Towards a Reduction of Greenhouse Gases: a New Decision Support System for Design, Management and Operation of Wastewater Treatment Plants

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Abstract

The increasing attention for the environment has led to reduce the emissions from wastewater treatment plants (WWTPs). Moreover, the increasing interest towards the greenhouse gas (GHG) emissions from WWTPs suggests to reconsider the traditional tools used for designing and managing WWTPs. Indeed, nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) can be emitted from wastewater treatment significantly contributing to the greenhouse gas (GHG) footprint. The reduction of energy consumption as well as GHG emission are of particular concern for large WWTPs which treat the majority of wastewater in terms of both volume and pollution load. Nowadays, there is an increasing need to develop new tools that include additional performance indicators related to GHG emissions and energy consumption as well as traditional effluent quality parameters. Energy consumption, in fact, can be considered as an indirect source of GHGs. This paper presents the development of a research project aiming at setting-up an innovative mathematical model platform for the design and management of WWTPs. The final goal of the project by means of this platform is to minimize the environmental impact of WWTPs through their optimization in terms of energy consumptions and emissions, which can be regarded as discharged pollutants, sludge and GHGs.

Keywords: Decision Support System; WWTPs integrated modelling; GHG emissions

Introduction

In the last years, studies about GHG emissions show that WWTPs are anthropogenic GHG potential sources, contributing to climate change and air pollution (Law et al., 2013). The reduction of energy consumption as well as monitoring and reduction of GHG emission are of particular concern for large WWTPs which treat the majority of wastewater in terms of both volume and pollution load. WWTPs produce the three major GHG (Shahabadi et al., 2009): carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), from both wastewater and sludge treatment lines, and additional amounts of CO_2 and CH_4 from the energy demands. GHGs are also produced during sludge disposal or reuse (transportation and off-site degradation of biosolids) and off-site production of energy and chemicals.

The estimation of GHG emissions from WWTPs has been traditionally based on the classification between on-site (direct and indirect) emissions and off-site (indirect) emissions. The first are due to liquid and solid treatment processes: aerobic substrate utilisation (CO_2), biomass decay (CO_2) and biological nitrogen removal processes (CO_2 and N_2O); stripping of dissolved gases (CH_4) in dewatering unit (Sweeteapple et al., 2013) as well as biogas/fossil fuel combustion for energy recovery/generation. The latest are due to the production of electricity required for pumping, aeration, heating and mixing, production and transportation of fuel and chemicals, as well as transportation, reuse and disposal of solids, and degradation of remaining constituents in the effluent (Shahabadi et al., 2009).

In the recent past, increasing attention is given to the assessment of N_2O emissions from WWTPs. Indeed, N_2O is a powerful greenhouse gas that is almost 300 times stronger than CO_2, for an atmosphere residence time of 100 – 120 years. N_2O emissions from WWTPs represent the 3% of the global emission from every source and it is the sixth most important contribution (IPCC, 2006). N_2O emissions primarily occur in aerated zones owing to the fact that the main contributors are active stripping and ammonia-oxidizing bacteria, rather than heterotrophic denitrifiers. Nevertheless, the source and magnitude of N_2O are relatively unknown and the knowledge is still incomplete (Kampschreur et al., 2009, Law et al., 2012). The quantity and distribution of N_2O produced is variable and depends on the characteristics of the incoming wastewater, the technologies used and the operating conditions of WWTPs.

The models to assess GHG emissions from WWTPs can be classified as: empirical models, simplified models and complex mechanistic models (Corominas et al., 2012). Mechanistic dynamic models have been demonstrated to have the advantages to estimate GHG emissions by considering effective plant design and operating conditions as well as variability of the influent wastewater (Shahabadi et al., 2009; Flores-Alsina et al., 2011; Ni et al., 2013). A new trend in GHGs emission modelling of WWTPs is to develop models able to describe the behaviour of the entire WWTP, including both water and sludge lines. In a plant-wide modelling approach, a WWTP is considered as a unit, where the water line and the sludge line are linked together and operated and controlled taking into account all the interactions between the processes (Nopens et al., 2010).

The research developed so far on the evaluation of GHG emissions from WWTPs is fragmented and can be subdivided into two types (Shahabadi et al., 2009): experimental and modelling. The experimental investigations have been focused on both the development of measurement techniques and acquisition of GHG data, which are used in order to understand the mechanisms of formation and emission of these gases (Ahn et al., 2010).

At the same time, two international research groups under the umbrella of the International Water Association (IWA) have been set up: the Benchmark Simulation model (Gernaey et al., 2014) and the Greenhouse gas emission. The main objective of the research groups is two-fold: deepening the aspects related to the setting up of a standard modelling tool for WWTPs to be used at an international level and deepening the knowledge concerning the assessment of GHG emissions from WWTPs. Both groups have highlighted the need to converge research efforts towards the implementation of integrated approaches in the design and management of WWTPs, in order to minimize emissions.

Despite the efforts undertaken so far at the international level, from an in-depth literature review on the project main field, it comes out that there are some important aspects that require further studies:

- lack of criteria for the design and management of WWTPs through integrated approaches that include GHGs;
- absence of extensive data base of measures of GHGs in terms of both temporal and spatial distribution (i.e. acquired on different WWTPs), for encoding GHG behaviour in the yield process and also for assessing the GHG temporal variability during the year. These extensive data bases are also essential for the development and application of robust and reliable mathematical models;
- lack of standard protocols for measuring emissions, that can allow the comparison of the data obtained in various WWTPs;
- identification of appropriate mitigation measures, which are based on process control, aimed at reducing GHG emissions;
- evaluation of the modelling uncertainty in order to quantify the potential error in the information "predicted" through the models and development of models that are characterized by combined (i.e. complex and simplified) approaches.

In this paper, we present the key methodological aspects of a project aiming at developing an innovative simulation platform for the design and management of WWTPs. Such a platform is aimed at reducing the energy consumption and pollutant/residue emissions (namely, residual pollutants in the effluent, sludge and GHGs). The main objective of the project is the development of a decision support system that will allow reducing GHGs as well as other emissions from WWTPs.

Basic principles of GHG emissions assessment at plant-wide scale

The main elements of the wastewater treatment scheme are outlined in Figure 1. Two WWTP schemes can be single out: anaerobic (complete) and aerobic (simplified) sludge digestion. Figure 1 also shows two different solutions to perform solid liquid separation: secondary settler (conventional biological treatment) or membrane bioreactor (MBR). Regardless of the employed plant scheme, processes occurring both in the water line (primary settling, biological treatment and solid-liquid separation) and in the sludge line (thickener, sludge digestion and dewatering) contribute directly or indirectly to the GHG emission.

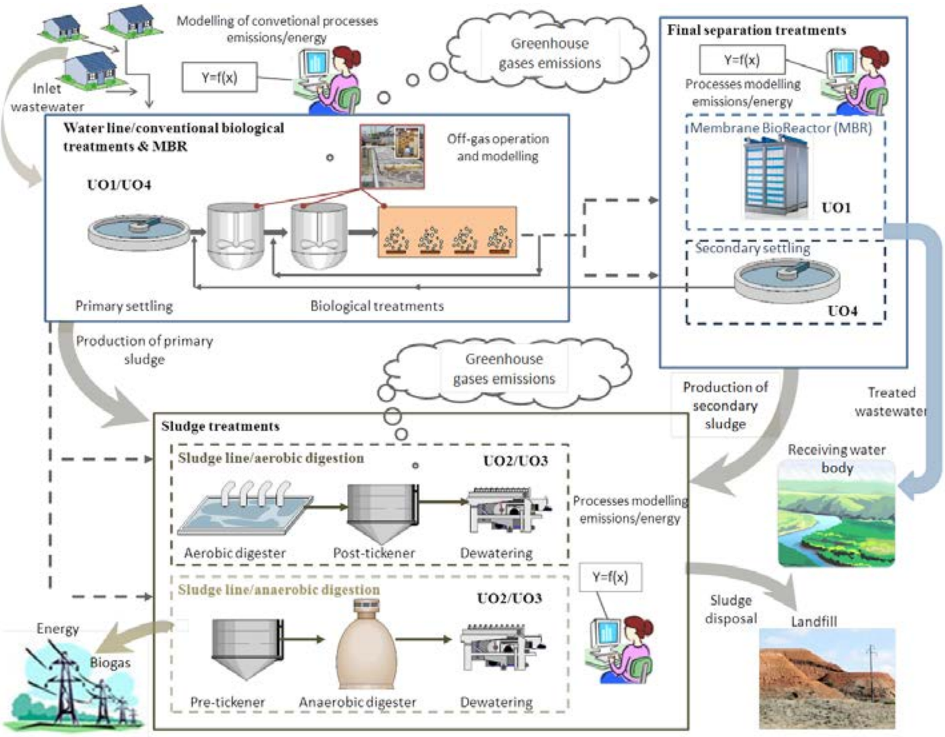

Figure 1 Schematic overview of WWTPs having different final separation treatment and sludge treatment processes with the indication of the main sources of GHG emissions.

CO_2 and nitrous oxide emissions

CO_2 is directly produced during wastewater treatment using both aerobic and anaerobic biological processes. In the first case, organic compounds are oxidized into CO_2 and other metabolites and accompanied by cell growth, while in the second case, organic matter is transformed into biogas (CO_2 and CH_4 in proportions of 30-40% and 60/70% v/v, respectively). This short-cycle CO_2 is considered negligible in terms of greenhouse effect (Kampschreur et al., 2009). However, fossil organic carbon was found in the influent of WWTPs and related direct fossil CO_2 emissions from oxidation of activated sludge may vary with the wastewater composition and treatment configuration (Law et al., 2013). Further, indirect CO_2 emission is associated to energy production.

Czepiel et al. (1995) show that 90% of the N_2O emission occurs from the activated sludge compartments, 5% from the grit tanks and 5% from the sludge storage tanks. N_2O emissions from the activated sludge compartments are related to the processes associated with the biological nitrogen removal (Kampschreur et al., 2009; Law et al., 2012). N_2O can be produced both during nitrification and denitrification processes (Kampschreur et al., 2009). Indeed, during nitrification, N_2O is formed during the chemical decomposition of intermediates, such as hydroxylamine and nitrite. N_2O is also produced during the incomplete oxidation of NH_2OH because of formation of nitrosyl radical (NOH). Moreover, N_2O is an intermediate in the denitrification pathway. N_2O is produced (as with denitrification) as an intermediate of reactions by nitrifiers heterotrophic bacteria. Under aerobic conditions, heterotrophic nitrifiers produce much more N_2O per cell than autotrophic nitrifiers. The pathway of nitrification, called nitrifier denitrification, in which the oxidation of NH_3 to NO_2^- is followed by the reduction of NO_2^- to N_2O and N_2, without NO_3^- production, might contribute to a major part of the loss of ammonium in the form of NO and N_2O (Wrage et al., 2001). However, the wide range of N_2O emission concentrations measured in the WWTPs and reported in literature (0.017 – 80 mg_{N2O}/l) underlines that the mechanisms involved in the N_2O formation are not completely known (Kampschreur et al., 2009; Law et al., 2012). Moreover, other studies are needed to better understand the mechanisms of emissions of N_2O from non aerated zones (i.e. secondary settles and dewatering units).

Methane production

Methane (CH_4) is an important GHG with a GWP of 25 over a 100-year period (IPCC, 2006). CH_4 is produced during the decomposition of a wide range of organic matter in the absence of oxygen (anaerobic decomposition). Typically 40 to 45 percent of volatile matter contained in the feed sludge of an anaerobic digester is converted into CH_4 and carbon dioxide. A large part of the processes related to management and treatment of domestic and industrial wastewater has been identified as an important source of CH_4 (CEC, 2006). CH_4, produced during the anaerobic decomposition of organic substrate (activated by methanogenic bacteria), can be released to the atmosphere through the surface of the opened tanks. Moreover, during anaerobic treatment of sludge CH_4 is produced as the main component of the biogas (Daelman et al., 2012). However this biogas can be recovered and used in a combined heat and power system to generate electricity and heat the feed sludge. CH_4 can be also emitted in the sewer system (Kampschreur et al., 2009). Large amounts of CH_4 can be produced also from the disposal of raw sewage sludge to landfill, with smaller but still significant levels produced from the disposal of digested sludge to landfill (Czepiel et al., 1993).

Liquid-gas mass transfer

The emission of GHGs produced in wastewater treatment are influenced by their solubility and by external factors (e.g. stripping effect due to the aeration or the stirrers). CO_2 and N_2O are easily soluble in water. The Henry's law constant, at 25°C and 0% salinity, of CO_2 and N_2O is 34 and 24 mM atm^{-1} respectively (Weiss and Price, 1980). These Henry's law constant of the O_2 is equal to 1.3 mM atm^{-1} (at 25°C and 0% salinity). Thus, an accumulation of CO_2 and N_2O in the liquid phase can occur especially in absence of external factors (e.g. non aerated tanks). Conversely, CH_4 has the same Henry's law constant as O_2 (1.3 mM atm^{-1} at 25°C and 0% salinity). Thus a great part of the CH_4 produced is emitted into the atmosphere. The main external factors influencing the GHG emission can be summarized as: i. temperature of the liquid phase, ii. aeration and iii. stirrer effect. Ahn et al. (2010) have found that N_2O emission is two to three orders of magnitude higher in aerated zones than in non-aerated ones.

Description of the research project

The research project, entitled "Energy consumption and GreenHouse Gas (GHG) emissions in the wastewater treatment plants: a decision support system for planning and management" supported by grant of the Italian Ministry of Education, University and Research (MIUR) through the Research project of national interest PRIN2012, started in 2014 and will end in 2017. The project is carried out by four Research Units (UOs) and is characterized by strictly connected experimental and modelling phases (Figure 2).

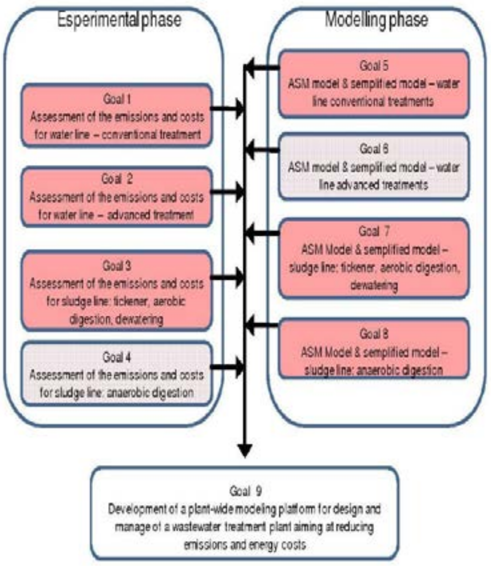

Figure 2 Scheme of the project goals.

We have analysed the main processes that take place in both the water and sludge lines in WWTPs. Both single treatment units and their interactions have been analysed. Particular care is dedicated to the energy consumptions and emissions. A specific protocol for assessing the emissions from the different treatment units has been set up (Gori *et al.*, 2015). An innovative mathematical model platform for the design and management of WWTPs has been set up (Figure 3) to achieve the main goal of the project. As show in Figure 3, the decision support system will be implemented by using the results of the simple and detailed modelling of the biological processes. The platform could be used both for conventional and advanced biological treatments.

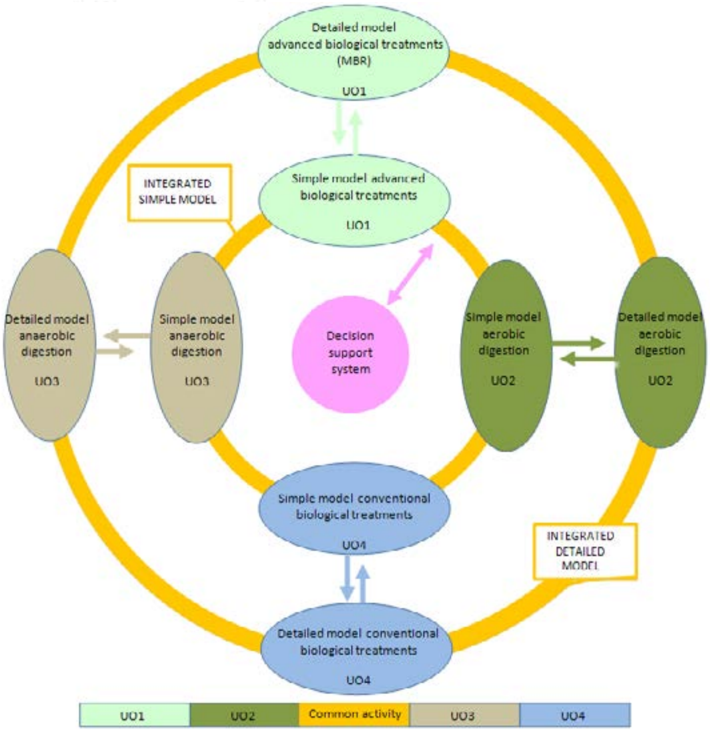

Figure 3 Integrated model layout of the WWTP with indication of the contribution provided by each research unit (UO).

Activities of the Research Units

The project is constituted by 4 research units (UOs): University of Palermo (UO1), University of Basilicata (UO2), University of Cassino and Southern Lazio (UO3) and University of Florence (UO4).

All UOs are performing both experimental and modelling activities. The expertise of each UO concerning specific topics has been shared among all the other UOs in order to achieve the final objectives of the project. Therefore, each UO is carrying out both transverse activities, i.e. in cooperation with all UOs, and individual activities, in relation to the different specific skills of each UO. All activities are carried out through methodologies which have been discussed, set-up and shared during dedicated meetings among the UOs in order to have uniform approaches. In Table 1 the timetable of the project is shown. The activities of the UOs are highly integrated and synergistic. Both pilot plant and full-scale studies are carried out in order to get a complementarity of the results aimed at a better interpretation of the processes.

In detail, UO1 has expertise on Membrane Bioreactors (MBRs) as well as on advanced modelling of WWTPs. The objective of UO1 is the study of the chemical/physical/biological phenomena of the water line of the advanced wastewater treatment systems, through designing, building and operating an MBR plant at pilot scale aimed at removing nutrients. The pilot plant is monitored in order to set-up an extensive database useful for phenomena interpretation and raising knowledge about some aspects that are still in need of further investigation. A complex mathematical model, based on the Activated Sludge Model (ASM), has been implemented in order to properly simulate biological process as well as physical phenomena. Furthermore, the UO1, will also implement empirical simplified models that should be characterized by a good reliability and an easier implementation. Sensitivity analysis, calibration, validation and uncertainty analysis will be carried out for all the implemented models.

In order to better deepen chemical/physical/biological phenomena of thickening and aerobic digestion, UO2 has designed, build and operate a pilot scale plant for such treatment units. The pilot plant is used to investigate the GHG emissions from the different pilot plant units, which are measured in different operating conditions, by using the tool developed by the UO4. An extensive monitoring campaign of the qualitative and quantitative characteristics of the sludge and operating parameters of a full-scale treatment plant is also in progress. Data gathered from experimental activities are collected in a database in order to increase knowledge concerning the influence of management parameters on GHG emissions from aerobic treatment of sludge and to develop and calibrate an ASM type model. The UO2 is using data from field activities and from the ASM type model to develop simplified models, which increase the possibility of applications in comparison to the more complex models.

UO3 has linked the operative conditions of the anaerobic digestion (sludge age, sludge concentration, retention time) and the quality of the reactors feed, to the biogas production, energy recovery and GHGs emission. The UO3 is giving essential information for operating the wastewater treatment line which greatly affects the quality of the anaerobic digestion feed and, in turn, affects the biogas and methane production and thus the GHGs emission of WWTPs. Activities of the U03 are carried through both experimental and modelling approaches. Data gathered from experimental activities are collected for setting up a database in order to increase knowledge and develop models (both detailed and simplified) able to properly predict the observed phenomena.

The U04 has defined a detailed protocol for the measurement of oxygen transfer efficiency from processes units and for GHG measurement. Such a protocol has been proposed as a standard and is one of the main results of the project. The U04 has supported the other UOs in measuring GHGs emissions from plants (both pilot and full scale) investigated. The U04 has carried out experimental activities on both conventional and innovative plants. Similarly to the other UOs, data gathered from experimental activities are collected in a database in order to increase knowledge and develop models able to properly predict observed phenomena. Particular attention has been given to the influence of operative conditions on GHGs emissions.

Preliminary results: development of a new protocol for field measurement of GHG emissions

The proposed protocol (Gori et al., 2015) set up materials and methods for measuring GHG direct and indirect emissions. In particular, the protocol allows us the measurement of CO_2, CH_4 and N_2O from the water treatment line (i.e. primary settler oxidation tank, secondary settler and/or MBR) and from the sludge treatment line (i.e. thickening, digestion and dewatering) and indirect emissions from the energy consumption due to aeration (oxidation tank and aerobic sludge treatment, if present).

Direct emissions from aerated tanks can be measured using online as well as offline methods. Indirect internal emissions caused by aeration can be predicted by using the off-gas method, in those WWTPs where power consumption of blowers is not logged.

Figure 4 shows the layout of the proposed device, that is a floating hood able to capture the off-gas leaving the tank surface. An hot wire anemometer measures the flow rate. The system is also equipped with a dissolved oxygen (DO) probe in the liquid phase, required for correcting the Oxygen Transfer Efficiency (OTE) to standard conditions (i.e. αSOTE). A PVC column (h=0.255 m, d=0.025 m) filled with silica gel ensures moisture removal at the end of the captured stream, which is sent to specific sensors for analyzing the concentration of O_2 and CO_2.

The hood should be positioned in different points of the aerated surface so that at least 2% of the tank surface in the end has been covered by the floating device (ASCE, 1997).

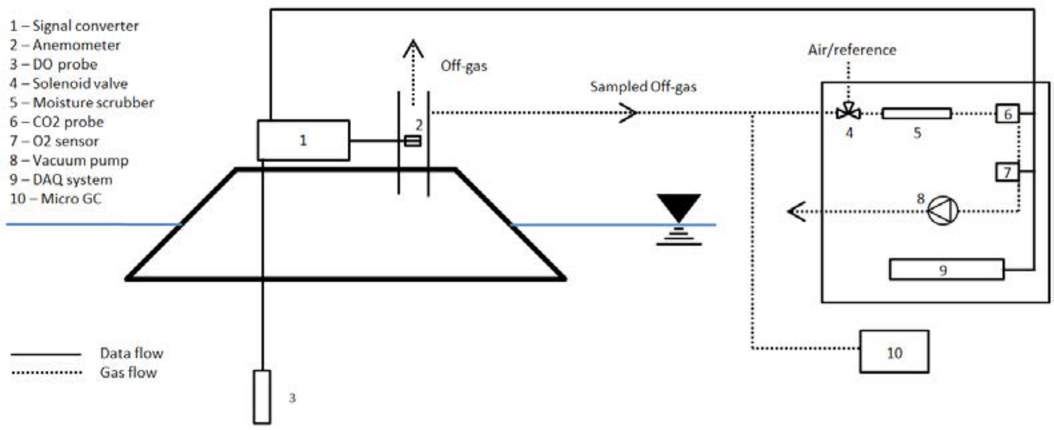

Figure 4 Scheme of the Off-gas analyzer (Gori et al., 2015)

In this protocol we propose online monitoring carried out with a portable micro gas chromatograph (micro-GC), which have many useful specifications for the application to online GHG measurements. The proposed protocol also covers aspects concerning the analysis of the biogas composition in order to properly assess GHG emission offset from biogas energy recovery and its potential effect on emission from biogas combustion. More details concerning the protocol can be found in Gori et al., 2015.

Conclusion

The analysis of the GHG emissions is conducted for both the water line and the sludge line (aerobic and anaerobic), for both conventional and advanced treatment systems (e.g. membrane bioreactors). A comprehensive plant-wide approach that integrates the data collected in all the treatment units of the WWTP with the results of simplified and complex models aimed at developing a decision support system for design, management and operation of WWTPs that is the main aim of the research project. The final results of the project will allow a better interpretation of the biological mechanisms of GHG formation in the different WWTP units with respect to technologies and treatment processes and the determination of the relationship between the adopted operating conditions for the system management (by varying the employed technology), the generated emissions (solid, liquid and gaseous) and their impact on the environment.

The extensive database obtained through measures conducted during the research project will allow us the determination of both spatial and temporal variability of the GHGs production and the evaluation and quantification of disadvantages and advantages for each treatment scheme, especially concerning energy consumptions and emissions. At the end of the project, a widening of the knowledge and increase of the reliability of the parameters that are used for the design of aeration systems will be obtained, resulting in the installation of more efficient systems. One of the innovative aspects is the integrated analysis of the WWTP considering both single treatment units and their mutual interactions, focusing on energy consumptions and emissions. The reduction of energy consumption as well as monitoring and reduction of GHG emission are of particular concern for large WWTPs which treat the majority of wastewater in terms of both volume and pollution load.

An important result already obtained is the setting up of a protocol to measure GHGs from WWTPs with the final aim to develop a standard protocol (still not available) (Gori et al., 2015).

Regarding the mathematical modelling activities in the project, a significant step is the identification of the most suitable techniques of sensitivity analysis, uncertainty analysis, calibration and validation for the complex environmental models developed during the project, which can be used as guidelines for future applications. The final synergetic objective consists of the development of an optimized simulation platform, made up of simplified mathematical models (derived from more complex models) integrated with the extensive databases of measures. The complex models are based on the well-known Activated Sludge Models (Henze et al., 2000).

The synergy of both complex and simplified mathematical models will result in the development of a decision support system of general application, which can be used by researchers and plant operators.

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