Water Research 87 (2015) 522–530

Contents lists available at ScienceDirect

Water Research

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

Does carbon reduction increase sustainability? A study in wastewater treatment

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ARTICLE INFO

Article history:
Received 9 February 2015
Received in revised form
24 June 2015
Accepted 27 June 2015
Available online 2 July 2015

Keywords:
Carbon neutral
Control
Energy
Sustainability
WWTP

ABSTRACT

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

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http://dx.doi.org/10.1016/j.watres.2015.06.047

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

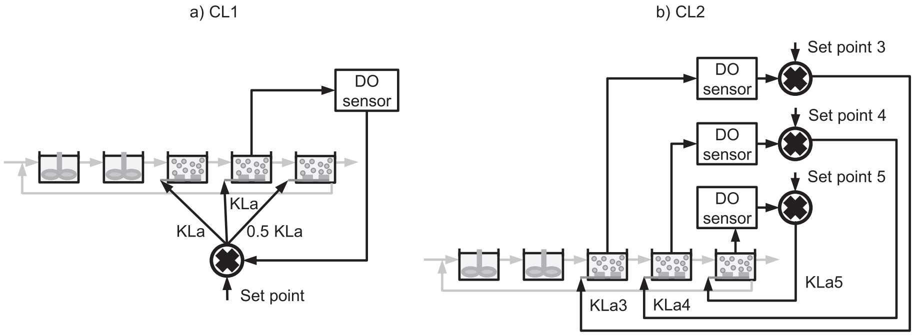

Fig. 1. DO control in the activated sludge unit in: a) the CL1 control strategy; and b) the CL2 control strategy.

optimisation with genetic algorithms, could be used in further study if computational capacity allows (e.g. Sweetapple et al., 2014c).

Selection of decision variables for sampling is guided by knowledge of control handles with significant impact on energy use, and previous sensitivity analyses with respect to indicators which may be used for sustainability.

Firstly, wastage flow rate is adjusted as this has been shown to be a key control handle with respect to its effects on GHG emissions, operational costs (which include energy use and recovery) and effluent quality (Sweetapple et al., 2014b). The two wastage flow rates, Q_{w_winter} and Q_{w_summer}, are both increased or decreased by the same factor simultaneously, using nine levels in the range 0.8–1.2 (e.g. for an adjustment factor of 0.8, $Q_{w\_winter} = 0.8{*}300\ m^3/d$ and $Q_{w\_summer} = 0.8{*}450\ m^3/d$). It is important to be aware here that, under low wastage flow rates, performance of a real plant may not match that simulated due to increased sludge concentrations and potential overloading of the sedimentation tanks. However, by restricting the wastage flow rate reduction to a maximum of 20%, this study aims to produce results which are at least indicative of those that may be achieved in a real plant.

Secondly, the DO setpoints are sampled, with ranges selected to encompass the default values. Selection of appropriate setpoints is important and a potential pathway to reduce energy consumption, since sufficient DO must be supplied to sustain aerobic activity and avoid bulking issues but over aeration represents a waste of energy, as the higher the DO level the lower the oxygen transfer efficiency.

The single DO setpoint in CL1 is sampled at five levels in the range 1.0–3.0 g O_2/m^3. Each setpoint is evaluated in conjunction with each wastage flow rate adjustment factor, yielding 45 solutions for evaluation in the CL1 control strategy. A 4-level factorial sampling design is used to generate sets of DO setpoints for the CL2 control strategy, with values in the range 0.5–2.0 g O_2/m^3. Instances in which the setpoint for the final reactor is greater than that for one or both of the preceding aerated reactors are removed, as such operation is likely to be inefficient in simulation studies due to high DO recirculation to the anoxic zone (DO recirculation is likely to be less significant in a real plant due to oxygen consumption in the settler or recirculation line; greater realism may be provided with a reactive settler model (Guerrero et al., 2013), but at the expense of greater computational demand). This results in 30 combinations of setpoints for analysis with each set of wastage flow rates, giving a total of 270 solutions for evaluation in the CL2 control strategy.

2.4. Performance assessment

Performance assessment of each control option is based on a one-year period which incorporates diurnal and seasonal phenomena. Simulation of each control option is carried out using the prescribed 200 day constant influent followed by 609 days dynamic influent, of which the last 364 are used for evaluation.

2.4.1. Effluent quality

Effluent quality compliance is assessed for every solution using the constraints summarised in Table 1 (based on the BSM2 requirements (Nopens et al., 2010)). For those that achieve acceptable 95 percentile values, energy use, energy recovery and sustainability indicators are also evaluated.

2.4.2. Net energy

Sources of energy use considered are activated sludge aeration, pumping (of internal recycle flow, return sludge, waste sludge, primary settler underflow and dewatering underflow), anoxic reactor mixing and digester influent heating. Energy recovery is calculated based on CH_4 production in the anaerobic digester, the theoretical energy content of CH_4, and a specified conversion efficiency. A net energy value is also calculated (energy use minus energy recovery); this is the energy measure considered in this study and should be minimised to improve the energy balance. A 'net energy use' rather that 'net energy recovery' value is chosen since for other sustainability indicators (see Section 2.4.3) a lower value corresponds with greater sustainability - it would be harder to compare indicators if one is to be maximised. This approach is also consistent with that of Flores-Alsina et al. (2011), who report net power using the same method. Note that when energy recovery is greater than the modelled energy use, this value will be negative; however, it is not possible to make any claims regarding the energy neutrality of the plant in such cases as not every source of energy use is considered in the calculation (influent pumping, for example, which is not included in the BSM framework as it is assumed to be the same under every scenario, being a significant omission). Energy requirements reported and used in literature cover a wide range, but typically 0.043 to 0.094 kWh/m^3 can be attributed to influent pumping, headworks, solids dewatering and lighting (Metcalf and Eddy, 2004), all of which are omitted in the BSM2G net energy calculation. As such, any solution providing a modelled net energy greater than −0.043 kWh/m^3 is unlikely to be energy

Table 1
Effluent quality constraints.

Effluent quality measure	Maximum concentration (g/m^3)
COD	100
Total nitrogen	18
Ammonia and ammonium nitrogen	4
TSS	30
BOD_5	10

neutral when considering the wider picture, but this is not a guarantee of carbon neutrality and a significantly lower net energy could be required.

Also note that BSM2G provides only indicative values of energy use and recovery; it is not entirely representative of reality. Calculation of energy use for digester heating, for example, is based only in the digester influent temperature and assumes no heat loss.

2.4.3. *Sustainability*

It is not possible to classify any solution as ‘sustainable’, but sustainability indicators should be able to show progress towards or away from sustainability (Lundin et al., 1999). Multiple indicators are used in this study for assessment of the environmental and economic aspects sustainability, guided predominantly by the work of Molinas-Senante (2014). These are summarised in Table 2.

Operational costs are represented by an operational cost index (OCI), as defined by Jeppsson et al. (2007). This accounts for sludge disposal, external carbon source and energy costs. Investment costs, another potential indicator for economic sustainability, are not considered in this case since the base case (against which the change in sustainability is assessed) already utilises DO control. Additional investment would be required for implementation of the CL2 control strategy (for both hardware and software), but this sum cannot be quantified and is assumed to be minimal compared with the costs reported by Molinas-Senante (2014) for comparison of different treatment technologies.

Treatment efficiency provides three indicators for environmental sustainability. In this study, percentage of influent COD, TSS and total nitrogen not removed, rather than percentage removed as in Molinas-Senante (2014), are reported. This is to ease comparison of sustainability indicators, since a reduction in indicator value now represents a move towards sustainability in all cases. Further environmental sustainability indicators (e.g. land area required, potential for water reuse and potential to recover products) which will not differ as a result of only operational changes are not included. GHG emissions are considered in addition to the indicators proposed by Molinas-Senante (2014), given that there is increasing interest in the impact of GHG emissions from wastewater treatment and their contribution to global warming.

The societal aspect of sustainability is not covered in this research since this cannot easily be quantified and adjustment of only WWTP control is expected to have negligible effect on typical indicators used for impact on society. Possible indicators for the social dimension of sustainability include odours, noise, visual impact and public acceptance (Molinos-Senante et al., 2014). These are useful when comparing treatment technologies but there would be no discernible or quantifiable difference resulting only from adjustment of control parameters. ‘Complexity’, a further indicator for social sustainability (Molinos-Senante et al., 2014), will be affected by the choice of control strategy – use of model predictive control, for example, would be considered more complex than conventional proportional integral (PI) controllers. However, the control strategies evaluated in this study all use PI controllers and, although the number of control loops differs between CL1 and CL2, it is assumed that there is insufficient difference in the complexity of each control strategy to warrant further attention.

3. Results and discussion

3.1. *Wastage flow rate adjustment*

Performance of control strategies with adjustment of only wastage flow rates is shown in Fig. 2. Within the range of wastage flow rates considered (base case ± 20%), all solutions produce an effluent with compliant 95 percentile values and net energy can be reduced by up to 63%. However, it is observed that a reduction in net energy does not correspond with a universal move towards sustainability. Whilst increasing wastage flow rate with respect to the base case in CL1 improves sustainability with respect to net energy, OCI, COD removal, TSS removal and GHG emissions, it also results in decreased sustainability with respect to sludge production and total nitrogen removal. This corresponds with trade-offs observed by Flores-Alsina et al. (2011) for operation with a low sludge retention time (SRT): low operational costs and GHG emissions but worsened effluent quality. In particular, the observed reduction in nitrogen removal when wastage flow rate is increased with no compensatory increase in DO setpoint is as expected, since nitrifiers will be washed out first under increased wastage flow rates due to their low growth rate, and higher DO concentrations are required to maintain nitrification at a low SRT (Eckenfelder and Argaman, 1991).

The CL2 control strategy is able to provide the greatest reduction in net energy and with significantly reduced operational costs and GHG emissions. However, there are trade-offs to consider, with reduced total nitrogen removal showing a move away from sustainability despite compliance being achieved.

Within the range considered, no overall improvement in WWTP sustainability can be achieved by adjustment of wastage flow rate alone: in both control strategies, increased wastage flow rate corresponds with improvements in net energy, TSS removal and COD removal, but also increases sludge production and can be detrimental to nitrogen removal. The base case is already near-optimal with respect to nitrogen removal, and performance in this respect is worsened by adjustment of wastage flow rate to improve sustainability as indicated by net energy, operational costs, COD removal, TSS removal or GHG emissions. However, improvements may be achieved with further adjustments to the WWTP operation, in particular by optimisation of the DO setpoint(s).

3.2. *Dissolved oxygen setpoint adjustment*

3.2.1. *Sustainability indicators*

When wastage flow rates and DO setpoint(s) are adjusted simultaneously, a wide range of solutions are produced which provide a reduction in net energy with respect to the base case whilst maintaining a compliant effluent. The greatest energy

Table 2
Indicators for sustainability assessment.

Dimension	Indicator	Units
Economic	Operational costs	–
Environmental	COD not removed	%
Environmental	Suspended solids not removed	%
Environmental	Total nitrogen not removed	%
Environmental	Energy consumption	kWh/m^3 treated wastewater
Environmental	Sludge production	kg TSS/m^3 treated wastewater
Environmental	GHG emissions	kg CO$_2$e/m^3 treated wastewater

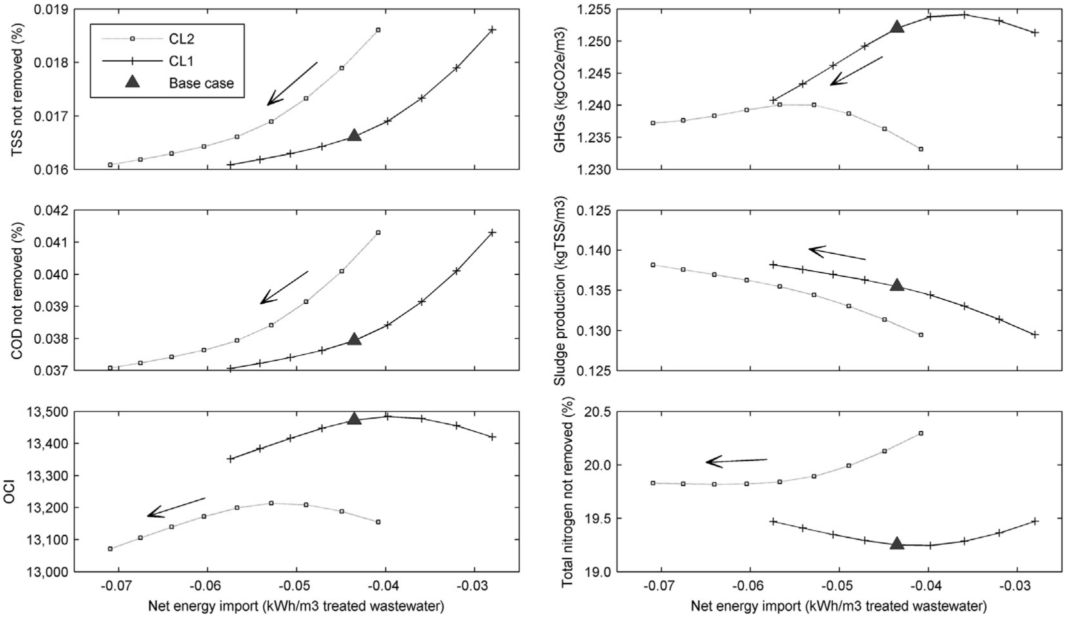

Fig. 2. Impact of wastage flow rate adjustment on net energy import and sustainability indicator values; arrows represent direction of change resulting from increased wastage flow rate.

reduction (73%) is achieved by implementing the CL2 control strategy with a 20% increase in wastage flow rate and DO setpoint in the final reactor reduced to 0.5 g O_2/m^3 (maintaining a setpoint of 1 g O_2/m^3 in reactors 3 and 4). This may be sufficient to achieve energy neutrality, but neutrality cannot be guaranteed given that the modelled net energy recovery (0.075 kWh/m^3) is less than the upper bound of typical energy requirements reported by Metcalf and Eddy (2004) for the sources not included and BSM2G provides only a relatively simplistic estimate of energy use. Even if energy neutrality is achieved, this solution still results in a move away from environmental sustainability as represented by sludge production and nitrogen removal.

A pair-wise comparison of sustainability indicators for all solutions which reduce net energy, provide a compliant effluent and are non-dominated based on the seven sustainability indicators considered (i.e. no one indicator value can be further improved without worsening another) is presented in Fig. 3. It is important to notice that a reduction in net energy does not necessarily correspond with a reduction in GHG emissions. Indeed, the second lowest net energy solution results in a 1.7% increase in GHG emissions with respect to the base case. This increase may be inconsequential given modelling uncertainties and uncertainty in emissions data collected from real plants. However, a not insignificant proportion (10%) of solutions which provide a reduction in net energy also result in an increase in modelled GHG emissions, showing that this is a potentially important issue of which awareness is important. This finding is supported by past observation that low DO setpoints lower energy consumption but yield higher GHG emissions due to increased N_2O formation (Flores-Alsina et al., 2014), and is significant given that the general aim of the CRC, in which energy use is measured, is to reduce GHG emissions. This suggests that, perhaps, improving the energy balance is not a reliable methodology for emission reduction, and shows that it is important to consider the wider effects of energy reduction measures.

Fig. 3 also shows that considering the effects of energy reduction measures on GHG emissions is particularly important if no loss of nitrogen removal capacity is to be accepted, since only 11% of solutions shown provide an improvement in both GHG emissions and nitrogen removal. Ensuring no increase in GHG emissions whilst maintaining required nitrogen removal is an important consideration due to the high global warming potential of N_2O emitted during nitrification and denitrification. N_2O emissions can be curbed to some extent by measures such as ensuring sufficient DO during nitrification (Kampschreur et al., 2009), and it has been suggested that no compromise is required since plants achieving high levels of nitrogen removal typically emit less N_2O (Law et al., 2012) – avoiding compromise may become more challenging if energy saving measures are required, however.

Distinct trade-offs between sludge production and TSS removal, and sludge production and COD removal are shown in Fig. 3. As may be expected, only marginal reduction in sludge production can be achieved if the COD and TSS removal indicators for sustainability are not to be worsened, again suggesting that trade-offs are likely to be required.

A significant proportion of solutions providing a reduction in net energy also worsen environmental sustainability as indicated by the pollutant removal efficiencies. Initially it appears that the potential negative effects on COD and TSS removal are most significant, as the performance loss of the worst solutions with respect to the base case is more than double the performance gain of the best, whereas for total nitrogen removal, the maximum potential performance loss is approximately equal to the greatest potential gain. More detailed observation shows, however, that total nitrogen removal can be reduced from 80.5% (base case) to 78.2% (corresponding to effluent 95 percentiles of 11.4 and 12.4 g N/m^3 respectively) by implementation of control strategies to reduce net energy, whereas COD and TSS removal remain above 99.95% in all solutions. Despite signifying a move away from sustainability, it may be that such a small reduction in COD and TSS removal with respect to the base case is an acceptable concession to achieve improvement in other indicators. Such decisions would be subjective, however, and for the purposes of this study no indicator weightings are applied and no one indicator is considered more important than any other.

Finally, 89% of solutions which provide a reduction in net energy

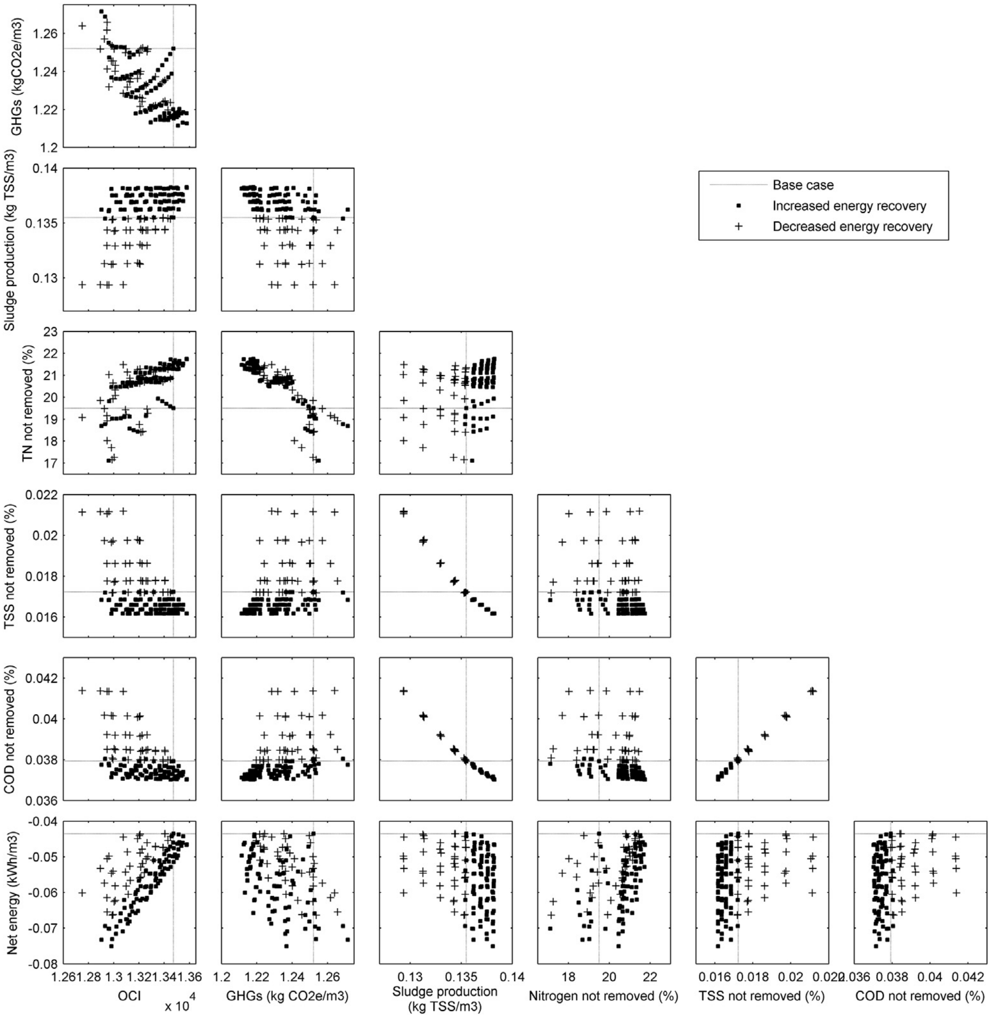

Fig. 3. Pairwise comparison of sustainability indicators, for solutions with adjusted wastage flow rates and DO setpoints which better base case net energy use (compliant and non-dominated solutions only).

demonstrate improved economic sustainability, as represented by the OCI. Although solutions providing the greatest energy reduction are not those with the lowest operational costs, modifying WWTP control to improve the energy balance appears to have detrimental effects on economic sustainability only when the energy reduction is small. A strong correlation between net energy and OCI is expected as energy costs are a key component of the OCI, and solutions which result in an increased OCI correspond with those in which sludge production (another component of the OCI) is increased.

3.2.2. *Net energy and energy recovery*

It is shown in Fig. 4 that increasing energy recovery is not necessary to reduce net energy – 34% of solutions which better the base case net energy do so despite reduced energy recovery, due to a greater reduction in energy use for aeration. However, to achieve the greatest potential reduction in net energy, increased energy recovery is required. To enable further investigation into the effects of selecting reduced or increased energy recovery solutions on each component of sustainability, solutions which provide a reduction in net energy with a decrease in energy recovery are distinguished in Fig. 3 from those in which energy recovery is increased.

All solutions in which a reduction in net energy is achieved without increasing energy recovery result in reduced nitrogen removal and/or reduced COD removal, both of which are considered a move away from sustainability. Simultaneous improvement of these two indicators is only achieved by solutions which provide increased energy recovery. Conversely, simultaneous improvement in nitrogen removal and sludge production is only achieved by solutions with reduced energy recovery, showing again that a universal move towards sustainability cannot be achieved within the range of simple control measures investigated. To provide greater sustainability, alternative control strategies and/or treatment technologies should be considered. Use of ammonium control, for example, can enhance nitrification during high load periods and save energy under low loads, and model predictive control can be advantageous when a plant is highly loaded and subject to stringent effluent fines (Stare et al., 2007). In such cases, however, it is important to also consider capital costs associated with their implementation, as these may impact significantly on their sustainability.

Solutions which provide an increase in energy recovery all correspond with an increase in sludge production (viewed here as undesirable with respect to sustainability). This confirms that research focussed solely on enhanced energy recovery from wastewater treatment may not necessarily be beneficial with respect to sustainability (as defined in this study), since it is necessary to consider the wider impacts. This is certainly not to

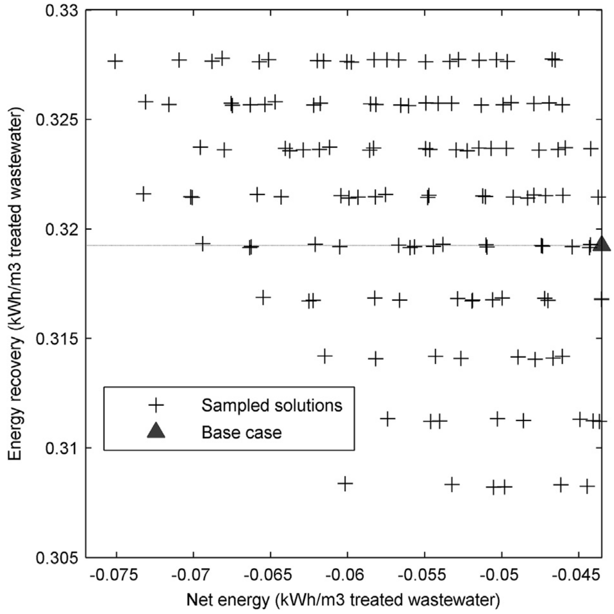

Fig. 4. Comparison of energy recovery and net energy for compliant solutions providing a reduction in net energy with respect to the base case.

suggest that increased energy recovery is always undesirable, however, as only a narrow range of control options were considered in this study, but it highlights the importance of considering the effects on sustainability when measures are taken to increase energy recovery.

3.2.3. Identification and analysis of 'best' solutions

The number of sustainability indicators improved by solutions in both the CL1 and CL2 control strategies is shown in Fig. 5. No options investigated here provide an improvement in all seven indicators, and more than 70% result in a move away from sustainability as measured by two or more indicators. Further improvements may be achievable with implementation of alternative or additional control strategies. However, it is widely recognised that trade-offs occur in sustainability assessment (e.g. Morrison-Saunders and Pope, 2013) and these must be considered in selection of the 'best' solutions.

The CL1 control strategy appears to perform best with respect to the number of sustainability indicators bettered, although this could be biased by the sampling strategy. In total, seven solutions are identified which better six of the seven sustainability indicators, including net energy. These could be viewed as preferable if the sustainability impacts of modifying WWTP control to improve the energy balance are to be minimised, but in reality selection of preferable solutions will be more complex: small deterioration in two sustainability indicators may be preferable to significant deterioration in one, but such decisions would have to be made on a case-by-case basis, taking into account local considerations. Given that no weightings are applied to sustainability indicators in this study and without further information it is not possible to prioritise improvements, however, this section of the research focusses on solutions providing improvement in the greatest number of indicators, irrespective of the magnitude of each improvement or deterioration.

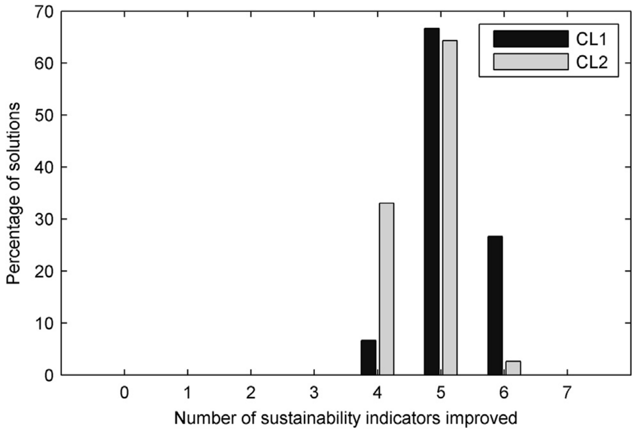

Fig. 5. Number of sustainability indicators bettered with respect to base case for solutions providing a reduction in net energy whilst retaining a compliant effluent quality.

Control details of the seven solutions which demonstrate a move towards sustainability in terms of six indicators (subject to achieving effluent quality compliance but regardless of sustainability credentials) and, for comparison, the base case and the lowest net energy solution are given in Table 3. Sustainability indicators for these solutions are shown in Fig. 6, with indicator values normalised with respect to the range observed across all solutions providing reduced net energy. Smaller values than those of the base case, i.e. those inside the dashed line, represent a move towards sustainability based on specific corresponding indicator.

Fig. 6 demonstrates the importance of assessing impacts of control adjustments with respect to different aspects and multiple components of sustainability as it shows that, although each solution provides a reduction in net energy, the sustainability impacts are quite different. For example, it is possible that only sludge production is worsened, only COD removal worsened, or only nitrogen removal worsened, depending on the choice of solution. There are also further trade-offs to consider, with the solutions providing the greatest reduction in net energy also showing the largest impact on the one sustainability indicator worsened: solution CL1-1 provides a 52% reduction in net energy but increases sludge production by 1.5%, whereas CL1-3 only reduces net energy by 36% but the increase in sludge production drops to 0.5%.

Although minimisation of sludge production is generally considered to correspond with improved sustainability (e.g. Molinos-Senante et al., 2014; Roeleveld et al., 1997), the magnitude of impact of sludge production on sustainability is dependent on the chosen means of disposal. Application to land, for example, might be considered to offset the WWTP's embodied energy as it reduces the need to use fossil fuel-based fertilisers (Mo and Zhang, 2012). As such, further information is required to determine the true extent of the negative sustainability impacts of solutions CL1-1, CL1-2, CL1-3 and CL2-1; if the sludge disposal method is chosen wisely then these solutions could be more desirable than appears based on the relatively large increases in sludge production shown in Fig. 6. In reality, the scale and direction of environmental impacts resulting from increased sludge production will be dependent on the chosen means of disposal.

Diagrams such as in Fig. 6 can be very useful for visualisation the trade-offs required under each solution and can aid selection of a preferable solution for implementation, based on the context-specific priorities and preferences. It can be seen, for example that, although the first seven solutions all provide an improvement in six sustainability indicators, the magnitude of improvement in each varies considerably, as does the deterioration in the final indicator. Without considering sustainability impacts, it is possible that the minimum net energy solution would be implemented; however, despite providing a significant move towards sustainability in terms of six indicators, performance with respect to

Table 3
Control parameters for base case, lowest energy solution and solutions which better six sustainability indicators with respect to the base case.

Solution	Base case	CL1-1	CL1-2	CL1-3	CL1-4	CL2-1	CL2-2	CL2-3	Min net energy solution
Control strategy	CL1	CL1	CL1	CL1	CL1	CL2	CL2	CL2	CL2
Wastage flow rate adjustment factor	1.00	1.15	1.10	1.05	1.00	1.20	1.00	1.00	1.20
Mean SRT (days)	16.35	14.28	14.92	15.61	16.37	13.71	16.36	16.36	13.71
Reactor 3 DO setpoint (g O_2/m^3)	–	–	–	–	–	0.5	0.5	1.5	1.0
Reactor 4 DO setpoint (g O_2/m^3)	2.0	1.5	1.5	1.5	1.5	2.0	2.0	1.0	1.0
Reactor 5 DO setpoint (g O_2/m^3)	–	–	–	–	–	0.5	0.5	1.0	0.5

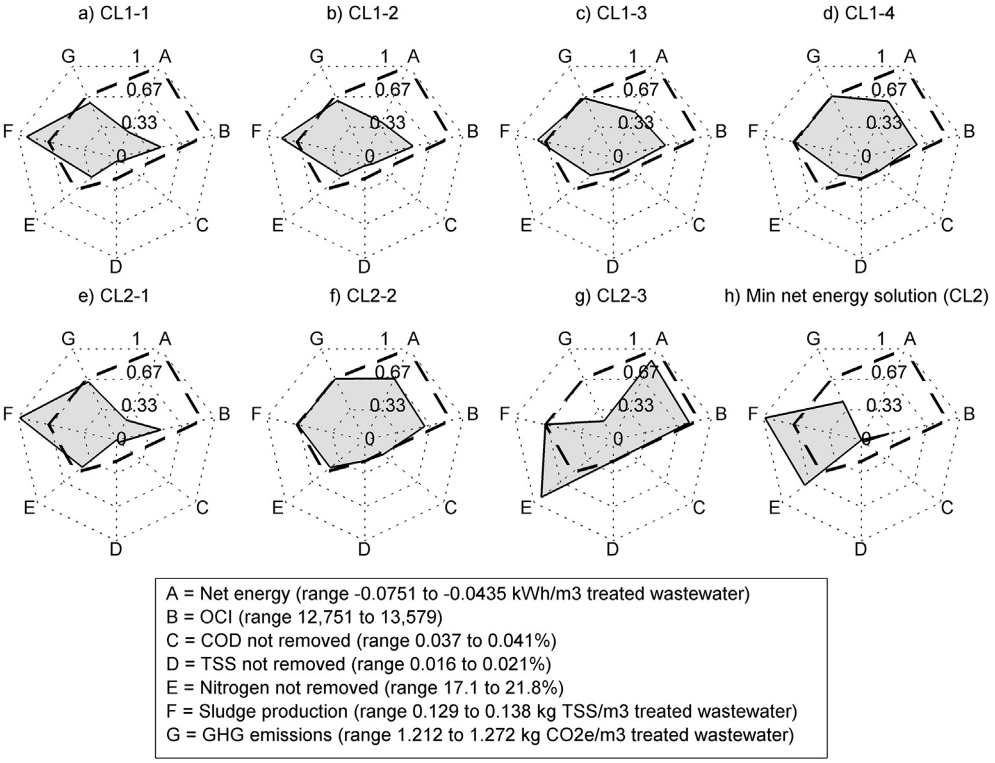

Fig. 6. Sustainability indicator values for lowest net energy solution and solutions demonstrating move towards sustainability in six indicators. Values nearer the centre of the plot are preferable, and dashed line represents the base case.

nitrogen removal and sludge production is among the worst of the solutions shown. The best solution may appear to be CL1-4, since only worsens one sustainability indicator (COD not removed) and the impact is negligible (0.1% change).

4. Conclusions

This research has explored the impacts of adjusting WWTP control to improve the energy balance on a range of sustainability indicators, by implementing a range of wastage flow rates and DO setpoints in two different control strategies. Based on analysis of the solutions generated which provide a compliant effluent with a reduction in net energy, the following conclusions are drawn:

- Implementing changes to WWTP control to reduce net energy use can be detrimental to sustainability. The energy balance of WWTPs may be improved by increasing sludge wastage flow rate alone, but this may result in a move away from environmental sustainability due to reduced nitrogen removal if additional changes to the aeration are not also made.
- Increased energy recovery does not necessarily correspond with a move towards sustainability, particularly in terms of environmental sustainability as represented by sludge production. Reduction in net energy can also be achieved by solutions in which energy recovery is decreased, but this results in different sustainability indicator trade-offs.
- Simultaneous improvement of both DO control and wastage flow rate selection can provide substantial energy savings, increase economic sustainability and enhance multiple indicators of environmental sustainability. However, it is particularly important that the impacts on sludge production and nitrogen removal are considered, as the lowest energy solutions developed are shown to be detrimental to these.
- Trade-offs between sustainability indicators have been identified and it is important that these are considered in future adjustment to WWTPs to achieve reduced energy use and carbon neutrality: reducing energy use does not guarantee an increase in sustainability. It is also important that a sufficiently large range of indicators is used to capture trade-offs present within the environmental component of sustainability since no solutions were found to provide a move towards sustainability with respect to every indicator.
- Improving the energy balance is not a reliable means of achieving a reduction in total GHG emissions. Although a

reduction in net energy was typically found in this study to correspond with reduced GHG emissions when energy recovery was also increased, solutions were also identified in which a significant reduction in net energy was achieved but at the expense of increased GHG emissions.

It is hoped that these findings will reinforce the need to consider the wider impacts of any WWTP control adjustments made with the aim of reducing energy use and/or increasing energy recovery, and in particular draw attention to potential unintended consequences of schemes such as the CRC.

Acknowledgements

Thanks are given for the Matlab/Simulink implementation of the BSM2G from the Department of Industrial Engineering and Automation, Lund University, Lund, Sweden. This work forms part of a 5-year fellowship for the last author funded by the UK Engineering & Physical Sciences Research Council (EP/K006924/1).

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