Water Research xxx (2015) 1–9

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Does carbon reduction increase sustainability? A study in wastewater treatment

Christine Sweetapple*, Guangtao Fu, David Butler

Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, North Park Road, Exeter, Devon EX4 4QF, United Kingdom

A R T I C L E I N F O

Article history:
Received 9 February 2015
Received in revised form
24 June 2015
Accepted 27 June 2015
Available online xxx

Keywords:
Carbon neutral
Control
Energy
Sustainability
WWTP

A B S T R A C T

This study investigates the relationships between carbon reduction and sustainability in the context of wastewater treatment, focussing on the impacts of control adjustments, and demonstrates that reducing energy use and/or increasing energy recovery to reduce net energy can be detrimental to sustainability.

Factorial sampling is used to derive 315 control options, containing two different control strategies and a range of sludge wastage flow rates and dissolved oxygen setpoints, for evaluation. For each, sustainability indicators including operational costs, net energy and multiple environmental performance measures are calculated. This enables identification of trade-offs between different components of sustainability which must be considered before implementing energy reduction measures. In particular, it is found that the impacts of energy reduction measures on sludge production and nitrogen removal must be considered, as these are worsened in the lowest energy solutions.

It also demonstrates that a sufficiently large range of indicators need to be assessed to capture trade-offs present within the environmental component of sustainability. This is because no solutions provided a move towards sustainability with respect to every indicator. Lastly, it is highlighted that improving the energy balance (as may be considered an approach to achieving carbon reduction) is not a reliable means of reducing total greenhouse gas emissions.

1. Introduction

Improving the energy balance of wastewater treatment plants (WWTPs), with the aim of moving towards carbon neutrality, is a topic of great interest. This is driven by numerous policies, initiatives and commitments, including the European Union's 2030 Climate and Energy Policy Framework (which requires a 40% reduction in greenhouse gas (GHG) emissions by 2030 with respect to a 1990 baseline and for 27% of energy to be from renewable sources), and the UK's Carbon Reduction Commitment (CRC) (under which companies, including those in the water industry, are compelled to reduce their energy use by 80% by 2050 with respect to a 1990 baseline (DECC, 2014). However, whilst such changes may benefit the environment due to reduced carbon emissions, there is a need to explore the wider economic, environmental and societal impacts.

There is on-going research into the maximisation of energy recovery/minimisation of use through increased methane (CH_4) production, improved biogas quality and use of alternative processes (e.g. Gao et al., 2014; Scherson and Criddle, 2014; Villano et al., 2013), and it has been suggested that carbon neutrality may be an achievable objective if multiple strategies are implemented (Mo and Zhang, 2012; Rosso and Stenstrom, 2008).

Indeed, carbon neutral WWTPs have been reported (Suez Environment, 2012; USEPA, 2014). However, there is no universal consensus as to what should be covered by the term ‘carbon’ in the context of carbon reduction and carbon footprint: Gori et al. (2011), for example, include direct carbon dioxide (CO_2) and CH_4 emissions, whereas the claim of carbon neutrality for the aforementioned WWTPs is based only on energy use. This is in line with the CRC, which incentivises only reduction in CO_2 emissions associated with energy use (taking into account different levels of emission from different energy sources), but in such cases there is still a need to investigate the potential implications of carbon reduction measures on CO_2 and CH_4 formation by biological treatment processes.

Reducing net energy use alone may prove to be ineffective if the goal is to mitigate global warming. In such cases, even a more

---

* Corresponding author.
E-mail address: C.G.Sweetapple@ex.ac.uk (C. Sweetapple).

http://dx.doi.org/10.1016/j.watres.2015.06.047
0043-1354/

comprehensive evaluation of carbon emissions (considered to be those containing carbon) may be insufficient since nitrous oxide (N_2O) emissions from WWTPs can provide a significant contribution to total GHG emissions (Kampschreur et al., 2009). Strategies have previously been identified, for example, in which a reduction in energy use corresponds with an increase in total GHG emissions (Flores-Alsina et al., 2014) and, whilst there is on-going research into strategies for the reduction of GHG emissions, there is a need to investigate the impacts employing the approach encouraged under the CRC – i.e. reduction of energy use – on total GHG emissions.

Carbon or energy reduction may also be used to address sustainability issues (e.g. Holmes et al., 2009). However, sustainability is a complex, multi-dimensional concept comprising of economic, environmental and societal components (Mihelcic et al., 2003), each of which can be sub-divided into a large number of elements represented by different indicators (e.g. Muga and Mihelcic, 2008). 'Carbon neutral' or 'energy neutral' do not necessarily imply sustainable operation, as they address only one element of sustainability and implementation of low carbon solutions may have unintended detrimental effects on other aspects. For example, WWTP control modifications which provide a reduction in energy consumption but correspond with neither a reduction in total GHG emissions nor an improvement in effluent quality have previously been identified (Flores-Alsina et al., 2014): this corresponds with a move away from sustainability with respect to two of three indicators. It has even been suggested that the most sustainable solution may not result in *any* recovery of resources from wastewater (Guest et al., 2009), highlighting the need to explore the relationship between carbon neutrality and sustainability.

This study, therefore, aims to investigate previously unexplored relationships between carbon neutrality and sustainability in the context of wastewater treatment, focussing in particular on the impact of energy reduction measures. The study highlights the potential benefits achievable and the associated consequences of adjustment to WWTP control for an activated sludge plant, rather than the development and/or application of new processes. An approach consistent with that required under the CRC, which is based only on energy use and recovery, is used in the assessment of carbon emissions; total GHG emissions, including direct and indirect CO_2, CH_4 and N_2O are evaluated separately. Low energy solutions are highly desirable under the CRC and there is much research focussed on enhancing energy recovery from wastewater to reduce the carbon footprint. By assessing the operational costs and a range of environmental performance indicators, including GHG emissions and pollutant removal efficiency, this research provides a more detailed picture of the potential impacts of pursuing carbon neutral/negative wastewater treatment on moving towards sustainability in the development of WWTP control strategies.

2. Materials and methods

2.1. Wastewater treatment plant model

The WWTP in which energy saving measures are implemented and sustainability indicators evaluated is an activated sludge plant, the Benchmark Simulation Model No. 2 for GHG emissions (BSM2G) (Flores-Alsina et al., 2014), with a mean influent flow rate of 20,648 m^3/d. Components include a 900 m^3 primary clarifier, an activated sludge unit containing two 1500 m^3 anoxic tanks and three 3000 m^3 aerobic tanks in series, a 6000 m^3 secondary settler, a sludge thickener, a 3400 m^3 anaerobic digester, a dewatering unit and a 160 m^3 reject water storage tank. A diagram of the plant layout is given by Flores-Alsina et al. (2011).

Biological processes are modelled using the Activated Sludge Model No. 1 (Henze et al., 2000) with extensions to enable modelling of N_2O emissions (Hiatt and Grady, 2008; Mampaey et al., 2013), as detailed by Guo and Vanrolleghem (2014). Additional GHG emission sources modelled include CO_2 produced and consumed in biological treatment, CO_2 from anaerobic digestion and biogas combustion, fugitive CH_4 emissions from anaerobic digestion, electricity consumption and generation, production of external carbon source, CO_2 and CH_4 from sludge storage and disposal, and N_2O from recipient due to effluent load. Further details on the model can be found in Flores-Alsina et al. (2014).

It is important to remember that mathematical WWTP models, as used in this study, do not provide an exact representation of reality. Control strategies that are successful when modelled may be less so in practice due to factors affecting full scale plants; however, benchmark simulation models do provide a means of objective control strategy evaluation (Copp et al., 2014).

2.2. Control strategy

Two different control strategies providing DO control (illustrated in Fig. 1) are investigated. These are selected since, as well as impacting energy consumption (e.g. Amand and Carlsson, 2012), DO control and aeration intensities in the activated sludge reactors are known to affect values of potential sustainability indicators, such as operational costs, effluent quality and GHG emissions (Aboobakar et al., 2013; Sweetapple et al., 2014b).

Firstly, the control strategy of Flores-Alsina et al. (2014) is implemented (referred to here as 'CL1'). This consists of two PI control loops: one in which DO concentration in the fourth activated sludge reactor is controlled by manipulation of aeration intensities in reactors 3–5, where aeration intensity in reactor 5 is half that in reactors 3 and 4, and one in which nitrite concentration in the second activated sludge reactor is controlled by manipulation of the internal recycle flow rate.

In the second control strategy, CL2, the DO spatial distribution is controlled with three independent control loops. This has previously been shown able to provide a significant reduction in GHG emissions and operational costs whilst maintaining a high effluent quality (Sweetapple et al., 2014a), and Jeppsson et al. (2007) found it to use significantly less energy for aeration than a wide range of alternatives. A setpoint of 1 g O_2/m^3 (Jeppsson et al., 2007; Vanrolleghem and Gillot, 2002) is provisionally set for every controller in CL2.

In both CL1 and CL2, two different wastage flow rates (Q_{w_winter} and Q_{w_summer}) are used to ensure sufficient biomass is maintained in the system during winter months. The higher flow rate, Q_{w_summer}, is applied when the influent temperature is greater than 15 °C (approximately start of May to end of October).

The CL1 control strategy with default parameter values (DO setpoint $= 2$ g O_2/m^3, $Q_{w\_winter} = 300$ m^3/d, $Q_{w\_summer} = 450$ m^3/d) (Flores-Alsina et al., 2014) represents the base case.

In all control loops, the sensors are assumed to be ideal (i.e. modelled with no noise and no delay) for testing the theoretical energy saving potential and sustainability impacts of different control options.

2.3. Decision variable sampling

A range of control options are developed for evaluation using factorial sampling of key decision variables, in order to identify solutions which improve the energy balance whilst maintaining a compliant effluent. Factorial sampling is chosen as it can provide good coverage of the search space with relatively few simulations, as demonstrated by Sweetapple et al. (2014a). Alternative techniques which provide greater coverage and may result in further improvements, such as Monte Carlo sampling or multi-objective

Please cite this article in press as: Sweetapple, C., et al., Does carbon reduction increase sustainability? A study in wastewater treatment, Water Research (2015), http://dx.doi.org/10.1016/j.watres.2015.06.047