Economical Evaluation and Operating Experiences of a Small-Scale MBR for Nonpotable Reuse

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Abstract: Because of their consistently high effluent quality, small footprint, and robustness to variations in influent quality, membrane bioreactors (MBRs) have become the technology of choice for small-scale reuse applications, such as in office buildings, hotels, and on cruise ships. The emergence of these systems arises from a number of drivers: lack of sewerage infrastructure, requirement for planning permission, subsidies, new guidelines for green buildings, and the public profile of recycling generally. This paper details the design and operation of a small-scale MBR providing 25 $m^3 \cdot d^{-1}$ of reclaimed water for toilet flushing and irrigation. Operational experience and outcomes from a 2-year evaluation period are included. An economic analysis of operational expenditures (OPEX) is also presented, revealing that for a plant of this scale, staffing costs account for the largest component (53%) of the OPEX followed by energy consumption (28%). The optimum design of these systems should therefore be focused on reducing operational complexity to minimize manual intervention. **DOI:** 10.1061/(ASCE)EE.1943-7870.0000505.

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Introduction

The increasing global population places an ever-growing pressure on water resources. In water-scarce regions and/or densely populated urban areas, water reuse is becoming increasingly attractive. Because of its small footprint, superior and consistent effluent quality, and robustness to changes in influent wastewater strength (Winward et al. 2008; Judd and Judd 2010), membrane bioreactor (MBR) technology is gaining momentum for urban nonpotable reuse purposes, as evidenced by recent implemented schemes over a whole spectrum of plant sizes.

Although high-profile large water reuse MBR installations exist (Ernst et al. 2007), a growing number of small-scale MBR (< 200 $m^3.d^{-1}$) are employed for niche reuse applications, ranging from single household (Abegglen et al. 2006, 2008), to holiday resort buildings/hotels (Boehler et al. 2007; Meuler et al. 2008; Paris et al. 2008), apartment/office blocks (Clerico 2007), and cruise ships (Institute of Marine Engineering Science and Technology 2006). The MBRs were shown to produce reliably high-quality effluent under conditions of highly variable loads, both seasonally (especially for tourist resorts) and diurnally, associated with these small plants. The product water is often used for toilet flushing (Boehler et al. 2007; Clerico 2007; Meuler et al. 2008; Merz et al. 2007) and for irrigation and cooling tower make-up water (Clerico 2007; Ogoshi et al. 2001).

Incentives and drivers for the emergence of these reuse schemes differ according to application and region. In areas with water scarcity, the main driver is water conservation through reuse for purposes such as golf course irrigation (Meuler et al. 2008). Outside of cities, the main driver for installing water reuse technology is often the lack of sewerage, such that no planning permission is given without an installed reuse system (Clerico 2007). In areas in which water scarcity is less critical, e.g., in metropolitan cities, such as New York City (NYC), the main driver is the green agenda linked with the reuse of blackwater. Several green-building schemes have emerged over the past decade, such as Leadership in Energy and Environmental Design (LEED) (USGBC 2010) and the Code for Sustainable Homes (CSH) (Department for Communities and Local Government 2010) in the UK, demanding decreased in-building water consumption to achieve improved environmental credentials. To obtain planning permission in Battery Park City, an area in New York City, developers must comply with the LEED standards, such that installation of a water reclamation system is imperative. Buildings with a high LEED rating can command higher rents, and an additional financial incentive was introduced in NYC in 2004, whereby water and wastewater charges are reduced by 25% for buildings that can reduce their water consumption commensurately (Clerico 2007). Similar drivers have been reported for Japan: the Tokyo Metropolitan Government requires large new buildings to adopt water saving measures, including rainwater harvesting and in-building greywater treatment for reuse

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for toilet flushing (Asano 2007). As early as 1997, 1,475 on-site individual building and blockwide water reclamation and reuse systems existed in Japan (Ogoshi et al. 2001), and 20 years of experience in Fukuoka city has proven water reuse for toilet flushing to be economically justifiable in many water-scarce urban areas.

Despite these drivers and the numerous reference applications, decentralized reuse systems are still subject to major drawbacks. In areas with very high land values, it can be more profitable to use the space required for a reuse system in the basement for other purposes, notwithstanding the relatively small footprint of a MBR system. Furthermore, required effluent quality for reuse purposes is significantly higher than that demanded from conventional treatment plants discharging into the environment. Posttreatment is thus required to provide residual disinfection and remove odors and color (e.g., granular activated carbon (GAC), ozone, UV, chlorination, or a combination), leading to increased costs and footprint (Clerico 2007; Abegglen et al. 2009). However, available quantitative literature data in this area, pertaining to small-scale systems costs, is scarce.

This paper presents a case study detailing the design and operation of a small-scale MBR for decentralized reuse in the UK. Plant performance and operational experience from 2 years of operation are presented. An economic analysis of operational costs was performed, and the main factors influencing operational expenditure (OPEX) identified; suggestions for improving system robustness and to limit operational complexity of small-scale plants are provided.

Materials and Methods

Plant Description

The wastewater reclamation plant (Fig. 1) is installed at a sustainable development in south London (UK), consisting of over 100 properties split into 8 housing blocks and a community center. Beside residential properties, the site also houses several offices, a nursery, an exhibition center, and a show home for visitors. The buildings are fitted with water efficient appliances, and the wastewater reclamation plant produces an average reclaimed water flow of 25 $m^3.d^{-1}$ for toilet flushing and irrigation.

The treatment process comprises the following (Fig. 1, Table 1):

1. Pretreatment: Domestic wastewater from the dwellings is collected through two pumping stations and septic tanks, which provide primary settling. The tanks have a residence time of up to 6 days; they were in place before the MBR system was installed and were not designed specifically as pretreatment for the MBR. The septic tanks only provide influent concentration equalization; they do not equalize the flows, because the septic tanks overflow to the second pump pit when influent enters. This results in highly variable diurnal loading to the MBR, as is typical for small-scale systems (Verrecht et al. 2010a). Further pretreatment is provided by 3-mm disposable sac screens (Copasac, Eimco UK) to remove hairs and fibers that could otherwise damage or clog the MBR membranes.
2. Membrane bioreactor: The MBR, a package plant designed by GE Zenon (Canada), contains both an anoxic (10.1 m^3) and aerobic (12.8 m^3) zone for denitrification and nitrification, respectively. The anoxic zone is equipped with a submerged agitator (3021, ABS, Germany) to keep the solids in suspension. Inflow of settled and screened sewage into the anoxic zone is controlled by the liquid level in the aerobic zone. The mixed liquor overflows through a weir from the anoxic zone to the aerobic zone, in which the dissolved oxygen concentration is maintained at around 2 $mg.l^{-1}$ through on/off control of a blower (GM3S DN 50, Aerzen, Germany) with a maximum capacity of 90 $Nm^3.h^{-1}$. The fine bubble aeration provided for dissolved oxygen (DO) control also keeps the contents of the aerobic tank mixed. Biomass is recirculated from the aerobic tank to the anoxic tank by means of a centrifugal pump (Sewabloc F50-250, KSB, Germany) with a maximum capacity of 8 $m^3.h^{-1}$, corresponding to a maximum recirculation ratio of 7.7. The solids retention time (SRT) is controlled by a timer-controlled automatic wastage valve, and sludge is wasted to the local sewer.

The ultrafiltration membrane separation step is provided by 2×3 ZW500c (GE Zenon, Canada) hollow fiber membrane modules, made from polyvinylidene fluoride (PVDF) with a pore size of 40 nm. The membrane cassettes are submerged in the aerobic zone and provide a total membrane surface area

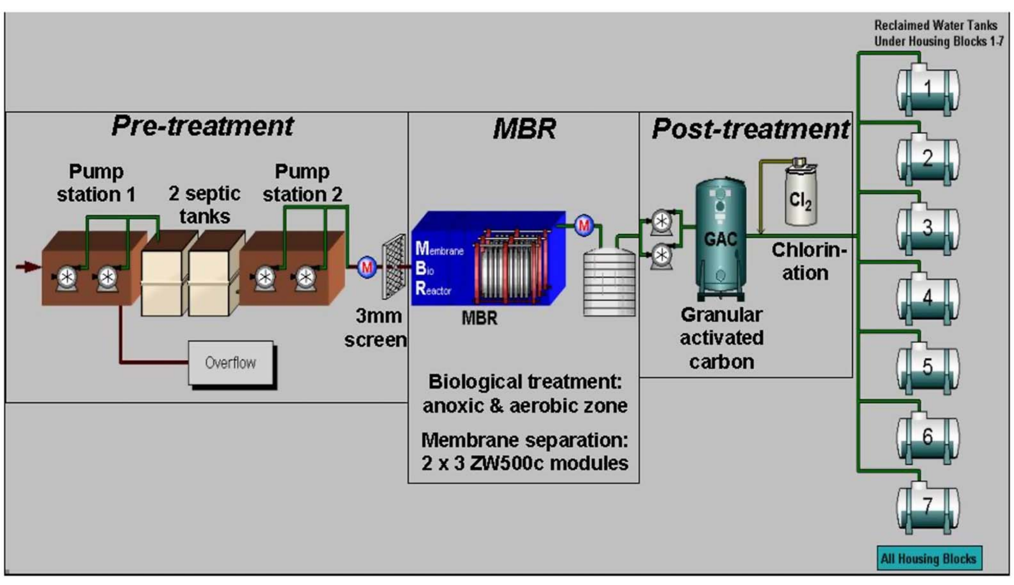

Fig. 1. Schematic overview of the wastewater recycling plant

Table 1. MBR Characteristics and Range of MBR Operational Parameters over the 2-Year Evaluation Period

Parameter	Unit	Value
Influent flow	$m^3.d^{-1}$	25
Volume anoxic zone	m^3	10.1
Volume aerobic zone	m^3	12.8
Recirculation ratio	—	2.3–4.3
Hydraulic retention time	*d*	1
Solids retention time	*d*	35–50
Mixed liquor suspended solids (MLSS)	$g.m^{-3}$	7,554–1,773
Temperature	°C	14–27
	Filtration parameters	
Membrane surface	m^2	69.6 and 139.2
Instantaneous filtration flux	Liters per m_2 per bar (LMH)	10.8–28.4
Filtration time	s	600
Relaxation time	s	30
Backwash time	s	30
Instantaneous backwash flux	LMH	10.8–28.4
Specific aeration demand per unit of time and membrane area (SAD_m)	$Nm^3.m^{-2}.h^{-1}$	0.11–1.25
Specific aeration demand per unit of permeate produced (SAD_p)	—	4.6–110
Aeration intermittency	—	Continuous; intermittent 10 s on −10 s off; intermittent 10 s on −30 s off
Permeability	$LMH.bar^{-1}$	~100

of 139 m^2. A lateral channel blower (Becker, Germany) provides air for membrane scouring to the coarse bubble diffusers incorporated in the module design, at a maximum flow rate of 115 $Nm^3.h^{-1}$, corresponding to a maximum specific aeration demand (SAD_m) of 0.82 $Nm^3.m^{-2}.h^{-1}$. Air cycling between the two cassettes is made possible by intermittent aeration valves controlled by an adjustable timer. Under normal operation, one cassette at a time is aerated for 10 s every 20 s.

3. Posttreatment: To ensure reclaimed water quality, posttreatment consists of filtration through a mixture of granular activated carbon and hydroxyapatite to remove residual color and odor, followed by chlorination for further disinfection and suppression of bacterial regrowth in the distribution pipework (Karim et al. 2005). The GAC vessel has a bed volume of 200 L and is normally run at an empty bed contact time of 10–20 min. A dose of 3 $mg.l^{-1}$ NaOCl is required to achieve a 1 $mg.l^{-1}$ chlorine residual after 24 h. The housing development has an existing dual pipe network to accommodate both the reclaimed and potable water supply to the houses, and reclaimed water is stored in tanks under each of the seven housing blocks.

The wastewater reclamation plant is automatically controlled by a programmable logic controller (PLC), and is monitored online with a dedicated supervisory control and data acquisition (SCADA) system displaying all relevant flows, levels, temperature, pressure, and concentrations. Grab samples are collected twice weekly from the influent, the aerobic zone mixed liquor, the MBR effluent, post GAC, and final effluent. Samples were analyzed according to the standard methods [American Public Health Association (APHA) 2005], and influent wastewater characterization and fractionation were published elsewhere (Verrecht et al. 2010a).

Calculation of Operational Costs

A cost sensitivity analysis was carried out, including energy consumption, staff cost for maintenance and plant attendance, chemicals and activated carbon usage, and sludge treatment and disposal. Tables 2 and 3, respectively, display the plant characteristics, derived from an evaluation period of 2 years, and assumptions used in the calculation of operational costs. Costs for the GAC adsorption media and chemicals were obtained from the suppliers, whereas costs for sludge treatment and disposal were derived from Ginest et al. (2006), who based their analysis on collection, thickening, digestion, and dewatering plus average values among different disposal/reuse routes, including hauling. Sludge production P_x was estimated from (Fletcher et al. 2007)

$$P_x = \frac{V \cdot \mathrm{MLSS}}{\mathrm{SRT}} \qquad (1)$$

where V = total biotank volume (m^3); and P_x = sludge production, in $kg.d_{-1}$. A maintenance clean [cleaning-in-place (CIP)] with 500 ppm NaOCl every two wk was sufficient to maintain permeability at around 100 $LMH.bar^{-1}$.

Results and Discussion

Effluent Quality

Because no guidelines currently exist for unrestricted urban reuse in the UK, the U.S. EPA standards for unrestricted urban reuse (U.S. EPA 2004) were adopted. Table 4 shows that the reclaimed water quality produced consistently meets and exceeds these standards, which is in line with the performance of other reuse MBRs

Table 2. Plant Characteristics used in OPEX Calculation

Parameter	Unit	Value	Parameter	Unit	Value
Pretreatment			NaOCl used per CIP	l	2
PS 1-kW rating	kW	1.6	MLSS	$g.m^{-3}$	8,000
PS 1-Flow	$l.s^{-1}$	4.25	SRT	d	50
PS 2-kW rating	kW	1.1	Posttreatment		
PS 2-Flow	$l.s^{-1}$	3.2	Energy consumption	kW	1.4
Membrane bioreactor			GAC capacity	BV	6,000
Energy consumption	kW	4.03	Chlorine dosing	$mg.l^{-1}$	3
NaOCl CIP frequency	$1.y^{-1}$	26	Maintenance/plant attendance		
CIP NaOCl concentration	ppm	500	Weekly staff attendance	$h.wk^{-1}$	8

Table 3. Cost Assumptions for OPEX Calculation

Parameter	Unit	Value	Reference
Electricity	$£.kWh^{-1}$	0.11	UK value, Energy EU 2010
Labor costs	$£.h^{-1}$	25	—
Granular activated carbon	$£.kg^{-1}$	2.98	Supplier
Sludge management	$£.tnDS^{-1}$	423–252	Ginestet et al. 2006
Septic tank cleaning	$£.(cleaning)^{-1}$	1,600	—
Septic tank cleaning frequency	—	Once every 2 years	—
NaOCl 14%	$£.l^{-1}$	0.3	Supplier

(Clerico et al. 2007; Winward et al. 2008). The chlorine residual was higher than that required under U.S. EPA guidelines, because the length of the distribution pipework and the residence time (> 30 days) provided by the product water storage tanks made ensuring a chlorine residual challenging. Undetectable levels of coliforms could not be guaranteed at all times in the tanks, despite coliforms being undetectable in the final effluent. This was addressed by shock dosing with sodium hypochlorite. These tanks were in place before installation of the water reclamation plant, are oversized for their purpose, and suffer from contamination from rainwater infiltration. Similar problems with bacterial regrowth in the distribution pipework were reported by Merz et al. (2007). The biological performance of the MBR in terms of nutrient removal has been discussed in detail (Verrecht et al. 2010a) and was in line with widely reported trends for MBRs, both on the large and small-scale (Fan et al. 2006; Abegglen et al. 2008; Gnirss et al. 2008a; Judd and Judd 2010).

Analysis of Operational Costs

Fig. 2 shows a breakdown of the operational costs for the wastewater reclamation plant. This breakdown can be compared to available cost data in literature, which is scarce and somewhat dated, as reviewed in Verrecht et al. (2010b). The total operational cost is £2.24 per m^{-3} of reclaimed water produced, 17–28 times higher than OPEX values reported for large scale MBR by Côté et al. (2004), who calculated a value of £0.09 m^{-3} for a 38,000 $m^{-3}d^{-1}$ plant and DeCarolis et al. (2004), who reported values between £0.08 and £0.13 per m^3 of permeate produced for plant sizes of 37,000 down to 700 $m^{-3}d^{-1}$, respectively, illustrating the influence of economies of scale on operational costs. Both studies included labor costs, and DeCarolis et al. (2004) also included costs for effluent disinfection with chlorine, which accounted for less than 3% of total OPEX.

The contribution of the pretreatment to total OPEX is 5%, primarily because of costs associated with septic tank cleaning required every 2 years. The MBR and the posttreatment both account for approximately 22%. However, these contributions are significantly lower than the cost of staff required for routine maintenance, plant attendance, sampling, and water quality analysis. Staffing accounts for 51% (£1.14.m^{-3}) of total OPEX, compared with 13–32% of OPEX for a large scale plant, as reported by DeCarolis et al. (2004). However, because of economies of scale, their absolute staffing costs are considerably lower (£0.01–0.04.m^{-3}). Fig. 2 also shows that the posttreatment train for color removal, primarily for esthetical reasons, increases total OPEX by 29%. This is in line with findings by Abegglen et al. (2009), who stated that a requirement for color removal increases OPEX by 10 to 30%. Thus, in a domestic environment and

Table 4. Comparison of Reclaimed Water Quality with the U.S. EPA Guidelines for Unrestricted Urban Reuse

		U.S. EPA recommended guidelines for unrestricted urban reuse	Product water quality
Parameter	Unit	Value	Value
Biological oxygen demand (BOD_5)	$g.m^{-3}$	< 10	< 1[a]
Suspended solids	$g.m^{-3}$	No suggestion	< 2[a]
Faecal coliforms	Colony forming unit (CFU) $(100\ ml)^{-1}$	No detectable	No detectable
pH	—	6–9	7.3–0.2
Turbidity	NTU	≤ 2	0.14–0.12
Cl_2 residual	$g.m^{-3}$	1 (after 30 min contact time)	1 (after 24 h contact time)

[a]Below limit of detection.

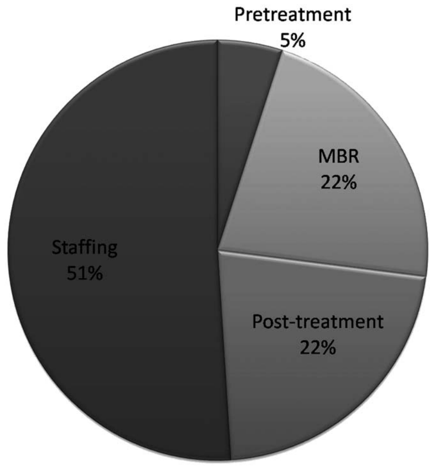

Fig. 2. Breakdown of operational costs for the wastewater reclamation plant, £2.24.m^{-3} total OPEX

especially in sustainable developments, in which inhabitants may tolerate color in toilet flushing water, the need for posttreatment of the MBR effluent could be eliminated, leading to substantial savings in capital expenditures (CAPEX) and OPEX.

Table 5 shows the major contributors to running costs for the MBR (£0.49.m^{-3}) and the posttreatment (£0.50.m^{-3}), excluding staffing costs. Energy consumption makes up 92% of the total operating costs for the MBR. Research at this plant has thus focused on reducing energy demand through intermittent membrane aeration, which has shown that sustainable operation can be achieved when running at a SAD_p of 9.2 under 10:10 aeration (Verrecht et al. 2011). Further, a modeling approach was followed to identify better operational parameters, resulting in a reduction of the MBR energy consumption from 4.03 to 3.11 kWh.m^{-3}, without compromising biological performance (Verrecht et al. 2010a). This reduces the running costs (excluding staffing costs) of the MBR by 20% but has only a minor effect on the operational costs of the entire plant (−4.4%). Table 5 also shows that the replacement cost of the granular activated carbon accounts for 69% of the total cost for posttreatment.

A simple cost sensitivity analysis (Table 6) shows that halving the plant attendance (to 4 h per week, which would be made possible through installation of remote monitoring and reducing the sampling regime) reduces OPEX by 26%. Assuming that the small-scale MBR could operate at an energy consumption of 1 kWh.m^{-3}, as typically reported for large scale plants (Brepols et al. 2010), OPEX would decrease by 14%. Conversely, this value would increase by 29% for an energy consumption of 10 kWh.m^{-3}, corresponding to the high end of values reported for small-scale MBR plants which range from 3 kWh to 11.5 kWh.m^{-3} (Boehler et al. 2007; Gnirss et al. 2008b; Verrecht et al. 2010a). An increased sludge treatment and disposal cost by 60% (423–252, as reported by

Table 5. Break-Up of Operational Costs for the MBR and Posttreatment

Parameter	Unit	MBR Value	Posttreatment Value
Energy	£.m^{-3}	0.430	0.149
Chemicals	£.m^{-3}	0.002	0.006
GAC	£.m^{-3}	—	0.348
Sludge treatment	£.m^{-3}	0.062	—
Total	£.m^{-3}	0.494	0.503

Table 6. Cost Sensitivity Analysis (Base Operational Cost: £2.24.m^{-3})

Parameter	OPEX (£.m^{-3})	Difference versus base scenario (%)
Maintenance−4h.wk^{-1}(−50%)	1.67	−26%
Energy consumption MBR		
1 kWh.m^{-3}(~ conservative value large MBR)	1.92	−14%
10 kWh.m^{-3}	2.88	+29%
Sludge treatment and disposal cost - £675.tnDS^{-1}	2.27	+1%
Plant capacity-100 m^3.d^{-1}	1.35	−40%

Ginestet et al. 2006) would increase total plant OPEX by only 1%. The influence of economies of scale is illustrated though varying the plant capacity; if plant capacity was 4 times higher (100 m^3.d^{-1}), OPEX per m^3 of reclaimed water produced would decrease by 40%, primarily because of staffing costs being static with respect to plant capacity up to a certain threshold. This demonstrates the importance of minimizing required attendance for small plants. Under the assumptions made, energy consumption would overtake staffing costs as the largest contributor to OPEX at a plant size of 51.2 m^3.d^{-1} and a specific energy demand for the MBR of 4 kWh.m^{-3}.

The previous analysis can be contrasted against large-scale MBRs, in which energy consumption is the largest contributor to operational costs (Brepols et al. 2010; Verrecht et al. 2010b) and has formed the focus of recent research and development (Garcès et al. 2007; Verrecht et al. 2008; 2010a). For small-scale MBRs, however, it is imperative that the plant design is robust and operational complexity avoided so as to minimize manual intervention. From 2 years of operational experiences on the wastewater reclamation plant, several design choices and operational parameters were identified that have a major effect on the amount of plant attendance required

- Built-in contingency: Because small-scale plants inherently have to cope with large daily influent variations (Gnirss et al. 2008a; Abegglen et al. 2008), they are generally designed to handle the maximum instantaneous influent flow. Consequently, they are overdesigned compared with their average influent flow, resulting in higher CAPEX as larger plants have to be installed, and larger OPEX attributed to inefficiencies and plant underutilization. Installation of a buffer tank can address some of these concerns. However, a large amount of built-in contingency can also be beneficial to ensure smooth operation, e.g., excess membrane area ensures that the plant can operate at low fluxes, reducing membrane fouling and the need for labor intensive recovery chemical cleaning. High hydraulic and solids retention times, 24 h and 50 days, respectively, in this case study also lead to stable biological performance.
- Membrane aeration: Because energy consumption in small-scale plants is not the main factor contributing to OPEX, optimization of membrane aeration is less important than for large plants. High aeration rates ensure stable membrane performance and reduce maintenance cleaning frequency. It may also be preferable to keep the aeration control to a minimum; valves for intermittent aeration may reduce energy consumption but present a possible cause of failure.
- Screens: Handling of screenings and cleaning screens is one of the most labor intensive tasks on-site. However, because of the presence of the excessively large septic tanks, having a hydraulic retention time of approximately 6 days, most fibers and rags that could potentially block the screens are retained and the

3-mm copasac screens are redundant. Installation of a large septic tank could therefore present a good option for small-scale plants, thus eliminating the need for additional screening. However, this potential reduction in OPEX is countered by the increased CAPEX incurred by septic tank construction.

- Influent pumps: Blockage of the influent pumps with rags, fibers, and sanitary towels is a regularly occurring problem. It is thus imperative that the influent pumps are easily accessible for cleaning purposes. Installation of oversized influent pumps, possibly with mascerator capacity, may help in reducing the number of blockages and so eliminate a source of frequent plant outages.
- Remote monitoring: Attendance/staffing costs can also be reduced by installation of remote monitoring and control, which can also benefit effluent quality and biological performance (Abegglen et al. 2008).

These operational issues show that a trade-off generally exists between CAPEX and OPEX for small-scale plants, as previously discussed for < 50 people equivalent package plant MBRs (Fletcher et al. 2007). It is generally the case that capital-intensive plants provide low operational costs because they include design elements that increase efficiency and reduce the need for maintenance and plant attendance.

On the basis of a model-based approach on the economic feasibility of on-site greywater reuse, Friedler et al. (2006) concluded that MBR-based systems were economically unrealistic, only becoming feasible when the building (or cluster of buildings) contained more than 160 apartments if no subsidies were provided for installation of such systems. This is confirmed on the example of the Solaire, a green-building in New York City, in which a life cycle costing (LCC) study by Arpke (2006) shows that a decentralized water reuse system is more expensive over a 25-year period, despite an incentive plan that includes a 25% rate reduction for such systems. However, a life cycle analysis (LCA) indicated that the decentralized water reuse system has a lower environmental effect than the conventional centralized approach.

Conclusions

A small-scale wastewater reclamation plant providing 25 $m^3.d^{-1}$ reclaimed water for toilet flushing and irrigation has been evaluated over a 2-year period, and an economic analysis performed to assess the main factors influencing operational costs. This has revealed the following:

- Operational costs are 17–28 times higher than those reported for large-scale MBRs without posttreatment, because of operational inefficiencies inherent in small-scale plants and the disproportionate amount of staff time required.
- Staffing costs incurred by plant attendance and maintenance are the largest contribution (51%) to total OPEX, followed by energy consumption (27%). This is contrary to findings for large-scale plants, in which energy costs are the dominating contributor to OPEX. The main focus for design and operation of small-scale plant should be on process robustness, limiting operational complexity so as to minimize manual intervention.
- Posttreatment of the MBR effluent, required primarily for aesthetic reasons, adds significantly to OPEX (29%). If reclaimed water color is acceptable for toilet flushing in a domestic environment the need for posttreatment can be eliminated, providing considerable CAPEX and OPEX savings.
- If posttreatment and labor are excluded, OPEX costs are approximately five times higher than those reported for large-scale plants, commensurate with the higher specific energy consumption of smaller plants.

A more comprehensive analysis on the basis of the life cycle analysis would establish the true cost benefit of installation of remote monitoring so as to reduce labor costs.

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