibility and cost. This certainly still holds, but the discussions on sustainability in general and the issue of climate change due to greenhouse gas (GHG) emissions in particular, have widened the scope for the utilities. An increasing interest in GHG emissions calls for new approaches to reach the high and increasing demands on effluent quality and at the same time predict and minimize the GHG emissions.

For this reason, the main objective of this paper is to complement the traditional effluent quality index (EQI) and operational cost index (OCI) used to evaluate control strategies in a WWTP with a new dimension dealing with GHG emissions. In the presented case study a modified version of the International Water Association (IWA) Benchmark Simulation Model No 2 (BSM2) is evaluated using a number of scenarios. Thus, changes in effluent quality, operational cost and CO_2, CH_4 and N_2O emissions are analyzed in a plant-wide fashion when modifications respectively are carried out in: i) the system aeration in the activated sludge (AS) section; ii) the capture efficiency of particulates in the primary clarifier (PRIM); iii) the temperature regime in the anaerobic digester (AD); and iv) the control of nitrogen rich return flows coming from the sludge line.

2. METHODS

2.1. WASTEWATER TREATMENT PLANT UNDER STUDY

The WWTP under study (BSM2G) has the same layout as the IWA BSM2 proposed by **Jeppsson *et al*. (2007)** and **Nopens *et al*. (2010)**. The activated sludge unit is a modified Ludzack-Ettinger configuration consisting of 5 tanks in series. Tanks 1 (ANOX1) and 2 (ANOX2) are anoxic, while tanks 3 (AER1), 4 (AER2) and 5 (AER3) are aerobic. AER3 and ANOX1 are linked by means of an internal recycle. The BSM2G plant further contains a primary (PRIM) and a secondary (SEC) clarifier, a sludge thickener (THK), an anaerobic digester (AD), a storage tank (ST) and a dewatering unit (DW). Further information about the models used can be found in **Corominas *et al.* (2012)** and **Guo *et al*. (2012)**.

From the original set of models, the Activated Sludge Model No 1 (ASM1) (**Henze *et al*., 2000)** has been expanded with the principles stated in **Hiatt and Grady (2008)**. This model incorporates two nitrifying populations: ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB) using free ammonia and free nitrous acid, respectively, as their substrates. The model also considers sequential reduction of nitrate to nitrogen gas via nitrite (NO_2^-), nitric oxide (NO) and nitrous oxide (N_2O) using individual reaction specific parameters. Additionally, the ideas summarized in **Mampaey *et al*. (2011)** are used to consider NO and N_2O formation from the nitrification pathway assuming ammonia as the electron donor.

The interfaces presented in **Nopens *et al.* (2009)** have been modified to link the modified activated sludge model and the anaerobic digestion model (**Batstone *et al*., 2002)**, by considering COD, N and charge balances for all oxidized nitrogen compounds. In the activated sludge model five new variables are defined compared to the ASM1 model used in BSM2: NO_2^-, NO, N_2O, N_2 and an additional autotrophic biomass variable (X_{BA2}). Further information about the models used can be found in **Corominas *et al.* (2012)** and **Guo *et al*. (2012)**.

2.2. CONTROL STRATEGY AND SIMULATED SCENARIOS

The plant is simulated in a closed loop regime, which includes two PI control loops. The first loop controls the dissolved oxygen concentration in AER2 by manipulating the air supply rate, here implemented as manipulation of the oxygen transfer coefficient K_La. The second loop controls the nitrate concentration in the 2nd anoxic tank (ANOX2) by manipulating the internal recycle flow rate (Q_{intr}). Two different waste sludge flow rates (Q_W = 300 m^3.day^{-1} // Q_W = 450 m^3.day^{-1}) are imposed in SEC depending on the time of the year in order to sustain the nitrifying biomass in the system during the winter period. Noise and delays are applied to sensor and actuator models to give the simulations more realism. External recirculation flow rate (Q_r) and carbon source addition (Q_{carb})

remain constant throughout the simulations. Additional details about the operational strategy can be found in **Flores-Alsina *et al.* (2011)**. The potential impacts of four different scenarios, which represent different modes of operations, are simulated in the presented case study:

- Impact of DO control (commonly used to reduce aeration costs) by varying the set-point value from 3 to 1 $g.m^{-3}$ (default value 2 $g.m^{-3}$);
- Impact of primary clarifier capture efficiency by varying the % TSS removal efficiency in PRIM from 33% to 66% (default value 50%);
- Impact of the digester operating mode by changing the temperature regime in the AD from mesophilic (35°C) to thermophilic (55°C) (default value 35°C);
- Impact return liquor loads by controlling the return flow rate coming from the DW unit. This control strategy stores the dewatering liquors during the day time (when the plant is highly loaded) and returns them at night (when the plant is low loaded) (the default strategy does not use this control approach and liquors are simply returned as they are generated).

2.3. EVALUATION CRITERIA

2.3.1. Effluent quality (EQI) and operational cost (OCI) indices

The overall pollution removal efficiency is obtained using the effluent quality index (EQI) from the standard BSM2 (**Nopens *et al.*, 2010**). EQI is an aggregated index of all the pollution loads: TSS, COD, BOD_5, total Kjeldahl nitrogen (TKN) and NO_X, leaving the plant. The economic objectives are evaluated using the operational cost index (OCI) (**Nopens *et al.*, 2010**). It consists of a weighted sum of all the major operating costs in the plant: aeration energy (AE), pumping energy (PE), mixing energy (ME), sludge production (SP), external carbon addition (EC), methane production (MP) and the net heating energy (HE^{net}) needed to heat the sludge in the AD. EQI and OCI are based on simulation results from one-year dynamic influent data described in more detail in **Gernaey *et al.* (2011)**.

2.3.2. Greenhouse gas (GHG) emissions

The comprehensive method proposed by **Flores-Alsina *et al.* (2011)** is used to calculate GHG emissions in the WWTP**.** The emissions considered are:

Direct secondary treatment emissions: The emissions from the activated sludge section include the CO_2 generated from biomass respiration and BOD oxidation (often not included in other analyses that do not count biogenic emissions, but accounted for in this analyses in order to investigate how they vary based on the different scenarios), the N_2O generated from nitrogen removal and the CO_2 credit from nitrification.

Sludge processing: The GHG emissions during sludge treatment are mainly generated in the anaerobic digester. In this case it is assumed that the biogas is fed directly into a gas-fired combustion turbine converting the CH_4 into CO_2 and generating electricity and heat (in turn used to heat the anaerobic digester). The CO_2 generated during anaerobic digestion and the CO_2 produced in the combustion process are assumed to be released to the atmosphere.

Net power GHG: The difference between energy usage and production. Energy consumption involves aeration, pumping, mixing and heating. Energy production comes from the electricity generated by the turbine. A value of 0.94 kg CO_2 per kWh is assumed for any external energy production (based on the efficiency of a coal-burning power plant (**Bridle *et al*., 2008**)).

Chemicals: The GHG emissions from production of carbon source for denitrification are accounted for (from industrial production of methanol data) (**Dong and Steinberg, 1997**).

Sludge disposal and reuse: The disposal of sludge is accounted for with CO_2 emissions from transport and mineralization of organic matter at the disposal site.

GHG emissions are also evaluated over one year. Finally, in order to deal with the different nature of the generated GHG emissions (CO_2, CH_4 and N_2O) they are converted into units of CO_2 equivalents (CO_{2e}). The assumed global warming potentials (GWP) for N_2O and CH_4 are 298 kg CO_{2e} per kg N_2O and 25 kg CO_{2e} per kg CH_4, respectively (**IPCC, 2006**).

3. RESULTS

EQI, OCI and GHG values for the different simulated scenarios are depicted in **Figure 1**. From the generated results it is possible to see that: 1) dissolved oxygen concentration has a paramount importance on the total GHG emissions (z-axis); 2) % TSS removal efficiency mainly influences effluent quality and operational cost, but the total GHG emissions remain almost equal (y-axis); 3) thermophilic conditions in the AD reveal that a higher operating temperature appears to be a more expensive way to operate the plant (with higher GHG emissions) without having substantial benefits in terms of gas production (y- and z-axis); and, 4) control of return flow rate slightly reduces effluent quality, but it does not have an effect on the GHG emissions unless DO is very low (see dotted lines in **Figure 1** right). Further details are provided in the following sub-sections

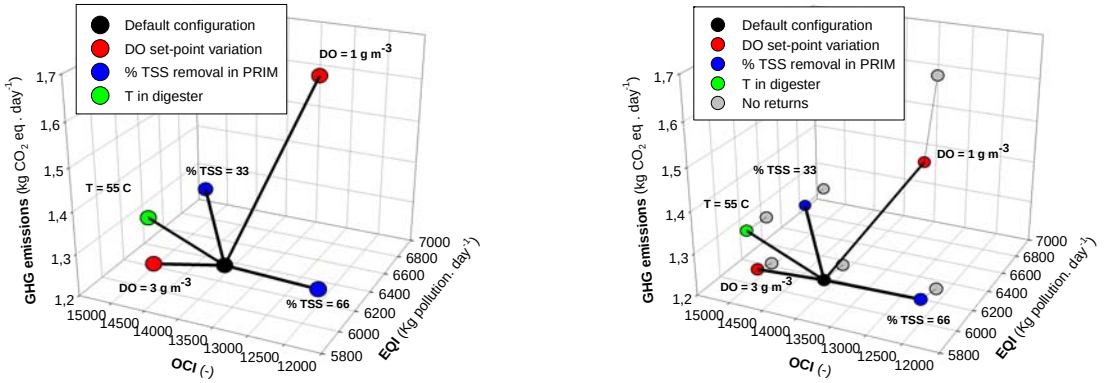

Figure 1. Effluent quality, operational cost and greenhouse gas emissions for the different control strategies with (left) and without (right) controlling the nitrogen rich returns from the digester

3.1. EFFECT OF DISSOLVED OXYGEN CONCENTRATION

Low DO set-points lead to a reduction of the off-site CO_2 production due to lower energy consumption (and subsequently operational cost) but the overall GHG emissions are increased compared to the default case. The reason for this GHG increase is due to increased formation of N_2O and its 300-fold stronger greenhouse effect than CO_2. In this case, the N_2O increase is mainly caused by accumulation of NO_2^- (see **Figure 2**, right) due to incomplete nitrification (see the increase of the EQI values in **Figure 1** and the dynamic performance of NH_4^+ in **Figure 2**, left). High DO set-points increase operational costs, but improve effluent quality (see **Figure 1** and complete nitrification in **Figure 2**). Although off-site emissions of CO_2 are higher, the overall GHG emissions are still lower due to reduced N_2O emissions. In **Figure 2**, but also in **Figures 3** and **4,** the seasonal variation can be seen (simulation start date: 1st of July, total time: 364 days).

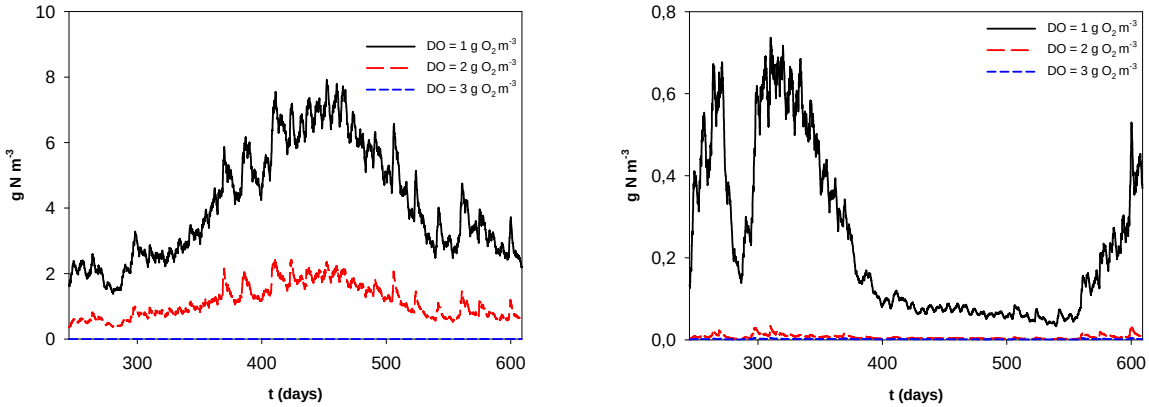

Figure 2. Effect of dissolved oxygen on nitrification: NH_4^+ (left) and NO_2^- (right) in the effluent

3.2. EFFECT OF PRIMARY CLARIFIER EFFICIENCY

High PRIM efficiency (TSS removal = 66%) decreases the quantity of TSS entering the activated sludge section leading to better effluent quality (although denitrification is significantly worsened because of lack of carbon). The lower operational cost is due to: i) better energy recovery in the sludge line due to an increased biogas production (see **Figure 3**, right); and, ii) lower aeration cost. However, the latter increases the overall N_2O emissions due to low C/N ratio as a trade-off (see **Figure 3**, left), especially in summer time. Serious nitrification failure in winter time decrease N conversions and also N_2O emissions. In terms of the other GHG emissions low clarifier efficiency (TSS removal = 33%) causes: i) an increase of the biogenic CO_2 emissions from BOD oxidation and biomass decay in the bioreactor; ii) an increase of off-site CO_2 emissions due to higher energy demand during nitrification; iii) a reduction of the energy recovery from settled organics (**Figure 3**, right); and, iv) a decrease of N_2O emissions due to a higher C/N ratio (**Figure 3**, left). Overall the variations of the total GHG emissions seem to be very similar (z-axis in **Figure 1**). However, the types of GHG and origin (biogenic/non biogenic) change substantially in the different simulated scenarios (see discussion section).

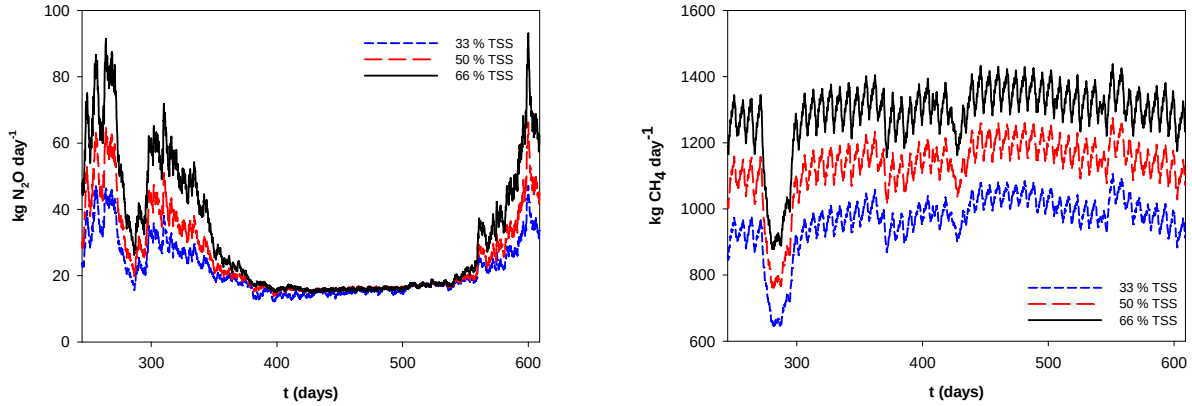

Figure 3. Effect of TSS removal efficiency in PRIM: N_2O emissions in AS (left) and CH_4 in AD (right)

3.3. EFFECT OF DIGESTER PERFORMANCE

Figure 4 shows the results of changing the digester's operating temperature from 35 °C (mesophilic conditions) to 55 °C (thermophilic conditions). In this system, no substantial benefits can be observed in either gas production or off-site CO_2 emissions. However, thermophilic conditions substantially increase the operational cost (see **Figure 1**) due to higher energy requirements for heating (see **Figure 4** left) without improving the digester performance (see **Figure 4** right). Subsequently this also leads to higher CO_2 emissions from off site power generation. The effect on effluent quality variables is negligible (see discussion section).

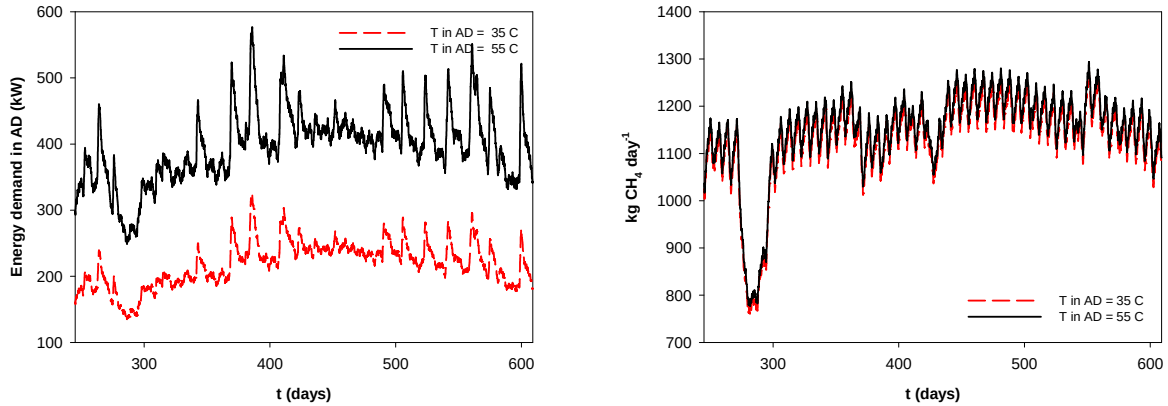

Figure 4. Effect of modified T regime on the AD performance: energy demand (left) and CH_4 (right) in AD

3.4. EFFECT OF NITROGEN RICH RETURNS FROM DIGESTION

From the results depicted in **Figure 1** one can see the effect of controlling the nitrogen rich returns from the AD section. In all cases, there is a slight improvement in the effluent quality (all the evaluated scenarios have lower values of the EQI, x-axis). This reduction is attributed to the storage tank's capability to reduce the effect of the ammonium peaks originating from the sludge treatment line when the plant is already highly loaded (see N load entering the AS section in **Figure 5**). The slight increase in the OCI (y-axis) is due to the extra pumping. Finally, with regard to GHG there is no substantial effect unless the DO concentration is very low. Again, this is caused by a substantial reduction in the N_2O emissions, as an oxygen deficiency combined with high ammonium loadings can increase its production.

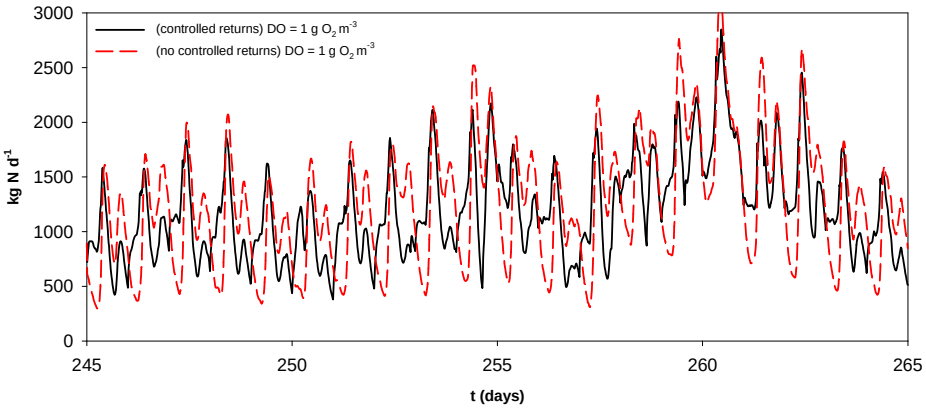

Figure 5. Effect on the nitrogen load entering the AS section with and without including control (20 day snapshot of 364 days simulation

4. DISCUSSION

The results reported in this paper lead to similar observations as the experiments reported in **Schulthess and Gujer (1996)** and **Kampschreur *et al.* (2009)**, related to DO, C/N ratios and N_2O emissions. There is also a good match with the studies of the effect of soluble/particulate compounds in the AS and the relation with the overall GWP of the plant **(Gori *et al.*, 2011)**. Nevertheless, there are aspects that still need to be addressed. For example, there is evidence that N_2O production increases during winter time (**Kampschreur *et al.*, 2009)**. In our case, lower temperatures have the opposite effect.

The authors are aware of the fact that a TSS removal of 66% in PRIM is hard to achieve in many treatment plants without the addition of chemicals (**Tchobanoglous *et al.*, 2003**). Further research is necessary to consider the role of these chemicals on the operational cost index and the overall GWP in a similar way as is done for carbon source usage, i.e. kg CO_{2e} for each kg of chemical used.

The lack of digestion improvement when the temperature is changed to thermophilic conditions can be explained by the following points: i) the used ASM/ADM interfaces (**Nopens *et al.*, 2009**) where the disintegration process (limiting factor in many digestion processes) is instantaneous; ii) the low biodegradable fraction coming with the influent (**Gernaey *et al.*, 2011**) and consequently limited amounts of organic material arriving to the AD (although kinetics are faster at thermophilic conditions, there is no more material to be converted); and, iii) the large digestion volume, i.e. sufficiently long hydraulic retention time during mesophilic conditions to convert all the potentially digestible organics into methane. If additional external organic waste would be available to make use of the extra digestion capacity in thermophilic conditions, results would be different.

The case study shows that wastewater treatment system models are useful to quantify the different GHG emissions when evaluating different control strategies or operational procedures by taking into account the different sources of CO_2, CH_4 and N_2O. However, from a climate change point of

view, not all these sources have the same importance. For example, biogenic sources of CO_2 such as the generation from the aerobic/anaerobic treatment processes are part of the natural carbon cycle. On the other hand, there are non-biogenic sources such as the off-site CO_2 emissions due to electricity consumption or production of chemicals that should be avoided. A clear example can be found in scenario 2 (% TSS removal efficiency), where the total GHG is almost the same, but the types and origins are quite different.

The study intended to demonstrate the additional degree of complexity that results from adding another dimension to the traditional evaluation criteria used to compare and evaluate (plant-wide) control strategies in wastewater treatment systems. Simulation of the modified BSM2 showed the existing interactions and trade-offs between effluent quality, economic cost and GHG emissions. For example, it was possible to analyse the side effects of energy optimization, particularly in the aeration system. Low DO levels decrease energy usage, but on the other hand reduce effluent quality and to a large extent increase GHG emissions substantially due to increased release of N_2O. The other example is energy recovery from digestion, where a change in the influent C/N ratio also increases N_2O. Even though an overloaded reactor might increase the quantity of biogenic CO_2 emissions (BOD oxidation, biomass decay) there is a drastic decrease in N_2O emissions.

It is important to highlight that some of the models used in the study are still under development. In this paper, the N_2O production is based on AOB denitrification with NO_2 as terminal electron acceptor. However, other possible mechanisms, such as the formation of N_2O as a by-product of incomplete oxidation of hydroxylamine (NH_2OH) to NO_2, are omitted. Recent investigations demonstrate that both the denitrification and NH_2OH pathways may be involved in N_2O production. A unified model that describes both mechanisms independently does not yet exist (**Ni *et al.*, 2012**).

Finally, the reader should be aware that the list of emissions applied in this study is not complete. There are other sources of GHG that potentially contribute to the overall GWP of the plant. Experimental observations have revealed that substantial stripping of methane might take place at the inlet of the WWTP **(Guisasola *et al.*, 2009**). Also, no fugitive emissions of methane are considered from the anaerobic digester (**Czepiel *et al.*, 1993**). In the ADM-ASM interfaces (**Nopens *et al.*, 2009**), the quantity of methane that remains in the liquid phase is stripped, but not quantified in the model. Finally, although CO_2 is included the N_2O and CH_4 emissions from sludge disposal and reuse are not considered either (**EPA, 2010**).

5. CONCLUSIONS

The key observations of these simulations can be summarized as:

- Low DO levels decrease off-site CO_2 emissions and cost (due to aeration) but increase the plant´s GWP (higher N_2O emissions) and worsen effluent quality (high NH_4^+ values);
- High TSS removal efficiency in PRIM improves energy recovery from the AD and the effluent quality, but increases N_2O emissions as well;
- Thermophilic conditions in the AD increase cost and GHG emissions without additional biogas production compared to mesophilic conditions (if the extra capacity can not be utilized);
- Control of returns slightly improves effluent quality and GHG emissions when DO levels are low.

Whilst these observations are for a specific system and model application, they may also provide guidance for others investigating the impact of different operational strategies.

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