The application of anaerobic ponds for UK domestic wastewater treatment

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ABSTRACT
Anaerobic ponds (APs) have the potential to provide many advantages for wastewater treatment in the UK, including low energy demand, minimal operation and maintenance requirements including sludge management, and the potential for renewable energy production. In order to quantify and examine the merits of incorporating APs into decentralised wastewater treatment for the UK water sector, a flowsheet modelling approach has been adopted to compare an AP flowsheet to a current standard decentralised flowsheet. An example works of 2,000 PE was chosen with a per capita flow rate of 200 L d^{-1} and a weak strength wastewater to reflect combined sewerage influent. Life-cycle cost assessment (LCCA) was conducted on the two flowsheets assuming a 20 year M&E asset life. Negative energy balances were calculated for both flowsheets, but the AP flowsheet required the least additional energy demand, as 56 % was offset by on-site energy generation. The desludge frequency calculated for the AP was 2 years, reducing tankering visits to site from 240 for the conventional flowsheet to 10 for the AP over the 20 year period, providing significant savings in O&M costs and carbon emissions. Over the 20 year LCCA, the TF and AP flowsheets were very similar in costs, at £240,481 and £252,749, respectively. Interestingly, the commonly cited prohibitive factor of APs, the costs associated with extended land requirements, were found to be negligible for the case of rural bare land sites. With rising energy and carbon prices putting pressure on the water sector to find alternative solutions for WWT in decentralised areas, APs may present a new approach to reduce the current burden of maintenance and sludge handling requirements.

KEYWORDS
Stabilization lagoons, decentralised works, low energy, biogas

INTRODUCTION
Anaerobic ponds have the potential to provide many advantages for wastewater treatment in the UK, including low energy demand, minimal operation and maintenance requirements including sludge management, and the potential for renewable energy production (Cruddas *et al.*, 2014). The opportunities APs could present to wastewater treatment flowsheets are especially suited to small decentralised treatment works, which pose unique challenges compared to larger centralised facilities. In the UK, treatment works serving < 2,000 PE account for 78 % of treatment works in the UK but only treat 4 % of the wastewater produced (Johnson *et al.*, 2007). These works present the greatest risk of non-compliance with effluent quality requirements (Griffin and Pamplin, 1998), and have a disproportionately high burden

on sludge management due to the need to tanker waste solids to centralised anaerobic digestion (AD) facilities (McAdam *et al.*, 2012; Cruddas *et al.*, 2014), and the associated infrastructure cost of ensuring suitable site access for these activities.

In order to quantify and examine the merits of incorporating APs into decentralised wastewater treatment for the UK water sector, a flowsheet modelling approach has been adopted to assess the relative impacts against existing technologies. The aim of this study is to compare an AP flowsheet to a current standard decentralised flowsheet in order to determine the suitability of APs for incorporation into decentralised wastewater treatment, and identify where potential benefits and barriers may lie. This aim will be achieved through three objectives:

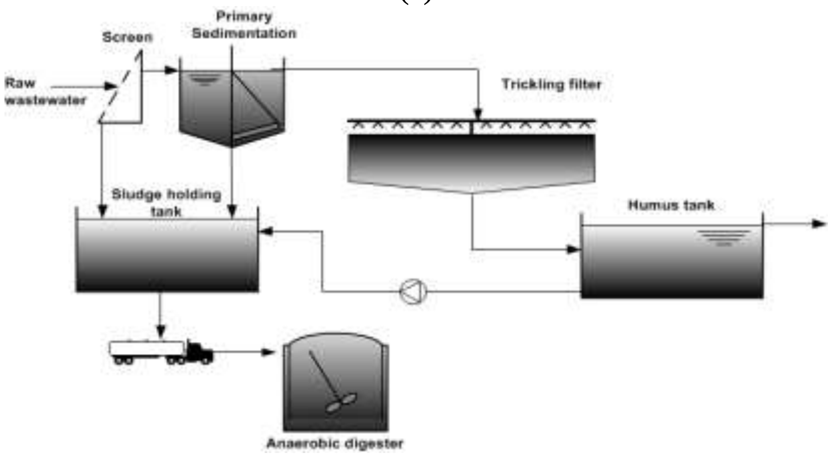
1. Modelling of energy balances for both flowsheets to determine energy requirements, both through on-site and off-site generation and demand
2. Carbon accounting of both flowsheets to assess carbon footprint, including direct impacts through fugitive emissions on site and indirect, through energy requirements and sludge transport
3. Life-cycle cost assessment (LCCA) for both flowsheets, to incorporate the energy demands and carbon footprint from objectives 1 and 2 with capital and operation costs

METHODS

Two flowsheets were chosen to be modelled, to compare a proposed AP treatment works with current established technologies (Figure 1). The base case flowsheet reflected a standard decentralised flowsheet, comprising a coarse screen followed by a primary sedimentation tank (PST), trickling filter (TF) designed for BOD removal and nitrification, and humus tank (HT) as final clarifier. An on-site sludge holding tank (SHT) was designed for 30 day sludge retention before sludge was exported to a centralised mesophilic AD. The second flowsheet modelled the AP, with secondary TF and HT, with additional on-site infrastructure of a micro combined heat and power (CHP) unit for conversion of biogas collected from the AP. The AP was designed for a 2.3 d hydraulic retention time based on data collected from a year-long pilot study on UK domestic wastewater (Cruddas *et al.*, 2014). The flowsheets were designed to meet an effluent quality of <10 mg L-1 BOD, <30 mg L-1 TSS and <3 mg L-1 NH4-N.

To reflect a decentralised UK treatment works with combined sewerage, a 2,000 PE was chosen with a per capita flow rate of 200 L d-1 and a weak strength wastewater as characterised by Tchobanoglous *et al.* (2003). Modelling was undertaken in Microsoft Excel assuming steady state conditions. Sludge held on site for 30 days was assumed to degrade in situ in accordance with the findings from a study of full-scale on-site sludge holding tanks in the UK (Cruddas *et al.*, 2014), and transportation distance to AD was set at 15 km. (McAdam *et al.*, 2011). Biogas yields and energy requirements for centralised AD have been attributed to sludge imports by normalising standard AD values per cubic metre sludge. Further parameters and assumptions for the energy and carbon modelling can be found in Table 1.

(a)



(b)

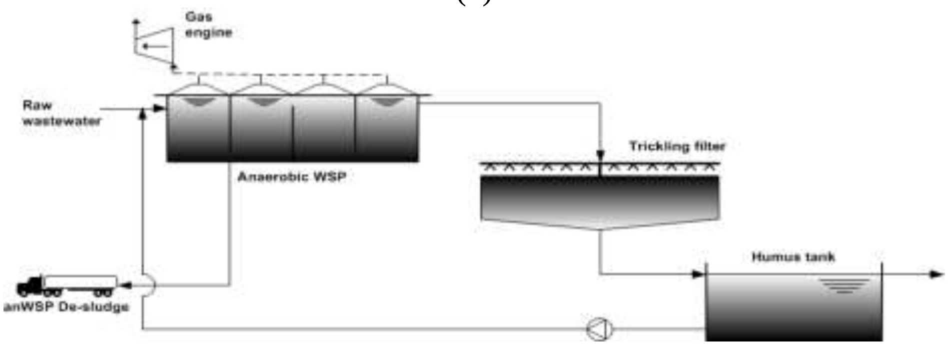


Figure 1 Model flowsheets for (a) a conventional decentralised treatment works, and (b) a decentralised works incorporating an anaerobic pond

Life-cycle cost assessment (LCCA) was conducted on the two flowsheets assuming a 20 year M&E asset life. Costs were calculated in British Pound Sterling (£), using costs sourced from the UK wherever possible. Where costs were quoted in alternative currencies conversions were made at the current exchange rate from XE.com. Capital expenditures (CAPEX) were not depreciated (Norris, 2001), and final disposal costs could not be estimated so were excluded for all assets. The PST, TF, AP and SHT were all assumed to be excavated reinforced concrete, with the HT above ground reinforced concrete. An intermediate pump was included to account for the additional pressure head required for the HT on both flowsheets, with an additional 15 % added to capital infrastructure costs to account for miscellaneous fittings, and 40 % for installation costs (Young *et al.*, 2012).

Table 1 Summary of parameters and assumptions for flowsheet energy and carbon modelling

Design parameter	Units	Value	Notes	Reference
Screen				
Energy demand	kWh m^{-3}	0.0023		McAdam *et al.*, 2012
Fugitive emissions	$kgCO_2e$ t^{-1}RDS	0.3		Czepiel, 1993
Primary sedimentation				
Hydraulic retention time	h	3.0		Foley *et al.*, 2010
Area	m^2	12.5	Assume 4 m depth	
Sludge generation	m^3 d^{-1}	1.18	60% solids removal	Tchobanoglous *et al.*, 2003
Energy demand (scraper)	kW d^{-1}	1.0	Assume 0.18 kWh PE^{-1} y^{-1}	Thöle, 2008

Anaerobic pond				
Hydraulic retention time	d	1.5		
Area	m^2	150	Assume 4 m depth	
Sludge generation	$m^3\ d^{-1}$	0.03	Assume 0.06 $m^3\ PE^{-1}\ y^{-1}$	Cruddas *et al.*, 2014
Biogas energy yield[a]	kWh d^{-1}	6.4	Assume 8 $LCH_4\ m^{-3}$WWT	Cruddas *et al.*, 2014
Trickling filter				
Organic loading rate	kg BOD $m^{-3}\ d^{-1}$	0.2		Tchobanoglous *et al.*, 2003
	g TKN $m^{-2}\ d^{-1}$	0.6	Assume 20 mg L^{-1} TKN	
Area	m^2	98	Assume 2 no. 3 m depth	Tchobanoglous *et al.*, 2003
Sludge generation	$m^3\ d^{-1}$	0.02		
Energy demand	kWh d^{-1}	1.6		Tchobanoglous *et al.*, 2003
Humus tank				
Upflow velocity	m h^{-1}	1.5		Tchobanoglous *et al.*, 2003
Area	m^2	11	Assume 3 m depth	Tchobanoglous *et al.*, 2003
Sludge generation	$m^3\ d^{-1}$	0.003		
Energy demand (scraper)	kWh d^{-1}	2.3	Assume 0.42 kWh $PE^{-1}\ y^{-1}$	Thöle, 2008
Sludge holding tank				
Area	m^2	40	For 30 d holding, 3m depth	
Fugitive emissions	$kgCO_2e\ d^{-1}$	2.4	Assume 57 $mgCH_4\ P^-E^{-1}\ d^{-1}$	Cruddas *et al.*, 2014
Anaerobic digester				
Hydraulic retention time	d	15		
Biogas energy yield[a]	kWh m^{-3} sludge	7.7		
Energy demand[b]	kWh m^{-3} sludge	2.2		Tchobanoglous *et al.*, 2003
Emissions for grid electricity	$kgCO_2e\ kWh^{-1}$	0.484		McAdam *et al.*, 2012
Emissions from sludge tankering	$kgCO_{2e}$/t/km	0.114		McAdam *et al.*, 2011

[a]Assumed methane conversion of 10 kWhe/m3 and on-site electrical conversion efficiency of 20%, centralised electrical conversion of 40%
[b] Includes energy for sludge dewatering, thickening, AD mixing and heating

In-house data for CAPEX and OPEX were provided on a confidential basis by a UK water utility. The price of the CHP engine was provided by the in-house data and includes built-in biogas scrubbing, however this cost is typically tailored to site-specific usage and therefore is only an estimate. Whilst energy and associated emissions costs were calculated for AD per cubic metre sludge imports from the flowsheets, capital assets for AD were assumed to be existing and therefore not included. Operational expenditures (OPEX) included an emissions cost set at the UK carbon floor price for 2014-15 confirmed by the UK Treasury (Ares, 2013) in order to incorporate environmental impacts into the economic assessment. Maintenance schedules were estimated after consultation with a UK water utility, with site visits occurring weekly for the TF flowsheet, and monthly for the AP flowsheet. All further parameters and assumptions for the LCCA can be found in Table 2.

Table 2 Summary of parameters and assumptions for the LCCA

Parameter	Units	Value	Notes	Reference
CAPEX				
Land	£ m^{-2}	1.84		(RICS, 2013)
Excavation	£ m^{-3}	5.30/3.50	First 200 m^3/additional	(SEERAD, 2001)
Reinforced concrete	£ m^{-3}	187/163/92	First 4 m^3/next 20 m^3/additional	(SEERAD, 2001)
Intermediate pump	£	5,200		In house data

CHP engine	£	6,000		In house data
AP cover	£ m^{-2}	20		(Aardvark EM Ltd., 2009)
TF media	£ m^{-3}	83	Assume 10 year replacement	www.alibaba.com
OPEX				
Civils maintenance	£ y^{-1}	3,250	Maintenance every 5 years	In house data
M&E maintenance	Maintenance once a year, 2% of capital costs			(Young *et al.*, 2012)
Maintenance visits	£ d^{-1}	41.80		In house data
Energy	£ kWh^{-1}	0.14	Same price for buy-back	(McAdam *et al.*, 2011)
Sludge transport	£ t^{-1} km^{-1}	0.14		(Jeanmaire and Evans, 2001)
Emissions cost	£ $t^{-1}CO_2e$	9.55		(Ares, 2013)

RESULTS

Energy Balance

Energy balances were calculated by subtracting the energy generated, both on and off site, from the overall energy demand of the flowsheets. Negative energy balances were calculated for both flowsheets, demonstrating that additional energy would be required in both cases (Figure 2). The AP flowsheet required the least additional energy demand, with 1.7 MWh y-1, with energy demand of 4.1 MWh y-1 offset by 56 % by the on-site energy generation. Whilst the TF flowsheet had a similar total energy balance to the AP, at 2.0 MWh y-1 required, the energy demand was offset by centralised AD, therefore the site requirements of the works would be 5.4 MWh y-1.

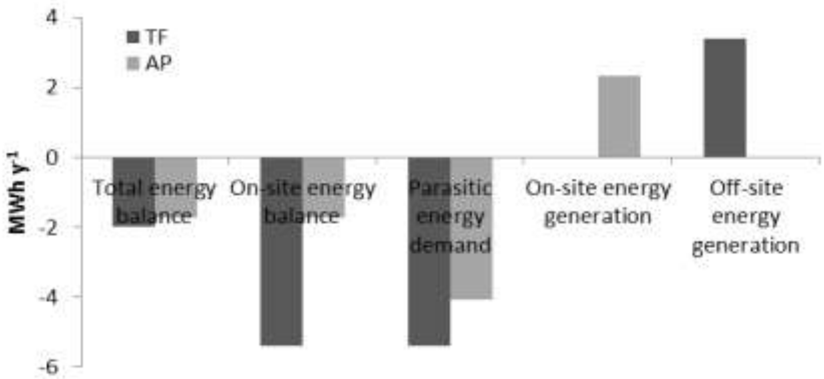


Figure 2 Energy balance trickling filter (TF) and anaerobic pond (AP) flowsheets

Carbon Footprint

Carbon accounting for each of the flowsheets was divided into three categories: emissions generated from net energy required; fugitive emissions calculated by release of greenhouse gases from the treatment processes, and emissions associated with the transportation of sludge from site to centralised sludge management facilities (Figure 3). Emissions from energy requirements formed the largest proportion of the AP and flowsheet, accounting for 93 % of total calculated emissions. Fugitive emissions primarily arose from on-site sludge storage, which not only has an environmental impact but also negatively affects the value of the sludge once imported to AD (Cruddas et al., 2014). For the TF flowsheet, emissions from sludge transportation were the most significant, comprising 36 % of total calculated emissions, and highlighting the impact of sludge management at decentralised sites. The desludge frequency calculated for the AP was 2 years, reducing tankering visits to site from 240 for the conventional flowsheet to 10 for the AP over the 20 year period.

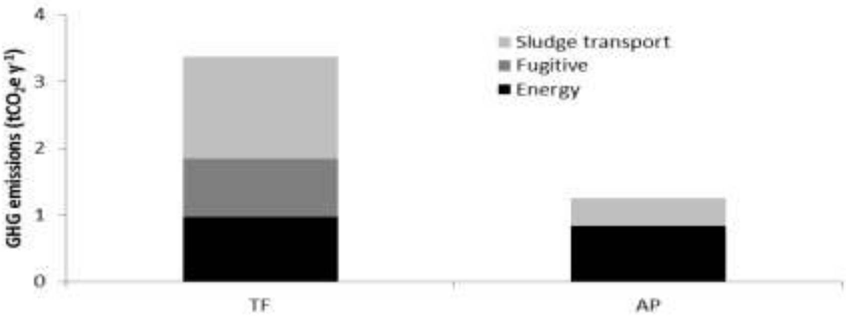


Figure 3 Greenhouse gas (GHG) emissions, expressed as carbon dioxide equivalents, from the trickling filter (TF) and anaerobic pond (AP) flowsheets

Life cycle cost assessment

Over the 20 year LCCA, the TF and AP flowsheets were very similar in costs, at £240,481 and £252,749, respectively (Figure 4). Higher CAPEX for the AP infrastructure, notably the size of the pond and the additional costs for biogas collection and utilisation, were offset by lower OPEX in maintenance requirements and sludge transport. In the AP flowsheet, CAPEX was actually higher than OPEX, with capital costs over three times the operational costs over the 20 year period. Interestingly, the CAPEX costs in the AP flowsheet were dominated by the infrastructure costs rather than the traditional assumption that land costs are prohibitive for extensive systems. The cost of land comprised 0.1 % and 0.2 % of the total costs for the TF and AP flowsheets, respectively, indicating cost of land was not a significant factor, whilst carbon costs also comprised less than 1 % in both flowsheets. Infrastructure was found to be the largest component, comprising 46 % and 76 % of total costs for the TF and AP, respectively.

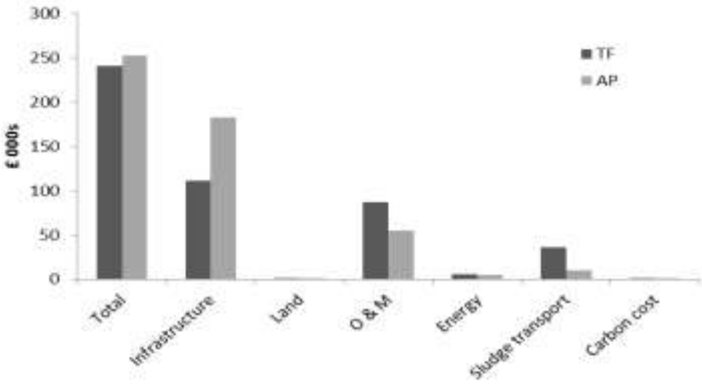


Figure 4 Costs calculated for the 20 year life cycle cost assessment (LCCA) for the trickling filter (TF) and anaerobic pond (AP) flowsheets

DISCUSSION

Flowsheet modelling of an AP flowsheet demonstrated the potential advantages of incorporating this technology into decentralised WWT flowsheets. Compared to a current standard aerobic example flowsheet, APs present opportunities for decreasing energy demands, particularly on-site, and lowering GHG emissions, whilst providing competitive whole-life costing. Whilst biogas produced from the AP was not able to cover the entire energy demand of the site, the small difference remaining of 1.7 MWhr y-1 could potentially be provided by renewable energy such as solar or wind, enabling an off-grid treatment works. If feasible, this would not only reduce carbon emissions and electrical costs further, but also eliminate the need for a grid connection, a significant capital cost which was not considered in this modelling exercise (Richards, 2014). Whilst the practicality of an entirely off-grid energy works would depend on the natural resources of the location, this potential further enhances the case of an AP flowsheet that is largely self-sufficient and requires little input, for energy or operation and maintenance. Furthermore, UK energy prices for medium sized industrial users have risen 5 % since 2008, whilst the UK has the poorest progress towards its renewable energy targets of any of the EU-27 countries (DECC, 2012). These additional drivers towards renewable energy and reducing reliance on grid-bought energy make pursuing the feasibility of off-grid WWT even more attractive. Additionally, the extended sludge storage time on site lead to a desludge frequency of 2 years. Whilst monthly sludge tanker visits would require the construction and maintenance of a permanent access road, a temporary access surface could be used for the AP desludge, eliminating another significant infrastructure cost (Richards, 2014).

The AP flowsheet demonstrated the potential to cut carbon emissions, however the economic gains from these reductions were not significant on an individual site basis. This is due both to the low emissions for such small works, and the economic cost of carbon as currently recognised in the UK. However, the government ‘floor price’ initiative will see significant increases in the price of carbon in subsequent years , with prices rising from £4.94 t-1CO2e in 2013/14 to the 2014/15 price used in this study, £9.55 t-1CO2e, up to an indicative rate of £24.62 by 2017/18 (Ares, 2013). This 398 % rise in carbon costs in 4 years will further the case for carbon savings from WWT works (Figure 5), alongside the current requirement of water utilities to report the associated emissions from their commercial activities as a sustainability indicator (Water UK, 2012).

Whilst the AP flowsheet included in this assessment demonstrate the potential for the AP to generate energy through a micro-CHP engine, an alternative option would be to flare the biogas on-site. Whilst this would eliminate the potential of energy generation from the AP, the benefit of low energy demand is still realised and the potential for off-grid energy from other renewable sources is still possible. The benefits of gas flaring would be a simpler on-site process requiring less operation and maintenance, whilst maintaining low air pollution and GHG emission. Additional resource recovery options, such as nutrient recovery from secondary treatment (Vohla *et al.*, 2011) or bioplastic production (Ben *et al.*, 2011) from the VFA-rich effluents from the AP could be explored in the future to complement the sustainability and resource recovery potential of the AP flowsheet.

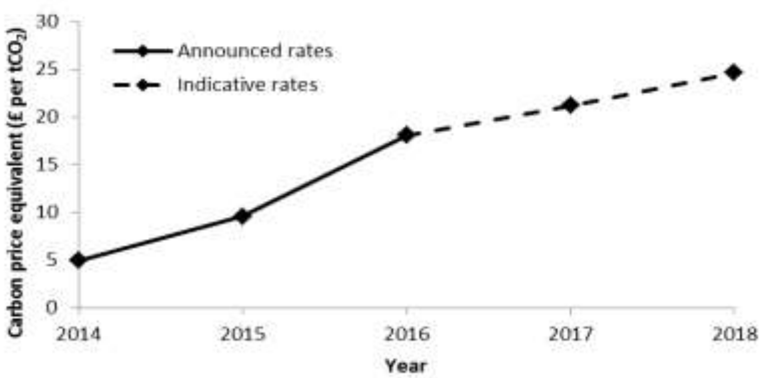


Figure 5 Carbon price equivalents announced by the UK Treasury, with set rates until 2016 and indicative rates until 2018 (adapted from Ares, 2013)

Surprisingly, the commonly cited prohibitive factor of APs, the costs associated with extended land requirements, were found to be negligible for the case of rural bare land sites. The land price used for modelling, £1.82 m-2, was a U.K. average for rural ‘bareland’ (farmland without buildings), with regional averages ranging from £1.11 m-2 in Scotland to £2.22 m-2 in North West England (RICS, 2013). Whilst prices have risen sharply in recent years, around 134 % since 2007, these increases are largely attributable to large holdings being purchased for commercial and residential development, whereas small holdings, where available, command much lower prices (RICS, 2013) and would be adequate for small WWT works. Previous studies have already determined that land costs are not prohibitive for the development of facultative pond systems in the UK (Mara, 2006; Johnson *et al.*, 2007), and with the potential decreases in HRTs possible in newer high-rate AP designs (Peña, 2010) the LCCA implications of land requirement are not significant. However, these costs only relate to new bareland sites, and in many situations water utilities will look to refurbish or retro-fit existing assets rather than purchase additional land. Therefore, the possibility of retro-fitting APs to existing infrastructure, such as PSTs or SHTs, should be explored, and reduction in HRT could be decisive in determining the feasibility of both the retro-fits and the possibility of constructing APs on land already owned. Importantly, in the case of the AP flowsheet, the CAPEX was greater than OPEX, and so if a LCCA was conducted over a period greater than 20 years the AP flowsheet would present further reductions in whole-life cost. If refurbishment of existing assets is a strategy for water utilities past the standard 20 year asset life, then initial investments in APs may provide greater payback in the long term.

Traditionally perceived benefits of APs in reducing operation, maintenance, and sludge handling requirements, were supported by the LCCA. The UK Water sustainability drivers to reduce sector GHG emissions and energy requirements, whilst increasing renewable energy utilised (Water UK, 2012), provide a strong case for the consideration of APs for decentralised WWT. These drivers are also reflected economically in the LCCA, where rising energy and carbon prices will continue to put pressure on the water sector to find alternative solutions for WWT in decentralised areas, and the large number of these small works require a new approach in order to reduce the current burden of maintenance and sludge handling requirements.

CONCLUSIONS

The potential advantages of incorporating APs into decentralised WWT flowsheets was assessed through flowsheet modelling against current standard options.

- Whilst neither of the flowsheets modelled could achieve full energy self-sufficiency, either on-site or as a total balance, the AP provided the closest balance to energy neutral, thereby reducing energy costs and associated emissions, and providing the opportunity for renewable energy sources to be explored to enable off-grid WWT.
- The AP flowsheet a lower carbon footprint compared to the standard flowsheet, with reductions from in fugitive emissions, energy requirement, and sludge transportation. Whilst current carbon prices do not present a strong economic incentive for carbon reductions when incorporated into a LCCA, significant rises in carbon pricing are expected in coming years, and non-economic incentives in reducing carbon emissions are strong.
- The cost of additional land for an extensive treatment system, commonly identified as a significant barrier to APs and other natural processes, was found to be largely insignificant when considered in the LCCA. However, in many scenarios retro-fitting or refurbishing of existing assets will be preferred to purchase of new bareland sites, and the potential of APs for these applications should be explored.
- Overall LCCA over a 20 year period found the AP to be competitive with a standard flowsheet. Significant savings were identified in OPEX, and therefore longer operational periods than 20 years would further improve the economic viability of the AP flowsheet.

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