Economic assessment of aerated constructed treatment wetlands using whole life costing

A. I. Freeman, S. Widdowson, C. Murphy and D. J. Cooper

ABSTRACT

There is increasing pressure on water treatment practitioners to demonstrate and deliver best value and sustainability for the end user. The aim of this paper is to evaluate the sustainability and economics, using whole life costing, of wastewater treatment technologies used in small community wastewater treatment works (WwTW) of <2,000 population equivalent (PE). Three comparable wastewater treatment technologies – a saturated vertical flow (SVF) aerated wetland, a submerged aerated filter (SAF) and a rotating biological contactor (RBC) – were compared using whole life cost (WLC) assessment. The study demonstrates that the CAPEX of a technology or asset is only a small proportion of the WLC throughout its operational life. For example, the CAPEX of the SVF aerated wetland scenario presented here is up to 74% (mean $= 66 \pm 6$%) less than the cumulative WLC throughout a 40-year operational time scale, which demonstrates that when comparing technology economics, the most cost-effective solution is one that considers both CAPEX and OPEX. The WLC assessment results indicate that over 40 years, the SVF aerated wetland and RBC technologies have comparable net present value (NPV) WLCs which are significantly below those identified for submerged aerated filter systems (SAF) for treatment of wastewater from communities of <1,000PE. For systems designed to treat wastewater from communities of >1,000PE, the SVF aerated wetland was more economical over 40 years, followed by the RBC and then the SAF. The aerated wetland technology can therefore potentially deliver long-term cost benefits and reduced payback periods compared to alternative treatment technologies for treating wastewater from small communities.

Key words | aerated constructed wetlands, economic valuation, net present value, small community wastewater treatment, sustainability, whole life cost assessment

A. I. Freeman (corresponding author)
S. Widdowson
C. Murphy
D. J. Cooper
ARM Group Limited,
Rydal House, Colton Rd, Rugeley, Staffordshire, WS15 3HF,
United Kingdom
E-mail: *andy.freeman@armgroupltd.co.uk*

INTRODUCTION

Freshwater systems provide a multitude of ecosystem services benefiting society. The quality and integrity of many freshwater ecosystems are under threat from a wide range of anthropogenic pressures including population growth, urbanisation, industrial development, water abstraction and discharge, and global climate change (Dodds Perkin & Gerken 2013; UNESCO 2015). Point sources of pollution potentially threaten the chemical status of receiving freshwater ecosystems, therefore centralised and decentralised water treatment systems are widely used to meet regulations and improve the quality of wastewater prior to discharge.

Over half of the centralised wastewater treatment works (WwTW) in the UK serve small communities, defined by article 7 of the European Urban Wastewater Treatment Directive 91/271/EEC (UWWTD) as agglomerations of <2,000 population equivalent (PE) (European Commission 2015). For example, over 70% of WwTW within the Severn Trent regional boundary in the Midlands (Green & Upton 1995) and 62% of WwTW within Southern Water's regional boundary in the South of England (Rowland & Strongman 2000) fall into the small community category. Furthermore, hundreds of decentralised small community treatment systems exist in the UK for those sites characterised by their rural location and lack of access to water company infrastructure.

Approximately half of the world's population lives in rural locations, with many awaiting proper sanitation

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systems or aiming to improve the efficiency of existing systems to enhance water quality entering freshwater systems and therefore protect ecosystem services (Capodaglio *et al.* 2016). Despite often limited financial resource (Garfí Flores & Ferrer 2017), small community WwTW are generally subject to higher costs per PE due to economies of scale; catchment characteristics such as variable flow and loads; and complexity of control, maintenance and monitoring in rural locations (Jacobs 2017). Treatment systems characterised by low capital expenditure (CAPEX), low power consumption and low maintenance and operational expenditure (OPEX) are therefore increasingly required to enhance the quality of wastewater discharging into freshwater ecosystems via point sources from small communities. Technologies with these characteristics also offer significant advantages in countries and locations where investment in centralised water treatment systems cannot be made or is considered disproportionately costly.

In comparison to conventional treatment technologies, constructed treatment wetlands offer many advantages given the treatment requirements of decentralised treatment systems described above (Kadlec & Wallace 2009). For example, they can be constructed from locally sourced materials resulting in reduced CAPEX (Kadlec & Wallace 2009); they have no or few moving mechanical parts, resulting in minimal maintenance requirements and reduced energy consumption; they can be built using a modular approach to meet population dynamics and future needs; and sludge can be captured and accumulated on the bed surface (in vertical downflow wetland configurations), therefore avoiding the need for dewatering equipment (Stefanakis & Tsihrintzis 2012; Morvannou *et al.* 2015) and resulting in reduced OPEX. The trade-off for these benefits comes in the form of increased footprint and land requirements compared to other forms of decentralised treatment, which may restrict the application of constructed wetlands in situations where land availability is at a premium or is limited. However, in recent years, constructed wetland technology has evolved from completely passive systems to intensified engineered systems such as artificially aerated wetlands (Wallace *et al.* 2006; Austin & Nivala 2009; Murphy & Cooper 2011; Murphy Nivala & Wallace 2012; Murphy *et al.* 2016; Freeman *et al.* 2018; Nivala *et al.* 2019). These systems have a much smaller footprint than earlier passive designs, allowing implementation at sites which were previously constrained by land availability. However, the reduced footprint comes at the cost of increased engineering and energy consumption (Austin & Nivala 2009; Nivala *et al.* 2019).

Some of the benefits of constructed wetlands compared to conventional water treatment systems are potentially difficult to quantify economically. Further, there has been a historical disconnect between CAPEX and OPEX, resulting in many commercial projects being awarded based on CAPEX alone. As such, there have been many studies, proposed methodologies and attempts to evaluate and quantify the benefits of constructed wetlands over alternative technologies, forming an interdisciplinary field within the constructed treatment wetland scientific community. Some of the most common valuation methods along with their pros and cons are presented in Table 1.

Currently, over 70 scientific papers have been published on the topic of constructed wetland valuation using an ecosystem services approach since 2009 (Masi Rizzo & Regelsberger 2018). Ecosystem services are the benefits that human populations derive, directly or indirectly, from ecosystem functions (Braat & de Groot 2012). These include but are not limited to enhanced outflow water quality, groundwater recharge, recreation, research and education amenity, flood management, carbon sequestration, biodiversity and habitat. To date, biodiversity, recreation and flood risk management are the most frequently evaluated constructed wetland ecosystem services (Masi Rizzo & Regelsberger 2018). One study established that the value of ecosystem services provided by constructed wetlands in the USA far outweighed their operational and running costs (Dunne *et al.* 2015).

An alternative valuation method is emergy: a measure of the energy and resource consumption required in the generation and construction of a service or product. This method converts each form of energy or matter from the production or construction process to solar energy equivalent using a conversion factor. Several researchers have used emergy accounting methods for the economic valuation of constructed wetlands. For instance, constructed wetlands were reported to have reduced emergy costs compared to the conventional activated sludge process and greater ecological waste removal efficiency, defined as the total energy cost of treatment divided by the mass of the waste removed (Zhou *et al.* 2009). Other emergy assessments include comparison of two wastewater constructed treatment wetlands in Florida resulting in a proposed set of emergy indices (Tilley & Brown 2006) and comparison of stormwater management wetlands in Beijing (Chen *et al.* 2009a).

Life cycle assessment is a tool for quantifying the environmental impacts of a product or process, and has been widely used to provide comparisons between constructed wetlands and other wastewater treatment systems.

Table 1 | Various quantification, valuation and environmental assessment methods found in the literature for constructed treatment wetlands

Method	Description	Pros and cons	References
Contingent valuation – ecosystem services	Proposes monetary values for ecosystem services such as outflow water, groundwater recharge, recreation, research and education amenity, flood management, biodiversity and habitat.	Adds a monetary value to ecological, environmental, aesthetic and societal aspects of the project. Lack of wider understanding and standard method. Numerous and conflicting approaches. Difficult to quantify.	Yang *et al.* (2008); Chen *et al.* (2009b); Sharma *et al.* (2015); McInnes & Everard (2017)
Emergy	Expression of the total energy consumed in the process of generating a product or service. Raw materials are examined.	Examines the supply chain of raw materials used in construction. Difficult to obtain comprehensive information for analysis, making direct technology comparisons difficult. Transformities are used as weighting factors, which can be subjective.	Siracusa & La Rosa (2006); Tilley & Brown (2006); Chen *et al.* (2009a); Zhou *et al.* (2009)
Life cycle assessment	Quantification of environmental impacts associated with each stage of the life cycle.	Comprehensive, incorporating costs of air and soil emissions throughout construction and operation over the asset's life cycle. Used widely with British Standards. Benchmarking and weighting can be subjective.	Fuchs *et al.* (2011); Lutterbeck *et al.* (2017)
Whole life costing	Considers all relevant costs and revenues associated with purchasing and operating an asset.	Uses standardised accounting methods, producing results as net present value. Standardised transparent method with British Standards. Focus on monetary values and tends to exclude values such as ecosystem services.	Machado *et al.* (2007); Corominas *et al.* (2013); Whitton (2016)

A standard methodology is published in BS ISO 14040:2006. Life cycle costs typically consider the extraction and processing of raw materials, the manufacturing process, operational environmental impacts and end of life disposal within their scope (Dixon Simon & Burkitt 2003). Both horizontal and vertical flow constructed wetlands were reported to have significantly better life cycle costs when compared to activated sludge wastewater treatment process (Fuchs Mihelcic & Gierke 2011). Saturated vertical flow wetlands were also reported to have better life cycle assessment results compared to the conventional activated sludge process due to having a significantly better carbon footprint (Pan Zhu & Ye 2011). Another study found that the life cycle costs of horizontal flow constructed wetlands are similar to those of biological aerated filters due to transport costs associated with the constructed wetland raw materials (Dixon Simon & Burkitt 2003).

A whole life cost (WLC) assessment is a variation of the life cycle cost assessment methodology. It involves identifying historic or future asset costs and referring them back to 'today's' present value, using standard accounting techniques such as indexation, discounting and net present value (NPV) (Green 2009; HM Treasury 2011). A standard methodology is published in BS ISO 15686-5:2017. The NPV principle infers that a risky pound tomorrow is less valuable then a certain pound today, and therefore all future cash flows are discounted annually. The discount rate reflects the opportunity cost of the capital mobilised, which increases with the estimated riskiness of the project, where riskier projects are expected to provide higher returns (Žižlavský 2014). The NPV method is widely used within the procurement decision-making process to identify the most economical and sustainable project solution from comparative technologies, assets or solutions, and it is having an increasing influence in UK water company procurement processes. Water companies within the UK are being challenged by the regulator OFWAT through price review (PR19) and the most recent asset management period (AMP 7) to demonstrate and deliver best value to customers, which is driving the use of whole life cost assessments. It is widely understood that the CAPEX of an asset is often only a small proportion of the total expenditure (TOTEX) over an asset's life or time scale of interest. For example, Figure 1 compares the CAPEX and the calculated WLC over 40 years of six aerated constructed wetland projects treating different strength effluents for 45–1,170PE. The

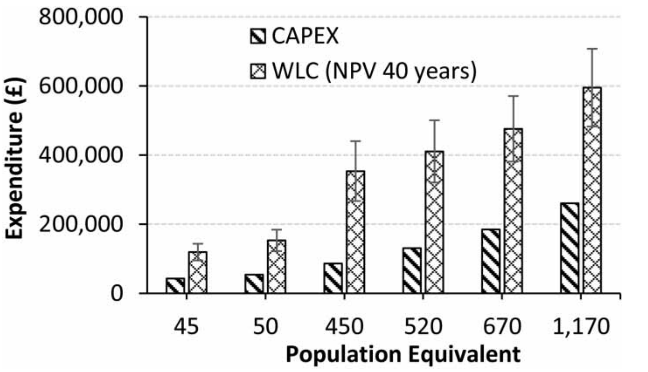

Figure 1 | A bar chart showing the capital expenditure (CAPEX) and net present value (NPV) whole life cost (WLC) over 40 years for six full-scale aerated constructed wetlands treating effluent for 45–1,170PE. The bars are the average of three estimations using inflation rates of 2.5% on future operation costs and annual discount rates of 4%, 6% and 8% ($n = 3$). Error bars show the standard deviation of the mean whole life cost assessment results based on the different discount rates.

CAPEX of the six systems reported in Figure 1 is up to 74% (mean $= 66 \pm 6\%$, $n = 6$) less than the cumulative expenditure over a 40-year operational lifetime due to the annual ongoing OPEX of the system. The most cost-effective solution is therefore one that considers both CAPEX and OPEX holistically using TOTEX and WLC models.

The aim of this paper is to evaluate the sustainability and economics of small community WwTW of <2,000PE, designed to protect and enhance the quality of freshwater ecosystems, using whole life costing. The results of the whole life cost assessment are potentially useful for consultants, water treatment practitioners, treatment system operators and public water authorities, to help inform the decision-making and technology selection process for wastewater treatment projects.

METHODOLOGY

Process of data gathering and calculation

Calculation of WLC results reported within this study followed the process outlined in Figure 2 and the methodology outlined within the British Standard BS ISO 15686-5:2017 (British Standards Institution 2017). In addition, a sensitivity analysis has been undertaken on all WLC results presented to establish the impact of the discount rate.

Information and costs incorporated within the whole life cost assessments

A summary of the WLC components is presented in Figure 3. These include all aspects of the project, from conception to completion, including:

- Design and consulting fees;
- Land costs (if appropriate);
- Mechanical equipment/material costs, including delivery;
- Connection to the existing infrastructure;
- Excavation/installation costs;
- Welfare during construction;
- Landscaping and reinstatement;
- Commissioning.

All future expenditure associated with owning and operating the asset, and when this expenditure is expected, is also required. These costs typically include:

- Servicing and maintenance costs;
- Energy consumption and charges;
- Sludge management and disposal costs;

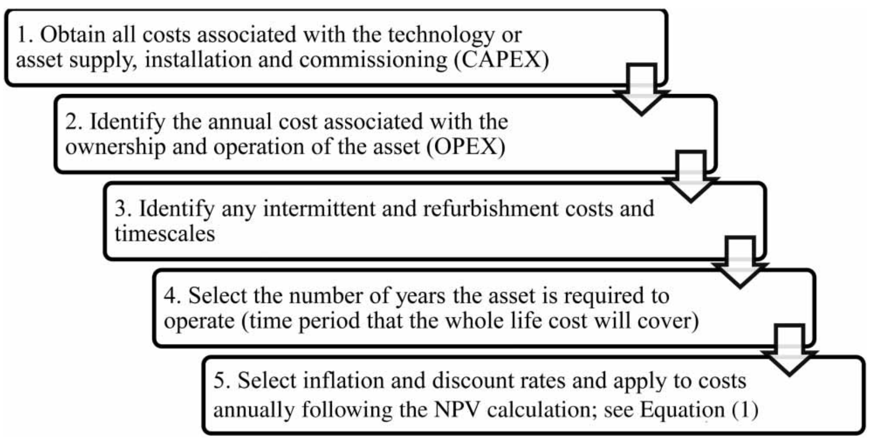

Figure 2 | Summary of the whole life cost assessment process.

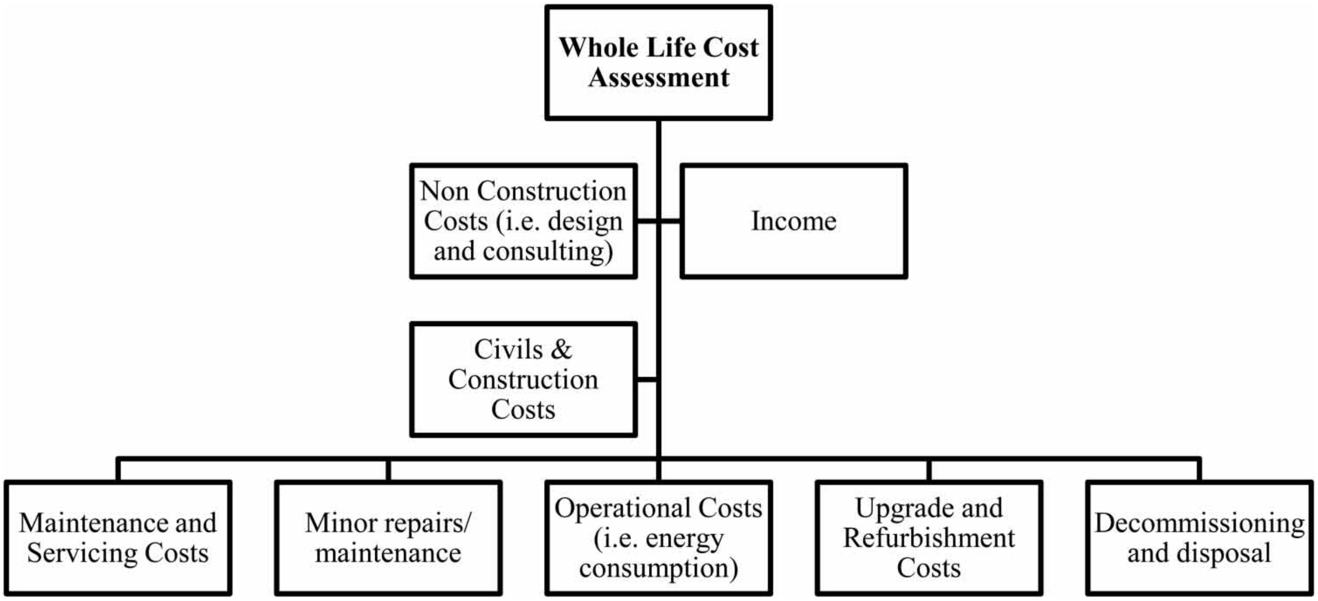

Figure 3 | Individual components used within the whole life cost assessment. Edited from Green (2009).

- Cost of consumables, including reagents, filters, grease cartridges etc.;
- Compliance and performance monitoring.

Calculation of whole life cost

All WLC results are presented as a discounted NPV, defined as the total funding that needs to be invested today to meet all future financial requirements as they arise throughout the operational life of the treatment asset. Future expenditure relating to OPEX and refurbishment is uplifted to account for inflation. An inflation rate of 2.5% is applied to all OPEX values used within the WLC calculations in this study. In line with standard accounting techniques, an annual discount rate of 6%, defined as the annual percentage for which the present value of a future pound is expected to depreciate over time, has been applied to all WLC calculations throughout the paper. The NPV is calculated by summing the inflation-adjusted annual expenditure over 40 years to cover at least one refurbishment requirement for each scenario, following Equation (1) (British Standards Institution 2017):

$$\mathrm{NPV} = \sum_{t=1}^{T} \mathrm{C}t/(1+\mathrm{r})^{t} \quad (1)$$

where:

NPV = discounted net present value
T = period of analysis in years (40 years)
C = annual inflation adjustment (2.5%)
t = estimated total expenditure in years 1 to 40
r = annual discount rate (6%).

Sensitivity checks

Whole life cost assessment results have been subjected to sensitivity checks to establish whether the discounting rate impacts the overall results of WLC comparisons between technologies. Large discount rates will make future operational and refurbishment costs appear insignificant in the final WLC results, whereas no or small discount rates will fail to convert future expenditure to NPV. A sensitivity check was performed to establish the effect of the discount rate on the final WLC analysis result for each scenario, using discount rates of 4%, 6% and 8%. Mean and standard deviation WLC results for the three values are presented for each scenario and technology. The inflation rate remained at 2.5% across all calculations.

Process flow descriptions

In this study, we present WLC analysis results for three wastewater treatment scenarios (Figure 4). The systems are approximately sized and designed to treat wastewater of 1,000PE and meet typical final effluent quality standards of 20:30:5 biological oxygen demand (BOD), total suspended solids (TSS) and ammonium (NH_4). A summary of the design characteristics, CAPEX and OPEX for the alternative treatment methods is presented in Table 2. Costs attributing

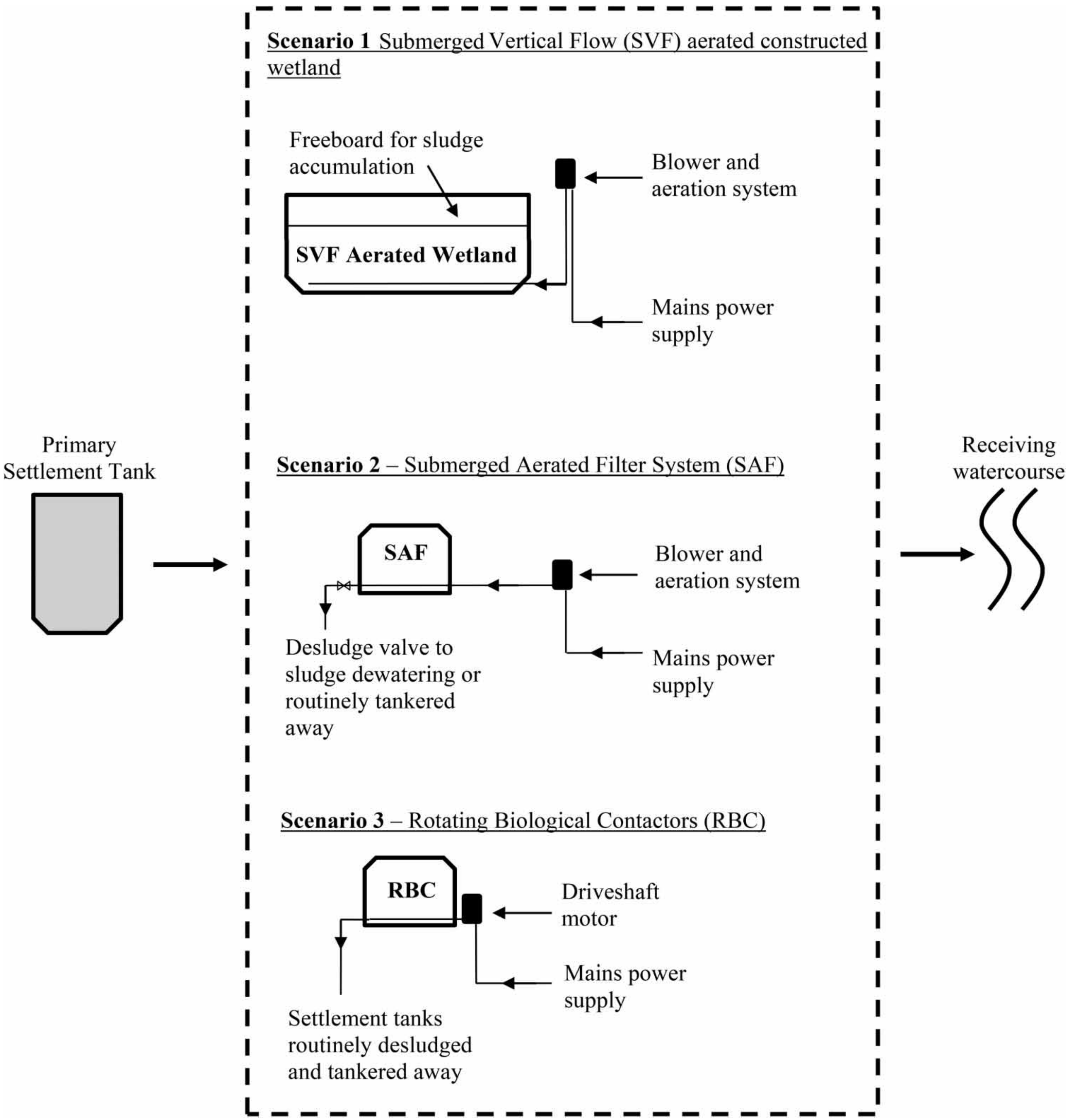

Figure 4 | Design process flow diagrams for three commonly used small community treatment systems.

to the ongoing OPEX of each asset are categorised and presented in Figure 5 as a percentage of the total OPEX.

Scenario 1 comprises a primary treatment septic tank and a saturated vertical flow (SVF) aerated constructed wetland. Design, consulting, excavation, liner, media, aeration equipment, concrete pad and blowers, construction, welfare and commissioning costs make up the CAPEX. The OPEX comprises costs associated with blower energy consumption, replacement blower filters and constructed wetland servicing and maintenance, including weeding and strimming the bed and surrounds and clearing inlet/outlet channels of vegetation. Annual desludge costs are not applicable as sludge accumulates on the surface of the aerated constructed wetland bed. In this scenario, sludge disposal costs are

Table 2 | Alternative wastewater treatment systems for treatment of 1,000PE

Scenario no. **Technology**	**1** **Aerated wetland**[a]	**2** **SAF**[b]	**3** **RBC**[c]
Design Information			
Footprint (m^2)	970	130	150
CAPEX			
Land cost (£)[d]	1,798	241	278
Materials, installation & commissioning (£)	234,051	287,836	311,572
Estimated CAPEX	235,849	288,077	311,850
OPEX			
Energy consumption (kW)	5.5	12	4.0
Annual energy cost (£)	7,227	15,768	5,256
Maintenance and servicing (£)	1,887	1,440	2,200
Annual desludge cost (£)	0	1,200	1,400
Total OPEX (£)	9,114	18,408	8,856
Refurbishment			
Frequency (years)	15	30	30
Refurbishment cost (£)	145,500	179,898	155,786

[a]Saturated vertical flow aerated wetland.
[b]Submerged aerated filter.
[c]Rotating biological contactor.
[d]Average arable land price for the first quarter of 2018: £7,500/acre (PropertyWire.com 2018).

effectively deferred until the point at which refurbishment is required when accumulated sludge is scraped from the surface of the bed and disposed of. Refurbishment costs also include removal, washing and reinstatement of the media.

Scenario 2 consists of a septic tank and submerged aerated filter system (SAF). The CAPEX includes design and consulting, construction, supply and delivery of the SAF unit, construction of concrete pad, crane lift and commissioning. The OPEX consists of blower energy consumption, desludge costs and maintenance and servicing, including diffuser cleaning and replacement blower filters.

Scenario 3 represents a septic tank followed by a rotating biological contactor (RBC). The CAPEX consists of design and consulting, construction, supply and delivery of the RBC unit, excavation, concrete pad, crane lift and commissioning. The OPEX includes motor energy consumption required to turn the drive shaft, servicing and maintenance (including replacement driveshaft grease cartridges), bio-disk inspection and quarterly desludging of the primary and final settlement zones within the RBC.

Several assumptions and omissions have been made in the WLC assessments undertaken within this study as described in Table 3.

RESULTS

Results of example whole life cost assessment for 1,000PE

The results of the WLC analysis for each treatment technology as described in Figure 4 are presented in Figure 5. The mean cumulative NPV 40-year WLC results were

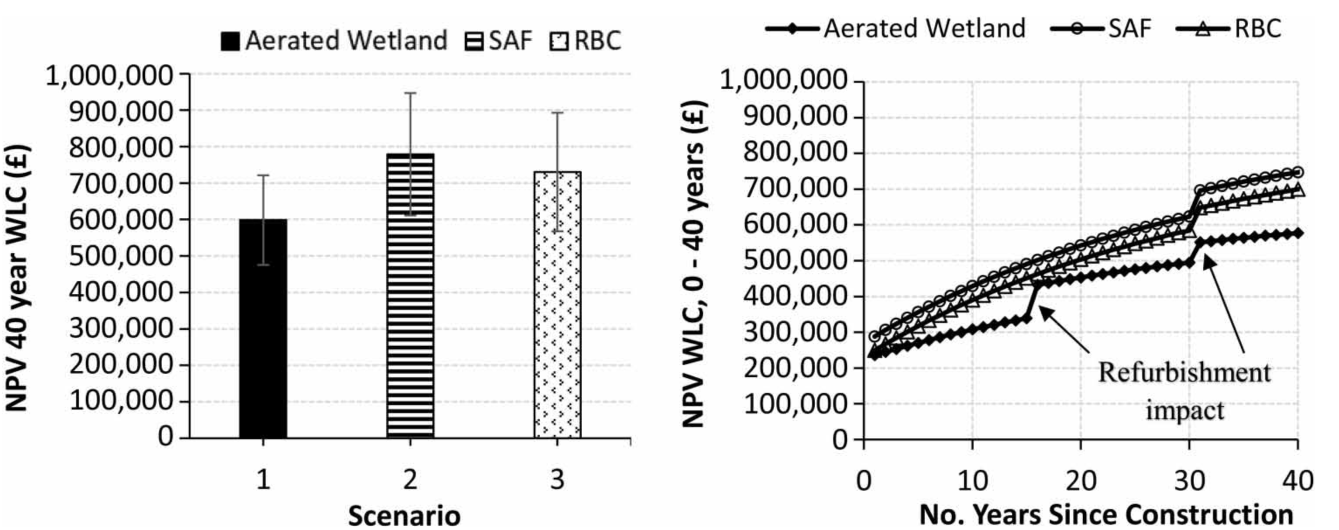

Figure 5 | Net present value whole life cost assessment results of three 1,000PE wastewater treatment scenarios. (Left): bar chart showing the cumulative net present value whole life cost assessment results over 40 years. The whole life cost bars are the average of three estimations using inflation rates of 2.5% on future operation and running costs and annual discount rates of 4%, 6% and 8% ($n = 3$). Error bars show the standard deviation of the mean whole life cost assessment results based on the different discount rates. (Right): line graph showing the net present value whole life costs accumulating from installation over 40 years.

Table 3 | Summary of whole life cost assessment assumptions and omissions

Scenario	Assumptions and omissions
General	• Systems to treat 1,000PE wastewater • Delivery pumps and pumping costs are excluded • Inlet and outlet pipework are excluded • Electrical components, controls panels, telemetry/SCADA are excluded • Water quality monitoring is excluded • Roads for desludging purposes are excluded • Energy costs calculated based on 24 hours/day running time over 365 days/year at a rate of 15 p/kWh • Assumes land is readily available to purchase at £7,500/acre
Scenario 1: Aerated wetland	• Sizing based on 0.1 kg BOD_5/d/m^3 (Freeman *et al.* 2018) • Media depth of 1 m • CAPEX estimated based on regression equations generated from as-built project data and costs • Assumes refurbishment is required at 15-year intervals
Scenario 2: SAF	• Sizing based on 4.6 kg BOD/d/m^3 media (Mendoza-Espinosa & Stephenson 1999) • Energy consumption equivalent to 1 kWh/kg BOD removed • CAPEX/OPEX estimated based on economy of scale regression equations generated from UK project data and costs • Glass reinforced plastic (GRP) degradation requires refurbishment at 30-year intervals
Scenario 3: RBC	• Sizing based on hydraulic loading rate of 0.04 m^3/d/m^2 disk area and organic loading rate of 3.9 g BOD/d/m^2 disk area (Tawfik *et al.* 2006) • CAPEX/OPEX estimated based on economy of scale regression equations generated from UK project data and costs • OPEX excludes replacement motor, drive shaft and belt • GRP degradation requires refurbishment in 30-year intervals

£598,489 ± £122,911, £779,060 ± £167,913 and £730,432 ± £162,560 for the SVF aerated wetland, SAF and RBC respectively. On average, the aerated wetland was the most competitive technology, having the lowest NPV 40-year WLC, followed by the RBC and the then the SAF. The reduction in sludge disposal costs of the aerated wetland compared to the RBC and SAF scenarios is a major factor in the overall reduced WLC results. For the aerated wetland solution, desludge costs are essentially deferred until year 15 when refurbishment would likely be required, as indicated by the stepped increases in years 15 and 30 (Figure 5). Further, the energy consumption contributed to 79%, 86% and 59% of the overall annual OPEX for each solution (Figure 6). Consequently, energy consumption had a major impact on the overall analysis results, with the aerated wetland and RBC having relatively low energy demands of 5.5 kW and 4 kW respectively, whilst the SAF had an energy demand of 12 kW, hence the higher overall NPV WLC of the SAF solution. However, the sensitivity checks using discounting rates of 4–8% revealed no overall significant difference between the three scenarios treating wastewater from a 1,000PE community.

Economies of scale

The 40-year WLC of each technology increases in line with population equivalent, due to increased treatment requirements and footprints, resulting in increased CAPEX plus increasing energy requirements and OPEX costs (Figure 7). This effect results in reducing WLC/PE as population equivalent increases. The benefits and competitiveness of the aerated wetland become increasingly evident as the population equivalent increases, especially when compared to the SAF. For the example PEs in Figure 7, some costs are fixed, including design, supervision and welfare, which partially explains the disconnect between the examples > and <450 PE. Further, there are economies of scale to consider, whereby some materials such as media and pipework may be cheaper per unit when buying in bulk.

CONCLUSION

On average, aerated constructed wetlands were shown to have reduced whole life costs over 40 years compared with other conventional wastewater treatment technologies for small community wastewater treatment, including both SAFs and RBCs. The reduced routine sludge disposal requirements and costs were a major factor in the reduced WLC results. For treatment of wastewater from communities of a 1,000 PE, the WLC results were shown to be sensitive to the discount rate selected, and overall no significant difference between the aerated wetland and RBC were observed, with WLC results for the SAF being significantly higher than the aerated wetland and RBC for all population equivalent scenarios. The aerated wetland became increasingly more cost effective as population equivalent increases beyond 1,000PE due to economies of scale. Ultimately, trade-offs between land requirements and

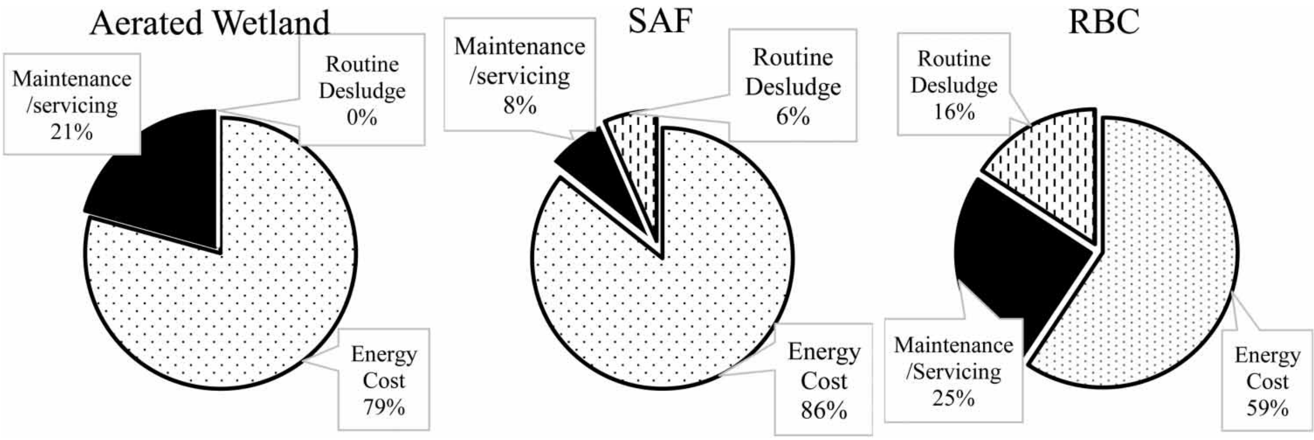

Figure 6 | OPEX categories as a percentage of estimated annual OPEX for each wastewater treatment scenario.

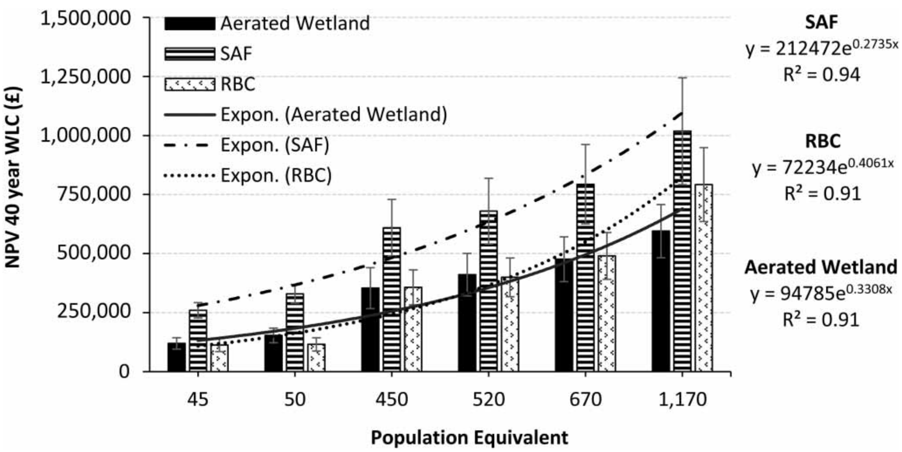

Figure 7 | Bar chart showing economies of scale for 45–1,170PE for three treatment technologies: vertical flow aerated constructed wetland, submerged aerated filter (SAF) and rotating biological contactor (RBC). The dotted line shows a good exponential relationship ($R^2 = 0.91$) between the 40-year net present value whole life cost and population equivalent for the aerated wetland technology.

mechanical complexity and energy requirements must be made during the technology decision-making process and early project concept stages. This study demonstrates how WLC analysis can be incorporated into the selection process to ensure long term value and sustainability are achieved.

Beyond reduced average WLC, constructed aerated wetlands have other amenity benefits, such as habitat creation and enhanced biodiversity, which are not quantified within the WLC analysis approach. Other methods such as ecosystem service valuation are justifiable to run in parallel and provide a more holistic approach to whole life costing, including benefits that may not have a direct monetary value but are more likely applicable to natural-based technologies, such as constructed wetlands, compared to more mechanical alternative systems. Further research in this area that is also extended to cover a broader range of treatment technologies and that considers factors of technology reliability to meet effluent standards would provide a valuable contribution to the current available literature.

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