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# Retrofitting options for wastewater networks to achieve climate change reduction targets

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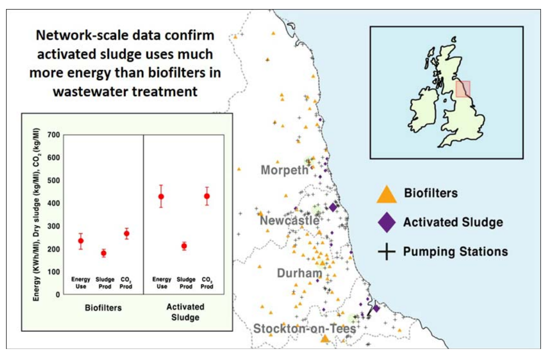
## HIGHLIGHTS

- Energy use and $CO_2$ emitted across a large wastewater network was quantified.
- Comparisons of energy and $CO_2$ from pumping vs biological treatment were made.
- Biological treatment demands the most energy and emits the greatest $CO_2$.
- Activated sludge plants use more energy and emit more $CO_2$ than biofilters.
- Retrofitting to include biofilters will make wastewater networks more sustainable.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

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## ABSTRACT

An alternate approach to urban and regional planning is presented that considers the wastewater infrastructure from an energy consumption and carbon production perspective. The existing wastewater infrastructure from four counties in North East England region is investigated, which includes energy and carbon dioxide ($CO_2$) data from 87 wastewater treatment plants (WWTPs) (16 activated sludge (AS) and 71 biofilter (BF) plants) and 196 pump stations across the region. This study provides a rigorous and novel way of justifying new investments for retrofitting treatment technologies to the wastewater network. Mass and energy balances are performed across the network utilising a spread-sheet based model. Overall, energy use and $CO_2$ emissions are greatest in biological wastewater treatment (relative to other network elements) with estimated median levels of 0.37 kWh/m$^3$ and 0.40 kg-$CO_2$/m$^3$, respectively, per waste volume processed. However, energy-use and $CO_2$ emissions differed according to treatment technology with AS plants using significantly more energy (median = 0.4 kWh/m$^3$) and producing more $CO_2$ (median = 0.4 kg-$CO_2$/m$^3$) than BF plants (medians: 0.2 kWh/m$^3$ and 0.3 kg-$CO_2$/m$^3$, respectively). Hence, directed interventions within WWTPs themselves will have the greatest positive influence on energy use and $CO_2$ emissions. Given water companies are often locked-in with their infrastructure, retrofitting existing treatment networks is strongly suggested. For example, adding BF pre-treatment to existing AS plants will reduce energy use, whereas anaerobic or photosynthetic technologies may be useful for reducing energy and $CO_2$ emissions in new-builds. This study confirms energy and carbon dioxide inefficiencies exist in modern wastewater networks, but uniquely identifies targeted actions to reduce inefficiencies, especially retrofitting existing WWTPs to reduce $CO_2$ emitted and energy used in the wastewater infrastructure to make major advances towards achieving climate change reduction targets.

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**Nomenclature**

| | |
|---|---|
| $r_{X,ps}$ | primary total suspended solids removal rate (g VSS/d) |
| $\%TSS_{X,ps}$ | percent removal of suspended solids in primary clarifier |
| $Q_i$ | influent wastewater average dry weather flow ($m^3$/d) |
| $X_i$ | influent total suspended solids (g/$m^3$) |
| $r_{S,pc}$ | primary $BOD_5$ removal rate (g $BOD_5$/d) |
| $\%BOD_{S,pc}$ | percent removal of BOD in primary clarifier |
| $S_i$ | influent $BOD_5$ (g/$m^3$) |
| $P_{x,VSS}$ | net waste activated sludge produced each day, measured in terms of total suspended solids, kg/d |
| $X_{o,i}$ | non biodegradable VSS in influent |
| $r_{o_2}$ | oxygen removal rate (g $O_2$/d) |
| $f$ | conversion factor to convert $BOD_5$ to BODu |
| $r_{S,B}$ | biological $BOD_5$ removal rate (g $BOD_5$/d) |
| $Y$ | mean cell coefficient |
| $\%Remv_{An}$ | fraction of total solids that is converted, a 50% conversion was assumed as suggested by Northumbria Water Ltd. |
| $VS_{deg.An}$ | solids that are reduced due to anaerobic digestion (g/day) |
| $Methane_{prod}$ = | volume of anaerobic digestion biogas produced ($m^3$/d) |
| $GPR$ = | anaerobic methane production rate ($m^3$ gas/tonne of dry solids fed) |
| $M_{Xww,t}$ | amount of wet solids that require transport (t/year) |
| $\%x$ | percentage of dry solids |
| $W_{load}$ | weight of sludge taken per load (t/load), a mean value of 11.2 t/load was used |

## 1. Introduction

There is a global need to reduce the amount of energy used and Greenhouse Gases (GHG) emitted, including Carbon Dioxide ($CO_2$), in all human activities. The European Parliament has committed member states to reduce GHG emissions and energy consumption by at least 20% between 1990 and 2020, and national action is occurring across Europe [1]. In England, a further commitment is to reduce $CO_2$ emissions by 80% by 2050 (1990 baseline) through the Climate Change Act [2]. However, achieving such ambitious targets will require substantial changes in delivering public services, including provision of drinking water and wastewater treatment systems and its associated infrastructure [3]. The challenge is that the operators are locked-in to its existing water and wastewater infrastructure, which was largely built when $CO_2$ emissions and energy use was not a major consideration. Therefore, chronic carbon and energy inefficiencies exist across water and wastewater networks, which require dramatic modifications to achieve a sustainable future. There is an urgent need for WWTP operators across the world to identify new ways to get the most value out of its existing infrastructures and this study provides a rigorous and novel way of justifying new investments for retrofitting new treatment technologies to the wastewater network. This paper demonstrates the energy and carbon dioxide inefficiencies that exist in modern wastewater networks, and provides novel actions and retrofitting options to reduce such inefficiencies.

Although minimising $CO_2$ emitted and energy used have become operating considerations in the water industry [4], there is still limited real data to guide targeted infrastructural changes to achieve the emission reduction goals. This is partly because alternate treatment technologies are not fully developed, and actual $CO_2$ emission and energy use data from full-scale operations have been unavailable. In fact, inadequate and dependable data on the water and wastewater infrastructure is recognised as a major knowledge gap [5,6]; making it very hard to baseline emissions and energy use in current networks, which in turn, makes informed strategic decisions difficult. This knowledge gap is closing [7,8], but the scale of mandated $CO_2$ and energy reductions within the urban water infrastructure is massive and more is needed. Indeed a recent review showed that most benchmarking methods are of diagnostic nature and do not provide improvement strategies to increase wastewater treatment plant (WWTP) efficiencies [9].

A case study utilising a system wide LCA, that is to include the construction and operation phase of the wastewater system, compared centralised and decentralised wastewater systems in California [10]. They found that decentralised system requires 37 GJ of primary energy for every million litres of wastewater treated, compared with 6.8 GJ with the centralised system. They attributed the significant difference mainly to the operational electricity, which was seven times higher for the decentralised system [10].

Comparing the electricity intensity and associated carbon emissions of WWTPs in USA, Germany, China, and South Africa, Wang et al. [11] showed that energy self-sufficiency is feasible for wastewater treatment if a combination of increased energy efficiency and energy harvesting from the wastewater is installed. A recent review of energy use and energy recovery in the wastewater treatment sector has shown that most energy self-sufficient WWTPs are using biogas from the anaerobic digestion of sludge for digester heating and electricity generation [12].

Drinking and wastewater infrastructures are intrinsically connected, but they differ in terms of how energy is used and where $CO_2$ is produced [3,6] as the wastewater industry can use two to six times more energy than the drinking water industry [13]. Wastewater infrastructures are more varied, ranging from small decentralised collection and treatment options, which discharge to large collection networks spanning whole cities or regions, to the local discharge to sensitive receiving waters. Further, wastewater treatment technologies range from activated sludge (AS) to biofilters (BF) to tertiary technologies (e.g., for nitrogen (N) and-or phosphorus (P) removal) to algal-based systems, which can potentially reduce $CO_2$ emissions [14,15].

The best combination to reduce energy consumption needs to be determined based on the local conditions [11]. The chosen technology is usually an industrial and commercial decision, and not a political or regional planning one, as decision depends on effluent load, plant age, installation and running costs, and other factors. Given such diversity, it is not surprising energy use and $CO_2$ emissions vary widely among different wastewater treatment options [9,16–18]. Historically, chosen treatment technologies have primarily focused on achieving effluent quality targets, which has biased decisions processes, such as AS, which readily achieves high organic removal rates, but also uses much more energy.

The question is how to satisfy future $CO_2$ emission and energy mandates in a world where existing infrastructure was not developed to minimise energy use or $CO_2$ emissions.

Wastewater treatment plants (WWTPs) have a typical life span of ~50 years for concrete structures and sewer lines are often designed for 80–100 years use [19]. Therefore, building new low-energy WWTPs and-or sewers is not a practical option in many cases, and it may be more feasible to retrofit existing WWTPs with improved treatment technologies. For example, most large WWTPs in the UK use AS for their secondary treatment step, which is energy-consuming due to active aeration in carbon degradation. Indeed a recent case study in Italy found that 50% of the energy is used from aeration in oxidation tanks [20]. However, if one could reduce carbon inputs to the existing AS plants, using lower pre-treatment options (e.g., BF), similar effluent quality could be retained using less energy [15]; an approach used in industrial waste treatment [21]. Retrofitting requires capital investment, but if such investment is strategic and considers economies of scale (i.e., retrofitting is most valuable in large WWTPs), considerable rewards could be reaped by reducing operational energy costs in a