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The optimal MBR configuration: Hybrid versus stand-alone – comparison between three full-scale MBRs

P. Krzeminski[a], W. Langhorst[b], P. Schyns[c], D. de Vente[d], R. Van den Broeck[e], I.Y. Smets[e], J.F.M. Van Impe[e], J.H.J.M van der Graaf[f], J.B. van Lier[a]

[a] Department of Water Management, Section Sanitary Engineering, Delft University of Technology, Stevinweg 1, PO Box 5048, 2600 GA Delft, The Netherlands
E-mail: p.krzeminski@tudelft.nl
[b] Waterschap Hollandse Delta, Handelsweg 100, 2988 DC Ridderkerk, The Netherlands
[c] Waterschap Rijn en IJssel, Liemersweg 2, 7006 GG Doetinchem, The Netherlands
[d] Waterschap Regge en Dinkel, Kooikersweg 1, 7609 PZ Almelo, The Netherlands
[e] BioTeC – Chemical and Biochemical Process Technology and Control, Chemical Engineering Department, Katholieke Universiteit Leuven, W. de Croylaan 46, 3001 Leuven, Belgium
[f] Witteveen+Bos, van Twickelostraat 2, PO Box 233, 7400 AE Deventer, The Netherlands

Abstract
Construction or modernization of a wastewater treatment plant (WWTP) with membrane bioreactor (MBR) technology requires selection of optimal configuration and design. The objective of this paper is to evaluate a hybrid MBR, i.e., a combination of a conventional activated sludge (CAS) process and an MBR, in comparison to a stand-alone MBR. This paper evaluates two different hybrid MBR configurations and a stand-alone MBR. The impact of these MBR configurations on operation, performance, energy consumption and economy is evaluated. A hybrid MBR operated in series provides certain operational flexibility, ensures more stable conditions for the activated sludge leading to a more stable MBR operation at energy and cost efficient conditions. Nevertheless, determination of the optimal plant configuration depends on the particular local situation.

Keywords
membrane bioreactor; hybrid configuration; design and operation; energy and cost analysis

INTRODUCTION

Membrane bioreactors (MBR) have become a more accepted municipal wastewater treatment process alternative and the amount of full-scale MBR plants is continuously increasing [1]. Growth in plant numbers is accompanied with diversity of configurations and design concepts. The MBR technology is commonly applied to new wastewater treatment plants (WWTPs), but they are also introduced in case of upgrades or retrofits of already existing WWTPs [2-4]. There are several reasons why wastewater treatment plants need to be modernized, for example, old and out-dated infrastructure, equipment upgrade, more stringent effluent quality requirements and insufficient hydraulic or biological capacity due to increasing pollution load.

There are also different options on how to modernize WWTPs with MBR technology. Whereas optimal design selection is very individual and site specific, two general solutions can be distinguished. One of the options is to completely replace the existing system with a newly built MBR, with or without reuse of the old infrastructure. In this case all incoming wastewater is treated in a stand-alone MBR (Figure 1a), also called separate, complete, full or classic MBR [5, 6]. Another option is to utilize existing buildings and infrastructure to combine old and new processes into a hybrid system, also known as dual configurations [6, 7]. In the hybrid design, part of the wastewater is treated in the conventional activated sludge process (CAS) and part is treated in the MBR. As such, CAS treatment is combined with MBR treatment which can be operated either in parallel (Figure 1b) or in series (Figure 1c).

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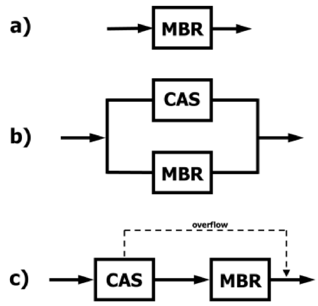

Figure 1. Schematic representation of basic configurations: (a) stand-alone, (b) parallel and (c) serial.

Advantages of hybrid MBRs compared to stand-alone MBRs are well reported in literature [2, 6, 8-10] and, among others, are extended lifetime of the old CAS system, lower membrane surface requirement due to treatment of the peak flows outside of the MBR, continuous operation at optimal designed conditions which results in energy efficient operation, cost effective option of WWTP retrofit, less membranes and infrastructure utilization reducing the investments costs. One of the obvious disadvantages of the hybrid concept is the bigger footprint of the plant because of the required surface needed for the CAS system and possibility of incidental discharge of suspended solids, bacteria and viruses due to potential overflow or bypassing of the peak flows. In addition, when less membrane is installed they need to be frequently used and, in consequence, rest periods of the membranes are limited. Therefore, life-time of the membranes due to often shorter 'out of operation' periods is probably shorter.

Hybrid MBR concepts were successfully established for treatment of domestic wastewater at full-scale in Schilde [11-14], Heenvliet [10, 15-18], Ootmarsum [19-22], Rietliau [23], Viareggio [24, 25], Ulu Pandan [26], Terneuzen [27], St. Peter ob Judenburg, Brescia and Eitorf [2].

The recent full-scale results and experience significantly broadened the understanding of the associated processes. However, despite the increase in applicability, information regarding the influence of a particular design on operation and performance is only scarcely available. Moreover, available information is scattered and hardly published and thus transfer of knowledge is very limited.

Our present work provides information on design concepts and plant configurations, and their impact on operation, performance, energy consumption and economy of the MBR plant. The specific objective of this study is to evaluate a hybrid concept of MBR design, i.e., a combination of a conventional activated sludge (CAS) process and an MBR, in comparison to a stand-alone MBR. Finally, advantages and disadvantages of each particular design are presented and discussed.

MATERIAL & METHODS

MBR plants description

Three full-scale MBR plants treating municipal wastewater and located in the Netherlands were under investigation. Two of the plants are hybrid installations and one is a stand-alone MBR. A detailed description of the investigated plants is presented in Table 1.

Table 1. Characteristics of the plants.

Parameter	Unit	Hybrid 1	Hybrid 2	Stand-alone
WWTP configuration	-	MBR+CAS	MBR+CAS/SF	MBR
MBR configuration	-	parallel and serial	parallel	stand-alone
Location	-	Heenvliet	Ootmarsum	Varsseveld
Membrane type	-	Flat sheet (FS)	Tubular (MT)	Hollow fibre (HF)
Membrane supplier	-	Toray	Norit	Zenon-GE
Total membrane area	m^2	4,115	2,436	20,160
Biological Capacity	p.e.	3,333	7,000	23,150
Hydraulic capacity (DWF)	$m^3.h^{-1}$	38-50	75	250-300
Hydraulic capacity (RWF)	$m^3.h^{-1}$	100	150	755
Average Flux (DWF)	$l.m^{-2}.h^{-1}$	12-24	26-40	15-25

Legend: SF – sand filter; DWF - dry weather flow; RWF - rain weather flow

Data collection and processing

Three full-scale MBR plants were monitored for a period of 2 years, both in summer and winter period. During this period filterability of activated sludge, as a quality indicator of the MBR filtration process, was quantified experimentally by the Delft Filtration Characterization method (DFCm). The filterability results were compared with automated image analysis results and collected process data of the plants. Several process parameters of each MBR are monitored and collected by the Waterboards at each location. The most important parameters that were under investigation include influent flow, permeate flow, flux, transmembrane pressure, permeability, temperature, pH, mixed liquor suspended solids concentration (MLSS) and dissolved oxygen concentration. In addition, several characteristics of influent and effluent were analysed, e.g., chemical oxygen demand (COD), biological oxygen demand (BOD), total kjeldahl nitrogen (TKN), total nitrogen (N-Total) and total phosphorous (P-Total). Together with the removal efficiency information, the performance of the MBR plants was evaluated in environmental and economical terms based on major performance indicators as proposed by Benedetti *et al*. [28] and Yang *et al*. [29]:

- effluent concentration of pollutants (mg/L),
- removal efficiencies of pollutants expressed as % of incoming load,
- energy consumption per volume of treated wastewater (kWh/m^3), and
- operational costs per population equivalent load (€/PE).

The energy consumption data, reported as kWh, are based on the electric power consumed at each investigated location. The specific energy consumption data are reported as specific electricity consumption per volume of treated wastewater and expressed as kWh/m^3. During the energy studies, total and specific energy consumption data were analysed, emphasizing the relation to treated flow, design capacity, membrane area and effluent quality. Additionally, economic studies were performed analysing the cost efficiency in design and operation of the full-scale MBR plants.

The Delft Filtration Characterization method (DFCm)

Delft University of Technology has developed a small-scale filtration characterization installation combined with a measuring protocol to investigate the activated sludge filterability. The DFCm comprises several steps, from the determination of membrane resistance to the membrane cleaning. For detailed description of the installation and method reader is referred to Evenblij *et al*. [30] and Van den Broeck *et al*. [31].

The main output of an experiment is the evolution of the resistance during filtration plotted as a function of the permeate production per unit of membrane surface. As a result of the membrane fouling during filtration, filtration resistance will increase. The slope of the curve gives an indication of the activated sludge filterability, e.g., a steep curve corresponds to poor filterability. For easy comparison between different tests, the value ΔR_{20} is used (Table 2) based on the classification proposed by Geilvoet [32]. This value is defined as the increase in resistance after a specific permeate production of 20 L/m^2.

Table 2. ΔR_{20} and corresponding filterability qualification.

ΔR_{20} [$10^{12} m^{-1}$]	Qualification
0 - 0.1	Good
0.1 - 1.0	Moderate
> 1.0	Poor

Activated sludge images

Activated sludge images are captured manually from two 10µL drops on a carrier slide using a light microscope (Olympus BX 51) with phase contrast illumination (Ph1) and a total magnification of 100 times. The microscope was equipped with a 3CCD colour video camera (Sony DXC-950p) which was connected to a computer. Microscopic images were digitized and stored as JPG (768x576 pixels) using Zeiss KS100.3 acquisition software.

RESULTS & DISCUSSION

MBR operation

Differently designed municipal MBRs had a very similar type of activated sludge, as confirmed by the microscopic activated sludge images (Figure 2) and by the filtration characterisation tests performed on samples originating from the membrane tanks. However, significant differences in activated sludge filterability, expressed by the ΔR_{20} parameter, were observed between the seasons (Figure 3). Also Van den Broeck *et al*. [31] observed improved activated sludge filterability in summer as compared to winter samples.

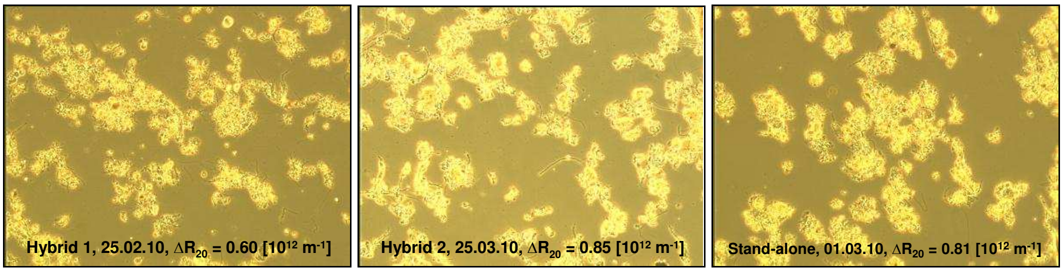

Figure 2. Microscopic images (x100, Ph1) of activated sludge from: (a, b) hybrid and (c) stand-alone MBRs.

During summer periods of 2008 and 2009, filterability of activated sludge measured in the three plants was qualified mainly as moderate ($0.1<\Delta R_{20}<1.0$) or good ($\Delta R_{20}<0.1$), respectively. In the case of Hybrid #1 MBR, samples were described as moderately filterable during both experimental campaigns. The results obtained during winter periods show in general moderate activated sludge filterability unless abnormal events appear. For instance peculiar chemical composition of the incoming wastewater or rapid temperature drop due to heavy storm and snow melt. The latter phenomenon was observed in the winter of 2009 and resulted in poor filtration behaviour. An abnormal event can occur in both hybrid and stand-alone configurations and often results in poorly filterable activated sludge. As a consequence, operation of the MBR is hampered and the performance can be affected.

In a stand-alone MBR, activated sludge is submitted to more frequent and rapid changes due to variations in the characteristics of incoming flow and results in unsteady-state operation [33]. Whereas depending on the operation concept of the hybrid system, i.e., parallel or serial, the probability of an operational upset as a consequence of activated sludge quality deterioration varies. In a parallel system, MBR and CAS are operated as two separate and stand-alone treatment plants. Hence, the likelihood of the operational upset is similar to the one in a stand-alone MBR. Conversely, in a hybrid MBR operated in series, the CAS system precedes the MBR and creates a buffer zone that provides the required time for the microorganisms to adapt to new conditions and consequently more stable conditions for the activated sludge are achieved [34-36]. This advantageous effect was most likely the reason for the better activated sludge filterability observed in Hybrid #1 MBR, both in summer and winter, during in series operation in 2008-2009, compared to parallel operation in 2009-2010 (Figure 3).

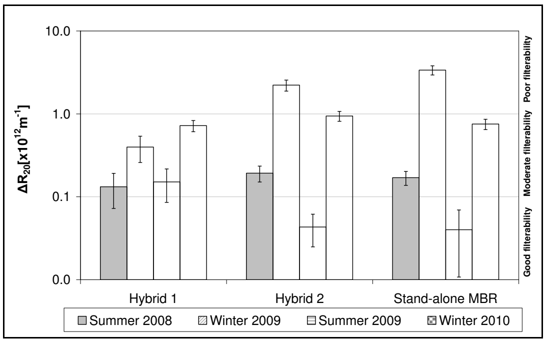

Figure 3. Filterability of activated sludge from hybrid and stand-alone MBRs.

Both concepts differ also in an operational strategy concerning excess flow treatment during rain weather conditions, i.e., peak flows, in case of connection to the combined sewer system. In a stand-alone MBR, incoming stormwater is treated exclusively by the MBR and may result in a nearly 3.5 times higher flow compared to the average dry weather flow. Typical flow patterns of the incoming wastewater, expressed as a 1 hour trend line and as a function of plant utilization (% of nominal Dry Weather Flow, i.e. incoming flow during dry weather conditions), in both configurations are presented in Figure 4.

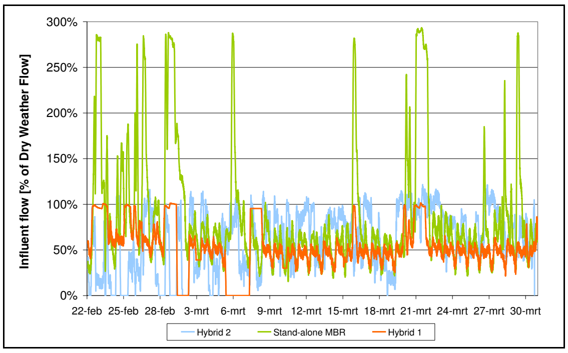

Figure 4. Comparison of MBR influent flow in hybrid and stand-alone MBRs.

Furthermore, in a stand-alone MBR configuration, overflow or bypassing of peak flows is not possible. Hybrid MBRs on the other hand, most often have an overflow option through the CAS system. Hence, one of the key advantages of the hybrid concept is the possibility of dealing with peak flows that exceed the hydraulic membrane capacity of the MBR. This results not only in lower membrane surface requirements but it also has an influence on the operation of the MBR. It provides operational flexibility for the operators and allows them to react upon certain situations. Therefore, in most cases, it enables stable MBR operation as the plant is less sensitive to abrupt changes, e.g., temperature shifts and hydraulic flow fluctuations. Contrary, in the stand-alone configuration, the whole system is more vulnerable to rapid changes, e.g., intensive rainfall combined with the snow melt results in a severe temperature drop of incoming wastewater and can seriously affect membrane operation for several hours or even a few days. The aforementioned reasons were responsible for 80% increase in the gross flux and 40-45% drop of permeability in winter 2009 (Figure 5). Figure 5 compare applied fluxes, activated sludge filterability and process permeability in three MBRs during the consecutive weeks of experimental periods.

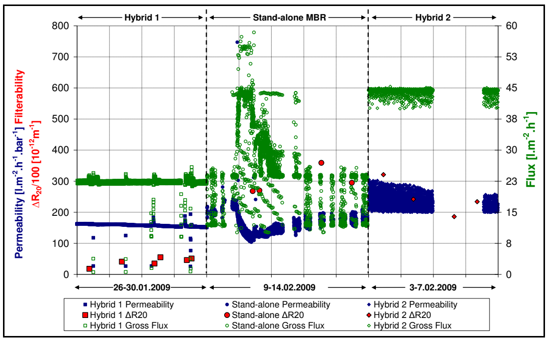

Figure 5. Comparison of applied fluxes, activated sludge filterability and process permeability in Hybrid #1, Hybrid #2 and the stand-alone MBR.

MBR performance

All three types of investigated MBRs removed COD, BOD and N-Total far below national and European discharge requirements with efficiencies of about 92-95% and 98-99% for COD and BOD, respectively. Good removal efficiencies of TKN were also achieved in all of the plants, i.e., 96-98% removal to concentrations of about 2.0 mgN/L.

Phosphorous removal efficiency in the hybrid MBRs was in the range of 67-72% and 73-74% in 2008 and 2009, respectively. Phosphorous removal of 94-96% reaching P-Total concentrations of 0.4-0.7 mgP/L was attained in the stand-alone MBR. However, better performance in the stand-alone MBR is not a result of particular design selection, but an effect of phosphorous removal in combination with the dosage of iron chloride sulphate. In the investigated hybrid MBRs chemicals are not added, which resulted in phosphorous removal of 67-74% and somewhat higher concentrations in the effluent, namely 1.7-2.2 mgP/L.

In case of hybrid MBRs the permeate produced by the MBR is mixed with the effluent of the CAS system before final discharge. Mixing of the CAS effluent and MBR permeate had negligible effect on the quality of the total combined effluent produced in both hybrid MBRs. For example, in case of the Hybrid #2 MBR the COD, BOD and N-Total concentrations increased up to 30 mg/L, 2.3 mg/L and 3.8 mg/L, respectively; values still below the requirements. Furthermore, in some cases, concentrations can actually be lower than in the MBR permeate as observed for N-Total (Hybrid #1) and P-Total (Hybrid #2) in Table 3, in agreement with the predictions of Futselaar *et al.* [20]. Hence, it can be concluded that selection of hybrid MBR configuration for communal wastewater treatment plants has no significant impact on effluent quality, especially with respect to the current discharge requirements. Nevertheless, potential differences in the effluent quality could probably be observed in the concentration of total suspended solids and in terms of disinfection, i.e., presence of bacteria and viruses. However, those parameters were not measured during this project.

The summary of overall performance of the investigated MBRs, in terms of pollutants removal efficiency, with minimum, average and maximum values, is presented in Table 3.

Table 3. Effluent characteristics and removal efficiencies of the three investigated MBRs.

MBR Performance			Permeate from MBR					Total effluent from WWTP					Removal efficiency			
			COD	BOD	N-Total	P-Total	TKN	COD	BOD	N-Total	P-Total	TKN	COD	BOD	P-Total	TKN
			mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	%	%	%	%
Hybrid 1	2008	Min	8	1.0	0	0.3	0.5	12	1.0	1.1	0.5	0.8				
		Mean	25	1.7	3.0	2.2	1.0	28	2.0	3.5	2.5	2.0	92	98.5	67	98
		Max	94	44	13	7.6	3.0	55	14	13	5.5	6.0				
		St. dev.	9	4.3	1.9	1.3	0.4	6	1.6	1.7	1.1	1.1				
	2009	Min	6	1.0	0.7	0.2	0.3	5	0.3	0.9	0.5	0.2				
		Mean	24	1.3	4.2	1.9	1.1	29	2.0	3.6	3.6	1.9	93	99.0	73	97
		Max	58	3.9	8.6	5.8	3.0	49	5.0	8	7.6	4.2				
		St. dev.	7	0.5	1.8	1.4	0.4	7	0.9	1.0	1.1	0.7				
Hybrid 2	2008	Min	15	0.5	1.4	0.1	0.6	16	0.5	1.9	0.6	0.7				
		Mean	23	0.9	3.6	2.0	1.5	24	1.3	3.7	1.6	1.5	95	99.5	72	97
		Max	46	2.2	8.7	11	7.7	40	3.3	6	6.4	4.4				
		St. dev.	5	0.4	2.0	2.1	1.1	4	0.7	1.1	1.1	0.6				
	2009	Min	15	0.5	1.5	0.1	0.5	19	0.5	1.4	0.2	0.9				
		Mean	24	0.8	3.6	1.7	1.7	30	2.3	3.8	1.2	2.0	95	99.6	74	96
		Max	39	2.1	8.8	5	7.3	71	9.3	11	4.0	6.8				
		St. dev.	5	0.3	1.7	1.4	1.2	10	1.8	1.9	0.8	1.1				
Stand-alone MBR	2008	Min	16	0.5	1.4	0.1	0.8	16	0.5	1.4	0.1	0.8				
		Mean	25	0.9	3.9	0.4	2.1	25	0.9	3.9	0.4	2.1	96	99.7	96	96
		Max	33	1.9	15	1.2	13	33	1.9	15	1.2	13				
		St. dev.	5	0.4	2.9	0.3	2.5	5	0.4	2.9	0.3	2.5				
	2009	Min	12	0.5	2.3	0.1	1.0	12	0.5	2.3	0.1	1.0				
		Mean	25	0.8	5.8	0.7	1.8	28	0.8	5.8	0.7	1.8	96	99.7	94	96
		Max	36	1.6	20	3.2	3.8	36	1.6	20	3.2	3.8				
		St. dev.	6	0.3	3.8	0.7	0.7	6	0.3	3.8	0.7	0.7				

Energy consumption

The specific energy consumption of the MBR in Hybrid #1 varied between 0.8-1.8 kWh/m^3 and was on average 1.1 kWh/m^3. For the total plant, thus for the combined MBR and CAS systems at Heenvliet, the specific energy consumption ranged between 0.3-1.1 and was on average 0.6 kWh/m^3. During the project, Hybrid #1 has been operated both in parallel and in series. When considering those two operational concepts – serial and parallel – a clear difference is observed in favour of the serial concept. The average energy consumption during in series operation was 0.75 kWh/m^3 compared to 1.15 kWh/m^3 during parallel operation, mainly due to a better utilization of the available membrane capacity (Figure 7).

It was also observed that the Hybrid #1 MBR consumed less energy for operation and maintenance comparing to the stand-alone MBR, although only during in series operation. The specific energy consumption of the stand-alone MBR varied between 0.6-1.4 kWh/m^3 and was on average 0.84 kWh/m^3, approximately 12% more than Hybrid #1 MBR during in series operation. However, after 5 years of operational experience with the stand-alone MBR further energy reduction is expected with a goal to reach 0.7 kWh/m^3 during normal MBR operation [37].

Figure 6 presents the energy consumption distribution of the MBR equipment for the hybrid MBR operated in series (Figure 6a) and in parallel (Figure 6b) as well as for stand-alone MBR (Figure 6c). Observed differences arise rather from the different membrane configurations installed in each plant, namely flat sheet and hollow fibre, and consequently certain operational requirements such as aeration strategy, than from the selected design configuration.

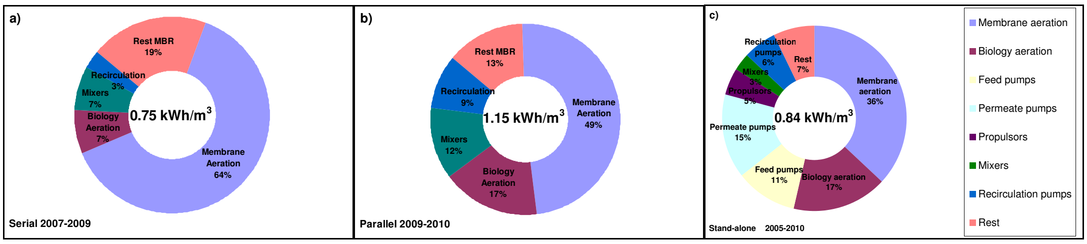

Figure 6. Energy consumption distribution of MBR equipment for Hybrid #1 MBR during (a) serial and (b) parallel operation and for (c) stand-alone MBR.

According to Figure 7a, the specific energy consumption in the Hybrid #1 MBR is higher during the period of parallel operation compared to in series operation. The permeate production was reduced by more than a half and consequently the specific energy consumption of the MBR increased while at the same time the total energy consumption decreased. Therefore, despite sub-optimal flow conditions, operation following the parallel concept can be energy efficient. However, at least 50% overall MBR utilization is required.
The impact of membrane capacity usage on energy consumption follows from the efficiency increase with the treated flow (Figure 7). Hence, the highest specific energy efficiency is attained when operating the MBR under optimal flow conditions, i.e., close to the design flow at dry weather conditions. Figure 7b shows the flow dependency of differently designed MBR plants, i.e., one stand-alone and two hybrid MBRs. It also shows the added value of CAS implementation in the hybrid concept. The specific energy consumption of the total Hybrid #1 WWTP, is nearly half (40% lower) of the Hybrid #1 MBR whereas the concentrations of N-Total and P-Total in the entire WWTP effluent increased by a maximum of 0.5 mg/L and 0.4 mg/L, respectively.

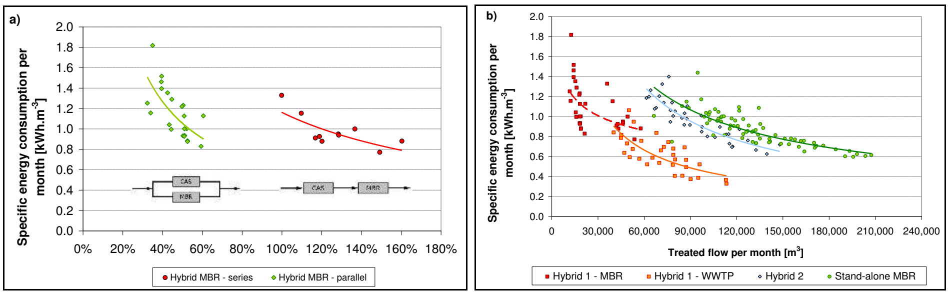

Figure 7. Energy consumption in relation to the flow for different design concepts: (a) Hybrid#1 in parallel (2008-2009) and serial (2009-2010); and (b) Hybrid#1 (2008-2010), Hybrid#2 (2008-2010) and stand-alone (2005-2010).

Figure 8 presents the specific energy consumption as a function of the plant design capacity. In general, the capacity of the plant does not determine the energy efficiency of the installation. The observed improvement for Hybrid #1 is a logical consequence of an operational concept change from serial to parallel where only a small fraction, i.e., 25%, of the influent is treated in the MBR. Higher specific energy consumption values for Hybrid #2 MBR are only partially explained by the energy consumption associated to the sand filter which is incorporated in the CAS process line. Another explanation could be found in excessive aeration and limited possibilities of fine-tuning and reducing blower input for the aeration. The fact that the biological load is lower and the alpha-factor is better than expected during the design also contributes to excessive aeration, which owing to technical reasons cannot be lowered. Furthermore, presence of small basins and compartments with numerous, not optimally operated, small mixers and abovementioned aeration issues contribute to the higher energy consumption in Hybrid #2.

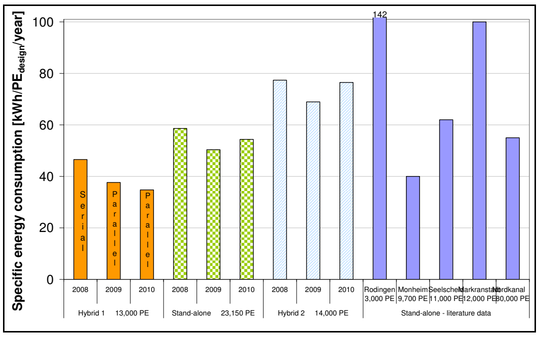

Figure 8. Energy consumption as a function of plant design capacity (1 PE$_{design}$ is equal to pollution load of 54 g BOD/day). German MBRs adopted from (Pinnekamp 2008).

The normalized energy consumption of the entire plant, expressed in kilowatt-hours per removed pollution load, was 81 kWh/PE$_{removed}$, 86 kWh/PE$_{removed}$ and 58 kWh/PE$_{removed}$ for the Hybrid #1, Hybrid #2 and stand-alone MBR, respectively. The PE$_{removed}$ value is the pollution load removed in the WWTP based on WWTP removal efficiencies in the 2008-2009 period and expressed as population equivalents based on 150 g of total oxygen demand (TOD, equal to COD + 4.57*TKN). Therefore, in this particular case, the stand-alone MBR required less energy to remove the same amount of pollutants than the hybrid MBRs, and is as such more energy efficient in this aspect.
The specific energy consumption per area of installed membranes was lower for the stand–alone MBR equipped with hollow fibre membranes. Thus, in terms of membrane surface specific energy consumption (in kWh/m^2), big MBR installations are more energy efficient compared to the small ones. Additionally, operation of side-stream membranes is the most energy demanding. However, because side-stream systems can apply higher fluxes, it needs less membranes than submerged systems and thus requires lower capital costs. When results are compared for similar capacity, side-stream systems require approximately 60-70% less membranes. Therefore, design of hybrid installations with tubular side-stream membranes allows to significantly reduce the required membrane area and possibly, if the price of the tubular membranes is not more than 60-70% expensive than submerged membranes, to lower capital costs even further.

Operational and capital costs

The selection of a particular configuration has an impact on the capital (CAPEX) and operational (OPEX) costs. In general, retrofitting an old conventional treatment plant with the hybrid MBR concept is more cost effective than replacing the entire system with a stand-alone MBR [7, 20, 38]. However, reusing old infrastructure while retrofitting an old WWTP into a stand-alone MBR also reduces capital costs [39]. As has been previously noted, hybrid concepts benefit from lower membrane surface requirement and, consequently, reduced investments costs. Besides, retrofitting a plant allows to utilize old structures to further reduce capital costs. Moreover, installed equipment can be designed for and operated at stable average flows in order to provide optimal work conditions and cost efficient operation.
At the same time investment costs for a hybrid plant in the case of new WWTPs can be higher due to the larger footprint of the plant because of the required land surface needed for the CAS system. In addition, installation of a smaller amount of membranes is also associated with some drawbacks. The lifetime of the membranes might be, depending on operational strategy, shorter due to the continuous operation of the filtration step. In the hybrid configurations the membranes have often shorter ‘out of operation’ periods and therefore, are likely ageing faster compared to the membranes in stand-alone configurations. Necessary adaptation to the treatment of peak flows requires a larger membrane surface which can, if configured so, create multiple process lines which can be operated alternately. In this situation higher number of installed membranes allow resting the membranes more frequently and probably extends their service life [8].

Average operational costs of the stand-alone MBR were 0.29 €/m^3 of treated wastewater in 2009 (Figure 9c). Dosage of iron chloride sulphate for chemical phosphorous removal result in additional chemical costs (6%) but also in significantly lower phosphorous concentrations in the effluent. Addition of required capital expenditure costs increase the total costs to 0.45 €/m^3.
Average operational costs of the total Hybrid #2 were 0.24 €/m^3 over a period of 2008-2009 (Figure 9b). The average operational costs of the total Hybrid #1 plant, thus, combined CAS and MBR, were 0.13 €/m^3 over a period of 2008-2010 (Figure 9a). When only the MBR is considered, the operational

costs increase to 0.29 €/m^3. Furthermore, during 22 months of parallel operation average operational costs of the MBR were 0.37 €/m^3 comparing to 0.17 €/m^3 during 14 months of in series operation. Obviously, the MBR in the parallel concept is hindered by operation under sub-optimal flow conditions and is consequently less cost-efficient, approximately by a factor of 2. In the parallel concept, costs of MBR operation are close to, yet still lower, than costs of stand-alone MBR operation. Therefore, both hybrid concepts are associated with lower operational costs compared to stand-alone MBR which is in accordance with Verrecht *et al.* [26]. Also Bixio *et al.* [6, 9] analysed the potential and economical aspects of two hybrid solutions for WWTP refurbishment in Bulgarian and Cyprus' markets. They reported a possibility of minimal cost reduction of 20-25% if hybrid MBR is selected.

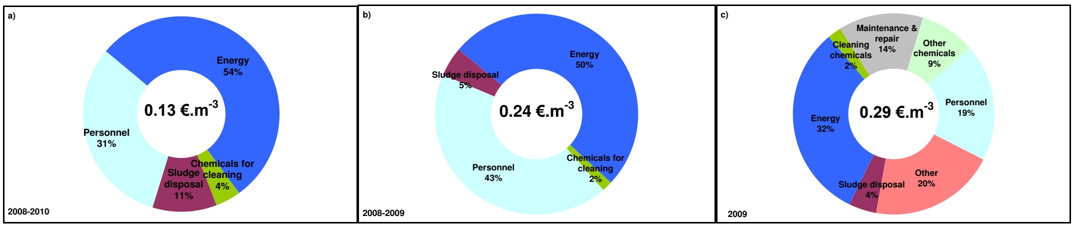

Figure 9. Operational cost distribution for (a) Hybrid #1 (b) Hybrid #2 and (c) stand-alone MBRs.

The normalized costs of the plant operation, expressed in Euro per removed pollution load per year, were 15.6 €/$PE_{removed}$, 23.6 €/$PE_{removed}$ and 17.2 €/$PE_{removed}$ for Hybrid #1, Hybrid #2 and stand-alone MBR, respectively. The benchmark value, based on data collected in 2009 from all of the treatments plants in the Netherlands, was 23.7 €/$PE_{removed}$ [40].

CONCLUSIONS

We carefully evaluated three full-scale MBR concepts in the Netherlands: two hybrid MBRs and one stand-alone MBR. In the hybrid configurations, an MBR is combined with a CAS system. Determination of the optimal plant configuration depends on the particular local situation, i.e. presence and condition of old infrastructure, availability of equalization tanks and space requirement. In the case of a CAS retrofit, if the CAS system is still in good condition a hybrid configuration is usually preferred. However, in case of a new WWTP, the stand-alone concept has the potential to be the most optimal option. Additionally, when retrofitting an old WWTP one should seriously consider utilization of old infrastructure to equalize peak flows. When analysing the performance data it was clear that the principle choice, i.e., hybrid or stand-alone, largely impacts the overall MBR functioning:

- A stand-alone MBR is generally more vulnerable to rapid changes compared to the hybrid configurations. Hybrid configurations provide operational flexibility and therefore, in most of the cases, enable stable MBR operation.
- In serial hybrid concept, the CAS system acts as a hydraulic and biological buffer zone which ensures more stable conditions for the activated sludge in the MBR.
- In the stand-alone and parallel operated hybrid MBRs, activated sludge is more often submitted to unsteady-state conditions that increase the likelihood of an operational upset.
- A sudden perturbation may occur in both configurations, resulting in poorly filterable activated sludge. As a consequence, operation of the MBR is hampered and the performance can be affected.
- Selecting a hybrid MBR configuration and the associated mixing of MBR permeate with CAS effluent has no significant impact on final effluent quality, especially with respect to the current discharge requirements.
- Only during operation in series, a hybrid MBR has 10.7% lower specific energy consumption for operation and maintenance than a stand-alone MBR.
- Depending on biological design, stand-alone MBR is also more energy efficient in terms of energy demand per amount of removed pollution load compared to hybrid MBRs: 58 kWh/$PE_{removed}$ versus 81-86 kWh/$PE_{removed}$.
- Operation of any MBR under optimal flow conditions and with high membrane surface utilization ensures good energy efficiency of about 0.8 kWh/m^3.
- Hybrid concepts are associated with at least 17% lower operational costs, compared to stand-alone MBR.

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